ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Final Technical Report

Solicitation and Call for Proposals (AFC820)

Project Title:	Application of Pressure Balancing Techniques at the West Elk Coal Mine.
Grant Number:	AFC113FO-12
Organization:	University of Utah Mining Engineering Department 135 S 1460 E # 313 Salt Lake City, Utah, 84112

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This study was sponsored by the Alpha Foundation 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.

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1. Executive Summary

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. 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, expenses incurred in attempting to extinguish the combustion, and loss of production and machinery.

The main objective of the project was to demonstrate a practical application of pressure balancing techniques to minimize the potential for spontaneous combustion of coal in the gob. The work included the following elements and tasks:

- Construction of two pressure chambers at the West Elk coal mine,
- Installation of pressure transducers and air quality monitoring devices,
- Managing pressure differentials across the chamber walls for different nitrogen injection rates.
- Developing methods and strategies to minimize the risks of in-gassing and out-gassing conditions into the gob and out from the gob.

For this research project, two pressure chambers have been constructed at the West Elk mine, Colorado, operated by the Mountain Coal Company (MCC): one in a mined-out area (B Seam Box Canyon 32 N), and the other one in the active area (Sunset 1 Headgate, 2E), near a longwall mine gob. Each chamber is equipped with an isolation stopping, safety doors, a nitrogen injection system, and a set of pressure and environmental monitoring sensors. Several pressure balancing tests for different nitrogen injection rates have been conducted in these chambers. The field data was collected by the mine's atmospheric monitoring system (AMS), then transmitted and processed at the University of Utah's computer center. In addition, during the various tests, ventilation and mine climate parameters were measured by means of hand-held instruments.

The results of this study showed that, at the West Elk mine, the barometric pressure varies daily as the air temperature on the surface increases or decreases. During summer, the daily change in barometric pressure can be in the order of 0.35 in. Hg. (4.8 in. wg); causing "in-gassing", or "outgassing" conditions around the ventilation stoppings and seals. A pressure chamber can be used to reduce the risk. However, this requires a special MSHA-approved plan to construct and operate the camber. A modified Kennedy stopping was used to establish a pressure chamber. When the chamber is properly designed, installed, and operated, it can hold a differential pressure across the Kennedy stopping ($P_2 - P_1$) up to 4.8 in. wg, without significant nitrogen leakage. Beyond this pressure, the pressurized nitrogen will leak into the work area through the chamber's hairline fissures and cracks (rib & back) rather than the Kennedy stopping. The various tests showed that to manage the pressure effectively, a steady flow of nitrogen should be supplied to the chamber. When the flow of nitrogen is stopped, the chamber will depressurize rather quickly.

This study presents a summary of the steps taken to construct the pressure chambers, the procedure used to conduct the tests, an evaluation of the results obtained, and the recommendations to reduce or eliminate the risk of starting a fire in a mine gob.

2. Introduction

2.1 Background Information

In 2016, the University of Utah completed a research project on "*Control of Spontaneous Combustion Using Pressure Balancing Techniques*", funded by the Alpha Foundation. The main objective of this project was to construct a physical ventilation model in which different types of pressure-balancing systems can be tested and evaluated. The model included a network of ventilation ducts assembled to represent a coal mine, a simulated mine gob, a CO_2-based pressure chamber, and an atmospheric monitoring and control system. The model was used to conduct pressure balancing tests designed to reduce pressure differentials between the simulated pressure chamber and the longwall mine-gob. In the field, this technique would reduce or eliminate the self-heating of coal, thus reducing the possibility of starting the spontaneous combustion of coal. The results of these tests showed that pressure balancing can be used effectively for the control of spontaneous combustion conditions in U.S. coal mines. Upon the conclusion of the project, a recommendation was to "*test the operation principles of a pressure balancing system in the field.*"

Testing the above principles in the field requires an underground coal mine where pressure balancing tests can be conducted. Several coal mine operators were contacted to test this technique in their mines. The Mountain Coal Company's West Elk mine was interested in participating because of its risk to Sponcom. The mine operates one longwall and up to three development sections. The mine uses a blower-type ventilation system equipped with two surface fans. 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 (Calizaya et.al. 2016).

The aim of the project is to construct two pressure chambers at the West Elk mine: one in a mined-out area (passive), and another near a longwall mine gob (active). Each chamber would be established by constructing a Kennedy stopping at about 10 ft (3 m) in front of an isolation seal. Each chamber would be equipped with a nitrogen gas injection system, connected to the mine nitrogen pipeline, and a set of pressure transducers to monitor pressure differentials. The standard stopping design used at the West Elk mine was modified to include two man-doors, ventilation curtains, and environmental monitoring devices to allow the mine personnel to inspect the seals safely. Each chamber was used to conduct pressure balancing tests under different ventilation conditions. This study presents a summary of the steps taken to construct and test two pressure chambers, the results achieved, and the recommendations provided by the research team from the University of Utah to reduce or eliminate the risk of starting a fire in the gob.

2.2 Literature Review

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 areas (gob) that are not easily accessible.

Depending on the characteristics of the coal seam 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 control method used to prevent fires and explosions in an underground coal mine. Another control method is pressure balancing. This is a technique of neutralizing pressure differentials in critical areas where there is potential for Sponcom.

Pressure balancing is a ventilation technique used mainly to neutralize the pressure differences around and across caved areas of an underground coal mine. If these differences are reduced to zero, then there would be no leakage through the stoppings and seals, thus there would 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 air 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 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 were not used in the US coal mines because of the need to inspect the isolation seals on regular bases. In addition, a special chamber design was needed in order to comply with MSHA regulations.

There are two types of pressure balancing systems: (1) passive, and (2) active. Both require the establishment and operation of pressure chambers and the monitoring of pressure differentials across the chamber walls. 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 limits its application. In an active system, an inert gas, such as nitrogen, is delivered to an area at very high pressure; therefore, it can be used to neutralize large pressure differences.

2.2.1 Passive Pressure Balancing

Passive pressure balancing is achieved by changing airway and regulator resistances, pressure differentials across the stoppings, and flow quantities near the gob. It can also be achieved by constructing pressure chambers and using atmospheric pressure to pressurize them. This practice is used mainly when the overburden of the caved area is shallow and fractured where barometric pressure fluctuations can influence air leakage and cause 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 atmospheric pressure through a borehole driven from the surface and an airflow distribution pipeline. A variation of this technique is called dynamic pressure balancing. Using this technique, pressure balancing is achieved by adjusting the flow rates, first through different airways around the affected area, and then through pressure chambers and flow control pipes. The pipes extend from the main intake or return to the chamber allowing the user to establish a continuous circulation of air even through the pressure chamber. The main disadvantage of this method is that it has a limited capacity that is defined by frictional and shock losses of the ventilation circuit of the affected area.

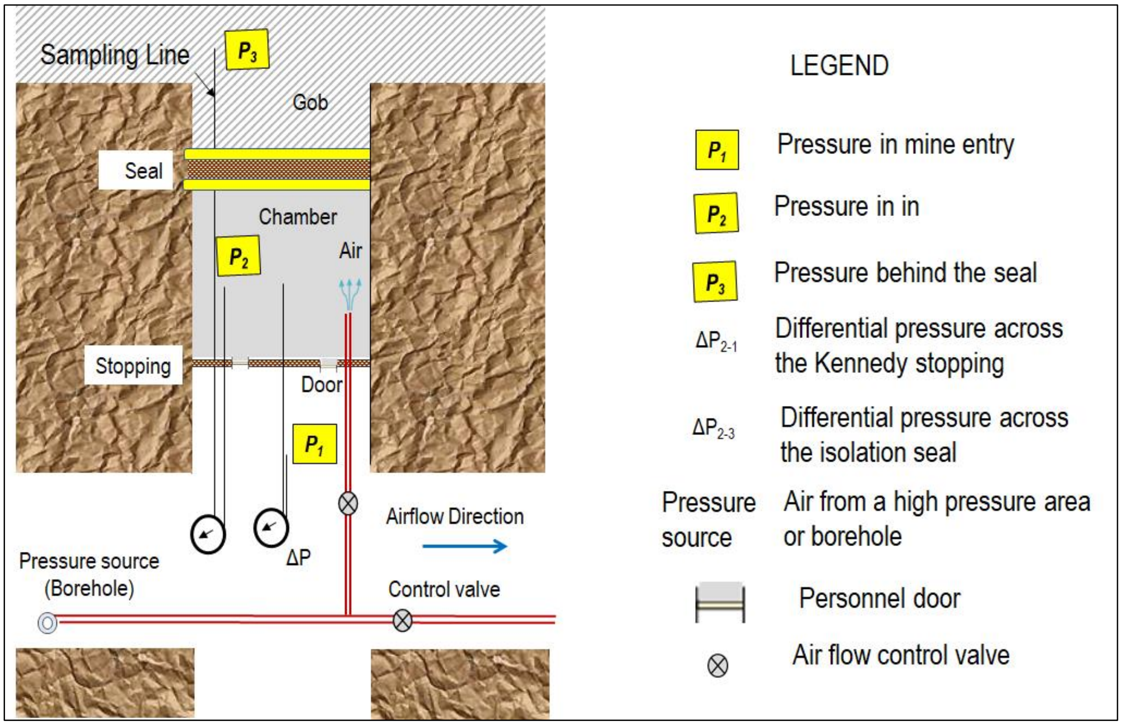


Figure 1: Passive pressure balancing.

2.2.2 Active Pressure Balancing

Active pressure balancing is achieved by using an external pressure source usually in the form of inert gas that is injected into the chamber in a controlled manner. It requires the construction of a pressure chamber, the installation of an inert gas injection system, and the operation of gas flow control valves when abnormal conditions are detected.

Barometers and manometers are used to monitor the atmospheric conditions and pressure differentials across the stoppings and seals and to determine the direction of the leakage flow. When significant leakage flow is detected from the gob to the chamber (outgassing of explosive gases) or from the chamber to the gob (ingress of air), the chamber is pressurized by using an inert gas. This method can be used to overcome high-pressure differentials such as those caused by sudden changes in barometric pressure. When the barometric pressure on the surface 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 ventilating air to migrate into the gob (Francart & Beiter 1997, and Schatzel et al. 2012). Pressure changes of this kind can be controlled by operating an active pressure-balancing system.

Figure 2 shows a schematic of an active pressure balancing chamber in which the pressure source is represented by a nitrogen tank.

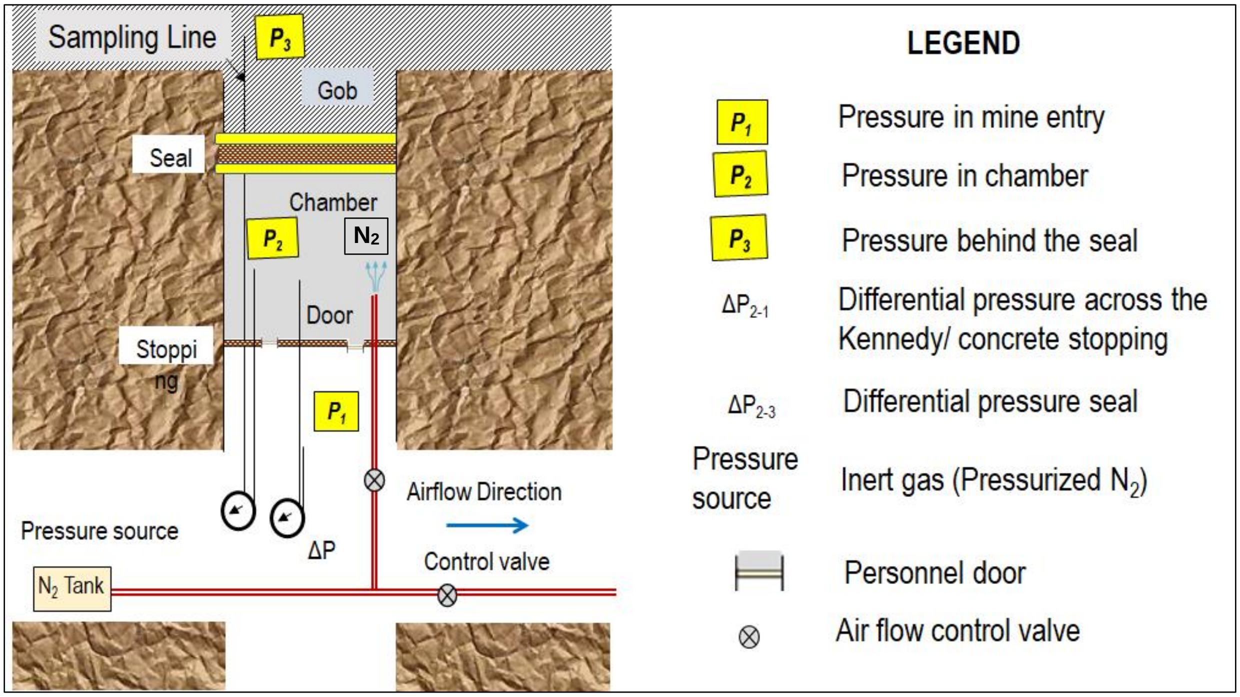


Figure 2: Schematic of active pressure balancing system.

3. Problem Statement and Objectives

3.1 Problem Statement

This research project was conducted in response to an invitation-only grant for completed projects that have compelling follow-on work as judged by the Alpha Foundation Board of Directors. The work includes the construction of two pressure chambers at the West Elk coal mine, pressurizing and testing them for their ability to reduce the ingress of fresh air into the mine gob and to determine the conditions under which these chambers can be used to reduce the risk of starting a spontaneous combustion (Sponcom) fire in a coal mine.

Spontaneous combustion is a safety hazard in underground coal mines, particularly in mined-out areas. It is estimated to be the cause of more than 20% of coal mine fires. The risk of Sponcom fires can be reduced by isolating the mine gob using rated seals and implementing a suitable ventilation system. However, the conventional seals are not fully airtight structures, and some leakage of air is expected, mainly around the perimeter of the seal and surrounding strata unless the pressure differentials across these seals are neutralized.

The alternative is to use pressure chambers to reduce the pressure differentials across the isolation seals. Through this 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.

It is mentioned that pressure balancing has not been used in the U.S. except for a few cases where a bleederless ventilation system is used to ventilate a longwall panel.

3.2 Objectives

The main objective of this study is to test the principles of pressure balancing in order to reduce the risk of starting a Sponcom fire in coal mines. Major tasks include the construction of two pressure chambers at the MCC's West Elk mine, conducting pressure balancing tests, monitoring and evaluating pressure differentials across the chamber walls, and determining the conditions under which this technique can be used to reduce or eliminate the risk of starting Sponcom fines. The study includes seven interrelated tasks, as follows:

1. Site selection and preparation
2. Complying with MSHA requirements
3. Construction of two pressure chambers
4. Conducting pressure balancing tests – Data processing and evaluation of results
5. Developing strategies to reduce the risk of Sponcom fires
6. Property restoration
7. Final report, and dissemination.

These seven tasks were accomplished by following the research approach described in the next section.

4. Research Approach

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

4.1 Site Selection and Preparation at the West Elk Mine

Between August 12 and August 14, 2019, Dr. Calizaya and Dr. Johnson visited the Mountain Coal Company's West Elk Mine to review the University of Utah's proposed plan with mine personnel, and to determine the locations for the construction of two pressure chambers. At the mine, the University of Utah personnel together with John Poulos, mine manager, decided on possible locations for the two chambers.

The 1st chamber would be installed in the "*B Seam Box Canyon 32 North*" area of the mine. This site is in a mined-out area, where the mine gob is isolated by means of rated seals. As such, the design of the chamber would require some modifications to current mine construction practices. The 2nd chamber would be installed in the "*E Seam*" near an active longwall panel. Later, due to changes in the mine production plan, the site was relocated to the "*Sunset 1 Headgate, 2E*" crosscut. During discussions, it was agreed that the B Seam chamber would be constructed and tested first, then, the lessons learned from the first chamber would be applied to the E Seam chamber.

Following the discussions with respect to the safety requirements, the University of Utah personnel were escorted by the mine manager to the B Seam seal location, 22 Recovery Room, 3 E-Seal. The cross-cut was mapped to determine the approximate location of the chamber, and the relative location of support cribs, ribs, etc. During the visit, it was also identified the required facilities in the area, such as ventilation controls, nitrogen pipes, and power lines.

Upon the completion of the mine visit, a preliminary plan was developed. The plan included the following steps:

1. The University of Utah will provide a letter of introduction addressed to Richard Gates, MSHA District 9 Manager outlining the nature of the Project.
2. The West Elk Mine will provide a list of Contract-work Companies to construct and equip the pressure chambers.
3. The West Elk Mine will prepare a ventilation plan for the proposed area. The plan will be reviewed by the research team of the University of Utah before the plan is submitted to MSHA for approval.

Following the on-site discussions, a letter of introduction to MSHA was written, and the conceptual designs for the chambers were drafted in consultation with the West Elk Mining Engineering Department and submitted to the MSHA District 9 manager on September 27, 2019. The letter was returned to us for corrections on three main issues: (1) two-way communication with the mine's control room, (2) minimum ventilation requirements, and (3) a procedure to operate the chamber.

The letter was discussed with the mine personnel and the requirements were incorporated in the revised plan.

