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Project Title: **SYSTEMATIC EVALUATION OF VENTILATION AIR
METHANE IN ILLINOIS COAL MINES**

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ABSTRACT

This research study was aimed at developing a technique to accurately quantify the ventilation air methane (VAM) released into atmosphere from gassy underground coal mines, and carry out a preliminary feasibility study for its utilization. As a first step, information was gathered about the overseas VAM utilization activities sponsored by the US Environmental Protection Agency (EPA) and Asian Development Bank (ADB). Next, information was collected about the various VAM utilization technologies available. Finally, effort was made to obtain information about WestVamp, the world's first commercial VAM utilization project in Australia, and Sihe Mine in China, where VAM has been used successfully on pilot-scale.

Along with the above continuous effort, a ventilation survey was carried out at a gassy underground coal mine in Illinois. This included airflow pressure and quantity (p-Q) measurements for all major branches of the mine ventilation network to estimate the airway resistances and pressure losses for use in a ventilation network simulation model. In order to quantify the methane emission from the mine, quarterly methane liberation data was first obtained from Mine Health and Safety Administration (MSHA). Next, methane concentration in the return air was measured on a weekly basis for one quarter, and daily basis for two weeks. For a few days, measurements were also taken every few minutes. Finally, coal production data was obtained for these days to enable correlating methane emission with mining activity.

A detailed analysis of the data revealed that the amount of methane emission from the mine, and methane concentration were very consistent. A correlation with the production data indicated that the nearby coal seams were a substantial source of methane. This suggested that the permeability/diffusion properties in the region are favorable, and the gas originating from other seams is able to move easily through the de-stressed coal. Furthermore, the emission increased during the year, and this trend is likely to continue as mining progresses further disturbing the stress equilibrium in the surrounding strata.

Finally, the most suitable technique for VAM utilization for the mine was determined to be its use as a primary fuel in flow reversal reactors since the concentration of methane is fairly stable and the overall emission rate is high. A preliminary economic analysis was carried out for a simplified VAM utilization project. The results were encouraging, clearly favoring such an investment.

EXECUTIVE SUMMARY

The ventilation air methane (VAM) emission from Illinois coal mines constitutes a significant addition of methane, a greenhouse gas, to the environment. On the other hand, it presents a good prospect for its utilization as a fuel source, while simultaneously preventing its release into atmosphere. However, the technical feasibility of a VAM utilization project depends primarily on the amount of methane emitted, consistency of the emission, and concentration of methane in the exhaust air. The overall cost effectiveness of the technology depends on the capital cost involved as well as the subsequent cash flow generated from use/sale of energy. Hence, this study was aimed at developing a reliable technique to quantify the VAM emission into atmosphere from underground coal mines, using one mine as a case study, and carrying out a preliminary technical and economic feasibility study of its suitability for VAM utilization. Although this study targeted one mine, the technique is applicable to any coal mine.

The research investigation started with a study and evaluation of the work carried out by the US Environmental Protection Agency (USEPA) and the US Agency for International Development (USAID) in the area of VAM utilization. This effort was divided into two parts. The first one involved studying the various techniques available to extract the energy out of VAM, that is, the different oxidation alternatives suitable for low and very low concentrations of methane. The second part included evaluating the case studies currently considering such options, mostly overseas mining operations with financial aid from the USEPA/USAID/Asian Development Bank (ADB), and the basis for such plans. A review of this material revealed that Australia is going ahead with its second VAM project, referred to as WestVAMP, for the West Cliff mine. Hence, effort was made to obtain information about the first Australian pilot-project at the Appin and Tower mines as well as the plan for the WestVamp project, which is designed to generate 6 MW of electricity. The second venture, the world's largest coal mine methane (CMM) project, is currently underway at the Sihe Mine in China, projected to generate 120 MW of power using coalbed methane (CBM) and CMM.

Before proceeding with the actual quantification of VAM at the underground mine, a mine-wide ventilation survey was carried out. This had two purposes. First, it is imperative to have a good understanding of the ventilation system in place at the present time, and how it contributes to the removal of methane from the mine. Second, it is important to have a ventilation simulation network model of the mine in order to evaluate the different alternatives on a comparative (if-then) basis. The first part of the ventilation survey was carried out using the trailing tube (p-Q) method. This involved stretching a 300 foot long, 3 mm diameter tube in the primary airways of the mine, and measuring the frictional pressure drop (p) resulting from the flow of air. Along with the measurement of pressure drop, airflow quantity (Q) was measured at all major stations of the mine. An evaluation of the ventilation system in place revealed that this survey alone was not going to be adequate to estimate the resistances of airway branches close to the shaft station. Hence, an altimeter survey was carried out, where a high precision altimeter was placed at a reference station on the surface, and pressure and temperature measurements were recorded every fifteen minutes. A second altimeter was taken underground, and

measurements were taken at all major stations. The surface measurements allowed correlating the underground measurements with atmospheric conditions since atmosphere is the starting point for ventilation air, and then estimating the pressure losses as air moved underground.

The existing ventilation model, developed by the mine personnel, was fairly complex, given the small size of the mine at this time. During development of the model, effort had been made to represent every airway with continuous airflow as an individual branch, which is simply not necessary. Several airways in the area surrounding the shaft bottom can easily be “clustered” and represented as a single branch in order to simplify the model. The results of the ventilation survey conducted jointly with two engineers at the mine as a part of this study were provided to the mine personnel for use in modifying the existing model. A line plot of the proposed model was also presented.

In order to assess the VAM emission, the ventilation system in place was studied carefully first. The mine has two exhaust shafts, one exhausting approximately 290,000 cubic feet per minute (cfm), and the second one exhausting 150,000 cfm. No methane was measured in the first shaft although there might be some emission via this shaft on a sporadic basis. Hence, further consideration of utilizing this air did not make economical sense. All effort to quantify VAM, therefore, concentrated on the second exhaust shaft. The mine personnel had already indicated that methane concentration in this return shaft was strongly correlated with mining activity and, with any stoppage of mining activity, the methane concentration in the exhaust air in the shaft went practically to zero. This was attributed to the fact that most of the methane was originating from the fresh coal being mined. Also, the mine was relatively new when this study started, and the surrounding rock was probably not overly disturbed, minimizing the flow of methane from overlying coal seams.

As a first step in quantifying the VAM emission, quarterly methane liberation data was obtained from the Mine Safety and Health Administration (MSHA). As a part of their routine inspection, MSHA conducts its own quarterly measurements of methane emission, although it is done on only one particular day every quarter. Also, the initial emission data obtained was for the entire mine, which essentially consists of two independent mines. Since this investigation concentrated on only one of the two, MSHA was later requested to provide data for only the mine being studied. The average daily emission, as estimated by MSHA for the portion of the mine being studied, was ~2,500,000 ft³/day. This emission rate, for an average daily coal production of 5,000 tons, translated to 500 ft³/ton of coal mined, which is significantly higher than the gas content measured by the Illinois State Geological Survey (ISGS) anywhere in the state. Hence, either MSHA was overestimating the liberation data, or there are additional sources contributing methane to the ventilation air.

In order to determine the actual amount of VAM in the exhaust air, a methane emission survey was carried out, which lasted for a fairly extensive period. The methane concentration in the return air of the second shaft was monitored on a weekly basis for thirty weeks. For two of the weeks, daily measurements were obtained. For five days

during this two-week period, measurements were taken every few minutes. For two of the days, when there was mining activity throughout the shift, readings were averaged for every hour. Using the airflow being exhausted via this shaft, the hourly emission rate was calculated. The emission rate was fairly constant, which is a very positive finding for any VAM utilization project. The variation for one of the days was between 68,000 and 71,000 ft³/hour, totaling to ~1.7 million ft³/day. For this particular day, the coal production was 4,422 tons, giving an emission rate of 384 ft³/ton of coal mined. This is still higher than the gas content measured by the ISGS in the area, again suggesting that a major source of methane might be the seams above and below the seam being mined. The information about the emission rate (ft³/ton of coal mined) is valuable in order to enable projecting future VAM emission as mining progresses. Later in the project, the mine experienced serious methane emission problems, and emission rates as high as 4,000,000 ft³/day were measured.

