TESTING AND EVALUATION OF AN INFLATABLE TEMPORARY VENTILATION CONTROL DEVICE

Michael A. Trevits, NIOSH, Pittsburgh, PA,

Cliff McCartney, Strata Products (USA) Inc., Marietta, Georgia and

H.J. (Bill) Roelofs, Minvent Solutions, Como, Western Australia

Abstract

The National Institute for Occupational Safety and Health (NIOSH) in partnership with Strata Products tested the sealing capability of Ventstop®™ as part of an ongoing mine fire control and suppression research program. Ventstop®™ is a multi-purpose, inflatable device that is produced by Minvent Solutions and is available world wide for use in the metal and nonmetal mining industry. Ventstop®™ is also used in the Australian coal industry as a temporary ventilation control device. The device can be quickly deployed, is reusable and can be placed in horizontal and vertical mine voids to control dust, fumes and smoke. Deployment, multi-day inflation and air leakage tests were conducted at the NIOSH Lake Lynn Laboratory to determine the capability and limitations of Ventstop®™ in a simulated coal mine setting. During the tests, Ventstop®™ was also subjected to low level forces of a nearby methane gas ignition. It is thought that Ventstop®™ could be used by the US coal mining industry to temporarily close an underground mine area in response to a fire or spontaneous combustion heating event, to temporarily redirect mine ventilation during longwall equipment moves or during stopping construction. This paper describes this inflatable temporary mine sealing technology and presents the results of the NIOSH tests.

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

Introduction

Subsequent to the underground coal mine tragedies early in 2006, at the Sago Mine, the Aracoma Alma Mine No. 1, and Darby Mine No. 1, sweeping changes were made to state and federal coal mining safety laws. With the promulgation of 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) was charged to establish the Office of Mine Safety and Health (OMSH) to enhance the development of new mine safety technology and technological applications and to expedite the commercial availability and implementation of such technology for the mining industry. In addition, the OMSH was charged to conduct research, development, and testing of new technologies and equipment designed to enhance mine safety and health. To carry out such functions, the OMSH is actively awarding competitive grants to institutions and private entities to encourage the development and manufacture of mine safety equipment. The OMSH is also awarding contracts to educational institutions or private laboratories for the performance of product testing or related work with respect to new mine technology and equipment, and has established an interagency working group to share technology and technological research and developments that could be utilized to enhance mine safety and accident response.

In June 2008, Strata Products entered into an agreement with NIOSH to test the sealing capability of a temporary ventilation control device called Ventstop®™ under the charter of the OMSH new technology evaluation program. NIOSH was also conducting a comprehensive program of research addressing metal/nonmetal and coal mine fire prevention, detection and suppression so this work fit well within the NIOSH program. It was thought that Ventstop® could be utilized by the US coal mining industry to temporarily close an underground mine area in response to a fire or spontaneous combustion heating event and to temporarily redirect mine ventilation during longwall equipment moves or during stopping construction.

Strata Products in partnership with Minvent Solutions are industry leaders in designing, manufacturing and supplying safe, innovative and cost-effective and efficient mining products. Strata Products had previously decided to partner with Minvent Solutions who produces Ventstop®™[1] and a host of other inflatable ventilation and protective structures for the metal and non-metal producing and processing segments of the mining industry globally. Minvent Solutions began in 1992 and had its start in the underground mining industry by designing and manufacturing an inflatable, reusable overhead protection system (Passline) for a 200 ft ore pass. Upon successful completion of that work, Minvent Solutions was then challenged to design a balloon that could be used as a plug/inflatable formwork base suitable for pouring concrete in a problematic ventilation shaft. From there the company designed inflatable devices for bulkheads, ventilation brattices and temporary walls. Since that time, the technology has evolved and now Minvent Solutions provides systems for the mining, milling and processing segments of the industry and has progressed into smelters and refineries.

Ventstop®™

Ventstop®™ is a multi-purpose, inflatable device that is produced by Minvent Solutions and is available world wide for use in the metal and nonmetal mining industry (figure 1). Ventstop®™ is used as an emergency temporary ventilation control device, for controlling ventilation in breakthrough situations, to combat radiation dust, thermal heating return vent, blast fumes and fires. The device can be quickly deployed, is reusable and can be placed in horizontal and vertical mine voids.

