24-073

Pressure Balancing Tests at a Colorado Coal Mine

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ABSTRACT

Two pressure balancing chambers were constructed at a Colorado coal mine to reduce the risk of spontaneous combustion. Each chamber was established by installing a Kennedy stopping at about 10 ft (3 m) in front of an isolation seal, and equipped with two safety doors, a nitrogen injection system, and a set of environmental monitors. Several pressure balancing tests for different ventilation conditions were conducted in these chambers. During each test, pressurized nitrogen was injected into the chamber and the pressure differentials across the stoppings and seals monitored. This study presents a summary of the results achieved, lessons learned, and the basic requirements to operate a pressure chamber effectively.

INTRODUCTION

The problem of spontaneous combustion (Sponcom) has been associated with coal mining for many years. It is estimated to be the cause of more than 20% of coal mine fires in the U.S. (Timko & Derick 1995). 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 a 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, and expenses incurred in attempting to extinguish the fire.

Depending on the characteristics of the coal seam and the ventilation conditions, self-heating of coal can start at temperatures as low as 35 °C. If the heat is not removed it will increase the coal temperature, leading to ignition and fire. Adequate ventilation is the primary control method used to prevent fires and explosions in underground coal mines. Another control method is pressure balancing. Pressure balancing is a ventilation technique used mainly to neutralize the pressure differences around and across caved areas. If these differences are reduced to zero, then there would be no leakage of air through the stoppings and seals, thus there would be no oxygen to start and sustain the self-heating of coal.

Pressure balancing has been used in many coal mining countries, but not in the US coal mines. Australia, the United Kingdom, South Africa, India, and some European countries have been utilizing this technique to combat as well as to prevent fires in underground mines for many years (Ray 2007, Chalmers 2008, and Grubb 2008). Except for a few passive pressure balancing cases, this technique has not been used within the United States (Smith & Lazzara 1987, and Bessinger et al. 2005). Pressure chambers are not used in the US coal mines because of the need to inspect the gob isolation seals on regular bases. This practice, would require a special chamber design to comply with MSHA regulations.

In 2016, the University of Utah completed a research project on "Control of Spontaneous Combustion Using Pressure Balancing Techniques." A physical model to mimic a coal mine ventilation system was constructed as part of this project. The model included a simulated mine gob, a CO2-based pressure chamber, and a ventilation monitoring system. The model was used to conduct several pressure balancing tests. The results of these tests showed that pressure balancing can be used effectively for control of spontaneous combustion conditions in

U.S. coal mines (Calizaya et al. 2016). Upon the conclusion of the project, a recommendation was given: "to test the operation principles of a pressure balancing system in the field." This study summarizes the result of a follow-up project to test the principles of pressure balancing to reduce the risk of starting a Sponcom fire in a coal mine.

SELECTING A COAL MINE

Testing pressure balancing chambers in the field required an underground coal mine where pressure chambers can be constructed, tested and evaluated. Several coal mine operators were contacted to test this technique in their mines. The coal mine located in Midwest Colorado was interested in participating in this project. In this mine, the coal seam is fairly flat, of about 3 m (10 ft) thick at about 150 m (500 ft) below surface. The mine operates one longwall and up to three development sections. The longwall panel uses a common three-entry gate roads. The mine is ventilated by a blower-type ventilation system equipped with two surface fans. The combined capacity of these fans is nearly 600 m^3/s (1,270 kcfm) at 2.50 kPa (10 in wg) of total pressure. The longwall panel is ventilated by a bleederless ventilation system where the mined-out areas are isolated by means of high-pressure seals and the gob is inertized with nitrogen gas that is injected from two to five cross-cuts inby to the face from the headgate side.

Ventilation and atmospheric conditions at the mine are monitored using a mine-wide Atmospheric Monitoring System (AMS). The system includes different types of transducers to monitor both ventilation parameters (barometric pressure, temperature, and air velocity), and mine gases (O2, CO, and CH4). The barometers used at the mine are set to display standardized (adjusted to sea level) barometric pressures.

CONSTRUCTION OF TWO PRESSURE CHAMBERS

Two pressure chambers were constructed at the ABC coal mine: one in a mined-out area (1st Chamber), and the other one in the active area (2nd Chamber), near a longwall mine gob. Each chamber was established by installing a Kennedy stopping in competent ground at about 3 m (10 ft) in front of an MSHA-approved 800-kPa (120-psi) pressure seal. To satisfy the MSHA requirements, the stopping design was modified to include two personal access doors to allow the mine personnel to inspect the seal weekly. Furthermore, to reduce leakage, the Kennedy stoppings and access door frames were sealed from both sides. Each chamber was equipped with ventilation curtains to naturally ventilate the chamber, a nitrogen injection system, pressure tubes, and a set of ventilation and environmental monitors.