The results of the methane emission data suggested that there were two sources of methane. First was the coal being mined, and second was other seams/sources immediately above and below the working seam. This is expected since mining disturbs the stress equilibrium in the surrounding rocks, and results in an immediate release of free gas in the coal seams within the envelope of disturbance. The situation is very similar to the mines in Virginia/West Virginia, where degasification is a standard practice at several mines. These results do suggest that the permeability of coal is very high, resulting in release of all of the methane almost immediately following mining. This would result in very little gas emission if the mining activity stopped for some reason, and concur with the observation that the gas emission decreases drastically with stoppage of the mining activity. However, this could also mean that the diffusion properties of the coal are very favorable. In most cases, where gob wells produce gas for long periods of time after the formation of gob, the mechanism of the movement of gas is by diffusion alone, and this is usually an extremely slow process. It is not very clear at this time which mechanism is dominating the release of gas. However, from a flow perspective, either of the two or a combination of the two favors CBM/CMM activity in the region being studied. Finally, it is anticipated that, as mining activity progresses at this mine, there will be greater stress release and re-distribution resulting in higher emissions of methane from the seams in the vicinity and higher concentrations of methane in the exhaust air. In fact, during this study itself, this was found to be the case.

Based on the results discussed above, different VAM oxidation alternatives were studied. The option of using VAM as a primary source of fuel was determined to be the best alternative, and flow reversal reactors were considered to be a good option. Using the findings of this study, and a few simplified assumptions, a preliminary design for VAM utilization was developed and an economic analysis of the alternative was carried out. The results showed that such a project is technically and economically feasible even with conservative estimates used for the analysis. When this is combined with the fact that VAM emission from this mine is almost certainly going to increase in the future, the alternative becomes even more attractive.

There was a serious setback in this study as a result of MSHA's announcement defining the air leaving the ventilation fan as return air, even though it is separated from the fan at that point. At the time when this study ended, MSHA had not given a defined point when ventilation air becomes ambient air. Based on its current stand, MSHA has indicated that oxidation equipment would be a part of the ventilation system and, therefore, subject to permissibility standards. Although the final MSHA ruling is still not known, this may be the end of any VAM utilization projects in US mines in the immediate future. However, such projects will continue overseas, particularly in Australia, China, India, Ukraine, Poland, and Mexico. It is believed that, just like longwall mining, once the success of these operations is proven overseas, MSHA might modify its stand.

Finally, it is recommended that extensive research not be pursued in this area at this time, except gathering information about the projects currently underway in Australia and China. Depending on the final MSHA ruling, further studies should be carried out only when US mines are in a position to pursue the venue of energy extraction from VAM. The potential success of such ventures in Illinois coal mines is high, the technology is available, and it is technically and economically feasible.

OBJECTIVES

Overall Objective: The primary objective of this research study was to develop a procedure to accurately quantify the ventilation air methane (VAM) emission, and evaluate the technical and economic feasibility of its utilization, with emphasis on application of this technology to gassy mines in southern Illinois.

Specific Objectives of the Study: In order to achieve the primary objective, the following specific objectives were pursued during the project period:

- I. Develop a reliable procedure to quantify the VAM exhausted from underground coal mines, and determine the methane emission distribution throughout the mine by identifying the primary sources of emission.
- II. Establish the dependence of VAM emission on natural factors (weather, gas content, etc.), and coal production factors (amount of coal mined, production time, and ventilation system in place).
- III. Consider the different alternatives for VAM utilization in a cost effective manner.
- IV. Develop a viable partnership for planning and funding a VAM utilization system.

Task I: General Study of VAM – Background: Since the technology of utilizing VAM is fairly new, the immediate thrust of this work was to develop a procedure to quantify VAM emissions. However, the ultimate objective of the work was to develop a plan for its utilization. Hence, this task included obtaining information about the different utilization alternatives for a thorough study and evaluation. Although one underground mine was targeted for this study, the objective was to develop a procedure with application to other coal mines as well.

Task II: Mine Ventilation Survey: This task included carrying out a ventilation survey of the mine. The survey had two components. The first part consisted of a pressure and quantity (p-Q) survey, and the second was a methane concentration survey. The objective of the task was to use the measurements to evaluate the existing ventilation system at the mine and calculate the amount of methane at different locations in order to identify the primary sources of methane. A secondary benefit of this task was to evaluate the efficiency and effectiveness of the bleeder system in place at the mine, and its adequacy with continued mining.

Task III: Estimation of VAM: Since the principal goal of the proposed work was to assess the VAM emission, and the future direction of VAM utilization is dependent primarily on the accuracy of the assessment, this task was aimed at developing a thorough and rigorous technique to do so. This included recording methane concentrations on a quarterly basis, weekly basis for one quarter, daily basis for two weeks, hourly basis for a few days, and finally, every few minutes for some of the days, thus obtaining a complete array of methane concentrations.

Task IV: Analyze Results and Develop Procedure: This task included correlating the VAM emission with the coal production data to determine the fraction of gas originating

from the seam being mined, and the part migrating from other sources. The task also involved comparing the Mine Safety and Health Administration (MSHA) estimates, based on measurements taken once every quarter, with the actual emissions. The goals of this task were to determine if there is, in fact, a need for detailed assessment as opposed to taking the MSHA estimates, and to develop a simple procedure to project future methane emissions.

Task V: Potential for VAM Recovery and Utilization: This task involved evaluating the different alternatives for utilization of VAM for the underground mine studied. The basis of evaluation was the estimated VAM quantity, and cost information gathered for the most suitable alternative. Based on an economic analysis, the task included a preliminary plan for a VAM utilization system, its merits and the associated shortcomings.

INTRODUCTION AND BACKGROUND

Introduction

Methane is the second most abundant greenhouse gas, and more than 20 times as harmful as carbon dioxide (CO₂) in terms of the greenhouse effect. It contributes 17% of the total emission of greenhouse gases into the atmosphere [1]. When released from underground coal mines, it is called coal mine methane (CMM), and represents a major source of methane emission, accounting for nearly 10% of the total [2]. Since it is released along with ventilation exhaust air, it is also known as ventilation air methane (VAM), forming a significant portion of the total CMM emission. To date, with a few exceptions, coal mines release VAM into the atmosphere without attempting to capture and utilize it. However, with the recent emphasis on reducing the adverse impact of VAM on the environment, effort has been made to develop economically viable technologies capable of capturing the VAM and using it as a fuel to produce energy. The utilization of VAM as a fuel, therefore, serves two purposes: 1) it prevents the release of methane into atmosphere, and 2) it provides a source of energy. Some VAM utilization technologies have been developed and shown to work successfully using mine exhaust air, while others are still in the development stage.

The ventilation exhaust stream from underground gassy mines is characterized by low methane concentrations, usually between 0.1% - 1% [2], which renders it unsuitable for use in conventional combustion technologies. However, new technologies, capable of extracting energy from air/methane mixtures containing low concentrations of methane, can utilize this resource commercially and economically. These technologies are primarily divided into three main categories: principal use technologies, which use VAM as a primary source of fuel; ancillary use technologies, which use VAM as an ancillary fuel along with a primary fuel; and other technologies involving lean fuel gas turbines, concentrators, etc.

The applicability of any VAM utilization technology depends primarily on the level and consistency of methane concentration in the ventilation air, and the amount of airflow

being exhausted from the mine. This highlights the need for accurately quantifying and characterizing the VAM emissions from a coal mine before the most suitable technology for the mine can be identified for further consideration.