Figure 1. Photo of Ventstop.®™

Ventstop®™ was introduced into the Australian Coal Industry in 2005. These units were specifically designed to be placed in strategic areas around a mine for emergency deployment. The original device was a cubed-shaped inflatable structure with square ends (new models for coal mining are cylindrical). The standard unit is constructed from a polyester scrim-based fabric with a double-sided polyvinyl chloride coating (Australia <30 mega ohms NCB Specification 245) and meets the Mine Safety and Health Administration (MSHA) requirements for ventilation materials (MSHA Approval No. 07-BA070011) [1-2].

In general, a Ventstop®™ unit will accommodate entry-width variations of 2 ft and height variations of 3 ft. The unit is typically sized 1 ft larger in diameter than the mine height to ensure the best fit because the surface of mine openings are typically rough and of non-continuous dimensions. Furthermore, if the diameter of the unit is larger than the mine height then mine roof and floor contact area is increased. There is a constraint on length of the Ventstop®™ unit relative to entry width. The unit should be no more than 1-to 2-ft longer than the entry width to minimize the possibility of wrinkling the fabric and thus increasing the potential for air to by pass the unit when inflated. Ventstop®™ is currently available in three standard sizes: 7 ft, 10 ft and 13 ft diameters by 18, 20 and 22 ft lengths (these sizes are designed to fit a maximum 6, 9 and 12 ft high mine opening respectively). It should be noted that a unit can be custom built to any size and shape specification to accommodate any individual application.

Ventstop®™ is completely portable and contains a single chamber that can be inflated from one fill port location by either mine compressed air or bottled compressed air with a venturi or a powered blower. The inflation pressure is very low, on the order of 0.25 to 0.35 psi. The unit can be kept inflated for days using an available filtered pressure demand control system. This system provides a small gas flow to the Ventstop®™ unit to maintain appropriate pressure, and is capable of keeping a unit inflated even when it contains small holes or cuts. Holes or cuts in the unit can be temporarily repaired using a self-adhesive patch, and a permanent repair can be made by welding on fabric patch in fresh mine air.

NIOSH Lake Lynn Experimental Mine

The research was conducted at the NIOSH Lake Lynn Experimental Mine (LLEM), located approximately 60 miles southeast of Pittsburgh, Pennsylvania. The LLEM is a world-class, highly-sophisticated underground facility where large-scale explosion trials, mine fire research and a myriad of other mine safety and health

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[1] Mention of a specific product or trade name does not imply endorsement by NIOSH.

research programs are conducted. The underground workings are sized to match those of commercial mines, thus making them true, full-scale test galleries. Movable bulkheads permit the setup of single-entry, triple-entry, and longwall face configurations for experiments (figure 2) [3].

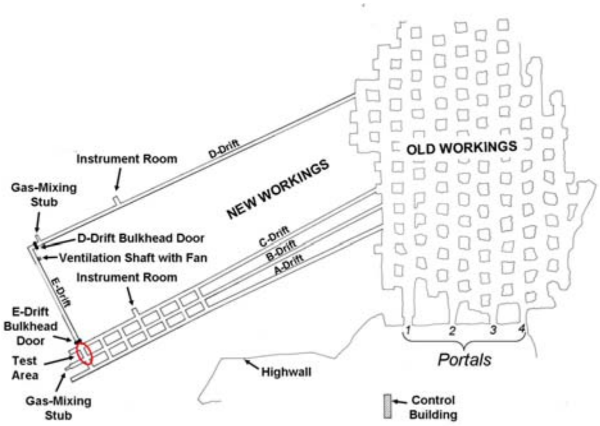

Figure 2. Layout map of the Lake Lynn Experimental Mine.

The air leakage and deployment tests were conducted in the first crosscut between the B and C-Drifts of the LLEM (figure 2). The crosscut measured 18.3 ft (wide) by 6.8 ft (high) by 40 ft (long). The mine floor sloped to the southwest at a 1.1% gradient. The test area was set up so the long axis of the Ventstop®™ structure could be installed perpendicular to the crosscut. The mine roof in this area was irregular and did not contain any roof bolts or steel protrusions.