Because the project involved the utilization of pressurized nitrogen and modifications to the current stopping construction practices, a conceptual design for the chamber was developed and submitted to MSHA. This was approved before the construction work begun. In its salient features, the design included:

a. Technical drawings of the chamber. The design specified the type of stopping to be constructed, type and size of man-doors, details of the nitrogen injection system, and the location of gas and pressure sampling points.
b. Communication system. The design specified the location of phone stations and warning signs near the test area. These were linked to the mine's communication system to provide the mine operator with the necessary information before, during, and after the test.
c. Location of ventilation monitors and control devices. In addition to the mine's atmospheric monitoring system, each chamber was equipped with oxygen sensors located upwind and downwind of the chamber with their alarm levels set at 19.5% O2.
d. Ventilation. A minimum air volume of 1.0 m^3/s (2,000 cfm) was provided at the chamber to allow enough air to dilute the contaminates from leakage.
e. Nitrogen injection system. The design specified the location of the nitrogen source, and size and length of pipelines. All flow control valves, gages and regulators were also specified.
f. Procedure to operate the chamber. This included steps to operate a pressure chamber, process the data and to determine the effect of pressure changes on the flow of air.

Figure 1 shows a plan view of the drawing used for the construction of the first chamber. It specifies the type of stopping to be installed, type and size of man-doors, details of the nitrogen injection system, location of gas sampling points and pressure taps, and the location of gas and ventilation monitors. Notice that the chamber is equipped with two ventilation curtains that can be rearranged to ventilate the chamber area and to allow the mine personnel to inspect the seal and to complete their weekly examination.

Construction of the First Chamber

The first chamber was located in a mined-out (passive) area. The chamber was established by constructing a Kennedy stopping at about 3 m (10 ft) in front of an existing isolation seal. The stopping included two personnel access doors that would swing the door leaves outwards (into the access entry) when the doors are open. To reduce leakage, the stopping was reinforced and sealant foam was applied from both sides. Once the stopping was installed, the chamber was equipped with two ventilation curtains, a nitrogen injection system, flow control valves, pressure and as sampling ports, a set of differential pressure transducers and oxygen sensors linked to the mine's AMS.

Figure 2 shows two photographs of the first chamber depicting construction details of the Kennedy stopping,

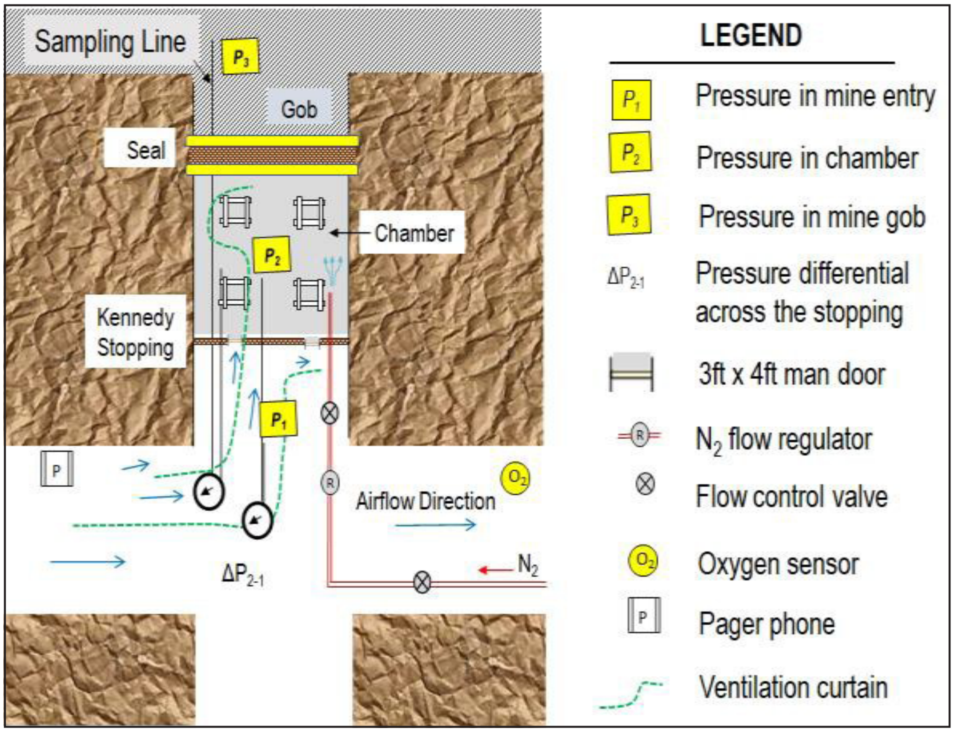

Figure 1. Plan view of a pressure chamber

Figure 2. First pressure chamber details. (a) Kennedy stopping with personal doors to open outwards, and (b) Nitrogen injection pipeline and flow control valves

the reinforcement bars, the sealant material used to reduce leakage, the personal doors (initially designed to be open outwards), and the nitrogen gas injection system.

Construction of the Second Chamber

The second chamber was installed in a cross cut, near an active longwall panel. Based on the lessons learned from the Fist chamber, the potential site was inspected and the existing joint patterns and stress- induced cracks examined and found to be in good conditions. The existing permanent seal was approximately 15 m (38 ft) from the outby intersection, which allowed for adequate space for the Second chamber without being too close to the corner of the coal pillar. As in previous case, the chamber was established by installing a Kennedy stopping at about 3 m (10 ft) in front of the existing seal. The floor and walls were trenched and cleaned before installing the Kennedy panels. Initially, the access doors were designed to open outwards as in the Fist chamber. During the test, this configuration induced significant gas leakage. To overcome this problem, for the second part of the test, the door design was modified to include a "bolt-on" rod assembly to open the door inwards when access into the chamber is needed, and to position the door against the door frame when the chamber is closed. The construction of the chamber was completed with the installation of two ventilation curtains, a nitrogen injection system and a set of sensors to record barometric pressure, pressure differentials, and oxygen concentration downwind of the chamber.

