USE OF CFD MODELING TO STUDY INERT GAS INJECTION INTO A SEALED MINE AREA

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Abstract

Since the promulgation of the MINER Act and the follow-up changes to the regulations governing mine seal construction and maintenance, mine operators must be acutely aware of the atmosphere in sealed mine areas and prepared to deploy control technologies when the conditions are warranted. On Site Gas Systems[1] in Newington, Connecticut was awarded a contract by the National Institute for Occupational Safety and Health (NIOSH) to construct a novel in-mine nitrogen (N_2) generation plant using pressure swing adsorption (PSA) technology. PSA technology utilizes carbon molecular sieve material and pressure to adsorb oxygen (O_2) molecules while allowing N_2 molecules to pass through the sieve material. The prototype PSA unit was tested at the NIOSH Safety Research Coal Mine (SRCM) where a 62,000 ft^3 area of the mine was rendered inert during a series of two tests. The resultant data were then used to construct a CFD simulation of both injection tests. In addition, O_2 depletion and gas leakage rates were quantified in the model and were compared to actual values. Once the model was calibrated, the sealed mine area was doubled and simulations were made with various injection rates and injection site locations to determine the impact on the time needed to render this area inert. This paper presents an overview of the PSA plant, the details of the gas injection tests and CFD modeling work.

Introduction

The concept of monitoring, sampling, and maintaining an inert atmosphere in sealed mine areas is a relatively new practice for the US coal mining industry. Subsequent to the enactment of the Mine Improvement and New Emergency Response Act of 2006 (PL 109-236) also known as the MINER Act, the Mine Safety and Health Administration (MSHA) issued mandatory health and safety standards relating to the sealing of abandoned areas in underground coal mines. On May 22, 2007, MSHA issued an Emergency Temporary Standard (ETS) addressing the strength, construction, maintenance, and repair of mine seals [1]. The ETS also included requirements for sampling and controlling the atmosphere behind seals. Because of the requirements of the ETS, mine operators had to seek technology to render and maintain a sealed mine area inert. On April 18, 2008, MSHA published a final rule that superseded the ETS. The final rule addressed seal strength design, construction, maintenance and repair of seals and monitoring and control of the atmosphere behind seals to reduce the risk of seal failure and the risk of explosions in abandoned areas of underground coal mines [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% or the methane (CH_4) concentration is less than 3% or greater than 20% [3]. When it is determined by sampling that the atmosphere in a sealed area is greater than 10% O_2 or CH_4 gas concentration is between 3% and 20%, the mine operator must, by law, take immediate action to restore an inert sealed atmosphere. Furthermore, when additional sampling indicates that the O_2

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[1] Mention of a company name or product does not constitute an endorsement by NIOSH.

concentration is 10% or greater and CH_4 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 [4].

A sealed mine area can be rendered inert through the natural accumulation of CH_4, over time, to levels beyond the explosive range, oxidation of the coal and possibly other materials (thereby removing O_2 and releasing carbon dioxide (CO_2) and the injection of N_2 into the sealed mine areas to quickly reduce the O_2 content to a level that will not support combustion. In the US, the available sources of N_2 gas for use by mine operators 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).

Under a program created by the MINER Act, the National Institute for Occupational Safety and Health (NIOSH) awarded a contract to On Site Gas Systems in Newington, Connecticut to design and construct an in-mine N_2 generation plant. The objective of this effort was to build a high volume, high purity PSA N_2 generator that could operate in an underground mine. PSA technology was selected because these systems are 12.5% more efficient than the alternative membrane systems in terms of the ratio of feed air required to N_2 gas produced. PSA systems operate over a broad range of incoming feed air temperatures without impacting the efficiency, thus external air heaters are not required. Electrical requirements for a PSA system are minimal and thus operating costs are less than a comparable membrane system. Also, the lifespan of a N_2 generating system using PSA technology is indefinite with regular maintenance and avoidance of oil and water contamination.