4.2 Complying with MSHA requirements

Because the project involved the utilization of pressurized nitrogen and modifications to the current stopping construction practices, we were advised by the MSHA to modify our original plan to address the following points:

1. <u>Communication system</u>. Phones and warning signs must be posted at all accesses to the area and must be linked to the mine's communication system to provide the mine operator with the necessary information before, during, and after the test.
2. <u>Location of monitors and control devices</u>. The chamber must be equipped with oxygen sensors upwind and downwind of the chamber with respective alert and alarm levels set at 19.7% and 19.5% O_2. All control valves must be located upwind of the chamber.
3. <u>Ventilation</u>. A minimum air volume of 2,000 CFM is to be provided at the chamber to allow enough air to dilute the contaminants from leakage.
4. <u>Procedure to operate the chamber</u>. There must be a written protocol to operate the pressure chamber, to open and close the man doors, to purge the enclosed area, and to allow the MSHA personnel to complete the weekly examination of the seals.

Based on the above requirements, technical drawings and procedures were revised, the communication and ventilation systems were modified, and a protocol to operate the chamber was developed.

Major changes to the original plan included: (1) the use of a modified Kennedy stopping, sealed from both sides, to establish the pressure chambers, (2) the use of West Elk mine's Atmospheric Monitoring System (AMS) to collect the data and to communicate with the mine's control room, (3) installation of oxygen sensors downwind of the chamber, (4) installation of two man-doors (3 ft x 4 ft) and air curtains to purge the chamber, and (5) a procedure to purge and to operate the chamber.

The two man-doors on the Kennedy stopping are needed to naturally ventilate the chamber. By rearranging Curtain #1 and Curtain #2, the chamber can be naturally ventilated before the seal condition is assessed (see Figure 3).

Figure 3 shows the revised drawing for the construction of the 1st pressure chamber. Notice that, all communication devices, gas sampling ports, and nitrogen control valves are located upwind of the Kennedy stopping, and the oxygen sensors which are equipped with alert/alarm devices are located downwind of the area. Also, notice how the ventilation curtains can be rearranged to ventilate the area and to allow the mine personnel to inspect the seal and to complete their weekly examination.

The chamber operating procedure included steps to open and close the safety doors, to purge the enclosed area, and to allow the mine and MSHA personnel to inspect the seal. The procedure also included a protocol to inject nitrogen into the chamber, to monitor pressure differentials across the Kennedy stopping and the isolation seal, and steps to analyze the data and to report the results to the mine's AMS operator. The procedure was developed by the research team of the University of Utah in collaboration with the MCC ventilation department. The modified plan, including a protocol to operate the pressure chamber and to communicate with the mine operator, was re-submitted and approved by the MSHA District Manager on January 22, 2020.

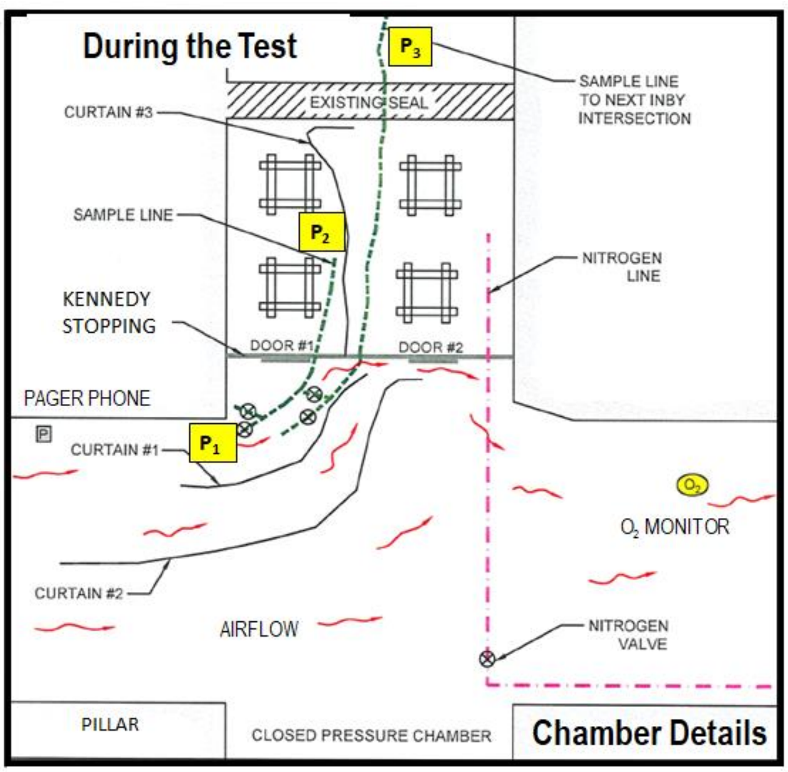


Figure 3: Plan view of the modified pressure chamber.

4.3 Construction of Two Pressure Chambers and Instrumentation

Our original plan was to employ a contractor to construct and equip the pressure chambers at the West Elk mine. Jenmar Services, with many years of construction experience in coal mines was selected for this job. However, due to unforeseen events caused by the coronavirus (COVID-19) outbreak, and the need to provide indemnity and insurance certification to the Mountain Coal Company (MCC) for the work to be performed by a contractor, and due to the travel ban in place at the University of Utah, we were unable to start the fieldwork in time. To overcome the problem, we were advised by our Legal Department to get a "*Temporary Right of Entry*" agreement with MCC, under which, the chambers would be constructed and equipped by the West Elk mine and all verified project-related invoices paid by the University of Utah. In such a case, the work performed by the University of Utah personnel would be limited to running the pressure balancing tests, collecting and interpreting the data, and writing/delivering the final report. An agreement between MCC and the University of Utah was reached on March 5, 2021, and the construction work started in June 2021.

4.3.1 Construction of the 1st Pressure Chamber

The first chamber was located at the "*B Seam Box Canyon 32 North*" area of the mine (see Figure 4). It was established by installing a Kennedy stopping at about 10 ft (3m) in front of an MSHA-approved 120 psi mine seal. The chamber was equipped with two safety doors, ventilation curtains, a nitrogen injection system, pressure tubes, and a set of ventilation and environmental monitors.

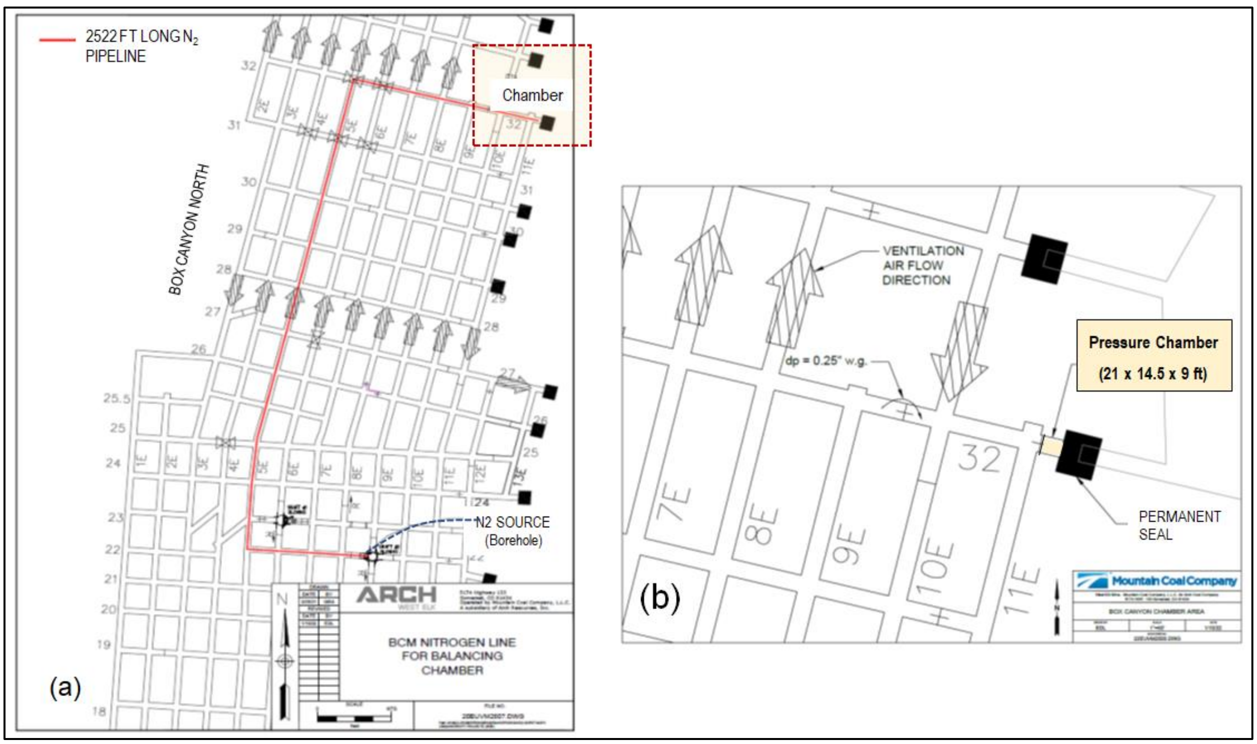


Figure 4: Location of the 1st pressure chamber: (a) General layout, (b) 32 N chamber.

Once installed, the Kennedy stopping was tested and sealed to minimize leakage, and two ventilation curtains were hung to purge the chamber after each test and to facilitate the mine personnel to inspect the isolation seal. A 2-in diameter, high-density polyethylene (HDPE) pipeline has been extended from the main nitrogen source to the 1st pressure balance chamber. The pipeline was equipped with a set of regulators, pressure gages, and flow and control valves. Two pressure sampling tubes were extended from the chamber to the control room, located on the upwind side of the Kennedy stopping. In addition, the chamber was equipped with a set of differential pressure transducers and oxygen sensors linked to the mine's AMS.

Figure 5 shows two photographs of the Kennedy stopping and personnel access doors that were installed to purge the chamber after each test and to allow the mine personnel to inspect the isolation seal.

Figure 6 shows details of the nitrogen injection system. Figure 6a shows the pipeline and the flow control valves and pressure reducers outby the Kennedy stopping. Figure 6b shows the nitrogen injection point, outby of the pressure chamber, with the ventilation curtain on the left rib, and the Tyvek curtain on the right.

All pressure sampling ports and nitrogen flow control valves were located upwind of the Kennedy stopping and the oxygen sensor was on the downwind side. All non-permissible electric monitors were installed in the intake air course using flexible tubing running from the chamber.

Figure 5. West Elk mine's 1st pressure chamber details: (a) Kennedy stopping sealed from access entry side, and (b) Personnel door open into the chamber.

Figure 6. Nitrogen injection system: (a) Nitrogen injection pipeline and flow control valves, (b) Pipeline extension into the chamber.

4.3.2 Construction of the 2nd Pressure Chamber

The second chamber is located at the "*Sunset 1 Headgate, 2E*" cross cut, near an active longwall panel (Figure 7). A visual inspection of this area showed that the existing joint patterns and stress-induced cracks of the roof, rib, and floor are in good conditions. The existing permanent mine seal is approximately 38 feet from the outby intersection, which allows for adequate space for the 2nd chamber without being too close to the corner of the coal pillar. As in the previous case, the pressure chamber was established by constructing a Kennedy stopping at about 10 ft in front of the 2E seal (or about 28 ft from the intersection). The same MSHA-approved plan shown in Figure 3 was used to construct and equip the chamber. The floor and walls were trenched and cleaned before installing the Kennedy panels. Five Simplex jacks were installed on the low-pressure side of the chamber wall for extra reinforcement. The construction job was completed with the installation of the nitrogen injection system and the tube lines to monitor pressure differentials. Four ventilation sensors have been installed at the chamber location to record the following parameters: barometric pressure, oxygen concentration downwind of the chamber, and pressure differentials across the seal and chamber respectively.

Figure 8 shows two photographs of the 2nd pressure chamber depicting the details of the chamber walls, the nitrogen gas injection system, and the Kennedy stopping equipped with two access doors. In the original plan, these doors were designed to open outwards (Figure 8a). During the test, this setup induced significant gas leakage. To overcome this problem, for the second part of the test, the design was modified to include a "bolt-on" rod assembly to open the door into the chamber (inwards) when access into the chamber is needed, and position the door against the door frame on the inside of the chamber when the chamber is closed, thus reducing nitrogen leakage (see Figure 8b). The "bolt-on" rod assembly was necessary to minimize exposure of the mine personnel to high nitrogen concentrations when the access doors are open to inspect the chamber and the seal.

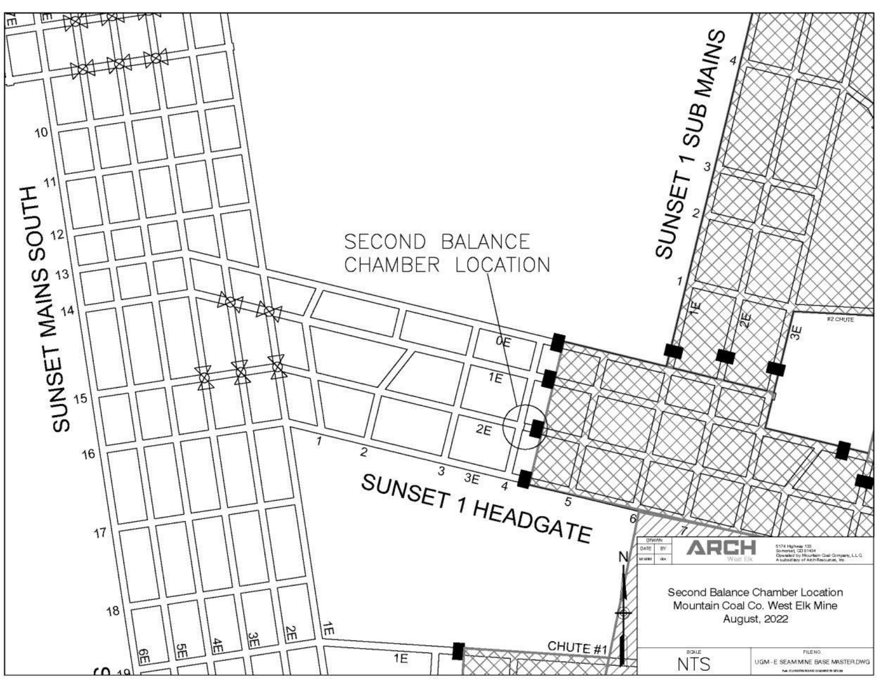


Figure 7: Location of the 2nd balance chamber

Figure 8: West Elk mine's 2nd pressure chamber: (a) Kennedy stopping with access door to open outwards, and (b) Stopping with access door to open inwards.

4.3.3 Nitrogen Injection System

Nitrogen is supplied to the balance chamber from the nitrogen plant located on the surface near the collar of Shaft 2 (Figure 4). An 8-inch diameter steel pipeline delivers nitrogen to the bottom of Shaft 2. Here the nitrogen enters a 2-inch ID HDPE poly pipe. This pipe continues from the bottom of Shaft 2 to the chamber location. This pipe is delivered in 500-foot rolls and the joints are fused. The only controls are the pressure-reducing valves (PRV) and pressure gages at the bottom of Shaft 2, and the flow control devices just outside the balance chamber.

Figure 9 shows two photographs of the nitrogen injection system seen from the access cross-cut side.

Figure 9: Nitrogen injection system: (a) Nitrogen pipeline and flow regulator, (b) Nitrogen control valves and gas sampling tubes.

Figure 10 shows two schematics of the flow control system located just outside the balance chamber. Figure 10a shows the nitrogen injection of the 1st chamber. It includes a 2-in diameter pipeline, two pressure-reducing valves (V1 and V2), two regulators (R1 and R2), and three pressure gages (G1, G2, and G3).

For the 2nd chamber, because of the longer length of the nitrogen pipeline than in the case of the 1st chamber (> 5 miles from the main supply center), and for practical reasons, regulator R2 and pressure gage G3 were removed from the system (Figure 10b).

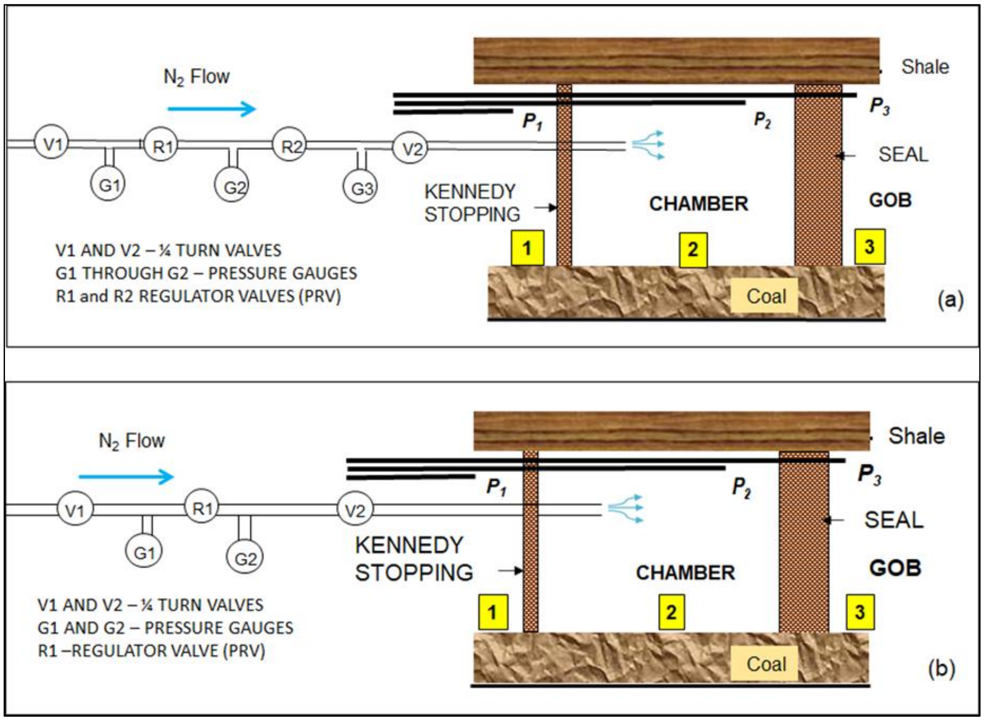


Figure 10: Nitrogen injection system: (a) Used with the 1st chamber, (b) Used with the 2nd Pressure chamber.

