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Utilization of Fuel Cells to Beneficially Use Coal Mine Methane

Final Report

James T. Brown
Darien G. O'Brien
Arnold R. Miller
Robert Atkins
Mike Sanders

March 1996

Work Performed Under Contract No.: DE-AC21-95MC32190

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

MASTER

By
Wendt & Associates, Inc.
Golden, Colorado

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COAL MINE METHANE

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April 1996

ABSTRACT

The U.S. Bureau of Mines and the Environmental Protection Agency estimated that in 1991, 190 to 300 billion cubic feet of methane was released to the atmosphere. Of this total, 70 to 80% was the result of underground coal mining operations. Aside from this being a waste of a potential energy source, methane has been identified as one of the gases responsible for global climate change. Although the concentration of methane in the atmosphere is only 1/200th that of carbon dioxide, the radiative forcing potential is many times that of CO₂. The atmospheric concentration of methane is increasing twice as fast as carbon dioxide. Methane emissions are expected to rise 1% annually.

As part of the Clinton Administration's Climate Change Action Plan, the Department of Energy (DOE) has been given the responsibility to encourage industry to recover and use methane that is currently being released to the atmosphere. Wendt & Associates, Inc., a Golden, Colorado based engineering consulting firm, in a coordinated effort with Solutions Engineering in Lakewood, Colorado, the Colorado School of Mines Joint Center for Fuel-Cell Vehicles in Golden, Colorado, and the Left Fork Mining Company, Inc. in Arjay, Kentucky are proposing technology that will beneficially utilize this energy source.

Historically the mining industry has not viewed methane as a resource. The existence of methane in an underground mine presents a great hazard as mixtures of methane and air are combustible over a wide range of concentrations. Methane has contributed to a large number of serious accidents. To reduce the hazard methane presents, the mining industry has developed systems to remove methane gas from the mine.

At this time the only method being employed at the Left Fork Mine to remove methane is the mine ventilation system. Data for the methane content of the ventilation air at the Left Fork Mine, as analyzed by the Department of Labor, was obtained. Consistently, the methane content was measured at one one-hundredth of a percent. We are not aware of any economically viable processes that can effectively recover this small fraction of methane.

To prevent this methane from being vented to the atmosphere, degasification wells are proposed. These wells could be drilled into the coal seam prior to the coal being mined. Over a five year period these wells could recover approximately 22% of the methane that exists in the coal. This methane would be of sufficient quality to be used in normal applications or sold to a pipeline.

Solutions Engineering, working with information presented by the Bureau of Mines, the United States Geological Survey, the Department of Energy and the Left Fork Mine estimated the methane gas reserves that exist in the mine. This estimate is based on current mine expansion plans. Using this information and a three dimensional dual porosity -- single permeability simulator, forecasts of methane production rates for various degasification well arrangements were made. This information indicated that

the degasification wells could deliver methane in sufficient quantities to be of beneficial use.

To use the coal mine methane, Wendt & Associates, Inc., is proposing a demonstration project to generate electricity. Working with the Colorado School of Mines Joint Center for Fuel-Cell Vehicles it is proposed to use phosphoric-acid fuel cells to convert methane to electric power. These fuel cells contain (1) a steam reformer to convert the methane to hydrogen (and carbon dioxide), (2) the fuel cell stack, and (3) a power conditioner that provides 200 kW of 60 Hz alternating current output. Thus from a methane input, the power plant provides a high quality, high reliability alternating current output that can be used on the mine site. The exhaust is high purity water and carbon dioxide.

There are several sources of methane available at the Left Fork Mine. It has been proposed that methane could be recovered from the abandoned workings; there are 4 abandoned degasification wells drilled during an earlier DOE / Bureau of Mines project that could be re-entered and placed on production; the petroleum affiliate of the company that owns the Left Fork Mine has drilled a gas well into a deeper horizon near the surface facilities and if required new degasification wells could be drilled.

The environmental impacts and benefits of using this technology are summarized in the report. The study indicates the methane emission reduction that could be achieved on a National and Global level. The important point being that this technology is economically viable as is demonstrated in the report.

Phase I of this project, the feasibility study, was completed in 60 days. Phase II which will perform the engineering required to install a fuel cell at the mine will be completed over the next twelve months. Phase II will address issues such as which methane source is the most practical, where to locate the fuel cell and how the electrical energy can best be utilized.

FORWARD

This report was prepared by Wendt & Associates, Inc. Golden office under DOE Contract No. DE-AC21-95MC32190. The contract was administered by the Morgantown Energy Technology Center (METC), Morgantown, WV, under the direction of the DOE's Office of Fossil Energy with Charles W. Byrer acting as Project Manager. Ms. Laura E. Brandt served as the Contract Administrator for the DOE. This report is a summary of the work completed as Phase 1 of this contract during the period of July 5, 1995 to September 5, 1995. The information contained in this report was compiled from on-site investigations, publications, open-file reports, and personal communications with those familiar with the geology, coal and coalbed methane emissions of the area. This report contains no patentable materials or features.

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I. EXECUTIVE SUMMARY

The Phase I part of this project consisted of four tasks. These tasks were: 1) Determine the mine gas potential, 2) Evaluate the coal mine methane reserves, 3) Technology application and 4) Topical report of proposed technology application. The first three tasks have been completed and by issuing this report the fourth task has been completed.

The following is a summary of the tasks and the conclusions that resulted:

Determine Mine Gas Potential

After visiting the mine it was determined that there have been no coal samples taken from the Left Fork Mine that have had desorption tests run to determine the amount of methane contained in the coal. Therefore, published data had to be used to determine the methane resources in place. Further investigations indicated it is not completely clear as to the correlation between LFM coals and other coal seams in the region. Finally a reference was found that indicated the Rim correlates to the Jellico coal in the surrounding area, and the Straight Creek is analogous to the Blue Gem.

These correlation's were used to extract information from published data to make an estimate of the gas in place. As a check, the work of Ann G. Kim was used to corroborate the gas content estimates that were determined from the USGS and USBM data. It was determined that the Rim seam contains 177 scf/ton and the Straight Creek contains 237 scf/ton. Total gas in place in the Rim and Straight Creek seams for the Left Fork Mine amounts to 20 billion standard cubic feet.

Evaluate the Coal Mine Methane Reserves

Currently the only methane recovery system that is in operation at the Left Fork Mine is the mine ventilation system. At the present time the mine is being ventilated by a 150 HP fan moving 140,000 scf per minute. Ventilation air analysis performed by the US Department of Labor, Mine Safety and Health Administration (MSHA) consistently measured the methane content at 0.01% (one one-hundredth of one percent). Currently there is no commercially available system that can economically recover this amount of methane from the ventilation stream.

To recover methane from the coal, it has to occur prior to the coal being mined and the methane entering the ventilation system. This can be accomplished by drilling degasification wells into the coal seam, hydraulically fracturing the coal and producing the essentially pure methane from these wells. The amount of methane that can be recovered depends on the length of time the degasification wells are allowed to produce. After five years a stimulated degasification well drilled on 36 acre spacing (the equivalent of 5 panels) will recover 22% of the in-place methane. If allowed to

produce for 25 years, 50% of the in-place gas can be recovered. This gas will be pure methane and is suitable for normal uses, or could be sold to a pipeline.

This information was then used to determine the National and Global impacts of implementing this technology to reduce methane emissions.

Technology Application

The technology being proposed is the use of a phosphoric acid fuel cell fueled by methane to generate electric power. The phosphoric acid fuel cell is proven off-the-shelf technology. There are over 60 of these cells in operation throughout the world at this time. A 200 kW cell requires 40,000 cubic feet of methane per day to power the cell. Initially three degasification wells will be required to provide this volume of fuel. Within two years an additional two wells will be required because of the expected 10 % *effective* decline in well productivity.

Because the main emphasis of this project is the use of a fuel cell, not the drilling of degasification wells, other methane sources may be pursued. There are several potential sources of methane at the Left Fork Mine.

The petroleum affiliate of Left Fork Mining, Company Inc., Cumberland Harlan Exploration Corporation, recently (February 1995) drilled a gas well into a deeper horizon. This well is located just south of the coal preparation plant. This well should have the potential to deliver 40 mcfpd methane. It has been proposed that methane could be recovered from abandoned workings by drilling a well into the abandoned mine. This source should provide essentially pure methane. There are four abandoned degasification wells drilled into the Rim coal seam. These wells were drilled during an earlier DOE/Bureau of Mines project. These wells have been hydraulically fractured in the Rim coal seam, but were never produced and were abandoned. It may be possible to re-enter these wells and place them on production. The conclusion is that: ***a suitable source of methane exists at the mine location.***

Important points to keep in mind are 1) gas ownership is not an issue, the mine owner owns the surface and all of the minerals, including the gas 2) the current mine owners have a good relationship with Kentucky Utilities, 3) because the mine owner owns the surface and right-of-way, siting concerns are simplified.

The resulting conclusion is it should be possible to find a source for the methane. The fuel cell is proven technology. The mine has a need for cost effective electric power and the economics of the project can be easily demonstrated. The resulting recommendation is that the Left Fork Mine is an excellent location for demonstration of the fuel cell technology.

II. INTRODUCTION

The United States is estimated to be one of the world's three largest emitters of methane from coal mining; the other two are the People's Republic of China and the former Soviet Union. U.S. coal mines account for an estimated 10 to 15 percent of methane emissions from coal mining worldwide [USEPA, April, 1993].

Coal mining is currently the third largest source of methane emissions in the United States, accounting for about 17 percent of total U.S. methane emissions. Underground mines account for about 75 percent of total methane emissions. The Northern and Central Appalachian coal basins have the largest number of underground coal mines and are therefore the major contributors of U. S. methane emissions from coal mining. Less than 10 percent of gas from these underground coal mines have been recovered and the remaining 90 percent is currently being vented to the atmosphere [USEPA, April, 1993].

Methane is very effective at absorbing infrared radiation (IR) reflected by the earth's surface. By absorbing IR and inhibiting its release into space, methane in the atmosphere contributes to increased atmospheric and surface temperatures. This process is commonly referred to as the "greenhouse effect". It has been estimated that approximately 18 percent of the greenhouse effect is due to increasing atmospheric methane concentrations. Methane's global concentration has more than doubled over the last two centuries, after remaining fairly constant for the proceeding 2000 years and continues to rise. Reductions in methane emissions of only 10 percent of annual anthropogenic (human related) emissions, would halt the annual rise in methane concentrations. Based on reported emissions data from a variety of countries, it appears that anywhere from 10 to 50 percent of the total methane emissions could be recovered with currently available recovery and use technologies. Barriers to the development of these recovery and use options depend on the country and the technology used, but frequently include: investment capital shortages, lack of resources, difficulties in maintaining gas quality, and regulatory or institutional barriers related to a country's coal mining or energy sector [USEPA, July, 1993].

For this reason, the United States Department of Energy's Morgantown Energy Technology Center issued a request for proposal to demonstrate existing technologies at a specific mine site for the recovery and utilization of coal mine methane. To the best of our knowledge, no current coal mine in the U. S. has recovered methane and used a phosphoric acid fuel cell to generate power for use at the mine site or for sale back to the power grid. This is the focus of this demonstration, using a Central Appalachian coal mine.

III. PURPOSE

The purpose of this program is to: 1) Determine the methane reserves associated with the Left Fork Mine located near Arjay, Kentucky. 2) Determine what portion of the methane is being vented to the atmosphere. 3) Investigate the feasibility of using waste methane from the underground mine to power a fuel cell to generate electricity. and 4) Estimate what impact implementation of this technology would have on both National and Global methane emissions.

The Department of Energy (DOE) program is divided into three phases. Phase I, this portion of the program, is the feasibility study to determine if it would be feasible to utilize fuel cells powered by waste methane to generate electric power at a mine setting. Phase II will be the engineering effort required to perform the work necessary to implement the technology and Phase III is the actual installation of the selected technology, in this case, a fuel cell.

IV. BACKGROUND

Wendt & Associates, Inc. (WAI), Solutions Engineering and the Colorado School of Mines Joint Center for Fuel-Cell Vehicles are working with Left Fork Mining Company, Inc. personnel to develop the project. The mine where the technology will be applied is the Left Fork Mine, located near Arjay, Kentucky. The fuel cell will be powered by methane, a by-product of the underground mining process. The mine is located in Southeast Kentucky, just north of the point where Tennessee, Virginia and Kentucky meet. Figure 1 is a map of the area [Murrie, et. al., 1984].

A. Mine History

Brian Whitfield purchased the mine in 1920 and was responsible for the excavation of the slope into the mine. The mine was operated by the Bell Coal Company as the Straight Creek Mine #1 from the 1920's to 1955. From 1955 to 1970 the property lay idle. In 1981 Eastover Mining, a subsidiary of Duke Power, re-entered the mine and developed both the Rim and Straight Creek coal seams. From 1983 to 1994 ownership changed several times, however, no sustained mining occurred. Left Fork Mining Company, Inc. of Brookside, Kentucky purchased the mine in July of 1994. The mine was renamed the Left Fork Mine. De-watering was initiated in November of 1994 and active mining began in March, 1995.