Figure 3 shows two pictures of the 2nd chamber depicting construction details of the ventilation curtains, used to purge the chamber, and the personal door equipped with a "bolt-on" rod assembly to open the door inwards when access into the chamber is needed.

Nitrogen Injection System

Pressurized nitrogen was delivered to a chamber through a nitrogen injection system. The system consisted of 5 cm (2 in) diameter pipe extended from the main nitrogen distribution center to the chamber location, fittings, and a set of flow control valves, regulators, and pressure gages. Figure 4 shows a schematic of the nitrogen injection system for a pressure chamber. Near the gas injection point, the system includes: two flow control valves, V1 and V2, one regulator, R, and two pressure gages, G1 and G2. At each chamber, a test was started by closing and locking the personal doors, opening the nitrogen flow control valves, setting the regulator to allow a fixed flow rate, and monitoring the pressure gages. This was followed by recording pressure differential across the stopping and seal, and testing for gas leakage from the chamber. Then, the gas flow rate was increased by opening the regulator knob by ½ turn and the data recording process repeated. The test was stopped when the nitrogen gas leakage reduced the oxygen level in the access drift to less than 19.5%.

PRESSURE BALANCING TESTS

Several pressure balancing tests were conducted on each pressure chamber. Once a chamber was constructed and equipped with a nitrogen injection system, pressurized nitrogen was injected into the chamber and the pressure differentials across the stoppings and seals were monitored. The results showed that while the seals held high-pressure differentials effectively, the Kennedy stoppings did not, mainly, because of leakage of nitrogen through the stopping and the access doors. To overcome the problem, the stopping was reinforced and sealant material applied from both sides. This helped but was not sufficient to hold pressure differentials greater than 750 Pa (3 in wg). At this point,

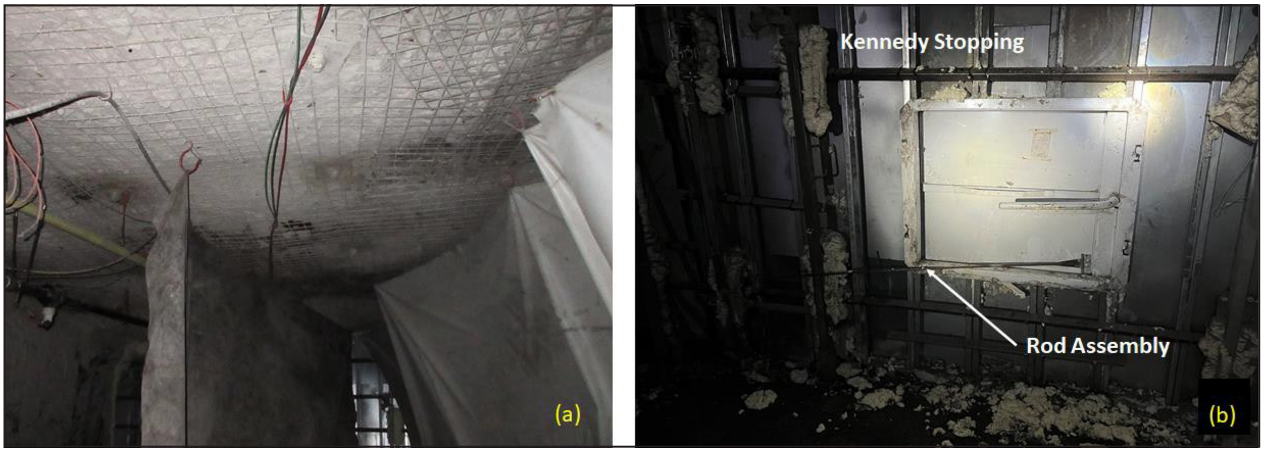

Figure 3. Second chamber access door details. (a) Ventilation curtains to purge the chamber, and (b) Kennedy stopping, and access door in closed position

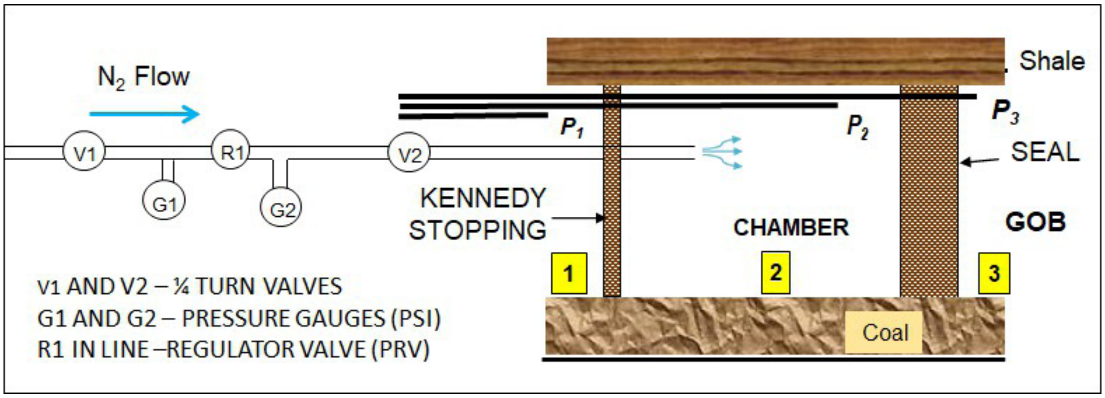

Figure 4. Schematic of a pressurized nitrogen injection system

significant leakage of nitrogen through the door gaskets was measured. To overcome the problem, for the 2nd chamber, the position of the doors was modified to open the doors into of the chamber (inwards) when the doors are open, and close them against the door frames (outwards) when the doors are closed. Following this change, the chamber was able to withstand pressure differentials in the range of 1250 to 1500 Pa (5.0 to 6.0 in wg) without any significant leakage.