4.3.4 West Elk Mine's AMS and Pressure Transducers

The ventilation and atmospheric conditions at and near the pressure chambers were monitored using the West Elk mine's Atmospheric Monitoring System (AMS). This is a CONSPEC-based mine-wide monitoring system used at the mine on a regular basis. It includes different types of transducers to monitor both ventilation parameters (barometric pressure, temperature, and air velocity), and mine gases (O_2, CO, and CH_4). The barometers used with the CONSPEC system are set to display standardized (adjusted to sea level) barometric pressures.

This system was expanded to include CONSPEC-compatible micro-manometers to measure pressure differentials, and oxygen sensors to monitor the quality of air near the pressure chambers.

Figure 11 shows a schematic of the West Elk Mine's monitoring system. It includes pressure transducers to monitor pressure differentials across the chamber walls, and oxygen sensors to determine the quality of air on the return side of the chamber.

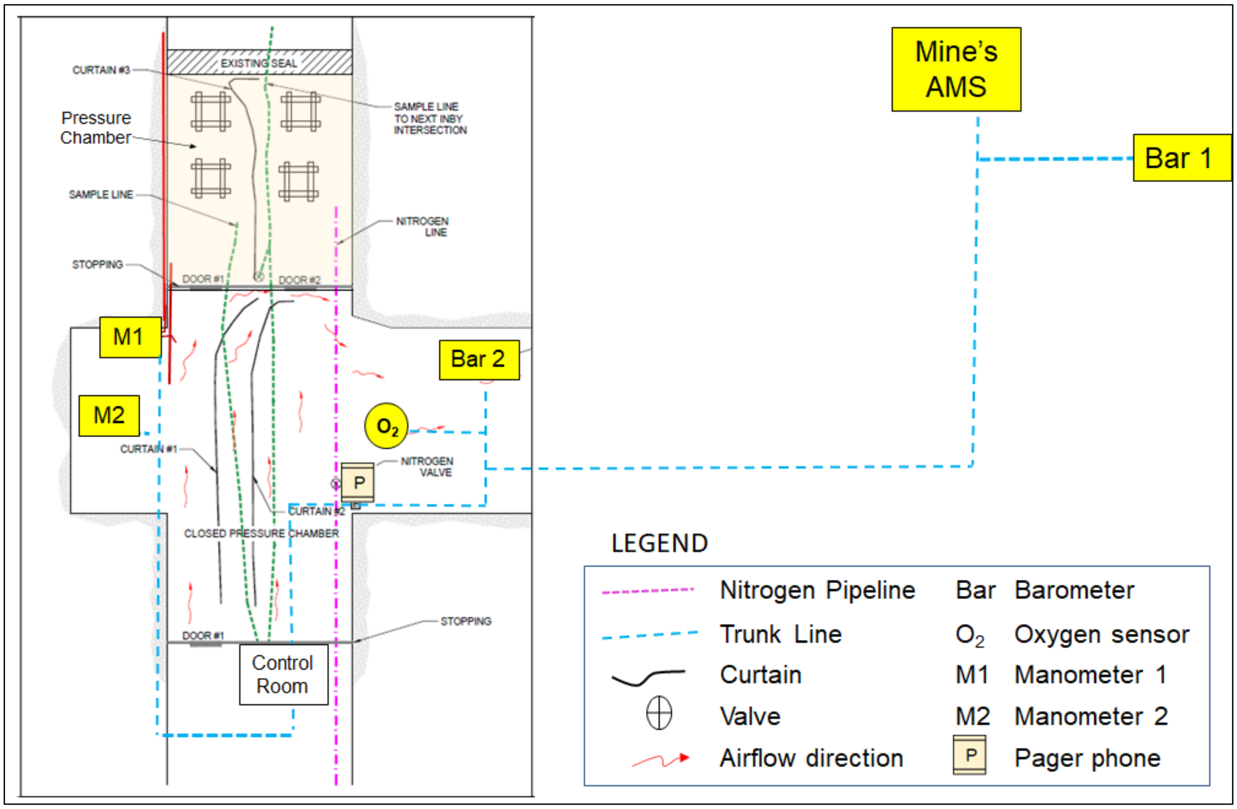


Figure 11: Schematic showing the West Elk mine's AMS and transducers used to monitor ventilation parameters near the 1st pressure chamber.

During the test, the data collected by the West Elk Mine's Atmospheric Monitoring System was transferred to a dedicated server located at the Mining Engineering Department of the University of Utah. This was possible through a Virtual Private Network (VPN) established through an agreement between MCC and the University of Utah. This system enabled us to collect and process the field data, generate trends, and return our findings to the mine. The parameters of interest were mainly the barometric pressure (surface and underground), pressure differentials across the chamber walls (seal and stopping), and oxygen concentrations on the downwind side of the chamber.

Figure 12 includes two pictures depicting the ventilation sensors used at the West Elk mine's AMS. In addition, Figure 12a shows three pressure transducers: two to monitor pressure differentials across the chamber walls, and one for atmospheric pressure. This figure also shows the tee fittings and valves that were installed on each sampling tube to provide additional ports for hand-held instruments. Figure 12b shows an oxygen sensor, installed near the work area to monitor the quality of air.

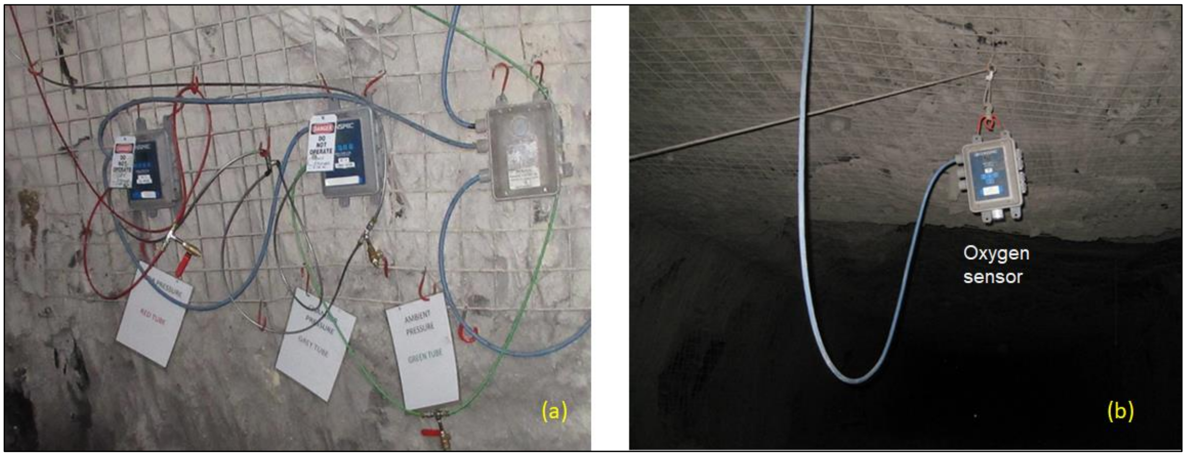


Figure 12: Ventilation sensors used at the West Elk mine's AMS: (a) Pressure differential transducers and barometer, (b) Oxygen sensor and data transmission lines.

In addition to the CONSPEC-compatible sensors purchased for the West Elk mine's AMS, we also purchased hand-held instruments equipped with data loggers. These include the following:

- Two portable 5825 DP-Cal TSI micro-manometers equipped with data loggers and software.
- Two ACR Smart-Reader (actual pressure) barometers equipped with data loggers and external sensors (barometric pressure, temperatures, and relative humidity)
- Software on US & USB interface cable for SRP data loggers
- Ventis MX4 (diffuser type) multi-gas measuring unit.
- A laptop computer to collect and process the data.

These monitors were used to cross-check the outputs generated by the West Elk mine's monitoring system and to collect field data from remote locations continuously.

4.3.5 Procedure to Operate the Pressure Chamber

This procedure includes steps to operate a pressure chamber and to determine the effect of pressure changes on the flow of air into the mine gob.

Note: Schematic of the nitrogen injection system for the 2nd chamber and a flowchart showing the operation of the pressure chamber is provided in Appendix A.

Pre-operation

a) Notify the mine AMS operator that you are in the test area.
b) Post "Do Not Enter" warning signs one cross-cut upwind and one cross-cut downwind of the pressure chamber.
c) Conduct a visual inspection of the chamber and measure airflow rates. Check operating conditions of doors, locks, nitrogen flow control valves, pressure sensors, etc.
d) Notify the AMS operator that the safety doors are closed and you are out of the chamber, in the control room.
e) Notify the AMS operator if any abnormal conditions are detected.

Operation (from control center)

The procedure includes the following steps:

a) Monitor and evaluate the pressure differentials across the permanent isolation seal and Kennedy stopping (P_3-P_2 and P_2-P_1, as shown in Figure 10).

b) Inject nitrogen into the chamber when ($P_3 – P_2$) is greater than 0.0 in. wg. This will avoid the egress of explosive gases from the gob to the face (outgassing condition).

c) Inject nitrogen into the chamber when the pressure difference across the stopping ($P_2 – P_1$) is less than 0.0 in. wg. This will avoid the leakage of ventilation air to the gob (in-gassing condition).

d) Stop nitrogen injection into the chamber when the pressure difference across the Kennedy stopping ($P_2 – P_1$) is greater than 4 in. wg (1,000 Pa). See Appendix A for details.

Post Operation

After the test or during seal inspection, notify the AMS operator that the nitrogen control valves are closed, the safety doors are opened, and you are in the control room processing the field data. The safety doors are open and the curtains extended to purge the enclosed area and to allow the MSHA or mine personnel to complete the weekly examination of the seals.

Data Analysis

a) The data collected by the mine's AMS is in ASCI format. Transfer the selected data to a PC and convert it into an Excel data file.

b) The Excel file contains several columns: the first is the sampling time in minutes, the second is the barometric pressure (surface) in inch-mercury, the third is the air temperature in ^{0}F, the fourth is the pressure differential across the seal in inch-water, etc. Convert them into engineering (SI) units: barometric pressure in kPa, differential pressure in Pa, etc.

c) Plot the barometric pressure and air temperature (surface and underground) vs. time series, and interpret their effect of pressure changes on the air flow across the chamber.

d) Plot differential pressures across the seal and stopping vs. time and determine the effect of nitrogen injection into the chamber on the leakage flow direction.

In a mine ventilated by a blower fan, such as at the West Elk mine, a negative pressure difference across the isolation seal ($P_3 – P_2 < 0$) means that the ventilation air is flowing to the gob through or around the seal. This is an "in-gassing" condition. This may be sufficient to start the self-heating of coal. The risk can be reduced by injecting pressurized nitrogen into the chamber. Conversely, when the pressure difference across the seal is positive ($P_3 – P_2 > 0$), it means an egress of explosive gases from the gob to the workings. Again, this can be controlled by injecting pressurized nitrogen into the chamber.

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 and a set of monitors, pressurized nitrogen was injected into the chamber and the pressure differentials across the stoppings and seals were monitored.

Figure 9 includes two photos of the nitrogen injection system connected to the pressure chamber. The system consists of a 2-in-diameter pipeline and a set of flow control devices. In the 1st chamber, the system included two flow control valves (V1 and V2), two regulators (R1 and R2), and three pressure gases (G1, G2 and G3). However, for practical reasons, one regulator (R2) and one pressure gage (G3) were removed in the 2nd chamber.

During each test, nitrogen flow rate and pressure differentials across the seal and stopping were monitored continuously. While the seals held high-pressure differentials effectively, the stoppings did not, particularly in the 1st chamber. To overcome the problem, the Kennedy stopping was reinforced by applying additional sealant material between the panels and around the access doors. This reduced the leakage but was not sufficient to hold pressure differentials greater than 2 in. wg mainly because of gas leakage through the cracks and fissures of the natural rock surrounding the chamber. Lessons learned from the 1st chamber were applied in the construction, testing and monitoring of the 2nd chamber. Major changes included selecting a more stable site for the pressure chamber, away from the nearest intersection, and modifying the design of the access door to swing against the frame when the door is closed.

5.1 Tests on the 1st Chamber

Several climate conditions and pressure differential tests were conducted on the 1st chamber. Initially, tests were performed to investigate the effect of barometric pressure variations on the pressure chamber, then, the chamber was filled with pressurized nitrogen and evaluated for gas leakage through the Kennedy stopping. The mine's AMS was used to collect the data which was then transferred to the Mining Engineering Department, University of Utah through a Private Virtual Network (PVN) for processing and data interpretation.

When a fixed flow rate of nitrogen was injected into the chamber, the pressure differentials across the chamber walls (e.g., stopping and seal) increased to a higher level rapidly and remained constant as a steady flow of nitrogen was maintained. When the gas flow was shut off, the chamber pressure dropped to its initial level quickly. This was mainly due to leakage through the access doors, fissures, and cracks (back and rib) around the Kennedy stopping. The stopping was repaired and sealed and the tests were repeated.

The results of three experiments (test 1, test 2, and test 3) are presented below.

5.1.1 Test 1 - The Effect of Surface Air Temperature on Atmospheric Pressure

This test was conducted to determine the effect of changes in surface air temperature on the barometric pressure and pressure differentials across the chamber's walls. The field data was collected using the mine's AMS for seven days (August 29, September 4, 2021).

The parameters monitored were: barometric pressure, air temperature, and associated pressure differentials. Figure 13 shows that the barometric pressure changes with surface air temperature on a daily basis. A quick evaluation of these graphs shows that these changes are significant and inversely related. For example, on Day 3 (August 31, highlighted area), the barometer reached a maximum of 30.15 in. Hg, when the surface temperature was 47 ^{0}F at 8 AM, and dropped to a minimum of 29.95 in. Hg when the temperature was 93 ^{0}F at 6 PM. In addition, these changes in barometric pressure significantly affected the pressure differentials across the chamber's walls.

Figure 14 shows that for a blower fan system (such as the one used at the West Elk mine), a drop in barometric pressure on the surface decreased the pressure differential across the seal (P_3-P_2 < 0), causing an in-gassing condition.

For example, on August 31 (Day 3), a drop of 0.20 in. Hg (2.72 in. wg) in barometric pressure, resulted in a decrease of ΔP = -2.4 in. wg across the seal. This figure does not show significant variations in the pressure differentials across the Kennedy stopping because during this period the personnel access doors were not kept fully closed after a seal inspection.

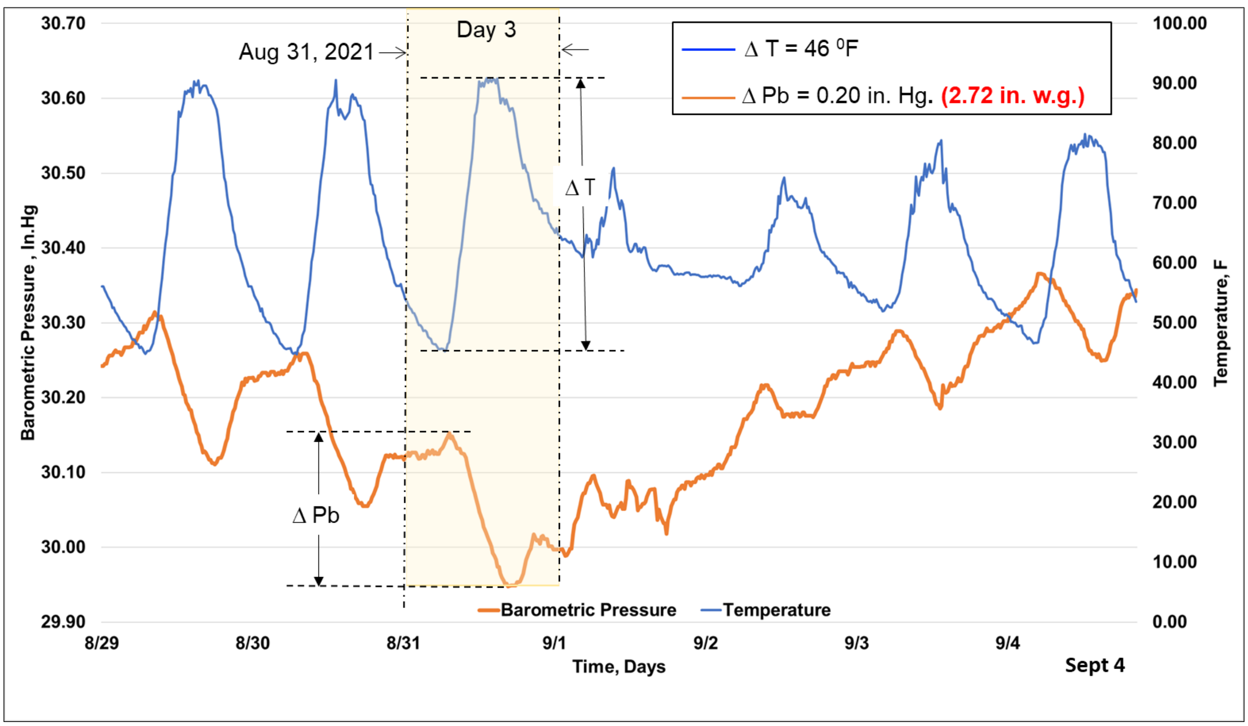


Figure 13: Variation of standardized surface barometric pressure as a function of changes in temperature - August 29 to September 4, 2021.

