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ABSTRACT

Timely and rapid intervention to underground combustion events (fires, explosions, and spontaneous combustion) is the key to the successful control of the mine atmosphere and restoring of a coal mine to production. The focus of this paper is the utilization of a GAG 3A jet engine system to combat either large out-of-control fires or to render an entire mine inert when access to problem areas is difficult or impossible. This system is based upon a Soviet designed agricultural jet engine which consumes aviation fuel with oxygen (O_2) from the intake air and exhausts combustion gases, primarily carbon dioxide (CO_2) and water (H_2O), along with the nitrogen (N_2) from the air and small amounts of carbon monoxide (CO) and hydrogen (H_2). The system is designed to approach stoichiometric combustion (ideally, pure burning that scavenges all the oxygen from the intake air). Therefore, these exhaust gases are almost entirely "inert gases"- i.e., gases which do not contribute to, and in fact, can suppress the combustion process due to the lack of oxygen. Other methods to inert mine areas have been used in the US and internationally, but these methods usually use low flow inertisation equipment or methods. Use of these low-flow inertisation equipment and methods has been successful in proactively rendering gob areas inert and has the ability to inert the entire mine workings. Due to the low flow rate, however, a substantial period of time is required. Two events where the GAG-3A system was used in the United States (U.S.) will be reviewed.

INERTISATION BACKGROUND

"Inertisation", is a technique that has been used around the world to enhance the safety of underground coal mine areas after a combustion event. The term refers to the fact that the atmosphere in the area is such that it can not sustain combustion, including ignitions, and is therefore "inert." This can be accomplished by reducing the O_2 component of the atmosphere to a level that will not sustain combustion of a gas or of a solid, such as coal, or by increasing the amount of an existing flammable gas, such as methane (CH_4), to an atmospheric concentration above which it becomes nonflammable relative to the O_2 concentration of the atmosphere. The O_2 concentration can be lowered to levels below that of normal air through consumption by slow or fast oxidation processes or by the addition of inert gases such as N_2 or CO_2 which do not participate in the oxidation or combustion processes. Such a technique enhances safety: should an ignition source be present in an inert atmosphere, combustion would not occur. Additionally, as will be discussed here, creating such an inert atmosphere in an area of a coal mine where combustion is ongoing, can extinguish the combustion process.

Use of inertisation techniques is generally more widespread in coal mining regions around the world than in the U. S. due to the more prevalent use of bleederless ventilation systems in active areas of coal mines in other countries, as opposed to the almost ubiquitous bleeder ventilation systems currently used in U. S. coal mines. Bleederless ventilation is common where the prevention of spontaneous combustion is a key parameter for the ventilation design of an active panel. Bleederless ventilation is an attempt to render the gob inert in that it permits the accumulation of CH_4 and other nonflammable gases, while limiting the introduction of O_2. This creates an inert atmosphere that will not sustain the self combustion of coal and, therefore, limits the potential for these types of hazardous fire events or as a potential ignition source for an explosion. While bleederless ventilation is rare in the U. S., the sealing of abandoned areas to permit benign, inert atmospheres to accumulate and to limit the area requiring mine ventilation is common to all coal mining regions.

Seals are ventilation structures that are designed to prohibit, or at least greatly minimize, the exchange of atmosphere between an abandoned area with any adjacent ventilated areas and are, therefore, often a key component of inertisation methods. In the U. S., as in many other world coal regions, seals are also designed to limit the potential that an explosion in a sealed area could impact the active mine areas or the safety of the mine workforce. Seals, even those virtually air-tight, do not ensure that the entire atmosphere in the sealed area is inert. Research and investigations have shown that the surrounding strata can permit an exchange of atmospheres between the sealed area and adjacent ventilated areas of a mine (Garcia, et al. 1995). Recent case study modeling work in Australia by Gale (2005) has likewise shown that strata interaction to mining can produce hydraulic conductivity changes in the strata and provides insight to the mechanism for these mine atmosphere exchanges. The sealed area most susceptible to not being inert is the periphery of areas adjacent to ventilated areas. The concern from the inertisation standpoint is mainly that O_2 from the ventilated area will enter the sealed area and render the atmosphere flammable or capable of sustaining combustion, although the reverse flow of CH_4 or O_2 depleted air from the sealed area can also be a safety concern.

INERTISATION AND PRESSURE DIFFERENTIALS

Ventilating pressure, or more precisely pressure difference, is a key parameter for successful inertisation strategies. For inert sealed areas adjacent to ventilated areas, it is obvious that the pressure difference between the two areas at any point in time will dictate the direction and volume of the atmosphere exchange at any given resistance to fluid flow through seals and strata. For this reason, many mine ventilation engineers attempt to minimize this pressure differential. However, normal swings of atmospheric barometric pressure will upset the balance between the sealed area and the ventilated area. The absolute pressure in the ventilated area is a function of the ventilation system with its controls and barometric changes. The pressure in the sealed area is a function of its pressure relative to the reservoir pressure of strata gases and any relief mechanisms that it may have, such as exchange through strata or seals with a ventilated area (or the ground surface in very shallow circumstances) or boreholes to the surface.

Greater controlled use of some of these relief mechanisms to regulate pressure differences between sealed and ventilated areas may be warranted in situations where maintaining the inert integrity of the sealed area or non-contamination of the ventilated area is a concern. For example, surface boreholes, when used to regulate pressure differentials, can be free-venting, forced to flow through an exhauster to create more negative pressures, or attached to a positive pressure inert gas supply system. For instance, as a result of the 1994 Moura #2 Mine explosion and resultant recommendations, some Australian coal mines pump inert gases into the partially sealed gob area of a panel immediately prior to and during panel sealing operations to inert the gob very quickly, i.e., within hours or directly following sealing (Brady, 1996). This procedure greatly reduces the time period necessary for the sealed gob to attain inert status, as opposed to solely relying on the CH_4 and other strata gas emissions to inert the gob naturally. Observations during such studies have shown that the rates of natural CH_4 gas emissions into sealed areas are very susceptible to small changes in pressure (on the order of 1-2 in. of water gauge) so that inertisation by CH_4 gas is slowed as the pressure increases in the sealed area (Brady, 1997; Humphries, 1999). Similar observations of rather large variances in CH_4 gas emission rates in development entries for relatively small changes in pressure have been noted by this author during conversion of gateroad entries from intake to return or visa versa, such as during longwall panel mining set-up. However, techniques such as pumping of inert gases into a sealed area, even though they increase pressure and slow CH_4 gas emissions into the sealed area, can reduce the time period for the sealed area to inert and often result in the sealed area not going through the explosive range, greatly reducing a potential hazard (Balusu et al., 2002).

