USE OF PRESSURE SWING ADSORPTION TECHNOLOGY TO INERT SEALED MINE AREAS WITH NITROGEN

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Abstract

Mine seals are used in underground coal mines throughout the United States to isolate abandoned mining areas from the active mine workings. The objective of adding inert gas to a sealed mine area is to quickly reduce the oxygen concentration in the sealed area to a level that will not support combustion. In the US, this process is typically conducted from the ground surface and because surface-to-mine access is constrained by so many variables, it is very difficult to provide a source of inert gas to the place where it is needed underground. To alleviate this problem On Site Gas Systems, under a NIOSH contract, built a nitrogen (N_2) generation plant that operates in the underground environment. The purpose of this work was to create a reliable in-mine mobile plant that would extract N_2 gas from the mine atmosphere and use the gas to create and maintain a safe sealed mine area. The plant is based on a novel design using pressure swing adsorption technology and is sized to fit on a standard shield car or mine dolly for easy transport in and around an underground coal mine. The plant is capable of producing about 900 scf/min of N_2 gas at ambient mine conditions. After an exhaustive series of laboratory tests, the plant was field tested at the NIOSH Safety Research Coal Mine (SRCM) where a portion of the mine was sealed and rendered inert. During the test, the movement of the injected gas was monitored at several underground points to observe the progress and extent of the inerting process. This paper describes the plant design and the results of the field test at the SRCM.

Introduction

Mine seals are used in underground coal mines throughout the United States to isolate abandoned mining areas from the active mine workings. Sealing is sometimes a more economical and possibly a safer alternative to ventilation since continued ventilation of abandoned areas of active mines is costly and may divert air away from other, more productive underground uses. Without sealing, large mined-out areas still require regular inspections and can expose miners to a variety of underground hazards [1]. Current federal mining laws permit sealing of mine areas providing the seals meet certain standards and the laws also require sampling of the atmosphere in the sealed area [2-4].

It is commonly known that in an underground coal mine, a methane/air mixture becomes explosive when a 5 to 16% methane gas concentration is present with at least 12% oxygen (O_2) concentration [5]. The homogeneity of the methane gas/air mixture can vary depending on the elevation, the methane gas liberation of the sealed area and outside factors such as the temperature and barometric pressure [2]. Under current US federal law (30 CFR §75.336 - except as provided in §75.336(d)), the atmosphere in the sealed mine area is considered inert when the O_2 concentration is less than 10.0% or the methane concentration is less than 3.0% or greater than 20.0% [3]. When it is determined by sampling that the atmosphere in a sealed area is greater than 10% O_2 or methane gas concentration is between 3% and 20%, the mine operator must, by law, take immediate action to restore an inert sealed atmosphere. Furthermore, when the additional sampling indicates that the O_2 concentration is 10% or greater and methane is between

4.5% and 17%, persons shall be withdrawn from the affected area which is the entire mine or other affected area identified by the operator and approved by the MSHA District Manager [3].

Inerting of Sealed Mine Areas

When a coal mine area is sealed, the atmosphere in the sealed area will change as coal, and possibly other materials, oxidizes (thereby removing O_2 and releasing carbon dioxide (CO_2) into the sealed mine atmosphere). Methane gas may also accumulate in the sealed area and will eventually enter and pass through the explosive range. According to Zipf et al, the time required for the atmosphere in the sealed area to pass beyond the upper explosive limit and become inert ranges from about 1 day to several weeks or more depending on the mine's methane gas liberation rate. Shallow mines, mines that have breached into old workings, and sealed areas with high leakage rates may never become inert [1]. Other strata gas emissions, such as $CO_{2,}$ may also impact the atmosphere in the sealed area.

The objective of adding inert gas to a mine area is to quickly reduce the O_2 level to below 10% as mandated by law. Gas can be injected into an area at any time (prior to sealing, immediately after sealing, or long after the area has been sealed) depending upon underground conditions. In general, monitoring, sampling, and maintaining an inert atmosphere in sealed mine areas is generally a new concept and practice for the US coal mining industry.

