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Heat mitigation for underground coal mine refuge alternatives

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ABSTRACT: Federal regulations require mines to place refuge alternatives (RAs) in underground coal mines in the United States. Because miners trapped in an RA could experience heat exhaustion or heat stroke, RA regulations mandate an apparent temperature (AT) limit of 35°C (95°F) in RAs. The National Institute for Occupational Safety and Health (NIOSH) conducted in-mine AT tests to evaluate three RA heat mitigation devices: a borehole air supply (BAS), a battery-powered air conditioner (BPAC), and a cryogenic air supply (CAS). The BAS limited the AT in a 60-person built-in-place (BIP) RA to 25°C (77°F) when the outside air temperature was 10°C–23.9°C (50°F–75°F) with relative humidity from 50%–95%. During tests on a portable tent-type RA with a 29.4°C (85°F) mine air temperature, the BPAC and CAS kept the AT below 35°C (95°F). AT tests showed the CAS allowed for 12 miners in a 29.4°C (85°F) 30-person BIP RA. RA manufacturers and mines can use this information to ensure RAs can meet the AT limit.

1 INTRODUCTION

Heat buildup inside a refuge alternative (RA) is a serious concern. Heat sources for an RA include the RA occupants and the RA's carbon dioxide (CO_2) scrubber system. RAs have a limited ability to dissipate heat due to the low thermal conductivity of mine strata materials. If conditions become severe enough, RA occupants could experience heat exhaustion or heat stroke (Bernard, 2011, OSHA, 2003). To guard against severe heat stress, federal RA regulations for underground coal mines specify a maximum apparent temperature (AT) of 35°C (95°F). The AT is a heat index that can be used to determine how severe a thermal environment appears (Steadman, 1979).

To ensure that the AT limit is not reached inside an RA, heat mitigation devices or occupancy derating could be necessary for warm or hot mines. The National Institute for Occupational Safety and Health (NIOSH) examined the cooling capabilities of an air-conditioned borehole air supply (BAS), a battery-powered air conditioner (BPAC), and a cryogenic air supply (CAS) through RA AT testing in its Experimental Mine in Bruceton, PA. This paper discusses the results of heat mitigation device AT testing.

2 HEAT MITIGATION DEVICE DESCRIPTION

2.1 *BAS – Borehole Air Supply*

The BAS (see Figure 1) consists of a rotary blower powered by a 460-V electric motor with a power rating of 18.6 kW (25 hp). The BAS incorporates a 45-kW (154,000-BTU/hr) heater and a 39.3-kW (134,000-BTU/hr) air conditioner. The BAS can provide a maximum airflow of 2039 m^3/hr (1200 CFM) at a pressure of 20.7 kPa (3 psi). At the minimum required fresh airflow rate of 21.2 m^3/hr (12.5 CFM) per person (CFR, 2018, CFR, 2019, CFR, 2022), the

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Figure 1. Pictures of a BAS for RAs.

BAS can supply fresh air for 96 miners. To use the BAS, a flexible duct is connected from its outlet to the top of a borehole.

2.2 *BPAC – Battery-powered Air Conditioner*

The BPAC (see Figure 2) was developed as part of Broad Agency Announcement (BAA) Contract 200-2016-91901 with HDT Global (DRS, 2016). The BPAC was designed to keep the thermal environment of a 30-person portable RA under the AT limit in a 29.4°C (85°F) mine. The BPAC consists of a vapor compression refrigeration system attached to a movable, rugged frame. To match the required cooling load, the BPAC uses a variable-speed compressor with two variable-speed condenser fans. The BPAC is powered by a bank of 48-V lead acid batteries contained within a separate battery tray. The BPAC and its battery tray would be stored near an RA until needed post-disaster.

Figure 2. Picture of a BPAC connected to a portable tent-type RA using flexible duct.

2.3 *CAS – Cryogenic Air Supply*

The CAS (see Figure 3) was developed as part of BAA contract 200-2016-91194 (Cryo Life Support Systems, 2016). The CAS was also designed to keep a 30-person RA under the AT limit. The CAS maintains air as a liquid at cryogenic temperatures until gaseous air would be needed in the event of a mine emergency. The primary components of the CAS are a cryocooler and a 2000-L horizontal dewar. The CAS uses a water-cooled, 480-V cryocooler with a power consumption of 7.5–7.8 kW (Yan et al., 2017, 2020, 2021). Liquid air is created by filling the dewar with the necessary quantities of liquid nitrogen and liquid oxygen to generate liquid air with the desired oxygen concentration. A pressure switch that senses the dewar pressure cycles the cryocooler on and off as needed to maintain the air inside as a liquid.