A classic U. S. example of employing such inertisation control techniques is used at BHP's San Juan Mine near Farmington, NM. Due to the potential for spontaneous combustion in the gob, San Juan is one of the few U. S. coal mines that use a bleederless ventilation system. At San Juan, gob and longwall face pressure are continuously monitored. The injection of N_2 in the area immediately behind the longwall face and the operation of the gob vent boreholes (GVB's) are controlled in unison to prevent atmospheric barometric swings from causing CH_4 gas migration toward the face or O_2 incursions into the gob. This example is also noteworthy in that it illustrates another major consideration for employing inertisation techniques, which is that the separation between the area to be inerted and other areas may not always be a high resistance barrier such as strata and seals. In San Juan's case, the barrier is the shields on the longwall face and the caving gob.

However, in mine emergency situations, such as mine fires or explosions and resultant ongoing combustion events like those that will be discussed herein, the area to be inerted may have low or virtually no resistance barrier between other areas of the mine. As a result, relatively small pressure differentials can have a major impact on the inertisation process. In mine emergency situations where the miners have been evacuated and direct fighting of the combusting area becomes unsafe or impossible, the usual next step is to stop forced ventilation and seal mine openings to begin and assist the inertisation process. However, if unabated by higher resistance barriers such as seals, stoppings, or strata; relatively small pressure differentials like those caused by barometric pressure swings or natural ventilating pressure and/or other thermodynamic effects (e.g., temperature/ventilation effects due to the fire) can often carry large volumes of O_2 rich mine air into the area of ongoing combustion to compromise the inertisation process. As a result, research is being conducted in the U. S. by the National Institute for Occupational Safety and Health (NIOSH) to develop a technique or techniques that can reliably place nearly air-tight seals remotely into strategic locations of a the mine to better isolate the combustion area and enhance and ensure the inertisation process (Gray et al., 2004; Trevits et al., 2005).

Depending on where the combustion event is located in the mine, the use of inertisation techniques in mine emergencies often presents a major challenge to control and evaluate the process. The more isolated a combustion event is from other areas of the mine due to physical barriers and/or its location relative to the mine ventilation system, the more effective the inertisation process (Prebble et al., 2000). The Dotiki Mine fire in February of 2004 is an example of the latter, as gas monitoring readings indicated that N_2 being injected into the fire area, which seemed to be in a relative "dead zone" within the sealed mine, was successful in controlling and suppressing the fire even before the area was more isolated- from a ventilation standpoint- by the installation of 18 remote seals from the surface.

LOW-FLOW INERTISATION

Some inertisation applications, such as those involving underground coal mine emergencies, can be dealt with using inertisation methods and equipment which are limited, or only practical, in low volumetric flow ranges of one thousand to a few thousand cubic feet per minute (cfm). Examples of these low flow methods that have been successfully used in coal mining applications through boreholes are liquid or gaseous N_2 or CO_2 supplied by tankers, N_2 supplied by a nitrogen membrane plant (although N_2 pressure swing absorption plants could also be used), and the Tomlinson Inert Gas Generator which produces mainly inert gases from a combustion process. Tomlinson Boiler units have been used in coal mine inertisation applications in Australia since 1994 (Tomlinson Boilers, 2002). Most of the Tomlinson Boiler applications have been used to deal with spontaneous heating events and to inert gobs during panel sealing. Per the company's product information, the flow rate of current Tomlinson Boiler units is approximately 1,060 cfm at about 14.5 psi, and the output gas composition is typically <2% O_2, 75% N_2, and 12.5% CO_2 (Tomlinson Boilers). Actual field trials using Tomlinson Boilers have shown 0_2 to be in the range of approximately 2.5% and a small amount of CO- if adjusted correctly (Brady, 1997; Humphries, 1999). To date, Tomlinson units have not been used in the U. S. coal mining industry; however, liquid N_2 and CO_2 have been used for a number of years. Most recently, liquid N_2 was used at the Dotiki, Excel No. 3 (late 2004-2005), Buchanan (2005), and to a lesser extent, Pinnacle (2003-2004) Mine fires. The liquid N_2 is supplied by bulk tankers and is vaporized to a gas phase at the injection site. However, this delivery method can suffer from availability and transport distance issues and borehole accessibility due to rugged terrain which can result in delayed arrival times disrupting what should be a controlled injection process. More recently, N_2 membrane plants, which typically can deliver 95-97% N_2 in ranges of 500 to 1,000 cfm or more depending on plant size, have been used at the Excel No. 3 and Pinnacle events (Smith et al., 2005; Smith et al., 2005; Trevits et al., 2005). Given their volumetric limitations, these low-flow methods and equipment are best suited to applications where localized inertisation can be employed and/or controlled, such as spontaneous combustion heating (Stephan, 2000).

HIGH-FLOW INERTISATION- THE GAG 3A SYSTEM

In some coal mine combustion events, localized or low-flow inertisation may not be effective or can be very time consuming. This may occur when there is a large area that cannot be controlled from a ventilation perspective or the location of the combustion event(s) can only be generalized, such as an event located in a gob environment. These situations tend to occur in large underground coal mines using both room and pillar and longwall mining methods. The size and production capacity of these large mines compounds the financial, safety, and resource issues associated with these emergencies. Therefore, a need exists for a larger scale inertisation capability. The GAG 3A system meets this need.

