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EVALUATION OF THERMAL DISPLACEMENT VENTILATION IN CONTAMINATION PURGING INSIDE A 60-PERSON BUILT-IN-PLACE REFUGE ALTERNATIVE (BIP RA) IN AN UNDERGROUND COAL MINE

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ABSTRACT

Federal regulations require the installation of refuge alternatives (RAs) in underground coal mines to ensure miners' survivability after a fire or an explosion where escape is impractical or even impossible. Both fires and explosions can generate dangerous or even lethal levels of carbon monoxide (CO) in a mine. As part of their function, RAs must be able to isolate miners from a CO-contaminated mine environment and to purge any CO that might enter the RA as miners enter it. In 2018, researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted purging research in a built-in-place (BIP) RA with a borehole air supply by testing 12 different mixing ventilation system configurations (MVSCs). Recently, NIOSH researchers evaluated the use of a thermal displacement ventilation system configuration (TDVSC) to purge a 60-person BIP RA using a borehole air supply. As in previous research, NIOSH researchers tested the TDVSC with the flow rates of 750 SCFM and then 1,000 SCFM. For each of the flow rates, the results showed that the average purge time for the more expensive TDVSC is within two minutes of the average purge times of previously tested MVSCs. Manufacturers can use this information to not only pursue 30 CFR Part 7 approval from the Mine Safety and Health Administration (MSHA), but also to determine the most practical method to purge contaminants inside RAs.

Keywords: Mining, mine disaster, fluid mechanics, experimentation, refuge alternative, refuge chamber, ventilation, carbon monoxide, purging, thermal displacement

NOMENCLATURE

α	exponential decay constant for perfect mixing equation
BAS	borehole air supply
BIP	built-in-place
C_0	initial concentration at time 0
$C(t)$	concentration at time t
CO	carbon monoxide
MSHA	Mine Safety and Health Administration
MVSC	mixing ventilation system configuration
NIOSH	National Institute for Occupational Safety and Health
RA	refuge alternative
SCFM	standard cubic feet per minute
SF ₆	sulfur hexafluoride
t	time
TDVSC	thermal displacement ventilation system configuration

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1. INTRODUCTION

According to federal mine safety and health regulations, refuge alternatives (RAs) must provide breathable air for trapped miners that are incapable of escape from a mine due to a disaster, such as a fire or an explosion. Both fires and explosions can generate unsafe carbon monoxide (CO) levels in an underground coal mine. Mine Safety and Health Administration (MSHA) inspectors recorded CO concentrations of approximately 2,600 ppm after the Sago Mine disaster [1], and 10,000 ppm after the Upper Big Branch disaster [2]. Previous NIOSH contamination ingress research on built-in-place (BIP) RAs showed that after 30 subjects entered a 30-person BIP RA the resulting CO concentration in the BIP RA could be 2%–3% of the mine's ambient CO concentration [3]. Thus, if a mine's ambient CO concentration is 10,000 ppm, the CO concentration in a 30-person BIP RA without an airlock would be 200 ppm to 300 ppm after 30 miners entered. These concentration levels are above the MSHA-allowable CO limit of 25 ppm [4] and can cause headaches or dizziness [5], which would be detrimental in a post-disaster scenario. Researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted contamination purging research to evaluate the effect of ventilation system layout on the average time to purge a concentration of 1,000 ppm to 25 ppm and to identify the presence of dead spots.

Federal regulations require that RAs must be able to provide a breathable air environment for a minimum of 96 hours. Three methods are commonly used to provide a breathable air environment for RAs. The most widely used method employs compressed oxygen cylinders that are stored on a cylinder rack in an RA. Another method uses an air compressor on the surface to deliver compressed air through hoses or compressed air lines. The final method uses a borehole air supply (BAS) consisting of a blower or a centrifugal fan on the surface to provide air through a borehole directly to an RA or through additional plumbing that leads inside the BIP RA. The research presented here used a BAS to deliver air to a BIP RA.

