1st Solicitation for Single Investigator Research Grants

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Final Technical Report

1.0 Cover Page

Project Title: Control of Spontaneous Combustion Using Pressure Balancing Techniques

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2.0 Executive Summary

The problem of spontaneous combustion (Sponcom) has been associated with the coal mining for many years. It is estimated to be the cause of more than 20% of coal mine fires. Some of these fires continue for a long time and result in the loss of large amounts of coal. Besides causing the waste of valuable coal, such fires also pose danger to life. From a safety point of view, even a small incident of spontaneous combustion can take a heavy toll in terms of injuries and fatalities to mine personnel, expenses incurred in attempting to extinguish the combustion, and loss of production and machinery.

The history of coal mining in the U.S. is replete with mine fires and explosions. In longwall mines, fires usually start in the caved gob areas that are not easily accessible. Depending on the coal characteristics and the ventilation conditions, self-heating of coal can start at temperatures as low as 35 ºC. If the heat is not removed it will increase the coal temperature, leading to ignition and fire. Adequate ventilation is the primary method used to prevent fires and explosion in an underground mining environment. Another method for fire prevention is pressure balancing. This is a technique of neutralizing pressure differentials in areas where there is potential for sponcom.

One objective of this study was to represent a mine gob by a physical model and then use a microprocessor-based, automatic, pressure balancing system to neutralize or control the flow of air into the simulated gob. The model was constructed and equipped with fans, stoppings, regulators, and a pressure balancing system, to accurately represent an underground coal mine. Another objective was to conduct ventilation surveys in at least two coal mines. Surveys were carried out in three coal mines: one in Illinois (mine A), one in Pennsylvania (mine B) and another in Colorado (mine C). Mine A is a room and pillar mine ventilated by an exhaust system. Mines B and C are longwall mines ventilated by bleeder and bleederless ventilation systems respectively. The results of these surveys were used to determine realistic input parameters for the physical model. Several pressure balancing experiments, both passive and active, were carried out at the University of Utah laboratory model. The results of three experiments are presented in this report.

This study has shown that selection of the proper ventilation system is crucial to control Sponcom. Of the various systems considered, flow-through and bleederless ventilation systems have been found to be more efficient at balancing pressures across the gob than other comparable systems. This study has also shown that a pressure balancing technique, operated by passive or active means, can be used to neutralize the flow of air through the gob, regardless the type ventilation system used. However, from an economic point of view, the technique is more suitable for a U-tube wrap-around ventilation system, because for the same flow distribution through the workings, it can be used to neutralize larger pressure differentials with about the same infrastructure.

Further laboratory research is recommended to more accurately model the effects of a large pressure-balancing chamber, which would also allow an assessment of changes in barometric pressure on the pressure-balancing system.

3.0 Problem Statement and Objectives

3.1 Problem Statement

This research project was conducted in response to the 2013 solicitation from the Alpha Foundation. It addresses the area of Ventilation and Dust Control, under the topic of “Design and Technology for Prevention” in Focus Area 1, “Safety,” as identified in the solicitation.

Spontaneous combustion is a safety hazard in underground coal mines. The history of coal mining in the U.S. is replete with mine fires and explosions. Sponcom accounts for approximately 15% of the total number of fires recorded in the U.S. since 1990. The risk of Sponcom fires can be reduced by isolating the mine gob using rated seals and implementing a suitable ventilation system (Mitchell 1996, and Leeming et al. 2008). However, isolation seals are not airtight structures, and some leakage of air is expected unless the pressure in the gob is neutralized. The alternative is to use a pressure balancing technique (Dawson 1954, Banerjee 2000, and Brady et al. 2008). This requires a thorough knowledge of the seal/stopping construction techniques, gas build-up behind the seal line, and the airflow behavior in the gob area.

A pressure differential in the gob atmosphere can be neutralized by applying different techniques including a positive pressure balancing system. This technique has not been used in the U.S. except for a few cases where bleederless ventilation system is used to ventilate a longwall panel. The technique, by maintaining the gob at a pressure slightly higher than the barometric pressure, can reduce or eliminate the ingress of oxygen to the gob, thus reducing the risk of Sponcom fires.

3.2 Objectives

The objectives of this study, as stated in the project proposal, were:

1. Represent a coal mine gob by a physical model equipped with a microprocessor-based pressure balancing system.
2. Conduct laboratory experiments for different ventilation layouts and mine gob conditions.
3. Evaluate the application of passive and active pressure balancing techniques (as defined and explained below) in different common ventilation systems used in underground coal mines.
4. Inform ventilation engineers of the potential benefits from using pressure balancing techniques to reduce or eliminate the leakage of ventilation air to caved areas to prevent sponcom.
5. Prepare guidelines for the use of pressure balancing systems in coal mines, so that such systems may be considered for use in the future.

6. Conduct ventilation surveys in two or more operating coal mines.

These six objectives were accomplished by following the research approach described in the next section.

4.0 Research Approach

The research for this project was approached in six areas, as described below:

4.1 Literature Review

Literature specifically relating to the use of pressure balancing for control of spontaneous combustion in coal mines was collected. Articles and papers were organized into three categories: (1) coal mine ventilation, (2) passive pressure balancing techniques, and (3) active pressure balancing techniques. A printed copy of each article is stored at the University of Utah's Ventilation Laboratory. Digital copies of all articles are kept in PDF format. Articles that could not be located in digital format were digitized for storage. This literature review allowed the establishment of a baseline for the beginning of the research. The literature review is summarized below.

Pressure balancing is a ventilation technique used to neutralize the pressure differences around and across caved areas (gob) of an underground coal mine. If these differences are reduced to zero, then there will be no leakage through the stoppings and seals, thus there will be no oxygen to start and sustain the self-heating of coal. In a mine, pressure balancing can simply be accomplished by either increasing the air pressure on the return side of the gob or by decreasing the pressure on the intake side until the leakage is reduced to zero. It can also be accomplished by establishing pressure chambers and pressurizing them with inert gas, such as nitrogen.

Pressure balancing has been used in many coal mining countries, but not much in US coal mines. Australia, United Kingdom, South Africa, India, and some European countries have been utilizing pressure balancing techniques to combat as well as prevent fires in underground mines for many years now (Bhowmick 1992, Ray 2007, Chalmers 2008, and Grubb 2008). Except for a few cases, this technique has not been used within the United States (Smith and Lazzara 1987, and Bessinger et al. 2005).

There are two types of pressure balancing systems: passive and active. **Passive pressure balancing** is achieved by changing airway and regulator resistances, and pressure differentials and flow quantities near the gob. It can also be achieved by using atmospheric pressure applied through boreholes. This practice is used mainly when the overburden of the caved area is shallow and fractured where barometric pressure fluctuations can influence leakage and potential airflow reversals in the sealed area (Bhowmick 1992, and Moreby 2009). Figure 1 shows a schematic of a passive pressure balancing system in which the chamber is pressurized by using ventilation air in a controlled manner. High pressure air is applied to the chamber whenever the gob pressure is larger than the chamber pressure. One variation of this technique is called

Dynamic Pressure Balancing that uses existing intake or return air pressures to equalize pressure differentials across the isolation seals. This usually involves the establishment of pressure chambers in front of the isolation seals and pressurizing them using existing ventilation pressures through pipes extended from the main intake or return to the chamber depending on the primary ventilation system.

Active pressure balancing is achieved by using an external pressure source usually in the form of inert gas that is injected to the chambers in a controlled manner. It requires the construction of pressure chambers, and the installation and operation of pressure gages, and an inert gas injection system. The gages are used to monitor pressure differentials across the seals and determine the direction of the leakage flow. When the leakage flow is from the gob to the chamber, the chamber is pressurized using an inert gas. Often, nitrogen is used as inert gas. Figure 2 shows a schematic of an active pressure balancing system in which the pressure source is represented by a small nitrogen tank. Nitrogen is injected to the chamber through a pipeline in a controlled manner. This method can be used to overcome high pressure differentials such as those caused by sudden changes in barometric pressure. When this pressure decreases, the gas volume in the gob will increase, causing emissions of air-gas mixture from the gob. Similarly, when the barometric pressure increases the gas volume will contract allowing the ventilation air to migrate into the gob (Francart and Beiter 1997, and Schatzel et al, 2012). Pressure changes of this kind can be controlled by operating an active pressure balancing system.

The main difference between these two systems is the amount of pressure difference that can be neutralized. In a passive system, the ventilation pressure available in the area to be neutralized limits its application. In an active system, the inert gas, such as nitrogen used to pressurize the chamber, is delivered at very high pressure; therefore, it can be used to neutralize large pressure differences.

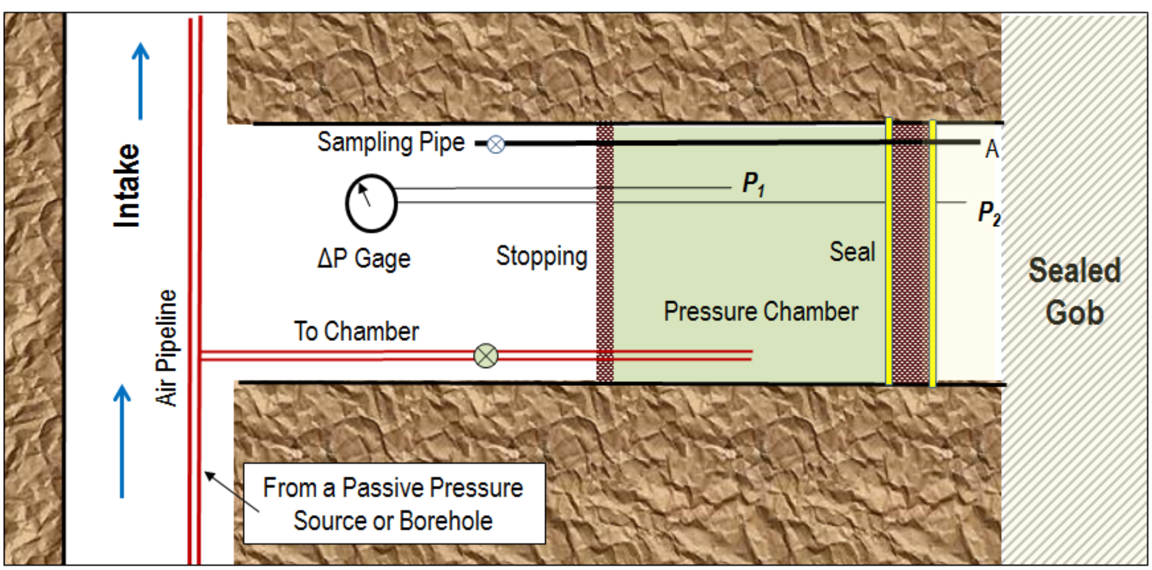

Figure 1. Schematic of a Passive Pressure Balancing Chamber

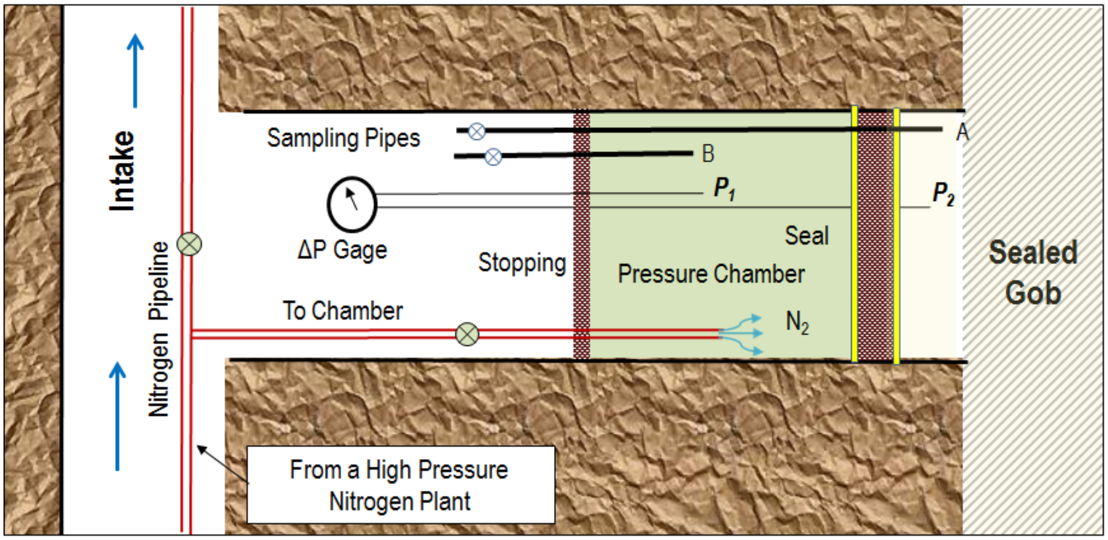

Figure 2. Schematic of an Active Pressure Balancing Chamber

The Austar Coal Mine's sponcom control method is one good example of the utilization of an active pressure balancing system. The incident took place at the Southland colliery, NSW, Australia in 2003. Sponcom fire was spotted in the sealed area. Efforts were made to control the problem using conventional means, but failed. The mine was sealed and sold. Yancoal Australia's, the new owner, main task was to manage the fire and re-open the mine. First, conventional seals were built and monitored. These failed to stop the air from entering the gob and oxidizing the coal. Seals are not airtight. They breathe "in and out" due to changes in barometric pressure. Next pressure chambers were built at each seal site to reduce pressure differentials from one end of the gob to the other, with limited success. The chambers were unable to control the leakage through the seals caused by sudden changes in barometric pressure. Finally, the chambers were pressurized using nitrogen. The gas was injected from an industrial size container to all chambers and the flow rates and pressure differentials monitored. The results showed that the new pressure balancing system was effective and sustainable in preventing the ingress of oxygen to the gob and inhibiting the egress of flammable gases to the working areas (Brady et al. 2008).

4.2 Mine Ventilation Surveys

As the study began, pressure-quantity surveys were conducted at underground coal mines in Utah, Colorado, and New Mexico. Each mine surveyed uses a retreat longwall mining method. In the Utah and Colorado mines, standard ventilation with bleeders is used. In the New Mexico mine, a bleederless system is employed.

Later in the study, surveys were conducted in three more mines. The first mine, in Illinois, uses a conventional room-and-pillar mining method of 15 entries (six intakes, six returns, one escapeway, one mantrip and one belt entry). The mine is ventilated by an exhaust system powered by a fan capable of extracting 380 m^3/s of air at 1.75 kPa. Of the total quantity, about 180 m^3/s of air was used to ventilate the three working areas and the remainder short-circuited to surface through stoppings and doors. Based on these results, the leakage flow rate was estimated at 53%.

The second mine, in Pennsylvania, uses a retreat longwall mining system. The mine has three active working sections—one longwall and two continuous miner development sections. These workings are located at about 206 m below surface. The mine is ventilated by an exhaust system consisting of two intake and two return airways powered by two fans: an exhaust surface fan and a bleeder fan.

The third mine, in Colorado, employs a unique ventilation system that requires a special permit from MSHA. It is a bleederless "U-tube" ventilation system equipped with two identical main fans on the surface, operating in parallel, in blowing mode. The return air is exhausted through a return shaft and a decline. This system was implemented because the mine is quite gassy. This mine operates one longwall and up to three development sections. The panel dimensions are: 360 m wide and about 4,300 m long.

The results of these surveys were used to accurately simulate leakage paths from intake to return airways, and to develop conceptual designs of pressure balancing systems for control of spontaneous combustion in various mine settings: room and pillar, longwall with bleeders, and bleederless longwall.