Emission Calculation Basis

MSHA measures methane concentration of ventilation air once every quarter, and utilizes this to estimate the daily and quarterly emission rates for every underground coal mine. These measurements, a snapshot of methane emission at a particular time, are the only data available for estimating the VAM inventory. Also, there is usually a significant variation in the estimated emission rates from one quarter to the next. Therefore, although MSHA data is used extensively to determine the annual methane emission, it does not provide a convincing argument for consideration in a VAM utilization plan. Furthermore, methane emission from underground mines is known to vary with coal production versus idle time, weather conditions, ventilation system in place, and whether or not the mine has a pre-mining gas drainage system in place [2, 3, 4]. Most mines record methane measurements of their own on a regular basis, but the locations for these measurements are usually dictated by safety concerns rather than quantification of the total methane emission. It is, therefore, difficult to estimate the total emission from a mine accurately using MSHA data or mine data.

VAM in Illinois Coal Mines

Based on MSHA data, more than 50 million cu ft per day of methane was released to atmosphere from underground coal mines in Illinois during 2004, totaling more than 18 billion cubic feet (BCF) for the entire year. Figure 1 shows the methane emission for the year 2004 from underground coal mines in Illinois. These emission rates show increased emission during the latter part of the year. This is expected to rise even further in the future, given that one of the gassiest mines in the state has started mining in a new area with higher gas content, and the production rate at other mines is expected to increase. In general, as mining progresses, there is an increase in not only the area of coal exposed, but also the disturbance around working areas, both resulting in increased methane emission rates.

For Illinois, the alternative to using VAM as combustion air for power projects, that is, its use as an ancillary fuel is particularly attractive since mine mouth power generation is currently being promoted in the state. The approach is technically straightforward and commercially proven. However, the methane reduction potential is limited since it requires siting of large, capital intensive, power projects close to ventilation shafts. If this is not the case, the cost of transporting VAM from ventilation shafts to power plants can be prohibitive. Hence, future mines with power plants at “mine mouth” would be able to avail of this technology. Coupled with the incentives/credits to reduce greenhouse gases, this technology has the potential of becoming the preferred one in the state. The technology using VAM as a principal fuel may also be used for power production, and/or heat exchange, although it is unlikely that mining companies would make the investment without a significant incentive. The United States Environmental Protection Agency

(USEPA) is currently encouraging mine operators to develop partnerships that would lead to such joint ventures.

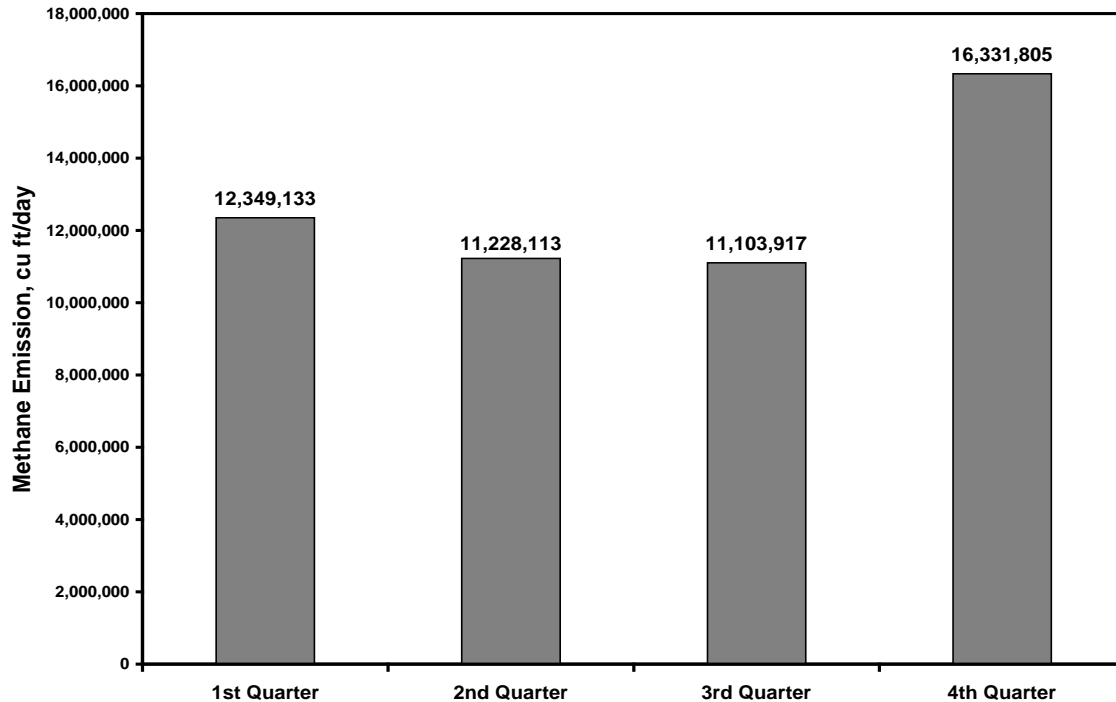


Figure 1: Daily methane emission in 2004 from underground coal mines in Illinois.

The emphasis of this study was to develop a procedure to assess the VAM emission, and therefore, was considered Phase 1 of a multi-phase study. Depending on the results of this phase, it was anticipated that the second phase would involve developing an elaborate partnership between mines; power producers; USEPA, which is currently involved in providing assistance with establishing such partnerships; DOE, since VAM utilization is energy that is otherwise wasted; and VAM utilization equipment manufacturers.

EXPERIMENTAL PROCEDURES

Ventilation Survey

This study targeted one underground mine as a case study. In order to understand the ventilation system in place at the mine, and how it contributed to the removal of methane, a mine-wide ventilation survey was carried out. In addition to improving the understanding, the survey also served the purpose of updating the ventilation simulation network model of the mine in order to evaluate the different alternatives on a comparative (if-then) basis. The first part of the ventilation survey involved carrying out a pressure-quantity (p-Q) survey. For this part of the survey, a tube, 300 feet in length and 3 mm diameter, was stretched in the primary airways of the mine, and the frictional pressure drop (p) resulting from the flow of air was measured. Along with the measurement of pressure drop, airflow quantity (Q) was measured at all major stations of the mine. An

evaluation of the ventilation system in place revealed that this survey alone was not going to be adequate for estimation of resistances of airway branches close to the shaft station. Hence, an altimeter survey was carried out, where a high precision altimeter was placed at a reference station on the surface, and temperature and pressure measurements were recorded every fifteen minutes. A second altimeter was taken underground, and similar measurements were taken at all major stations. The surface measurements allowed correlating the underground measurements with the atmospheric conditions, since atmosphere is the starting point for ventilation air, and estimating the pressure losses as air moved underground. For both surveys, the mine personnel provided significant assistance.

VAM Survey

In order to assess the VAM emission, the ventilation system in place was studied carefully. The mine has two exhaust shafts, one exhausting approximately 290,000 cubic feet per minute (cfm), and the second one exhausting 150,000 cfm. No methane was detected in the first exhaust shaft. This was consistent with the comments of the mine personnel. There might be some emission via this shaft, but only on a sporadic basis. Hence, any further effort into looking at utilization of this air did not make economical sense. All effort to quantify VAM, therefore, concentrated on the second exhaust shaft serving as the bleeder shaft.

The mine personnel felt rather strongly that there was a very strong correlation between mining activity and methane concentration in the bleeder shaft. With any disruption in the mining activity, methane concentration in the shaft dipped to almost zero. One interpretation of this at the time was that most of the methane originated from the coal being mined. This is true for relatively new mines, where the surrounding rock is not overly disturbed. The second possible explanation was that the emission from any other sources, like nearby coal seams or gas pockets in the surrounding rock, occurred almost immediately after mining in the area.

As a first step in quantifying the VAM, quarterly methane liberation data was obtained from MSHA. MSHA conducts its own quarterly measurements of methane emission although it is carried out on one particular day every quarter. Also, the initial emission data obtained was for the entire mine. Later on, MSHA was requested to provide data only for the portion of the mine being studied under this investigation. Figure 2 shows the methane emission data obtained from MSHA in ft^3/day for the four quarters of the year 2004.