PSA technology uses a carbon molecular sieve material and pressure to adsorb O_2 molecules while allowing N_2 molecules to pass through the sieve material. A typical PSA unit has at least two adsorber beds filled with the carbon molecular sieve material. During each half cycle, one adsorber bed produces N_2 while the other is purged of O_2. Compressed air (feedstock gas) is used to pressurize the adsorber sieve beds and, during this process, the smaller O_2 molecules of the feedstock gas are adsorbed by the sieve material while the larger N_2 molecules float free (figure 1). Once an adsorber bed is saturated with O_2, a bit of the gas pressure is released in the bed to draw off the N_2 molecules. The N_2 molecules are then collected in a surge/storage tank for use. A valve is then opened in the saturated adsorber 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 and with the use of multiple adsorber beds, working at opposing ends of the cycle, and a storage/surge tank, a consistent flow of N_2 gas is achieved [5].

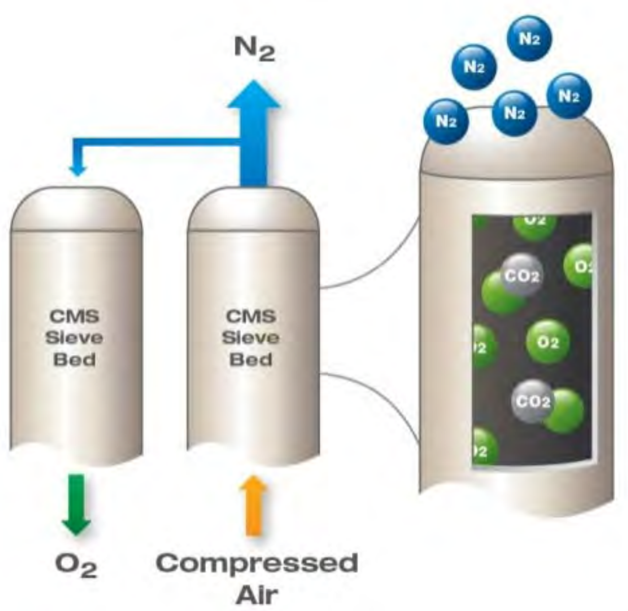

Figure 1. Conceptual drawing of PSA Technology.

Under this effort, On Site Gas Systems conceived and designed a completely new concept in PSA sieve bed design which enabled a substantial decrease in sieve bed heights while still maintaining sufficient N_2 gas production. The N_2 generating system is capable of producing up to 300 scfm of N_2 at 50 psig (figure 2). Currently, the electrical requirement for the N_2 generating system is 110 Vac and approximately 10 A, but the unit could be reconfigured to operate on some other type of power supply. The feed air requirement is 600 scfm air at minimum 90 psig with a temperature between 32° F and 100°F and a dew point of less than 40ºF non-condensing.

In order to facilitate transportation and movement within a mine, it was determined that the N_2 generating system had to fit within the confines of a standard-sized shield car transport and also within height of typical entries of mines operating in the Pittsburgh Coalbed (about 6 ft). These constraints resulted in overall unit dimensions of 206 in (length) by 84 in (wide) by 44 in (height). A complete description of the development of the N_2 generating system is available in [6].

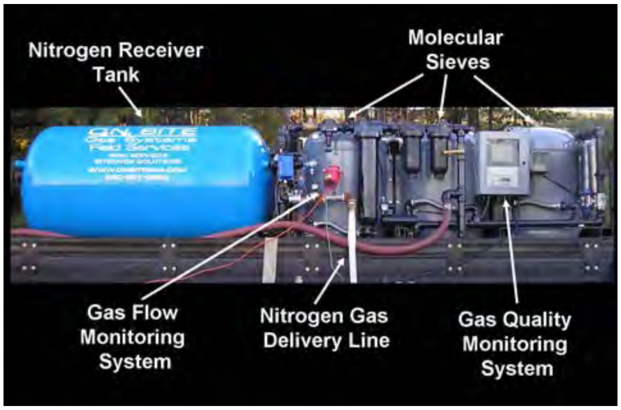

Figure 2. Novel PSA N_2 generating system.

On Site Gas Systems also designed and built a skid-mounted air dryer/filter that modifies the feed air for the PSA plant for circumstances in which feedstock air is unable to meet required input temperatures and dew point (figure 3). The air dryer/filter was also designed to meet dimensional constraints mentioned above and would be a separate, ancillary part of the N_2 generating system. Currently, the air dryer/filter design calls for 240 V, 3-phase power, but it could be reconfigured to operate on single-phase 110 Vac or some other available power supply.