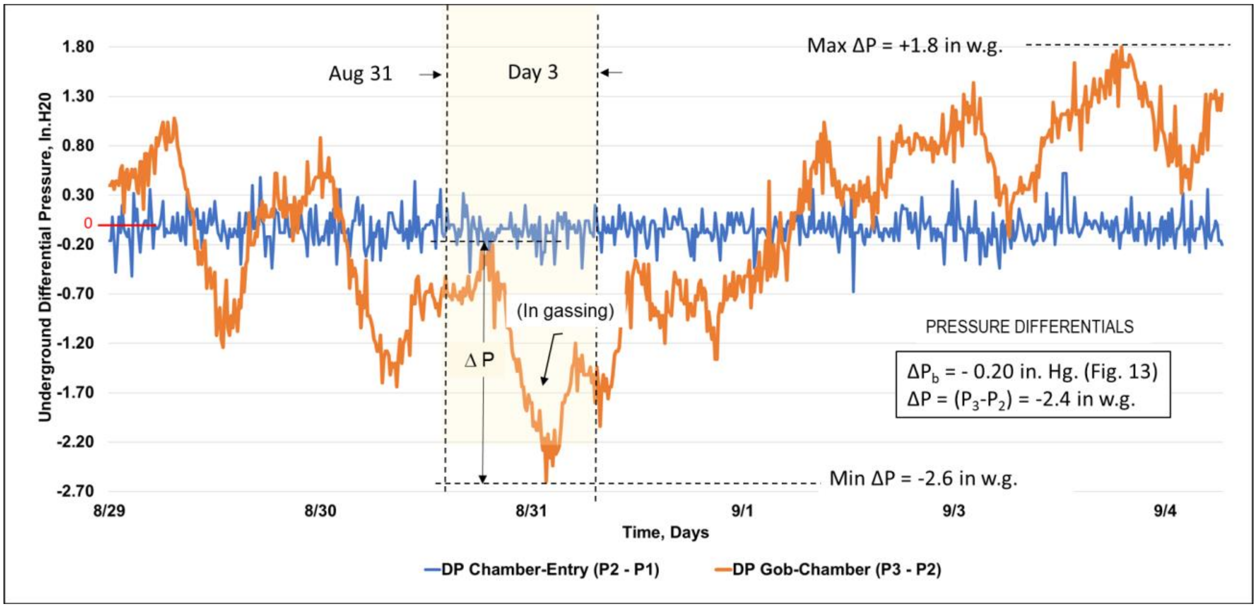


Figure 14: The effect of barometric pressure variation on the differential pressures across the chamber stopping and seal – August 29 to September 4, 2021.

5.1.2 Test 2 - 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 15 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 a digital barometer, located on the surface at the West Elk mine's main office. 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 P_3-P_2 in Figure 10), and another between the chamber and the entry (Stopping DP or P_2-P_1). In Figure 15, the orange line represents the pressure differentials across the seal (P_3-P_2), and the blue line the pressure changes across the stopping (P_2-P_1). A quick evaluation of these graphs shows that the barometric pressure and temperature are inversely related and vary on a daily basis with changes in air temperature. These variations affect both pressure differentials across the chamber's stopping and seal.

For example, on September 22, as shown in Figure 15, the barometric pressure varied between a maximum of 30.6 in. Hg. at about 5 AM and a minimum of 30.3 in. Hg. at 4 PM (a 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. w.g). 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 (P_3-P_2) increases to even become positive (P_3-P_2>0), causing an out-gassing condition (see highlighted areas in Figure 15). On the contrary, when the barometric pressure on the surface decreases, the differential pressure across the seal (P_3-P_2<0) becomes negative, creating an in-gassing condition.

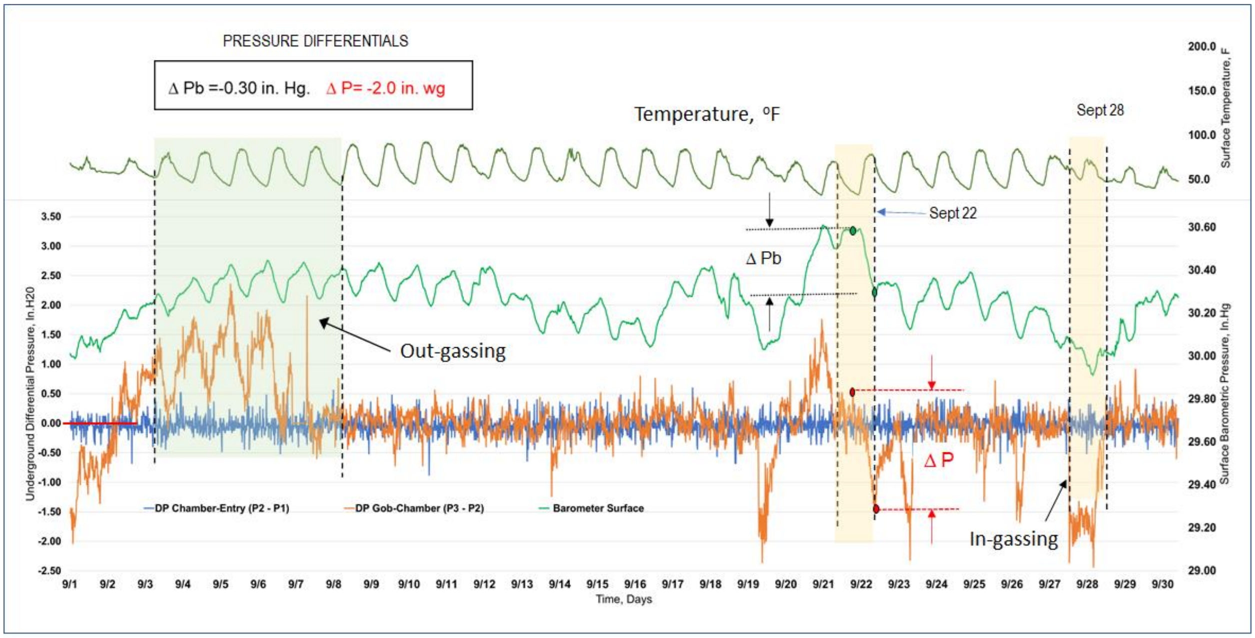


Figure 15: Effect of barometric pressure on chamber walls (isolation seal and stopping).

5.1.3 Test 3 - 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 condition, the personnel doors were closed and locked, the nitrogen flow control valves opened, and the chamber tested for different gas flow rates. The test started on December 2, 2021, at approximately 9:07 AM. The control valves V1 and V2 (Figure 10a) were opened, and the regulators R1 and R2 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 close vicinity of the stopping (in the access cross cut), dropped to less than 19.5%.

Figure 16 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 16), 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 flow regulator was opened, the pressure differential (P_3 -P_2) decreased from 0.2 in. wg (outgassing condition) to -3.48 in. wg (in-gassing), yielding a combined pressure change of ΔP = -3.68 in. wg. During the time period highlighted in Figure 16, the ΔP across the stopping (P_2-P_1) fluctuated between -0.40 and +0.35 in. wg. Figure 16 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.

Figure 16 provides important information on how the changes in barometric pressure affect the pressure differentials across the chamber walls. While the permanent seal is robust and durable, the Kennedy stopping still requires some additional reinforcement work to withstand high-pressure differentials.

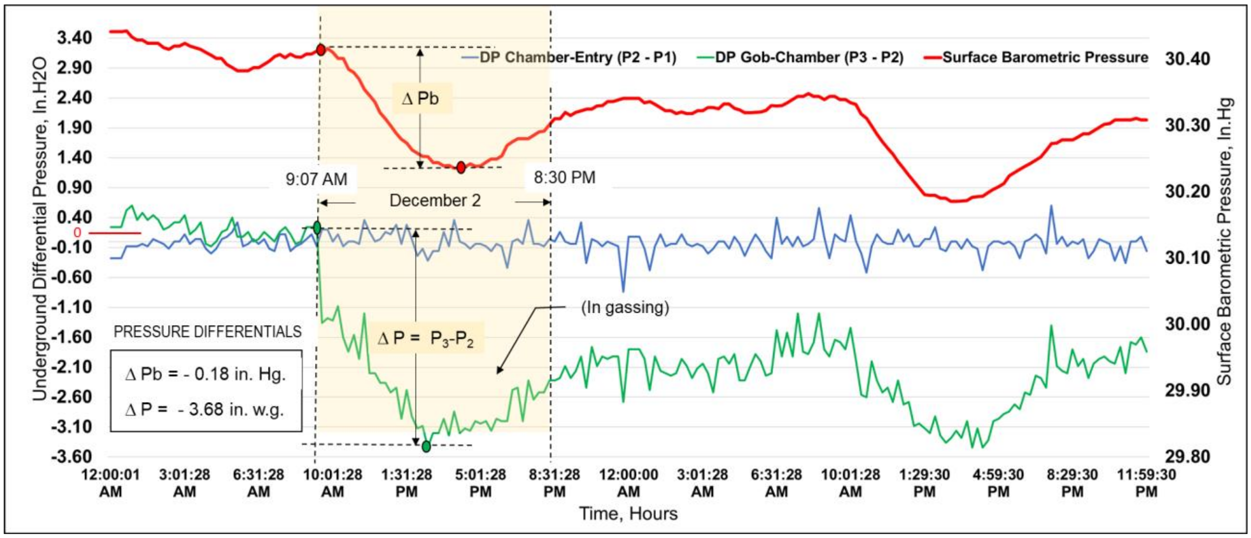


Figure 16: Pressure differential series after nitrogen gas injection (December 2-3, 2021)

The above results showed that nitrogen leakage through the Kennedy stopping was the main problem. Initially, when the chamber was pressurized, the stopping was unable to hold pressure differentials greater than 1 in. wg. Then, the stopping was reinforced and sealant foam was applied between the panels on the high-pressure side of the stopping and tested again. This has improved the ability of the stopping to hold pressure differential up to 3 in. wg. At this point, it was noticed that the leakage was mainly through the coal fissures and cracks around the stopping. To overcome this problem, it is recommended to install the chamber on stable ground, deep inside the crosscut, and away from the nearest intersection.

5.2 Tests on the 2nd Chamber

Three pressure balancing tests were conducted on the 2nd chamber: two with the personnel doors installed to open toward the fresh air side, and one with the doors reversed to open toward the chamber in order to minimize the leakage when the doors are closed. The first two tests were conducted between August 9 and 10, 2022, and the last on June 7, 2023. In each case, hand-held micromanometers and barometers were used to collect the data.

A test started by closing and locking the personnel doors, opening the nitrogen flow control valves, V1 and V2, and changing the flow rate by means of regulator R1 (Figure 10b). Initially, valves V1 and V2 were open to full pressure, and the opening of the regulator R1 varied by adjusting a control knob in steps of ½ turn and monitoring two pressure gages. This allowed us to pressurize the chamber and monitor the pressure differentials. The results of each test are presented below.

5.2.1 Test 1 - August 9, 2022

Prior to starting the test, the pressure chamber was inspected for safe conditions, the nitrogen injection control valves checked, the flow control regulator set to allow for a very low flow rate, the hand-held manometers attached to the mine's AMS, and the personnel doors closed and locked to isolate the chamber from the surrounding mine entries. The test started by opening the pressure control valves V1 and V2 and fixing the gas flow rate to a minimum value by means of regulator R1. This was followed by recording pressure differential across the stopping and seal and monitoring for nitrogen gas leakage into the surrounding area. The process was repeated for different gas flow rates. The test was immediately stopped when the nitrogen gas leakage from the chamber reduced the oxygen level within close vicinity of the Kennedy stopping to less than 19.5%.

Chronology of Events – August 9, 2022

11:25 AM. For regulator R1 set to allow a minimum flow, Valves V1 and V2 were open, pressure gages displayed: G1 = 58 psi, and G2 = 0. Differential pressure across the stopping DP_{2-1} was 0.17 in. wg.

11:30 AM. Regulator position was increased by ½ turn. Pressure gages displayed: G1 = 56 psi, and G2 = 3 psi. Differential pressure, DP_{2-1} = 0.97 in. wg.

11:37 AM. Regulator position increased by another ½ turn. Gage pressures were: G1 = 53 psi, and G2 = 3 psi, and the differential pressure, DP_{2-1} = 1.97 in. wg.

11:41 AM. Regulator position increased by another ½ turn. Gage pressures monitored: G1 = 55 psi, and G2 = 5 psi, and differential pressure, DP_{2-1} = 2.52 in. wg.

11:42 AM. Regulator position increased by ½ turn. Gage pressures monitored: G1 = 49 psi, G2 = 4 psi, and the differential pressure, DP_{2-1} = 3.23 in. wg.

11:45 AM. Significant leakage of nitrogen through door gaskets were detected. The nitrogen control valves were shut off. It took approximately 20 seconds to depressurize the chamber.

Note: As previously mentioned, after closing the access doors on the Kennedy stopping, barometric pressure measurements were manually taken within the entry area of the pressure chamber. From this point forward, for each test, differential pressure measurements only were performed across the stopping (chamber-entry, or P_2-P_1) and across the seal (gob-chamber, or P_3-P_2).

Figure 17 shows two actual barometric pressure variations (surface and underground), and two pressure differentials across the stopping ($\triangle P_2$-P_1) and another across the seal ($\triangle P_3$-P_2). Notice that when the gas flow rate increased, the pressure differentials across the seal and stopping increased rapidly and remained fairly constant thereafter, indicating that both walls can hold pressurized nitrogen with reduced leakage when nitrogen supply is continuous.

Table 1 summarizes the differential pressures across the chamber walls.

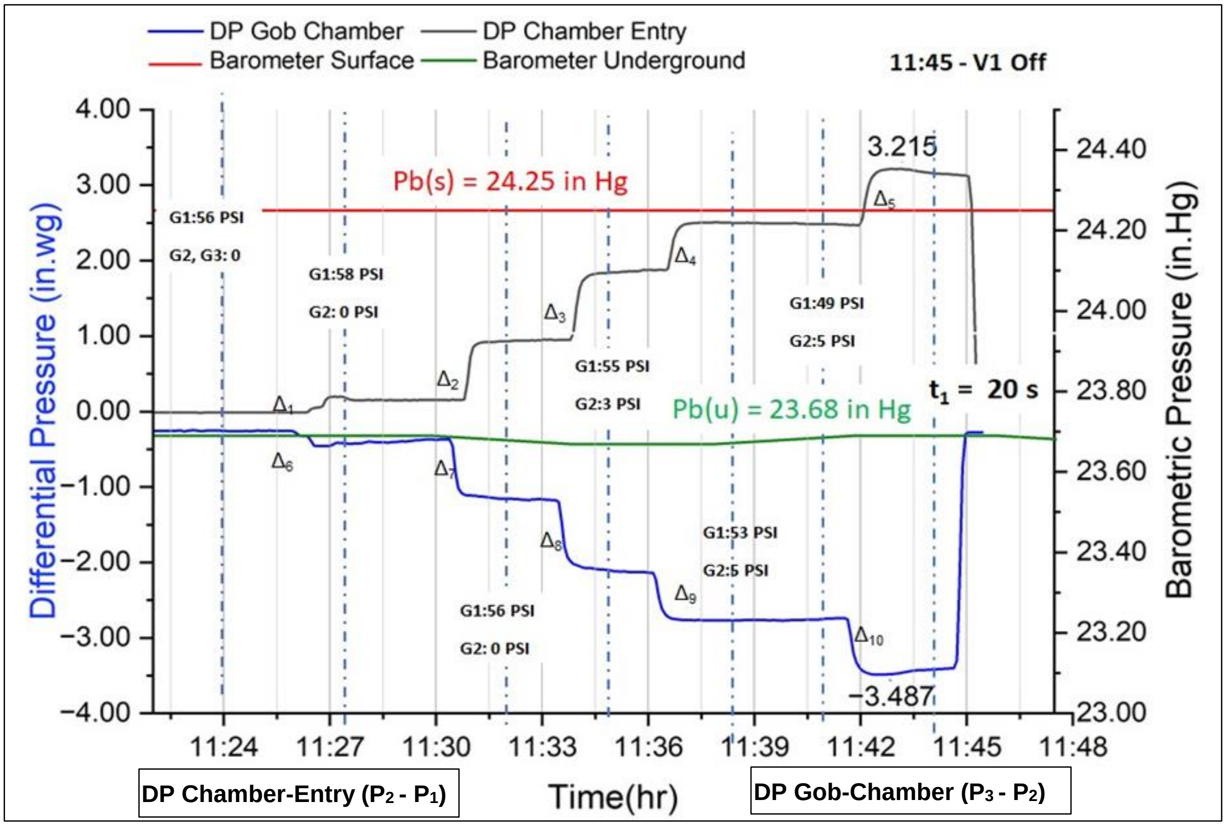


Figure 17: Pressure differentials across the chamber stopping and seal - Test 1

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

Chamber - Entry Gage Pressure (DP_{2-1})	Average DP_{2-1}		Gob - Chamber Gage Pressure (DP_{3-2})	Average DP_{3-2}	
	Pa	in. wg		Pa	in. wg
Δ1	42	0.17	Δ6	-51	-0.20
Δ2	241	0.97	Δ7	-229	-0.92
Δ3	471	1.89	Δ8	-467	-1.88
Δ4	628	2.52	Δ9	-624	-2.51
Δ5	804	3.23	Δ10	-805	-3.23

5.2.2 Test 2 - August 10, 2022

After a quick evaluation of the results of Test 1, the chamber walls, perimeter, and doors were checked for leakage. Leaks were found around both personnel access doors and near the right side of the chamber. The problem was fixed by sealing up the leakage paths and making the Kennedy stopping to withstand higher pressures. Following a visual inspection of the chamber and the nitrogen gas injection system, the access doors were closed and locked, and the 2nd test started on August 10. As in the previous case, the chamber was pressurized in steps by changing the regulator setting and stopped when significant nitrogen leakage through the stopping was detected. The highlights of these tests are presented below.