The GAG 3A system (figure 1) is based upon a Soviet designed agricultural jet engine which consumes aviation fuel with O_2 from the intake air and exhausts combustion gases, primarily CO_2 and H_2O, along with the N_2 from the air and small amounts of CO and H_2. The system is designed to approach stoichiometric combustion (ideally, pure burning) that scavenges all the oxygen from the intake air. The GAG 3 A inertisation system technology was originally developed by the Polish mining industry in the early 1970s and has been used extensively in Poland, Czech Republic, China, and more recently to combat an extensive gold mine fire in South Africa. The initials GAG come from the Polish for gas to gas combustion. During a joint effort with the Polish Central Mining Institute (CMI) in 1982, testing of the GAG 3 A inertisation system technology was conducted at the U. S. Bureau of Mine's (USBM) Safety Research Coal Mine in Bruceton, PA (USBM, 1982). For whatever reasons, the technology was not embraced by the U. S. coal mining industry at that time. The technology was further refined and successfully used in Poland and was imported into Australia in 1997 in response to some recommendations resulting form the Moura #2 explosion investigation. Currently, the hardware and trained system operators are maintained by the Queensland Mines Rescue Service (QMRS). More recently, two of these jet engines were purchased from Poland by Phoenix First Response[1], a subsidiary of Micon, Inc., a U. S. mining support company. A QMRS GAG 3A[1] engine was used at Loveridge Mine (2003) and a Phoenix First Response unit, manned by Polish operators, at the Pinnacle Mine (2003-2004) events. A Phoenix First Response unit was also on standby for the Buchanan Mine fire (2005), but alternative fire fighting methods were ultimately used.

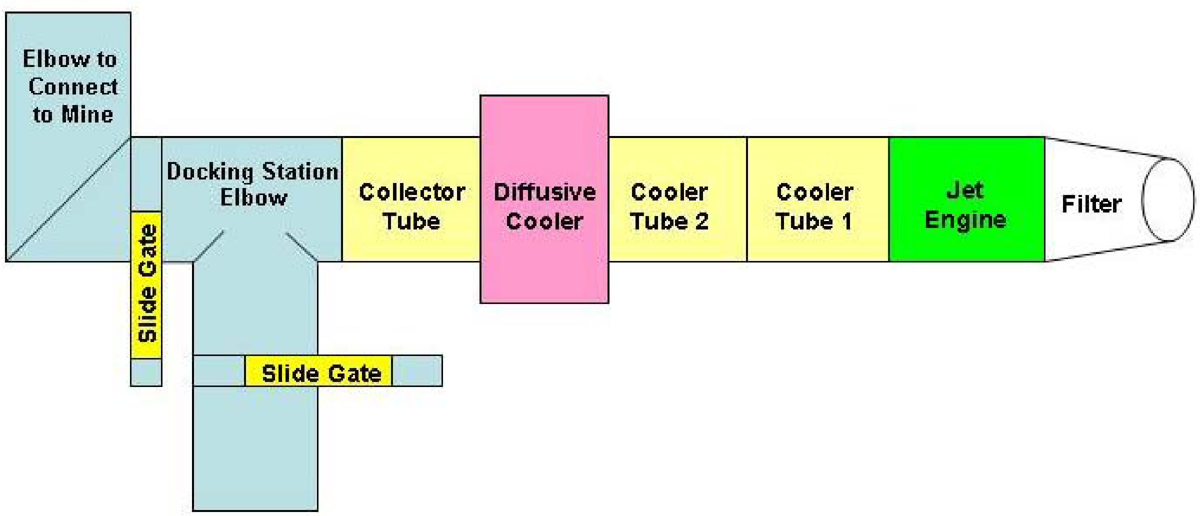

Figure 1. Schematic plan view diagram of the GAG 3A Jet Engine System.

The process of producing inert gases, utilizing a jet engine and associated equipment, involves the combustion of A1 Jet fuel. The exhaust contains low O_2 levels and high levels of CO_2. CO and O2 levels, although low, vary according to back pressure on the jet exerted by mine resistance and ambient temperature. There maybe production of isobutene and isopentane dependent on fuel grade and additives but these will be at low levels. Volumetric flows from the system have been stated in the literature in the 50,000 cfm range, and as high as 64,000 cfm. However, the volume of the engine output is susceptible to the site specific backpressures experienced in a mine inertisation application. It is thought that these backpressures are a function of mine ambient temperature, gas mixture and buoyancy effects, barometric fluctuations, and mine resistance to air flow. While it was not possible- in the U.S. applications that follow- to accurately measure the volumetric GAG 3A system output, most observers felt that output was below this level. High backpressures, experienced at times during these applications, were probably the main reason for this conclusion.

[1] Mention of a specific product does not mean endorsement of the product by NIOSH.

A specially designed afterburner (part of the engine in figure 1) is utilized to achieve near stoichiometric combustion (complete consumption of O_2). This is achieved by varying fuel pressure, engine speed (air intake), and water cooling the tubes which contain the flame. The heat produced by the afterburner is as high as approximately 1,300^{O}F in the chamber and temperatures of almost 3,200^{O}F have been recorded at the flame tip.

A diffusive cooler (figure 1) is utilized to serve a two-fold purpose.

1. Provide a barrier between mine atmosphere and the GAG system. Maintained between critical maximum and minimum pressure requirements, so as not to impinge on the water curtain and create O_2.
2. Cool the exhaust gases prior to mine injection, typically to a 160^O F to 190^O F temperature range.

This afterburner cooling device, under operational conditions, will produce H_2 levels and higher O_2 concentrations due to "thermal cracking" when the flame impinges on the water curtain. The concentrations produced have been as low as 5 ppm and as high as 8,000 ppm in the case of H_2, while O_2 concentrations have been seen as high as 0.5%. The steam exiting the system is slightly acidic and is known to have produced a secondary reaction with carbonaceous material and/or steel, resulting in the production of H_2. The concentration levels of produced H_2 have not been thoroughly studied during operations, but have been recorded as high as 125 ppm (differential between measured levels prior to entering the mine and mine detection system measured values some 7,200 ft remote from the mine inflow point).

COMPARISON OF HIGH-FLOW WITH LOW-FLOW INERTISATION SYSTEMS

As mentioned previously, low-flow inertisation systems have been successful in the proactive inertisation of gob areas and have the ability for total mine inertisation, but obviously a substantial period of time is required due to their low flow rates. To put it simply, large-volume units take less time to achieve the same results as the smaller capacity systems, but consideration must be given to the relative cost factors. Experience to date has shown that, where large volumes of inert gases are required, the GAG 3A system can deliver these large volumes on a lower cost per cubic foot of inert gas than many of the low-flow methods for which cost information was approximated during actual deployment of the systems.