Currently the mine employs a staff of 30 working two active areas in the Straight Creek seam. Present production is 300 tons per area per day or 600 tons per day. Much of the area mined during the early period has been abandoned and sealed off from the current active mining areas. Figure 2 shows the areas currently being mined and the abandoned workings. The preparation plant is idle. It is planned to re-build the preparation plant.

B. General Information

The mine owner owns the minerals, and the surface (approximately 6010 acres) located in Bell and Knox Counties. There is one gas well, one oil well, one dewatering well and four abandoned coal bed degasification wells on the property as shown in Figure 3. The coal bed degasification wells were drilled in 1982 during an earlier DOE / US Bureau of Mines project where wells were drilled and hydraulically fractured in the coal seam. As mining operations progress the fracture was to be mined and observations made as to the effectiveness of the fracturing and if damage to the roof occurred. At the Left Fork Mine, mining was discontinued before the mine-by activities were completed [Murrie, et. al., 1984].

FIGURE 1
Regional Map Showing Location of Left Fork Mine

FIGURE 2
Mining Areas and Abandoned Workings

FIGURE 3
Structure Contours on Rim Seam Base with Well Locations

Bell County has a moderate oil and gas industry. According to records at the Kentucky Geological Survey, there are currently 174 oil and gas wells in the County. Two natural gas pipelines exist in the vicinity of the mine: an 8" diameter line approximately 2 miles north of the northwest edge of the property and a 6" diameter line two miles to the southeast. Both pipelines are operated by Delta Natural Gas Company, Inc.

Electrical power is provided to the mine by Kentucky Utilities. Presently the mine is paying \$.035 per kWh demand and \$.03 per kWh load for a total of \$.065 per kWh. The mine owners have a good relationship with Kentucky Utilities.

C. General Geologic Setting

The Left Fork Mine is located in the Central Appalachian Coal Region. The mine is located in the southern portion of the Cumberland Plateau. The mine is situated less than 5 miles north of a complexly faulted area which includes the White Mountain, Dorton Branch and Pine Mountain Overthrust Fault Zones. The Pine Mountain Fault marks the northern boundary of the Cumberland Overthrust -- a geologic feature about 120 miles long and 25 miles wide, trending northeast - southwest. The overthrust disrupts the coal-bearing strata and renders mining along the zone impossible. Within short distances from the zone, such as at the location of the Left Fork Mine, however, the seams are relatively flat and appear to be relatively unaffected. No faults are known to occur on the property, and no faults were encountered underground.

Two coal seams have been mined in the Left Fork Mine. The Rim coal, located about 140 feet below drainage and the Straight Creek coal, 80 - 100 feet below the Rim. Both the Rim and Straight Creek coals are part of the Lower and Middle Pennsylvanian. There is not widespread agreement as to the correlation of the Rim and Straight Creek coals with other predominant coals in the surrounding areas. The main coalbed of the Rim coal zone, also known as the Moss coalbed, has been correlated with the Amburgy coalbed, however, the Rim is probably an older coalbed as much as 400 feet below the thin Amburgy equivalent which underlies the Kendrick Shale of Jillison; it is probably the same as the Jellico coalbed [Froelich, et. al., 1973]. The Rim coal zone is commonly overlain by bluish-gray silty shale, but in some areas it is overlain by a cross-bedded sandstone. The Straight Creek coalbed in Bell County has been correlated with the Jellico coalbed, however, the principle coalbed in the Straight Creek coal zone of this quadrangle is probably an older coalbed possibly as much as 200 feet below the stratigraphic position of the Jellico. It is probably the same as the Blue Gem [Froelich et. al., 1973]. Figure 4 is a generalized stratigraphic section of the mine area [Murrie, et. al., 1984].

Figure 5 is an isopach of the Straight Creek Seam. Seam thickness ranges from 28 to 44 inches in thickness. The Straight Creek dips to the northeast at about 0.5°. Both the Rim and the Straight Creek are below drainage in the area of the mine. The area is characterized by crooked valleys, winding ridges, steep slopes and flat land is scarce.

FIGURE 4
Generalized Stratigraphic Section

LEGEND

Coal		Shale
Sandstone		Underclay
Sandy shale		

FIGURE 5
Isopach of Straight Creek Seam

A section of the topographic map of the area is shown as Figure 6. Maximum relief in the area of the mine is 600 - 1000 feet.

Both the Rim and Straight Creek have a rank of high-volatile B bituminous. Their sulfur content is usually less than 1% on an as-received basis [Murrie, et. al., 1984].

D. Mining Techniques

Access to the mine (Rim and Straight Creek) is by both slope and shaft. For the Straight Creek two continuous miners are being used in two active areas of the mine. A room-and-pillar recovery technique is employed. Coal is removed from the face using conveyors. There are plans to mine the Rim Seam using long wall mining. Therefore, any technology employed to recover methane from the Straight Creek coal, located below the Rim coal, has to provide for the eventual mining of the upper seam.

E. Methane Emissions

Methane is vented from the mine using two ventilation fans, a 150 HP fan located at the slope entrance to the mine and a 600 HP fan located near the elevator shaft. With the current level of activity at the mine, only the 150 HP fan is presently in operation. Air flow from this fan is 140,000 cubic feet per minute (201 million cubic feet per day, 24 hour day). When operating, the 600 HP fan can move 500,000 to 600,000 scfm. The maximum methane content of the ventilation stream is 1% (mine has to be evacuated when this is exceeded).

Recovering the less than 1% methane from the ventilation stream represents the process engineering equivalent of the "needle in a haystack". Without enrichment, the ventilation stream would not be a suitable fuel for a fuel cell. The stream would require enrichment prior to use. We are not aware of any processes that could efficiently handle this volume of throughput and recover the small fraction of methane economically.

As a result, our efforts will be concentrated on recovering the methane prior to its entering the ventilation stream. Once the methane reaches the ventilation air we can see no practical way to recover the hydrocarbon gas.

FIGURE 6
Topographic Map of Area

V. METHODOLOGY

The methodology used to evaluate the volume available and quality of methane from the Left Fork Mine involved several steps:

- Review available public information (USGS, USBM, MSHA) to obtain gas content and methane emissions data.
- Mine specific information related to coal properties including thickness and depth, areal extent, formation pressure and temperature, existing drainage techniques, current and planned mine expansion plans.
- Gas analysis performed to determine quality of methane source(s).
- Calculation of methane gas in place.
- Use of a commercially available coalbed methane simulator, COMET2™, to obtain gas production forecasts based upon various drainage scenarios (number of degas wells, well spacing, number of coal seams providing methane source and effects of hydraulic fracturing on production performance).
- Determine the number of degas wells required to provide a continuous fuel source for the fuel cell(s).

A. Review Available Public Information

The determination of gas content for the Left Fork Mine's two coal seams (Rim and Straight Creek) was determined from public information sources. No coal samples have been taken for the purpose of performing desorption tests to determine gas content, adsorption isotherms, etc. Several sources of public information were used to obtain an estimate for this information as follows:

USBM: Direct measurement desorption data from the U. S. Bureau of Mines (see Table 1) for coalbeds in counties surrounding Bell County where the Left Fork Mine is located have estimates ranging between 32 to 102 cf/ton. [Diamond, W. P., et. al., 1981 and 1986].

TABLE 1
U. S. Bureau of Mines Direct Measurement Desorption Data

Coalbed	State	County	Sample Depth ft	Lost Gas cc/gm	Desorbed Gas cc/gm	Residual Gas cc/gm	Total Gas Content	
							cc/gm	cf/ton
Pond Creek	KY	Pike	125	0.2	1.2	0.7	2.1	67
		Floyd	132	0.0	0.2	0.8	1.0	32
		Martin	400	0.1	1.4	1.4	2.8	90
		Pike	500	0.1	0.8	0.3	1.2	38
		Mingo	1070	0.1	0.5	2.6	3.2	102

One problem with these estimates is that they are not corrected to standard temperature and pressure conditions, and are not specific to the coalbeds at Left Fork Mine. Discussions with W. P. (Pat) Diamond at the USBM (who was one of the authors of this data source) suggested that this information be used cautiously for these reasons, and that the numbers reported are within ± 10 percent of the standard temperature and pressure results [Diamond, 1995]. In comparison, data for the gasiest coal seam in the Central Appalachian (Pocahontas No. 3) has gas content measurements varying between 339 and 573 cf/ton (again not corrected to standard conditions) [Diamond, W. P., et. al., 1981]. Discussions with Left Fork Mine personnel felt that the Rim and Straight Creek coal seam's gas content probably lie somewhere between the neighboring county and Pocahontas No. 3 estimates.

USGS: A reservoir simulation study of U. S. coalbed methane was conducted in support of the USGS CD Rom, "1995 National Assessment of United States Oil and Gas Resources" [Young, et. al., 1995]. In this simulation effort, properties for Central Appalachian coals were estimated to determine desorption of methane as described by a Langmuir isotherm [Langmuir, 1916] according to:

$$C(p) = \frac{V_L p}{(p_L + p)} \quad (\text{Equation 1})$$

where $C(p)$ is the gas concentration, p is the coal cleat pressure, V_L is the maximum amount of gas that can be adsorbed and p_L is a characteristic pressure which is a measure of the residence time for a gas molecule on the surface. The USGS data provided values from Central Appalachian coalbeds (determined from laboratory adsorption isotherm measurements) for p_L of 157 psia and V_L of 540 scf/ton (or if divided by the coal density V_L is 17 scf/ft³) which result in the adsorption isotherm depicted in Figure 7. The average depth (below drainage) to the midpoint of the Rim seam is 144 feet and is 250 feet to the midpoint of the Straight Creek seam. Using a hydrostatic gradient of 0.433 psi/ft yields coal cleat pressures of 77 psia and 123 psia at these depths for the Rim and Straight Creek seams, respectively. Therefore, computed values for gas content based upon the Langmuir isotherm give results of 177 scf/ton and 237 scf/ton for the Rim and Straight Creek seams, respectively.

Other properties that were used from this USGS source included the sorption time, cleat porosity and permeability, cleat spacing, initial water saturation and water PVT and relative permeability properties.

USBM: Proximate analysis data were available for the coal seams considered to be analogous to the Rim (Jellico) and Straight Creek (Blue Gem) coal seams as shown in Table 2 [Keystone, 1980].

FIGURE 7
Adsorption Isotherm

TABLE 2
Proximate Analysis of Coals Analogous to Rim and Straight Creek

State	Formation Group	Coalbed	Moisture %	Volatile Matter %	Fixed Carbon %	Ash %	Sulfur %	BTU
North TN	Slatestone	Jellico	2.0 - 7.6	30.8 - 39.4	45.3 - 59.6	1.9 - 18.2	0.7 - 3.2	11,690 - 14,210
		Blue Gem	3.4 - 5.7	36.8 - 39.8	51.1 - 56.3	1.2 - 5.2	0.7 - 2.2	13,480 - 14,300

Using correlations developed by Kim [Kim, 1977 and 1978] estimates for gas content from proximate analysis data for the analogous coal seams give estimates of 190 scf/ton and 240 scf/ton for the Jellico and Blue Gem, respectively (see Table 3).

TABLE 3
Estimation of Gas Content from Proximate Analysis Data by Kim Method

Coal Seam	Analog Seam	Depth ft	Pressure psia	h m	P atm	FC %	VM %	ko	no
Rim	Jellico	143.63	76.89	43.78	5.232	52.45	35.10	6.80	0.30
Straight Creek	Blue Gem	250.00	122.95	76.2	8.366	53.70	38.30	6.72	0.30

Coal Seam	Analog Seam	b	Vw/Vd	Moisture + Ash + Sulfur %	Proximate Anal. Gas Content		COMET2 Gas Content scf/ton
					cm ³ /g	scf/ton	
Rim	Jellico	0.14	0.75	16.80	5.94	190.26	177.52
Straight Creek	Blue Gem	0.14	0.75	9.20	7.50	240.21	237.16

Abbreviations/Computations:
FC - Fixed Carbon
VM - Volatile Matter
ko - constant, in cubic centimeters per gram per atmosphere
ko = 0.8 FC/VM + 5.6
no - constant
no = 0.315 - 0.01 FC/VM
b - constant, in cubic centimeters per gram per degree Celsius, average value is 0.14
Vw/Vd - ratio of adsorptive capacity in moist and dry coal; in the absence of other data, the amount of gas adsorbed in moist coal can be estimated as 75 % of that adsorbed on dry coal

Gas Content Correlation: $V, \text{cm}^3/\text{g} = \frac{(100 - \% \text{moisture} - \% \text{ash})}{100} \frac{V_w}{V_d} [k_o P^n - b(\frac{1.8h}{100} + 11)]$

These numbers corroborate the USGS numbers within 6.7% for the Rim and 1.3% for the Straight Creek. Discussions with Ann Kim (author of the correlation) stated that her correlation has been used successfully when adsorption data is not available and has been found to be within $\pm 30\%$ of direct measurement determinations [Kim, 1995]. For the purposes of performing simulations, the Langmuir results based upon the USGS data were used.