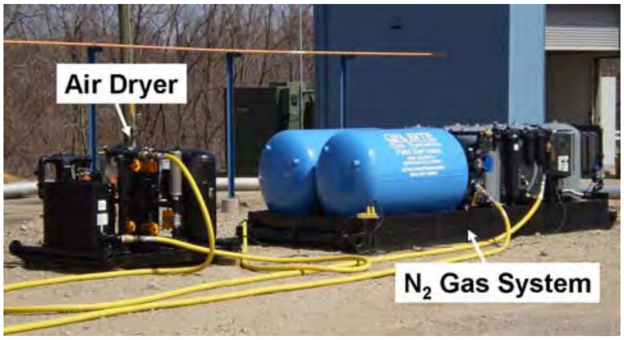

Figure 3. N_2 generating system with air dryer.

In-House Testing

The N_2 system was tested in-house at the On Site Gas System facility at specific maximum and minimum design parameters. Testing involved extended, continuous operation at maximum input and output rates. The tests showed that the system was able to maintain gas flow at approximately 300 scf/min with a purity of below 5% O_2 content given feedstock air input of 600 scf/min across an input pressure range of 90-140 psig. From the in-house tests subtle changes were made to maximize performance of the system as well as to simplify operation and maintenance.

Field Testing – NIOSH Safety Research Coal Mine

The N_2 generation plant was delivered to the SRCM located near Pittsburgh, Pennsylvania for a series of tests. The SRCM 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 [7].

A 62,000 ft^3 area of the SRCM was selected as the area to be sealed and rendered inert by the N_2 generation plant (figure 4). This area included two long entries with 6 intervening cross-cuts. The area was isolated from the rest of the mine by using an existing 3-ft thick concrete seal and 2 newly constructed ventilation seals. To observe the progress of the inerting process, a gas sampling array was installed in the area being sealed. Gas from the N_2 generation plant was injected into the sealed mine area during the tests through a 1-in diameter line that was placed into and through a water trap. The N_2 generation 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 N_2 generation plant and the dryer insured that the feedstock air was free of oil (from the compressor) and moisture. Gas from the N_2 generation plant was piped to the sealed mine area using 450 ft of 1.5-in diameter fire hose. The N_2 generation plant was not placed in the mine because a shield car transport 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.

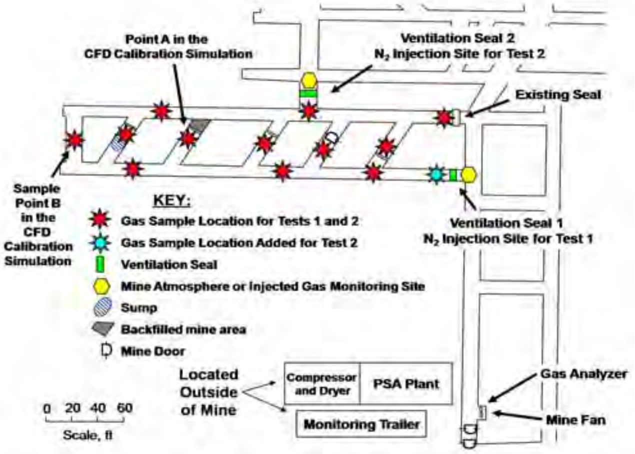

Figure 4. Layout map showing sealed mine area gas and CFD calibration simulation sample points.

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 4). 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 being sealed for 36 hrs, it was determined that the sealed area would not self-inert quickly, and N_2 injection operations were initiated. The PSA plant was then operated continuously for 23.3 hrs (figure 5).

Shortly after N_2 injection was initiated at ventilation seal 1, 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. After 23.3 hrs of injecting gas at an average rate of 280 scfm at 50 psig, the O_2 content over entire sealed area was reduced to an average of 5.2% (maximum value 5.4%) over the array which was near the O_2 level being produced by the PSA unit. The test was completed and the sealed mine area was opened and ventilated.

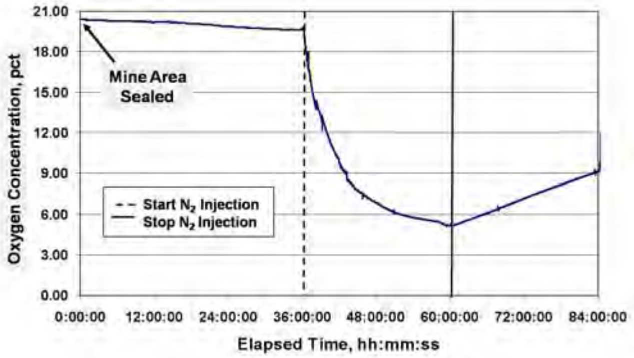

Figure 5. Average O_2 concentration in the sample array during test 1.