Tests on the 1st Chamber

The results of two tests performed on the 1st chamber are presented in this section: (1) to show the effect of barometric pressure on pressure differential across the chamber walls, and (2) to shows the effect of pressurized nitrogen on the chamber walls. In each case, the chamber was filled with pressurized nitrogen, the pressure differentials monitored, and the chamber walls evaluated for their ability to reduce the flow of oxygen into the gob, thus reducing the risk of starting a fire. The results of the two tests are presented below.

Test 1—The Effect of Atmospheric Pressure on the Chamber Pressure

This test was performed to determine the effect of changes in atmospheric pressure on the pressure differentials across the chamber's stopping and seal. Figure 5 shows four-time series data for a month (September 1–30, 2021): one for surface air temperature, one for barometric pressure and two for pressure differentials across the chamber's stopping and seal. Temperature and barometric pressure data (brown and green lines) were recorded by digital sensors located at the mine's main office (on surface). The pressure differentials (DP) were monitored by two digital manometers: one used to measure pressure differentials between the gob and the chamber (Seal DP or P3–P2 in Figure 4), and another between the chamber and the entry (Stopping DP or P2–P1). In Figure 5, the orange line represents the pressure differentials across the seal (P3–P2), and the blue line the pressure changes across the stopping (P2–P1). A quick evaluation of these graphs shows that the barometric pressure and temperature are inversely related and vary on a daily basis. These variations affect both pressure differentials across the chamber walls. For example, on September 22, as shown in Figure 5, the barometric pressure varied between a maximum of 30.6 in–mercury (Hg) at about 5 AM and a minimum of 30.3 in–Hg at 4 PM (a total decrease of 0.3 in Hg or 4.1 in wg). During the same period, while the pressure differentials across the seal varied significantly (between +0.6 in wg and –1.4 in wg), the pressure differentials across the stopping remained practically constant with a mean of –0.1 in wg). These results showed that while the permanent seal is robust and has the ability to hold high–pressure differentials, the Kennedy stopping is not strong enough to hold pressurized gas. Another finding is that the pressure differentials across the permanent seal are directly related to changes in barometric pressure i.e., when the barometric pressure on the surface increases the pressure differential across the seal (P3–P2) also increases to even become positive (P3–P2>0), causing an out–gassing condition (green highlighted area in Figure 5). On the contrary, when the barometric pressure on the surface decreases, the differential pressure across the seal (P3–P2<0) becomes negative, creating an in–gassing condition.

Test 2—The Effect of Nitrogen Injection on the Pressure Chamber

This test was performed to determine the ability of the chamber to hold pressurized nitrogen. Following a site inspection and having found the chamber to be in good conditions, the personnel doors were closed and locked, the nitrogen flow control valves opened, and the chamber tested