MSHA: A calculation was made to determine if the GIP numbers that were calculated were reasonable. Assuming the mine experiences a normal working day and 600 tons of coal are mined from the Straight Creek seam. Using this information, 600 tons of coal would contain 142,200 scf of methane (600 tons X 237 scf/ton). With the ventilation fan running 24 hours, 202 million scf of air would be circulated through the mine each day. If all of the gas contained in the coal were liberated in the mine and carried out by the ventilation air, the methane content in the ventilation stream would be equal to 0.07% (142,200 / 201,600,000). Figure 8 is a tabular and graphical display of the Department of Labor MSHA data for methane content in the ventilation stream from the Left Fork Mine. Since all of the methane contained in the coal is not liberated in the mine, and it would be difficult to determine how much remains in the coal, all we can say is we are in the ball park. At least we are calculating the same order of magnitude as what is measured.

If the MSHA data that has been gathered since last November were used and the above calculation were performed in reverse, a GIP of 33 scf/ton results (201 million scf/d, 20,000 scf methane emitted). The only conclusion that can be drawn is the real number is probably greater than 33 scf/ton.

FIGURE 8
Department of Labor / MSHA Measured Methane Content in Ventilation Air

Date	Measured Methane Concentration %	Ventilation Rate scf/min	Methane Emission scf/day
7/21/92	0.01	160000	23040
9/22/92	0.14	140000	282240
9/22/92	0.14	140000	282240
1/4/93	0.04	150000	86400
1/21/93	0.05	150000	108000
1/23/93	0.05	150000	108000
1/25/93	0.01	149600	21542
1/28/93	0.01	149500	21528
2/18/93	0.01	150000	21600
3/18/93	0.01	149500	21528
3/23/93	0.03	149500	64584
3/29/93	0.02	150000	43200
3/29/93	0.02	150000	43200
3/30/93	0.01	148000	21312
4/28/93	0.01	172200	24797
4/28/93	0.01	172200	24797
7/6/93	0.01	155012	22322
7/6/93	0.01	155000	22320
11/23/94	0.01	132300	19051
11/23/94	0.01	132300	19051
1/9/95	0.01	118900	17122
2/21/95	0.01	91140	13124
3/1/95	0.01	115200	16589
3/1/95	0.01	115200	16589
7/31/95	0.01	138008	19873
Average	0.0264	143342	54562

Data Source - US Department of Labor
 Mine Safety and Health Administration
 Analysis of Ventilation Samples

B. Mine Specific Information

Figure 5 shows an isopach of the Straight Creek seam obtained from borehole measurements conducted at Left Fork Mine. Planimetered volumes (as shown in Table 4) give average thickness of 2.75 feet over a 6010 acre area. The areal extent of the overlying Rim seam is the same as the Straight Creek seam. Left Fork Mine personnel estimate that the Rim seam's average thickness over this area is 10 feet. The Rim seam is a multi-bedded unit usually containing two coal benches split by a shale parting (Figure 4). Drilling data obtained by the 4 DOE wells northeast of current mining operations (Locations shown on Figure 3) showed that the seam contains as many as five coal benches in a 7.6 feet seam and as few as one bench as thin as 1.9 feet [Murrie, et. al., 1984].

Discussions with Left Fork Mine personnel concerning the amount of water associated with the Rim and Straight Creek seams suggest that the Rim is wetter. An initial water saturation of 10% was assigned for both seams. This is comparable to the USGS data for other Central Appalachian coalbeds.

A bulk coal density of 70 lb per cubic feet was reported by Robert Atkins, Left Fork Mining Engineer. Correcting this for ash, sulfur and moisture content (10%) gives an in-situ density of 63 lb per cubic feet.

The panel dimensions are 260 feet by 1220 feet. Pillar dimensions are 40 feet by 40 feet and Room dimensions are 20 feet by 20 feet. According to mine personnel, 1 unit shift working 8 hours/day will remove coal from one panel in 2 1/2 months. The mine currently has 2 unit shifts working per day, removing 300 tons/unit/day from two separate panels for a total of 600 tons/day. It is anticipated that during the course of one year, the equivalent of 5 panels will be developed by the 2 unit shifts. The mine is looking to increase the number of unit shifts from 2 to perhaps 4 by year-end, and perhaps to 6 next year, depending upon market conditions.

TABLE 4
Straight Creek Seam Planimetered Volume

Planimeter Constant: 1 unit = 200.00 acres									
Isopach Region	Isopach Contour (inches)	Contour Interval (inches)	Area Enclosed (Planimeter Units)	Isopach Contour (ft)	Contour Interval (ft)	Area Enclosed (acre)	Trapezoidal Rule Volume (acre-ft)	Pyramidal Rule Volume (acre-ft)	Average Trapezoidal Pyramidal Volume (acre-ft)
NW	36	1	0.03	3.00	0.0833	6.00	1.00	0.50	
NW	34	2	0.20	2.83	0.1667	40.00	6.67	3.42	
NW	32	2	0.52	2.67	0.1667	104.00	17.33	11.58	
NW	30	2	0.80	2.50	0.1667	160.00	26.67	21.83	
NW	28	2	1.80	2.33	0.1667	360.00	30.00	42.22	
NW	28	28	1.80	2.33	2.3333	360.00	840.00	840.00	
						TOTAL:	921.67	919.55	920.61
SW	36	1	0.83	3.00	0.0833	166.00	27.67	13.83	
SW	34	2	3.40	2.83	0.1667	680.00	113.33	65.67	
SW-SE	32	2	15.74	2.67	0.1667	3148.00	524.67	293.95	
SW-SE-NE	30	2	26.09	2.50	0.1667	5218.00	869.67	689.94	
SW-SE-NE	28	2	28.25	2.33	0.1667	5650.00	470.83	905.43	
SW-SE-NE	28	28	28.25	2.33	2.3333	5650.00	13183.33	13183.33	
						TOTAL:	15189.50	15152.15	15170.83
NE	36	1	0.72	3.00	0.0833	144.00	24.00	12.00	
NE	34	2	1.02	2.83	0.1667	204.00	34.00	28.86	
NE	32	2	5.58	2.67	0.1667	1116.00	93.00	99.84	
						TOTAL:	151.00	140.70	145.85
SE	40	1	0.91	3.33	0.0833	182.00	30.33	15.17	
SE	38	2	1.86	3.17	0.1667	372.00	62.00	45.23	
SE	36	2	3.34	3.00	0.1667	668.00	111.33	85.47	
SE	34	2	6.35	2.83	0.1667	1270.00	105.83	158.84	
						TOTAL:	309.50	304.71	307.10
								TOTAL:	16544.39

C. Gas Analysis to Determine Quality of Methane Source(s)

Figure 9 shows the anticipated per day methane requirements for a fuel cell based on various operating efficiencies. A conservative estimate for efficiency of 40% was assumed such that 200 scf/day methane is required per kW of power. This assumes that the quality (as represented by mol % composition) of methane in the natural gas is 90 - 95 %. In order to determine the quality of methane from the coal source, gas samples were obtained and a gas/vapor fractional analysis was performed by Pantechs Laboratories, Inc., Lubbock, Texas.

Two gas samples were collected from the Cumberland Harlan #1 LFM well annulus and casing (well location is shown in Figure 3, gas analysis for annulus and casing included as Tables 5 and 6, respectively). This well was drilled through the Rim and Straight Creek seams to the Devonian Shale at a total depth of 3500 feet below ground level. This well was drilled in February, 1995, was fracture stimulated using nitrogen and then shut-in. The well was cemented across and below the Rim & Straight Creek seams to the total depth. The source of gas for the upper annulus gas sample, between the borehole and casing, comes from coal gas, whereas the deeper Devonian Shale is the source for the casing gas sample. The gas composition (mol %) in the annulus (coal gas) sample is 94% methane, 2% ethane and 4% nitrogen with very little contaminants. In comparison, the composition for the casing (Devonian Shale gas) sample is 69% methane, 11% ethane, 4% propane, 1% higher molecular weight hydrocarbon gases and 15% nitrogen. The high nitrogen content in the Devonian Shale sample is believed to be from the nitrogen used to stimulate the well.

The required methane quality, concentration and pressure for operating a fuel cell is discussed in a later section of this report (see section VI. Feasibility of Proposed Fuel Cell System, part C: Feasibility Issues). The conclusion reached is that based upon the annulus gas sample (coal gas), the quality of the methane gas is well suited for use in the fuel cell and will not degrade its power output.

FIGURE 9
Fuel Cell Efficiency vs. Methane Volume Requirements

TABLE 5
Cumberland Harlan #1 Gas Well, Annulus Sample (Coal Gas)
Gas/Vapor Fractional Analysis

806-797-4325 • P.O. BOX 64489 • LUBBOCK, TX 79464-4489
 806-669-6821 • P.O. BOX 2439 • PAMPA, TX 79066-2439

GAS/VAPOR FRACTIONAL ANALYSIS

SAMPLE ID	COMPONENT	MOL %	GPM
CUSTOMER..... CUMBERLAND HARLAN	NITROGEN	4.028	0.443
EXPLORATION	CO2	0.036	0.006
STATION NO.... LEFT FORK #1 - ANNULUS	H2S	-----	-----
OPERATOR..... CUMBERLAND HARLAN EXPLOR.	OXYGEN	-----	-----
LEASE..... LEFT FORM MINING	HELIUM	-----	-----
PURCHASER.....	HYDROGEN	-----	-----
SAMPLE OF..... WELL HAEQ	ARGON	-----	-----
PRESSURE..... 5#	METHANE	93.806	15.932
TEMPERATURE... 90F	ETHANE	1.645	0.441
ATM. TEMP.....	PROPANE	0.405	0.112
SAMPLE DATE... 08/11/95	I-BUTANE	0.025	0.008
SAMPLE TIME... 12:30 PM	N-BUTANE	0.042	0.013
SAMPLED BY.... MIKE SANDERS	I-PENTANE	0.006	0.002
ANALYSIS DATE. 08/22/95	N-PENTANE	0.007	0.002
SAMPLE CYL. NO PL 2052	HEXANE+	0.000	0.000
	TOTALS:	100.000	16.959

CALCULATIONS/METHODS

REAL GAS, 14.73 PSIA & 60F
 APPLICABLE CURRENT GPA METHODS,
 PROCEDURES, AND CONSTANTS ARE USED.

DISTRIBUTION

3-MICHAEL P. SANDERS
 836 EUCLID AVE., SUITE 303
 LEXINGTON, KY, 40502

GASOLINE CONTENT (GPM)

ETHANE & HEAVIER	0.578
PROPANE & HEAVIER	0.137
BUTANES & HEAVIER	0.025
PENTANES & HEAVIER	0.004
26# GASOLINE	0.006

HEATING VALUE (GROSS BTU/CF)

WATER VAPOR SATURATED ..	977.6
DRY	993.7

SPECIFIC GRAVITY

WATER VAPOR SATURATED ..	0.5858
DRY	0.5850

COMPRESSIBILITY FACTOR (Z)

WATER VAPOR SATURATED ..	0.99769
DRY GAS BASIS	0.99800

COMMENTS

LABORATORY SULFUR DETERMINATION

=====

HYDROGEN SULFIDE = 0.05 GRAINS/100 CU FT
 = 0.8 RPM VOLUME
 MERCAPTAN = 0.00 GRAINS/100 CU FT

TABLE 6
Cumberland Harlan #1 Gas Well, Casing Sample (Devonian Shale Gas)
Gas/Vapor Fractional Analysis

806-797-4325 P.O. BOX 84489 LUBBOCK, TX 79484-4489
 806-689-6821 P.O. BOX 2439 PAMPA, TX 79066-2439

GAS/VAPOR FRACTIONAL ANALYSIS

SAMPLE ID	COMPONENT	MOL %	GPM
CUSTOMER..... CUMBERLAND HARLAN	NITROGEN	14.674	1.613
EXPLORATION	CO2	0.035	0.006
STATION No.... LEFT FORK #1 - CASING	H2S	-----	-----
OPERATOR..... CUMBERLAND HARLAN EXPLOR.	OXYGEN	-----	-----
LEASE..... LEFT FORM MINING	HELIUM	-----	-----
PURCHASER.....	HYDROGEN	-----	-----
SAMPLE OF..... WELL HAED ...	ARGON	-----	-----
PRESSURE..... 478#	METHANE	68.838	11.699
TEMPERATURE... 90F	ETHANE	11.225	3.010
ATM. TEMP.....	PROPANE	3.768	1.041
SAMPLE DATE... 08/11/95	I-BUTANE	0.227	0.074
SAMPLE TIME... 1:15 PM	N-BUTANE	0.779	0.246
SAMPLED BY.... MIKE SANDERS	I-PENTANE	0.100	0.037
ANALYSIS DATE. 08/22/95	N-PENTANE	0.154	0.056
SAMPLE CYL. NO PL 1183	HEXANE+	0.202	0.087
	TOTALS:	100.000	17.869

CALCULATIONS/METHODS

REAL GAS, 14.73 PSIA & 60F
 APPLICABLE CURRENT GPA METHODS,
 PROCEDURES, AND CONSTANTS ARE USED.