Ventilation for the mine is provided by a ventilation shaft with a fan located about 550 ft away in the E-Drift (figure 2). The fan speed is adjustable to 4 different settings and provides for a variety of test conditions. Figure 3 shows the flow rate for the fan for two different mine configurations for three of the fan speeds (note the C-Drift closed, D-Drift bulkhead door closed configuration was used in this study).

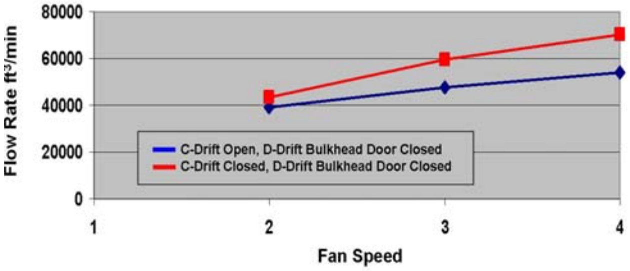

Figure 3. Flow rate for the LLEM fan at 3 speed settings

The test area was set-up so that the all of the air (and resulting pressure) from the fan would be directed at the Ventstop®™ unit. To minimize air leakage, the intersecting drift openings (B- and C-Drifts) were closed-off using brattice cloth affixed to a wooden frame. To permit differential pressure measurements, ¼-in diameter tubing was attached to the mine roof across the opening spanned by the Ventstop®™ unit and extended through the nearby downstream brattice cloth and wooden frame structure. This location served as the evaluation point for the tests (figure 4). Air leakage rates were determined using a vane anemometer and the measurements were made at a hole that was cut into the brattice cloth (at the B-Drift intersection) the same diameter as the anemometer. Mathematical calculations were then made to determine the final air leakage rate using the anemometer and differential pressure measurements. Video cameras were mounted on both sides of the Ventstop®™ unit to document the tests.

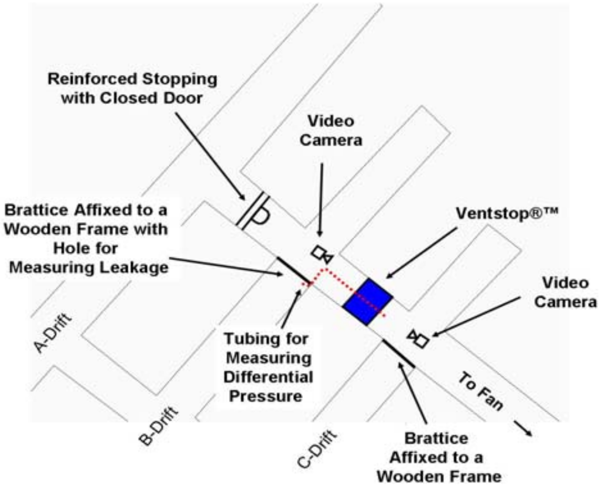

Figure 4. Layout map of the study area in the No. 1 crosscut of the LLEM.

Deployment Tests

The Ventstop®™ unit used in this study was a prototype constructed of the fire-retardant and anti-static fabric. The unit measured 10 ft in diameter and was 20 ft long and weighed 150 lbs. The Ventstop®™ unit was installed by two persons several times in the mine opening to determine how long it would take to fully deploy the unit. The unit was inflated using mine air and a venturi. On average it took approximately 7.5 minutes to install the unit from the carry bag to full inflation in the mine opening (5.5 minutes to inflate the unit only) (figures 5-6). Deflation of the unit, folding and replacement into the carry bag took about 15 minutes (11 mnutes to deflate the unit only). Once the unit was installed in the mine opening, it was determined that 91.5 ft^2 of contact area (5 ft by 18.3 ft) was made at both the mine roof and floor areas with a total contact area of 340 ft^2 including the roof, floor and side areas.