Exchange of the atmosphere between a sealed mine area and the active mine workings regularly occurs [6]. The common pathway for atmosphere exchange, or leakage, is around a mine seal, through fractures, bedding planes, and through other common or anomalous geologic features in the adjacent rock strata. Changes, in both the magnitude and the rate of change of barometric pressure affect how an atmosphere exchange occurs. In addition, the mine ventilation pressure difference between inert sealed areas and adjacent ventilated areas, at any point in time, will dictate the direction and rate of the atmosphere exchange as the pressures strive to equilibrate. For this reason, many mine ventilation engineers attempt to minimize this pressure differential. However, normal changes in barometric pressure will upset the balance between the sealed and ventilated area. The absolute pressure in the ventilated area is a function of both the ventilation system (with its controls) and barometric pressure changes. The pressure in the sealed area is a function of its pressure relative to the reservoir pressure of strata gases and any relief mechanisms that it may have, such as exchange through strata or seals with a ventilated area, the ground surface in very shallow circumstances, or boreholes to the surface [7].

Inerting Technology

The typical available sources of inert gas for use by mine operators in the US includes liquid or gaseous N_2 that is trucked to a mine site in tankers, on site cryogenic plants that separate the components of air through rectification, or technologies that separate and extract N_2 gas from the atmosphere using hollow fiber membranes or pressure swing adsorption (PSA). All of these sources of N_2 are injected from the ground surface through boreholes or pipelines to the underground mine. Use of these sources requires surface road access (good surface roads in the case of trucked gas and cryogenic plants), sufficient lead time to obtain permission from surface property owners, time to build roads, install pipelines, construct surface locations and drill boreholes. When direct underground access cannot be achieved through a borehole because of difficult surface topography or other reasons, underground pipelines must also be constructed to deliver the gas from a borehole to the underground location. Of late, separation technologies have received favorable interest by the mining industry because these plants are more amenable to field deployment using earthmoving equipment or a helicopter. Because surface access to the underground mine is constrained by so many variables, it is very difficult to provide a source of inert gas to the place where it is needed underground. Therefore, it became very desirable to place a N_2 generating plant underground at or near the point of need.

Under a program created by the Mine Improvement and New Emergency Response Act of 2006 (PL 109-236) also known as the MINER Act, the National Institute for Occupational Safety and Health (NIOSH) awarded a contract to On Site Gas Systems in Newington, Connecticut (in conjunction with Thomas P. Mucho and Associates, Washington, Pennsylvania) to design and construct a novel in-mine N_2 generation plant. The objective was to build a high volume, high purity PSA nitrogen generator for placement in an underground mine.

PSA technology uses a carbon molecular sieve material and pressure to adsorb oxygen molecules while allowing N_2 molecules to pass through the sieve material. Compressed air is used to pressurize a vessel filled with this carbon sieve material, which sifts the air molecules by physical composition or structure. By forcing air into this pressure vessel or sieve bed, O_2 molecules are trapped in the sieve, while N_2 floats free (figure 1). After a period of time, a bit of the pressure is released in the sieve bed to draw off the N_2 molecules, and collect them in a surge/storage tank for use in the application. A valve is then opened in the sieve bed which releases all of the pressure, forcing out the captured molecules of the unwanted gases, and cleanses the sieve for the next cycle (the molecules of the released gas immediately diffuse back into the atmosphere at essentially the ambient percentages). This cycle repeats continuously. With the use of multiple sieve beds, working at opposing ends of the cycle, and a storage/surge tank, a more consistent flow of N_2 gas is achieved.

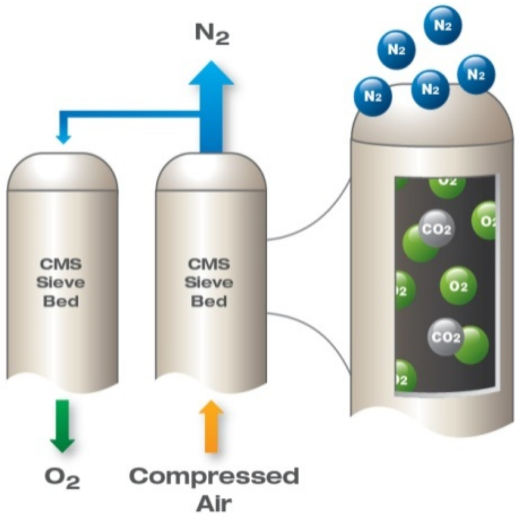

Figure 1 Conceptual drawing of PSA technology.

PSA N_2 generating systems are 12.5% more efficient in terms of the ratio of feed air required to N_2 gas produced than membrane systems. They operate over a broad range of incoming feed air temperatures without impacting the efficiency, thus no external air heaters are required and electrical requirements for the PSA system are minimal. Operating cost is less than a comparable membrane system. The lifespan of a N_2 generating system using PSA technology is infinite with regular maintenance and avoidance of oil and water contamination.