In a general exhaust ventilation system, air enters the enclosure through one or more inlets, and diluted contaminants are exhausted through one or more outlets [6]. For a BIP RA, air is delivered using a source, such as a BAS, and is exhausted through outlets with check valves. The check valves prevent contaminants from entering the BIP RA from the mine, protect the ventilation system from blast pressures, and help maintain positive pressure inside the BIP RA. There are two types of ventilation systems that could be used: mixing ventilation system configurations (MVSCs) and thermal displacement ventilation system configurations (TDVSCs).

For MVSCs, air enters an enclosure through one or more inlets and exits through one or more outlets. Because the air enters at a relatively high velocity compared to the contaminated air inside the enclosure, eddy currents are created that mix the clean air and the contaminated air. The diluted contaminated air exits the enclosure via the outlets.

The basic principles of a TDVSC are a relatively low, uniform air velocity and the use of thermal gradients. In this

configuration, the main air inlet is piped to the bottom of the enclosure. An air diffuser is placed at the main inlet to spread the entering air over a broad area to reduce the velocity of the incoming air. The reduced air velocity from the main inlet minimizes mixing with the contaminated air inside the enclosure. The wall of low-velocity incoming air acts as a piston as it moves uniformly along the bottom of the enclosure where the coldest air is located. Heat sources inside the enclosure warm the surrounding air to create thermal gradients. Generally, the cool air entering the enclosure moves along the floor until it is heated, which causes it to rise as it moves through the enclosure, thus creating temperature stratification. The thermal gradients lift the contaminants, and the piston-like action of the incoming air forces them out of the enclosure through one or more air outlets located near the top of the enclosure. This paper describes how NIOSH researchers evaluated the effect of a TDVSC on contamination purging in a 60-person BIP RA. Results for the TDVSC were then compared to the results of previous NIOSH testing for MVSC purging systems.

2. MATERIALS AND METHODS

This study builds on prior NIOSH research on MVSC purging systems for BIP RAs [7] and uses the same test facility and methods. The purpose of the test was to investigate the purging characteristics of a TDVSC. As in the previous study, a BIP RA facility built in the NIOSH Experimental Mine was used to conduct the tests. The BIP RA is approximately 13.0-m (42.5-ft) long by 6.1-m (20-ft) wide by 2.1-m (7-ft) high. To conduct the tests, NIOSH researchers used sulfur hexafluoride (SF_6) as a surrogate for CO. Prior to beginning a test, SF_6 was injected into the BIP RA and mixed using fans until a uniform concentration of 1,000 ppm $\pm$ 100 ppm was achieved. Inside the BIP RA, the researchers used eight infrared gas monitors to measure the SF_6 concentration at 16 sampling locations at two heights, 0.71 m (28 in) and 1.57 m (62 in), as shown in Figure 1. To provide clean air to the BIP RA, the researchers used a ChemBio Shelter emergency BAS system with a rotary screw compressor at flow rates of 750 SCFM and at 1,000 SCFM. Expanding upon the previous research, NIOSH researchers created a TDVSC which incorporated the three principles that constitute a TDVSC: low velocity, thermal gradients, and temperature stratification.

NIOSH researchers connected diffusers to the BIP RA air inlet to achieve uniform and low-velocity airflow. As shown in Figure 2 and Figure 3, NIOSH researchers split the main air inlet into three branches at the bottom rear of the BIP RA and installed 0.61-m (24-in) tall by 0.15-m (6-in) wide by 1.83-m (72-in) long air diffusers in each branch. The researchers placed the diffusers 1.85 m (73 in) from the rear of the BIP RA wall and 0.36 m (14 in) apart.