The deployment tests were conducted with the mine fan turned off and thus in the absence of active mine ventilation air currents. When the fan was turned on and all of the air was directed through the crosscut, problems were experienced when trying to hold the unit in place to initiate inflation even at the lowest fan setting. Although the unit contained two hold down loops, it was not possible to securely fasten the unit to the mine opening because the loops were designed for maneuvering the prototype unit during inflation and were affixed to the outside of the unit rather than through the fabric and secured from the inside surface. When the test was repeated and the brattice was removed from the C-Drift opening (thus providing an alternative flow path for the air when the Ventsop®™ unit was deployed), the problem experienced earlier with inflating the unit did not occur (for the air leakage tests, the brattice was reinstalled across the C-Drift opening).

The problem of installing the unit in high flow mine ventilation air can be overcome by setting a line of wooden posts (cribbing blocks or other supplemental mine roof support structures can also be used) across the width of the entry and inflating the unit against the posts. The use of nylon netting was also suggested by previous researchers to deploy other inflatable devices in active mine air [4]. To alleviate the installation problem in active mine air, the design of the unit has since been altered to include additional hold down loops that are attached from the inside and are intended for affixing it to a rib or roof bolts prior to inflation.

Figure 5 – Carry bag for transporting the Ventstop®™ unit.

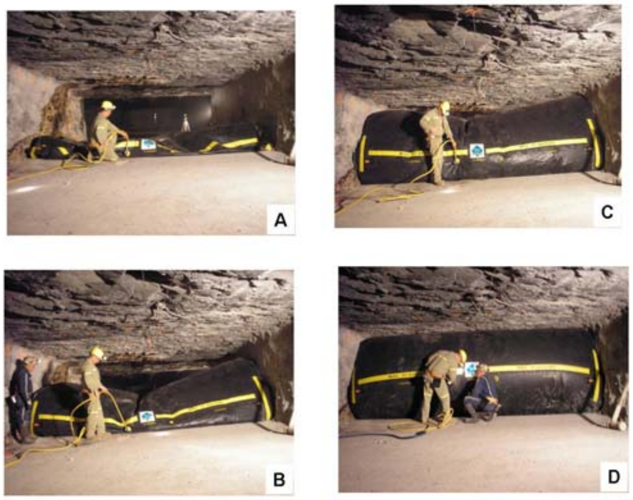

Figure 6. Inflation sequence for the Ventstop®™ unit.

During deployment, adjustments were made to position the unit correctly in the mine opening and to remove wrinkles in the fabric. These adjustments were made by holding the fabric (either at the hold down loop or by clutching the fabric) and moving it to the desired position. This task was relatively easy provided it was done before the unit was fully inflated. If a problem area (such as a wrinkle) was observed after the unit was fully inflated, the problem could be easily corrected by partially deflating the unit, making the adjustments in the fabric and re-inflating the unit. Figures 7 and 8 shows the unit fully inflated in mine opening.

Figure 7. Fully deployed Ventstop®™ unit as viewed from the C-Drift side.

Figure 8. Fully deployed Ventstop®™ unit as viewed from the B-Drift side.

Air Leakage Tests

A series of 4 air leakage tests were conducted to determine the sealing capability and limitations of the prototype Ventstop$^{®™}$ unit. The test area was set up as described earlier and all of the air from the fan was directed towards the Ventstop$^{®™}$ unit (refer to figure 4). A description of the tests, objectives and commentary about the tests are shown in Table 1.

Table 1. Description of Air Leakage Tests.

Air Leakage Test No.	Objective	Procedure and Comments
1	Compare air leakage rates at two different inflation pressures.	Air leakage measurements made on two separate days.
2	Apply polyurethane (PUR) sealant and compare pre- to post-sealant application air leakage rates.	Measurements made on same day after sealant had cured.
3	After PUR application, compare air leakage rates after 24 hrs.	Pressure demand control system was used to ensure that unit would remain inflated. Pressure maintenance level for control system was set below the initial setting pressure. Measured air leakage at start of test, after 24 hrs, then re-pressurized unit to previous day's inflation pressure and measured air leakage.
4	Observe effects of nearby methane gas ignition on unit.	Inflated unit measured air leakage. Conducted nearby methane gas ignition. Unit set for 24 hrs without the use of the pressure demand control system. Measured air leakage, then re-pressurized to previous day's inflation pressure and measured air leakage.