Novel PSA Plant Construction

Under this effort, On Site Gas Systems conceived and built a completely new concept in PSA sieve bed design which enabled a substantial decrease in sieve bed heights yet still maintain sufficient N_2 gas production. One of the most stringent criteria for the design of the underground PSA N_2 generating system was the overall dimensions/footprint of the unit. In order to facilitate transportation and movement within a mine, it was determined that the PSA system should fit within the confines of the width and length of standard-sized shield car as well as the height of typical mine entries operating in the Pittsburgh Coalbed. That resulted in an overall dimension of the unit of 206 in (length) by 84 in (wide) by 44 in (height). The system built is capable of producing up to 300 scfm of N_2 at 50 psi (approx. 1,000 scfm at ambient pressure) (figure 2). Currently, the electrical requirement for the prototype PSA N_2 generating system is 110V AC and approximately 10 amps, but the unit could be reconfigured to operate on some other type power supply. The feed air requirement is 600 scfm air at minimum 90 psi with a temperature between 32° F and 100°F and a dew point of less than 40ºF non-condensing.

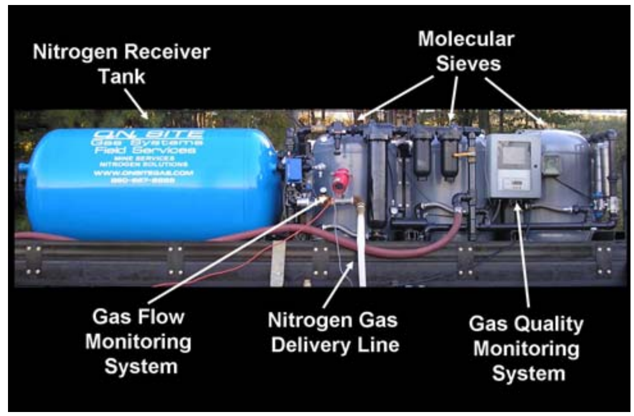

Figure 2. Novel PSA N_2 generating system.

On Site Gas Systems also designed a skid-mounted air dryer/filter that modifies the feed air for the PSA plant for cases when the available feed air is unable to meet required input temperatures and dew point. The air dryer/filter was also designed to meet dimensional criteria regarding height and width limitations and would be a separate, ancillary part of the PSA N_2 generating system. Currently the air dryer/filter design calls for 240V, 3-phase power, but could be reconfigured to operate on 110V AC or some other available power supply.

In-House and Field Testing of the PSA Unit at the NIOSH Safety Research Coal Mine

Once the PSA unit was built, On Site conducted testing to ensure that the design requirements, as identified through interviews with mining experts, were achieved. The N_2 system prototype was tested at specific maximum and minimum design parameters. Extended, continuous operation at maximum conditions was also completed and verified. The system was able to maintain approximately 300 scf/min at purity of below 5% O_2 content with air input of 600 scf/min across an input pressure range of 90-140 PSIG. From the test data, subtle changes were made to maximize performance as well as simplify operation and maintenance. The prototype N_2 system was then delivered to the NIOSH Safety Research Coal Mine (SRCM) located near Pittsburgh, Pennsylvania for a series of two tests. The Safety Research Coal Mine is a room-and-pillar operation approximately the size of a working section of a coal mine and is utilized for mine health and safety research in areas such as ground control, ventilation, fires, explosives use, materials handling, and environmental monitoring [8].

A 62,000 ft^3 area of the SRCM was selected as area to be sealed and rendered inert by the PSA plant (figure 3). This area included two long entries with 6 intervening cross-cuts. The area was isolated from the rest of the mine by an existing 3 ft concrete seal constructed some time in the past and 2 newly constructed ventilation seals. To observe the progress of the inerting process, a gas sampling array was installed in the area to be sealed. Some of the gas sample points were located in open entry areas or in an open equipment door while others were located in areas closed by ventilation seals or a mine seal. A gas sample point was placed outside the sealed mine area to monitor the mine atmosphere and a sample line was attached to the N_2 injection line to monitor the quality of the injection gas. Gas from the PSA plant was injected into the sealed mine area during the tests through a 1-in diameter line that was placed into and through the water trap. The PSA plant was positioned outside of the mine on a flat bed tractor trailer along with a dryer and compressor. The compressor provided the feedstock air for the PSA plant and the dryer insured that the feedstock air was free of oil (from the compressor) and moisture. Gas from the PSA plant was piped to the sealed mine area using 1.5-in diameter fire hose. The PSA plant was not placed in the mine because a shield car was unavailable at the time of the tests. Also, the SRCM does not produce much gas so the components of the mine atmosphere are essentially the same as the normal atmosphere, thus operating the unit inside or outside of the mine would produce similar results.