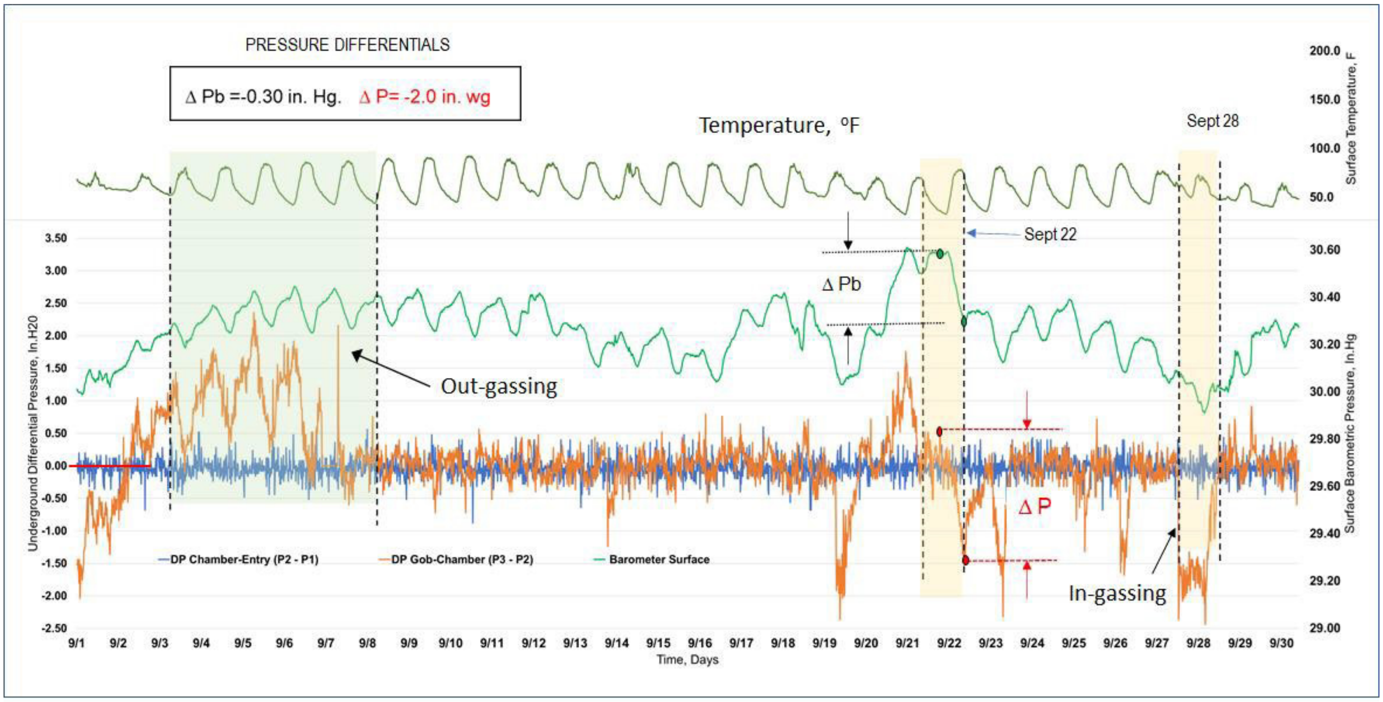

Figure 5. Effect of barometric pressure on chamber walls (seal and stopping)

for different gas flow rates. The test started on December 2, 2021, at approximately 9:07 AM. The control valves V1 and V2 (Figure 4) were opened, and the regulator R1 adjected so that the pressure gages G1 and G2 displayed 6 psi and 2 psi respectively (gas flow rate of about 20 cfm). For the same flow rate, the test continued for several hours. During this period, the barometric pressure and pressure differentials across the chamber walls were monitored continuously, and the stopping was checked for leakage of nitrogen or decrease in oxygen level frequently. The test was immediately stopped when the oxygen concentration in the access cross cut, outby the stopping, dropped to less than 19.5%.

Figure 6 shows three time series for two days: one for barometric pressure and two for pressure differentials across the chamber walls. During the test period (highlighted area in Figure 6), while the barometric pressure did not show any significant change from its natural trend, the differential pressure across the seal decreased with the nitrogen pressure. When the gas flow regulator was opened, the pressure differential (P3 – P2) dropped from –0.4 in wg (almost neutral) to –3.48 in wg (in–gassing), yielding a combined pressure change of ΔP = –3.08 in wg. During the time period highlighted in Figure 6, the ΔP across the stopping fluctuated between –0.40 and +0.35 in wg. Figure 6 also shows that, during this period, the barometer readings dropped from 30.42 in. Hg to 30.24 in. Hg. This represents a decrease of –0.18 in. Hg., or –2.45 in wg. Consequently, it is appropriate to assert that the decrease in differential pressure across the seal is the result of a combined influence of a decrease in barometric pressure underground coupled with pressure loss in the chamber.

The above results showed that while the permanent seal is robust and durable, the Kennedy stopping still requires some additional reinforcement work. To overcome the problem, the stopping was reinforced and sealant foam was applied from both sides and tested again. This has improved the ability of the stopping to hold pressure differential up to 750 Pa (3 in. w.g). At this point, it was noticed that the main leakage of nitrogen was through the coal fissures and cracks around the stopping.

Tests on the Second Chamber

The results of two tests performed on the 2nd chamber are presented in this section: (1) when the personal doors were insatalled to open toward the fresh air side (outwards), and (2) when the doors were installed to open toward the chamber (inwards). The first test was conducted between August 9 and 10, 2022, and the second on June 7, 2023. In each case, hand-held TSI-micromanometers and ACR Smart-Reader barometers were used to collect the data. The results of these tests are presented below.