Figure 9 shows the results of Test No. 1. The objective of this test was to compare air leakage at two different inflation pressures that could be used in an actual underground mine setting. As shown in the figure, air leakage was decreased by about 25% at the higher inflation pressure. In all likelihood, the increased pressure forced the unit to fit more tightly across the irregular surface of the mine opening.

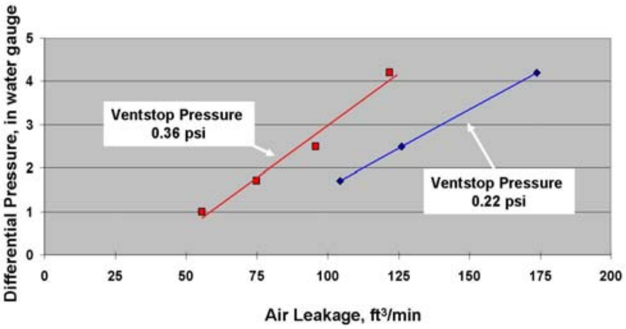

Figure 9 Plot of air leakage during Test 1.

Figure 10 shows the application of a PUR sealant to the upwind side of the Ventstop$^{®™}$ unit as a supplemental means of minimizing mine air leakage. The PUR sealant was sprayed along the entire perimeter at the interface between the Ventstop$^{®™}$ unit and the mine opening. The expanded thickness of the applied sealant was about 5 in and tapered in thickness to 1/8 in at a depth of about of 18 in using the standard spray head provided with the PUR material.

Figure 10. Application of PUR to the perimeter of the Ventstop$^{®™}$ unit.

Figure 11 shows the results of Test 2 in which pre- and post-PUR sealant application air leakage tests were conducted. As expected, a dramatic decrease in air leakage (85%) occurred subsequent to the application of the PUR sealant. Smoke tube testing prior to the PUR application showed that most of the air leakage was occurring near the mine roof and rib interfaces and these air leakage paths were mostly eliminated with the application of the sealant.

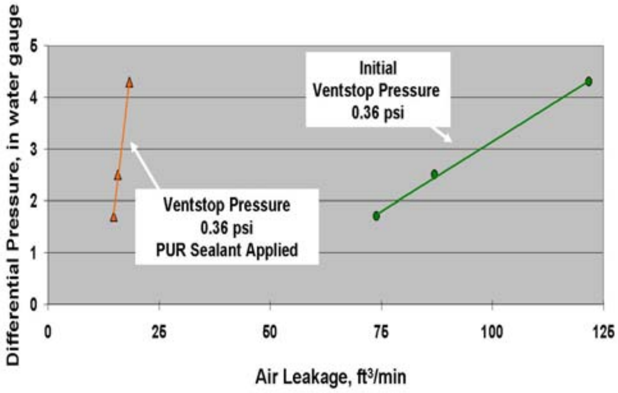

Figure 11. Plot of air leakage as observed during Test 2.

Recently, there has been some concern about heat build-up in conventional mine seals constructed from PUR material. Though the intended use of the Ventstop®™ unit is for temporary ventilation control and the PUR material is a supplemental sealing material that is applied to one side of the perimeter of the unit (up to 5.5 in thick), it was decided to conduct a heat build-up test using a swatch of the Ventstop®™ fabric and the PUR sealant. In this test, a 24-in square piece of the Ventstop®™ material was affixed to a wooden frame. Attached to the frame were four wooden legs that positioned the frame 2 ft above the ground surface. Three thermocouples were used in the experiment: one measured ambient mine temperatures; one was positioned to measure heat build-up in the polyurethane mass and was located 1 in above the top surface of the fabric (in the center of the square); and the third one measured heat transfer through the Ventstop®™ material and was affixed to and touching the underside of the fabric (also in the center of the square). The temperature of the fabric surface was allowed to equilibrate to the ambient mine temperature for 4 days before the PUR sealant was applied. PUR sealant (the same type used in the air leakage tests) was then sprayed onto the top surface of the Ventstop®™ fabric to an expanded thickness of 5.5 in. The temperatures at all locations were recorded for 23 hrs and until they were at or near the ambient mine temperature. Figure 12 shows a photograph of the PUR material after it was cut apart to recover the thermocouple.