Each inertisation system has an optimum application dependent on the site-specific variables existing at a mine at the time of a combustion event. Experience has indicated that a risk based logic approach will aid in the selection and determination of the appropriate system for a particular application. To assist with utilizing an inertisation system of choice, the following table (Table 1) indicates both positive and negative variables for consideration prior to application.

Table 1. Comparison of inertisation methods.

Inertisation Method	Advantage	Disadvantage
GAG 3A Jet Engine Inertisation System	Large Volume	Manpower (12 people/24 hrs)
	Low cost per cfm	Support Materials/Supplies
	Mobility	Training
	Access to the mine ventilation system	Higher O_2 (than CO_2 and N_2)
	Self Contained	Fire gas ratios unstable (due to CO & H_2 production)
Tomlinson Boiler	Versatility	Low Flow
	Manpower (2 people/24 hrs)	Time Duration
	Portability	High Maintenance
	Minimal support materials/supplies	Greater than 2% O_2 Levels
CO_2 Liquid and/or Gaseous	Cool	Low Flow
	Denser than air (can be advantage-application dependent)	Method of application
	Ease of movement	Transport & Availability
	Detection relatively easy	Fire gas ratios unusable
N_2 Liquid and/or Gaseous	Cool	Low Flow
	Lighter than air (can be advantage-application dependent)	Specialized Operators
	Injection ability	Transport & Availability
	Operational logistics relatively simple	Detection requires specialized instrumentation

GAG 3A SYSTEM UTILIZATION IN THE U. S.

Loveridge Mine

On February 13, 2003 a fire began in a trash car near the bottom of the slope in the Sugar Run area of the Loveridge Mine (figure 2). The mine is situated in West Virginia near the town of Fairmont and employs approximately 370 people. The mine normally operates a longwall and continuous miner development sections. The mine owner, Consol Energy, is the largest underground coal producer in the U. S. and the operation at Loveridge is pivotal to their West Virginia operations. The company's mines rescue response capability is structured around each operating mine, with a mutual response arrangement between the mines to ensure operational capability in the event of an extended incident at any of their operations.

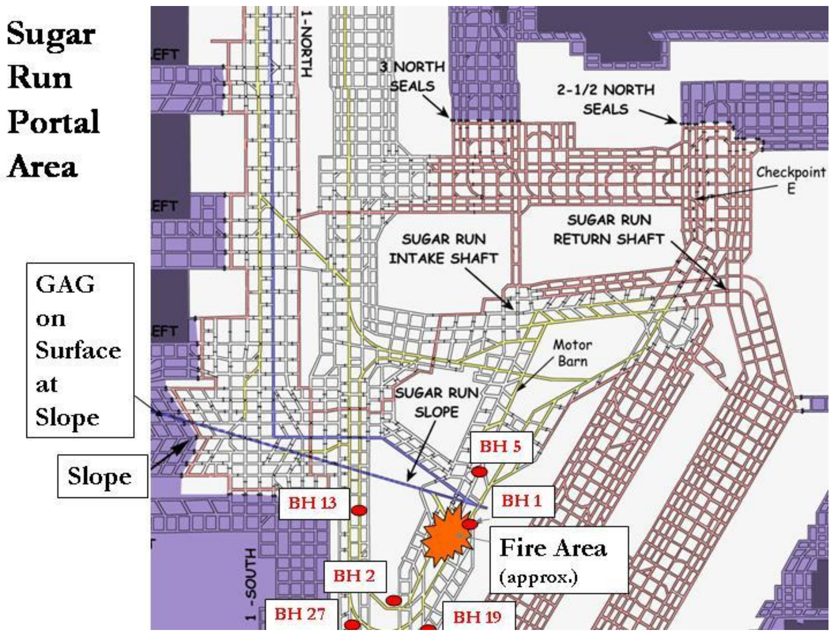

Figure 2. Sugar Run Bottom and slope area at the Loveridge Mine.

After some direct fire fighting attempts, the Loveridge Mine was evacuated, the mine openings sealed, and six boreholes drilled in and around the fire area for monitoring and water pumping. By March 2003, attempts to suppress the fire with water pumped from the surface was not fully successful due to existing floor elevations that limited uniform and complete water dispersal through the fire area. In addition, there were concerns that there was sufficient air leakage through the mine opening seals to keep the fire in a presumed "smoldering" state. A decision was then made to attempt to inert the fire area using the GAG 3A jet engine technology. The QMRS was contacted to deploy an engine and operating personnel in a joint collaboration with Consol Energy, the U. S. Department of Energy (DOE), the National Institute for Occupational Safety and Health (NIOSH), the United Mine Workers of America (UMWA), and the Mine Safety and Health Administration (MSHA) (Parkin, 2005). A ventilation simulation of the inertisation situation at Loveridge Mine was done by the operator, which concluded that it was feasible to inert the whole mine. On March 8, 2003, preliminary plans for a means (a docking facility) to connect the GAG 3A system to the existing slope entrance structure were discussed and the design of the necessary components was begun. The slope, initially sealed with a make-shift seal, would permit the inert gases to travel to the fire area near the slope bottom and continue through the main entries of the mine to the other shaft areas (figure 2).

On April 1, 2003, the QMRS teams arrived at Loveridge mine for site familiarization, identification of operational protocols, and requirements to be implemented prior to commissioning the GAG 3A system at the mine. As a result, two mine rescue people with breathing apparatus, support engineers/staff, drivers, and bulk fuel monitoring people were identified as key Consol personnel to support the use of the GAG 3A system for an ongoing 24-hour-per-day operation.

By April 4, 2003, the GAG 3A system had arrived at the Loveridge Mine site and, after some maintenance to the jet engine and its components, the system was commissioned for inertisation operations (figure 3). Set-up time for the system was approximately 11 hours. Following the first 12 hours of engine operation, it was noted that there was a need for additional cooling for the tube connections, as well as readjustment of some joints (afterburner connection flanges), and the input water pressure needed to be increased. On April 5, 2003, after 16 hours of run time, the slope seal was leaking steam and the outer connection to the slope (figure 4) developed gaps and was leaking badly. The engine was shut down while repairs were made. Instrument readings indicated that the engine was working against approximately 8 in of water gauge backpressure.

Figure 3. GAG 3A jet engine and afterburner, Loveridge Mine.