The second test was designed to determine if the PSA plant could render the sealed mine area inert, maintain the inert environment, and to 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 (refer to figure 4). 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 at an average rate of 272 scfm at 49 psig. 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 10.5 hrs later. Injection operations were then re-started and continued for 5.8 hrs at an average rate of 276 scfm at 49 psig. 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 increased (through inward leakage) to 7.5% some 5.5 hrs later. Injection operations then resumed and continued for 2 hrs at an average rate of 269 scfm at 49 psig. 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 inward leakage) for 10 hrs when the test was completed. The maximum average O_2 value observed in the sample array at the time of completion was 8.3% (figure 6). A detailed description of the tests and discussion of the test results can be found in [6].

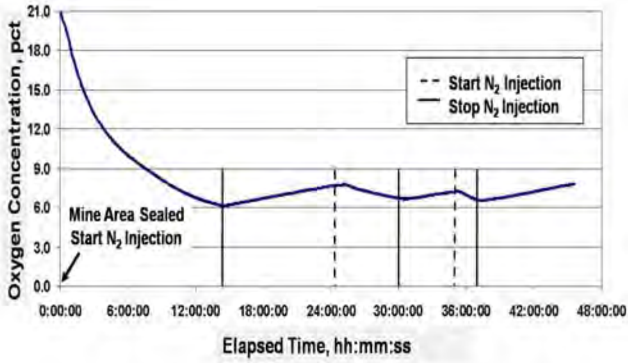

Figure 6. Average O_2 concentration in the sample array during test 2.

Computational Fluid Dynamics (CFD) Modeling

In order to estimate the capability of the N_2 generating system without the expense and time required to conduct a large scale underground experiment at an operating coal mine, it was decided to construct a CFD model of the same dimensions and geometry as the field test at the SRCM. Once the model was calibrated, using the data from the field test, then the size of the mine could be expanded and the volume of inert gas injected changed to measure the resultant effects at two selected monitoring points in the model.

CFD is a sophisticated computationally-based design and analysis technique that enables users to simulate flows of gases and liquids, heat and mass transfer, multiphase physics, chemical reaction, and fluid-structure interaction through computer modeling. Using CFD, the user then builds a 'virtual prototype' of the system or device and then applies real-world physics and chemistry to the model to generate images and data, which predict the performance of that design [8].

The injection and migration of N_2 in the SRCM was modeled using the Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) program developed by National Institute of Standards and Technology. FDS is a three-dimensional, large eddy simulation model that was developed to study the transport of smoke and hot gases during a fire in an enclosed space. It was believed by the authors that this model would be useful to analyze inert gas movement. FDS is the most widely used large eddy simulation model in the fire science field and has demonstrated good agreement with experimental data in numerous validation studies. The model uses finite difference techniques to solve the Navier-Stokes equations numerically for fluid flow with a mixture fraction combustion model.

In the simulations, N_2 gas leakage at the ventilation seals (as observed during the SRCM field tests) was replicated by creating a very small rectangular opening in the seal. The size of the opening was reduced to the point where leakage through the seals matched the N_2 gas injection rate and the measured differential pressure across the seals. The gas leakage rate was held constant in the model. Also, no attempt was made to simulate the periods in the tests at the SRCM where the N_2 injection was stopped. Figures 7 to 10 show a comparison between the actual field data from the test at the SRCM and the CFD model for two select points. The gas injection rate and injection point for the first simulation was the same as that used in Test 1 (ventilation seal 1) and similarly the rate and injection point was the same as used in Test 2 (ventilation seal 2) for the second simulation. Sample point A was located in a closed cross-cut while sample point B was in the preferred N_2 gas flow path as shown in figure 4. These points were selected for comparison with the model because they were far away from the N_2 gas injection points. Note there is close agreement between the SRCM data and the output of the model.