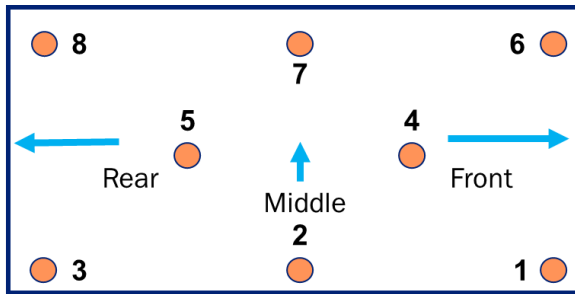


Figure 1: The sampling locations to measure the SF_6 concentration inside the BIP RA.

To create a temperature gradient, NIOSH researchers placed heat sources inside the BIP RA. To align the study with potential real-life scenarios, NIOSH researchers used simulated miners, which have been used extensively by NIOSH in prior RA heat/humidity research [8]. A simulated miner is a device made from a 55-gallon barrel with internal electrical resistance heaters capable of generating sensible heat and latent heat. Each simulated miner generates about 120 watts, representing the metabolic heat rate of a miner inside an RA. During operation, the average surface temperature of the simulated miners was between 32°C (90°F) and 33°C (92°F) at steady state.

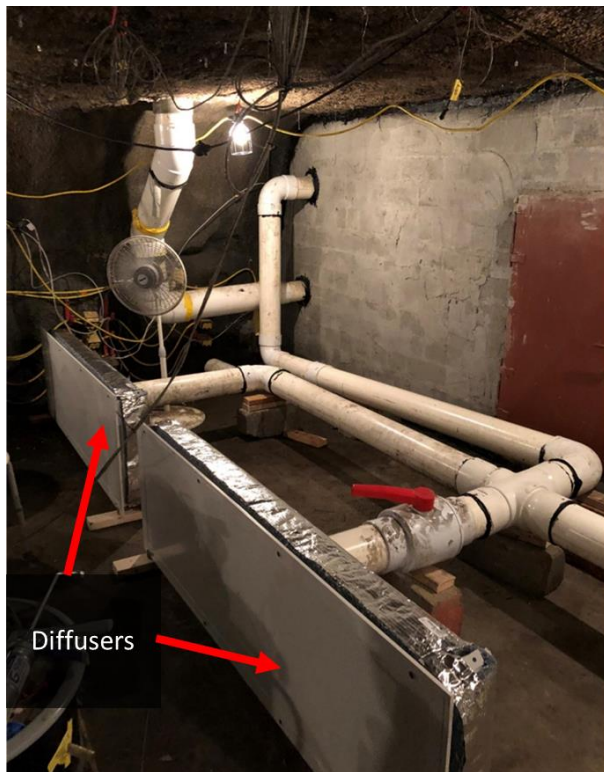


Figure 2: The main air inlet is split into three branches. The three branches are connected to three diffusers in the rear of the BIP RA.

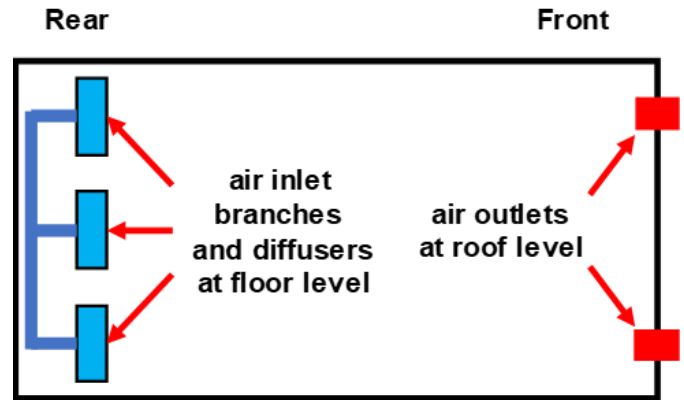


Figure 3: This layout shows the TDVSC in the BIP RA with the main air inlet split into three branches attached to the diffusers and the two air outlets.

As the test progressed, NIOSH researchers verified that using the simulated miners created a vertical temperature gradient in the BIP RA. For reference purposes, the researchers divided the BIP RA into three sections: front, middle, rear. Each section had three air temperature sensors located at three heights: 0.30 m (12 in) from the floor, 1.04 m (41 in) from the floor (mid-height), and 0.30 m (12 in) from the roof, which has a height of approximately 2.1 m (7 ft.). Temperatures from each sensor were recorded prior to and during the tests.