4.3 Physical Model Construction

The University of Utah coal mine ventilation model, previously used to simulate a two-entry development heading, was modified and upgraded to include two working areas (a continuous miner section and a longwall section), a mine gob, a pressure balancing chamber, and a bleeder section. A container filled with broken rock is used to simulate the mine gob. This section is equipped with a bleeder fan and a set of regulators to allow simulation of different gob ventilation scenarios. The pressure chamber was built by isolating a section of the gob using three fully-closed "stoppings" equipped with pressure relief valves. The model has been used to conduct several pressure balancing experiments. In each experiment, the main fan has been used as the main pressure source.

4.4 Integrated Automatic Pressure Balancing System

The modified model was equipped with a PC-based monitoring and control system, which is described in detail elsewhere in this report. An external, automated CO_2 injection system is used to pressurize the chamber. A portable compressor is used to create high pressure differentials between the chamber and the gob.

4.5 Pressure Balancing Experiments

Using the modified ventilation model, with the automated pressure balancing system, several experiments were conducted using the baseline operational parameters determined in the mine ventilation surveys. Those experiments and their results are described in detail later in this report.

4.6 Preparation of Guidelines

Based on the results of the experiments conducted with the ventilation model, guidelines for the safe use of pressure balancing techniques were developed. Those guidelines are also found later in this report.

5.0 Summary of Accomplishments

Pressure balancing is a ventilation technique that is used prevent or halt spontaneous combustion in coal mine gobs. This is accomplished by neutralizing the pressure differences around and across the gob areas. If these differences are reduced to zero, there will be no leakage through the stoppings and seals, so there will be no oxygen to start and sustain the self-heating of coal. In a mine, *passive* pressure balancing can be accomplished by either increasing the air pressure on the return side of the gob or by decreasing the pressure on the intake side until the leakage is reduced to zero. It can also be accomplished *actively* by establishing pressure chambers and pressuring them by using an external pressure source such as nitrogen.

According to the 30CFR, mined out areas must be either ventilated or sealed. Bleeder entries developed around the perimeter of the mining areas are used to dilute methane from mined-out areas. This practice does not prevent the development of hot spots in the gob. The alternative is to isolate the abandoned areas by constructing seals. These are high strength barriers constructed from solid and incombustible materials such as concrete (Zipf et al. 2007, and McMahon et al. 2009). The main objective is to separate the abandoned panels from active areas, and to keep the atmosphere in the sealed area inert, especially in gassy mines. However, seals are not airtight structures. They breathe in and out with changes in barometric pressure. Regardless the strength, when this pressure increases the gob volume will contract allowing the ingress of oxygen to the gob. This might be sufficient to start the self-heating of coal (McPherson 1993). Pressure balancing, when implemented and managed properly, can be used to eliminate all oxygen from entering the gob, thus eliminating the risk of spontaneous combustion within the gob.

Figure 3, below, shows a ventilation schematic of a longwall mine where the mined out areas are isolated by means of high pressure (120 PSI) panel seals. These are the ideal sites where positive pressure chambers can be established and operated to reduce the risk of spontaneous combustion within the isolated gobs.

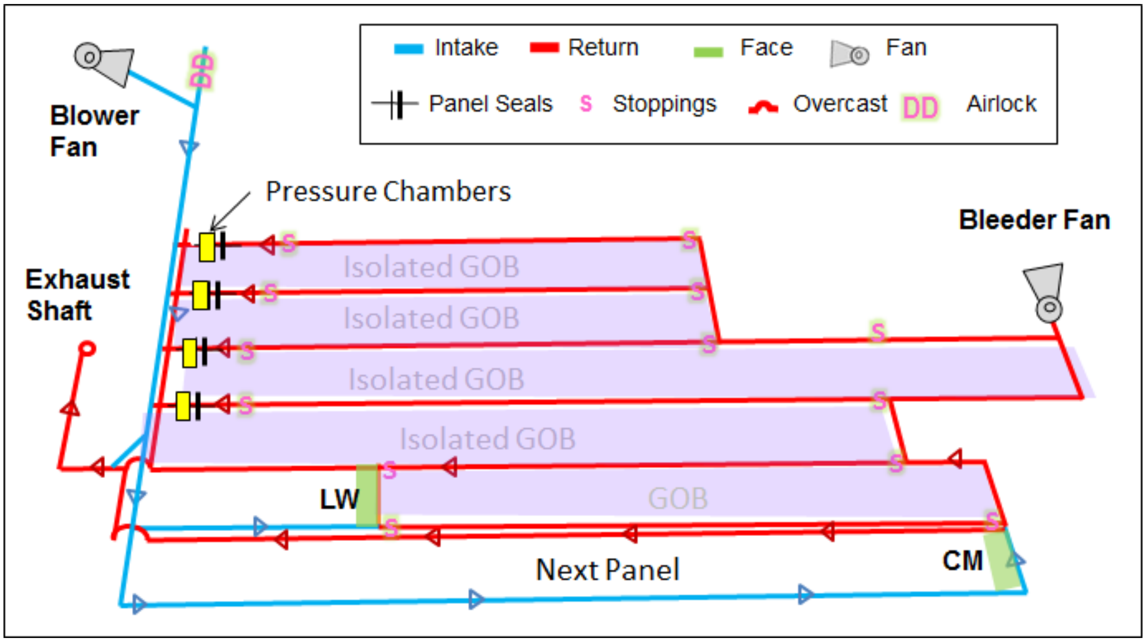

Figure 3. Longwall Mine Ventilation Schematic with Pressure Balancing

In an attempt to better understand the problem and to develop pressure balancing strategies to reduce the risk of spontaneous combustion, this study was started by conducting ventilation surveys, formulating numerical models, and using this information to construct a ventilation laboratory model to evaluate different ventilation systems with and without pressure chambers.

For the purpose of this study, ventilation surveys were conducted in three underground coal mines: one room and pillar and two longwall mines. These are identified as mines A, B and C. Mine A uses a U-tube ventilation system equipped with an exhaust fan. Mine B is ventilated by a bleeder system with a “Flow-through” method assisted with a bleeder fan. Mine C is ventilated by a bleederless “U-tube” system that uses nitrogen injection to inertize the mined out areas. Pressure and quantity surveys were conducted at each mine, and the collected data used to develop numerical models to evaluate the pressure distribution in the gob area. The data from these surveys was further used to configure the University of Utah lab model to simulate different ventilation scenarios.

The University of Utah lab model emulates a longwall mine that includes two working areas (a continuous miner section and a longwall section), a mine gob, a pressure balancing chamber, and a bleeder section. It is ventilated by a blower fan equipped with a variable speed drive. This model has multiple regulator components that can be manipulated to mimic different coal mine ventilation systems. Systems such as “U-tube” and “Flow-through” for both bleeder and bleederless ventilation systems were tested. Once the model was rearranged to simulate a ventilation system, pressure differentials across the isolation stoppings were measured and balanced using both passive and active pressure balancing techniques. Pressure gradients were used to evaluate the results of each experiment.

Three cases of pressure balancing experiments are presented in this report:

a) Passive Pressure Balancing for a U-tube Ventilation System
b) Passive Pressure Balancing for Mine B
c) Active Pressure Balancing for Mine C

In case a), pressure balancing was achieved by closing the open area of a regulator located near the bleeder shaft (passive), in case b) pressure balancing was achieved by opening a flow control valve of a pipe extended between a high pressure point in the intake duct and the chamber (passive), and in case c) pressure balancing was achieved by injecting carbon dioxide (in place of nitrogen) to the chamber automatically (active).

5.1 Mine Ventilation Surveys

The University of Utah personnel visited three underground coal mines: one room and pillar mine in Illinois (identified as mine A), and two longwall mines in Pennsylvania and Colorado (identified as mines B and C). A brief summary of each mine is presented below.

5.1.1 Mine A

On October 17 and 18, 2014, four representatives from the University of Utah visited mine A, located in southern Illinois. The purpose of the visit was to conduct a pressure-quantity survey, to inspect seals and stoppings used to isolate mined-out areas, and to use this information to develop conceptual pressure balancing designs. Following the necessary safety instruction by the mine engineers, the Utah personnel were escorted by the ventilation engineer to the 4th Main entrance, working face C, sealed area A, and the return airways located near the bottom of an exhaust shaft. In this mine, coal is extracted by a conventional room-and-pillar mining method where panels are ventilated by a fish-tail ventilation system. Mine A uses 21-entry panels: three intake airways (primary escape-ways), three neutral airways comprising of belt, one travel way (secondary escape-way) and storage entry, seven return entries on the left side and eight return entries on the right side of the panel. The coal seam, fairly flat, is located at about 76 m (250 ft) below surface.

The mine uses an exhaust ventilation system equipped with twin fans in parallel arrangement. Of these, only one is used at a given time. The capacity of each fan is 380 m^3/s of air at 1.75 kPa of total pressure. Of the total quantity, about 180 m^3/s of air is used to ventilate the three working areas and the remainder short-circuited to surface through stoppings and doors. Based on these results, the leakage quantity is estimated at 53%. Table 1 shows a summary of results of the survey. A brief evaluation of the surveyed data shows that of the total quantity, about 64.3 m^3/s were available to ventilate area B. The largest pressure differential recorded across the intake- return stopping near the face was 37 Pa.

Table 1. Ventilation Survey Data for Mine A

Station No.	Quantity Measurements			Types of airways	Delta Pressure Pa
	Area m^2	Velocity m/s	Quantity m^3/s		
1	17.4	0.52	9.0	Intake	4.0 (across intake and belt)
2	11.7	2.1	24.6		
3	14.8	1.82	26.9		
Total Quantity			64.3		
4	11.9	0.31	3.7	Return	37.0 (across intake and return)
1	13.3	2.26	30.1		
2	14.2	2.24	31.8		
Total Quantity			65.1		

In this mine, intake and return airways are separated by cinder block stoppings and the mined-out areas (gob) are isolated using high pressure seals, rated at 827 kPa. These seals are not completely airtight, and some leakage (ingress and egress of air) into or from the gob area is expected, especially when such an area is fractured and subject to changes in barometric pressure.

Figure 4 shows a ventilation schematic for this mine. This figure also shows the locations of three active workings, and a summary of the surveyed data.

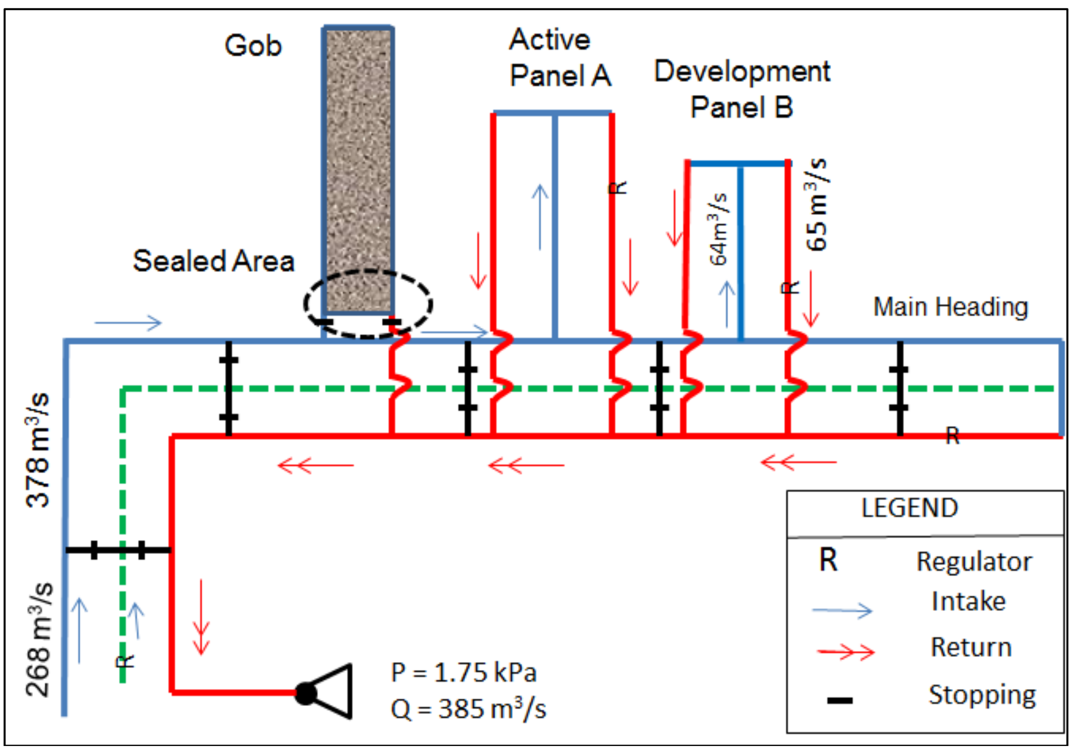

Figure 4. Mine A Ventilation Schematic with Pressure/Quantity Survey Results

The results of this survey were used to simulate leakage paths from intake to return airways, and to develop a conceptual design of a pressure balancing system to control spontaneous combustion in a room and pillar mine where the caved area is subject to changes in barometric pressure (See Appendix A).

5.1.2 Mine B

On March 16-17, 2015, four representatives from the University of Utah visited a coal mine in Pennsylvania, identified as mine B. The purpose of the visit was to conduct pressure quantity surveys and observe the seals and stoppings used to isolate mined out areas. Following the necessary safety instruction by the safety engineer, the University of Utah personnel were escorted with the Consol's staff to the Main Shaft portal. The mine has three active workings, one longwall and two continuous miner development sections. These workings are located at about 206 m (675 ft) below surface. The mine is ventilated by an exhaust system consisting of two intake airways (one shaft and one incline), and two return shafts (one main and one bleeder). These shafts are equipped with two exhaust fans. Table 2 shows the capacities of the fans.

Table 2. Mine B Fan Data

Description	Quantity, m^3/s	Pressure, kPa
Main Exhaust Fan	331	2.55
Bleeder Fan	139	5.30

Air velocities, pressure differentials, and cross sectional areas were measured at many stations along the ventilation network. The air velocities were measured in the main intake and return airways, longwall face, and at the bottom of the bleeder shafts. About 324 m^3/s ventilation air was supplied through the main intake shaft, and 146 m^3/s through the conveyor decline. The longwall panel was ventilated with a flow of 71 m^3/s. Pressure differentials were measured across the stoppings and regulators at multiple locations. These varied from 40 Pa. near the tailgate of the longwall gob to 860 Pa near the bleeder shaft.

Of the total quantity delivered to the mine, about 162 m^3/s were directed to the north main entries and 161 m^3/s to the south mains. From the north mains, approximately 71 m^3/s were branched westward and used to ventilate the longwall panel. The pressure differentials across the gob varied from 387 Pa near the tailgate of the longwall gob to 860 Pa near the bottom of the bleeder shaft. Table 3 shows a summary of measured flow quantities and pressure losses for a set of critical airways for mine B. Figure 5 shows a ventilation schematic of this mine. It also shows the locations of the three active workings, mined out areas, measuring stations, and exhaust shafts.

Table 3. Mine B Survey Data

Flow Quantity			Delta Pressure		
Station No.	Description	Quantity m^3/s	Station No.	Description	Delta Pressure Pa
1	Exhaust shaft	323	7	Base Intake shaft	2052
2	Active LW # 1	28	8	XC5 inby LW HG	398
3	Active LW # 2	23	9	XC20 inby LW HG	187
4	CM Face	14	10	Base Bleeder Shaft	50
5	Bleeder Fan	139	11	TG Bleeder	174
6	Intake	286			

In addition to ventilation surveys, the University of Utah personnel observed the seals that had been recently installed to isolate mined-out areas. Three types of seals are used in this mine: Jennchem, Ribfill, and Micon seals. The seals are designed and installed for different conditions included differing geology, ground control, and entry dimensions. All three types of seals are MSHA approved and rated for 827 kPa.