DISTRIBUTION

3-MICHAEL P. SANDERS
 836 EUCLID AVE., SUITE 303
 LEXINGTON, KY. 40502

GASOLINE CONTENT (GPM)

ETHANE & HEAVIER	4.551
PROPANE & HEAVIER	1.541
BUTANES & HEAVIER	0.500
PENTANES & HEAVIER	0.180
26# GASOLINE	0.278

HEATING VALUE (GROSS BTU/CF)

WATER VAPOR SATURATED ..	1030.0
DRY	1047.0

SPECIFIC GRAVITY

WATER VAPOR SATURATED ..	0.7306
DRY	0.7322

COMPRESSIBILITY FACTOR (Z)

WATER VAPOR SATURATED ..	0.99700
DRY GAS BASIS	0.99735

COMMENTS

LABORATORY SULFUR DETERMINATION

=====

HYDROGEN SULFIDE = 0.08 GRAINS/100 CU FT
 = 1.2 PPM VOLUME
 MERCAPTAN = 0.00 GRAINS/100 CU FT

D. Calculation of Gas Resources in Place

The calculation of methane gas resource in place is accomplished via the formula:

$$GIP = GC * h * A * \rho \quad (\text{Equation 2})$$

GIP = Gas in place (cubic feet)
 GC = Gas content (cubic feet/ton)
 h = Total coal thickness (feet)
 A = Mineable area (acres)
 ρ = Coal density (tons/acre-foot)

Computations for GIP on a per panel basis for each seam are shown in Table 7. The Rim seam GIP/panel = 17.74 MMscf (assuming an average thickness of 10 ft) while the Straight Creek seam GIP/panel = 6.52 MMscf (for an average thickness of 2.75 ft). Assuming the same 6010 acre areal extent, the total GIP would therefore be 14.64 Bscf for the Rim seam and 5.38 Bscf for the Straight Creek seam.

TABLE 7
Computations for Gas-In-Place by Seam and per Panel

SUMMARY FOR RIM SEAM:		SUMMARY FOR STRAIGHT CREEK SEAM:	
TOTAL Volume:	16544.39 acre-ft	TOTAL Volume:	16544.39 acre-ft
TOTAL Acres:	6010.00 acres	TOTAL Acres:	6010.00 acres
Avg Thickness:	10.00 ft	Avg Thickness:	2.75 ft
Avg Thickness:	120.00 inches	Avg Thickness:	33.00 inches
GIP = GC*h*A*RHO		GIP = GC*h*A*RHO	
GC =	177.52 scf/ton	GC =	237.16 scf/ton
h =	10.00 ft	h =	2.75 ft
A =	6010.00 acres	A =	6010.00 acres
RHO =	1372.14 ton/acre-ft	RHO =	1372.14 ton/acre-ft
GIP =	1.464E+10 scf	GIP =	5.38E+09 scf
FOR A PANEL WITH DIMENSIONS (260 ft X 1220 ft):		FOR A PANEL WITH DIMENSIONS (260 ft X 1220 ft):	
GIP = GC*h*A*RHO		GIP = GC*h*A*RHO	
GC =	177.52 scf/ton	GC =	237.16 scf/ton
h =	10.00 ft	h =	2.75 ft
A =	7.28 acres	A =	7.28 acres
RHO =	1372.14 ton/acre-ft	RHO =	1372.14 ton/acre-ft
GIP =	1.77E+07 scf	GIP =	6.52E+06 scf

E. Fractured Reservoir Simulator COMET2™

E. 1 Description/Theory

To carry out the computations required to forecast gas production, a dual porosity/single permeability coalbed methane reservoir simulator was used. COMET2™ is a three-dimensional, two-phase, fully implicit, finite-difference fracture reservoir simulator specifically designed for coalbed methane engineering evaluations. Coal cleat-matrix represents a well-defined dual porosity – single permeability system as described by Warren and Root [Warren, Root, 1963]. The coal matrix consists of a microporous system through which gas diffuses to the fractures. The dual porosity function of the simulator models methane diffusion in the coal matrix and Darcy flow in the coal cleat system. Based upon the Langmuir expression previously discussed (Equation 1) which defines the non-linear relationship between adsorbed gas concentration and pressure, pseudo-steady-state diffusion is modeled as a function of cleat spacing and sorption time.

The fracture system relative permeability defines the two-phase flow of gas and water as shown in Figure 10. Capillary pressure effects were not considered in the Phase 1 simulations.

Reservoir parameters used in the simulator are found in Tables 8 and 9 for the Rim and Straight Creek, respectively. Sources for the data are also given. Plots of fluid properties for gas and water are shown in Figures 11 and 12 respectively.

FIGURE 10
Fracture System Gas-Water Relative Permeability

TABLE 8

Reservoir Parameters for Left Fork #1 Coal Mine (Rim Seam) Reserve Evaluation and Degasification Sensitivity Simulations		
	Coal Seam	Source
Midpoint Depth, feet	143.625	LFM
Mined Thickness, feet	10.00	Planimeter Isopach
Pressure Gradient, psi/ft	0.433	LFM
Initial Reservoir Pressure, psia	76.89	Calculated ^c
Initial Water (Gas) Saturation, %	10 (90)	USGS
In-situ Langmuir Volume, scf/ton ^a	540	USGS
Langmuir Pressure, psia	157	USGS
Coal Density, lb/ft ³ ^a	63	LFM
In-situ Gas Content, scf/ton ^a	177.52	Calculated ^d
Desorption Pressure, psia ^b	76.89	USGS
Sorption Time, days	5	USGS
Reservoir Temperature, °F	66.7	LFM
Cleat Porosity, %	0.02	USGS
Absolute Cleat Permeability, md (kh = kv)	10	USGS
Pore Volume Compressibility, 10 ⁻⁶ psi ⁻¹	50	USGS
Cleat Spacing, inches	0.25	USGS
Gas Gravity	0.591	Gas Sample
Water Viscosity at Reservoir Conditions, cp	1.0192	Correlation
Water Formation Volume Factor, RB/STB	1.01	1.01
Number of Panels (current and planned)	1 panel/2.5 months, 5 pan./year	
Panel Dimensions, feet	260' X 1220'	
Mining Technique	Longwall (planned)	
^a In-situ conditions include correction for ash and moisture content (10%)		
^b Assumes low volatile bituminous coal that is 100% saturated relative to its adsorptive capacity		
^c $P_{\text{reservoir}} = \text{Pressure Gradient} \times \text{Midpoint Depth} + 14.7 \text{ psia}$		
^d $\text{Gas Content} = \frac{V_{\text{Langmuir}} P_{\text{reservoir}}}{P_{\text{Langmuir}} + P_{\text{reservoir}}}$		

FIGURE 11
Fluid Properties - Gas

FIGURE 12
Fluid Properties - Water

E.2 Gridding

Two approaches were used to simulate degasification well performance based on the gridding for a single panel and for a grid based upon 5 panels. A single panel was chosen because of its natural field analog and a 5 panel area was chosen because its drainage area (36 acres) is very similar to what conventionally spaced natural gas wells occupy when drilled on 40 acre spacing. Figure 13 shows an isometric schematic for a single panel and Figure 14 shows a plan view with grid numbers and dimensions.

FIGURE 13

MODEL VERTICAL DIMENSIONS AND GRID SHOWING PILLAR AND ROOM CELLS OF STRAIGHT CREEK COALBED AND OVERBURDEN (INCLUDING RIM COALBED)

FIGURE 14

MODEL DIMENSIONS
AND GRID LAYOUT
FOR ONE PANEL

E.3 Sensitivities and Results

The first series of sensitivities were performed to determine the drainage efficiency associated with using one well to deplete a single panel in the Straight Creek seam and a well's optimal spacing by locating the well at various locations shown on Figure 14. A finely grided panel (with dimension $l=33$, $j=7$, $k=1$) was used. An 8 3/4" wellbore was assumed to communicate with the Straight Creek seam throughout its thickness. Results of these sensitivities are shown in Table 10 (the first five cases) and demonstrate that placement of a well in the center of a panel depletes the gas most rapidly, as expected. The steep initial decline rate indicated in Figure 15 demonstrate that a single well sees the boundary effects in a short period of time when draining the limited radial area surrounding the borehole in a single panel.

The next run was to look at how quickly the resources associated with one panel could be depleted if more than one well were used. As shown in Table 10 (6th case), if 5 wells are used to deplete one panel (assuming an additional well is drilled every 45 days), although the cumulative recovered is almost double through the first five years, the efficiency as reflected in the MMscf/well is about one fourth compared to if only one well were used during the same time period. Obviously, it wouldn't make sense to spend the additional money on these wells if the objective was to deplete a single panel. The high decline rates shown in Figure 16 show that in a single panel not only are boundary effects noticeable, but other wells interfere with one another, causing rapid production declines.

To see the impacts of hydraulic fracturing the Straight Creek seam, various values for skin were used according to the relationship:

$$X_f = 2r_w e^{-s} \quad (\text{Equation 3})$$

where X_f is the fracture half-length (for an infinite-conductivity fracture), r_w is the wellbore radius and s is the skin. For the r_w of 0.3646 ft (for an 8 3/4" diameter hole), a skin factor of -3.0 would represent an effective fracture half-length (X_f) of 15 feet. This would be analogous to removing wellbore damage caused by drilling by a conservative successful hydraulic fracture treatment. Work conducted by the USBM [Elder, et. al. 1975] showed that in successful hydraulic fracture treatments of the Mary Lee Coalbed in Jefferson County, Alabama and the Pittsburgh Coalbed in Washington County, Pennsylvania, average propped fracture half lengths of 110 feet were obtained. This would be the equivalent to a skin factor of -5 for the Straight Creek coal seam. The effects of hydraulic fracturing for skins of -2 and -3 for the Straight Creek using 5 wells in one panel are shown in Table 10 (cases 7 and 8, respectively) and compared against a 0 skin (case 6). A 30% initial production increase is predicted between the 0 skin and -3 skin cases. The rate and cumulative plots for these comparisons are shown in Figure 16.

TABLE 10
Variations in Gas Recovery for Various Degasification Well Simulation Cases

LEFT FORK MINE #1, RIM AND STRAIGHT CREEK SEAM SENSITIVITY SIMULATIONS
 VARIATIONS IN FORECASTED 1.0-YEAR DEGASIFICATION WELL PERFORMANCE

Case No.	Simulation Run Identifier	Seam(s)	Number of Panels	Number of Wells	Grid Size i, j, k	Simulator Well Location(s)	Skin	IGIP Mscf	IGIP MMscf/Panel	Cum Gas Mscf	Gas Recovery MMscf/Well	% IGIP
1	WELL10	Straight	1	1	33, 7, 1 i=6; j=4	0	0	6516.13	6.52	1195.02	1.20	18.34
2	WELL20	Straight	1	1	33, 7, 1 i=12; j=4	0	0	6516.13	6.52	1344.67	1.34	20.64
3	WELL30	Straight	1	1	33, 7, 1 i=18; j=4	0	0	6516.13	6.52	1374.34	1.37	21.09
4	WELL40	Straight	1	1	33, 7, 1 i=24; j=4	0	0	6516.13	6.52	1311.81	1.31	20.13
5	WELL50	Straight	1	1	33, 7, 1 i=30; j=4	0	0	6516.13	6.52	1105.52	1.11	16.97
6	SKIN0	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	0	0	6516.13	6.52	3085.49	0.62	47.35
7	SKIN-2	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-2	0	6516.13	6.52	3531.75	0.71	54.20
8	SKIN-3	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-3	0	6516.13	6.52	3925.52	0.79	60.24
9	STRAIGHT	Straight	5	1	33,17,1 i=17; j=9	0	0	32582.88	6.52	2233.61	2.23	6.86
10	RIM&STR	Rim, Straight	5	1	33,17,2 i=17; j=9	0	0	121268.30	24.25	5076.10	5.08	4.19
11	RIM&STRX	Rim, Straight	5	1	33,17,2 i=17; j=9	-3	0	121268.30	24.25	8117.92	8.12	6.69