In order to determine the actual amount of VAM in the bleeder shaft, a methane emission survey was carried out, which lasted for a fairly extensive period. The methane concentration in the return air (bleeder shaft) was monitored on a weekly basis for thirty weeks. For two of the weeks, daily measurements were obtained. For five days during this period, measurements were taken every few minutes. Fortunately, for two of these days, there was mining activity throughout the shift, presenting an opportunity to correlate coal production and methane emission data. The readings were averaged for

every hour, and using airflow passing through the shaft, the hourly emission rate was calculated.

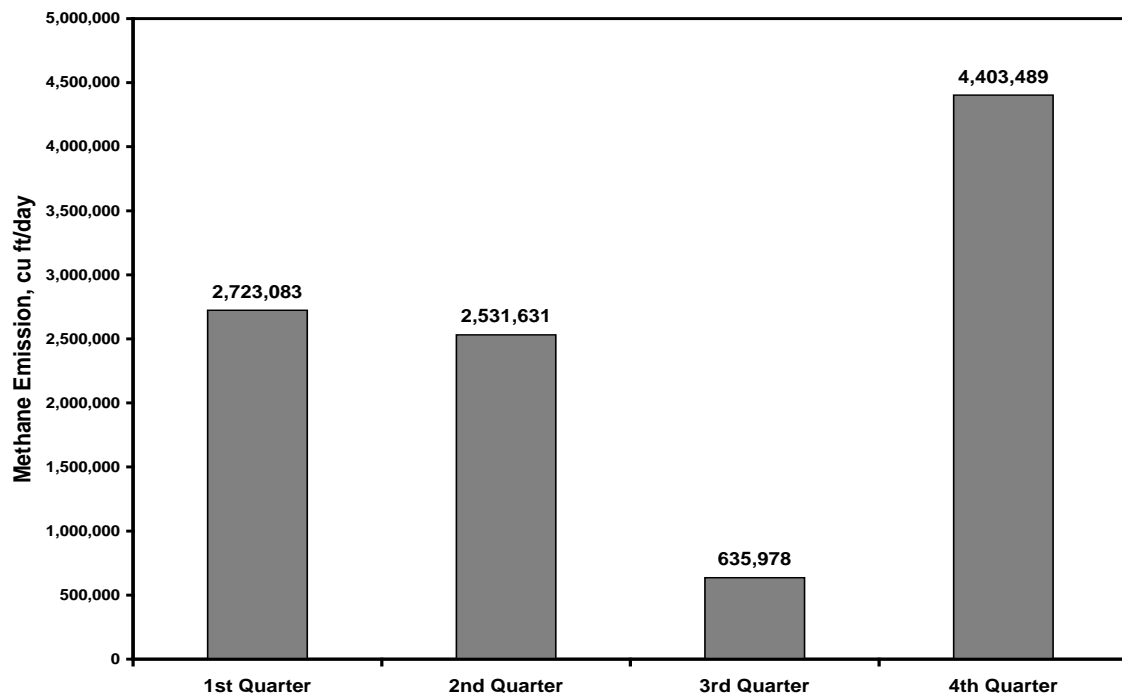


Figure 2: MSHA daily methane emission data for the case study mine.

VAM Utilization Alternatives

All of the different VAM oxidation alternatives were studied carefully. Based on the findings of VAM quantification, utilization of VAM as a principal fuel was felt to be the best option. Hence, flow reversal reactors were studied in detail with information obtained from various publications and company brochures. The emission data was used to develop a first design of a VAM utilization system for the mine. This included an economic analysis highlighting the cost advantage. For the analysis, reasonable but conservative values were taken for several parameters, such as percentage extraction, cost of electricity, etc.

RESULTS AND DISCUSSION

Task I: General Study of VAM – Background

The technologies available/proposed for VAM utilization can be divided into three categories: 1) ancillary use technologies, 2) principal use technologies, and 3) other technologies. Table 1 shows the status of several technologies developed for utilization of VAM, including those that are in the development stage. A description of the different alternative technologies is included in this section.

Table 1: Current Status of Technologies Available/Proposed for VAM Utilization [5]

Vendor/Technology	Description	Status
MEGTEC/ VOCSIDIZER®	Thermal Flow Reversal Reactor (oxidizer)	Completed To be used in WestVamp Project, Australia
CANMET- Le-febvre Freres Ltd/ CH ₄ MIN	Catalytic Flow Reversal Reactor (oxidizer)	Laboratory trials completed. Demonstrated in pilot plants
CSIRO/Lean-fueled turbine with catalytic combustor	1.0% gas turbine with catalytic combustor	Research phase
CSIRO/Hybrid coal and VAM fueled gas turbine	Energy produced by co-firing waste coal and VAM is used to heat compressed air which in turn is used to power a gas turbine	Test Phase Tested on 1.2 MW unit on waste coal and simulated VAM
FlexEnergy/Lean – fueled catalytic micro-turbine	Lean fueled (1.3%) micro-turbine	Test Phase Tested on 30 kW unit on simulated VAM
EDL/Carbureted gas turbine (CGT).	Lean Fueled (1.6%) solar gas turbine	Test phase Undergoing full scale trials with simulated VAM results.
EDL/Ancillary VAM use	VAM used as combustion air in Caterpillar 1MW engines	Successful operation at commercial scale

Ancillary Use Technology: The ancillary use technologies involve use of methane in the ventilation air as a supplemental fuel, which combines with the primary fuel in the combustion process, resulting in the release of useful energy. The VAM can be supplied as combustion air, substituting ambient air, in various prime movers like turbines, IC engines and boilers or furnaces. The fuel value associated with methane results in lower consumption of primary fuel and, therefore, in better project economics. The ancillary technologies present only a limited potential of methane mitigation as they use a fraction of the ventilation air methane, depending upon the requirements of the system. Due to limited use of VAM, and cost considerations, these projects are viable only if the facility that can use VAM is located close to the exhaust shaft. The presence of a coal fired power plant near the mine ventilation shaft presents the ideal situation for VAM utilization as an ancillary fuel, where VAM can replace ambient air for all, or a part of, combustion air requirements. The technology obviously has potential in Illinois since mine mouth power generation is being promoted at this time. It is, however, imperative that the facility is really close to the exhaust shaft to avoid the cost of transporting VAM, which can be prohibitive.

An excellent example of this application was the Appin Colliery in Australia, the world's first successful pilot project for VAM utilization using ancillary technology, where 54

one-MW Caterpillar CAT 3516 IC engines used VAM as combustion air [2, 3, 4]. The concentration of methane in the ventilation air ranged from 0.3% to 0.7%, and accounted for ~10% of engine fuel. The entire system consumed approximately 20% of the ventilation emissions. Although the project was later discontinued due to changes in the ventilation system of the mine, it demonstrated successful commercial use of ancillary VAM technology. Another Australian company, Powercoal, plans to use VAM as a combustion air for a large coal-fired steam power plant [2, 3]. This project, when operational, is expected to reduce methane emission into atmosphere by 4.4 million tons (Mt) of equivalent carbon dioxide reduction (CO₂e) between the years 2008-2012.

The first commercial VAM utilization project using ancillary technology is the world's largest CMM project underway at the Sihe Mine in Shanxi Province, China. Using reciprocating IC gas engines, the project is designed to generate 120 MW of power utilizing both CBM and CMM as feedstock. Currently, the mine produces ~15 million ft³/day of CMM. With projected increase in coal production to 8 million tons by the year 2008, the targeted time for completion of the VAM project, the CMM emission is expected to increase to 17.5 million ft³/day. This project is unique since it uses a combination of CBM and CMM.

Several field projects and small scale experiments have shown that the ancillary use technologies are feasible and straightforward in application. These techniques allow the user to reduce the consumption of primary fuel by 8 to 10% [2].