The results of this survey were used to calibrate the University of Utah ventilation laboratory model set up to investigate pressure balancing techniques to control the onset of spontaneous combustion in mines where the gob is ventilated by a bleeder ventilation system.

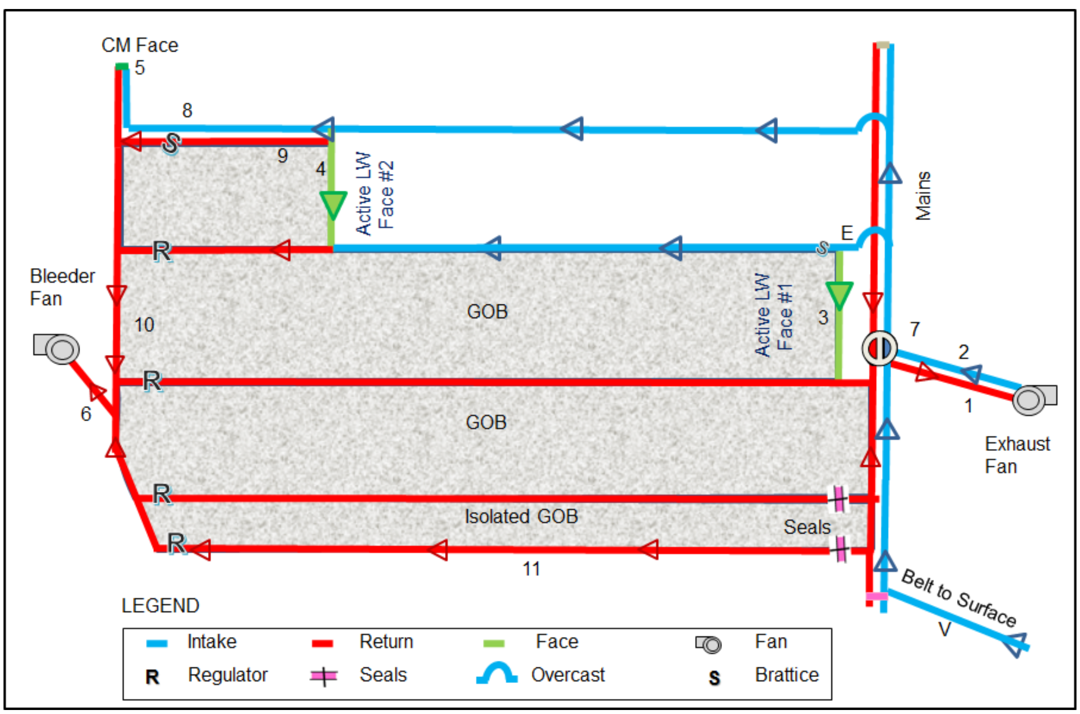

Figure 5. Mine B Ventilation Schematic

5.1.3 Mine C

The University of Utah personnel visited the Arch Coal's mine C in Colorado on July 13–14, 2015. This mine's unique ventilation system requires a special permit from MSHA to operate. The mine uses a bleederless, U-tube ventilation system equipped with two surface fans. The used air is exhausted through a return shaft and a decline. This system was implemented because the mine was found to be a gassy mine. This mine operates one longwall and up to three development sections. The panel dimensions are: 360 m wide and about 4300 m long. The coal seam is about 3 m thick. The seam is nearly planar and located on average 120 m below surface. The production rate of this mine is about 6.4 million tons per year.

Mine C uses a flow-through bleederless ventilation system with two identical parallel main fans. These fans ventilate in blowing mode. Fan #1 is on top of a split compartment shaft with a hoist on one side and return air on the other side. The intake side has a cross sectional area of 39.5 m^2. Fan #2 is on top of an 8.5-m diameter shaft that has a cross sectional area of 56.7 m^2. Both intake shafts are about 122 m (400 ft) deep. The mains are nine entries wide, the headgates and tailgates are three entries wide. Both fans are operating with nearly 2.50 kPa each at the surface. The fans supply nearly 600 m^3/s of air. Table 4 shows the operating points of these fans.

Table 4. Mine C Fan Data

Description	Quantity, m^3/s (kcfm)	Pressure, Pa (in.w.g.)
Fan 1	273 (578)	2459 (10.0)
Fan 2	328 (694)	2550 (10.1)

Of the total quantity (600 m^3/s) supplied by both fans to the mine, 85% was directed to the workings and 15% short-circuited through a set of airlock doors in a decline. The longwall section was ventilated with 80 m^3/s, of which 50% was directed to the longwall face, 35% to the development heading, and the remainder returned to surface in the form of leakage through stoppings and doors. The pressure drop along the longwall face was 350 Pa and the pressure differentials across the gob decreased from about 300 Pa near the face to less than 50 Pa in the end of the panel. Table 5 shows a summary of the survey data. Figure 6 shows a simplified ventilation schematic for mine C. It also shows the locations of mine workings, mined out areas, and survey stations.

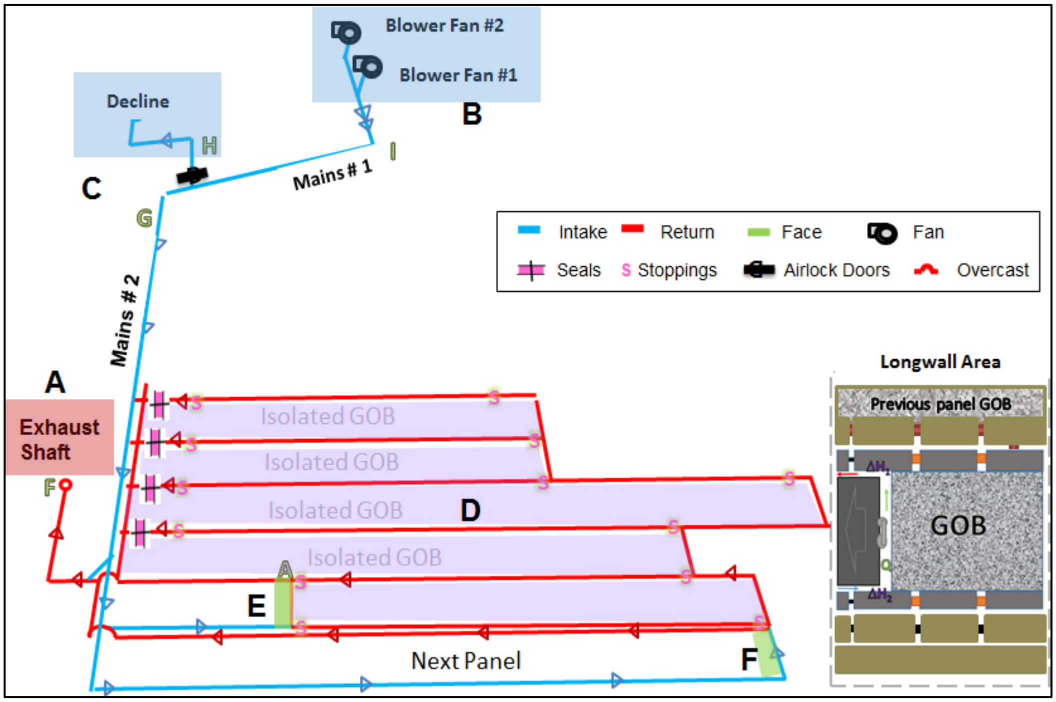

Figure 6. Mine C Ventilation Schematic

Table 5. Mine C Survey Data

Airflow Data			Pressure Data		
Sta. #	Location	Quantity, m^3/s	Sta. #	Location	Pressure, Pa
A-B	LW Face	40	A	Face, TG End	50
C	CM Face	28	B	Face, HG End	200
I	Intake Q	600	A-B	LW Face	350
G	Leakage	83	C	XC 9, HG	420
G	Main Return	513	D	XC 3, HG	500

Mine C uses a retreat longwall mining method with a common three-entry gateroad system. The mine progressively installs gob isolation stoppings in the headgate and tailgate entries in the cross-cuts nearest the gob. The intake air is delivered in a “U-tube” system across the longwall face and is then returned out of an exhaust shaft across the mains. The exhaust shaft does not have a fan. The exhaust shaft is 7.3 m in diameter and 122 m tall. Nearly 512 m^3/s of return air exits the mine through this shaft.

The results of this survey were used to calibrate the University of Utah ventilation model and to develop strategies to control spontaneous combustion in a longwall mine where the longwall section is ventilated by a U-tube bleederless system.

5.2 University of Utah Laboratory Model

The University of Utah coal mine ventilation model, previously used to simulate a two-entry development heading, was expanded and modified under this grant to include two simulated working areas (one continuous miner section and one a longwall section), a mine gob, a pressure balancing chamber, a bleeder section, two fans, and a PC-based monitoring and control system (Figure 7).

5.2.1 Ventilation Model

The model is constructed of 0.15-m- (5.75-in.-) diameter pipe and has a main blower fan and a bleeder fan. The pipes are configured in a standard U-shaped ventilation system with one intake and two return airways. Crosscuts are constructed of 0.06-m- (2.5-in.-) diameter pipes that are fitted with regulators to act as leakage paths between the intake and the return airways. Perforated gate valves are used as regulators and stoppings to control the flow of air in the model. There are nine sets of perforated gate-valves each, having holes of different diameters. The regulators are sized to model stoppings and regulators with open areas ranging from 0.001 to 50%. High resistance regulators are used to simulate doors, stoppings and seals located between the intake and return ducts. They are also used to establish a pressure chamber and analyze strategies for equalizing the pressure differentials across the simulated gob. Figure 8 shows the gate valves into which regulators can be inserted to simulate doors, stoppings and seals.

A container filled with broken rock was used to simulate the mine gob. This section was equipped with bleeder ducts, a set of flow control valves machined to allow minimal leakage, and an exhaust fan. The pressure chamber was built by isolating a section of the gob using three fully-closed “stoppings” equipped with flow control pipes and pressure relief valves. An external, automated CO_2 injection system was used to pressurize the chamber. A portable compressor was also used to create high pressure differentials between the chamber and the gob.

The model was equipped with two centrifugal fans: a blower fan and an exhaust bleeder fan. Each fan has a variable frequency drive (VFD). This allows the motor to be set at any speed from zero to 3,600 rpm. The fans can be operated individually or in combination as required.

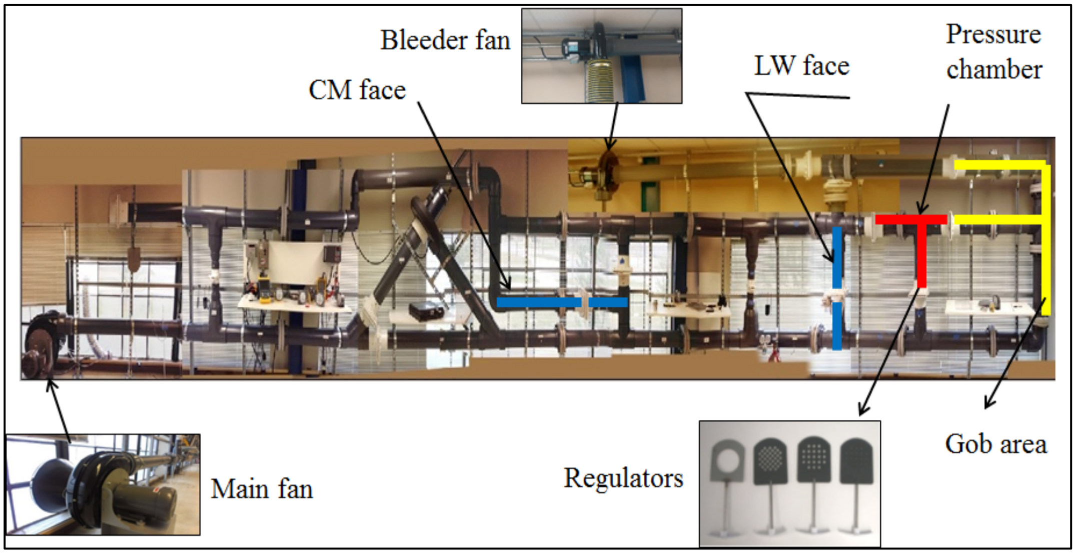

Figure 7. Mine ventilation Model

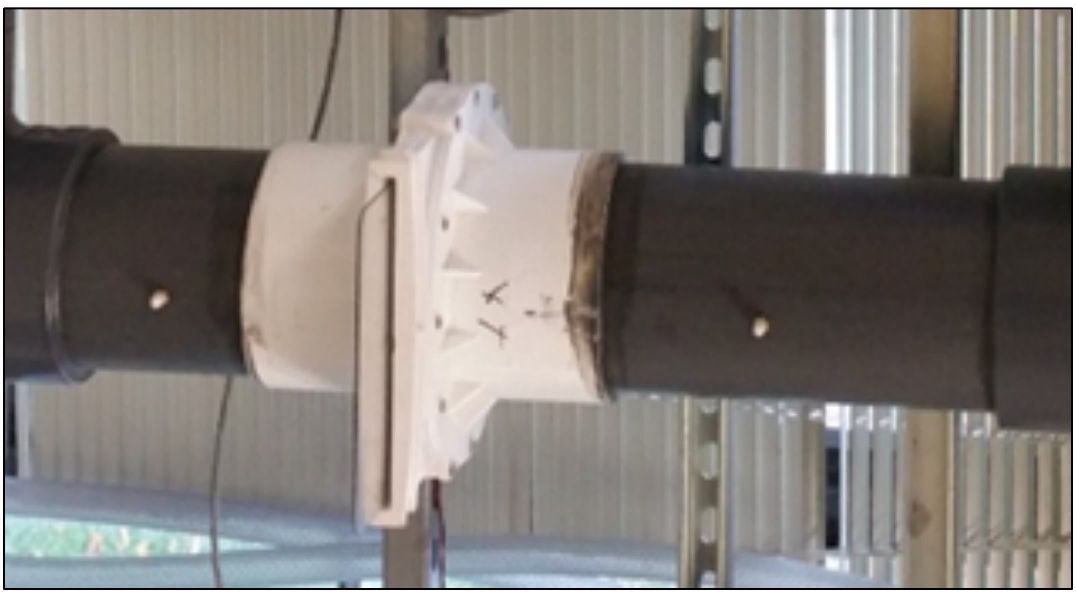

Figure 8. Gate Valve with Regulator

The ventilation monitoring system consists of a host PC and a set of sensors attached to a communication network. It is capable of monitoring the status of up to 35 sensors and controlling the operation of two fans and two gas injection points. The sensors are used to monitor the following parameters: air velocity, fan pressure, differential pressure across the stoppings, barometric pressure, air temperature, and CO_2 gas concentration.

5.2.2 Atmospheric Monitoring and Control System

The University of Utah laboratory model is equipped with a micro-processor based atmospheric monitoring and control system. The system consists of a set of instrument sensors and ventilation control modules attached to a communication network and a power bus. Each instrument on the bus has a unique network address and responds to control and query commands sent across the network. The system is controlled by a host computer. In the model, the sensors and control points are placed in the air stream by drilling and tapping the PVC pipes at strategic locations, and then installing the various sensing probes. Figure 9 shows a sample Pitot tube and a pressure transducer (module) set up to monitor total head. The system is equipped with 25 transducers of this kind. In addition, the system includes three hot wire anemometers, two CO_2 gas injection points, and one atmospheric monitor. Each module draws a small amount of current (~ 30 milliamps) from 12-VDC bus for its internal digital and analog circuitry. All data acquisition and control commands occur within a 1-, 3-, 5-, 10-, or 30-second period. These cycles were to provide maximum flexibility in recording data.