In the event of a mine emergency requiring breathable air from the CAS, the following procedure would be followed. First, power to the CAS would be turned off. Next a vacuum-jacketed hose would be connected from the CAS to a heat exchanger positioned within an RA. A pressure buildup valve on the CAS would be activated to allow vapor pressure from the dewar to force liquid air to flow to the heat exchanger. As the liquid air passes through the heat exchanger, it would absorb heat from the surroundings and become gaseous air at roughly 5°C–15°C (41°F–59°F), thus providing cooling to the RA.

Figure 3. Picture of a cryogenic air supply for refuge alternatives.

3 APPARENT TEMPERATURE (AT) TESTS

NIOSH researchers developed an AT test method to evaluate the thermal environment of RAs (Yantek, 2014, 2019). This test method uses devices called simulated miners (SMs) to provide the representative metabolic heat from actual miners and heated water tanks to provide the representative heat input from an RA's CO_2 scrubber system. The SMs and heated water tanks use electrical resistance heaters as heat sources. The SMs also served to provide moisture input to the RAs via vapor or simulated sweat using water from the heated water tanks. The heat input for the SMs was set at 117 W per person, and the heat input of the heated water tanks was set to 27.5 W per SM (Yantek, 2014, 2019). During the AT tests, the total heat input was controlled using programmable variable autotransformers (PVAs). The heat input from the heated water tanks was controlled via manual variable autotransformers (MVAs).

Each of the heat mitigation devices were tested using either a built-in-place (BIP) RA, portable tent-type RA, or both. The BAS was tested on a 60-person BIP RA constructed inside the NIOSH Experimental Mine in Bruceton, PA. The BPAC was tested on a 20-person portable tent-type RA that was installed in a crosscut in the Experimental Mine. The CAS was tested on the 20-person portable tent-type RA and a 30-person BIP RA.

3.1 *Setup for BAS testing in 60-person BIP RA*

The 60-person BIP RA was built by constructing two stoppings using two layers of solid 20.3-cm-thick (8-in-thick) concrete blocks at either end of an entry. The interior dimensions of the BIP RA are 13.7-m (45-ft) long by approximately 6.1-m (20-ft) wide and roughly 2.0-m (6.5-ft) high. The BIP RA floor is a nominally 20.3-cm-thick (8-in-thick) layer of concrete, and the roof and ribs are covered with a roughly 25.4-mm-thick (1-in-thick) layer of shotcrete. The BIP RA is approximately 30.5 m (100 ft) below the surface.

The BAS delivered air to the BIP RA via a borehole located near the left rear corner (when viewed from the entry door). A 2.4-m-long (8-ft-long), 20.3-cm-diameter (8-in-diameter) PVC pipe was connected to the borehole to provide a long straight section to allow for accurate measurement of the delivered airflow. The outlet of the PVC pipe delivered the air near the right rear corner (when viewed from the entry door). The BAS delivered air at a nominal volumetric flow rate of 1317 m^3/hr (775 SCFM), which is slightly higher than the required 21.2 m^3/hr (12.5 SCFM) of fresh air per person for 60 people. The BAS air conditioner was set to deliver air at a dew point of 12.8°C (55°F).

The air temperatures and relative humidity (RH) levels inside the RA were measured using Vaisala HMP155 (Vaisala, 2022b) and HMP110 Humidity and Temperature Probes (Vaisala, 2022a). For ease of reference, the RA was split into three equal-sized hypothetical sections: Section 1, Section 2, and Section 3. One Vaisala HMP155 was placed in the center of Section 2 at mid-height, one Vaisala HMP110 was placed at the center of Section 1 at mid-height, and one Vaisala HMP110 was placed at the center of Section 3 at mid-height. Averaging resistance temperature detectors (RTDs) with a length of 1.2 m (4 ft) were used to monitor the air temperature at additional locations.

The nominal total heat input was set to 8670 W to provide the representative metabolic heat input of 60 occupants. The SMs were evenly distributed using 6 SMs across the width of the BIP RA with 10 SMs along the length of the BIP RA. Because borehole air supplies provide enough air to dilute miner-generated CO_2, heated water tanks were not needed. The water tanks were used only to provide moisture via the SMs.

3.2 *Setup for BPAC and CAS testing in 20-person portable tent-type RA*

The 20-person portable tent-type RA was deployed in an entry in the Experimental Mine. Two insulated walls were built to create an isolated test area. One wall was about 3.0 m (10 ft) from the metal box of the RA, and the other wall was about 3.0 (10 ft) from the tent end of the RA. The insulated-wall frames were built using 2x4 wooden studs spaced 40.6 cm (16 in) from center to center with a layer of 50.8-cm-thick (2-in-thick) polystyrene foam attached to each side of the wall frame. The cavities of each wall were filled with fiberglass insulation batts.