Figure 4. GAG 3A jet engine system interface with Sugar Run Slope. Note steam indicating exhaust gas leakage.

On the afternoon of April 6, 2003 the slope seal yielded with 9.5 inches water gauge registering on the gauge. Repair of the slope seal and connections permitted a shutdown and a visual inspection of the engine and its components. This inspection did reveal some degradation of the flame stabilizer rings, thought to be a result of the relatively high backpressure on the engine. The stabilizer rings were later replaced with Inconel®[1] steel flame stabilizer rings (a higher melting point than the original 316 stainless steel) and thereafter showed little sign of degradation. Other maintenance issues that surfaced were: a change of oil in the lubrication system had resulted in severe coking in the afterburner chamber, and the need for periodic engine shut down and inspection. By April 9, 2003, boreholes and shafts in the Sugar Run area were outgassing and readings indicated the presence of the exhaust gases. Examples of the presence and effectiveness of the engine exhaust gases in the Sugar Run bottom area, indicated by the presence of exhaust gases (CO_2 as the identifier) and the decrease in O_2 are shown in figures 5, 6, and 7. By the sixth day of operation, the jet exhaust gases had reached St Leo shaft (figure 8) and by April 13, 2003, St Leo and Miracle Run fans were first started, which helped to pull inert gases through the mine from the Sugar Run bottom area. At 8 pm on April 15th, 2003, the first rescue team re-entered Loveridge, 61 days after the mine was sealed and 10 ½ days after the GAG engine was started. The GAG 3A system was operated intermittently during the mine rescue re-entry operations until April 21, 2003, when operations were terminated. In total, the engine operated for 270 hours with minor servicing and replacement of consumable parts and the engine consumed an average of 423 gal (1,600 liters) of fuel per hour and 4,887 gal (18,500 liters) of water per hour.

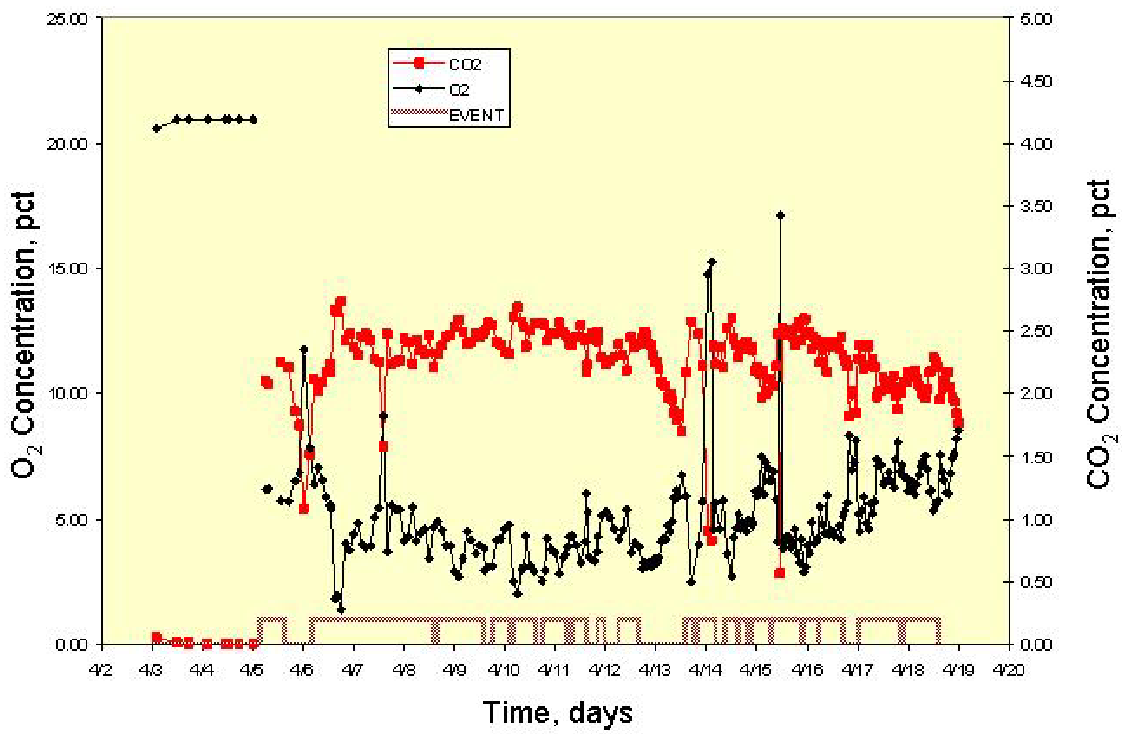

Figure 5. CO_2 and O_2 concentrations in Sugar Run Slope, Loveridge Mine.
"Event" as shown on the graph indicates GAG 3A operation (on/off).

During its 17 days of operation at the Loveridge Mine , the GAG 3A system was able to render inert the Sugar Run bottom area and the over 9.5 miles of passageways at the Loveridge Mine by reducing the O_2 concentrations (Conti et al., 2003). As a result, the mine rescue teams were able to safely re-enter the mine to explore and ultimately isolate the fire area, which still had indications of active combustion, and was further inerted with N_2 injection and permanently sealed. At the time, this was the longest that the jet engine had operated for a mine inertisation application and some system components failed, but these occurrences were handled without major impact to the overall inertisation process. The potential benefit of more positive sealing of connections, ports, and mine seals was also recognized. Finally, the Loveridge Mine experience also provided a learning process for those involved and demonstrated that the GAG 3A system would be a valuable tool for fighting mine fires in the U. S.