Principal Use Technology: The principal use technologies use methane present in the ventilation air as a primary fuel without using another source of combustion. Under the principal use technologies, two processes have been identified for destroying, or using, the methane contained in ventilation air. These are: 1) Thermal Flow-Reversal Reactor, and 2) Catalytic Flow-Reversal Reactors. Both technologies employ a similar principle of regenerative heat transfer between a gas and heat exchange medium. They can operate at uniform methane concentrations, as low as 0.1%, and can use up to 100% of methane in the ventilation air.

The VOCSIDIZER, a thermal flow-reversal reactor (TFRR) developed by MEGTEC Systems, is employed worldwide to oxidize volatile organic compounds (VOCs). This system oxidizes methane present in the ventilation air, and the heat of oxidation is converted to electric power. The equipment, shown in Figure 3, consists of a bed of silica gravel or ceramic heat exchange medium with a set of electric heating elements in the center. To initiate oxidation, electric heating elements pre-heat the middle of the bed to, or above, the temperature required to initiate auto ignition, which is approximately 1000⁰C. When ventilation air containing methane enters at ambient temperature and flows through the reactor in one direction, its temperature increases until oxidation of methane takes place at the center of the bed. The oxidized gas continues to flow to the far side of the bed, transferring heat to the bed, thus increasing the temperature at the far side. When it becomes sufficiently hot and the near side cools due to the incoming ambient temperature ventilation air, the reversal of flow occurs due to closing of the inlet valve on the near side. The ventilation air now enters from the far side of the bed, which

is hot, and gets oxidized at the center, transferring heat to the near (cold) side of the bed, and then exits the reactor. The process reverses and the oxidation cycle continues.

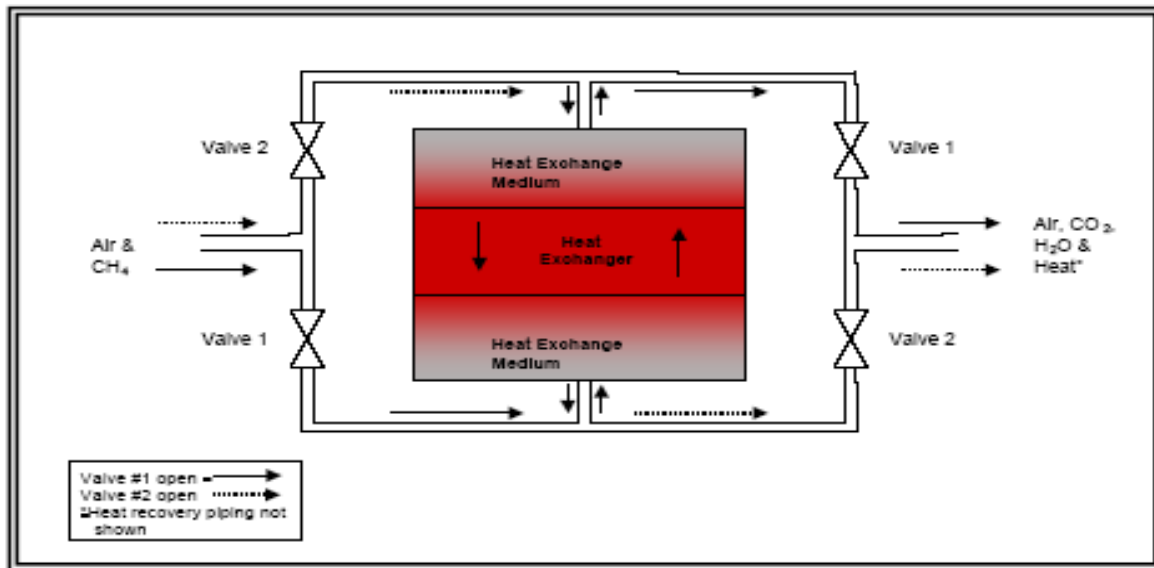


Figure3: Thermal flow-reversal reactor [3].

Recently, MEGTEC Systems AB and BHP Billiton have announced the world's first commercial VAM oxidation project that will use principal use technology [3, 4]. With co-funding from the Australian government, the plan to install a VAM utilization project was approved. The project, referred to as WestVAMP project, will use MEGTEC VOCSIDIZER technology and is expected to begin operation in 2006. The project, in addition to reducing methane emissions from the mine, is estimated to generate 6 MW of electricity from a steam turbine. This, along with past experience at Appin and Tower collieries, puts Australia at the forefront of development projects using VAM principal use technology.

Catalytic Flow-Reversal Reactor (CFRR) technology, developed exclusively for coal mine ventilation air methane by Canadian Mineral and Energy Technologies (CANMET), is similar except that it uses a catalyst to reduce the auto ignition temperature of methane in the oxidation reaction. CANMET has demonstrated this system in pilot plants and is in the process of commercializing the technology [2, 3, 4]. There are currently no examples of application of this technology, although it has tremendous potential due to low operating costs.

Other Technologies: Apart from ancillary and principal use technologies, other technologies are being developed/reviewed that can partially or even fully employ VAM as a fuel source. The two main systems that fall under this category are: 1) concentrators and gasifiers, and 2) lean fuel gas turbines. Concentrators are used to control the concentration of volatile organic compounds (VOCs) in industrial processes – air exhaust streams. These can be used to increase the concentration of methane in the ventilation air,

which is typically in the range of 0.5% to 1% [3]. The increased methane concentration in VAM allows it to be used as a fuel in gas turbines, reciprocating engines, etc.

The use of VAM as a fuel in gas turbines is also being studied. The selected gas turbine models are being modified to operate directly using VAM, or VAM that has been enhanced with additional concentrated fuels. Some of these technologies, like Lean Fueled Turbine, developed by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), or Lean Fueled Micro Turbine, developed jointly by FlexEnergy and Capstone Turbine Corporation, employ a catalyst for VAM combustion. Finally, CSIRO is in the process of developing an innovative system to oxidize and generate electricity with VAM in combination with waste coal [3].

Task II: Mine Survey

The existing ventilation model, developed by the mine personnel, was fairly complex, given the size of the mine at the time. During the development of the model, effort had been made to represent every airway with continuous airflow as an individual branch, which is simply not necessary. Several airways in the area surrounding the shaft bottom can easily be “clustered” and represented as a single branch in order to simplify the model. The results of the ventilation survey conducted by SIU, jointly with the mine personnel, were provided to the mine personnel for use in modifying the model developed in-house. A line plot of the proposed model was also presented.

Task III: Estimation of VAM

The primary objective of the case study at the underground coal mine was to develop a systematic technique of taking methane measurement: 1) to measure the methane concentration in the ventilation air and quantify the VAM emission, 2) to study the mine ventilation system in order to predict long-term methane emissions, and 3) to use the data obtained to identify the most suitable VAM technology for the mine.

As a first step, the average daily emission data, as estimated by MSHA for the portion of the mine being studied, was obtained. This is shown in Figure 2 (previous section) for the entire year. Since the estimates are based on a single measurement, the reason for the significantly lower third quarter estimate may be that the measurement was taken on a down day. Based on MSHA data, the average daily emission for the year was ~2,500,000 ft³. This emission rate, for an average daily coal production of ~5,000 tons, translated to 500 ft³/ton of coal mined, which is significantly higher than the gas content measured by the Illinois State Geological Survey (ISGS) anywhere in the state. Hence, the reported values had two interpretations at the time: MSHA overestimates the liberation data; or, there are additional sources other than the coal seam being mined contributing methane to the ventilation air.

As mentioned earlier, the primary escape route for VAM at the mine was the bleeder shaft, exhausting 150,000 cfm. A methane monitoring system capable of measuring methane concentration once every minute was placed in the main bleeder airway.

Methane concentration was monitored for two months. The measured methane concentration values were analyzed to obtain hourly, daily and monthly emissions in order to evaluate the consistency of the emission and the level of emission.