The air temperatures and RH levels inside the RA were measured using Vaisala HMP155 (Vaisala, 2022b) and HMP110 Humidity and Temperature Probes (Vaisala, 2022a). For ease of reference, the RA was split into three equal-sized hypothetical sections: Section 1, Section 2, and Section 3. One Vaisala HMP155 was placed in the center of Section 2 at mid-height, one Vaisala HMP110 was placed at the center of Section 1 at mid-height, and one Vaisala HMP110 was placed at the center of Section 3 at mid-height.

The mine air temperatures around the RA were measured using Lascar Electronics EL-WiFi-T+ High Accuracy WiFi Temperature Data Loggers (Lascar Electronics, 2022). Four data loggers were positioned over Sections 1, 2, and 3 of the tent and over the RA's metal box midway between the RA and the mine roof. Four data loggers were positioned around the sides of the RA, and one data logger was positioned at either end of the RA. These six data loggers were positioned at mid-height and 30.5 cm (12 in) from the RA.

The heat input was set to the nominal value corresponding to 30 occupants, 4335 W. This value was selected because each device was designed to provide cooling for an RA with 30 occupants. The SMs provided a nominal 3510 W, and the heated water tanks provided a nominal 825 W. Be-cause the space and volume inside the 20-person RA is less than would be required per RA regula-tions, these conditions are more severe than those of an actual 30-person RA.

To represent a hot mine, the mine air temperature around the RA for these tests was elevated to 29.4°C (85°F) using portable thermostatically controlled space heaters that were positioned around the RA. The heaters were on for the entire duration of the tests. The test was begun as soon as the desired mine air temperature was reached.

3.3 *Setup for CAS testing in 30-person BIP RA.*

The 30-person BIP RA was created by partitioning the 60-person BIP RA with an insulated wall. The resulting BIP RA was 6.86-m (22.5-ft) long by approximately 6.10-m (20-ft) wide and roughly 1.98-m (6.5-ft) high. The insulated-wall frame was built using 2x4 wooden studs spaced 40.6 cm (16 in) from center to center. A layer of 50.8-mm-thick (2-in-thick) polystyrene foam was attached to each side of the wall frame. The cavities between the studs were filled with fiberglass insulation batts.

The air temperatures and RH values were measured using Vaisala HMP155 and HMP110 Humidity and Temperature Probes located at the centers of three equal-sized hypothetical sections: Section 1, Section 2, and Section 3. One Vaisala HMP155 was placed in the center of Section 2 at mid-height, one Vaisala HMP110 was placed at the center of Section 1 at mid-height, and one Vaisala HMP110 was placed at the center of Section 3 at mid-height. The mine strata surface temperatures and temperatures at depth were measured using patch-style Class A RTDs and PVC rods with RTDs affixed.

In order to evaluate the CAS in hot-mine conditions, the interior of the BIP RA was preheated to a strata surface temperature of 29.4°C (85°F) using a 30-kW heater that was positioned near the center of the BIP RA and six MVA-controlled baseboard heaters that were distributed within the BIP RA. The 30-kW heater and the baseboard heaters were operated together to rapidly increase the BIP RA air and strata surface temperatures. After the initial preheat period, the 30-kW heater was turned off and the MVAs were iteratively adjusted so that the mine strata temperature stabilized at about 29.4°C (85°F) for 8 hours prior to beginning the test.

The number of occupants that could be housed in the BIP RA with the CAS operating was determined through a set of iterative tests. To provide cooling, liquid air was delivered to the BIP RA from the CAS to a heat exchanger located inside the BIP RA. Because it was assumed that CO_2 scrubbers would be necessary for a CAS, the total heat input for each test was the number of SMs used times 144.5 W, which includes 117 W to represent metabolic heat input and 27.5 W to represent CO_2 scrubber heat input. The liquid airflow rate from the CAS was kept roughly constant. Small adjustments to the flow rate were made in an attempt to keep the AT below 35°C (95°F) and to ensure that the liquid air would last for 96 hours.