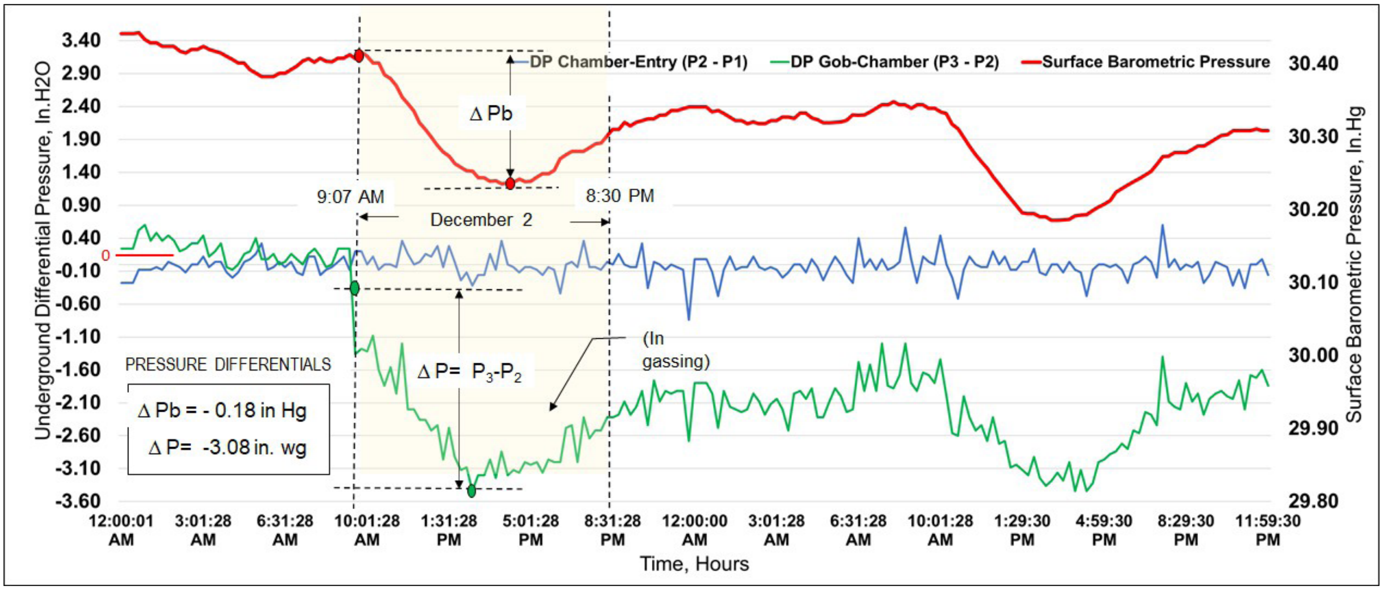

Figure 6. Pressure differential series after nitrogen gas injection (December 2–3, 2021)

Test 1—Chamber with access door to open outwards (August 9, 2022)

Prior to starting the test, the pressure chamber was inspected for safe conditions, the pressure gages zeroed, the hand-held instruments set to record the field data, and the personnel doors closed. The test started by opening the pressure control valves V1 and V2 and setting the regulator to allow a minimum flow rate. This was followed by recording barometric pressure and the pressure differential across the chamber walls, and checking for gas leakage into the surrounding area. The process was repeated for different gas flow rates.

Chronology of Events – August 9, 2022

- 11:25 AM. Regulator R1 set to minimum flow, valves V1 and V2 were open. Pressure gages: G1 = 400 kPa (58 psi), G2 = 0, DP2-1 = 42 Pa (0.17 in wg)
- 11:30 AM. Regulator position was increased by ½ turn. Pressure gages recorded: G1 = 385 kPa (56 psi), and G2 = 20.7 kPa (3 psi), and DP2-1 = 243 Pa (0.97 in wg)
- 11:37 AM. Regulator position increased by another ½ turn. Gages: G1 = 365 kPa (53 psi), and G2 = 20.7 kPa (3 psi), and DP2-1 = 492 Pa (1.97 in wg)
- 11:41 AM. Regulator increased by another ½ turn. Gage pressures: G1 = 379 kPa (55 psi), and G2= 34 kPa (5 psi), and DP2-1= 630 Pa (2.52 in wg) 11:42 AM. Regulator position increased by ½ turn. Gage pressures: G1 = 338 kPa (49 psi), and G2 = 28 kPa (4 psi), and, DP2-1 = 808 Pa (3.23 in wg)
- 11:48 AM. Significant leakage of nitrogen through door gaskets was detected (O2 < 19.5%). The nitrogen control valves were shut off. It took 20 sec. to depressurize the chamber.

Figure 7 shows barometric pressure variations (actual, not standardized), and pressure differentials recorded during this test. Notice that when the gas flow rate increased, the pressure differentials across the seal and stopping increased rapidly and remained constant thereafter, indicating that both walls can hold pressurized nitrogen with reduced leakage. The test was repeated for increased flow rates. It was stopped when the nitrogen gas leakage from the chamber reduced the oxygen level in the access drift to less than 19.5%. Table 1 summarizes the differential pressures across the chamber walls.

Test 2—Chamber with access door to open inwards (June 7, 2023)

Once the access doors in the Kennedy stopping were reversed, the chamber was inspected for safe conditions, the hand-held instruments set to record the field data, and the regulator set to allow for a minimum flow rate, the test started on June 7, 2023. Initially, the chamber was pressurized so that the gage pressure across the stopping reached 250 Pa (1 in wg). Then, the chamber was inspected again for unsafe conditions. Having found it to be in good standing, the gas flow rate was increased by adjusting the