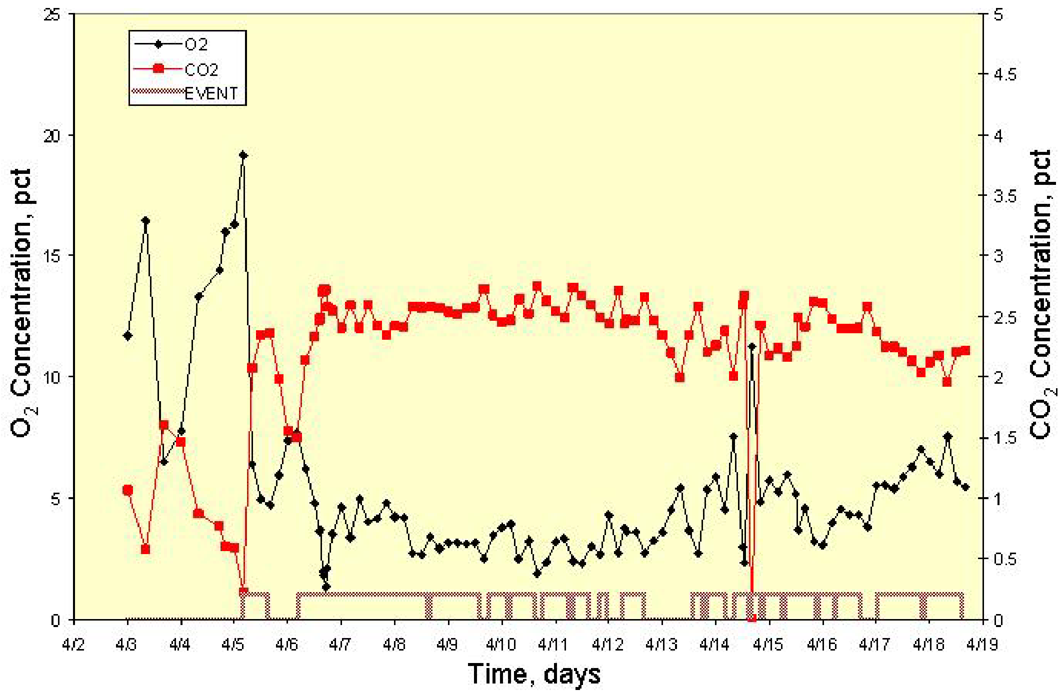

Figure 6 - CO_2 and O_2 concentrations at borehole #1, Loveridge Mine.
"Event" as shown on the graph indicates GAG 3A operation (on/off).

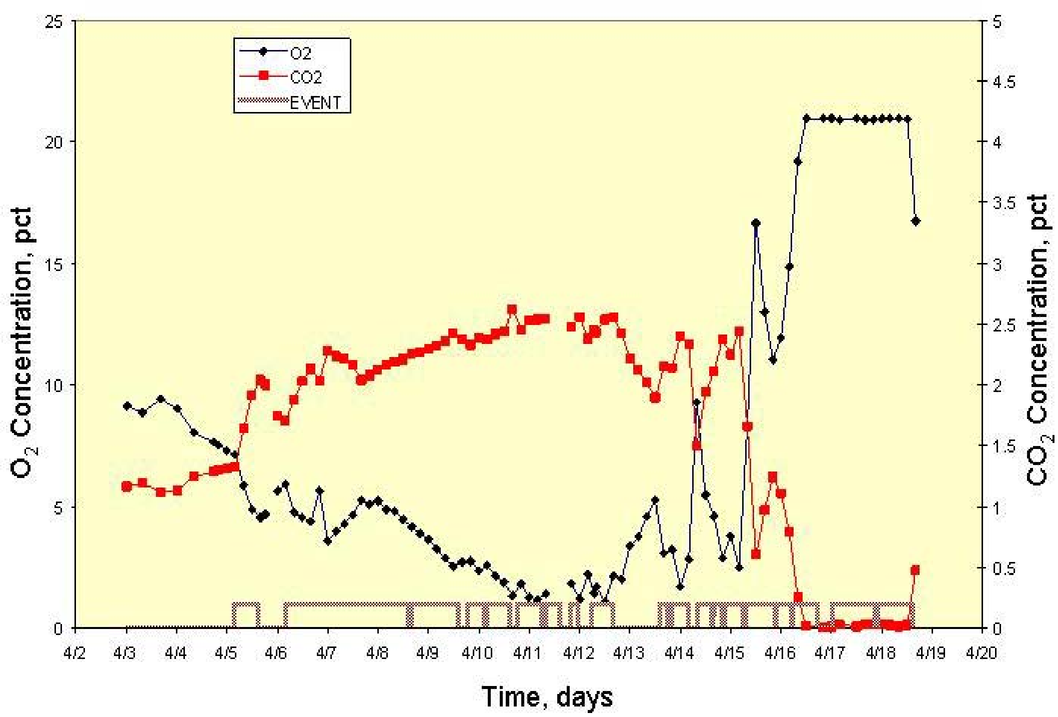

Figure 7 - CO_2 and O_2 concentrations in borehole #13, Loveridge Mine.
"Event" as shown on the graph indicates GAG 3A operation (on/off).

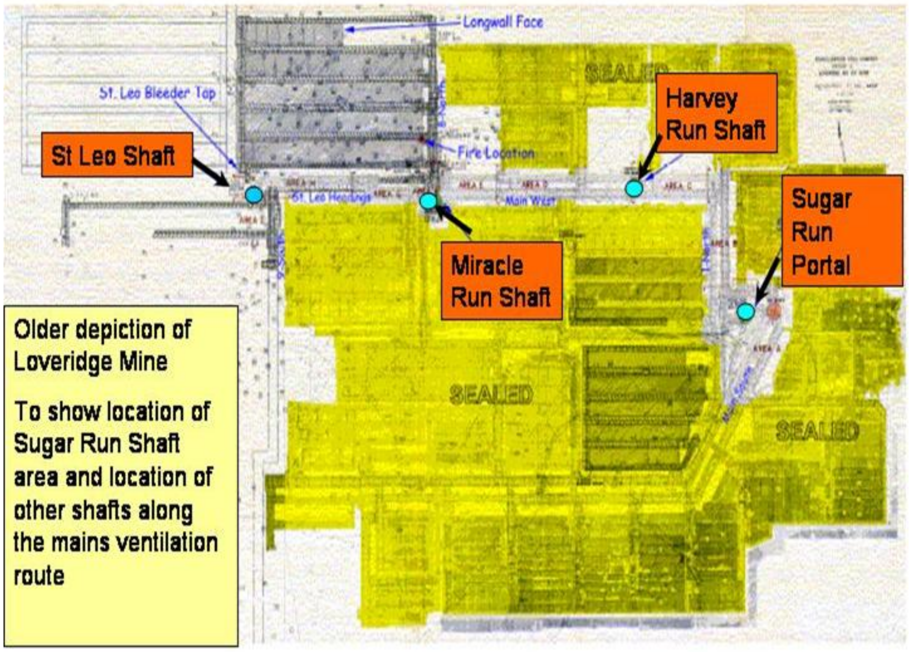

Figure 8. Map of the Loveridge Mine showing Sugar Run and other shaft locations.