Chronology of Events – August 10, 2022

12:15 PM. For regulator R1 set to allow a minimum flow (½ turn open), Valves V1 and V2 were open, and pressure gages displayed: G1 = 54 psi, and G2 = 0. Differential pressure across the stopping DP_{2-1} was 0.13 in. wg.

12:17 PM. Regulator position was increased by a full turn, pressure gages displayed: G1 = 52 psi, and G2 = 3 psi. Differential pressure, DP_{2-1} = 2.58 in. wg

12:22 PM. Regulator position increased by ½ turn. Gage pressures were: G1 = 52 psi, and G2 = 3 psi, and the differential pressure, DP_{2-1} = 4.87 in. wg.

12:27 PM. Regulator position was increased by ½ turn. Pressure gages recorded: G1 = 50 psi, and G2 = 3 psi. Differential pressure, DP_{2-1} = 6.24 in. wg.

12:29 PM. Significant leakage of nitrogen through door gaskets was detected. The nitrogen control valves were shut off. It took approximately 57 seconds to depressurize the chamber.

Figure 18 shows barometric pressures and pressure differentials across the stopping and seal during the test. Notice a slight decline when the differential pressure across the stopping reached 6.41 in wg.

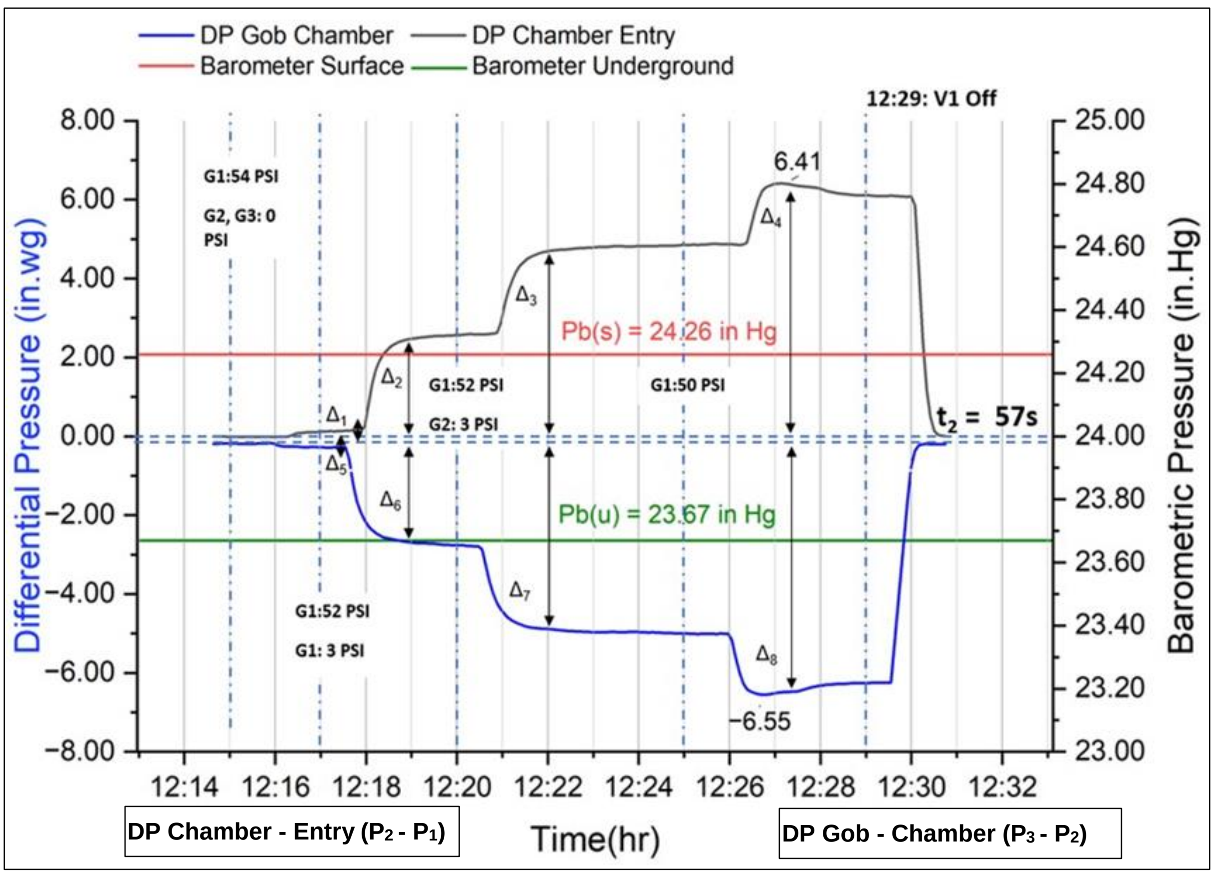


Figure 18: Pressure Differentials across the chamber stooping and seal - Test 2.

Table 2 shows the differential pressures between the chamber-entry (P_2-P_1) and Gob-chamber (P_3-P_2).

Table 2 – Pressure differentials across the chamber stopping and seal – Test 2

Chamber - Entry Gage Pressure (DP_{2-1})	Average DP_{2-1}		Gob - Chamber Gage Pressure (DP_{3-2})	Average DP_{3-2}	
	Pa	in. wg		Pa	in. wg
Δ1	33	0.13	Δ5	-26	-0.10
Δ2	641	2.58	Δ6	-643	-2.58
Δ3	1,212	4.87	Δ7	-1,200	-4.82
Δ4	1,600	6.42	Δ8	-1,586	-6.37

The above results show that the balance chamber will hold pressurized nitrogen as long as a steady flow of nitrogen gas is supplied to the chamber. Because of gas leakage through the personnel doors and fractured coal, the chamber was not able to hold pressurized nitrogen for a long time. In test 1, when the flow control valves were shut off, it took only 20 seconds to depressurize the chamber. When the leakage points were fixed for test 2, it took approximately 57 seconds for the chamber to depressurize.

To improve the quality of the stopping and to reduce leakage, it is recommended to *reverse the position of the access doors* so that the door gaskets are compressed when the chamber is pressurized.

5.2.3 Test 3 - June 7, 2023

It is mentioned that before each pressurized test, the barometric pressure at the entry (BP_{entry}) and in the chamber ($BP_{chamber}$) was manually measured with a portable barometer (e.g., Mensor CPG 2300). These manual BP measurements were performed in addition to continuous BP monitoring on the surface and underground.

For example, during Test 3 performed on June 7, 2023, with the access doors on the Kennedy stopping wide open, the barometric pressure in front of the chamber was measured at BP_{entry} = 78,675 Pa (23.24 in. Hg), while the barometric pressure in the chamber was measured at $BP_{chamber}$ = 78,674 Pa (23.23 in. Hg). When testing started, the access doors on the Kennedy stopping were closed and nitrogen was injected in the chamber gradually by turning the pressure valve on the camber side (V2) ½ turn (180 degrees) at a time. From this point the pressure differential between the chamber and entry (P_2-P_1) and between the gob and chamber (P_3-P_2) was measured using a hand-held differential pressure unit (e.g., TSI 5825).

Note: During testing, while barometric pressure measurements were still collected at the entry (BP_{entry}), no barometric pressure measurements were taken in the pressure chamber ($BP_{chamber}$) and gob (BP_{gob}).

Initially, the 2nd pressure chamber was established by installing a Kennedy stopping in the "*E Seam, Sunset 1 Headgate*", at about 3m (10 ft) in front of an MSHA-approved mine seal. The same MSHA-approved plan of the 1st chamber was used to construct and equip this chamber. When the chamber was pressurized to about 5.0 to 6.0 in. wg., leakage through the stopping started to became a problem. This was due in part to the installation of the access doors.

With respect to this problem, it is important to mention that in the original plan, the access doors were assembled so that the doors would open outward, toward the entry. Under these conditions, the door gaskets are not in compression when the chamber is pressurized with nitrogen.

To overcome this problem, the position of the doors had to be reversed. This required a new MSHA-approved plan. MSHA's main concern was that if the door opens inward, a miner, or maintenance person who is opening the door, may be exposed to an oxygen-deficient atmosphere. To address this issue and reduce leakage, for the second part of the test, a "*bolt-on*" rod assembly was added to operate the access doors. Using this mechanism, the access doors would always be in compression when the chamber is pressurized.

Figure 19 includes two photos highlighting the "*bolt-on*" rod mechanism that was added to the chamber design.

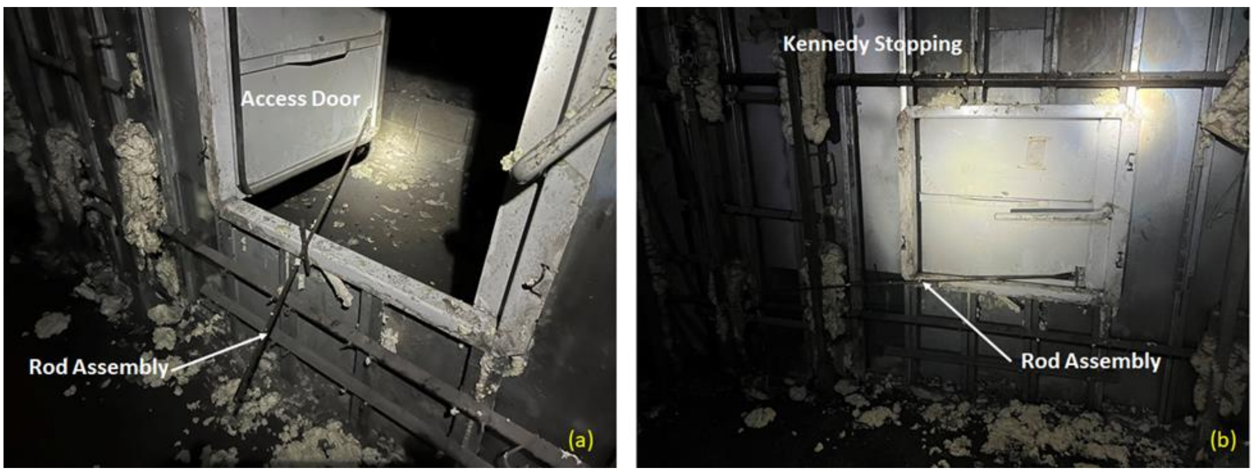


Figure 19: Access doors assembled to open onto high-pressure side: (a) door open, (b) door closed.

Once the new plan was approved and the modifications to the stopping and doors were completed, the chamber was tested on June 7, 2023.

Initially, the chamber was pressurized so that the gage pressure across the stopping reached 1.0 in. wg Then, the chamber was inspected for unsafe conditions. Having found it to be in good standing, the gas pressure was increased by adjusting a regulator knob in steps of ½ turns to reach 5.9 in. wg between the chamber and entry (P_2-P_1) and 6.1 in. wg between the chamber and the gob (P_3-P_2), respectively.

With the access door reversed, leakage of nitrogen around the doors was reduced to a level that was not detectable with a "Ventis MX4" four-gas detector, which was used to detect low oxygen concentrations.

Table 3 shows the differential pressures between chamber - entry (P_2-P_1) and gob - chamber (P_3-P_2).

Table 3: Pressure differentials across the stopping (P_2-P_1) and seal (P_3-P_2)

Chamber-Entry Gage Pressure (DP_{2-1})	Average DP_{2-1}		Chamber-Entry Gage Pressure (DP_{3-2})	Average DP_{3-2}	
	Pa	in. wg		Pa	in. wg
Δ1	224	0.90	Δ6	-272	-1.09
Δ2	676	2.72	Δ7	-895	-3.60
Δ3	902	3.62	Δ8	-951	-3.82
Δ4	1,165	4.68	Δ9	-1,185	-4.76
Δ5	1,371	5.51	Δ10	-1,412	-5.68
Δ6	1,506	6.05	Δ11	-1,553	-6.24

Figure 20 shows the differential pressures between the chamber and entry (P_2-P_1) and between the gob and chamber (P_3-P_2) as nitrogen is injected into the chamber. Notice a slight decline when the differential pressure between chamber-entry and gob-chamber reached 6.07 in. wg and -6.24 in. wg, respectively.

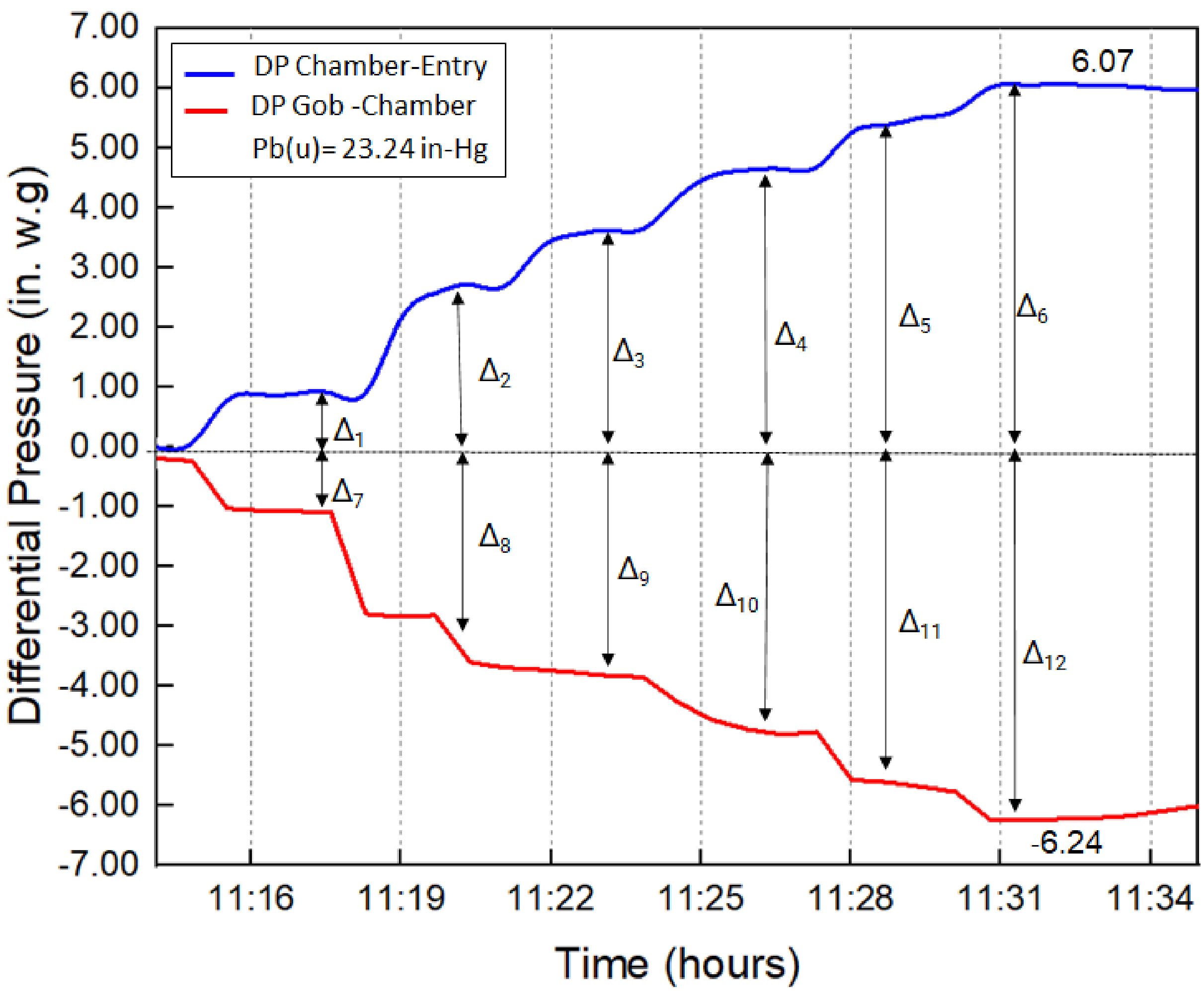


Figure 20: Pressure differentials across the stopping (P_2-P_1) and seal (P_3-P_2)

The following facts were observed during the test:

- Nitrogen gas was injected into the chamber in steps by means of a Parker Model 21U844 regulator. The gas flow rate increased from 20 cfm to 80 cfm.
- The pressure buildup in the chamber was a function of the regulator opening and increased more rapidly compared to the previous tests.
- Within 13 minutes from the start of the test, the differential pressure across the Kennedy stopping (ΔP_{2-1}), (see Figure 10b) increased from 0.00 to 5.96 in. wg.
- During the same time, the differential pressure across the seal (ΔP_{3-2}), (see Figure 10b) decreased from 0.00 in. wg to -6.08 in. wg, as the pressure in the chamber (P_2) compared to the pressure in the gob (P_3) increased.
- When the regulator was completely turned off, the chamber depressurized within 72 seconds.
- When the chamber was pressurized to about 5-6 in. wg, nitrogen started leaking into the ambient more through the chamber's hairline fissures (rib & back) rather than the Kennedy stopping.