NIOSH measured the flow rates, the ambient air temperatures, the simulated miner surface temperatures, and the power delivered to the simulated miners. A Fluid Components International ST98 thermal mass flowmeter was used to measure the flow rate in line with the BIP RA air inlet. The flowmeter can measure air flow across a range of 0–900 SCFM within an accuracy of $\pm 1\%$ of the reading, plus 0.5% of full scale. The power provided to the simulated miners was measured with an Ohio Semitronics GW5 with an accuracy of 0.2% across a range of 0–5,000 watts. To measure the ambient temperature inside the BIP RA, Class A RTDs and Vaisala HMP 110 humidity/temperature probes were placed in three sections at three heights. The Vaisala HMP 110s had a temperature accuracy of $\pm 0.2^\circ\text{C}$ ($\pm 0.36^\circ\text{F}$) across a range of 0°C – 40°C (32°F – 104°F). Class A RTD sensors were also used to measure the temperature of the two simulated miners. One simulated miner was in the front section and another in the middle section of the BIP RA.

Eight Honeywell IR 148 SF_6 monitors were used to measure the SF_6 concentration at 16 sampling locations inside the BIP RA. Each gas monitor measured SF_6 concentration using two sample ports at two heights—0.71 m (28 in) and approximately 1.57 m (62 in)—as shown in Figure 1. The SF_6 monitors simultaneously measured the concentrations from the lower locations and the concentrations from the upper locations. The gas monitors are capable of measuring SF_6 concentrations from 0–100 within ± 4 ppm, 250 ppm within $\pm 2.5\%$, 500 ppm within $\pm 5\%$, and up to 1,000 ppm within $\pm 10\%$.

NIOSH researchers collected data while purging from an initial SF_6 concentration to an arbitrary final SF_6

concentration. Next, researchers curve fit the measured data with the perfect dilution equation (1) to determine the α exponent that describes the decrease in concentration over time. Then, they used the α to determine the time to reduce the SF₆ concentration in the BIP RA from an arbitrary initial concentration of 1,000 ppm to 25 ppm, the MSHA limit for RAs using equation (2) where C is 25 and C₀ is 1,000.

$$C(t) = C_0 e^{-\alpha t} \quad (1)$$

$$t = \left(\frac{1}{\alpha}\right) * \ln\left(\frac{C_0}{C}\right) \quad (2)$$

Prior to collecting data, NIOSH researchers performed a calibration and function check on each monitor. First, calibration of the SF₆ monitors was performed using zero air to set the 0-ppm reading for a monitor followed by the use of R134A refrigerant gas to set the monitor to a factory-programmed value on the unit's internal computer. After calibrating the monitors to ensure each unit was functioning properly, the researchers performed a calibration check using SF₆ gas with concentrations of 25 ppm and 1,000 ppm.

Prior to each test, to achieve a uniform concentration of 1,000 ppm, the researchers released about 1 kg (2.2 lbs.) of SF₆ inside the BIP RA using an injection port in the front of the BIP RA. A fan at each of the four corners of the BIP RA stirred the contaminants for five minutes. Next, the fans were turned off and the researchers waited for five more minutes to ensure that the SF₆ concentrations at each location were 1,000 ppm within 0–50 ppm. Finally, the researchers turned on the BAS to deliver air and recorded the SF₆ concentrations until the readings dropped below 10 ppm. The resulting data were curve fit using Equations 1 and 2 as described above.

NIOSH researchers conducted the contamination purging tests with two airflow rates. Because the regulation requires RAs to provide at least 12.5 SCFM of air per person and testing was done in a 30-person BIP RA, 750 SCFM was used for one of the flow rates. The researchers also used a flow rate of 1,000 SCFM

because it was the maximum flow rate for the BAS. For each flow rate, the researchers performed three trials.