Figure 4 shows a typical average hourly methane concentration for sixteen hours. It can be seen that methane emission from the mine for most of the day was very consistent. Figure 5 shows the correlation between the monthly average methane emission rate and monthly coal production from the mine for a period of eleven months. It is apparent that there is a good correlation between mining activity and methane produced, highlighting the fact that most of the methane produced originates from the coal being mined, or is closely associated with the mining activity. Also, the mine studied is relatively young. Since the estimated future life of the mine is 20 years, it is logical to assume that the mine would remain a continuous source of methane in the foreseeable future. On the basis of monthly methane readings, the average methane concentration in the mine exhaust was conservatively estimated to be 0.65%. This is conservative since the concentration increased during the last part of 2004, and early 2005.

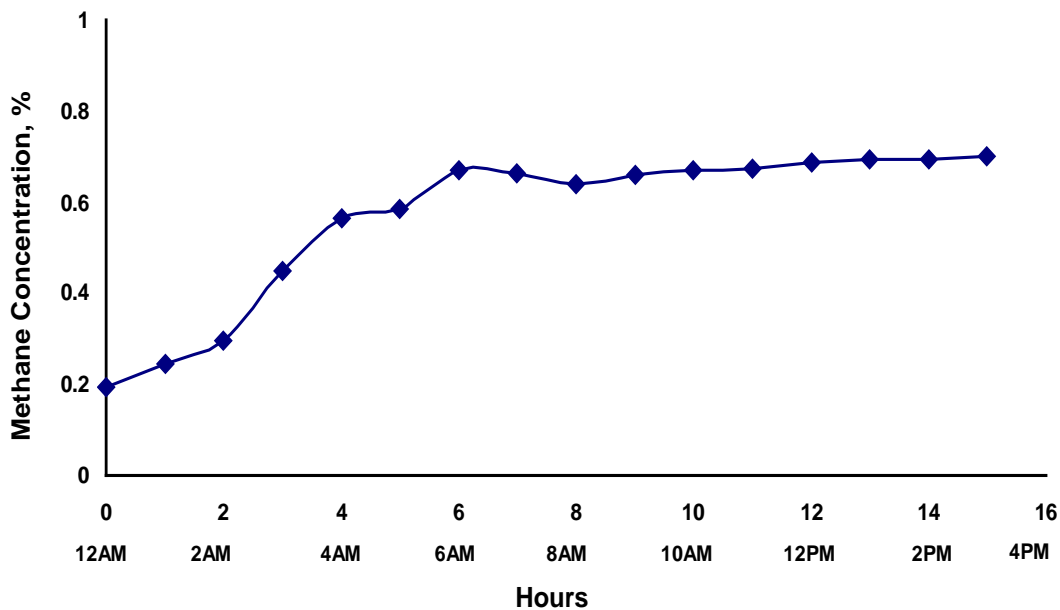


Figure 4: Measured hourly methane concentration.

In addition to the finding that the concentration of methane in the exhaust air was adequate to justify a VAM utilization plan, there was another revelation that was very positive from this perspective. The emission rate was found to be fairly constant. The average for one of the days was calculated to be $\sim 60,000$ ft³/hour, totaling to ~ 1.45 million ft³/day. For the particular day, the coal production was 4,422 tons, giving a gas content of 325 ft³/ton of coal mined. This is still higher than the gas content measured by the ISGS in the area, again, confirming that a second source of methane might, in fact, be the seam(s) above and below the seam being mined. The information about the emission rate (ft³/ton of coal mined) is valuable in order to enable projecting future VAM emission

as mining progresses. It should, however, be noted that this number cannot be treated as a constant since it would change as mining progresses.

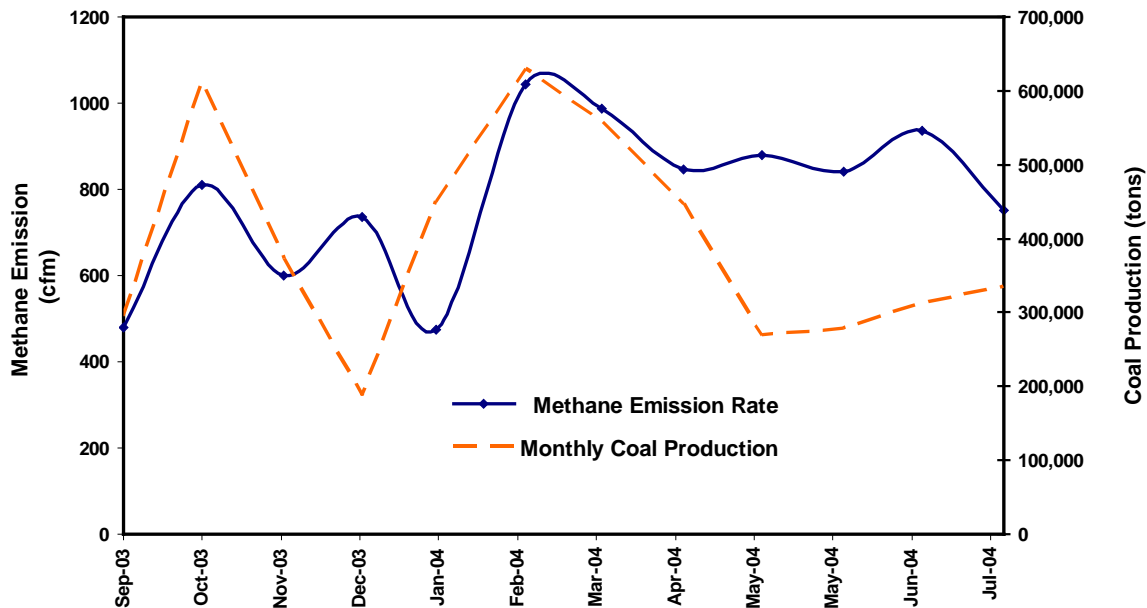


Figure 5: Monthly methane emission and coal production.

The results of methane emission data collected suggest that the source of the gas is not only the seam being mined, but “other” seams in the vicinity of the coal seam being mined as well. This is expected since the mine is a longwall mine and extraction of coal results in caving of the overlying strata, forming gob, as shown in Figure 6. The gas contained in the overlying coal seams is released almost immediately following the formation of gob due to an increase in permeability of coal by several orders of magnitude. Also, mining disturbs the stress equilibrium in the surrounding rocks, and results in the immediate release of gas in the coal seams within the envelope of disturbance. This is shown in Figure 7. The situation is very similar to the coal mines in Virginia/West Virginia, where gob degasification is a standard practice at several mines.

The results do suggest that the permeability of coal is high, resulting in release of all of the methane almost immediately after mining. This would result in very little gas emission if the mining activity stopped for some reason, and concur with the observation that the gas emission decreases drastically when there is no mining activity. However, this could also mean that the diffusion properties of the coal are very favorable. In most cases, where gob wells produce gas for long periods of time after the formation of gob, the mechanism of the movement of gas is by diffusion alone, and this is usually an extremely slow process. It is not very clear at this time which mechanism is dominating the release of gas. From a flow perspective, either of the two favors CBM/CMM activity in the region being studied. Finally, it is anticipated that, as mining activity progresses at this mine, there would be a greater stress release and re-distribution, resulting in higher emissions of methane. The result, of course, would be higher concentrations of methane

in the exhaust air. This is evident from the data obtained from MSHA, where the emission in the fourth quarter of 2004 was significantly higher than that observed in any of the previous quarters (Figure 2).