6. Research Findings and Accomplishments

6.1 Research Findings from Tests on the 1st Chamber

- Measurements performed on the 1st chamber showed that nitrogen leakage through the Kennedy stopping was the main problem. Initially, when the chamber was pressurized, the stopping was unable to hold pressure differentials greater than 1 in. wg Then, the stopping was reinforced and sealant foam was applied between the panels on the high-pressure side of the stopping and tested again. This has improved the ability of the stopping to hold pressure differential for up to 3 in. wg. At this point, it was noticed that the leakage was mainly through the coal fissures and cracks around the stopping. To overcome this problem, it was agreed to install the chamber on stable ground, deep inside the crosscut, and away from the nearest intersection.
- Figure 14 shows that for a forcing ventilation system (blower fan) such as the one used at the West Elk mine, barometric pressure variation on the surface significantly influenced the differential pressure (P_3-P_2) across the seal. When the barometric pressure on the surface decreased, the differential pressure across the seal (P_3-P_2) decreased to even become negative ($P_3-P_2< 0$), causing an in-gassing condition.
- Figure 15 also shows that the pressure differentials across the permanent seal are directly related to changes in barometric pressure on the surface. When the barometric pressure on the surface increases, the pressure differential across the seal (P_3-P_2) also increases to even become positive ($P_3-P_2>0$), causing an out-gassing condition (see highlighted area in Figure 15).

6.2 Research Findings from Test #1 on the 2nd Chamber

- Figure 17 shows two pressure differentials, one across the stopping ($\triangle P_2$-P_1) and another one across the seal ($\triangle P_3$-P_2). When the nitrogen flow rate increased, the pressure differentials across the stopping increased an those across the seal decreased rapidly and to remain fairly constant thereafter. This indicates that when the nitrogen supply is continuous, both chamber's walls, stopping and seal, can hold pressurized nitrogen for low pressure differentials (up to ± 2.50 in. wg).

6.3 Research Findings from Test #2 on the 2nd Chamber

- Test results show that the chamber is able to hold pressurized nitrogen as long as a low-pressure steady flow of nitrogen gas is supplied to the chamber. Because of nitrogen leakage through the access doors and fractured coal, the chamber was not able to hold pressurized nitrogen for a long time.
- To improve the quality of the stopping and to reduce leakage, it was recommended to reverse the position of the access doors so that the door gaskets are compressed when the chamber is pressurized.

6.4 Research Findings from Test #3 on the 2nd Chamber

- Site selection for establishing the chamber is very important to reduce leakage. The chamber stopping must be constructed on solid ground, deep inside the crosscut, and away from the nearest intersection. In this case, the stopping was constructed at about 3m (10 ft) from a permanent mine seal and 8.5m (28 ft) from the nearest intersection.
- To further reduce leakage, the stopping must be reinforced and sealed from both sides and equipped with two access doors that would swing the door leaf into the chamber using the "bolt-on" rod assembly when the door is open and against the frame when the door is closed. Under these conditions, the positive pressure created in the chamber when nitrogen is injected will push outward on the doors, thus minimizing leakage.
- During Test 1, when the flow control valves were shut off, it took only 20 seconds to depressurize the chamber. During Test 2, when the leakage points were closed using foam sealant, it took approximately 57 seconds to depressurize the chamber. During Test 3, with the access doors revered, it took approximately 72 seconds to depressurize the chamber.
- With the access doors opening inward (toward the chamber), when the chamber was pressurized to 5-6 in. wg, leakage around the doors was reduced to a level that was not detectable with a four-gas detector that is used to detect low oxygen concentrations. Nitrogen leaked into the ambient more through the chamber's hairline fissures (rib & back) rather than the Kennedy stopping.
- Based on the pressure differentials recorded at the West Elk mine, calculations show that a constant nitrogen flow rate of $Q_n \cong 0.02$ m^3/s (40 cfm) at approximately 20.6 kPa (3.0 psi) at the discharge end of the regulator (regulator knob at ½ turn) would be sufficient to maintain a constant positive pressure in the chamber of greater than 0.36 in. wg, thus avoiding "in-gassing" and "out-gassing" conditions.

7. Publication Record and Dissemination Efforts

7.1 Papers and Presentations

To date, the following papers, thesis, and presentations have been delivered to the mining community through conferences, symposiums and workshops on topics describing the outcomes of this project:

1) Kocsis C., Calizaya F., Johnson J., Dias T., Nunes N., Lindgren E., Atchley G., and Poulos J. 2023. Application of Pressure Balancing Techniques at the West Elk Coal Mine. *Proceedings of the 19th North American Mine Ventilation Symposium*. South Dakota School of Mines & Technology, Rapid City, South Dakota: 411-420.
2) Kocsis C., Calizaya F., Johnson J., Dias T., and Nunes N. 2024. Pressure Balancing Tests at a Colorado Coal Mine. *To be presented at SME 2024*, Phoenix.

7.2 Graduate Students

Two international graduate students were engaged in this research project: Natanna Nunes (MS Program), and Tulio Dias (Ph.D. Program).

Natanna Nunes, MS Thesis Title: "*Application of Pressure Balancing Techniques at a Western U.S. Coal Mine*".

This work describes pressure chamber construction details, instrumentation and monitoring of pressure balancing tests performed at the West Elk mine. Pressure differentials across the chamber stopping and seal were monitored using both the mine's AMS and hand-held barometers and micromanometers equipped with data logger. On November 9, 2023, Mrs. Nunes defended her thesis successfully. Her thesis has been approved by all members of her thesis committee subject to addressing comments and recommendations. Currently, she is working on corrections before submitting her thesis to the Graduate School of the University of Utah.

Tulio Dias (Ph.D. Program) was involved in processing all ventilation and mine climate data that was transferred during this research project from the mine site to the Mining Engineering Department, University of Utah through a Virtual Private Network (VPR). In addition, Mr. Dias developed a graphic user interface (GUI) and an automated control system (ACS) using process logic controllers (PLCs) to manage nitrogen distribution to the pressure chamber (see Appendix B – Automated Nitrogen Injection System).

8. Conclusions and Impact Statement

- Barometric pressure at the West Elk mine changes on a daily bases as a function of changes in surface air temperature. Measurements showed that these two variables are inversely related. Depending on the weather conditions, changes in barometric pressure can be large enough to change the leakage flow direction of the mine air and explosive gases across the seals.
- West Elk mine uses MSHA-approved 120 psi seals to isolate the gob. These seals are not fully airtight. Depending on the weather conditions, they will allow some ingress of fresh air into the gob (in gassing condition) or egress of explosive gases into the work environment (outgassing condition). For example, when a seal was evaluated for leakage on August 31, 2021, it was observed that a decrease of 0.20

in. Hg (2.72 in. wg) in barometric pressure, resulted in a decrease in pressure differential across the seal (P_3-P_2) of -2.4 in. wg ($\triangle$P deceased from -0.2 in. wg to -2.6 in. wg) creating an in-gassing condition (see Figure 14).

- As part of this research, two pressure chambers were established at the West Elk mine: one at the "*B Seam Box Canyon 32 North*", in a mined-out area, and another at the "*Sunset 1 Headgate, 2E*" crosscut, near an active longwall panel. In both cases, Kennedy stoppings were installed to establish the pressure chambers. When the chambers were pressurized with nitrogen, leakage through the stopping became a problem, particularly in the 1st chamber.
- The 1st chamber was established by constructing a stopping at about 10 ft. from a permanent stopping but only 3 ft. away from the nearest access intersection (e.g. pillar corner). When the chamber was pressurized, leakage through the stopping became a problem. To overcome this, the stopping was reinforced and sealed from both sides. This reduced the leakage, but this was not sufficient to hold pressure differentials greater than 3 in. wg. This was mainly due to nitrogen leaking through the naturally fractured coal surrounding the stopping.
- Based on the lessons learned from the construction of the 1st chamber, the stopping for the 2nd chamber was constructed in competent ground at about 10 ft. in front of a permanent seal, and 28 ft. from the nearest intersection. Under these conditions, the stopping held pressure differentials up to 3.2 in. wg. Beyond this pressure, significant 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 modification was implemented, the chamber held pressure differential in the order of 5-6 in. wg without any significant leakage.
- Because of the leakage problem, the 1st chamber was mainly used to determine the effect of pressurized nitrogen on the pressure differentials across the seal. A pressurized chamber can reduce or reverse the flow of explosive gases from the gob to the work environment.
- When the 2nd chamber was established and pressurized to a pipe discharge pressure of about 3 psi, the pressure differential across the seal (P_3-P_2) decreased from 0.2 in. wg to -3.48 in. wg (in-gassing condition), while the pressure across the stopping (P_2-P_1) increased from 0 to +3.21 in. wg. Beyond the discharge pressure of 3 psi, significant leakage of nitrogen through door gaskets was detected.
- When the access doors of the 2nd chamber were reversed (opening towards the inside of the chamber), the chamber was able to withstand pressure differentials in the range of 5.0 to 6.0 in. wg. Under these conditions, leakage around the doors was reduced to a level that was not noticed by a multi-gas detector used to detect oxygen deficiency. Nitrogen leaked into the ambient 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. This requires a well-engineered design and construction of pressure chambers. The design must include:

- – Proper site selection for the chamber: The chamber must be established in competent ground, deep inside a crosscut, and at least 20 ft away from the nearest intersection. The site must be specified at the planning stage.
  – An MSHA-approved stopping: A Kennedy stopping can be used to establish and operate a pressure chamber. However, to satisfy the MSHA requirements, the design must be modified to include two personnel access doors to allow the mine personnel to inspect the seal on a regular basis.
  – Reinforced Access Doors: The doors must be designed to open into the chamber (inwards) when the chamber is open and to swing them against the gaskets (outwards) when the chamber is closed.
  – Stopping Construction Practice: To reduce leakage, the floor and walls should be trenched and cleaned, and the frames anchored to the roof and floor before installing the Kennedy panels. Furthermore, the panels should be sealed from both sides.
  – Nitrogen Injection System: The system must include at least two flow control valves, a regulator, and two pressure gages. Of these, the regulator plays an important role during the gas injection. A Parker Model 21U844 regulator was found to be suitable for this task.
  – Atmospheric Monitoring and Communication System: West Elk mine's AMS coupled with the University of Utah's Virtual Private Network was used to monitor pressure differentials across the chamber walls and ventilation conditions at the mine. Hand-held instruments equipped with data loggers were also used to cross check the readings. These instruments are sufficient to monitor and evaluate the performance of the chambers.
  – Chamber Operating Procedure: There must a written procedure to open and close the personnel access doors, to purge the chamber in order to inspect the seal, and to operate the chamber safely.
- For the best-case scenario, i.e., when the chamber is established in competent ground, the stopping sealed from both sides, and the doors installed to swing outwards, the chamber can hold pressure differences of about 5.0 in. wg to 6.0 in. wg, with minimal nitrogen leakage. At such high-pressure differences, nitrogen will leak into the work area more through the chamber's hairline fissures (rib and back) rather than the Kennedy stopping.
- To uphold high pressure differentials across the chamber's walls (stopping and seal) and to minimize the ingress of air into the gob or the egress of explosive gases into the longwall, a continuous flow of nitrogen into the chamber is needed. Based on barometric pressure variations measured at the West Elk mine, a continuous nitrogen flow of 40 cfm along the piping system at about 3 psi gage pressure at the injection point would be sufficient to maintain a positive pressure in the chamber, thus minimizing in-gassing and out-gassing conditions.
- With the current technology, the gas injection system can be fully automated (see Appendix B – Automated Nitrogen Injection System).

9. Recommendations and Future Work

The following tasks are recommended as future work:

1. Develop guidelines to construct and operate a pressure chamber to reduce the risk of Sponcom fires in coal mines.
2. Modify the nitrogen injection system to the chamber to include high-precision flow control valves and PLC-controlled regulators.
3. Develop and test an automatically-controlled nitrogen injection system.
4. Test new inflatable stoppings to mitigate chamber leakage.
5. Evaluate ways to mitigate chamber leakage through more robust stoppings and polyurethane injection into the chamber and nearby strata.
6. Disseminate the findings of this research work to the mining community.

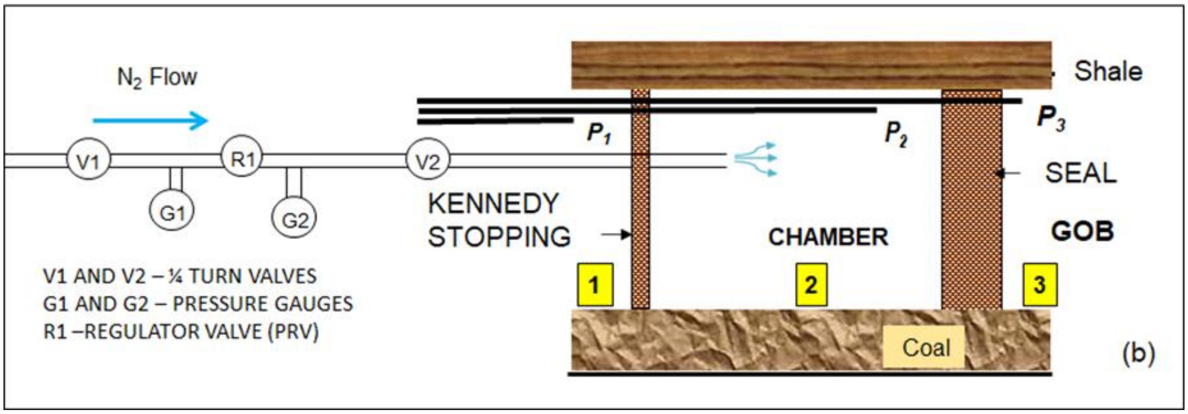
10. References

- Banerjee, S.C. 2000. Preventing and Combating Mine Fires. Boca Raton, FL: CRC Press.
- Brady, J.P., Burra, S. & Calderwood, B.R. 2008. The Pressure Balancing Chamber. *Proceedings of the 12th North American/U.S. Mine Ventilation Symposium*, Reno, NV: University of Nevada. pp. 171–177.
- Bessinger, S.L., Abrahamse, J.M., Bahe, K.A., McCluskey, J.E. & Palm, A.T. 2005. Nitrogen inertization at San Juan Coal Company's longwall operation. SME Annual Meeting, Salt Lake City, UT.
- Bhowmick, B.C., et al. 1992. Dynamic Balancing of Pressure for Control of Fire in Underground Coal Mines. *Journal of Mining Research*. 1:1. New Delhi.
- Calizaya F., Nelson M. G., Bateman, C., and Jha A. 2016. Pressure Balancing Techniques to Control Spontaneous combustion. SME Annual Meeting, Preprint 16-050. Phoenix, AZ.
- Chalmers, D.R. 2008. Sealing design. *Proceedings of the 12th North American/US Mine Ventilation Symposium*, Reno, NV: University of Nevada. pp. 219–223.
- Dawson, A.B. 1954. The Control of Atmosphere in Sealed-off Areas by Pressure Chambers. *Transactions of the Institute of Mining Engineers*. Vol 115. pp. 157-173.
- Francart, W.J. & Beiter, B.A. 1997. Barometric Pressure Influence in Mine Fire Sealing. *Proceedings of the 6th International Mine Ventilation Congress*. Littleton, CO:S ME. pp. 341–342.
- Grubb, J.W., 2008. Preventative Measures of Spontaneous Combustion in Underground Coal Mines. Ph.D. dissertation, Colorado School of Mines, Golden, CO.
- Leeming J.R., Hunneyball S.R., Jobling S. & Shead P.R. 2008. The Application of Nitrogen to Control a Spontaneous Combustion Event during a Longwall Face salvage. *Proceedings of the 12th North American/US Mine Ventilation Symposium*, Reno, NV: University of Nevada. pp. 135–140.

- Mitchell, D.W. 1996. Mine Fires—Prevention, Detection, and Fighting, 3rd Edition. Chicago: Intertec Publishing Inc.
- Moreby, R. 2009. Ventilation. Australasian Coal Mining Practice. Carlton, Victoria: Australasian Institute of Mining and Metallurgy.
- Ray, S.K. & Singh, R.P. 2007. Recent Developments and Practices to Control Fire in Underground Coal Mines. Fire Technology (Central Mining Research Institute, Dhanbad, India). 43:285–300.
- Schatzel, S.J., Krog, R.B. & Dougherty H. 2012.Methane Emissions and Airflow patterns on a Longwall Face. SME Annual Meeting, Preprint 12-016. Seattle, WA.
- Smith, A.C. & Lazzara, C.P. 1987. Spontaneous Combustion Studies of U.S. Coals, USBM RI 9079.