3. RESULTS AND DISCUSSION

Prior to beginning the purging tests, the researchers validated that the ventilation system setup met the required principles of a TDVSC, including a relatively low, uniform flow velocity and a vertical temperature gradient. The researchers measured the air velocity across the faces of the diffusers with the BAS set to an airflow of 750 SCFM. The air velocities ranged from 0.18 m/s to 0.24 m/s. For comparison purposes, the air inlet velocity from a MVSC with a single (6-inch) diameter air inlet would be from 6.5 to 8.1 m/s. The researchers measured the temperature inside the BIP RA for a 50-minute period after turning on the BAS to verify that a temperature gradient was created. The average temperature for each height was calculated using the temperature readings for the three BIP RA sections. As shown in Figure 4, the lowest average temperature was 0.30 m (12 in) from the floor, and the highest average temperature was 0.30 m (12 in) from the roof. Figure 4 shows that, prior to turning on the airflow, the temperature near the floor was slightly higher than the temperature at mid-height. After the BAS was turned on, as indicated by the increase in the airflow from 0 to 750 SCFM just after 10 minutes, the temperature near the floor decreased throughout the time period and it was the lowest of the three temperatures, while the temperature at mid-height was consistently 0.56°C (1°F) lower than the temperature near the roof. Thus, the criteria for a TDVSC were met.

Next, tests were conducted to examine the contamination purging performance of the TDVSC. Three trials were conducted at each of the tested airflow rates. The tests were carried out by establishing a uniform initial SF₆ concentration of 1,000 ppm, and then purging was conducted until the SF₆ concentrations at all locations dropped below 10 ppm as described in the Materials and Methods section. The data were then curve fit to determine the α exponent for each measurement location and for each of the three trials for each airflow. Then, Equation 2 was used to determine the purge time to decrease the SF₆ concentration from 1,000 ppm to 25 ppm.