Each module has its own microprocessor to perform communications and localized data processing. Each module also has sufficient processing power to perform self-calibration and auto-zeroing of analog inputs (Fredsti 2012). Typical functions performed by the microprocessor include scaling, filtering, and verification of signals throughout the system. All communication in the system uses RS 485 standard interface hardware.

Following is a summary of the components currently used with this system:

- Pressure transducers (25), used to monitor static, velocity, and total pressure heads across the system.
- Velocity transducers (3), used to monitor low speed velocities in the of area
- Atmospheric monitor (1), used to monitor barometric pressure, temperature and relative humidity.
- CO_2 gas injection and sampling system (2), used to control the flow of carbon dioxide in the model and to determine its concentration at three locations.
- Fan control devices (3), used to start, stop and control the speed of each fan as required for different experimental conditions.

Figure 9. Velocity and pressure transducers

The system is operated by a program called VENTLAB, written in Microsoft Visual Studio C++. Once activated, the program interrogates each system component for feedback and control signals. This information is then evaluated and the data gathering process is initialized.

Figure 10 shows a screenshot of the computer display for the University of Utah atmospheric monitoring system, with the locations of monitoring modules, environmental sensors, and flow control devices used to operate the fans and the CO_2gas injection system. Figure 11 shows the instantaneous display of three sensors used to monitor ventilation parameters in the exhaust duct.

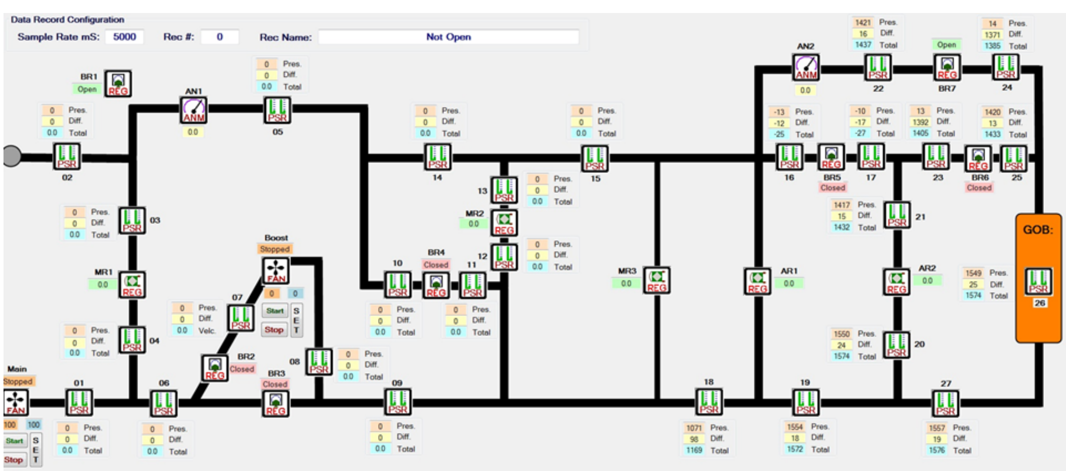

Figure 10. Screenshot of the University of Utah Ventilation Monitoring System

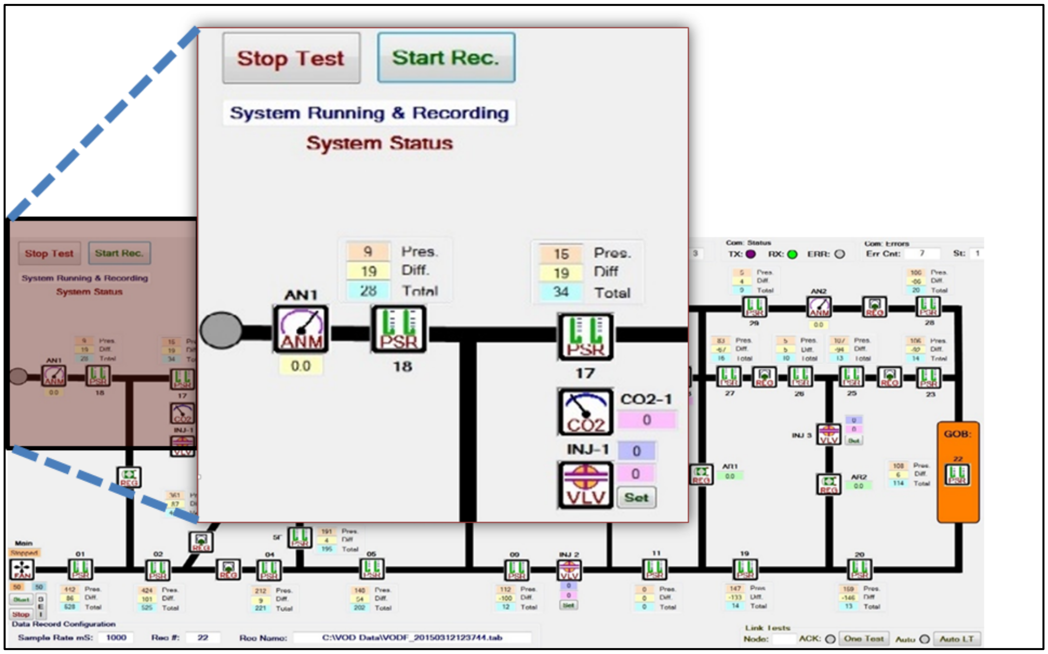

Figure 11. Instantaneous Display of Three Sensors

5.2.3 Automatic Pressure Balancing System

Automatic pressure balancing is a form of an active pressure balancing in which the evaluation of pressure differentials across the isolation seals and the injection of an inert gas into the chamber are performed automatically. Figure 12 shows a schematic of a pressure balancing system in a mine cross-cut. The pressure chamber is established by erecting an outer stopping (stopping 1) some distance away from the inner isolation seal (seal 1). Pipes extending across these stoppings are used to monitor pressure differentials and to inject pressurized gas (nitrogen) into the chamber. A manometer is used to measure the pressure differential between the chamber and the gob (across seal1). When this pressure differential is negative, pressurized gas is injected into the chamber by activating a flow control valve using a microprocessor. A program such as the APBCON sub-routine developed at the University of Utah ventilation model can be used to this purpose. The process will stop only when the pressure in the chamber is slightly higher than the pressure in the gob.

In practice, a central nitrogen line, extended along the intake airway is used to inject nitrogen in the chamber when negative pressure differentials are recorded. The whole process can be automated by monitoring pressure differentials and activating the appropriate flow control valve when a pressure imbalance signal is received. This has the consequence of the pressure in the chamber always being slightly greater than the pressure in the gob.

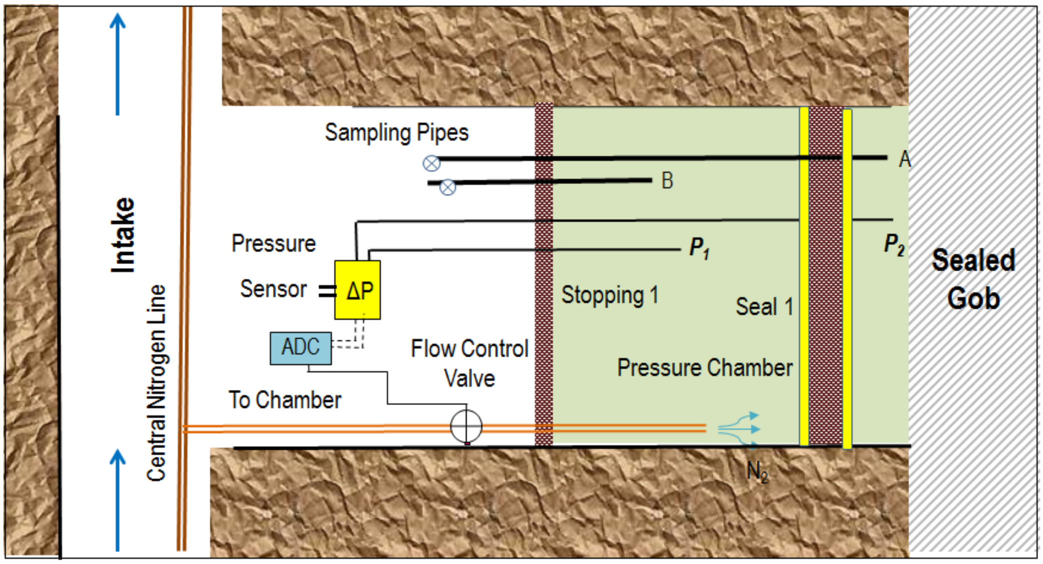

Figure 12. Schematic of an Active Pressure Balancing System

To emulate the active pressure balancing system depicted in Figure 12, the University of Utah laboratory model was modified to include a pressure chamber, a set of pressure taps, a CO_2 cylinder (the external pressure source), and a gas injection system. In the lab, the chamber was established by isolating a portion of the simulated mine gob using gate valves of different resistances. Gate valves of variable open areas were used to simulate different types of stoppings and seals. When required, CO_2 gas was injected to the chamber, first manually and then automatically.

To automate the CO_2 injection system, the chamber was equipped with flow control valves, pressure transducers, an external pressure source (a CO_2 cylinder), and a software-operated, CO_2 gas injection system. Figure 13 shows a picture of the chamber that was established by isolating a section of the gob using three gate valves (F, G and H). The open areas of these valves varied from “fully-closed” to 0.05 % of the cross-sectional area. Two pressure transducers (23 and 26) are used to determine the pressure differential across the isolation stopping (G). Finally, a computer operated gas injection system was used to pressurize and maintain the pressure in the chamber slightly higher than the pressure in the gob. Figure 13 illustrates the injection point (X), the pressure transducers (Y), and the flow control valves (Z).

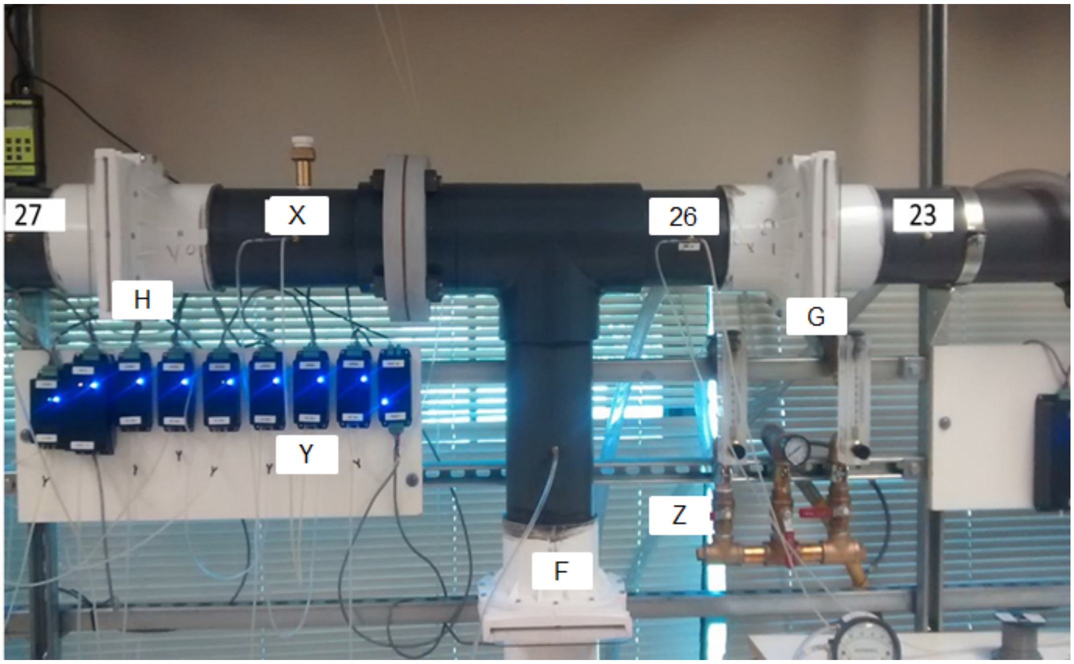

Figure 13. Pressure and Velocity Transducers Near Simulated Gob

Figure 14 shows parts of the CO_2 gas injection system. It consists of a CO_2 cylinder, a rotameter, and two flow control valves joined by high pressure plastic hoses. To avoid freezing in the delivery hose, CO_2 is injected at gage pressures of less than 56 kPa (8 PSI.) In addition, the system is equipped with two CO_2 sensors to determine the gas concentration in the system.

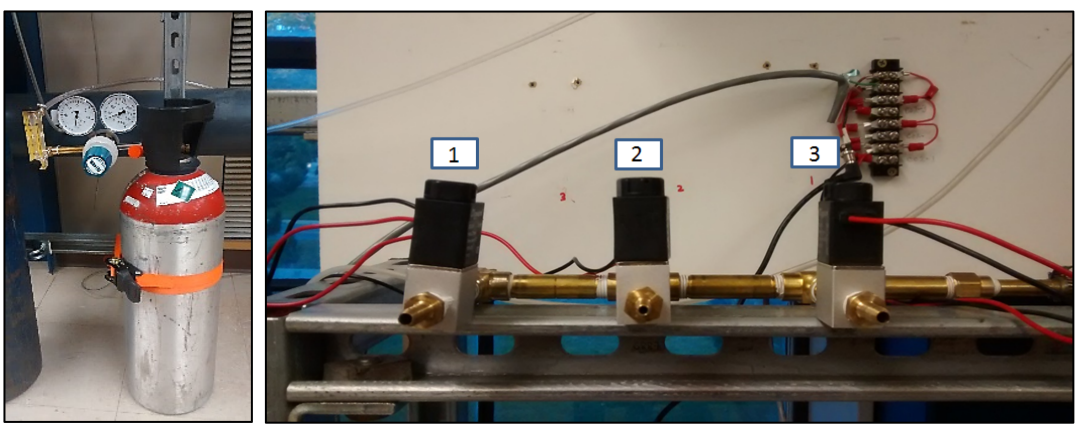

Figure 14. Gas Injection System CO_2 Cylinder and Transducers

To operate the system automatically, a sub-routine, APBCON (automatic pressure balancing controller), was written in Microsoft Visual Studio C++, and added to the monitoring software, VENTLAB. Evaluation of pressure differentials and operation of the gas injection system are the key functions of this subroutine. Once activated, the program evaluates the transducer outputs for pressure differentials across the isolation stoppings. If the program detects a pressure differential greater than 100 Pa (lower bound) across the stopping separating the chamber from the gob, a microprocessor will switch on the flow control valve and pressurize the chamber. When this pressure is equal to or greater than a pre-set value (with an upper bound of 2000 Pa), the microprocessor will switch off the flow control valve. This will reverse the leakage through the stoppings. Since the chamber is not continuously replenished, the pressure in the chamber will decrease. The process will continue until the pre-set lower bound (100 Pa) is reached. Upon reaching this limit, the program will re-start the gas injection system. This process can be repeated as often as needed in the experiment. The bounds of the program can be changed to simulate different conditions, such as the changes of gob pressure due to changes in atmospheric pressure, especially in shallow mines where the gob is connected to the surface through fractured rock.