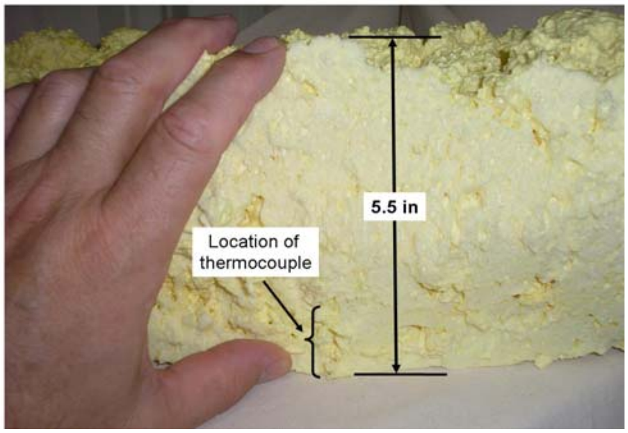

Figure 12. Cutaway view of the PUR mass from heat build-up test.

This figure shows that the PUR was applied correctly and the material cured evenly across the test surface. Figure 13 shows the temperature data for this test. It can be observed from the test results that the heat build-up rate was very fast and achieved a maximum temperature of 188ºF (well below its auto-ignition temperature). Heat transfer to the underside of the fabric was much less and reached a maximum value of 83ºF.

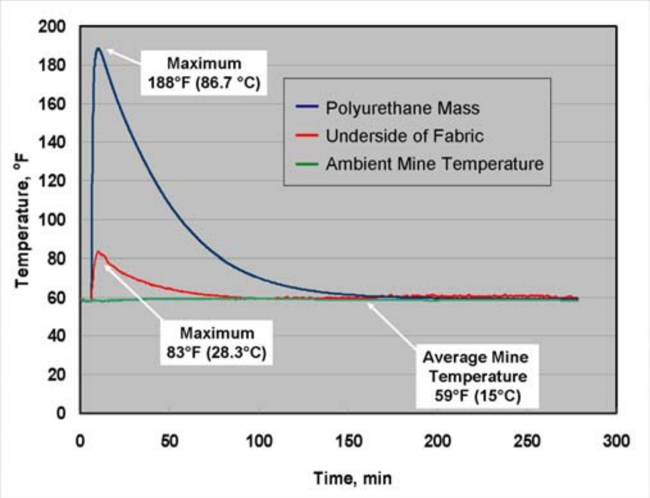

Figure 13. Plot of temperature data for the PUR heat build-up test.

Air leakage Test 3 involved a 24 hr inflation test with use of the pressure demand control system. This system was designed to maintain a set inflation pressure on the Ventstop®™ unit. An air leakage measurement was made at the beginning of the test (at 0.36 psi inflation pressure) after the PUR sealant was applied and 24 hrs later at the maintenance pressure of 0.22 psi. The unit was then inflated to 0.36 psi (the original inflation pressure) and another air leakage measurement was made.

Figure 14 shows the results of Test 3. It is unknown how many times the pressure demand control system was used to re-pressurize the Ventstop®™ structure during the overnight test. When mine air leakage was measured (after 24 hrs), the unit actually leaked less air at the lower inflation pressure (0.22 psi). Furthermore, when the unit was re-pressurized to the previous day's pressure setting (0.36 psi), the unit leaked less air than the day before. It is thought that the re-pressurizing cycle (or cycles) caused the Ventstop®™ structure to seat more tightly in the mine opening and thus leak less air as observed in the test. It should also be kept in mind that these air leakage rates are very low, approaching the limits of the measuring method and may not be completely accurate.