11. Appendix A - Chamber Operation Flowchart

The nitrogen injection system for the 2nd pressure chamber is provided below:



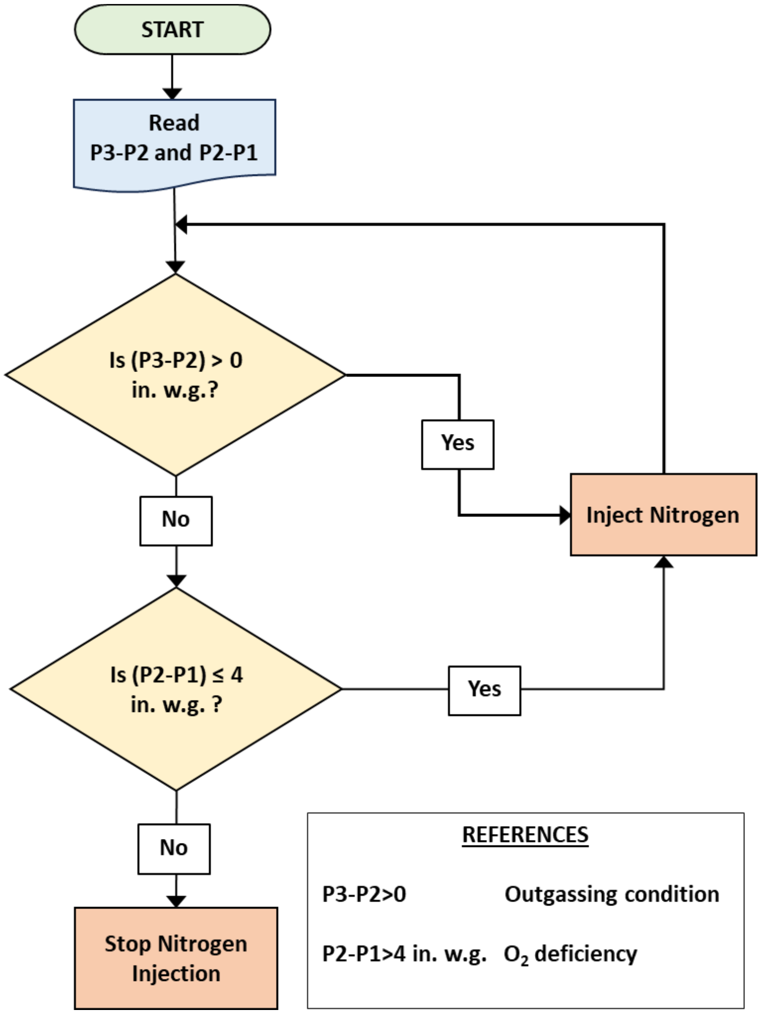


Figure A1: Flowchart depicting the operation of the nitrogen injection system.

12. **Appendix B** - Automated Nitrogen Injection System

B1. Minimizing In-Gassing and Out-Gassing Conditions

During Test 3 nitrogen gas was injected into the chamber in steps using a regulator. The pressure buildup in the chamber was a function of the regulator opening. Within 13 minutes from the start of this test, the differential pressure across the stopping (P_2-P_1) increased from 0.00 in. wg to 5.96 in. wg. During the same time, the differential pressure acres the seal (P_3-P_2) decreased from 0.00 in. wg to -6.08 in. wg, as the pressure in the chamber (P_2) compared to the pressure in the gob (P_3) increased. However, when the regulator/valve was turned off, the chamber depressurized within 72 seconds.

Based on pressure differentials recorded at the West Elk mine, calculations show that a constant nitrogen flow rate of Q_n = 40 cfm at approximately 3.0 psi at the 2nd gage inby the regulator G2 (See Figure 10b) would be sufficient to maintain a constant positive pressure in the chamber, thus avoiding in-gassing and out-gassing conditions.

The flowchart of the automated nitrogen injection system is provided in Figure B1.

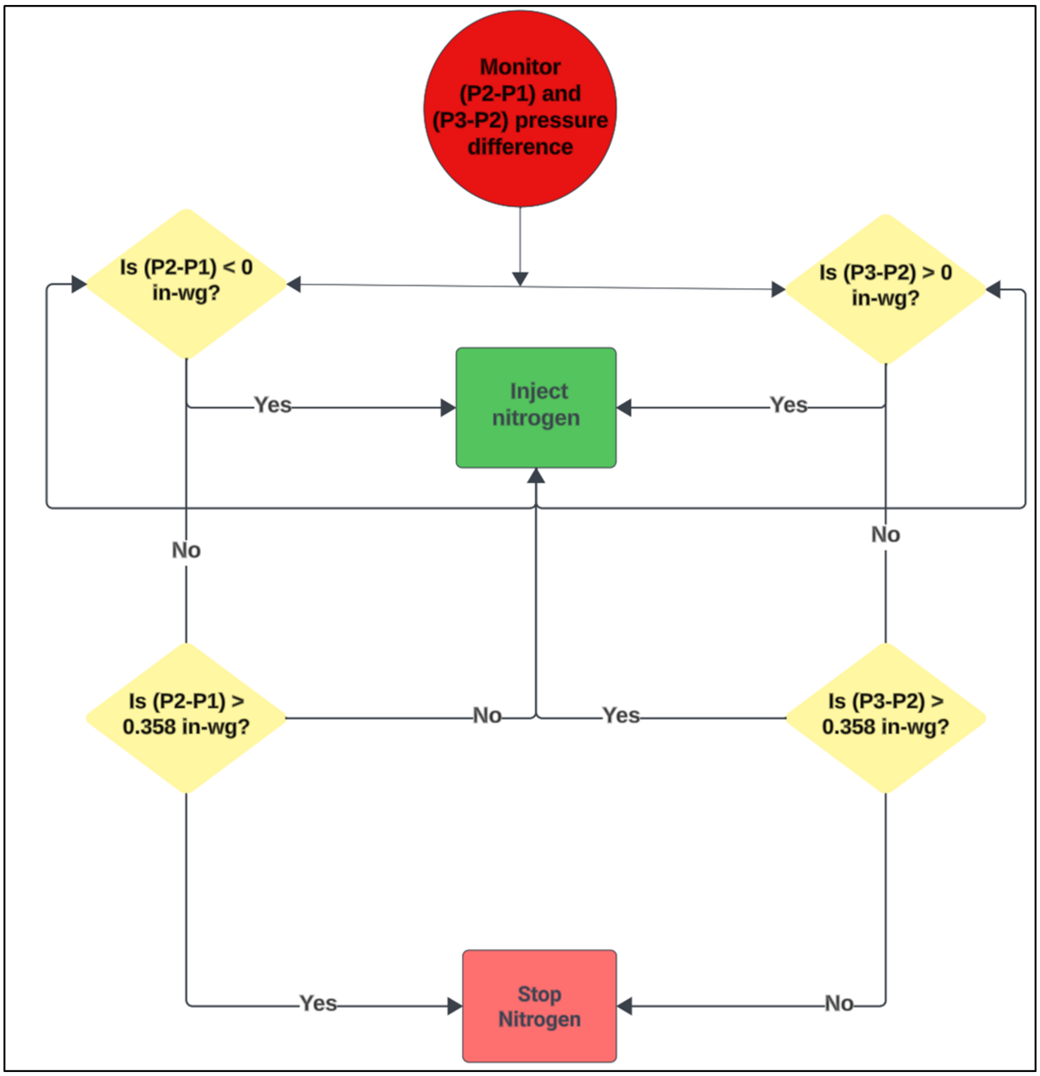


Figure B1: Flowchart schematic of the automated nitrogen injection system.

Based on the logic presented in this flowchart, the nitrogen injection system follows these steps:

1) Start monitoring the pressure differentials DP gob-chamber (P3-P2) and DP chamber-entry (P2-P1).
2) If either (P2-P1) is less than zero in. wg, or (P3-P2) is greater than zero in. w.g, inject nitrogen into the chamber.
3) If the first condition for (P2-P1) is not met, another reading is performed to verify whether (P2-P1) is greater than 0.358 in. wg If this is true, N_2 injection into the chamber stops. If not, the system keeps injecting nitrogen into the chamber.
4) If the first condition for (P3-P2) is not met, another reading is performed to verify whether (P3-P2) is less than 0.358 in. wg If this is true, the system keeps injecting N_2 into the chamber. If not, N_2 injection stops.

B2. Chamber Operation from the Control Center

The chamber operation is described in section 4.3.5. In addition, Figure B1 is also used to highlight the main steps of the control system. To automate the nitrogen injection system at the West Elk mine, the following hardware is needed:

1) Two differential pressure sensors to monitor (P3-P2) and (P2-P1)
2) One programmable logic controller (PLC)
3) Three industrial stepper motors to vary the opening of regulator R1 and the opening of the valves (V1 & V2).

To automate the nitrogen injection system, the following considerations and assumptions were made:

Chamber considerations:

1) There is a PLC that controls the N_2 storage tank, the regulator (R1), and the valves (V1 and V2) that allow N_2 delivery into the chamber.
2) The differential pressure sensors (P2-P1) and P3-P2) have the ability to send signals (pressure values) to the PLC.

Chamber assumptions:

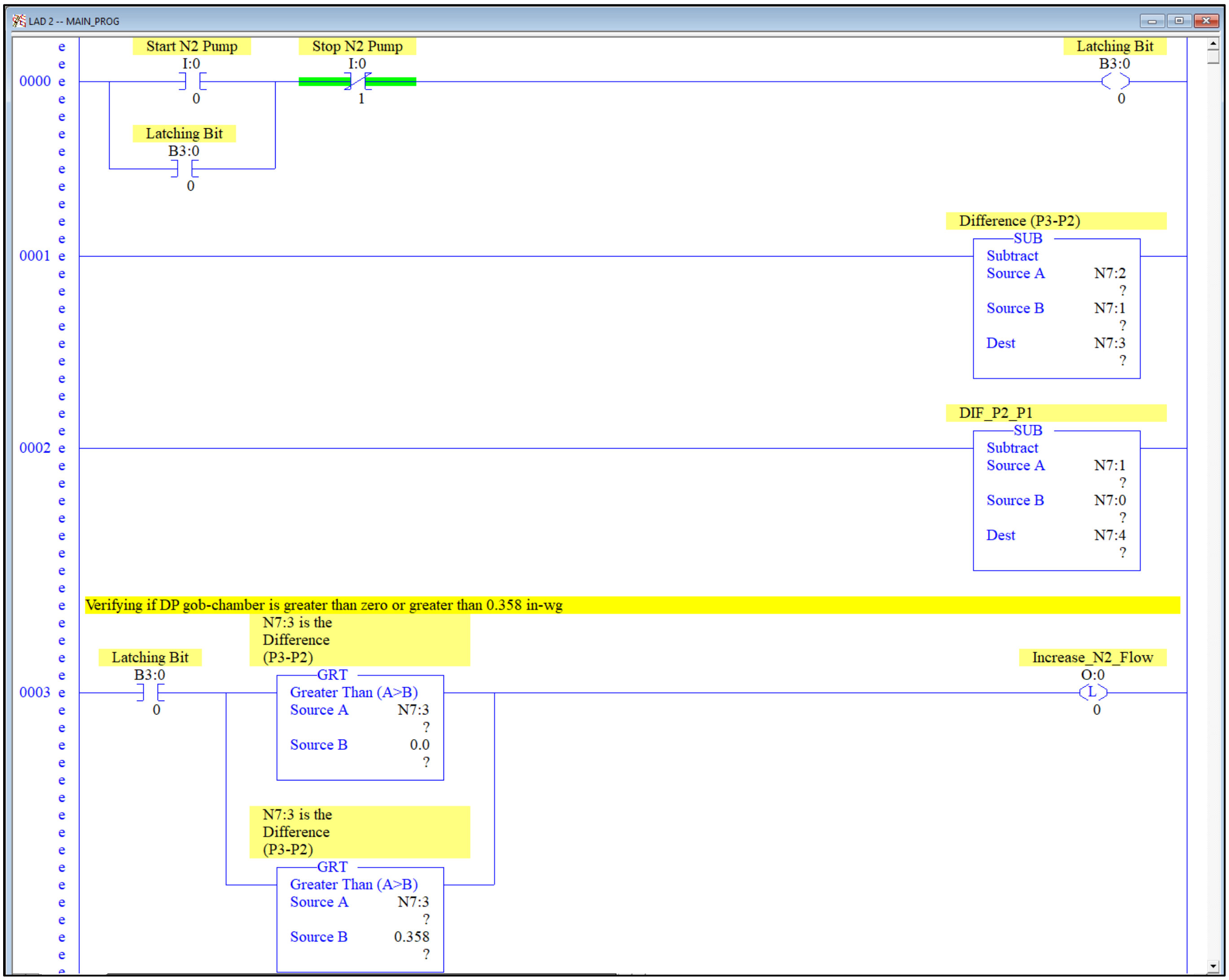
From a PLC standpoint, the following assumptions were made:

1) The state (On or Off) of the Nitrogen storage pump is stored in the “Input” data file. Its specific address is I:0/0 for “On” operation and I:0/1 for “Off” operation.
2) There is a “Latching Bit” (binary value) operation that is used to latch the N_2 pump, keeping the N_2 pump “ON” even after the operator has released the “ON” button of the pump. Its address is B3:0/0. There is also a latching bit (B3:0/3) that gets energized when the DP chamber-entry (P2-P1) is greater than 0.358 in. wg, and another latching (B3:0/1) that gets energized when DP gob-chamber (P3-P2) is greater than 0.358 in. wg
3) The signals coming from the pressure sensors installed in the chamber are stored in the “Integer data file” of the PLC memory.
4) Address N7:0 stores the value of P1
5) Address N7:1 stores the value of P2

6) Address N7:2 stores the value of P3
7) Address N7:3 stores the value of P3-P2 (differential pressure across the seal)
8) Address N7:4 stores the value of P2-P1 (differential pressure across the stopping)
9) The "Output data file" send signals to the regulator/valve to either increase or decrease N_2 flow into the chamber.
10) Address O:0/0 holds the bit that sends the instruction to the regulator/valve to either increase or decrease N_2 flow into the chamber.

The ladder logic presented below was developed using the "rslogix 500" software package provided by Rockwell Automation. The ladder logic assumes that there is a nitrogen storage tank always available to supply nitrogen into the chamber, and all the necessary sensors are installed and running.

Based on the flowchart, chamber considerations, and assumptions provided above, the ladder logic developed by means of the "rslogix 500" software package is presented in Figure B2.



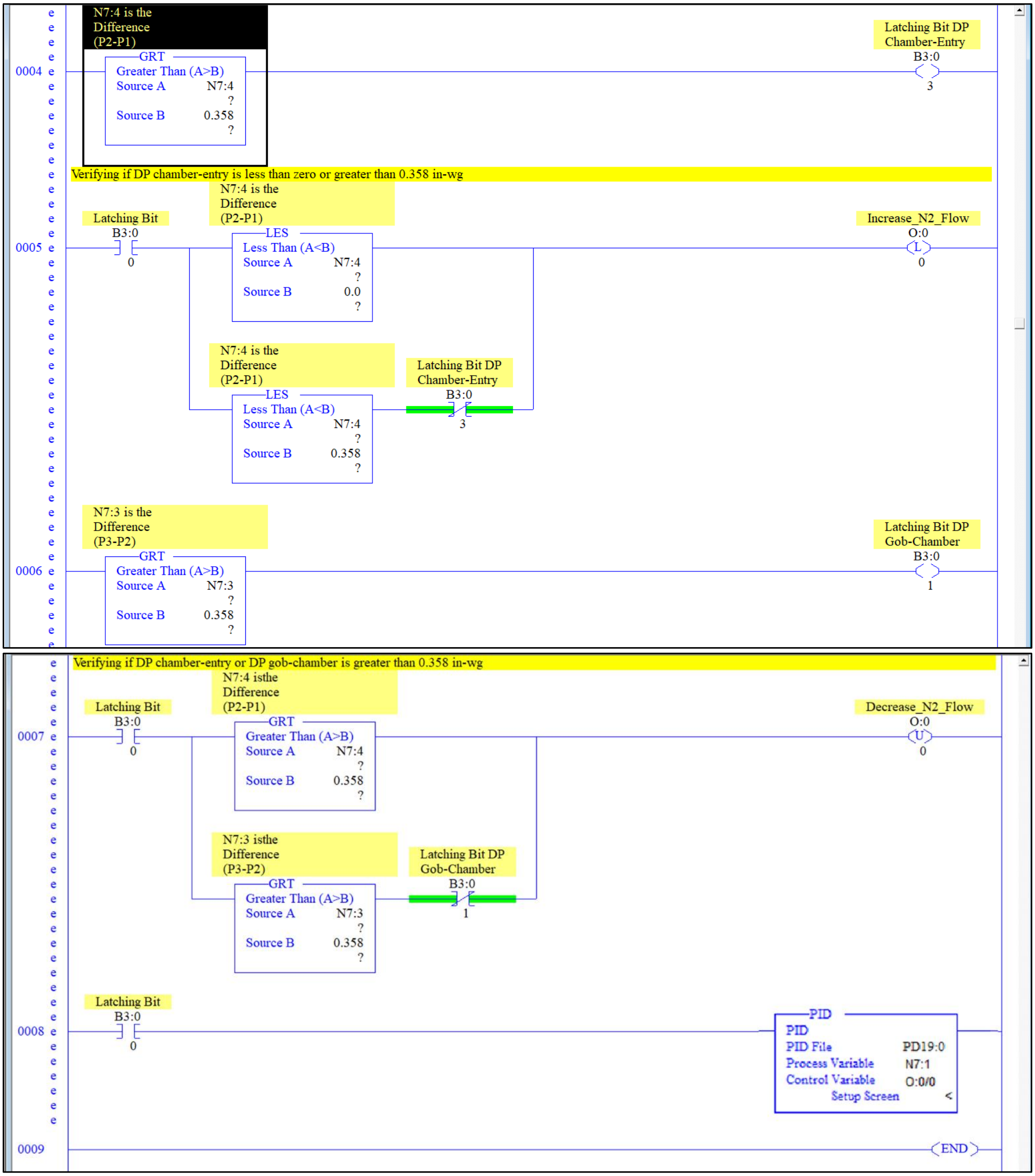


Figure B2: Schematic of the ladder logic instructions to automate N_2 flow into the chamber.