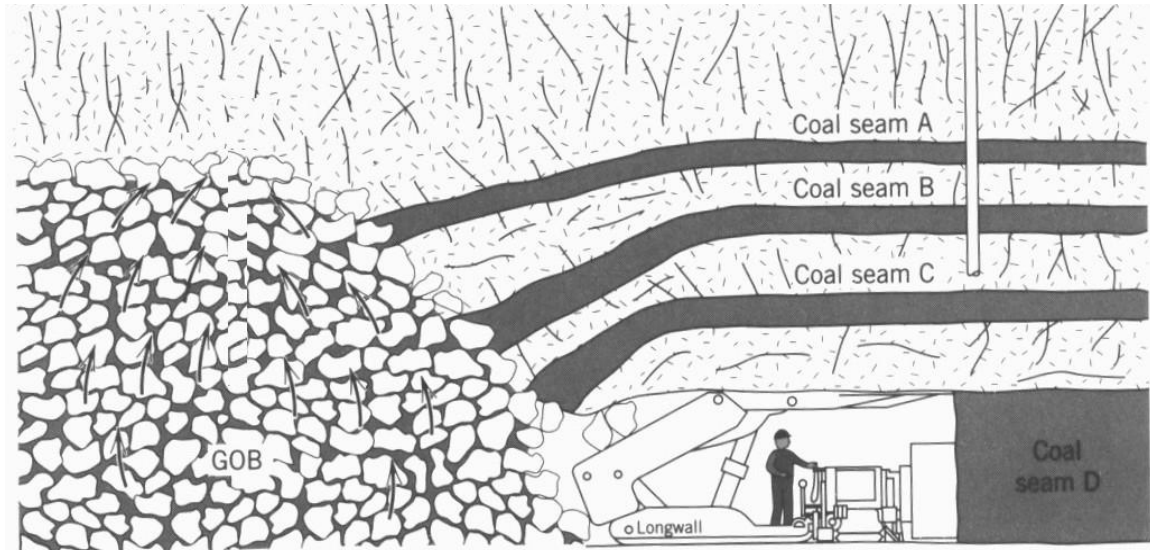


Figure 6: Schematic representation of caving associated with longwall mining [6].

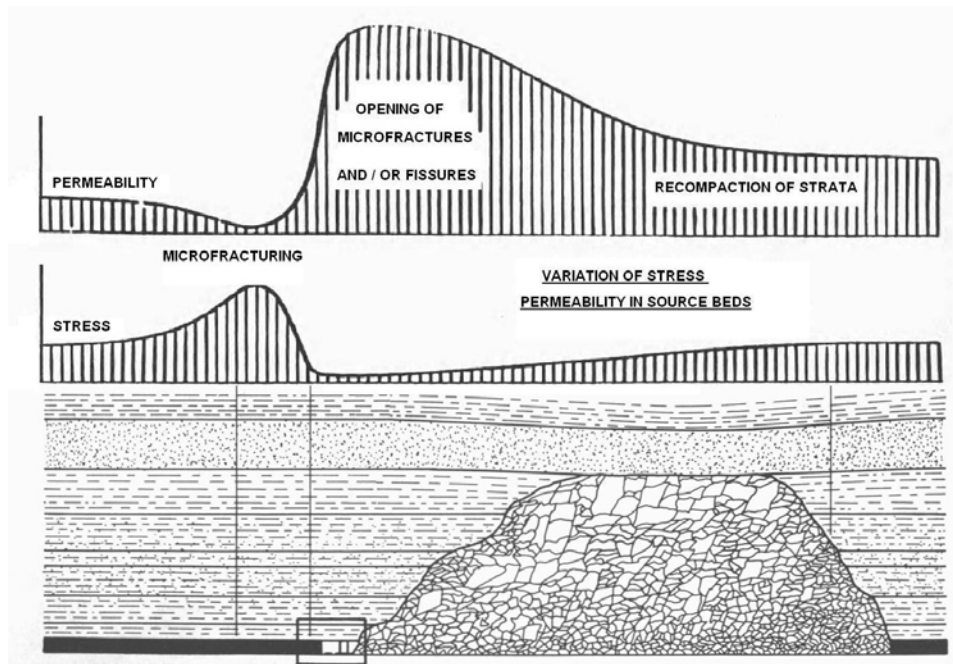


Figure 7: Variation of stress and permeability around an advancing longwall face [7].

Towards the end of 2004, coal production at the mine had to be stopped due to a very serious build-up of gas in the return air. An investigation of the source of the gas revealed that most of the methane was originating from a hair-line fracture in the roof, primarily sandstone. It was not clear whether the fracture was caused by the gas pressure in the overlying seam, or it simply provided a path for flow of gas originating from the overlying seam. However, it became apparent that a major source of gas in the mine is “other” coal seams, or gas pockets, in the vicinity. It took a few days before MSHA allowed coal production to resume. Although the production resumed, the strata damage above/below the working seam is expected to become more extensive as a result of continued production. This may again result in flow of large quantities of gas emanating from the overlying, and possibly, underlying, seam(s). In fact, the mine continued to encounter high methane concentrations early this year.

Task IV: Analyze Results and Develop Procedure

Identification of Technology: The consistency of methane emission and the amount of methane in the exhaust air make a good case of utilizing VAM as a primary fuel source. The absence of any gas or coal power plant nearby, where VAM can be used as a secondary fuel, rules out ancillary use technologies. Flow Reversal Technology was, therefore, determined to be the best suited technique for the mine, as methane concentration is consistent and the ventilation air flow is moderately high. Both TFRR and CFRR can be used to oxidize VAM and capture the heat produced although the latter technique does not have a record for commercial application. The heat produced during oxidation of methane can be recovered from the heat exchangers embedded in the reactor. The thermal energy produced can be used either for direct heating purposes, or electricity generation. The direct use of thermal energy would be the simplest and least capital-intensive option for the mine. It can be used for various in-house operations, like heating, coal drying, and heating ventilation air inflow, if necessary, during the winter months.

The second option for the mine studied is producing electricity from thermal energy, if necessary, either by using the steam cycle or gas turbine. The latter is preferred, and is proposed for the mine in the study because the steam cycle involves higher capital cost and produces low cycle efficiencies, roughly between 20 and 25% [2]. On the other hand, the efficiency of a gas turbine to convert thermal power to electrical power can reach as high as 40%, which makes this option economically more attractive. The gas turbine can also work in a cogeneration mode, if desired, recovering the waste heat from the turbine in a waste heat boiler. Figure 8 shows a schematic of a gas turbine unit, which can be used to generate electricity from VAM [3]. It consists of a compressor mounted on the air turbine’s shaft. Compressed air flows through the heat exchanger embedded in the reactor, where it receives excess heat of combustion. It then returns to the turbine expansion section where a part of its energy gets converted to mechanical energy and then into electrical energy in the generator. Spent hot air then enters a waste heat boiler, which captures the useful thermal energy before venting it out.

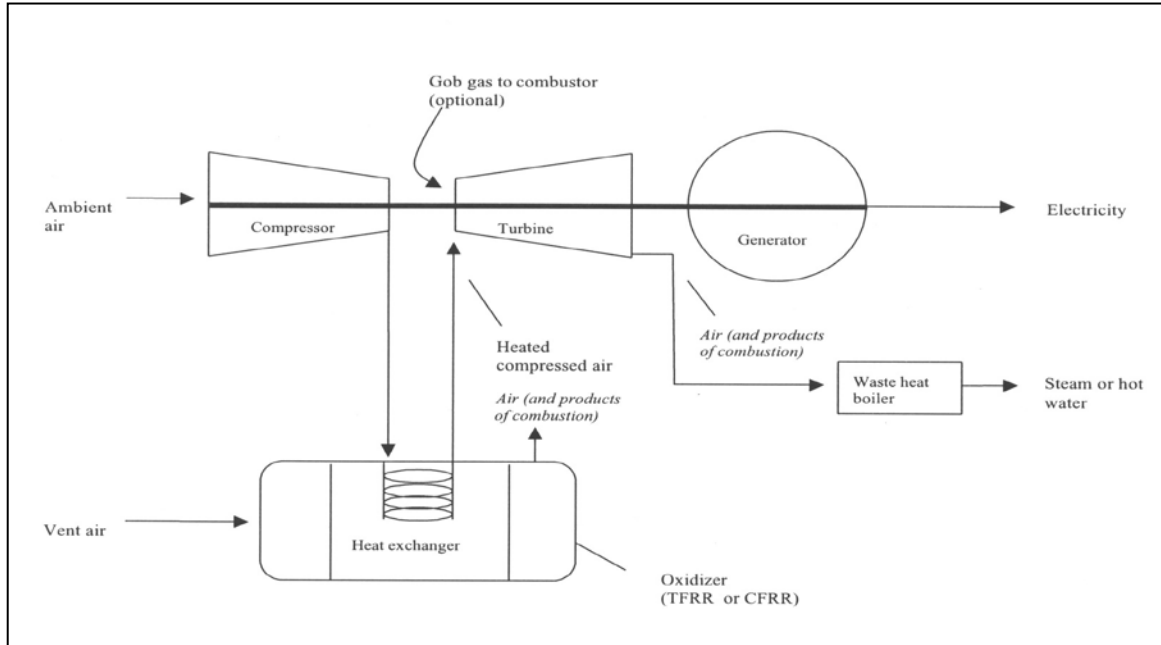


Figure 8: Schematic of gas turbine unit [3].