VARIATIONS IN FORECASTED 2.0-YEAR DEGASIFICATION WELL PERFORMANCE

Case No.	Simulation Run Identifier	Seam(s)	Number of Panels	Number of Wells	Grid Size i, j, k	Simulator Well Location(s)	Skin	IGIP Mscf	IGIP MMscf/Panel	Cum Gas Mscf	Gas Recovery MMscf/Well	% IGIP
1	WELL10	Straight	1	1	33, 7, 1 i=6; j=4	0	0	6516.13	6.52	1774.55	1.77	27.23
2	WELL20	Straight	1	1	33, 7, 1 i=12; j=4	0	0	6516.13	6.52	2022.15	2.02	31.03
3	WELL30	Straight	1	1	33, 7, 1 i=18; j=4	0	0	6516.13	6.52	2080.91	2.08	31.93
4	WELL40	Straight	1	1	33, 7, 1 i=24; j=4	0	0	6516.13	6.52	1961.69	1.96	30.11
5	WELL50	Straight	1	1	33, 7, 1 i=30; j=4	0	0	6516.13	6.52	1650.11	1.65	25.32
6	SKIN0	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	0	0	6516.13	6.52	4007.22	0.80	61.50
7	SKIN-2	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-2	0	6516.13	6.52	4339.54	0.87	66.60
8	SKIN-3	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-3	0	6516.13	6.52	4561.09	0.91	70.00
9	STRAIGHT	Straight	5	1	33,17,1 i=17; j=9	0	0	32582.88	6.52	3740.37	3.74	11.48
10	RIM&STR	Rim, Straight	5	1	33,17,2 i=17; j=9	0	0	121268.30	24.25	9367.20	9.37	7.72
11	RIM&STRX	Rim, Straight	5	1	33,17,2 i=17; j=9	-3	0	121268.30	24.25	14317.80	14.32	11.81

VARIATIONS IN FORECASTED 5.0-YEAR DEGASIFICATION WELL PERFORMANCE

Case No.	Simulation Run Identifier	Seam(s)	Number of Panels	Number of Wells	Grid Size i, j, k	Simulator Well Location(s)	Skin	IGIP Mscf	IGIP MMscf/Panel	Cum Gas Mscf	Gas Recovery MMscf/Well	% IGIP
1	WELL10	Straight	1	1	33, 7, 1 i=6; j=4	0	0	6516.13	6.52	2718.37	2.72	41.72
2	WELL20	Straight	1	1	33, 7, 1 i=12; j=4	0	0	6516.13	6.52	3041.59	3.04	46.68
3	WELL30	Straight	1	1	33, 7, 1 i=18; j=4	0	0	6516.13	6.52	3127.70	3.13	48.00
4	WELL40	Straight	1	1	33, 7, 1 i=24; j=4	0	0	6516.13	6.52	2957.27	2.96	45.38
5	WELL50	Straight	1	1	33, 7, 1 i=30; j=4	0	0	6516.13	6.52	2571.86	2.57	39.47
6	SKIN0	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	0	0	6516.13	6.52	4657.30	0.93	71.47
7	SKIN-2	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-2	0	6516.13	6.52	4777.81	0.96	73.32
8	SKIN-3	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-3	0	6516.13	6.52	4820.28	0.96	73.97
9	STRAIGHT	Straight	5	1	33,17,1 i=17; j=9	0	0	32582.88	6.52	7100.00	7.10	21.79
10	RIM&STR	Rim, Straight	5	1	33,17,2 i=17; j=9	0	0	121268.30	24.25	16200.00	16.20	13.36
11	RIM&STRX	Rim, Straight	5	1	33,17,2 i=17; j=9	-3	0	121268.30	24.25	27470.70	27.47	22.65

VARIATIONS IN FORECASTED 10.0-YEAR DEGASIFICATION WELL PERFORMANCE

Case No.	Simulation Run Identifier	Seam(s)	Number of Panels	Number of Wells	Grid Size i, j, k	Simulator Well Location(s)	Skin	IGIP Mscf	IGIP MMscf/Panel	Cum Gas Mscf	Gas Recovery MMscf/Well	% IGIP
1	WELL10	Straight	1	1	33, 7, 1 i=6; j=4	0	0	6516.13	6.52	3466.48	3.47	53.20
2	WELL20	Straight	1	1	33, 7, 1 i=12; j=4	0	0	6516.13	6.52	3775.11	3.78	57.93
3	WELL30	Straight	1	1	33, 7, 1 i=18; j=4	0	0	6516.13	6.52	3860.84	3.86	59.25
4	WELL40	Straight	1	1	33, 7, 1 i=24; j=4	0	0	6516.13	6.52	3692.94	3.69	56.67
5	WELL50	Straight	1	1	33, 7, 1 i=30; j=4	0	0	6516.13	6.52	3329.61	3.33	51.10
6	SKIN0	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	0	0	6516.13	6.52	4817.23	0.96	73.93
7	SKIN-2	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-2	0	6516.13	6.52	4836.77	0.97	74.23
8	SKIN-3	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-3	0	6516.13	6.52	4839.35	0.97	74.27
9	STRAIGHT	Straight	5	1	33,17,1 i=17; j=9	0	0	32582.88	6.52	10100.00	10.10	31.00
10	RIM&STR	Rim, Straight	5	1	33,17,2 i=17; j=9	0	0	121268.30	24.25	31000.00	31.00	25.56
11	RIM&STRX	Rim, Straight	5	1	33,17,2 i=17; j=9	-3	0	121268.30	24.25	41054.80	41.05	33.85

VARIATIONS IN FORECASTED 25-YEAR DEGASIFICATION WELL PERFORMANCE

Case No.	Simulation Run Identifier	Seam(s)	Number of Panels	Number of Wells	Grid Size i, j, k	Simulator Well Location(s)	Skin	IGIP Mscf	IGIP MMscf/Panel	Cum Gas Mscf	Gas Recovery MMscf/Well	% IGIP
1	WELL10	Straight	1	1	33, 7, 1 i=6; j=4	0	0	6516.13	6.52	4285.07	4.29	65.76
2	WELL20	Straight	1	1	33, 7, 1 i=12; j=4	0	0	6516.13	6.52	4489.84	4.49	68.90
3	WELL30	Straight	1	1	33, 7, 1 i=18; j=4	0	0	6516.13	6.52	4546.89	4.55	69.78
4	WELL40	Straight	1	1	33, 7, 1 i=24; j=4	0	0	6516.13	6.52	4435.57	4.44	68.07
5	WELL50	Straight	1	1	33, 7, 1 i=30; j=4	0	0	6516.13	6.52	4192.13	4.19	64.33
6	SKIN0	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	0	0	6516.13	6.52	4839.72	0.97	74.27
7	SKIN-2	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-2	0	6516.13	6.52	4839.77	0.97	74.27
8	SKIN-3	Straight	1	5	33, 7, 1 i=6,12,18,24,30; j=4	-3	0	6516.13	6.52	4839.77	0.97	74.27
9	STRAIGHT	Straight	5	1	33,17,1 i=17; j=9	0	0	32582.88	6.52	16173.00	16.17	49.64
10	RIM&STR	Rim, Straight	5	1	33,17,2 i=17; j=9	0	0	121268.30	24.25	49607.40	49.61	40.91
11	RIM&STRX	Rim, Straight	5	1	33,17,2 i=17; j=9	-3	0	121268.30	24.25	60411.40	60.41	49.82

FIGURE 15
Gas Rate and Cumulative Comparison Plots, Cases 1-5

Straight Creek Seam, 1 Panel, 1 Well in Various Locations, Skin = 0
MULTIPLE RUNS: WELL10 WELL20 WELL30 WELL40 WELL50

Straight Creek Seam, 1 Panel, 1 Well in Various Locations, Skin = 0
MULTIPLE RUNS: WELL10 WELL20 WELL30 WELL40 WELL50

FIGURE 16
Gas Rate and Cumulative Comparison Plots, Cases 6-8

Straight Creek Seam, 1 Panel, 5 Wells, Skin = 0, -2 and -3 Impacts
MULTIPLE RUNS: SKIN-3 SKIN-2 SKIN0

Straight Creek Seam, 1 Panel, 5 Wells, Skin = 0, -2 and -3 Impacts
MULTIPLE RUNS: SKIN-3 SKIN-2 SKIN0

A more realistic representation of the intended degasification wells is to look at depleting a larger volume to achieve a higher sustainable rate. Case 9 of Table 10 shows the results when 1 well is used to deplete a 5 panel area (36 acres). Figure 17 shows rate and cumulative comparisons between one well depleting a single panel (Case 3, Table 10), the performance of one well of 5 wells used to deplete a single panel (Case 6, Table 10) and finally one well depleting 5 panels (Case 9, Table 10). Clearly, the boundary effects are reduced (shallower decline in rate) with access to the larger drainage volume.

For the final simulation comparisons, a single well in a 5 panel area was simulated first for a well communicating with the Straight Creek (Case 9, Table 10), then for a well in communication with both the Rim and Straight Creek (Case 10, Table 10), and finally for the Rim and Straight Creek seams both hydraulically fractured to achieve an effective completion which cleans up damage incurred while drilling the well (Case 11, Table 10). In this last scenario, a skin factor of -3.0 was assigned. Figure 18 shows the rate and cumulative comparisons. Case 11 was used as the defining single well performance for evaluating project feasibility economics.

FIGURE 17
Gas Rate and Cumulative Comparison Plots, Case 3, 6 and 9

Straight Creek Seam, Drainage Area and Well Interference Effects, Skin = 0
MULTIPLE RUNS: STRAIGHT WELL30 SKINO

Straight Creek Seam, Drainage Area and Well Interference Effects, Skin = 0
MULTIPLE RUNS: STRAIGHT WELL30 SKINO

FIGURE 18
Gas Rate and Cumulative Comparison Plots, Cases 9-11

Rim & Straight Seams, 5 Panels, 1 Well, Stimulation (Skin = -3) Impacts
MULTIPLE RUNS: RIM&STRX RIM&STR STRAIGHT

Rim & Straight Seams, 5 Panels, 1 Well, Stimulation (Skin = -3) Impacts
MULTIPLE RUNS: RIM&STRX RIM&STR STRAIGHT

VI. FEASIBILITY OF PROPOSED FUEL CELL SYSTEM

A. Overview of Fuel Cell Powerplant

The energy conversion device for deriving electric power from the waste methane will be a Model PC25 phosphoric-acid fuel cell powerplant manufactured by International Fuel Cells of South Windsor, Connecticut. The powerplant (see photo in Figure 19, schematic in Figure 20) is a complete energy conversion device. The unit contains (1) a steam reformer to convert the methane to a mixture of hydrogen and carbon dioxide, (2) the fuel cell stack, and (3) a power conditioner, a solid-state inverter, that provides 200 kW of three-phase 60 Hz alternating current output. Thus, from a methane input, the powerplant provides high-quality, high-reliability alternating-current output that will be used to supplement grid-power for stationary applications essential to the mine's operation. The exhaust is virtually entirely high-purity water and carbon dioxide.

The PC25 is a phosphoric-acid fuel cell system; that is, 70% phosphoric acid is the electrolyte. Phosphoric-acid cells, by operating at the relatively high temperature of approximately 200°C, require lower electrocatalyst loadings, since the redox reactions proceed relatively rapidly by virtue of the temperature, and the catalyst is relatively immune to catalyst poisoning by carbon monoxide because the equilibrium at high temperature favors the unbound form of carbon monoxide. The high temperature also allows the recovery of high-grade waste heat via cogeneration. The efficiency for conversion of the chemical energy of the fuel into electricity is 40%. Recovery of thermal energy brings the efficiency up to 85%.

Reliability and life of the powerplant are excellent. For example, a PC25 operated without interruption at Southern California Gas for more than 7,500 hours [McClelland, 1994]. Mean time between forced outages for the installed fleet is 2,400 hours, which is substantially better than the 300 to 500 hours for similar size gas reciprocating engines and gas turbines. Maintenance costs for the PC25 are \$0.01-0.015/kWh, which compares favorably with \$0.02/kWh for internal-combustion engines [Hogan, 1993]. Powerplant life, of course, is much longer than an uninterrupted run. Life of the overall plant is 20 years; life of the reformer is 10 years. If the initial operating specifications are to be maintained, the stack must be overhauled or replaced at 40,000 hours (approximately every 5 years). Current cost of stack replacement is \$180,000; however, the cost is expected to be lower by the time replacement is required. The reason for stack replacement is not that it fails, but because the stack potential slowly decays over time (due to slow degradation such as catalyst sintering) until it cannot--at the design specifications for operation--provide sufficient voltage for operation of the inverter. However, if the design specifications can be compromised, e.g., if a lower power output than 200 kW can be accepted, stack life can be substantially greater than 40,000 hours.