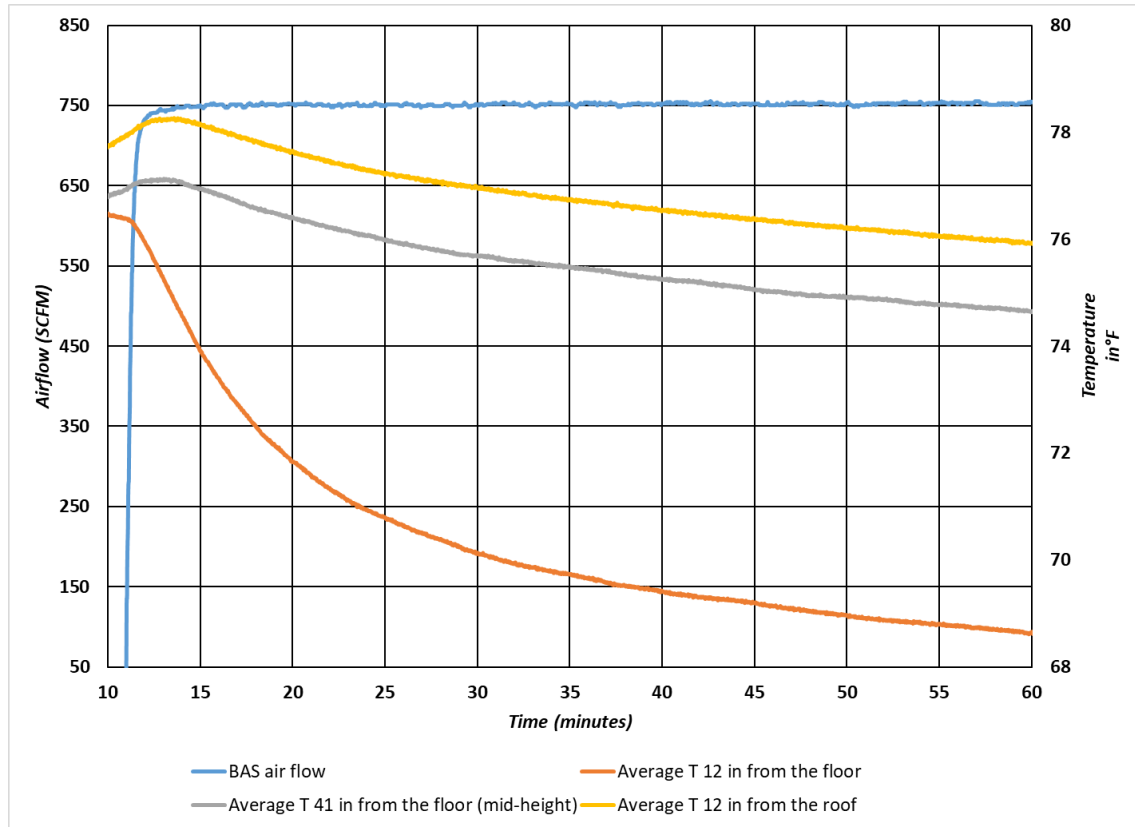


Figure 4: The air flow and average temperature at each height as the test progressed for a flow rate of 750 SCFM.

Average purge times for the entire BIP RA were calculated using an average α value, while purge times at an individual sampling location were calculated using the α value determined for that location. At an air flow of 750 SCFM, the average purge time was 29 minutes, and at a flow rate of 1,000 SCFM the average purge time was 20 minutes. Thus, the average purge time was decreased by 31% by increasing the flow rate from 750 SCFM to 1,000 SCFM, which is a flow rate increase of 33%. The individual purge times ranged from 25–32 minutes at a flow rate of 750 SCFM and from 18–21 minutes at a flow rate of 1,000 SCFM. For a flow rate of 750 SCFM, the location with the longest purge time was the lower height of sampling location #5, and the location with the shortest purge time was the lower height of sampling location #2 (see Figure 5). At a flow rate of 1,000 SCFM, the locations with the longest purge times were the lower heights of sampling locations #3 and #8, and the locations with the shortest purge times were the lower heights of sampling locations #2 and #6.

The first goal of this study was to determine the effects of TDVSCs on the average time to dilute an initial CO

concentration of 1,000 ppm to the maximum allowable concentration of 25 ppm. The second goal was to identify locations where contaminants would be slow to purge. In addition, NIOSH researchers wanted to assess the cost/benefit of using a TDVSC instead of one of the MVSCs.

NIOSH researchers compared the results of the TDVSC to those of the 12 previously tested MVSCs [7] to assess the difference in the average purge times for both flow rates (refer to Table 1). For the TDVSC, increasing the flow rate from 750 to 1,000 SCFM reduced the average time to purge an initial concentration of 1,000 ppm to 25 ppm by 31%. The average purge times were 29 minutes at 750 SCFM and 20 minutes at 1,000 SCFM. For the TDVSC, the average purge times were 29 minutes at 750 SCFM and 20 minutes at 1,000 SCFM. Except for MVSC #9, the average purge times of the other MVSCs ranged from 26 to 29 minutes for a flow rate of 750 SCFM and from 18 to 23 minutes for a flow rate of 1,000 SCFM [7]. Therefore, the purge times for the TDVSC were similar to those of the MVSCs.