Task V: Potential for VAM Recovery and Utilization

Economic Viability of VAM Projects: The USEPA conducted preliminary estimates of the performance and cost of VAM utilization systems, based on the information provided by various vendors. The estimates showed that the cost of installation of a system, capable of oxidizing VAM, recovering heat, and generating electricity was much higher than that for a conventional system. The overall project economics also suffered due to low energy recovery factor, approximately between 20 and 30% with the currently available technologies. Using conservative economic and financial assumptions, EPA constructed a simple cost model for a project capable of utilizing VAM at a consistent concentration of 1.0%. The model assumed that the project owner would require a 25% before-tax internal rate of return (IRR).

Economic Analysis (Electricity Generation Option): An economic analysis of the proposed electricity generation project for the mine was carried out using the measured airflow and methane emission data. The project cost and total revenue that would be generated from the sale of electricity, or savings resulting from its use, and earned carbon credits were calculated. The economic analysis was based on the assumption that a single flow-reversal reactor capable of handling 150,000 cfm of ventilation air flow with 0.5% methane concentration would be used. These numbers are somewhat conservative but reasonable. Table 2 presents a detailed economic assessment of the proposed electricity generation project. The cost of electricity was calculated to be 1.6 cents/kWh and the project was estimated to generate 2.9 MW of electricity. The selling price of electricity was taken to be 3 cents/kWh, which along with the earned CO₂ credits, translated to a total yearly revenue of \$1.15 M.

Table 2: Preliminary Economic Analysis

A	Ventilation Air Flow Rate	77 m ³ /s (150,000 cfm)
B	Methane Concentration in Air	0.5 % (v/v)
C	Methane Flow Rate [A x B]	0.385 m ³ /s (705 cfm)
D	Methane Heating Value	42 MJ/m ³
E	Percentage Energy Recovered	80%
F	Life of the Reactor	20 years
G	Global Warming Potential (CH ₄ vs. CO ₂)	21
H	Net Energy Recovered [C x D x 10 ⁶ x (E/100) x 3600] / [10 ⁹]	47 GJ/Hour
I	Turbine Efficiency	30%
J	Utilization Factor	90%
K	Operating Hours [24 x 365 x (J/100)]	7,884 hours/year
L	Electrical Output from the Turbine [H x (10 ⁹) x (I/100)] / [1000 x 3600]	3881 kWh
	REVENUE ASSUMPTIONS	
M	Electricity Sales Price	3 cents/kWh
N	Revenue from Electricity Sales	\$ 0.92 Million/ year
O	Reduction in CH ₄ Emission [C x 0.67* x 3600 x K] / 1000	6,993 ton/year
P	Equivalent CO ₂ Reduction (CO _{2e}) [O x 21]	153,746 ton/year
Q	CO ₂ Credit Rate	\$1.50 per ton
R	Total CO ₂ Credits Earned [P x Q]	\$0.23 Million/year
	Total Revenue Generated [N + R]	\$1.15 Million/year
	COST ASSUMPTIONS	
R	Capital Cost (Reactor Cost, Turbine Cost, Construction and Engineering)	\$6 Million
S	Operating Cost and Maintenance Cost 20 years)	\$4 Million
T	Total Cost (over 20 years) [R + S]	\$10 Million
	Cost of Electricity [T / L]	1.6 cents/kWh

* Density of Methane (Gaseous Phase) = 0.67 kg/m³

The cost analysis of the model for different alternatives showed that, without any carbon credits, the project would have to sell the generated electricity for ~\$0.05/kWh. However, with carbon credits of ~\$2.28 per ton of CO₂e, the project could achieve its target IRR with an electricity selling price of only \$0.035/kWh. Although the model is based on preliminary estimates and its results would change significantly with variations in different input parameters, it nevertheless shows that, even with the current power reduction and carbon emission pricing, many VAM projects can be economically viable.

CONCLUSIONS AND RECOMMENDATIONS

Based on the work completed as a part of this study, the following conclusions and recommendations for future research effort are made:

- This study was a valuable one from the point of developing a procedure for assessment of VAM emission from a mine. Based on the findings, it is recommended that the feasibility of pre-mining gas drainage be evaluated. The estimated methane flowrates into the mine, and flow characteristics call for a detailed study of this alternative.
- In general, the component of methane originating from nearby sources and being emitted into mine air should be taken into consideration when planning any VAM utilization projects. This can be a significant part of the overall methane emission in a mine. Also, due consideration should be given to the fact that emission rate increases significantly with continued mining. This might be due to increased exposure of coal as well as fracturing of the overlying and underlying rock resulting from stress redistribution as mining progresses. Regardless of the reason, the change in flow characteristics can be significant, and so can the overall methane emission from these sources.
- Specifically, the work included studying methane emission characteristics at an underground coal mine, and carrying out a preliminary economic analysis of the proposed method. The measured airflow and methane emission data, and the subsequent economic analysis based on several assumptions made regarding capital and operational cost, indicate viability of such a project for the mine. Although the analysis considered several oversimplified assumptions, it justifiably suggests an opportunity for electricity generation by oxidizing the methane present in the ventilation air. The primary problems foreseen at this time are the capital investment required for such a project, and the uncertainty about carbon credits. The former problem can be overcome because, if VAM utilization projects are pursued in the US, Federal agencies, primarily the USDOE and USEPA, would consider providing financial assistance due to the environmental and energy benefits associated with VAM utilization.
- The observation that methane concentration drops practically to zero with stoppage of coal production suggests favorable permeability/diffusion properties of coal in the region. Hence, there appears to be good potential for pre-mining gas drainage from mine working as well as overlying, seams. This might result in recovery of methane as CBM and reduce its release as CMM, thus lowering the emissions into the mine

and improving mine safety and productivity. At the present time, application of any VAM utilization technology does not present much promise in US coal mines. The reason for this setback is that, in 2004, MSHA defined air leaving the ventilation fan as return air even though it is separated from the fan. MSHA did not provide information about a defined point when VAM actually becomes ambient air. Based on this, MSHA believes that oxidation equipment for VAM utilization should be considered a part of the ventilation system, and therefore, be subject to permissibility standards, depending on the design and specifications. Although the final MSHA ruling is not known at this time, this may be the end of any VAM utilization projects in US mines in the near future. However, such projects will continue overseas, particularly in Australia, China, India, Ukraine, Poland, and Mexico. Just as with longwall mining, once the success of these operations is proven overseas, MSHA might modify its stand.

- For future work, it is recommended that case studies be carried out at other mine locations. At another coal mine in Illinois, the problem of methane emission has increased significantly, and might escalate even further in the future. Furthermore, a more detailed and extensive economic analysis is required to determine the feasibility of such projects. During the next three years, at least two large VAM utilization projects overseas will start producing electricity. Hence, some real data would become available about the technical and economic viability of such projects. Close attention should be paid to the development and progress of these projects. Finally, MSHA's stand on the issue needs to be clarified. Hence, it is recommended that any potential VAM utilization projects in the US be placed on "hold" at this time. This would also provide an opportunity to evaluate the success of such programs in Australia (WestVamp) and China (Sihe Mine in Shanxi Province).

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