FIGURE 19
Photograph of PC25 Fuel Cell

FIGURE 20
Schematic of PC25 Fuel Cell

THE FUEL CELL POWER SYSTEM

Emissions of NO_x, carbon monoxide, and hydrocarbons are negligibly small. For all of these pollutants, the actual emissions are less than 1/30 that allowed by the South Coast (Los Angeles, CA) Air Quality Management District Standard Rule 1110.2. The PC25 has been granted a blanket exemption from emissions permitting. Acoustic noise is less than 60 dBA at 30 feet, or about as loud as a window air conditioner. Emissions are summarized in Table 11 as follows:

TABLE 11
Comparison of PC25 and Engine Emissions

Emissions	PC25 (ppmv for 200 kW)	California Standards for Engines (ppmv for 200 kW)
NO _x	1	36
SO _x	Negligible	--
Particulates	Negligible	--
Smoke	None	--
CO	5	2000
Non-methane hydrocarbons	1	250

The PC25 is an off-the-shelf powerplant. IFC is stepping up and improving its automated manufacturing assembly line. We visited the plant and witnessed first-hand the assembly process, which uses robotic machining and assembly techniques. The manufacturing processes are entirely successful and operational. The current facility's manufacturing capability is 200 stacks per year. Manufacturing scale is expected to reduce cost of the PC25 from a current value of \$3,000/kW to \$1,500/kW by 1998. [Note: While this cost reduction is an expectation of the company, it is a much firmer promise than the promises of competing fuel cell technologies: Both molten carbonate and solid oxide fuel cells will be fortunate if they can meet a promise of actually being in commercial production--with true cost unknown at present--by 1998.] Sixty of the PC25 units have been sold and installed worldwide; 76 have been produced. Customers include hospitals, hotels, universities, research laboratories, office buildings, industrial facilities, government facilities, airports, and military bases. The high reliability of the PC25--because the system depends only on the natural-gas supply and not the electric power grid--makes it very attractive to installations (e.g., hospitals) that need an uninterruptible power source.

Relevant specifications of the PC25 powerplant are shown in Table 12 as follows:

TABLE 12
PC25 Specifications

Rated power	200 kW (235 kVA)
Electric output	480/277 V, 3-phase, 60 Hz
Power factor	0.85 lag/lead (adjustable)
Transient overload	240 kW (282 kVA) for 5 sec
Frequency accuracy	One minute per year
Ambient temperature	-20° to 110° F
Dimensions	10 x 10 x 18 feet
Weight	41,500 lb

B. Alternative Technologies

Although there are alternative technologies to accomplish the above applications, the PC25 phosphoric-acid fuel cell (PAFC) is the most attractive. Competing fuel cell technologies are alkaline, proton-exchange membrane (PEM), molten-carbonate (MCFC), and solid oxide (SOFC) fuel cells. Alkaline and PEM are technically developed but are too costly or inadequately commercially developed for stationary applications; at present, their high power density gives them advantages as vehicular powerplants. Neither MCFCs or SOFCs, because of corrosion and life problems, are adequately developed for the high reliability application proposed. Of all the fuel cell types, only the phosphoric acid cell manufactured by International Fuel Cells is available as an off-the-shelf powerplant--it can in short order be shipped to the mine, connected to the gas line, and can begin generating electric power.

As part of the feasibility study, Dr. A. R. Miller made a site visit to four fuel cell manufacturers representing each of the three main competitors for stationary applications: PAFC, MCFC, and SOFC.

PAFC: On August 24, 1995, International Fuel Cells (IFC) of South Windsor, Connecticut, was site-visited and a complete tour of the robotic manufacturing plant was given by the company. Also, a lengthy technical discussion session was undertaken with a total of four employees of the company. The site visit demonstrated that availability and manufacturing capacity are immediate. The company was helpful and generous in providing technical support.

Dr. Miller also had a lengthy in-person discussion with the chief representative of Fuji Electric Co. in the U.S. While Fuji has a lengthy experience with phosphoric-acid fuel cells, and indeed was the vendor for the DOE 30-ft fuel cell bus project, the conclusion from the discussion is that Fuji cannot compete with IFC on price. To a large extent, this is due to the high current value of the yen. To a lesser extent, the company has not been as successful as IFC in manufacturing techniques. Fuji is not presently marketing the system in the U.S.

MCFC: On August 25, 1995, Energy Research Corporation (ERC) of Danbury, Connecticut, was site-visited as a potential supplier of MCFC fuel cells for the coal-mine application. The purpose of the visit was clearly stated, and some of the ideas of this proposal were described. While Dr. Miller was given a complete tour of the research facility, he was not allowed to see the manufacturing facility. Commercial production is not yet underway, although prototypes of ERC's internal reforming MCFC system are under development.

The conclusion drawn from the visit, and after speaking with third-party experts in the area of fuel cell technology, is that commercial production of the system--along with the service and distribution network required to support it at the level of IFC's PC25--is 5-10 years in the future. The company has scheduled hardware production for 1999. However, a sales and service infrastructure equal to IFC's, which takes many years to develop, will probably be well beyond the year 2000.

Besides a fairly distant production schedule, a potential technical problem of the ERC design is the internal reformer. Although it can probably reduce the capital cost of the system, its reliability and repairability are unknown and untested. It is likely that carbon deposition will occur in any reformer; however, in an internal reformer, this process may also involve the anode. Repair of the system will probably be more difficult and costly than repairing an external-reformer system. Partly for this reason, we would favor MC-Power's external reformer MCFC system if we were to use MCFC. (MC-Power of Burr Ridge, Illinois, is scheduled to be site-visited on September 15, 1995, after this report is submitted.)

SOFC: On July 31, 1995, Dr. Miller site-visited Ceramatek in Salt Lake City as a manufacturer of SOFC fuel cells. A number of small prototypes were under test, but the system is not scheduled for production until 1998, and then only as a 10 kW unit. Westinghouse is farther along in commercialization than Ceramatek, but the technology is still probably 5-10 years behind the IFC PC25.

Summary of alternative fuel cells. Among fuel cell types and makes, the IFC PC25 is substantially the best choice for this demonstration because of the following:

- It is the only truly commercially available fuel cell system in the world. It is available today. The competing fuel cell technologies are not likely to be equally available and supported until after the year 2000.

- IFC offers outstanding customer support and will provide assistance as this demonstration project proceeds. The competing fuel cell technologies are, by comparison, only proposed products, and the support the companies will provide to the customer is unknown, as is the true availability of the product and even the existence of the companies in 5-10 years.

Heat engines. Various kinds of heat engines, e.g., gas turbines and piston engines, could be used to generate electric power from the available methane. However, these energy conversion devices are less attractive in several respects than fuel cells:

- They have lower thermodynamic efficiency than the fuel cell and thus less energy will be recovered from the methane.
- They have much higher emissions, in particular, nitrogen oxides. In contrast, the PC25 has a blanket exemption from emissions permitting in California.
- They are not as safe in a coal mine setting because of fire hazards. The PC25, by operating far below combustion temperatures (except for its reformer heater), poses very little fire hazard.
- They are not as environmentally friendly toward workers because they emit air pollutants and noise. In contrast, the PC25 could be a source of drinking water and makes little noise.

C. Feasibility Issues

General. Most installation conditions required by the PC25 are easily met at the Left Fork Mine. These include the following: The PC25 required gas pressure is low, between 0.14 and 0.5 psi above atmospheric, and this is easily obtained by regulation of the waste methane from the proposed wells. Several satisfactory sites for placing the unit on mine property are available. The mine has good relations with the utility company, Kentucky Utilities, and interfacing with the grid will present no problem. Using the detailed installation instructions provided by IFC, the mine personnel, along with the power company, should be capable of installing the PC25 powerplant by themselves.

There are only two significant feasibility issues in the proposed demonstration--the gas composition and the economics of the system. Gas composition is discussed below and the economics are discussed in another section of the report (see section VII. Results and Discussion, part A: Economic Analysis).

Gas composition. A general discussion of the available coal gas is provided in earlier parts of this report (see section V. Methodology, part C: Gas Analysis to Determine Quality of Methane Source(s)). The coal gas available at the mine from wells

compares with the required gas composition for operation of the PC25 on *pipeline natural gas* as follows:

TABLE 13
Coal Gas and PC25-Required Gas Compositions

Gas Component	Coal Gas (mol %)	PC25-Required ¹ (mol %)
Nitrogen	4.028	≤ 4.0
Carbon dioxide	0.036	≤ 3
Hydrogen sulfide	-- (≤ 0.8 ppmv)	≤ 30 ppmv total S
Oxygen	--	≤ 0.2
Methane	93.806	93 ²
Ethane	1.645	≤ 10
Propane	0.405	≤ 5
Higher hydrocarbons	0.080	≤ 1.75
TOTAL:	100.000%	

¹From [ONSI, 1995, p. 2-3]. ²Assuming no higher hydrocarbons and maximum concentrations of all non-hydrocarbon components, i.e., 7%. PC25s will operate on methane concentrations of around 50%, as produced by landfills, but they must be derated in power output.

Unlike a PC25 operating on landfill gas, which has a methane concentration of around 50%, the high methane content of the coal gas will allow full rated power output of 200 kW. The coal gas is essentially natural gas, the gas for which the fuel cell was designed.

D. Commercialization

Our interest in this project is twofold: (1) The system is an attractive power source for the stationary power applications of coal mines, and (2) the system will provide a hydrogen infrastructure for hydrogen fuel cell powered underground mining vehicles, a program of the Joint Center for Fuel-Cell Vehicles at the Colorado School of Mines. Regarding the second interest, hydrogen may be generated from the system in two ways: (a) electrolytically from the stationary fuel cell power or (b) by splitting the reformat stream before it enters the fuel cell and removes the carbon dioxide, thus leaving hydrogen for the vehicles. A schematic of the system using the reformat as a hydrogen source is shown in Figure 21, as well as an artist's conception of a 10 MW version of the system shown in Figure 22. Availability of hydrogen from the reformat for underground vehicles is another advantage of having an external reformer as in the PC25 or the MC-Power MCFC system.

FIGURE 21
Schematic of Fuel Cell Power System Using Reformate as a Hydrogen Source

FIGURE 22
Artist's Conception of 10 MW Coal Mine Methane System

VII. RESULTS AND DISCUSSION

A. Economic Analysis

A.1 Degasification Wells

Table 14 summarizes the costs required to drill a degasification well into the Rim and Straight Creek coal seams. Refer to Table 10, which shows the simulation results for gas recovery for various degasification well scenarios. From this data, it is evident that one well completed in both coal seams draining five panels is the most effective option. Under this scenario, one well develops 27 thousand cubic feet per day of methane. To operate a 200 kW fuel cell requires 40,000 standard cubic feet (scf) of methane per day. Based on the well performance generated from the simulator, initially 3 degasification wells will be required. Because of natural production declines (10% effective decline), in two years, 5 degas wells will be required to deliver 40,000 scfd.

TABLE 14
Cost Estimate to Drill a Well to Rim and Straight Creek Coals

Cost Item	Estimated Cost
Survey	\$500
Surface Location	\$2500
500' of 9-5/8" casing	\$5000
700' of 4-1/2" casing	\$2800
Cementing casing	\$7000
Rig @ \$10/ft (600')	\$6000
Wellhead, valves, misc	\$2000
Stimulation (2 treatments)	\$20,000
Dewatering Pump	\$8000
Total well cost	\$53,800

Once these wells are drilled a gathering system will be installed to gather the gas and deliver it to the fuel cell. Since the mine owner is also the surface owner any problems locating equipment and pipelines are minimized. For the purpose of the estimate, it will be assumed that the gathering pipeline can be installed for \$1.50 per foot. We would suggest the line be laid on the surface using PVC or similar material. The total gathering system is estimated to require 5,000 feet of pipeline at an installed cost of \$7,500.

The economic analysis will be done under three sets of assumptions: (a) the most conservative analysis, (b) an analysis assuming continuation of the DOE/DOD \$1,000/kW subsidy of the capital cost, and (c) an analysis assuming a capital cost of \$1,500/kW, but without subsidy, in 1998. The starting point of these analyses was an analysis by Farris [Farris, 1995].

(a) *Conservative analysis.* Assume: (1) an annual carrying charge of 15%, which includes interest, taxes, depreciation, a return on investment, and a system life of 20 years, (2) overhaul and maintenance cost amounting to \$0.01-0.015/kWh over the 20-year life, (3) an 80% load factor, (4) no cogeneration, (5) no federal subsidy and hence a capital cost of \$3,000/kW installed, and (6) zero cost for methane. With these assumptions, the cost of electricity over the 20-year life is \$0.079/kWh. This compares to the rate of about \$0.07 the mine now pays for electricity from the grid.

This analysis is very conservative: (1) The load factor is conservative, (2) cogeneration will be used, but the cost saving is not presently known, (3) there is presently a federal subsidy that reduces the capital cost to \$2,000/kW, and (4) the capital cost of the PC25 will undoubtedly drop toward \$1,500/kW, half the value used in the analysis, in a few years. Two of these less conservative assumptions are the basis of the following two analyses.

(b) *Continuation of subsidy.* Retaining the assumptions of (a) above but assuming a capital cost of \$2,000/kW due to continuation of the DOE/DOD subsidy gives an estimated cost of electricity during the 20-year life of \$0.058/kWh.