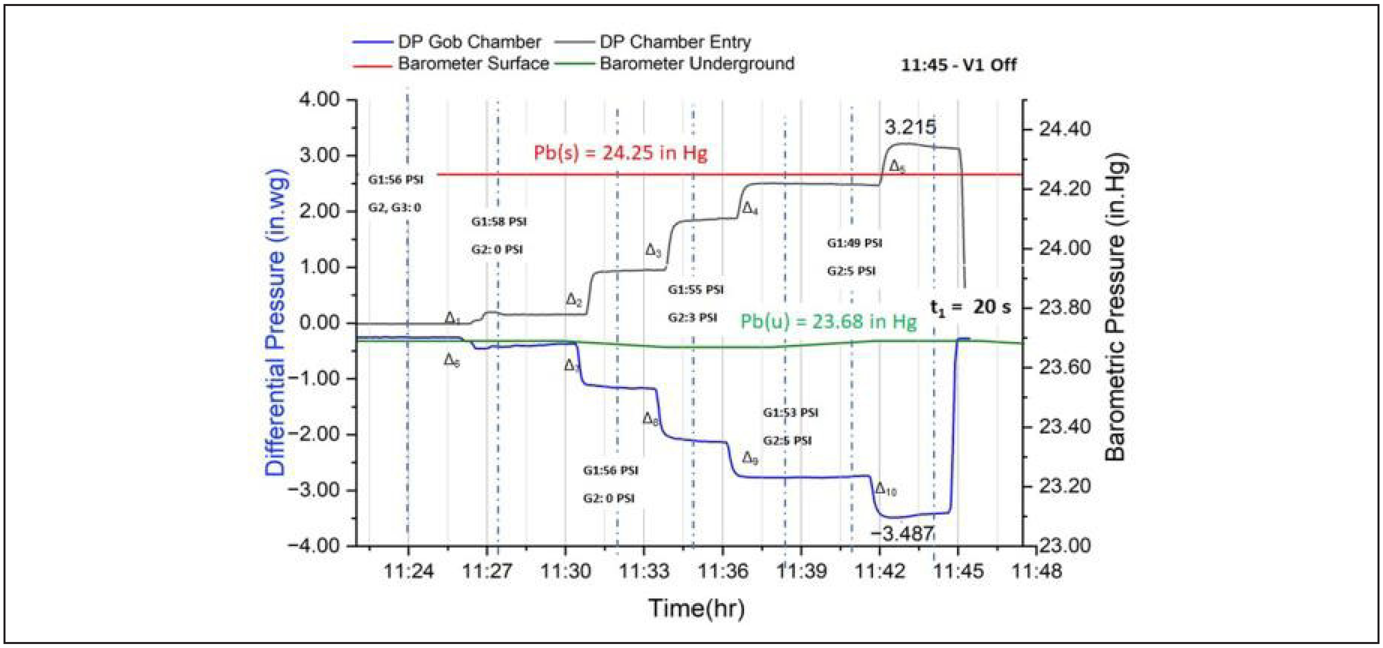

Figure 7. Pressure differentials across the chamber stopping and seal - Test 1

Table 1. Pressure differentials across the chamber stopping and seal - Test 1

Delta P (Chamber)	Average P P2-P1, Pa	Delta P (Seal)	Average P P3-P2, Pa
Δ1	42	Δ6	–51-
Δ2	241	Δ7	–229
Δ3	471	Δ8	–467
Δ4	628	Δ9	–624
Δ5	804	Δ10	–805

regulator knob in steps of ½ turns to reach 1475 Pa (5.9 in wg) between the chamber and entry (P2-P1) and –1525 Pa (6.1 in wg) between the chamber and the gob (P3-P2), respectively. At this time, nitrogen started leaking into the entry more through the chamber's hairline fissures (rib & back) rather than the Kennedy stopping. When the regulator was completely turned off, the chamber depressurized within 72 seconds.

Figure 8 shows the differential pressures between the chamber and entry (P2-P1) and between the gob and chamber (P3-P2) as nitrogen is injected into the chamber. Notice a slight decline when the differential pressure between chamber-entry and gob-chamber reached 1575 Pa (6.07 in wg) and 1560 Pa (6.241 in wg), respectively. During this period, the barometric underground pressure in front of the chamber "Pb(u)" remained fairly constant at 78.67 kPa (23.24 in Hg). Table 2 shows the differential pressures between chamber - entry (P2-P1) and gob - chamber (P3-P2).

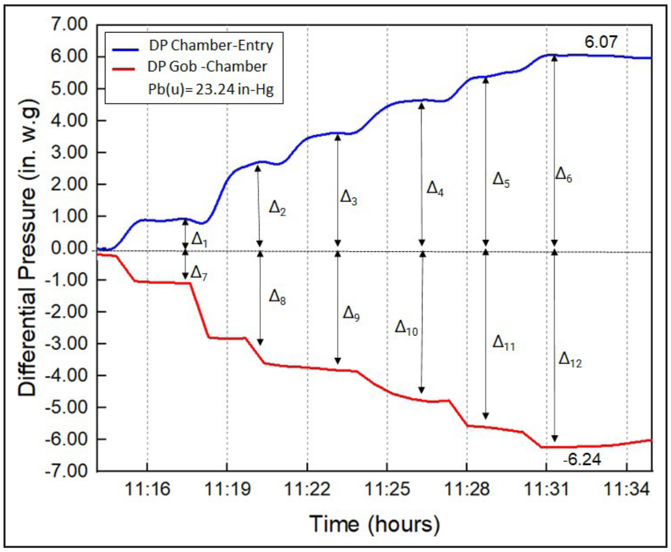

Figure 8. Pressure differentials across the stopping (P2-P1) and seal (P3-P2)

Table 2. Pressure differentials across the stopping (P2- P1) and seal (P3-P2)

Delta P (Chamber)	Average P P2-P1, Pa	Delta P (Seal)	Average P P3-P2, Pa
Δ1	224	Δ7	–272
Δ2	676	Δ8	–895
Δ3	902	Δ9	–951
Δ4	1,165	Δ10	–1,185
Δ5	1,371	Δ11	–1,412
Δ6	1,506	Δ12	–1,553

CONCLUSIONS AND DISCUSSIONS

Barometric pressure at the mine changes on a daily bases as a function of changes in surface air temperature. These two variables are inversely related. Depending on the weather conditions, changes in barometric pressure can be large enough to change leakage flow direction of air and explosive gases across the seals.