Figure 15 shows the flow chart of the APBCON sub-routine that was developed to automate the pressure balancing system at the University of Utah lab model (Jha 2015). As shown in this chart, automatic pressure balancing is performed by evaluating the outputs of two pressure transducers (23 and 26). If the pressure differential, ΔP_{26-23} is less than or equal to 100 Pa, the gas injection system is switched on and the chamber pressure increased by P_1 (build-up rate). If ΔP_{26-23} is greater than or equal to 2000 Pa, the valve is switched off and the chamber pressure decreased by P_2 (decay rate). The subscripts in ΔP_{26-23} refer to pressure differentials between two corresponding stations. The preset pressures of 2000 Pa and 100 Pa are the upper and lower bounds used by the program to maintain the pressure in the chamber slightly higher than the pressure in the gob. The variable N_T in the flow chart is the maximum number of iterations set by the user for one experiment. In an operating mine, iterative adjustment of the pressure balance in a gob may extend over a period of days to months, depending on local conditions.

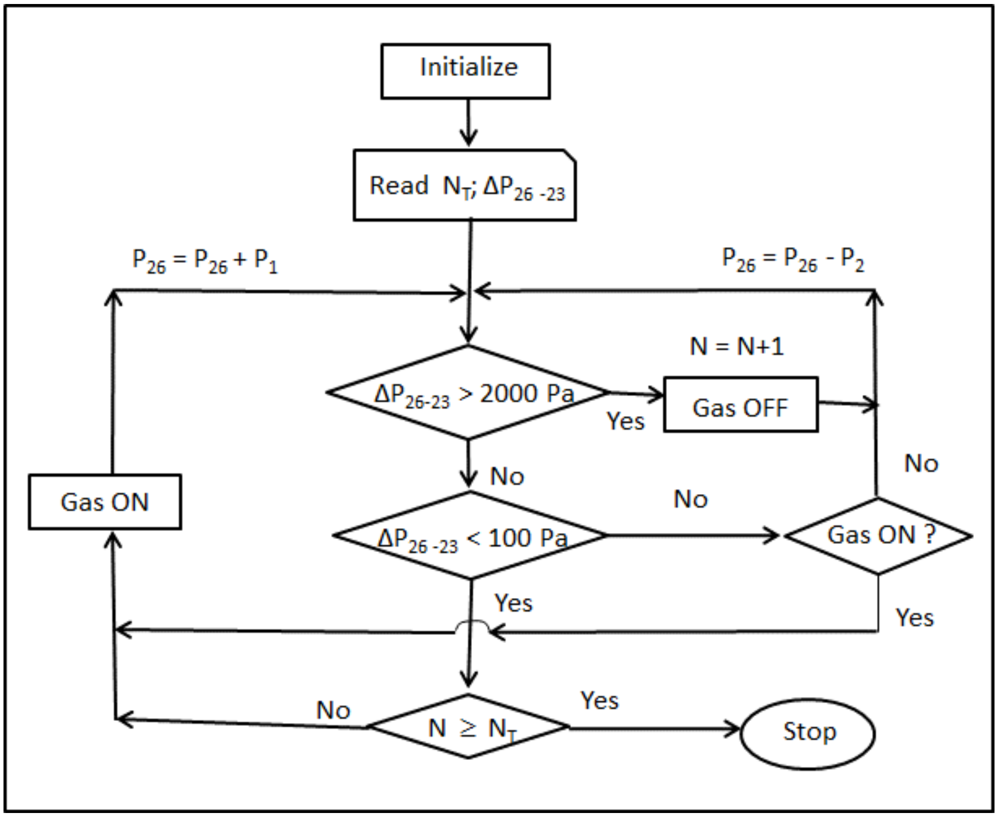

Figure 15. APBCON Pressure Balancing Automation Flow Chart.

5.3 Lab Modeling and Result

Several laboratory experiments on pressure balancing were carried out using the University of Utah ventilation model. Prior to each experiment, the model was reconfigured to emulate a ventilation system commonly used in underground coal mines. The following gob ventilation systems were considered:

- Flow-through system *
- Flow-through with punch-out borehole system
- Wrap-around (U-tube) system *
- Push-pull system
- Bleederless system *

*: These systems have been tested through laboratory experiments.

Depending on the fan location, the above systems can further be sub-divided into blower- and exhaust-fan systems. Prior to any modeling exercise a baseline model was first established, then the pressure differentials across the gob evaluated and a pressure balancing technique implemented.

The initial conditions and the results of three experiments are presented below.

5.3.1 Case 1 - Passive Pressure Balancing for a U-tube Ventilation System

The aim of this experiment was to test a passive pressure balancing technique in a U-tube punch-out longwall gob ventilation system, representing Mine C. In this case both working faces (CM and LW) are ventilated by parallel ventilation system in which a large fraction of the contaminated air was is exhausted through the main return and the remainder through a bleeder borehole (Figure 16a). The objective of this test was to minimize the pressure differentials across the gob by changing the airway resistances in the model.

For the initial condition the regulator of the bleeder borehole (regulator K in Figure 16b) was partially blocked so that only 28% of its total area was open. This allowed a fraction of the gas generated in the gob be vented to the surface. For the final condition, this regulator was fully closed and regulator J was partially open. These changes have transformed the punch-out ventilation system to a U-tube wrap-around system. In each case the main fan was the only source of pressure.

The experiment was conducted under the following conditions:

- Main fan pressure 1,947 Pa, quantity 0.45 m^3/s
- Regulators A, B, C and D fully closed
- Regulators J partially closed with 8% open area
- Isolation regulators: F, H and G with 2% open area
- For final condition regulator K fully closed, regulator J 28 % open.

Air pressure–quantity measurements were taken during the experiment. The results of these measurements were used to determine the fan duty and plot pressure gradients. Figure 17(a) shows a ventilation schematic of the model depicting the air path used to plot the pressure profiles. This Figure also shows the relative location of the pressure taps along this path. Figures 17(b) shows the static pressure profile for this model before pressure balancing, and 17(c) the pressure profile after pressure balancing. The x-axis of the pressure profile shows the distance to the pressure tap measured from the main blower fan; the y axis is the static pressure. In this figure, the blue line indicates pressure profile in the intake airway and the red line the pressure profile in the return side. Under this condition, the differential pressure across the simulated gob area was about 100 Pa. The total quantity supplied by the main fan was 0.45 m^3/s. Of this quantity, about 0.10 m^3/s were directed to the continuous miner section, 0.30 m^3/s to the longwall section, and the remainder sent back to the return in the form of leakage.

For the final condition, regulator K was fully closed, and regulator J, in the inby cross-cut, was partially open. This arrangement was used to minimize the pressure differential across the gob. Figure 17(c) shows the static pressure profile for this condition. The pressure generated by the main fan was 2,040 Pa, slightly higher than that recorded in the baseline model. Under this condition, the pressure differentials across the gob were practically nil, indicating that the gob air was stagnant. This can be observed by comparing the pressure profiles around the simulated mine gob, indicated by the dashed vertical lines in Figures 17 (b) and 17 (c).

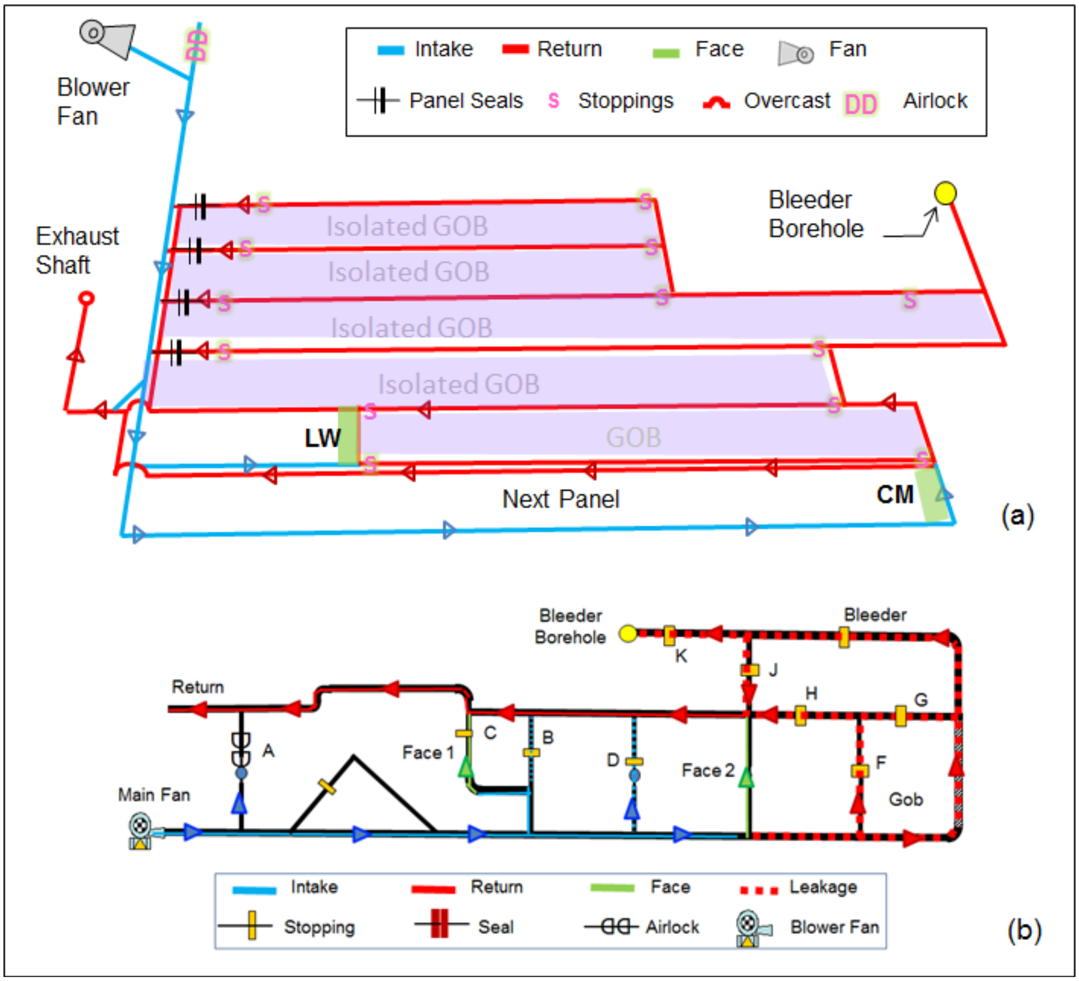

Figure 16. Schematic of U-tube Ventilation System, Case 1

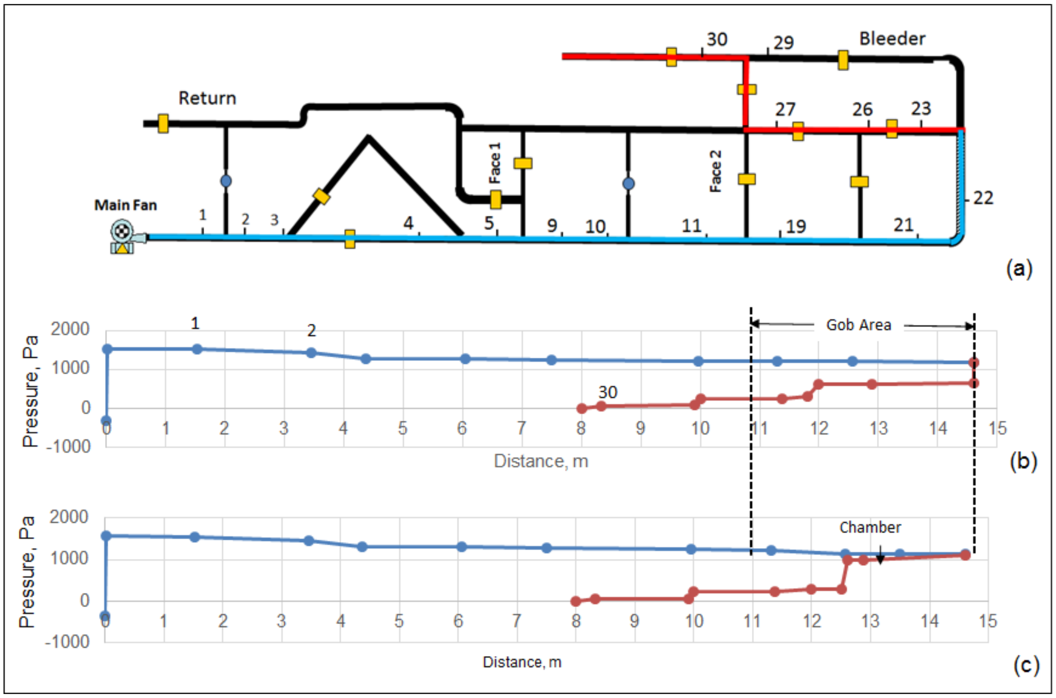

Figure 17. Static Pressure Profiles for U-tube System; (a) Air path and location of pressure taps, (b) before pressure balancing and (c) after pressure balancing.

5.3.2 Case 2 - Passive Pressure Balancing for a Flow-through Ventilation System

The aim of this experiment was to test a passive pressure balancing technique to equalize pressure differentials across the simulated mine gob. The University of Utah model was modified to mimic mine B's flow-through ventilation system, in which intake and return airways are geographically separated, and the working areas are ventilated with fresh air from separate splits.

Figure 18 shows a ventilation schematic of this model. This model was developed based on the physical mine layout shown previously in Figure 5. In the model, the exhaust fan represents two fans used by mine B with one main fan on top of the return shaft and one bleeder fan on top of a borehole. The gob is ventilated with fresh air taken directly from the main split. The required flow rates for the two workings were scaled down by a factor of 144. In this case, the demands for fresh air at the two sections (continuous miner and longwall) were represented by respective ratios of 1/3 and 2/3 of the total demand. To produce these ratios for the full fan capacity, the regulators and stoppings of the model were rearranged so that the ratios of the scaled down quantities were similar to those found in the field.

To reduce the pressure differentials across the gob the model was equipped with a pressure chamber and a flow control pipe, connecting the chamber to a high pressure point in the intake duct (station 16 in Figure 18). A 3-mm-diameter silicone pipe, equipped with a pressure gage and a control valve was used to pressurize the chamber. The experiment was conducted under the following conditions:

- Main exhaust fan pressure 2,340 Pa, quantity 0.37 m^3/s.
- Regulators V_1, V_2, B, D, and J fully closed
- Regulator C partially closed with 28% open area
- Regulators A, E, I, and K were fully open
- Isolation regulators F and H were fully closed, and G with 2% open area.

During the experiment the pressure differential between the gob and the chamber was monitored continuously. When this difference was "notably significant" (> 100 Pa), the chamber was pressurized by manually opening a flow control valve (C_1 in Figure 18). In this case, the relative pressure at station 16 is higher than the chamber pressure, and when valve C_1 is open, the air would flow towards the chamber. Figure 19(a) shows a ventilation schematic of the model highlighting the air path and the measuring stations used to produce the pressure gradients. Figures 19(b) and 19(c) show the pressure profiles obtained before and after the opening of valve C_1. A comparison of these two profiles shows that when the control valve C_1 is opened, the chamber is pressurized to reach a maximum level and remain constant, as is illustrated by the pressure jump in Figure 19(c). In this case, the maximum pressure reached is slightly lower than that of station 16. In practice, this increase in chamber pressure would be sufficient to eliminate any possible migration of explosive gases from the gob to the workings. Based on these results it was concluded that a passive pressure balancing system equipped with a pressure chamber linked through a pipe to a high pressure point in the ventilation system can be used to reduce or balance the pressure across the mine gob.