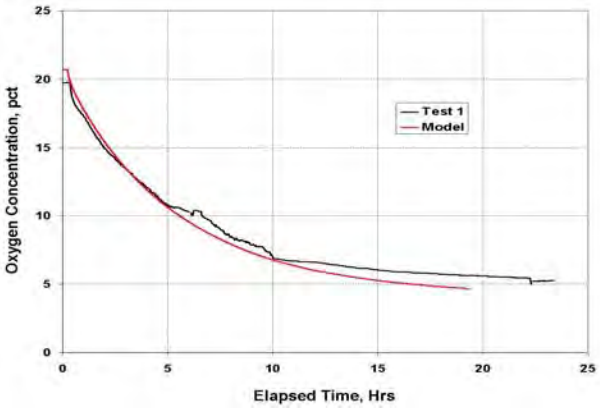

Figure 7. Comparison of SRCM Test 1 data and CFD model for sample point A.

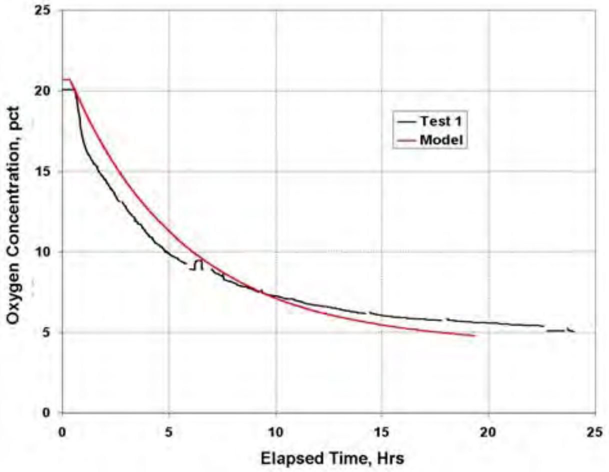

Figure 8. Comparison of SRCM Test 1 data and CFD model for sample point B.

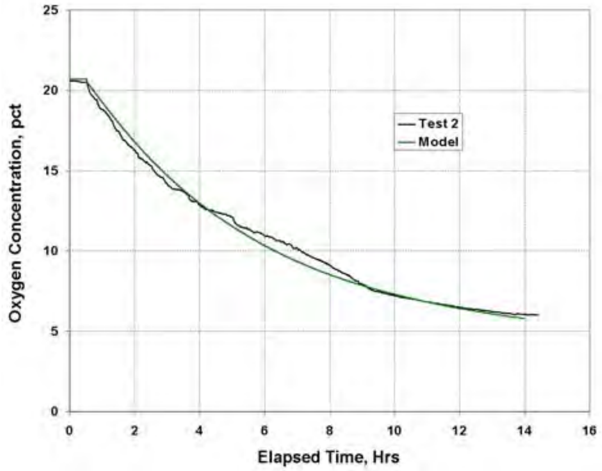

Figure 9. Comparison of SRCM Test 2 data and CFD model for sample point A.

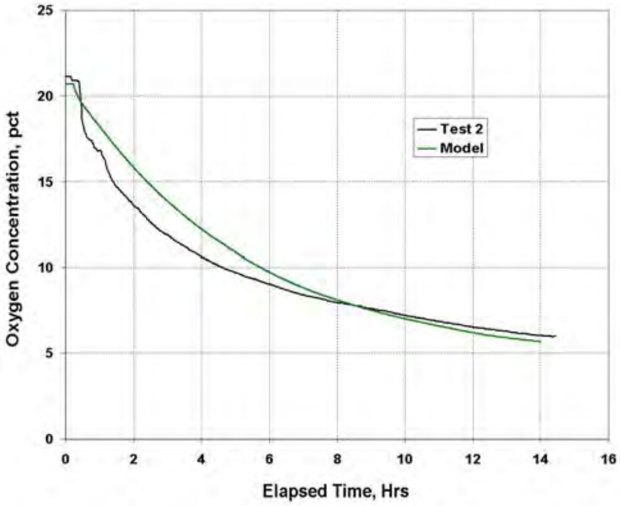

Figure 10. Comparison of SRCM Test 2 data and CFD model for sample point B.

In the next series of simulations, the mine volume was approximately doubled (figure 11) and the N_2 gas injection rate at ventilation seal No. 1 was incrementally increased in the model from 1 to 5 times (from 280 to 1,400 scfm) to observe the time needed to reduce the O_2 level in the simulated mine to below the 10% statutory limit. Figures 12 and 13 show the reduction of O_2 levels in the simulated mine at sample points C and D (figure 11). A horizontal red line was added to plots to signify the 10% O_2 level. The simulations were stopped at an O_2 concentration of 9.2%. Note the reduction in the time needed to reduce the O_2 level in the simulated mine is not substantially reduced with each incremental increase in rate of N_2 gas added.