(c) *\$1,500/kW capital cost.* By reducing manufacturing costs via robotic techniques, IFC intends to reduce the cost of the PC25 to \$1,500/kW by 1998. Assuming this capital cost, the cost of electricity over the 20-year life is computed as \$0.047/kWh.

The electricity costs under the three sets of assumptions are summarized as follows:

TABLE 15
Electricity Costs for Three Sets of Assumptions

Assumptions	Electricity Cost (\$/kWh)
(a) Conservative	0.079
(b) Subsidy	0.058
(c) \$1,500 capital cost	0.047

The above analyses assumed zero cost for gas. However, costs will be incurred due to the requirement for drilling the vent wells. If this cost is included in the analyses, the electricity costs are increased by \$0.019/kWh. We propose that drilling the well will reduce other costs in the mining operation: (1) lower capital costs resulting from smaller ventilation fans, (2) less grid power for smaller fans, (3) enhanced worker safety from lower methane concentrations and lower noise, and (4) monetary credits from lowered methane emissions will be generated. Therefore, we feel there will be benefits that offset the cost of well drilling.

Table 16 provides a different view of the economic calculation for the installation of 5 degasification wells, a gathering system and the fuel cell. The top line of the table is the annual cost of 200 kW of electric power at a cost of \$0.065 per kWh. The economic calculation is based on the premise that if the fuel cell is installed, the mine would reduce operating costs by \$113,800 per year. Therefore the economic impact of installation of a fuel cell is a reduction in operating cost.

Using the economic basis described above and an installation cost of \$2000/kW for the fuel cell, the installation of the wells and fuel cell is an economic venture. Payout takes just over 5 years. This analysis is comparable to the continuation of subsidy analysis presented above and indicates there is not a strong economic preference when compared to purchasing power from the utility (\$0.077/kWh vs \$0.065/kWh).

Keep in mind that the basis for the degasification wells and gathering network is the methane production forecast developed by the simulation software. Since basic data was not available, many assumptions and analogies were used to provide input data. Prior to spending the capital required to develop this project it would be worth the time and effort required to substantiate the basic data used to develop the forecasts.

TABLE 16
Summary Economic Calculation for Installation of 5 Degasification Wells
and a Phosphoric Acid Fuel Cell

Initial Investment	Year									
	1	2	3	4	5	6	7	8	9	10
Fuel Cells - Methane From Drilled Degasification Wells										
Annual Cost of 200 kW Power at a cost of \$0.065 per kWh										
\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)
Installation cost of 5 De-gas wells, Gathering System and Fuel Cell (3 wells first year one well per year thereafter)										
\$ (536,500)	\$ (43,000)	\$ (43,000)								
Annual cash flow after installation										
\$ (422,620)	\$ 70,880	\$ 70,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880
Cumulative Cash Flow										
\$ (422,620)	\$ (351,740)	\$ (280,860)	\$ (166,980)	\$ (53,100)	\$ 60,780	\$ 174,660	\$ 288,540	\$ 402,420	\$ 516,300	\$ 630,180
	MIRR		NPV(12%)	<div>Notes: MIRR is Modified Internal Rate of Return assumed: cost of capital is 10% reinvestment rate is 12% NPV calculation assumed mid-year discounting</div>						
5 Year	7%		(\$65,088.28)							
10 Year	15%		\$181,424.55							
Base Case Assumptions										
Installed cost is \$2000 per kW, reflects \$1000/kW subsidy										
No cost for methane										
Power savings \$0.065 per kWh										
No maintenance cost for Fuel Cell										

A.2 Alternate Sources of Methane

Alternative sources of methane exist at the mine site. Extensive abandoned workings are owned by the mine. An alternative source for the methane would be to drill a well into the abandoned workings and produce methane from that source. Robert Atkins, Mining Engineer for the LFM, is of the opinion that with time, there would be extensive roof falls that should enhance the methane producing capability similar to a GOB well where longwall mining is used. One well should be able to drain a significant area, as the network of abandoned pillar and rooms would provide an extensive fracture network with (extremely) high permeability. The cost of the well should be less than the degasification well estimated above. No stimulation would be required and it might be possible to drill the well where the Rim coal has been mined, or where there are no plans to mine the Rim coal.

The petroleum affiliate of Left Fork Mining Company, Inc., Cumberland Harlan Exploration Corporation, has drilled a gas well on the mine property near the surface facilities (well name Cumberland Harlan #1, LFM as shown in Figure 3). Currently the well is shut in. During a site visit to the mine the surface pressure was measured at 450 psig. Indications are that this well should initially be able to produce 40,000 scf (40 Mcf) per day. However, the rate of decline and the reserves associated with the well are unknown at this time.

Table 17 is an estimation of the economic viability of installing a fuel cell using methane from either the abandoned workings or the existing well. It was assumed that a glycol dehydrator would be required to dehydrate the gas and a single pipeline would be required to deliver the methane stream to the fuel cell. The cost for the dehydrator and the pipeline was estimated at \$25,000. As can be seen from the economic calculation, this is a very economically robust project. This project could be installed in a short period of time and would demonstrate the technology of using a fuel cell to generate electricity.

TABLE 17
Summary Economic Calculation for Installation of a Phosphoric Acid Fuel Cell
Using an Alternate Source of Methane

Initial Investment	Year									
	1	2	3	4	5	6	7	8	9	10
Fuel Cells - Alternate Methane Source										
Annual Cost of 200 kW Power at a cost of \$0.065 per kWh										
\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)	\$ (113,880)
Installation Cost of Fuel Cell and a pipeline to deliver methane										
\$ (425,000)										
Annual cash flow after installation										
\$ (311,120)	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880	\$ 113,880
Cumulative Cash Flow										
\$ (311,120)	\$ (197,240)	\$ (83,360)	\$ 30,520	\$ 144,400	\$ 258,280	\$ 372,160	\$ 486,040	\$ 599,920	\$ 713,800	\$ 827,680
	MIRR		NPV(12%)	<div>Notes: MIRR is Modified Internal Rate of Return assumed: cost of capital is 10% reinvestment rate is 12% NPV calculation assumed mid-year discounting</div>						
5 Year	18%		\$123,319.83							
10 Year	20%		\$369,832.66							
Base Case Assumptions										
Installed cost is \$2000 per kW, reflects \$1000/kW subsidy										
No cost for methane										
Power savings \$0.065 per kWh										
No maintenance cost for Fuel Cell										

A.3 Summary of Economics

When all economic factors, including cost of capital are included, the economics of the proposed system are comparable to buying power from the grid. However, there are indirect factors that result in costs, e.g., down-time of the mine, that tilt the economic balance to make the proposed system very attractive.

The indirect economic factors—that is, factors that result in unexpected or hidden costs — that make the system even more attractive are as follows:

- The system will have higher reliability than the present system or any competing heat-engine technologies. Hence, costs associated with down-time will be reduced.
- The fuel cell, behaving like a battery across a circuit, can shave power peaks in the mine's electricity consumption. This will reduce demand charges billed by the utility company.
- There are monetary credits available for methane emissions abatement, or possibly penalties will be levied if methane emissions continue at their present levels.

Our conclusion is that, based on direct costs alone, the proposed system is economically viable. Increased reliability, lower demand charges, and the avoidance of environmental penalties further increase the attractiveness of the system.

B. Benefits

The proposed fuel cell conversion technology offers the following economic and environmental benefits:

- Increased Safety. The facility will provide greater safety in a coal mine setting because only a very small part of the total energy consumption (namely, the energy to maintain the reformer at operating temperature) results in temperatures high enough to initiate fire.
- Reduced Costs. The Left Fork Mine has an electric power requirement of 6.4 MW, which costs at least \$3 million per year at the \$0.07 per kWh the mine must pay for electric power from the grid. Viewed from this perspective, the mine methane is very valuable. Fuel cells--by being more efficient than the competing heat-engine technology--can produce as much as twice the electric power from a given amount of methane. Clearly, the difference can amount to millions of dollars. Increased reliability, and consequent reduced down-time, is also a significant overall cost advantage.
- Advanced Environmental Technology. The fuel cell, by avoiding the Carnot efficiency limitation and avoiding atmospheric pollution by using electrochemical oxidation of the fuel, is the most environmentally sound technology available. Only negligible amounts of nitrogen oxides, carbon monoxide, and hydrocarbons will be produced by the conversion technology. Installation of a fuel cell energy conversion device to clean up atmospheric methane pollution and also provide quiet, clean, reliable electric power will provide favorable social benefits. The global environment, the local neighbors of the mine, and the mine's workers will all benefit from this environmental technology. In general, this installation of the most advanced "green" technology will make the demonstration a showcase of environmental technology and result in very positive public relations for both the funder and the mine.
- Increased Coal Mine Reliability. Failure of the components described above for more than periods of a few minutes results in a shut down of mine operations and can result in as much as eight hours of lost production. It is thus valuable to the mine that the power supply operate with high reliability. The International Fuel Cells PC25 will provide high reliability. This will be obtained because (1) the powerplant has few moving parts or parts requiring close mechanical tolerances, and (2) the data link to the manufacturer assures that the specifications that can drift (for example, electrolyte composition) will be monitored and adjusted accordingly.

- Fuel Cell Mining Vehicles. Carbon dioxide can simply be removed from the reformat (the effluent from the fuel cell reformer), leaving hydrogen. The hydrogen, stored safely and compactly as the metal hydride, can be used as a fuel for underground mining vehicles. Such vehicles—which would have no emissions whatever (only water vapor will be the exhaust) and will be virtually silent—are the object of one program area of the Joint Center for Fuel-Cell Vehicles, Colorado School of Mines. For a discussion, see the reference by Miller [Miller, 1995].

VIII. EMISSION IMPACTS ON NATIONAL AND GLOBAL SCALE

A. Comments on Scale-Up

As previously shown on Figure 8, according to MSHA data the methane emissions from the Left Fork Mine amount to approximately 20,000 scf of methane per day. This methane is entrained in a ventilation stream of 201 million scf of air. By employing degasification wells we are recovering a portion of the methane from the coal prior to it being mined and therefore should see a reduction in the methane emissions. It is a logical conclusion that if the coal contains less methane, there should be less methane released when the coal is mined.

A problem arises when a material balance is performed on the methane contained in the coal. From analogous data it has been inferred that the Straight Creek coal seam contains 237 scf per ton. The ventilation stream, on a normal day removes 20,000 scf, or approximately 33 scf per ton. It has been stated that as much as 25 to 40 % of the methane in the coal is released during "post mining" activities [USEPA, April, 1993]. This would account for an additional 60 - 95 scf per ton. So, where is the other 110 - 140 scf per ton? Either our methane in place numbers are overstated, or there are phenomenon occurring that are not fully understood. Additionally, the simulation results reported in this report, and in the literature indicate that degasification wells drilled prior to the mining recover on the order of 50% of the in-place methane. The conclusion to be made is there is ample methane left in the coal to provide the small concentrations that are measured in the ventilation streams.

Although it makes sense to state that degasification wells will reduce the methane content in the ventilation stream, our investigation does not provide any technical basis for determining the amount of reduction. We conclude that the methane will be reduced, but make no estimate as to the amount.

B. Reduction of Emissions

Where fuel cells have the potential to reduce methane emissions is where degas systems are in place and methane is being released into the atmosphere without being beneficially used. An example would be where longwall mining is being employed and gob wells are drilled to degas the mine. This is a methane source that could readily be used by a fuel cell. A fuel cell can operate on methane streams that vary from 100% to approximately 50% methane. This would allow a gob well to produce directly into a fuel cell with little or no pretreatment of the gas stream. Most mines are large consumers of electrical power, so the electricity generated could be used on site, or sold back through the grid.

Table 18 below shows the breakdown of methane emissions from U.S. coal mines for the year 1990 [USEPA, April, 1993]. This information reports there is between 0.5 and 1.6 teragrams (26.1 and 83.4 Bcf) of methane gathered in degasification systems that is eventually released to the atmosphere. This is the methane emission stream that fuel cells can reduce. Because fuel cells can operate on a methane stream that has varying concentrations, they are ideal for installation on degasification systems where gob wells will be drilled and initially produce high quality methane that decreases with time. No treatment of the fuel stream would be required.

TABLE 18
U. S. Coal Mine Emissions (1990)

EMISSIONS SUMMARY		
Source	1988 Emissions (Tg)	
	low	high
Underground Coal Mines Ventilation Systems Degasification Systems	0.5	1.6
Surface Coal Mines	0.2	0.7
Post Mining	0.5	0.8
Total (1988)	3.3	5.2
Total (1990)	3.6	5.7

Figure 23 is a graphical demonstration of the methane emissions being generated by mines using different mining techniques. Based on 1993 Underground Coal Mine Emission Data [USBM, 1995], the 158 mines listed in the study are emitting 260 million cubic feet of methane into the atmosphere every day. Of this total, 210 million cubic feet per day (1.5 teragrams per year) are from mines employing the longwall mining process. Figure 24 shows the methane emissions from mines by mining technique employed in the U.S. that emit 100,000 scf per day or greater. The interesting point is the number of mines using longwall mining represents 39% of the mines. The conclusion is that one could work with 39% of the mines to reduce methane emissions and potentially eliminate or reduce 81% of the problem. Based on this information, it is feasible to suggest that implementation of fuel cells could eliminate 210 million cubic feet of methane emissions using existing technology.