Test 1

The first test was designed to determine if the PSA plant could render the sealed mine area inert and if the inert environment could be maintained. The test area was set up to inject inert N_2 gas through ventilation seal 1 (refer to figure 3). The first portion of Test 1 was designed to determine if coal in the sealed mine area would oxidize and start to self inert by using up the available O_2. After 36 hrs of sealing, it was determined that the sealed area would not self-inert quickly and N_2 injection operations were initiated. The PSA plant operated continuously for about 23.3 hrs, producing on average approximately 900 scf/min at ambient mine conditions, or about 1.28 million scf of N_2 (figure 4).

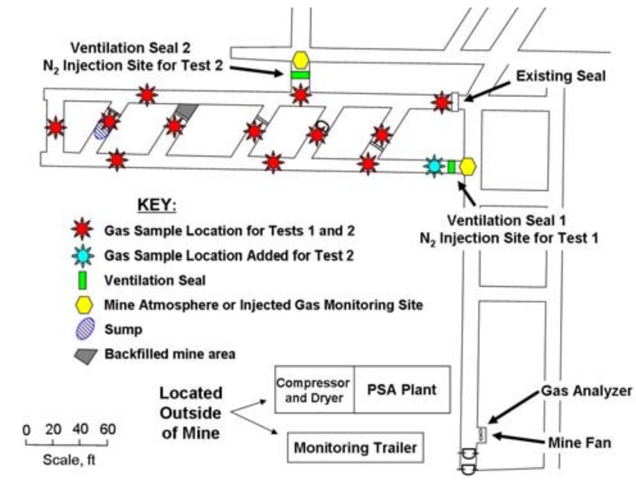

Figure 3. Layout map showing the gas sample points in the sealed mine area.

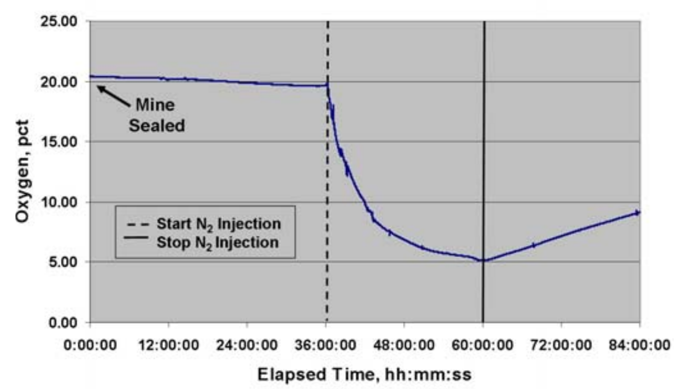

Figure 4. Average O_2 concentration in the sample array during test 1.

Shortly after N_2 injection was initiated, it was noticed that the pressure within the sealed area was not increasing, but remained constant; indicating that gas was escaping from the sealed area at the same rate it was being injected. This leakage was confirmed during an underground inspection and showed that gas was escaping from the mine roof areas above each ventilation seal but not through the seal itself, the ribs or the mine floor. Figure 5 shows a plot of O_2 concentration reduction as a function of elapsed inert gas injection time. In the figure, the two important O_2 thresholds mentioned earlier are highlighted. The first threshold shows that 4 hrs of inert gas injection time was needed to reduce the sealed area from the starting concentration of 19.6% to below 12% O_2 and that about 7.2 hr of gas injection time was needed to reduce the O_2 content below 10%. After about 23.3 hrs of injecting gas, the O_2 content over entire sealed area was reduced to 5.4% which was near the O_2 level being produced by the PSA unit. It was also determined that because the O_2 content could be reduced to such a low value relatively easily, maintaining the inert environment in the sealed area would not be difficult. The test was completed and the sealed area was opened and ventilated.

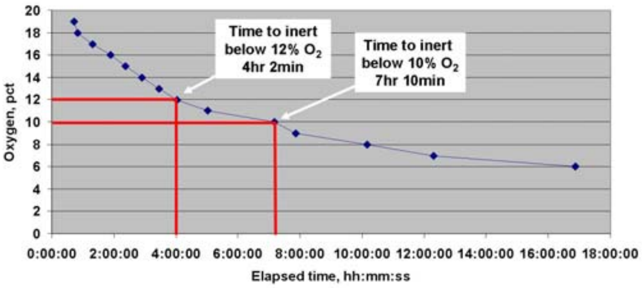

Figure 5. Plot of O_2 reduction in the sealed area for the initial gas injection segment of Test 1.