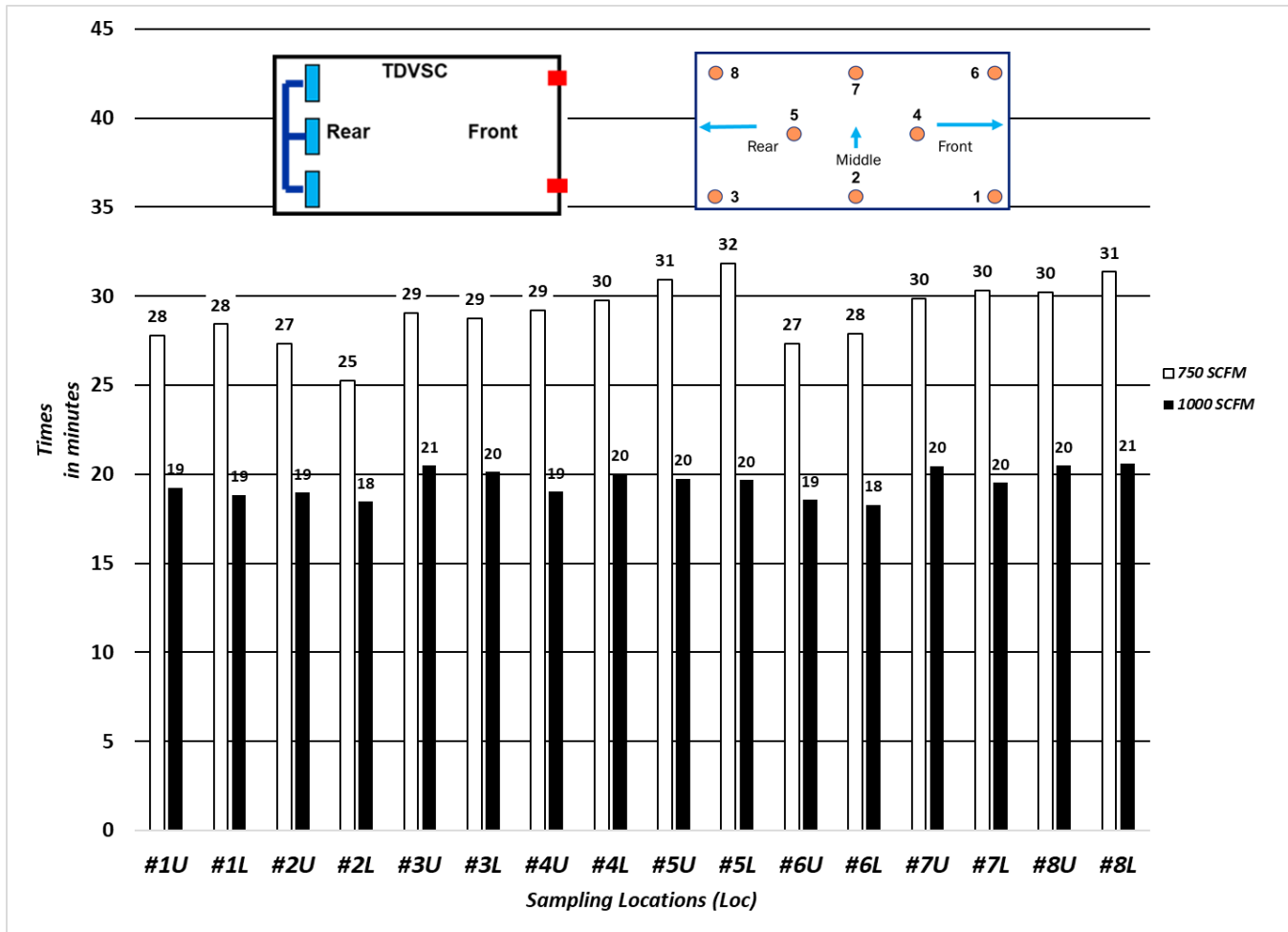


Figure 5: The purge times from sampling location to sampling location (NOTE: #1U stands for monitor 1 upper and #1L stands for monitor 1 lower, etc.).

In addition to comparing average purge times, NIOSH researchers compared the minimum and maximum purge times for the sampling locations with the TDVSC to those with the MVSCs for both flow rates. For the TDVSC, the minimum purge time was 25 minutes and the maximum purge time was 32 minutes at a flow rate of 750 SCFM. At a flow rate of 1,000 SCFM, the minimum purge time was 18 minutes and the maximum purge time was 21 minutes. For the MVSCs, except for MVSC #9, the minimum purge times ranged from 24 to 27 minutes and the maximum purge times ranged from 27 and 29 minutes at a flow rate of 750 SCFM. At a flow rate of 1,000 SCFM, the minimum purge times ranged from 17 to 22 minutes and the maximum purge times ranged from 19 to 24 minutes (see Table 2). Thus, the minimum and maximum purge times for the TDVSC were similar to those for the MVSCs.