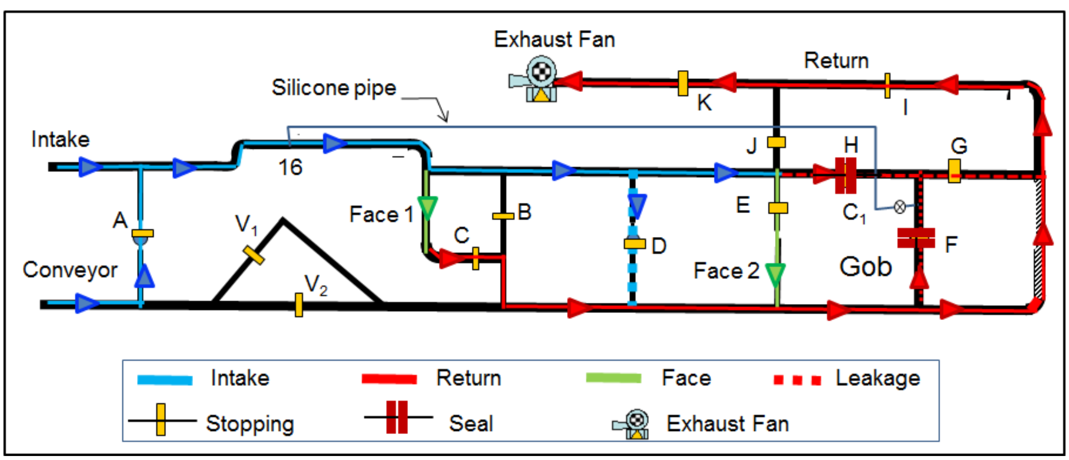

Figure 18. Schematic of Flow-through Ventilation System, Case 2

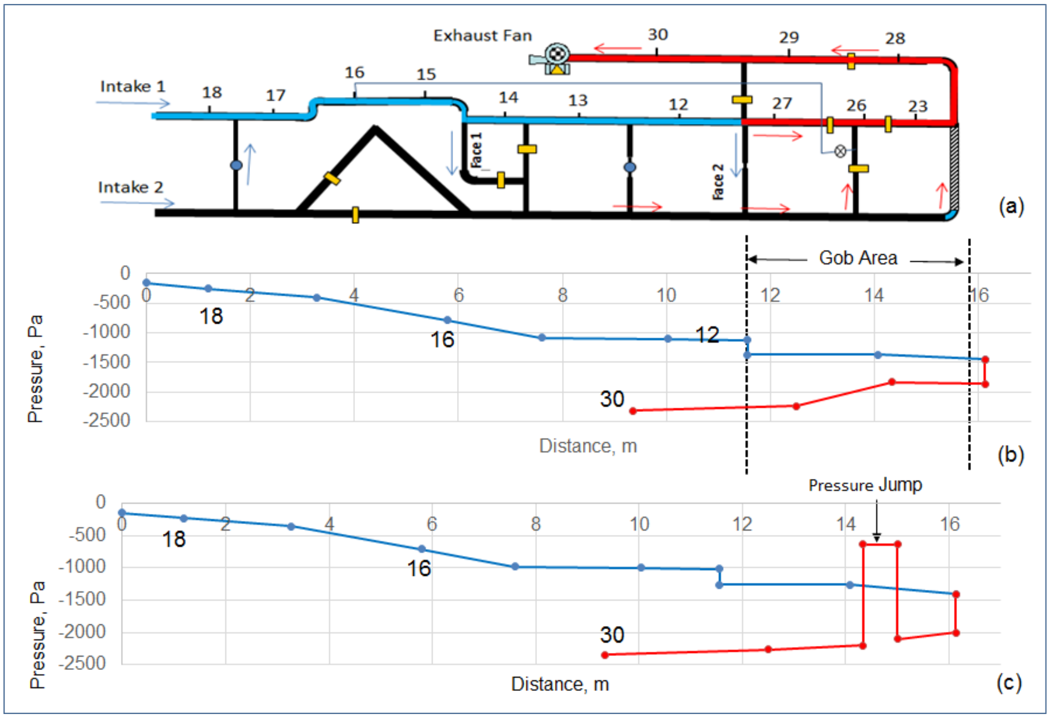

Figure 19. Static Pressure Profiles with Pressure Chamber in Place; (a) Air path and location of pressure taps, (b) Valve C_1 closed, and (c) Valve C_1 open.

5.3.3 Case 3 - Active Pressure Balancing for U-tube Ventilation System

The aim of this experiment was to test an automatic pressure balancing system that was added to the University of Utah lab model. Figure 20 shows a schematic of the model which was rearranged to mimic mine C's ventilation system. The working areas of this mine were ventilated by a U-tube, bleederless ventilation system. This is a gassy mine where methane drainage is practiced regularly and the gob is isolated progressively, as the longwall retreats (Figure 6). The field data showed flow quantity demands of 40 m^3/s for the longwall face and 28 m^3/s for the continuous miner section. These demands can be represented respectively by 2/5 and 3/5 fractions of the total demand for the section. To produce these ratios in the baseline model, the regulators and stoppings were rearranged so that the scaled-down quantities were similar to these ratios, as described in Appendix B.

Once the baseline model was created, the pressure differentials across the gob were evaluated and when adverse conditions were detected, these were neutralized by automatic pressure balancing system. The pressure balancing was accomplished by activating a flow control sub-routine, APBCON, while the monitoring system was operating. The sub-routine evaluates the pressure differentials against two pre-set values: 2,000 Pa and 100 Pa (upper bound and lower bound respectively). When the pressure differentials fall outside this range, the sub-routine activates a flow control valve to pressurize the chamber and to reduce the pressure differentials across the isolation stoppings (Jha 2015).

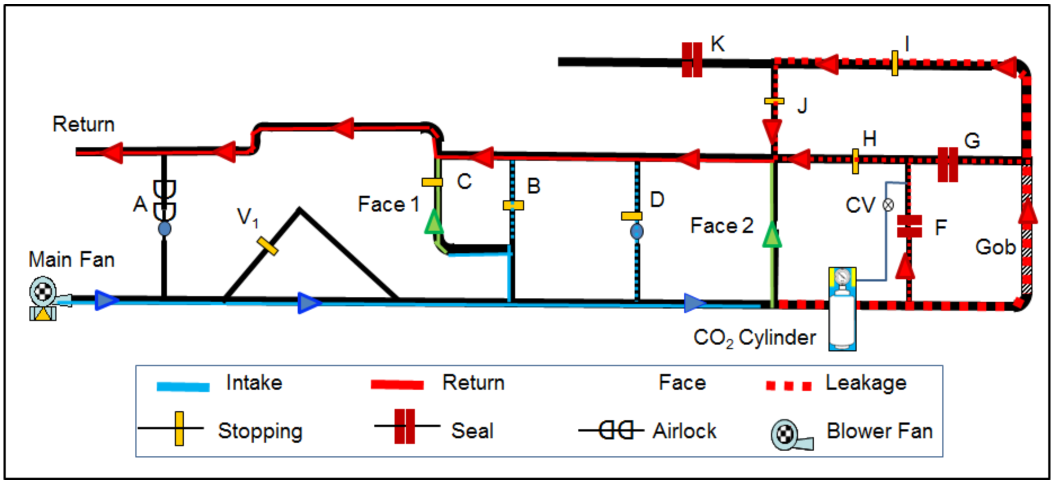

Figure 20. Schematic of U-Tube Ventilation System, Case 3

The initial and final conditions for this experiment are given by:

- Main fan pressure 2,086 Pa, quantity 0.43 m^3/s
- Regulators V_1, A, B, D, J and K fully closed
- Regulators C and J partially open at 50% open area
- Isolation regulators F and G fully closed (0.001% open), H nearly closed with 0.01% open area
- Final condition established by switching on and off the CO_2 flow control valve (CV) automatically.

Figure 21 shows the pressure variations in the chamber and gob areas when the CO_2 flow control valve (CV in Figure 20) was activated by the monitoring system. Once the injection system was started, the pressure build-up in the chamber was quite rapid. This increased from 1,500 Pa to 3,500 Pa in 6 seconds. When a preset pressure differential of 2,000 Pa was reached, the injection system was stopped automatically. Because of the reverse leakage, the chamber pressure decayed over time to a point when the minimum pressure differential of 100 Pa (lower bound) was reached. This process of starting and stopping the gas injection system can be repeated as long as significant pressure differentials are monitored. Six such cycles were observed in this experiment.

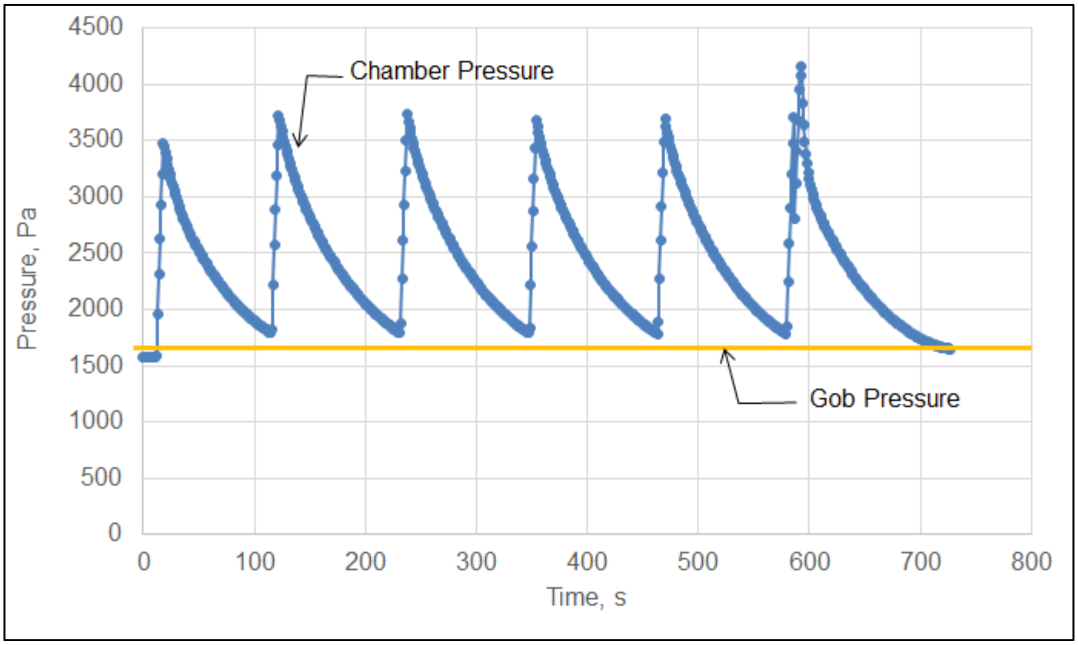

Figure 21. Gob Pressure Profile with Automatic CO_2 Gas Injection System

Figure 22(a) shows a ventilation schematic of the model highlighting the air path and the measuring stations used to produce the pressure gradients.

Figure 22 shows a ventilation schematic of the model and two pressure profiles generated when the pressure balancing sub-routine was activated. Figure 22(a) shows a ventilation schematic of the model highlighting the air path and the measuring stations used to produce the pressure gradients. Figure 22(b) shows the pressure profile before the CO_2 injection system was activated, and Figure 22(c) shows the profile when the gas injection system was activated, and the chamber pressure held at was about 3,000 Pa. These graphs show that when a bleederless ventilation system is used, the pressure differentials across the gob are quite small compared to those in other methods of ventilation, except when the gob pressure is affected by changes in barometric pressure. When an automatic gas injection system is activated the chamber can be pressurized to any allowable level so that leakage through the isolation seal is always from the chamber to the gob.

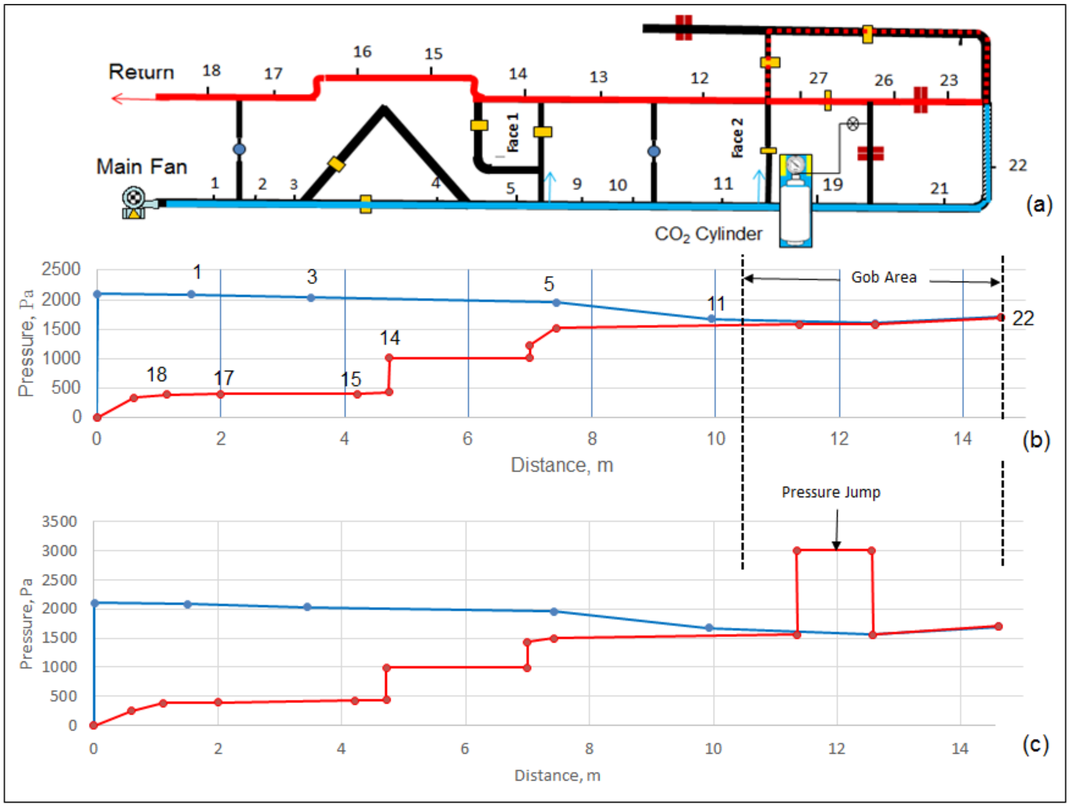

Figure 22. Automatic Gas Injection Pressure Profiles

6.0 Dissemination Efforts and Highlights

6.1 Guidelines for the Safe Use of a Pressure Balancing System

6.1.1 Determine Propensity of Coal to Spontaneous Combustion

Whenever air is allowed to percolate through broken coal it will produce heat. If this heat is not dissipated self-heating of the coal will ensue, subsequently leading to coal ignition. The path followed by spontaneous heating depends on several factors including the characteristics of the coal, the geometry of the caved area, and the rate of the leakage flow. During the early stages of mine planning, mine operators must evaluate the propensity of coal to spontaneous combustion. The leading best practices used in the industry include the bulk-scale test, the R70 adiabatic oven laboratory test (Ren and Edwards 1997, Beamish and Arisoy 2008, and Beamish and Beamish 2012), and the expert system based upon the NIOSH SponCom 2.0 program (Smith 1995 and NIOSH 2011). These resources can be used to evaluate and determine the propensity of coal to sponcom.