3.4 *AT calculation*

To develop an equation to calculate the AT, or heat index, using the dry-bulb air temperature and relative humidity, Rothfusz carried out a multiregression analysis on the tabular data from Steadman (Rothfusz, 1990). The National Weather Service refined this approach to calculate the AT. For dry-bulb air temperatures above 26.7°C (80°F) and an RH above 13%, the AT was calculated using (National Weather Service, 2023):

$$\begin{aligned} AT = & -42.379 + 2.04901523(T) + 10.14333127(RH) - 0.22475541(T)(RH) - \\ & 0.00683783(T)^2 - 0.05481717(RH)^2 + 0.00122874(T)^2(RH) + \\ & 0.00085282(T)(RH)^2 - 0.00000199(T)^2(RH)^2 \end{aligned} \quad (1)$$

where T is the dry-bulb air temperature in °F amd RH is the percent relative humidity. If Equation 1 resulted in an AT below 26.7°C (80°F), the following simplified formula was used to calculate AT (National Weather Service, 2023)

$$AT = 0.5[T + 61.0 + 1.2(T - 68) + 0.094RH] \quad (2)$$

4 RESULTS

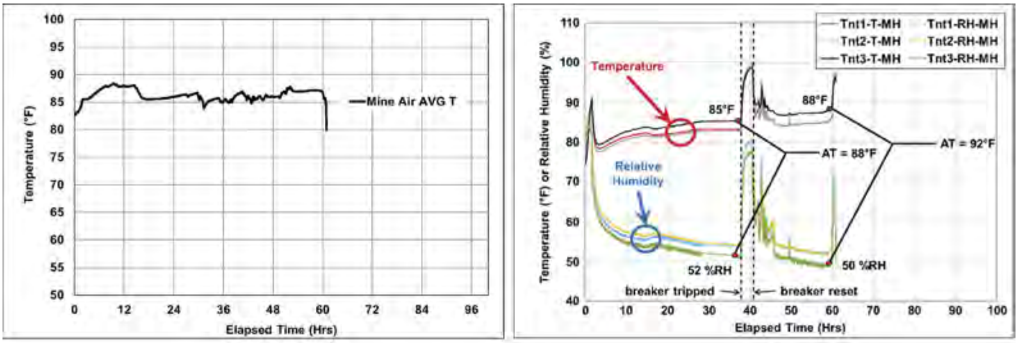
4.1 *BAS tested in 60-person BIP RA*

The BAS was able to keep the AT below the AT limit. The highest AT was calculated to be 24.2°C (75.5°F) and this occurred in Section 1, which was furthest from the location of the air delivered from the BAS. The air temperature in Section 1 varied from 20.2°C–24.0°C (68.4°F–75.2°F) with an average of 22.6°C (72.7°F), and the RH ranged from 54.4–80.7% with an average of 62.9%. The AT in Section 1 varied from 20.2°C–24.2°C (68.3°F to 75.5°F) with an average of 22.6°C (72.7°F). For these tests, the outside air temperature ranged from 9.2°C–25.8°C

(48.6°F–77.5°F) with an average of 17.7°C (63.8°F), and the outside RH ranged from 36.8%–95.2% with an average of 72.0%.

4.2 *BPAC tested in 20-person portable tent-type RA*

The BPAC unit kept the AT under 35°C (95°F) until battery issues occurred during testing, and the test was ended prior to 96 hours (refer to Figure 4). The average mine air temperature near the RA varied from 28.3°C–29.4°C (83°F–88°F). The test was expected to last for 96 hours, but higher than expected power consumption caused the BPAC's main breaker to trip at about 38 hours. With the breaker tripped, the AT increased from about 29.4°C (88°F) to about 37.8°C (100°F) within about 2 hours. After the breaker was reset, the BPAC was able to bring the AT below 35°C (95°F). However, the battery ran out of power around 60 hours, so the test was terminated. Just prior to the batteries running out of power, the AT was 33.3°C (92°F).



(a) (b)

Figure 4. (a) Mine air average temperature and (b) RA interior temperature and %RH for BPAC AT test.

4.3 *CAS tested in 20-person portable tent-type RA*

The mine air temperature around the RA was elevated to a nominal 29.4°C (85°F). After the first 18 hours of the test, the actual average mine air temperature around the RA varied from about 28.3°C–29.4°C (83°F–85°F) as shown in Figure 5. For the first 20 hours of the test, the CAS was able to keep the AT below 35°C (95°F). However, due to ice build up on the heat exchanger inside the tent, the AT exceeded 35°C (95°F) after about 18 hours. After 48 hours, researchers temporarily halted the test to enter the tent and remove the builtup ice from the heat exchanger. When the test was resumed, the CAS kept the AT below 35°C (95°F) from 60 hours until about 90 hours, when the CAS ran out of liquid air. Without cooling from the CAS, the AT climbed to 60°C (140°F) in less than 8 hours.