Test 2

The second test was designed to again determine if the PSA plant could render the sealed mine area inert, maintain the inert environment, and to also observe inerting frequency and duration as well as the time period between cycles (periods of gas injection followed by a periods of equilibration). During this test all gas injection was through ventilation seal 2. Once the mine area was re-sealed, inerting operations were initiated. For the first part of Test 2, the PSA plant was operated continuously for 14 hrs producing an average of 865 scf/min (at ambient mine conditions) and injecting about 735 thousand sfc of N_2. Pressure in the sealed mine area, similar to Test 1, did not increase indicating leakage was reoccurring. Figure 6 shows a plot of O_2 concentration reduction as a function of elapsed inert gas injection time for the first part of Test 2 (note this data is very similar to that observed in Test 1, refer to figure 5).

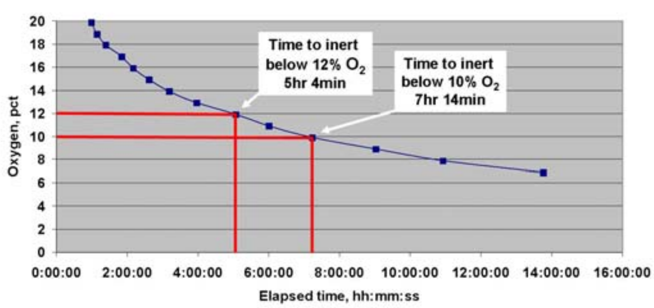

Figure 6. Plot of O_2 reduction in the sealed area for the initial part of Test 2.

Injection operations were then stopped and the sealed area was allowed to equilibrate (through the inward leakage at ventilation seal 2) until the O_2 level reached 8% in the sealed area. This occurred at about 10.5 hrs later. Injection operations were then re-started and continued for 5.8 hrs, producing an average of 882 scf/min (at ambient mine conditions) and injecting about 303 thousand sfc of N_2. At that point, the O_2 level throughout the sealed mine area had been reduced to below 7%. Injection operations were then stopped again and the O_2 content of the sealed area was allowed to increase to 7.5%. This occurred about 5.5 hrs later. Injection operations then resumed and continued for 2 hrs, producing an average of 865 scf/min (at ambient mine conditions) and injecting about 104 thousand sfc of N_2. At that point the O_2 level in the sealed mine area had been reduced to below 7%. The sealed area was then allowed to equilibrate (through leakage) for about 10 hrs when the test was completed. The maximum O_2 value observed in the sample array at the time of completion was 8.3%. Figure 7 shows the average O_2 concentration in the sample array during test 2.

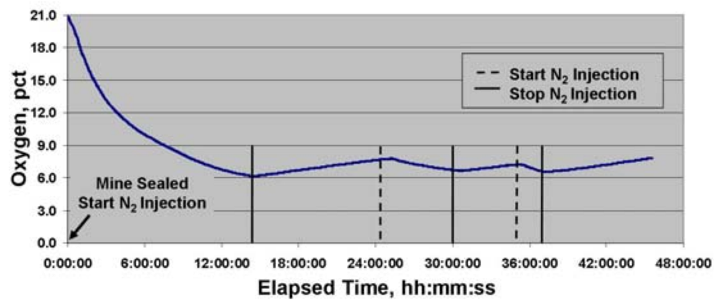

Figure 7. Average O_2 concentration in the sample array during test 2.

Summary

The objective of this effort was to build a high volume, high purity PSA nitrogen generator to provide mine operators with the ability to inert a sealed mine area for as long as needed without the potential obstacles that are associated with injection of N_2 from the ground surface through a borehole. The PSA system was designed and built to operate at or near an underground sealed mine area. Under this effort, On Site Gas Systems conceived and built a completely new concept in PSA sieve bed design which enabled a substantial decrease in sieve bed heights yet still maintain sufficient N_2 gas production. The PSA N_2 system constructed under this effort was intended for use in the underground mine environment taking into account factors such as minimal power requirements, sturdiness of construction, ease of use, ease of maintenance, reliability and transportability. After undergoing a series of exhaustive tests at the On Site Gas Systems facilities, the unit was moved to the NIOSH SRCM for a series of two inerting tests, where it was demonstrated that the PSA N_2 system could successfully reduce the oxygen concentration in the sealed mine area and maintain an inert gas environment. To fully understand the capacity and limitations of this novel inerting system, it is recommended that the system be further tested at an actual mine site, over a longer duration of time, with a larger sealed mine area.

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