A3. Control Logic

Each set of instructions in the ladder logic program is placed on a “Rung”. As a result, considering the schematic in Figure B2, Rung 0 has the set of instructions to turn “On” or “Off” the nitrogen storage pump.

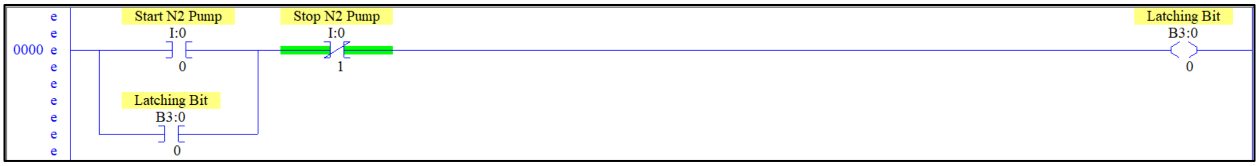


Figure B3: Rung 0

Rung1 takes the value of P3 and subtracts P2 from it and stores the differential pressure (P3-P2) in its appropriate destination.

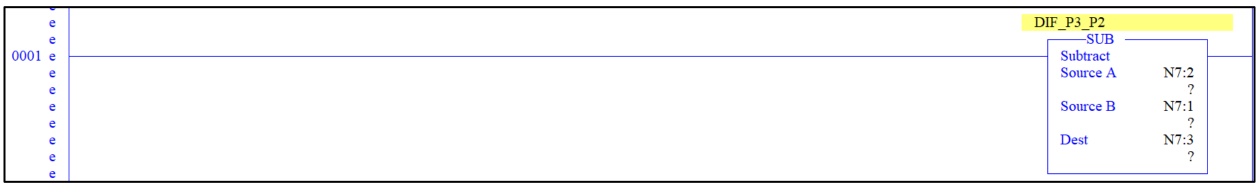


Figure B4: Rung 1

Rung 2 takes the value of P2 and subtracts P1 from it and stores the differential pressure value in its appropriate destination.

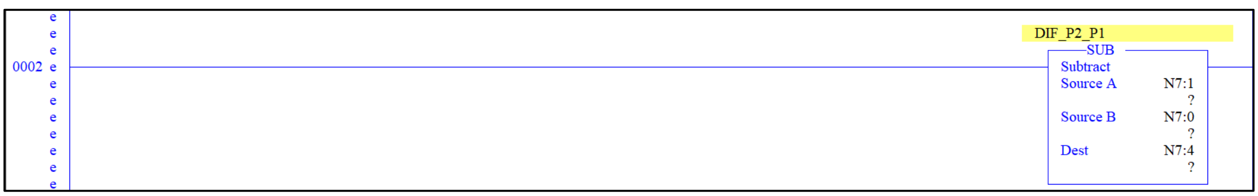


Figure B5: Rung 2

Rung 3 checks if DP gob-chamber (obtained from Rung 1) is greater than zero or greater than 0.358 in. wg If either of the conditions are met, an instruction is sent to the pressure regulator/valve to increase the nitrogen flow into the chamber.

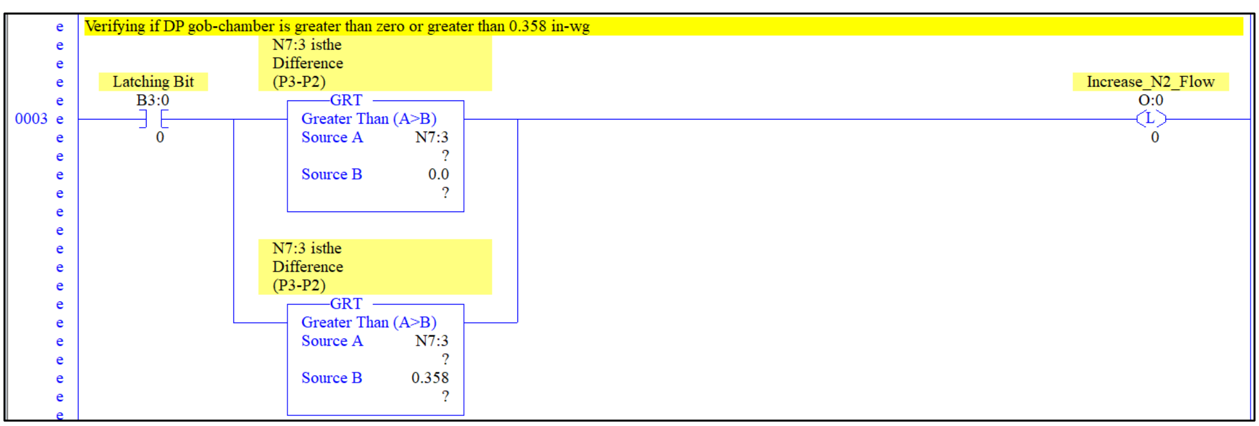


Figure B6: Rung 3

Rung 4 checks if DP chamber-entry (P2-P1) is greater than 0.358 wg If it is, the bit B3:0/3 is energized (set to ON).

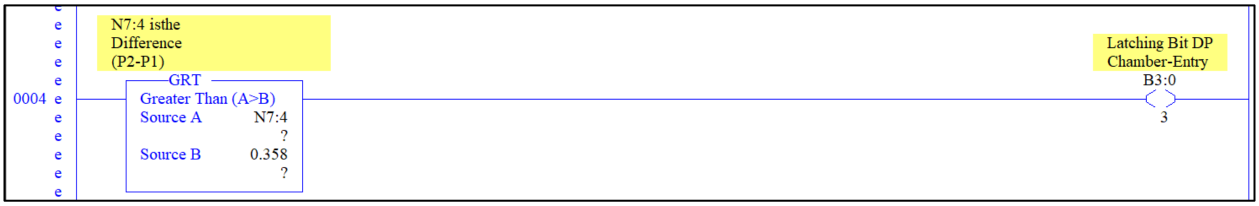


Figure B7: Rung 4

The upper line on Rung 5 checks if DP chamber-entry (P2-P1) is less than zero. If it is, an instruction is sent to increase N_2 flow into the chamber. The bottom-line checks if DP chamber-entry is less than 0.358 in. wg, and if is not, an instruction is sent to increase N_2 flow into the chamber. The reason having a normally closed instruction after the previous one is that when N7:3 is greater than 0.358, B3:0/3 (from Rung 4) will be energized (set to ON). This will cause the normally closed contact of B3:0/3 in Rung 6 to open, preventing N_2 flow to decrease. When N7:3 is not greater than 0.358 in. wg, B3:0/3 will not be energized (remains OFF). This will cause the normally closed contact of B3:0/3 in Rung 6 to remain closed, allowing the N_2 flow to decrease until the flow stops.

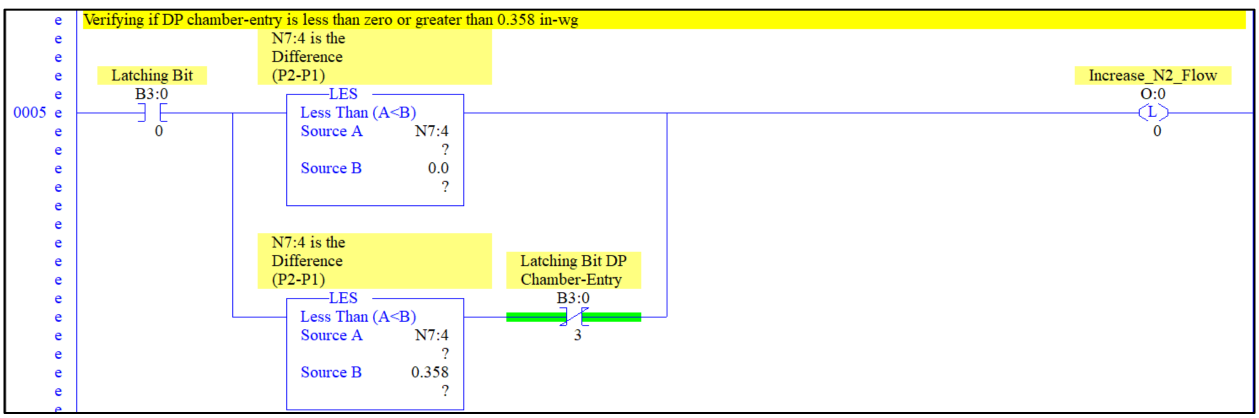


Figure B8: Rung 5

Rung 6 checks if DP gob-chamber (P3-P1) is greater than 0.358 in. wg If it is, the bit B3:0/1 is energized (set to ON).

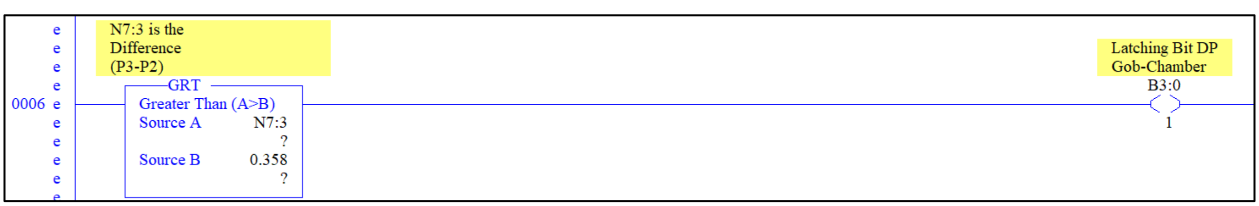


Figure B9: Rung 6

The upper line on Rung 7 checks if DP chamber-entry (P2-P1) is greater than 0.358 in. wg If it is, an instruction is sent to decrease N_2 flow into the chamber. The bottom-line checks if DP gob-chamber (p3-P1) is greater than 0.358 in. wg, and if it is not, an instruction is sent to decrease N_2 flow into the chamber. The reason to have a normally closed instruction after the previous one is the same for that on Rung 5.

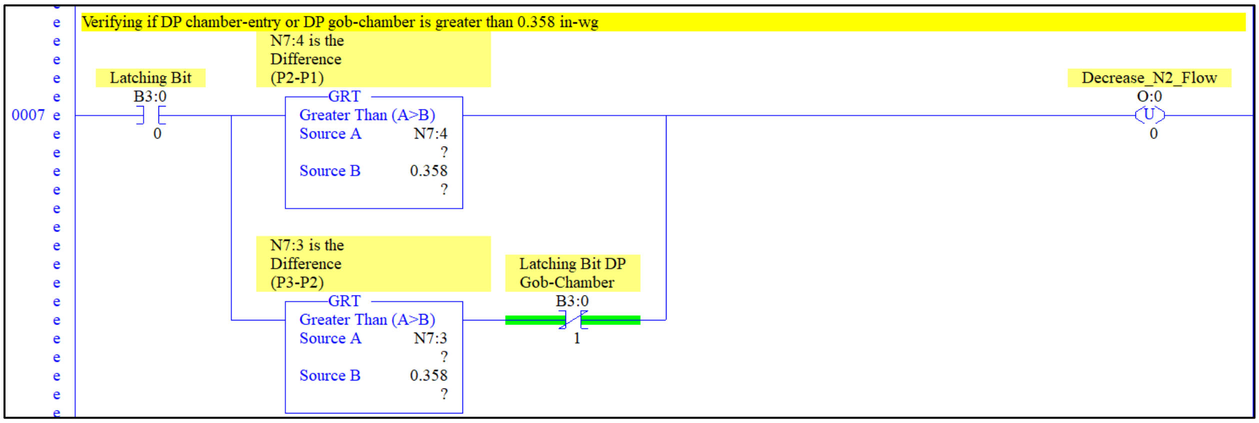


Figure B10: Rung 7

Rung 8 is where the proportional-integral-derivative (PID) controller is setup. The PID file is defined as PD19:0. This sets up all the parameters needed for the PID block, which is accessible within the whole project. The process variable (e.g., the pressure inside the chamber) takes the address of N7:1, which is the pressure sensor inside the chamber. The control variable (in this case the regulator that delivers N_2 into the chamber), takes the address O:0/0 (the valve that either increases or decreases the flow of nitrogen into the chamber). In this case, we are considering that the set point for the PID control is the pressure inside the chamber and it should be maintained at 0.358 in. wg

The PID instruction will constantly look at the pressure coming from the sensor inside the chamber, and if that value is lower than the setpoint, it will send an instruction to the regulator that controls N_2 flow into the chamber to increase that flow until the setpoint is reached. This way, a constant pressure will be kept inside the chamber.

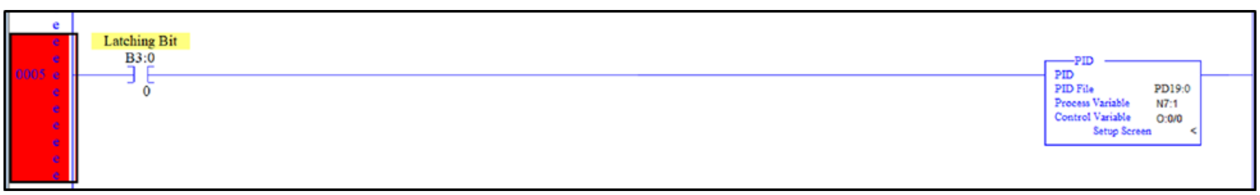


Figure B11: Rung 8

The PID setup interface is provided in Figure B12. The interface allows for inputting all the necessary parameters to make the PID instruction work.

The PID setup interface presented in Figure B1 includes default values, except for the Setpoint value of 0.358 in. wg (see Figure B1 below).

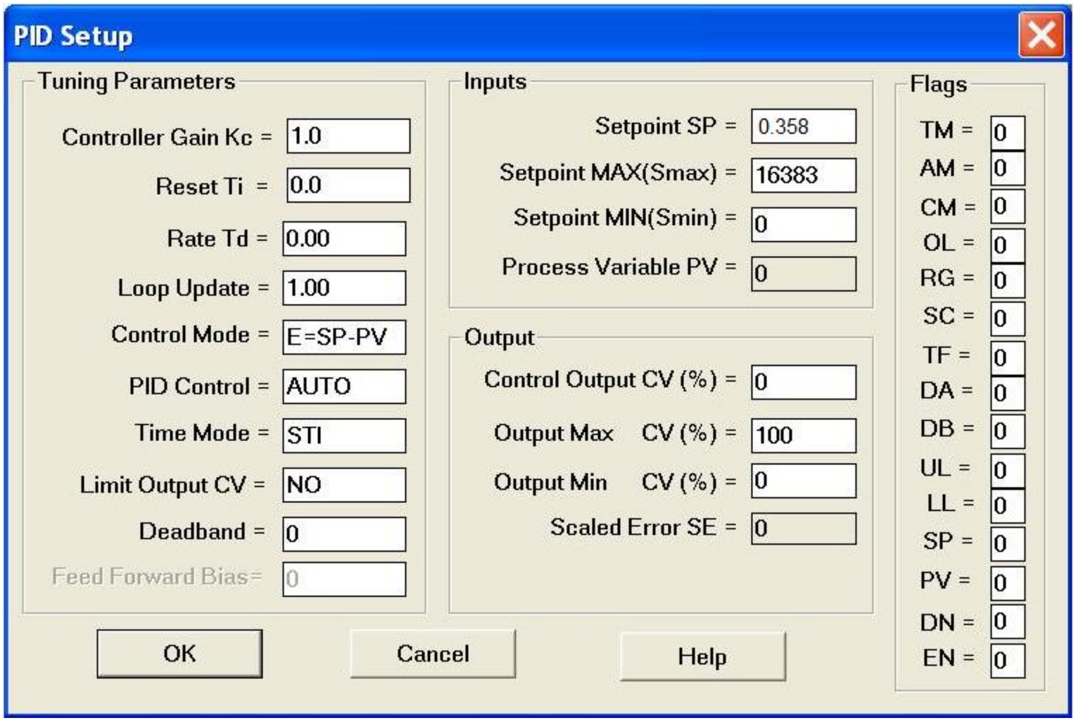


Figure B12: The proportional-integral-derivative (PID) setup screen