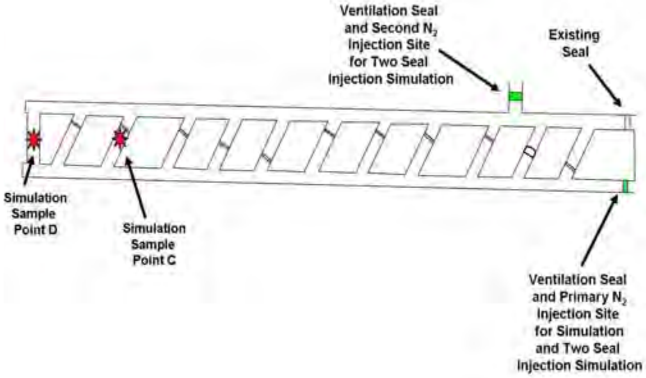

Figure 11. Map of simulated mine in CFD model.

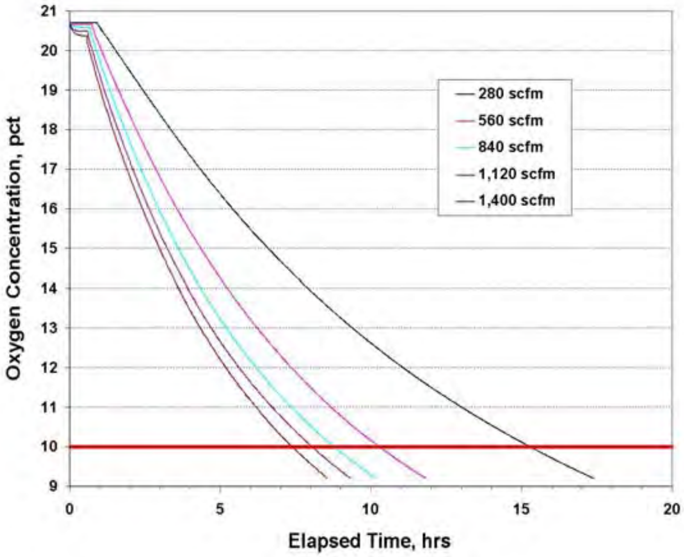

Figure 12. Multiples of the N_2 injection rate and model results at sample point C.

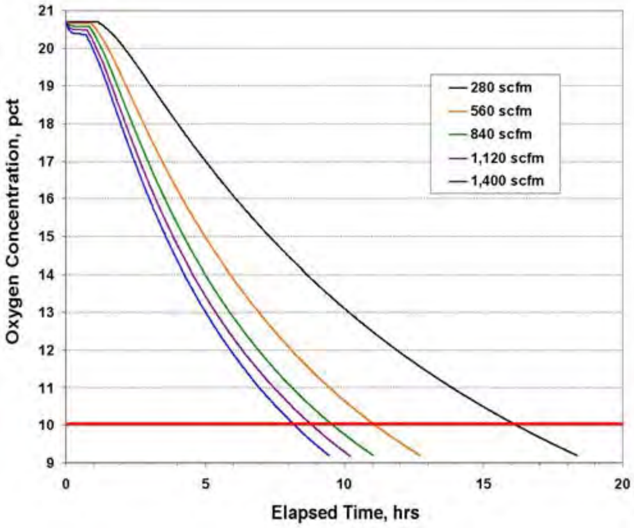

Figure 13. Multiples of the N_2 injection rate and model results at sample point D.

Figure 14 shows a graph of the average decrease in the time needed to reduce the O_2 level for sample points C and D to just below 10% as a function of multiples of the base injection rate (280 scfm). As can be observed in the graph, the reduction in time is not linear and the benefit of increasing the injection rate diminishes. It should be noted, that under the conditions studied in the model, a 50% reduction in the time needed to reduce the O_2 level to just below 10% (from 15 to 16 hrs to around 8 hrs) was achieved from a fivefold increase in the injection rate (from 280 to 1,400 scfm.