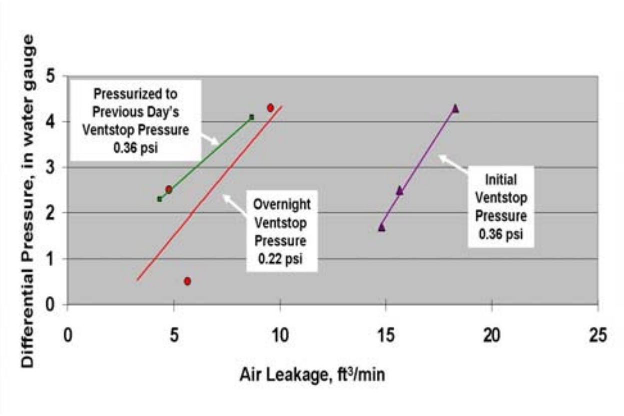

Figure 14. Plot of air leakage as observed during Test 3.

Air leakage Test 4 was carried out while a methane gas ignition test was being conducted at a different part of the mine. The Ventstop®™ unit was approximately 1,250 ft from the A-drift ignition zone. The pressure pulse from the ignition traveled through the A-Drift, crossed into the B- and C-Drifts and then was applied to the Ventstop®™ unit at two slightly different times due to travel distance. Pressure transducers were placed on both sides of the Ventstop®™ unit to capture the magnitude of the pressure pulse. Based on the B-Drift pressure data, the Ventstop®™ unit was subjected to an initial peak positive pressure (after some oscillations) of about 0.08 psi, followed by a peak negative pressure of about 0.25 psi, then another peak positive of about 0.15 psi followed by a peak negative of about 0.1 psi; this oscillation continued until the end of the 12 second data acquisition time. Based on the C-Drift pressure data, the Ventstop®™ unit was subjected to an initial peak positive pressure of about 0.45 psi, followed by a peak negative pressure of about 0.65 psi, then another peak positive of about 0.5 psi; at that point, the 12 seconds of acquisition time ended. The peak sweeping pressure value appears to be in the 0.5-0.6 psi range [5]. Upon visual inspection, the Ventstop®™ unit appeared to be intact. Figure 15 shows the results of air leakage tests conducted before the ignition, 1 day after the ignition (the unit had lost 0.12 psi) and then when it was re-inflated to the pre-ignition conditions. The data on the plot suggests that no significant change in air leakage occurred as a result of the ignition.

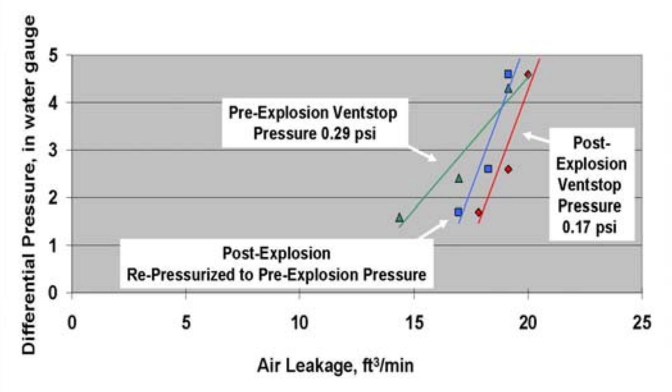

Figure 15. Plot of air leakage as observed during Test 4.

Comparison of Ventstop®™ Air Leakage Rates with Stoppings

In a study conducted by the US Bureau of Mines (USBM), five different stopping construction techniques were evaluated and air leakage tests were performed [6]. The stoppings studied included conventional stoppings that were built by dry-stacking hollow-core concrete blocks and troweling mortar on one stopping face; quick-build stoppings that were built in the same manner as conventional stoppings except brushed-on glass-fiber enhanced mortar (modified mortar) was substituted for troweling; universal stoppings that were built of dry stacked hollow-core blocks, had a footer, keyed ribs, sealed roof and one face sealed with one coat of modified mortar; high-pressure stoppings that were built of hollow-core wet-laid concrete blocks, had a footer, keyed ribs, a sealed roof, two brushed-on coats of modified mortar on one face and one coat of brushed-on modified-mortar on the other face; and hybrid stoppings that were built the same way as high-pressure stoppings, except that solid-core blocks were used instead of hollow-core blocks. Figure 16 shows a comparison of the leakage rates for Ventstop®™ at 0.22-, 0.36-psi and 0.36-psi inflation pressure with PUR applied from this study with the other types of newly constructed stoppings from the USBM study. Also for comparative purposes, the air leakage rates were converted to cubic feet per minute per hundred square feet of stopping area per inch water gauge pressure differential [6]. As can be observed in the figure, the air leakage rates for the Ventstop®™ unit were among the lowest leakage rates observed. Also, the leakage rate for the Ventstop®™ unit with PUR applied was the lowest rate measured.