Pinnacle Mine

At the Pinnacle Mine located near Pineville, WV, a series of four explosions occurred between August 31 and September 16, 2003 in the active #8 longwall district, shown in figure 9. Mine gas readings from the various monitoring boreholes indicated that there was active combustion ongoing at an unknown location in the longwall district. The operator began drilling additional boreholes into the longwall gateroads to detect the heat source. Phoenix First Response was contacted by the operator and arrangements were made to utilize the GAG 3A jet engine in an attempt to inert the approximately 9,000 ft by 9,000 ft longwall district to extinguish the fire. Arrangements were also made to have trained GAG operators from Poland man the operation of the jet engine. By October 1st, the engine had been set up at the 8A bleeder shaft (figure 9) and the operators had arrived. The engine was started late in the day after a crane had removed the bleeder fan elbow conduit from the shaft and replaced it with a specially designed GAG docking hood that was then fastened to the shaft coping (figure 10). This system had considerably less leakage issues than the Loveridge slope structure and temporary seal which were not as amenable to a pressurized, leak-proof connection.

Prior to the GAG 3A engine start-up, NIOSH had been asked by the mine operator to provide technical assistance in locating the fire source. It was hypothesized that as the inert gas from the GAG engine pushed through the gob, there was a possibility that explosive mixtures of CH_4 and O_2 could be pushed through the fire zone, causing an explosion. NIOSH developed and implemented a plan to instrument five boreholes near the active longwall panel with sensitive pressure monitoring devices that could detect an explosion. If an explosion occurred, triangulation techniques could then be used to determine the point source of the explosion. Figure 11 depicts the #8 longwall district including the bottom of coal elevation contours, the active 8I longwall face, monitoring boreholes, and the final 12 NIOSH pressure transducer monitoring holes. However, at the time of the GAG engine start-up, only boreholes BH-1, BH-4, BH-5, 8-I-1, and 8-HI-1 were being pressure monitored.

The GAG 3A system ran successfully through October 7th with only occasional operational or maintenance issues. S. Fork fan was operated and ventilation adjustments made to assist in drawing the inert exhaust gases toward the active longwall. Even so, as occurred at the Loveridge Mine, there were periods when the engine would see more or less backpressure from the mine. Theories as to why this was occurring abounded and included flow restrictions, barometric pressure influences, and an "air bubble". Obviously, the exact cause could not be determined, but perseverance in terms of continuous operation of the engine seemed to overcome the variable backpressure problem.

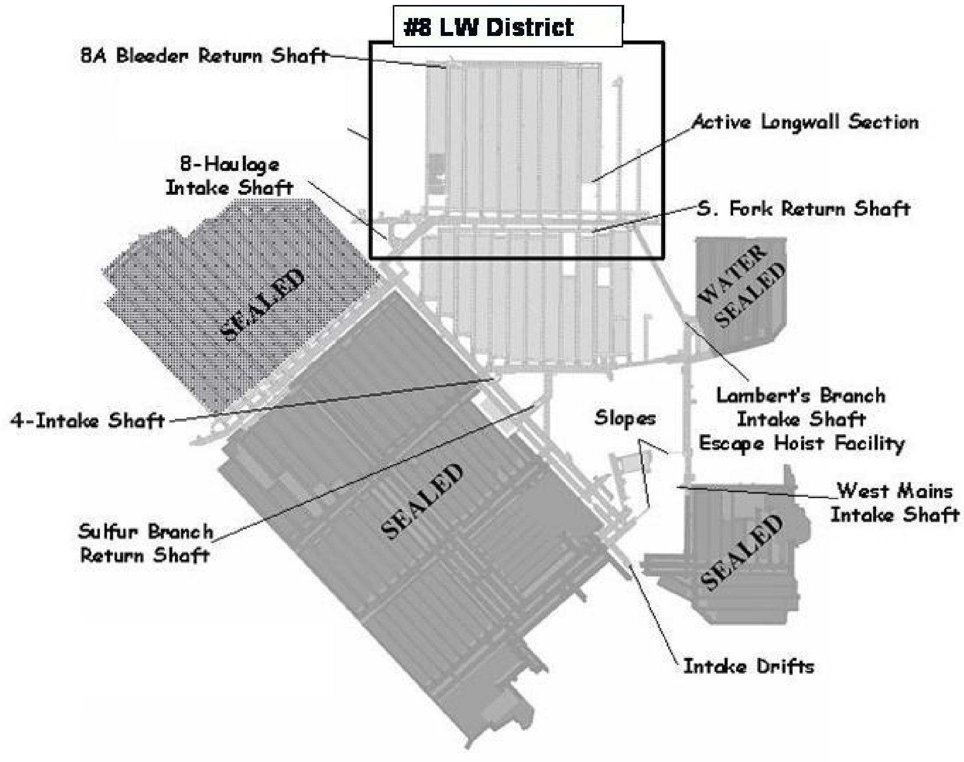

Figure 9. Pinnacle Mine showing #8 Longwall District, 8A Bleeder fan, and active longwall.

Figure 10. Photo of GAG 3A System set-up at 8A Bleeder Shaft, Pinnacle Mine. Note fabricated shaft hood for docking.