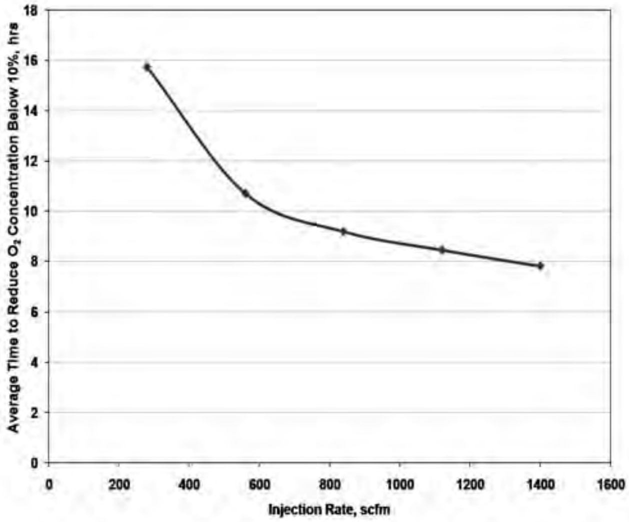

Figure 14. Time needed to reduce the O_2 level to below 10% in the simulated mine as a function of increasing the N_2 gas injection rate above the base rate used in the CFD model (280 scfm).

Figure 15 shows a comparison of simulations where the mine volume was doubled and the N_2 gas was injected at both ventilation seals simultaneously versus a two fold increase in the injection rate (from 280 to 560 scfm) only at ventilation seal 1 (for sample points C and D). As can be observed from the plot, the time to lower the O_2 concentration in the sealed area below 10% was decreased by about 2.5 hrs when the gas was pumped into both seals. Most likely the injection of N_2 simultaneously at two different locations altered the gas flow pattern in the model resulting in a more rapid decrease in the O_2 gas concentration.

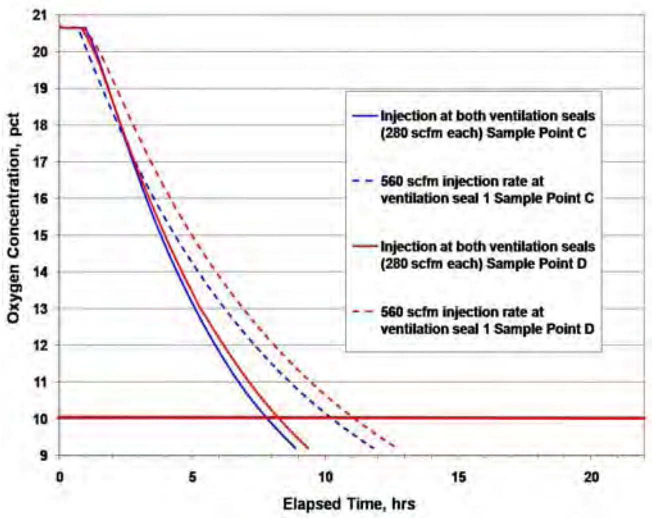

Figure 15 Comparison of N_2 injection at both ventilation seals simultaneously compared to a two fold increase in the injection rate only at ventilation seal 1 (for sample points C and D).

Summary and Conclusions

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 N_2 gas generating system is intended for use in the underground mine environment. The design of the unit included considerations for minimizing power requirements, sturdiness of construction, ease of use, ease of maintenance, reliability and transportability.

The N_2 gas generation system was tested in-house by On Site Gas Systems at the NIOSH SRCM where the atmosphere in a 62,000 ft^3 area of the mine was rendered inert during a series of two tests. Furthermore it was demonstrated that the system could successfully maintain an inert gas environment.

A CFD model of the NIOSH SRCM test layout was constructed and a good match was achieved with the field data collected from the SRCM tests. The most difficult challenge in the model design was gas leakage in the vicinity of the ventilation seals. Once the model was calibrated, the volume of the model mine was doubled and simulations were made using successive increases in the rate of gas injection.

The results of the CFD simulations show that with multiple increases in the N_2 gas injection rate, the average percent decrease in the time needed to reduce the O_2 level to just below 10% in the simulated mine is not linear and the benefit of increasing the injection rate diminishes as the N_2 injection rate is increased. Furthermore, simulations show that N_2 gas injection at both seals simultaneously reduces the O_2 content in the sealed area below the statutory limit more quickly as compared to doubling the injection rate at one seal location.

Acknowledgments

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