The isolation seals used at the mine are not fully airtight. Depending on the weather conditions, they will allow some ingress of fresh air into the gob or egress of explosive gases into the work environment. For example, when a seal was evaluated on August 31, 2021, it was observed that an increase of 1016 Pa) (0.30 in Hg) in barometric pressure, increased the pressure differential across the seal (P3-P2) from –50 Pa (–0.2 in wg) to 425 Pa (1.7 in wg), creating an out-gassing condition.

As part of this research, two pressure chambers were established at the mine: one in a mined-out area, and another near an active longwall panel. In both cases, Kennedy stoppings were installed to establish a chamber. When the chambers were pressurized with nitrogen, leakage through the stopping became a problem, particularly in the 1st chamber. To overcome the problem, the stopping was reinforced and sealed. This reduced the leakage, but was not sufficient to hold pressure differentials greater than 500 Pa (2 in wg).

Based on the lessons learned from the 1st chamber, the stopping for the 2nd chamber was constructed in competent ground at about 3 m (10 ft) in front of a permanent seal, and 8.5 m (28 ft) from the nearest intersection. Under these conditions, the stopping held pressure differentials up to 800 Pa (3.2 in wg). Beyond this pressure, leakage through the access doors' gasket was detected. To overcome the problem, the door design was modified to include a "bolt-on" rod assembly to swing the door against the frame when the chamber is closed.

When the access doors of the 2nd chamber were reversed, the stopping was able to withstand pressure differentials in the range of 1250–1500 Pa (5.0 to 6.0 in wg). Under these conditions, leakage around the doors was reduced significantly. Nitrogen leaked into the entry more through the chamber's hairline fissures (rib & back) rather than the Kennedy stopping.

Pressure chambers can be used to reduce the risk of self-heating of coal by reducing the ingress of fresh air into the gob. However, this requires a well- engineered design and construction of pressure chambers. The design must include:

- Proper site selection for the chamber
- An MSHA approved stopping design
- Access doors designed to open inward into the chamber when opening the chamber
- A reliable nitrogen injection and monitoring system, and
- A safe operating procedure to open and close the access doors, to purge the chamber after each test, and to operate the chamber.

To uphold high pressure differentials across the chamber walls and to minimize the ingress of air into the gob, a continuous flow of nitrogen into the chamber is required. Based on barometric pressure variations measured at the mine, a continuous nitrogen flow of 0.02 m^3/s (40 cfm) at about 10 kPa (3 psi) gage pressure at the injection point would be sufficient to maintain a positive pressure in the chamber.

DISCLOSURE

This study was sponsored by the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. 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 its staff.

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24-074

Principal Horizontal Stress Contributing to Massive Roof Collapse at the Subtropolis Mine

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ABSTRACT

In 2015, the Subtropolis Mine in Petersburg, OH, experienced a massive ground collapse that continues to grow over time. Horizontal stress effects have affected the roof at this operation in the past and may have played a large role in this collapse. Horizontal stress can impact the roof and floor stability and endanger the health and safety of underground stone miners. Mines experiencing damaging effects from horizontal stress typically find that the principal stress direction is the same throughout the mine and the region. At the Subtropolis Mine the principal horizontal stress direction appears to change as conditions change and differs from the regional horizontal stress, particularly near the collapse or other roof fall areas. The growth over time of this collapse and other roof falls have been captured and analyzed using geologic mapping, 3D LiDAR scanning, numerical modeling and geographic information systems like ArcGIS. Utilizing these tools to better understand site-specific conditions can be critical to reducing the potential of massive ground collapses in the underground limestone industry.

INTRODUCTION

Since 2015 there have been several massive ground collapses in the underground limestone industry. A massive ground collapse, as defined in this study, consists of broken strata partially filling multiple entries and rendering them unsafe to enter. Miners working in areas of unstable ground are at risk of serious falls of roof and rib injuries. In the most severe cases, escapeways can be blocked and a subsidence basin could occur on the surface. These massive ground collapses can occur or grow unexpectedly, and they represent a high- consequence health and safety hazard with the potential to produce serious injuries to underground mine workers.

There have been several massive ground collapses; however, the Subtropolis is one of very few where horizontal stress may have played a role. The Subtropolis Mine extracts the Vanport Limestone, which is part of the Allegheny Formation, Pennsylvanian System, and ranges in thickness from 16 to 22 ft with a mining height of approximately 16 ft and a roof span of approximately 40 ft (Iannacchione et al., 2019). Generally, the Vanport Limestone is overlain by a closely laminated, slightly weathered to weathered siltstone- sandy-shale immediate roof (Newman, 2019). The standard production pillars at this mine are from 40 ft to 60 ft in length by 30 ft wide. At the Subtropolis Mine, the Vanport Limestone includes several weak bedding planes in the roof. In order to create an adequate beam, the mine implements a primary bolting strategy of five 5-ft tensioned fully grouted resin bolts per row with 8-ft spacing and a secondary bolting strategy (typically in the crosscuts or