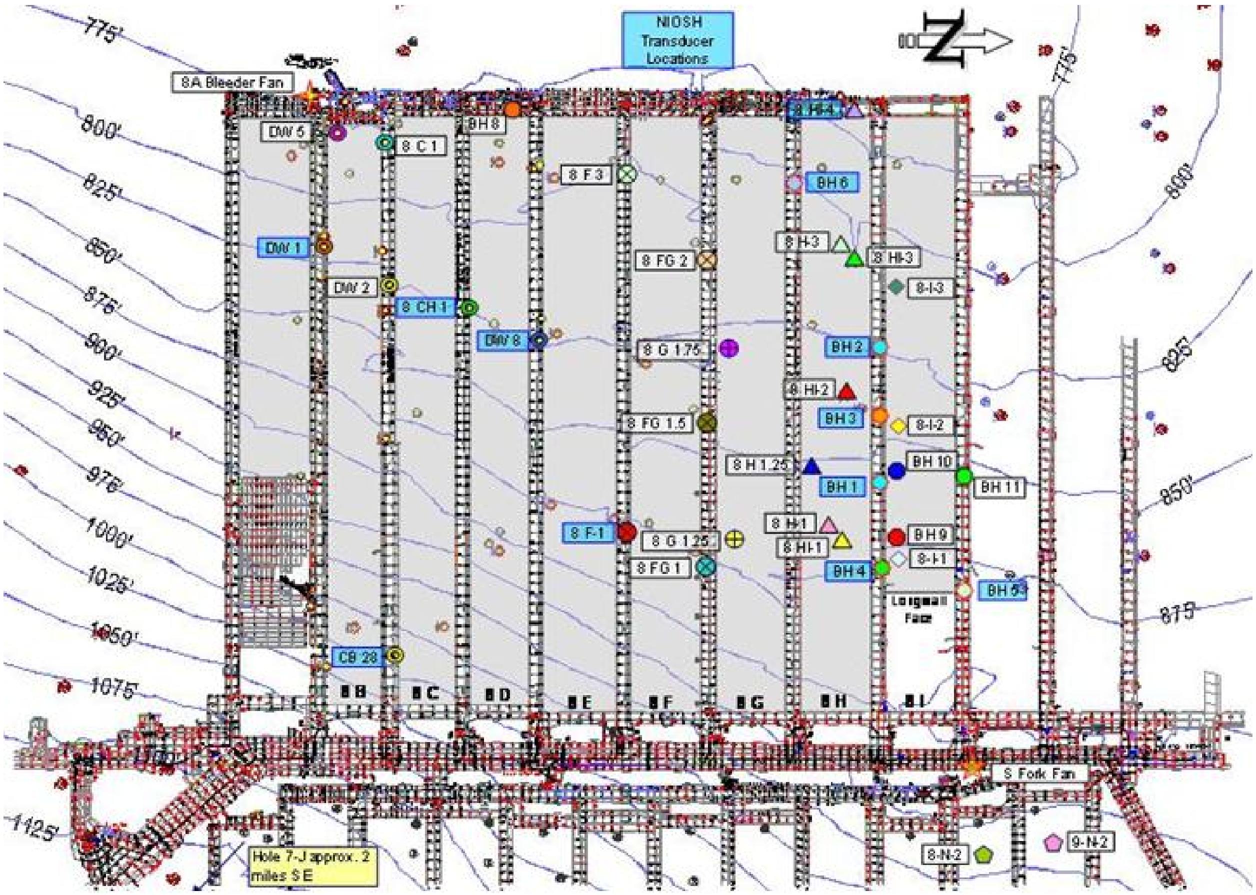

Figure 11. Pinnacle #8 Longwall District depicting bottom of coal elevation contours, 8I active longwall face, monitoring boreholes, and final 12 boreholes pressure monitoring boreholes (NIOSH).

Tracking the underground movement of the exhaust gases via the monitoring boreholes in the #8 longwall district indicated that the exhaust gases initial migration was generally down-dip from the 8A shaft bottom, i.e., the structurally low northwest corner of the district inerted first and then the inerted zone gradually moved up-dip. Gravity (their higher density) may have been a reason for this, although ventilation (the operating S. Fork fan), ventilation controls, water accumulations, or gob resistance could also have been reasons in whole or in combination.

By October 8th, the inert gas front was approaching the active 8I longwall area and the five pressure monitoring borehole sensors measured a sudden pressure increase attributed to a gas ignition or explosion. Determination of the location of this event was much more difficult than originally envisioned as it appeared that the pathway to the nearest pressure monitoring boreholes may have been mostly or entirely through the gob itself. The data was analyzed using three empirical methods based on 1) the arrival times of peak pressures, 2) the magnitude of the peak pressures, and 3) the difference of arrival time between peak one and two at each location. All three methods showed the most probable location of the source of the explosion to be in caved area of the active longwall panel, just inby the face.

The time to initially inert the desired area of the mine took approximately 7 days, which is the length of time that the mine had originally estimated. The GAG 3A engine continued to be operated through October 19th in an attempt to maintain the inert area near the active longwall face. During this time, the pressure transducers measured another, much lower magnitude and less sudden, pressure increase on October 14th, indicating a possible explosion. Also during this time period, the mine operator, using a compressor, brought inert gases out of a borehole in the lower elevation area of the longwall district, transported the gases overland via a pipeline, and pumped the inert gases into boreholes closer to the area of the suspected ignition source in the gob behind the active longwall face. In the time period following the inertisation process, a more extensive array of pressure monitoring was installed in the longwall district and the mine was alternately ventilated using different ventilation scenarios. This ventilation process was an attempt to determine whether the ongoing ignition source had been successfully and completely extinguished by the inertisation process. While gas readings did not show conclusively that combustion was ongoing in the area, concerns about the presence and interrelationship of relatively small amounts of H_2, CO, and CH_4 delayed re-entry until a localized inertisation plan was instituted early in 2004. This re-entry plan is presented by Smith (Smith et al., 2005). The #8 longwall district was first temporally sealed and then permanently sealed in February and March of 2004, permitting continuous miner production to resume on April 7, 2004. Following re-ventilation of the 8I longwall panel in May, longwall production resumed on May 17, 2004.

SUMMARY

Underground coal mine fires and explosions are major events impacting miner safety, job security, the nation's resources, and the financial well-being of coal producing companies. When such events arise and can not be dealt with directly, a suite of remote (from the surface) tools have been, and are being developed, to minimize the event's impact and provide for the safe re-entry and re-start of the mining operation. A number of these remote techniques use the long employed mining concept of inertisation of the mine atmosphere, to suppress the combustion process to enhance the safety of the miners on re-entry, and to minimize the highly time-dependent impact of the event. Some of these events can use localized inertisation techniques, while others call for more generalized and larger area inertisation, or in some cases, a combination of the two. The Loveridge and Pinnacle Mine inertisation experience demonstrated the ability for the GAG 3A system technology to inert major portions of large mines to deal with combustion events and shorten the time frame for safe re-entry. Experience gained from these two applications of the technology and its potential use with other remote mine firefighting technologies will be of substantial benefit to the industry in responding to such future events in the U.S., if and when they should occur.

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