A cost comparison was performed on the TDVSC and MVSCs. The TDVSC is more expensive and labor intensive to install than any of the MVSCs. The total cost for the three diffusers was \$2,025—not including the cost of labor to transport and install them into the BIP RA. The installation of the TDVSC

was more laborious than the MVSCs because the main inlets required an additional fitting to create the three air inlet branches. In addition, the three branches needed to be aligned with the air inlets of the diffusers. The diffusers also required additional pieces of pipe to connect the air inlets from the three branches to the air inlets of the diffusers. Additionally, legs were added because the diffusers could not stand on their own.

Excluding MVSC #9, the data showed no clear advantage of using the TDVSC over the MVSCs. For both flow rates, the average purge times for the TDVSC were within 0–3 minutes of the average purge times of the MVSCs. The differences between the minimum and the maximum purge times are 7 minutes at a flow rate of 750 SCFM and 3 minutes at a flow rate of 1,000 SCFM. In comparison, the differences between the minimum purge times ranged from 0–3 minutes at both flow rates for the MVSCs, except for MVSC #9. The results of the TDVSC did not justify the extra cost and labor.

Table 1. Average purge times (in minutes) for TDVSC and 12 previously tested MVSCs.

Ventilation System	Air Flow	
	750 SCFM	1,000 SCFM
TDVSC	29	20
MVSC #1	27	21
MVSC #2	26	21
MVSC #3	26	21
MVSC #4	27	22
MVSC #5	27	21
MVSC #6	26	22
MVSC #7	29	23
MVSC #8	27	23
MVSC #9	39	30
MVSC #10	28	22
MVSC #11	28	22
MVSC #12	26	18

Table 2: The maximum and minimum purge times (in minutes) at each of the flow rates.

Ventilation System	Air Flow			
	750 SCFM		1,000 SCFM	
	Max	Min	Max	Min
TDVSC	32	25	21	18
MVSC #1	28	26	22	21
MVSC #2	28	25	22	21
MVSC #3	27	25	22	20
MVSC #4	28	26	23	21
MVSC #5	28	26	22	20
MVSC #6	27	24	23	20
MVSC #7	29	27	24	22
MVSC #8	28	26	24	22
MVSC #9	43	36	34	27
MVSC #10	29	27	22	21
MVSC #11	29	27	22	21
MVSC #12	27	25	19	17

4. CONCLUSION

With the exception of MVSC #9, the results showed that there are no benefits of using the TDVSC over the MVSCs. The average purge times for the TDVSC are within 0–3 minutes of the MVSCs. In addition, the TDVSC costs are more than the MVSCs, and the TDVSC is more labor intensive to install. Stakeholders can use this information to evaluate the performance of the TDVSC to that of the MVSCs and compare the cost/benefit of using the TDVSC inside of BIP RAs. In

addition, stakeholders could assess whether it is worth spending more than \$2,000 to achieve little variation in performance when comparing the TDVSC to the MVSC.

4.1 Limitations

Several factors limited this research. NIOSH researchers could not find any data on the CO concentration level immediately following a mine explosion or fire. This would affect the CO concentration inside a BIP RA due to miners entering it. As a starting point, the researchers used an initial SF6 concentration of 1,000 ppm for the BIP RA purging tests. However, the initial CO concentration inside a BIP RA might be greater or less than 1,000 ppm following a mine disaster. Thus, the purging times listed in the Results and Discussion section are for comparative purposes only. In addition, this research did not consider the secondary safety measure that require RAs to have a supply of self-contained self-rescuers (SCSRs)—a self-contained emergency breathing apparatus—in case of a delay in starting the supply of breathable air.

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DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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