6.1.2 Select an Appropriate Ventilation System

Mine ventilation plays an important role in the initiation and propagation of spontaneous combustion in coal mines. Early in the planning stage, an appropriate ventilation system for the mine should be determined. Select a system that minimizes the pressure differentials across the stoppings and sealed areas (McPherson, 1993). This typically requires the implementation of a flow-through system instead of a U-tube system. In a flow-through system, intake and return airways are geographically separated, that is, adjacent entries are all either intakes or returns. Given the same airway resistances and airflow requirements, this system will reduce the main fan pressure, thus reducing the leakage flow. While developing panel entries, the use multiple parallel entries for intakes and returns is preferable. This will reduce the overall system resistance. In a U-tube or wrap around system, intake and return airways are separated by stoppings and/or doors installed in connecting cross-cuts. Stoppings and doors are not airtight structures and they will allow some leakage. As a result, the higher the required fan pressure the higher the leakage rate. To reduce leakage, use a flow-through or punch-out system.

If a bleederless ventilation system is chosen, isolate the gob by means of stoppings and seals, and inertize the caved area by injecting an inert gas such as nitrogen (Bessinger et al. 2005, and Stoltz et al. 2006). If the mine is gassy, implement a methane drainage system to reduce the required quantity of air that is needed to dilute dust and other contaminants.

6.1.3 Seal Mined-out Areas

In order to limit the ingress of oxygen into mined out areas, explosion proof seals should be erected in all entries contiguous with the mined out areas. According to the 30 CFR § 75.335, these seals must be designed to withstand explosion pressure waves of 50 PSI, if the sealed area is monitored, and 120 PSI or greater, if the area is not monitored. These high strength seals will reduce leakage. Seals are not completely airtight; they breathe in and out with changes in barometric pressure. This is especially evident in mines in which the strata above the gob is fractured. Even when very high strength seals are used, leakage will take place. This may not occur through the seal, but through the strata and the surrounding perimeter coal. This could be sufficient to start the self-heating of coal. Interconnected passive pressure chambers can be used to mitigate this problem. To effectively neutralize pressure differentials, these chambers should be equipped with boreholes connected to the surface directly or through a piping network.

6.1.4 Utilize An Atmospheric Monitoring System

Atmospheric monitoring is an integral part of any pressure balancing system used to control spontaneous combustion. It is required to determine pressure differentials across the seals and to monitor for gas concentrations in the sealed area and mine workings. Pressure differentials are used to determine the direction and quantity of the leakage flow, especially in mines where the gob is subject to changes in barometric pressure. The objective is to ensure that ingress of oxygen into the mined-out area is reduced to within acceptable limits in order to eliminate the potential for spontaneous combustion. Gas samples taken from the sealed area, through pipes or a tube bundle system, are analyzed for oxygen and methane concentrations. These concentrations are used to determine the inert or explosive nature of the air-gas mixture in the gob. In accordance with the 30 CFR § 75.336, the atmosphere in the sealed area is considered inert when the oxygen concentration is less than 10% by volume or when the methane concentration is less than 3% or greater than 20% (MSHA 2015). Environmental monitors, including methane and carbon monoxide, are used to assess the quality and quantity of air at the workings near the sealed area.

Most of the atmospheric monitoring systems used in coal mines can also be used to monitor pressure differentials across the seals and the composition of the gob atmosphere continuously. However, this should be incorporated into the mine ventilation plan and approved by the District Manager.

6.1.5 Evaluate the Need for Pressure Balancing

Pressure balancing is the process of equalizing pressure between two or more target areas. Balancing of pressure across the gob precludes ingress and egress of air to and from the gob, respectively. There are two types of pressure balancing: passive and active. Passive pressure balancing can be achieved by changing airway resistances or by adjusting regulator settings. Active pressure balancing is achieved by using an external pressure source, which could be a fan, compressor, or a pressurized fluid. It is based on the principle that if there is no pressure difference across the mine and gob interface, then fresh air cannot move into the gob. If there is no air there is no oxygen to start the oxidation process, thus eliminating the risk of spontaneous combustion. Early in the planning stage one must analyze the coal characteristics, the mining method, and the ventilation system and determine whether a pressure balancing system is required.

In both systems of pressure balancing, pressure chambers are required. These can be installed as single units or as multiple units interconnected by a piping system. The main difference between the two is the amount of pressure difference that can be neutralized. In a passive system, the ventilation pressure available in the area to pressurize the chamber limits this pressure difference. In an active system, an inert gas, such as nitrogen is used to pressurize the chamber. Nitrogen is often delivered in a gaseous state at very high pressure; therefore, it can be used to neutralize large pressure differences.

6.1.6 Implement and Operate a Pressure Balancing System

Once the decision to use a pressure balancing system is made, a detailed plan justifying the usage of pressure chambers, atmospheric monitors, and pressure sources should be developed. This plan must specify the type of pressure balancing system to be used, the strength of required stoppings, the types of environmental monitors, and details concerning system operation. If a passive pressure balancing system is chosen, then the plan must specify the pressures required to equalize the pressure differentials and how equalization can be specifically accomplished. If an active pressure balancing is chosen, then the plan must provide details about the inert gas injection system, pressure transducers to be used, and a procedure on how to maintain the chamber pressure slightly higher than the gob pressure.

In addition, for each system, the plan must include an inventory of hazards, risk evaluation results, and the control measures that must be implemented to bring the associated risks to tolerable levels.

6.1.7 Maintain the Pressure Balancing System

A passive pressure balancing system is used when the pressure differentials across the gob are relatively small and the gob area is maintained in isolation by means of seals. Ventilation pressure of existing airway is used as the pressure source. This requires an air distribution pipeline connecting a high pressure point in the main intake or return to the chamber, depending on the ventilation system. Sometimes, atmospheric pressure, applied through boreholes, is used to pressurize the chambers. This practice is used mainly when the overburden lying above the caved area is fractured. An active pressure balancing is used when large pressure differentials across the gob are expected. Pressurized nitrogen is injected to the chamber in a controlled manner. The chamber pressure is always kept at or slightly above the gob pressure. The main objective of this is to eliminate air leakage from mine workings into the gob, and the egress of the explosive gas mixture into the workings. In every case pressure differentials across the isolation seals and the quality of air in the gob should be monitored continuously.

6.1.8 Automate the Pressure Balancing System

An automatic pressure balancing system is a form of active pressure balancing in which the gas injection system is automated by using stepper motors and microprocessors, which are activated by the pressure imbalance signal received from the pressure transducers. Control logic can be structured taking into account seal pressure, gob gas concentration, barometric pressure changes, and gas concentration in the chamber. When this pressure differential across the isolation seal is negative, pressurized gas can be injected into the chamber. The process will stop only when the pressure in the chamber is slightly higher than the gob pressure in the gob. A small capacity nitrogen plant such as the one supplied by Air Liquide Australia can be used to this purpose. In this case, nitrogen is used to pressurize the chamber, not to inertize the gob.

6.2 Papers and Presentations

To date, the following papers and conference presentations have been made on topics describing the outcomes of this project:

Jha, A., Calizaya, F., and Nelson, M.G., 2015. Spontaneous Combustion Prediction and Remediation Techniques. *Proceedings of the 15th US/ North American Mine Ventilation Symposium*. Blacksburg, VA: Virginia Tech. pp. 501-508.

Calizaya F., Nelson, M.G, Bateman, C., and Jha, A., 2015. Prevention of Spontaneous Combustion with the Implementation of Pressure Balancing Techniques. Conference presentation delivered at the Eastern Utah Coal Symposium, Price, UT. October 2015.

Calizaya, F., Nelson, M.G, Bateman, C., and Jha, A., 2016. Pressure Balancing Techniques to Control Spontaneous Combustion. To be presented at SME 2016, Phoenix, AZ. (Manuscript submitted for peer review.)

Bateman, C., Calizaya, F., and Nelson, M.G., 2016. Pressure Balancing Methods Used to Reduce Spontaneous Combustion in Coal Mines. To be presented at SME 2016, Phoenix, AZ.

In addition to these publications, two M.S. theses have been completed under this grant. These are based on research work of two graduate students, Ankit Jha and Chris Bateman.

Ankit Jha's thesis is entitled *Control of Spontaneous Combustion using Pressure Balancing Techniques*. This work describes physical modeling of a coal mine ventilation system that includes a simulated mine gob, bleeder entries, pressure chambers, and an atmospheric monitoring system. The model has been used to conduct several experiments to equalize pressure differential across the simulated gob. The model was rearranged to emulate different ventilation systems including flow-through, wrap-around, punch-out, and common U-tube systems. Pressure differentials across the simulated gob were equalized using both passive and active pressure balancing techniques. Mr. Jha defended his thesis successfully on October 21. His thesis has being reviewed and approved by the Thesis Office of the University of Utah Graduate School. A copy of this is attached to this report.

Chris Bateman's thesis is entitled *Prevention of Spontaneous Combustion with the Implementation of Pressure Balancing Techniques*. This work describes numerical and laboratory modeling experiments that were designed to simulate the ventilation systems in two of the underground coal mines visited as part of the research in this project. Those mines are identified as mine B and mine C. In both mines, coal is extracted using a retreat longwall mining method. Mine B uses a standard flow-through bleeder system, while mine C uses a bleederless ventilation system. Mr. Bateman's thesis includes pressure-quantity surveys in these mines, computer simulations of both mines' ventilations systems, and laboratory simulation tests performed at the University of Utah. A numerical model was developed and calibrated for each mine. The calibrated model was then used to configure the laboratory model and to conduct preliminary simulations. Once the baseline conditions were established, the model was used to develop strategies to prevent spontaneous combustion, create safe working conditions, and minimize ventilation requirements. Passive and active pressure balancing techniques were then applied to each model and the key factors for reducing or eliminating pressure differentials across the simulated gob determined. Mr. Bateman defended his thesis successfully on December 21. Currently, his thesis is being reviewed by the Thesis Office of the University of Utah Graduate School. A final copy of his dissertation will be available in February.

The abstracts for both theses are presented in Appendix C.

7.0 Conclusions and Impact Assessment

Pressure balancing is a proactive ventilation technique for control of spontaneous combustion in underground coal mines. There are two types of pressure balancing, passive and active. Passive pressure balancing is used when moderate pressure differences across the gob are expected. These pressure differentials can also be reduced by changing the resistances of regulators and stoppings or changing the fan duty. The most significant advantage of the passive method is that it does not require any active external pressure source. However, pressure chambers can also be used with a passive pressure balancing system. Such chambers are typically pressurized by piping in pressure from an external source to the immediate seal area. Active pressure balancing requires pressure chambers and an external pressure source. Inert gases such as nitrogen and carbon dioxide are used for pressurizing chambers. Active pressure balancing is used to overcome large pressure differentials or where a passive pressure balancing is not effective. The University of Utah coal mine ventilation model was upgraded to include two simulated working areas (continuous miner and longwall sections), a mine gob, a pressure balancing chamber, a bleeder section, two fans, and a PC-based monitoring and control system. Both passive and active pressure balancing techniques were tested in this model.

The laboratory model is versatile and can be re-arranged to mimic nearly any type of ventilation system. During the modeling process, the following systems were considered: (1) Flow-through bleeder system, (2) U-tube system bleeder system, (3) Push-pull system and (4) U-tube bleederless system. Emphasis was placed on systems that were inspected during the fieldwork. Prior to each experiment, a baseline model was first established. Then the pressure differentials across the gob evaluated and a pressure balancing technique was implemented.

Passive pressure balancing was achieved by opening a flow control valve in a 3-mm diameter silicone pipe extended between a high-pressure point in the inlet duct and the chamber. Active pressure balancing was achieved by injecting CO_2 into the pressure chamber, first manually, and then automatically. For automatic injection, a computer-controlled injection system was activated so that the chamber pressure was always kept slightly higher than the gob pressure.

This study has shown that a pressure balancing technique, operated by passive or active means, can be used to neutralize the flow of air through the gob, regardless the type ventilation system used. However, from an economic point of view, the technique is more suitable for a U-tube wrap-around ventilation system than any other system, because for the same flow distribution through the workings, this technique can be used to neutralize larger pressure differentials with about the same infrastructure.

The results of these simulations show that pressure balancing systems can be used effectively for control of spontaneous combustion in U.S. coal mines, especially in sub-bituminous coal mines. However, such use will always require a thorough evaluation of the coal characteristics, geologic properties, and the propensity of coal to spontaneous combustion. Prediction tools such the R70 adiabatic oven laboratory test used in Australia, and the NIOSH SponCom 2.0 program, originally developed by the U.S. Bureau of Mines, can be used for this purpose. Once it has been established that a coal seam is liable to spontaneous combustion, a decision should be made on the appropriate ventilation system. Flow-through and bleederless ventilation systems have been found to be more efficient at balancing pressures than other comparable systems. The optimal ventilation design should reduce the pressure differentials across the gob so the potential for spontaneous combustion can be mitigated effectively.

In shallow mines, with fractured overburden, changes in barometric pressure pose a significant risk to spontaneous combustion and methane gas inundation. A set of pressure chambers connected to surface through boreholes can be used to mitigate the problem.

8.0 Recommendations for Future Work

The following tasks are recommended for future work:

1. Modify the University of Utah lab model to include a large pressure chamber equipped with high-precision flow control valves and pressure transducers. The current chamber has a limited capacity (less than 3 ft^3). Using commercially available CO_2 cylinders, target pressures (4000 Pa) are reached in less than 10 seconds. It is recommended to increase the pressure chamber volume to at least 30 ft^3, to allow more realistic simulation of pressure balancing in a mine setting.

2. Install an automatically-controlled stopping/ regulator in the bleeder duct of the University of Utah lab model. This can be accomplished by fitting a gate valve of the type currently in use in the lab with an automated control system using stepper motors connected to the computer control system. This would accelerate the simulation process and increase the accuracy of the measurements.

3. Test the operation principles of a pressure balancing system in the field. This could be done by establishing a pressure chamber in a crosscut with construction of an additional stopping at about 5 m in front of the main stopping separating an intake airway from a return airway. The chamber then could be equipped with pressure control pipes, gas sampling points, and pressure transducers located in the intake side. Both passive and active pressure balancing techniques could be tested in the chamber.

4. Disseminate the findings of this research work to the mining community. Two M.S. theses on pressure balancing have been completed at the University of Utah. The results of these studies should be published as papers in widely read publications. Two abstracts have been submitted for the 2016 SME Meeting to be presented in Phoenix, AZ, in Feb 2016. Currently, one of these abstracts has been developed into a paper and submitted to SME to be reviewed for publication.

5. Publish guidelines for safe utilization of pressure balancing techniques in underground coal mines.

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10.0 Appendices

10.1 Appendix A - Conceptual Pressure Balancing Design for Mine A

Figure A1 shows a schematic of a proposed pressure balancing chamber for mine A. This is a conceptual design of a passive pressure balancing system that can be used to neutralize the pressure difference across the isolation seals and the chamber so that the leakage of air to the sealed area (gob) is excluded. To this purpose, the mine gob is isolated by means of high-pressure (120-PSI) seals. A set of low pressure (60-PSI) stoppings is used to separate the chamber from the intake airways. The chamber is equipped with two pipes connecting the chamber with the intake and return airways respectively. The pressure in the chamber is monitored by a manometer (gage 1 in Figure A.1). The pressure difference across the low pressure seals is balanced by adjusting the flow rates through the pipes. A third pipe is used to draw air samples from the gob area and to monitor the pressure difference between the chamber and the gob (gage 2).