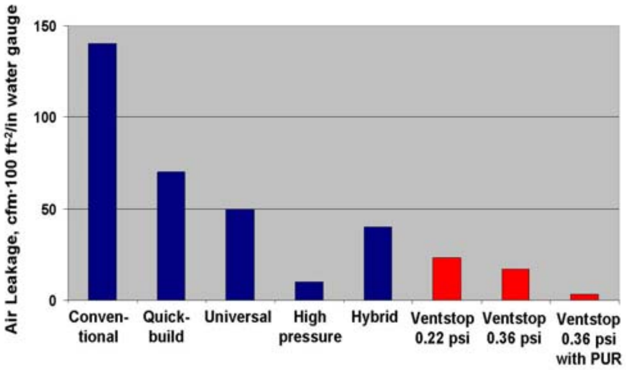

Figure 16. Air leakage for various newly constructed stoppings and Ventstop®™.

Summary and Conclusions

Ventstop®™ is a multi-purpose, inflatable device produced by Minvent Solutions and is available world wide for use in the metal and nonmetal mining industry. Ventstop®™ is used as an emergency seal (temporary ventilation control device), controlling ventilation in breakthrough situations, radiation dust, thermal heating return vent, blast fumes, fires, pass plugs and shaft sealing system. The device can be quickly deployed, is reusable and can be placed in horizontal and vertical mine voids. Ventstop®™ was introduced into the Australian Coal Industry in 2005.

A series of tests, conducted at the NIOSH LLEM, showed that Ventstop®™ could be quickly deployed by two persons in approximately 7.5 minutes (to install the unit from the carry bag to full inflation in the mine opening and 5.5 minutes to inflate the unit only). Deflation of the unit, folding and replacement into the carry bag took about 15 minutes (11 minutes to deflate the unit only). The tests noted a difficulty when attempting to install the unit in high flow mine ventilation air that can be resolved with additional more robust hold down loops (used in the newest design) or propping the unit during inflation against a series of posts, cribbing blocks or other supplemental roof support structure. Air leakage testing showed that the unit could provide an effective temporary mine seal that could be further enhanced through the application of PUR sealant. Inflation of the unit for extended periods of time (24 hrs or greater) is possible through the use of a pressure demand control system. In these tests, mine ventilation air leakage rates were between 55 and 175 ft^3/min depending on inflation pressure without the use of PUR sealant. When PUR sealant was applied to the unit, air leakage rates were substantially reduced by 85%.

The Ventstop®™ unit was also subjected to the oscillating pressure pulses from a methane gas ignition. Though the ignition zone was approximately 1250 ft away and the resulting pressure pulse degraded as it traveled through a series of drift openings to the Ventstop®™ unit, it successfully withstood a maximum peak positive pressure pulse of 0.5 psi and maximum peak negative pressure pulse of 0.65 psi and a peak sweeping pressure value in the 0.5 to 0.6 psi range. Pre-and post-explosion tests show that the air leakage past the Ventstop®™ unit was not affected by the forces of the pressure pulses.

Comparison of air leakage rates for Ventstop®™ at 0.22-, 0.36-psi and 0.36-psi inflation pressure with PUR applied from this study with the several types of newly constructed stoppings from a previous USBM study showed the air leakage rates for the Ventstop®™ unit were among the lowest rates observed. Also, the leakage rate for the Ventstop®™ unit with PUR applied was the lowest rate measured.

Ventstop®™ unit appears to be a promising technology for use as a temporary ventilation control device in US coal mines. The Ventstop® unit could be utilized by the US coal mining industry to temporarily close an underground mine area in response to a fire or spontaneous combustion heating event and to temporarily redirect mine ventilation during longwall equipment moves or during stopping construction.

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