FIGURE 23
U. S. Underground Coal Mine Methane Emissions by Mining Technique

FIGURE 24
Mines with Methane Emissions ≥ 100 mcf/d by Mining Technique

Utilization of Fuel Cells to Beneficially Use Coal Mine Methane

Table 19 lists the methane emissions related to mining of coal for the 10 countries recognized as having the most methane emissions [USEPA, October, 1993]. Using the same approach as used to estimate methane emission reductions in the U.S., we have listed the methane emissions that could be reduced in these countries. From the information presented, it appears that employing technology developed in the U.S. similar to what we have proposed, has the potential to reduce these emissions even further.

TABLE 19
Top 10 Countries Coal Mine Methane Emissions (1990)

Country	1990 Total Coal Mined		Methane Emissions		Degasification System Methane Emissions				
					Total Recovered		Amount Used	Amount Wasted	
	Underground	Surface	Low	High	Low	High		Low	High
China	1023	43	9.5	16.6	0.29		0.18	0.11	
United States	385	548	3.6	5.7	0.7	1.8	0.25	0.45	1.55
CIS	393	309	4.8	6	0.83		0.19	0.64	
Poland	154	58	0.6	1.5	0.19		0.14	0.05	
South Africa	112	63	0.8	2.3	n/a		n/a	n/a	
India	109	129	0.4	0.4	n/a		n/a	n/a	
Germany	77	359	1	1.2	0.35		0.25	0.1	
United Kingdom	75	14	0.6	0.9	0.21		0.14	0.06	
Australia	52	154	0.5	0.8	0.1		.05 - .08	0.02	0.05
Former Czechoslovakia	22	85	0.3	0.5	0.09		0.08	0.01	
Top 10 Total	2402	1762	22.1	35.9	2.76	2.55	1.28 - 1.31	1.25	2.57
Global Total	4740		24.4		39.6				

The following were calculated using the same ratio as for US mines

Country	Other Emissions				Ventilation	
	Surface		Post-Mining			
	Low	High	Low	High	Low	High
China	0.02	0.05	0.6	0.9	8.62	15.34
United States	0.2	0.7	0.5	0.8	2.20	3.50
CIS	0.11	0.39	0.4	0.6	3.48	4.17
Poland	0.02	0.07	0.1	0.2	0.28	1.05
South Africa	0.02	0.08	0.1	0.2	n/a	n/a
India	0.05	0.16	0.1	0.2	n/a	n/a
Germany	0.13	0.46	0.2	0.4	0.29	0.02
United Kingdom	0.01	0.02	0.0	0.1	0.34	0.60
Australia	0.06	0.20	0.1	0.2	0.23	0.33
Former Czechoslovakia	0.03	0.11	0.1	0.1	0.12	0.21
Top 10 Total	0.64	2.25	2.2	3.6	15.6	25.2

IX. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Several opportunities exist for demonstrating that a fuel cell can provide electricity for meeting power generation requirements at the Left Fork Mine. Table 20 lists the estimated horsepower, equivalent kW and the amount of methane gas required to run a phosphoric acid fuel cell (assuming a conservative 40% efficiency) to power the equipment used at the mine:

TABLE 20
Mine Methane Utilization Options

Equipment Description	HP Requirements	kW Requirements	Fuel Cell Mscf/day
Vent Fan	150	112.5	22,500
Vent Fan	600	450	90,000
Belt Drives (Surface)	2800	2100	420,000
Preparation Plant	2000	1500	300,000
Office, Lights, Misc.	500	375	75,000

A 200 kW fuel cell will require 40,000 scf/day of methane. Based upon simulation results which suggest that 5 wells (3 initially and an additional 2 by the fifth year) will be required to sustain this per day methane consumption requirement for 10 years, it is realistic to assume that the power requirements for the 150 HP fan and some miscellaneous equipment could be powered by a 200 kW fuel cell for demonstration purposes.

A.1 Fuel Cell Feasibility

The principle conclusions pertaining to the fuel cell part of this feasibility study are the following:

- Waste methane available at the mine is essentially natural gas and is well suited to running the IFC PC25. The gas is nearly 94% methane, with low concentration of deleterious impurities, and the powerplant can operate at the same design specifications as the powerplant operating on natural gas.
- If only the cost to generate electricity versus the cost to purchase it is considered, the proposed fuel cell system can be significantly less than purchasing power from the utility company. Lowered demand charges will lower the cost of electricity taken from the grid, which the PC25 may supplement.
- The fuel cell is expected to be more reliable than the grid or competing heat-engine technology. Enhanced reliability offers a strong economic incentive--

because of less mine down-time--that further tilts the economic balance in favor of the fuel cell versus competing technologies.

- While competing fuel cell technologies, namely, molten carbonate and solid oxide fuel cells, are promised to be cheaper to purchase than the phosphoric acid type, it will be 5-10 years before they reach the state of commercial development of the IFC PC25 phosphoric acid powerplant. Even when they do catch up to the manufacturing position that IFC now commands, the PC25 will be cheaper than it is now, and their proposed advantage will be diminished.
- The fuel cell system will reduce methane emissions (in proportion to the power capacity of the powerplant) and have lower emissions than any heat-engine technology.

A.2 Mine Gas Potential, Reserves and Applications

- It is estimated there are 15 BCF of methane in place in the Rim coal seam and 5.38 BCF methane in place in the Straight Creek coal seam at the Left Fork Mine site. This resource is exclusively owned by the mine.
- Methane ownership is not an issue. The mine owner also owns the methane.
- As measured by the MSHA, about 20,000 scf per day of methane are emitted into the atmosphere from the ventilation system at the LFM.
- No practical method to utilize the methane in the ventilation stream at the LFM or any US mine is proposed. The methane has to be captured prior to entering the ventilation stream.
- Several potential sources for methane gas are available at the Left Fork Mine:
 - 1) Existing natural gas well
 - 2) Four DOE wells (drilled in the early 1980s) to the Rim seam - these wells have already undergone major hydraulic fracturing and depending upon their completion status may be reentered and opened to flow - ahead of mining operations.
 - 3) Abandoned workings - drill a new well to recover methane from the overburden gob created during mining of these seams (waiting on dewatering permit)
 - 4) Drill new degasification wells penetrating virgin Rim and Straight Creek seams
- Based on simulation results, after five years a stimulated degasification well drilled on 36 acre spacing (the equivalent of 5 panels) will recover 22% of the in-

place methane. If allowed to produce for 25 years, 50% of the in-place gas can be recovered.

- Fuel cells have the capability to utilize the methane gas stream that could be produced from various sources at the LFM site.
- Fuel cells are quieter and therefore safer to work around. They are also highly reliable.
- More efficient use of energy - fuel cells are 40% to 85% efficient as compared to 25% and 30 % for IC and gas turbines, respectively.
- The phosphoric acid fuel cell manufactured by IFC is "off-the-shelf" technology that can be applied in a reasonable time.
- Using fuel cells where degasification wells need to be drilled and fracture stimulated is comparable to purchasing power off the grid. When a less costly source of methane is available, the project is economically robust.
- Environmental benefits would be reduced emissions of NO_x, CO and other pollutants when compared to internal combustion technologies.
- National and Global emissions of methane could be reduced by using methane to convert the emitted gas into electrical power. Methane that is collected in degasification systems could be utilized immediately.

B. Need for the Demonstration

An actual demonstration is necessary to validate the feasibility analysis. The most important claims to demonstrate are the following:

- Demonstrate that the PC25 will operate at its design specifications and have a satisfactory life when operated with the coal gas.
- Demonstrate load-leveling and thus a reduction in demand charges assessed by the utility company. (This effect is expected to be small because the power of the demonstration powerplant is relatively low.)
- Demonstrate that the reliability of the fuel cell system is indeed greater than the grid.
- Demonstrate that, when increased reliability is included in the calculation, the overall cost of mining is reduced by installation of the system.

- Demonstrate that all emissions from the powerplant operating on coal gas are not significantly different from those observed from the powerplant operating on pipeline natural gas.

C. Proposed Demonstration

For the demonstration, one PC25 fuel cell powerplant will be connected in parallel to the grid to provide supplemental power for one of the following loads:

- the 2,000 hp (1,500 kW) preparation plant, which cleans the coal prior to shipment
- the 2,800 hp (2,100 kW) belt system that hauls coal out of the mine
- a 600 hp (450 kW) ventilation fan
- a 150 hp (113 kW) ventilation fan
- miscellaneous office power for heating, cooling, lights, etc. at 500 hp (375 kW)

All of these components are essential to mine operation, and a power failure, which is not uncommon since they are currently powered from the utility grid, can result in as much as one shift of lost production.

The power conditioner (inverter) of the PC25 can be programmed to operate in various modes of response to changes in power requirements. Because (at the request of Left Fork Mine) only one 200 kW PC25 will be used in the demonstration, the single powerplant cannot absorb the full load of any of the applications. If it were of larger power, the PC25 would act as an uninterruptible power supply. It *will* be able to smooth power demand from the grid. In this regard, the PC25 will act like a storage battery connected across the line: It will provide supplemental power, automatically and as needed. The PC25 will thus have the capability of load-leveling. The value of load-leveling is that it will reduce demand charges billed by the utility company.

It is conventional in PC25 installations to have a data link with the factory, using the phone lines for data transfer, to monitor the system and to make minor adjustments to maintain the system within specifications. This data link will be used in the proposed installation and will contribute to the expected high reliability of the system.

The waste heat from the PC25 can be used for a cogeneration application, and we propose its use as supplemental heat for the mine office buildings in the winter.

In summary, we propose that the installation will demonstrate the following technical features and benefits of using a fuel cell system to recover the energy of waste coal-mine methane:

- Waste coal-mine methane can be practically recovered for use as the fuel of a fuel cell system.
- The methane is chemically compatible with the commercially available phosphoric-acid system of IFC.
- The fuel cell system is economically viable.
- The fuel cell system, operating on coal gas, emits negligibly low air pollutants and is environmentally friendly to mine personnel.
- The fuel cell system has a satisfactory life while operating on coal gas.
- The fuel cell system has an improved mean-time-between-outages compared to heat engines or the grid.

D. Recommendations

The authors of the report recommend that a phosphoric acid fuel cell be installed at the Left Fork Mine as a demonstration project. Prior to the actual installation of the fuel cell, the following tasks will need to be completed:

- 1) Determine which is the "best" source of methane to power the cell
- 2) Select a location for the fuel cell
- 3) Determine how the cell should be connected to the electrical system. Should the fuel cell have a dedicated load, or should the fuel cell be connected into the grid.
- 4) Perform detail engineering for all facets of the installation. Prepare cost estimates for the equipment and labor required for the installation.
- 5) Determine what criteria and information will be required to determine the success of the program.

As has been mentioned several times in the report, there are several potential sources of methane at the LFM. A task for Phase II will be to determine which is the best source for the fuel cell. The most readily accessible source is the gas well drilled by Cumberland Harlan Exploration Company. This well is on the mine site. Prior to selecting this source, additional work will have to be undertaken to determine if the well is a suitable source and has the reserves required to sustain the fuel cell for several

years. It is assumed that production from the well may have to be processed through a common gas separator to remove free water and any oil or condensate that may be produced with the gas. Since the fuel cell requires 14" of water pressure to operate, the gas well should be able to deliver the gas at that pressure, without any additional compression.

As a back-up, the abandoned workings and the abandoned DOE/USBM wells should be investigated as a potential source. The gas analysis indicates these sources should produce essentially pure methane with little other contaminants. Information as to how the DOE/USBM wells were abandoned would be very helpful. If a sand and/or cement plug were set in these wells, they could be returned to production without a large capital investment.

Considerations will have to be given as to how the well is connected to the electrical system and where on the site the fuel cell will be located. It may be desirable to have a dedicated load connected to the fuel cell. This would allow more direct information as to the reliability of the system to provide quality power. It may be more beneficial to the mine, however, to have the fuel cell connected to the grid where more of the electrical energy could be utilized. All of these factors may provide insight as to where the fuel cell should be located.

Taking all of the above into consideration, a detailed engineering effort will have to be undertaken to design the equipment installations and provide a bill of materials to allow cost estimates to be made.

A task that will have to be performed concurrently with much of the above work is to establish what defines a successful program. Additionally, what data and information will need to be gathered to help access the program. Efforts will have to be undertaken early in the process so if additional equipment or instrumentation is required it can be incorporated into the design early in the process.

We anxiously look forward to performing Phase II of this contract.

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