In a mine, an increase in barometric pressure may be sufficient to induce leakage through the seals and initiate the self-heating of coal. This problem can be avoided by monitoring the pressure difference and adjusting the flow control valves.

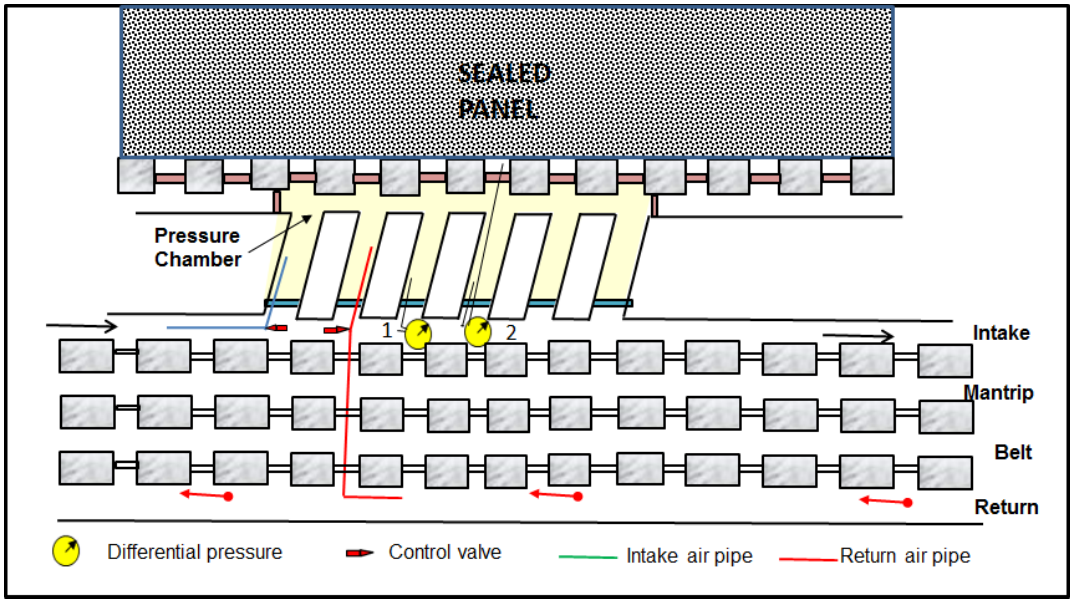

Figure A1. Conceptual Pressure Balancing Design for Mine A

10.2 Appendix B - Baseline Model for Mine C

To gain order-of-magnitude information regarding factors that are being investigated, a numerical model was developed for mine C. The model was then used to reconfigure the University of Utah lab model to emulate mine C's ventilation system. A ventilation simulator, Ventsim, currently available at the University of Utah, was used to build the numerical model. This was then calibrated using surveyed field data, so that the correlation factor was reduced to less than 5%. Figure B1(a) shows a ventilation schematic of mine C produced by Ventsim. This mine uses a U-tube bleederless ventilation system powered by two blower fans in parallel. The fresh air, once used at the workings, is returned to surface through an exhaust shaft. Table B1 shows the surveyed and simulated values of flow quantities and pressure differentials at critical locations of the model. In the numerical model, the flow requirements for the continuous miner (CM) and longwall (LW) sections were set at 28 m^3/s and 40 m^3/s respectively. These quantities were recorded during the survey. They can be represented respectively by 2/5 (CM face) and 3/5 (LW face) ratios of the total demand. When the laboratory model was reconfigured to emulate mine C, these ratios were maintained while the regulator resistances and fan duties were adjusted. To generate approximate ratios in the lab model, the fan had to deliver 0.43 m^3/s or air at 2,086 Pa. While the pressure was nearly the same as that of the mine, the flow quantities were scaled down by a factor of 1,413.

Figure B1(b) shows a schematic of the laboratory model reconfigured to emulate mine C. Each section is color-coded and alphabetically labeled to represent six critical areas: A) exhaust, B) intakes, C) leakage through a decline/airlock, D) gob, E) longwall face, and F) continuous miner face. Once the model was reconfigured, the regulator and stopping settings were adjusted so that quantity ratios at critical locations could be replicated from the baseline model.

Table B1 shows the similarities and correlations of the field, Ventsim, and lab data for mine C.

The baseline model was used to develop and test different ventilation scenarios with and without a pressure chamber to reduce or eliminate pressure differential across the simulated gob.

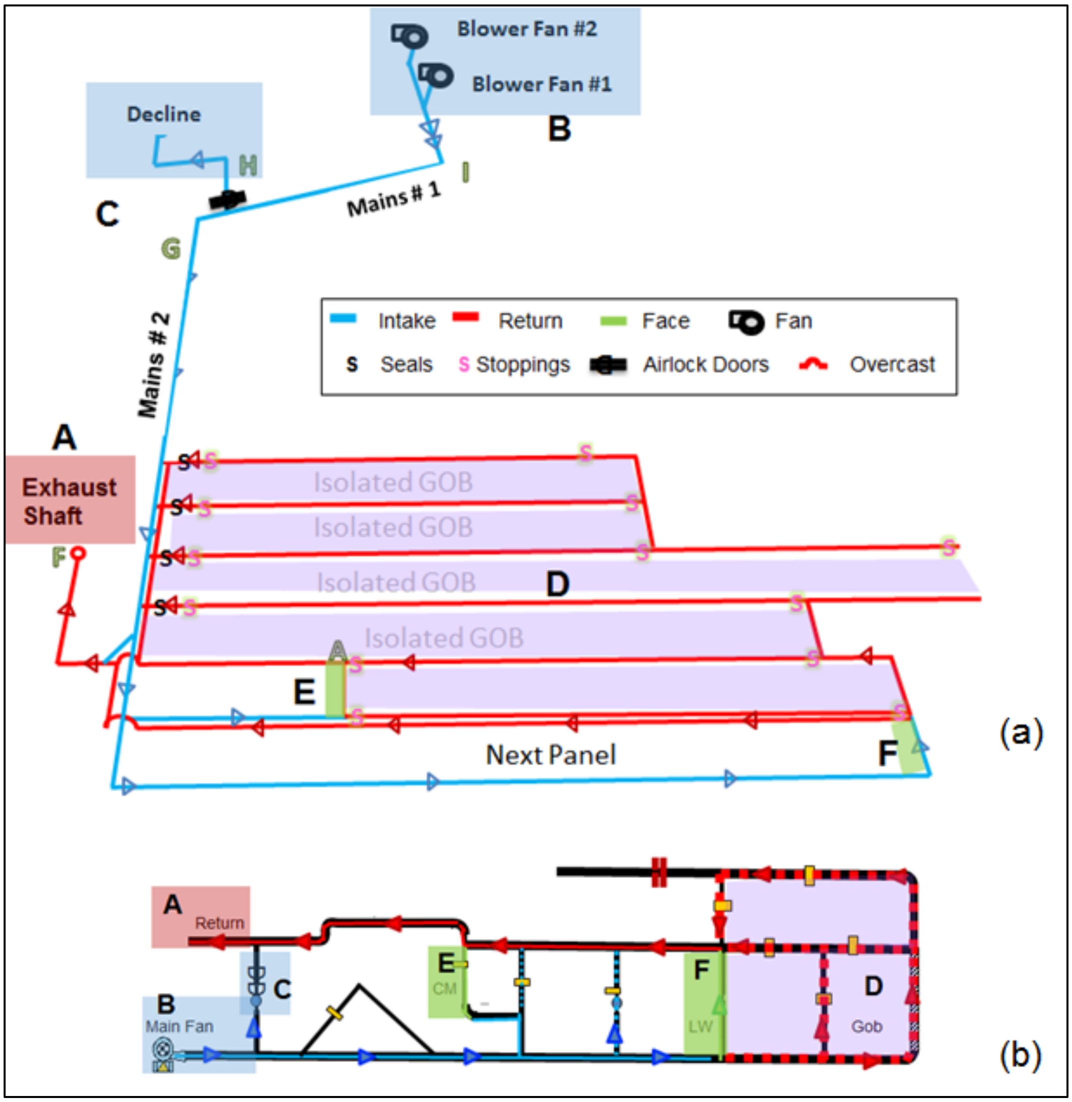

Figure B1. Numerical and laboratory ventilation schematics for mine C

Table B1. Comparison of Field and Simulated Data for Mine C

Location	Airflow Quantity, m^3/s		
	Field Data	Ventsim Data	Lab Model Data
Longwall Face	40	40	0.18
Continuous Miner Face	28	28	0.14
Total Intake	600	598	0.43
Total Exhaust	601	598	0.43
Location	Pressure, Pa		
	Field Data	Ventsim Data	Lab Model Data
ΔP across Longwall Face	398	399	157
ΔP across the Gob	-	50	49
ΔP Base of Exhaust Shaft	37	42	62
ΔP Base of Intake Shaft 1	2,052	2,117	2,086

10.3 Appendix C - Thesis Abstracts

10.3.1 Ankit Jha Thesis Abstract

Coal has an inherent tendency to combust in the presence of oxygen. This phenomenon is known as the process of spontaneous combustion (sponcom). The consequences of spontaneous combustion can vary from small fires to explosions that can lead to loss of production and fatalities. Ventilation systems with the incorporation of pressure balancing techniques can be used to prevent sponcom. Pressure balancing is the process of equalizing pressure differentials between two areas to control the directional flow of air. Controlling airflow in critical areas such as mine gobs, pillars, and leakage points in critical locations can prevent and reduce the oxidization process for fires, explosions, and sponcom.

Critical factors that contribute to the spontaneous combustion process of coal have been thoroughly evaluated. These factors include; the quality of coal, geological features, and mining methods used to extract the coal. The prediction of conditions that will lead to self-heating of coal within specific environments can be done by using the computer programs such as SPONCOM 2.0. This program analyzes many variables that contribute to the probability of ambient coal to spontaneously combust in specific environments. Once the probability and contributing factors are known for the likelihood of self-heating and sponcom then preventive measures can be designed and implemented. Pressure balancing is a versatile and preventive solution to the spontaneous combustion problem.

There are two different types of pressure balancing techniques, passive and active. Passive balancing is achieved by increasing or decreasing resistance of critical regulators and modifying fan duties. Active pressure balancing is achieved by incorporating an external pressure source to designed pressure chambers and locations. Pressure chambers can be pressurized actively or passively. Chambers can be pressurized with duct work by connecting pressure sources from locations with higher pressures to the chamber. Passive pressure balancing can be applied to areas where pressure differentials are relatively low. Active pressure balancing techniques are used where pressure differentials are relatively large values and when external pressure sources can easily be implemented. Inert gas such as nitrogen that is commonly used to pressurize gobs can also be used to pressurize the chambers. This is an ideal external source because inert gas does not pose a danger to the health and safety of the mine workers.

The University of Utah uses a laboratory ventilation model that includes a simulated mine gob, bleeder entries, pressure chambers, and an atmospheric monitoring system. The model was used to conduct several experiments to equalize pressure differential across the simulated gob. Different ventilation scenarios were emulated to model various ventilation systems such as flow-through, wrap-around, punch-out, and common U-tube systems. Pressure balancing was achieved by using both passive and active pressure control methods for various commonly used mine ventilation systems.

The atmospheric monitoring system, installed at the University of Utah laboratory model consists of 29 pressure transducers, two velocity transducers, and a CO_2 gas injection and control system. This system is described in great detail within this thesis. All the vital ventilation control parameters can be observed and recorded instantaneously with this system. A sub-routine computer program was developed to accomplish the pressure balancing system automatically. Using this system, pressure differentials around the simulated gob were recorded by the program and, when needed, a flow control valve was switched on automatically to activate the pressure balancing process. The results of multiple automatic pressure balancing tests are reported within this study.

Three underground coal mines were visited and surveyed as part of this study. Each mine used different ventilation techniques to supply adequate amounts of air throughout each mine. Mine A was a room and pillar system, mine B was a longwall mine with a flow-through bleeder system, and mine C was a U-tube bleederless system. The objective of these visits was to conduct pressure-quantity surveys in the active workings and mined out areas. The surveys were completed to determine the pressure differentials across the worked-out areas that are prone to sponcom. The results of these were used to design and calibrate the laboratory models that replicate field survey data. These models were then used to develop conceptual designs for pressure balancing applications for different ventilation systems. The results of the surveys conducted for mine A are presented and discussed in this study. The study concludes with an inventory of hazards related to spontaneous combustion, control measures, and risk analyses to identify the critical factors associated with pressure balancing and sponcom within the industry.

10.3.2 Chris Bateman Thesis Abstract

Mine fires and explosion associated with spontaneous combustion (sponcom) can be the cause of mines closings temporarily or permanently. The risk of fatalities and production losses is quite high especially in mines where the coal is liable to sponcom. Over the last 175 years nearly 13,000 deaths have been attributed to mine fires or explosions in U. S. coal mines. Some of these fires could likely have been prevented with proper ventilation precautions. Ventilation is a primary tool used to prevent fires and explosion in an underground mining environment. Diluting contaminants with proper air quantity and quality is the general method for preventing fires and explosions. Another method for fire prevention is pressure balancing. Pressure balancing is a technique of reducing or eliminating the pressure differentials in areas where there is potential for sponcom.

Passive and active pressure balancing techniques can be used to reduce the risk of spontaneous combustions and accumulation of explosive gas mixtures in confined areas. These methods have been applied in mines outside of the United States, mostly in Australia, India, and some European countries. Pressure balancing, when applied correctly, may reduce or eliminate the flow of air through caved areas, thus reducing the possibility of self-heating of coal in critical areas where sponcom is more prevalent. Each mine in the United States has a unique ventilation design that either employs bleeders or is bleederless, with multiple variations depending on local conditions.

Passive and active pressure balancing designs were engineered for two underground coal mines, one ventilated by a bleeder system and the other by a bleederless system. The mines are identified as mine B and mine C. In both mines, coal is extracted using a standard longwall mining method. This study includes pressure-quantity surveys in these mines, computer simulation exercises, and laboratory tests performed at the University of Utah. A numerical model was developed for each mine and the model results compared with field data to produce a calibrated, baseline model. The calibrated models were used to develop strategies to prevent spontaneous combustion, create safe working conditions, and minimize ventilation requirements for various underground coal mines. The numerical models were also used to reconfigure the physical model to emulate the ventilation system of these mines. Passive and active pressure balancing techniques were used in the physical modeling.

The experiments associated with pressure balancing for this project will assist ventilation engineers to better understand this technique and its potential benefits in costs and prevention of sponcom. Common ventilation systems used in U.S. coal mines have been replicated in the laboratory models so that practical implementation of pressure balancing systems can be evaluated. The accuracies of these systems have been determined through correlation studies. Pressure balancing systems could

potentially save lives and reduce capital and operating costs in underground coal mines in the United States when designed and implemented corrected.

The likelihood of spontaneous combustion should be evaluated in every underground coal mine, so that efficient preventive methods of ventilation can be implemented. The ventilation plan and system characteristics must be understood before considering pressure balancing applications in any mine. All ventilation systems will experience some leakage that must be mitigated and controlled as reasonably possible. Seals, stoppings, and surface cracks (especially in shallow mines) must be considered in designing ventilation plans, as should environmental conditions such as geology, climate, and barometric pressure changes. An understating of all these parameters is equally important when considering the implementation of pressure balancing techniques. Effective ventilation plans that comply with regulations and other safety standards should be the primary objective while practicing pressure balancing applications.

11.0 Disclosure

The Alpha Foundation sponsored this study for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION). The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by the ALPHA FOUNDATION, its Directors and staff.