4.4 *CAS tested in 30-person BIP RA*

The BIP RA was preheated to a mine strata surface temperature of 29.4°C (85°F). The corresponding mine strata temperatures at 0.15-m (6-in), 0.61-m (24-in), and 1.22-m (48-in) deep were 29.4°C (85°F), 24.4°C (76°F), and 14.4°C (58°F), respectively. With the CAS operating, tests were conducted with the heat input of 24, 16, and 12 miners. The cryogenic airflow rate was adjusted to keep the AT below 35°C (95°F) and to have enough liquid air to last 96 hours. An 8-hour-long test with the heat input of 12 miners was conducted without the CAS for comparison.

When the heat input was set to that of 24 miners, the AT was 37.4°C (99.4°F) when the CASran out of liquid air at 91 hours (refer to Table 1). With the heat input of 16 miners, the CAS lasted the entire duration, but the AT reached 35.2°C (95.3°F), just over the AT limit.

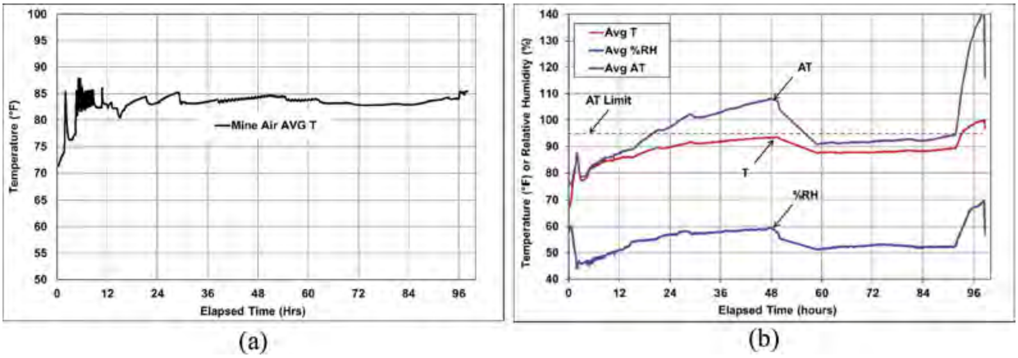


Figure 5. (a) Average mine air temperature and (b) average RA interior temperature, %RH, and AT for CAS AT test.

Table 1. Summary of CAS AT test results for a 29.4°C (85°F) 30-person BIP RA.

Parameter	Test 1	Test 2	Test 3	Test 4
Number of SMs	24	16	12	12
Test Duration	96 hrs	96 hrs	96 hrs	8 hrs
CAS used	Yes	Yes	Yes	No
Time when CAS empty	91 hrs	96 hrs	91 hrs	–
AT when CAS empty	37.4°C (99.4°F)	–	30.3°C (86.6° F)	–
AT at end of test	48.1°C (118.6°F)	35.2°C (95.3°F)	37.9°C (100.3°F)	40.7°C (105.2°F)

The CAS kept the AT below 35°C (95°F) with the heat input corresponding to 12 miners, but at 91 hours, the CAS ran out of liquid air. At this time, the AT was 30.3°C (86.6°F). For the test without the CAS with the heat input of 12 miners, the AT reached 40.7°C (105.2°F) after just 8 hours.

5 DISCUSSSION

The BAS was able to keep the AT well below the AT limit. In addition, the BAS had no performance issues during testing. However, the outside atmospheric conditions were not as severe as desired, as the dry-bulb air temperature was a maximum of only 25.8°C (77.5°F). Ideally, the BAS would be evaluated with an outside air temperature matching that of southern mines, such as the ones in Alabama, which are hotter than other United States underground coal mines. In Brookwood, AL, July is the hottest month with an average high temperature of 33.1°C (91.6°F) and an average RH of 73% (Weather U.S., 2022). Furthermore, to ensure adequate cooling in Alabama-mine-like conditions, the BIP RA should be preheated to 29.4°C (85°F) as was done with the evaluations of the BPAC and the CAS.

The BPAC was able to keep the AT below the limit, but higher than expected power consumption caused issues with the unit's power system. Because the device uses a compressor that adjusts to the cooling demand, and the cooling demand was greater than expected, the power consumption exceeded the capacity of the batteries and of the circuit breaker. In order to ensure the device could last for an entire 96 hours, the battery capacity would have to be increased. Under the test conditions here, the unit operated for about 60 hours. Therefore, the battery capacity would need to be increased by about 60% to ensure the BPAC could operate for 96 hours. The BPAC would need to satisfy federal requirements for permissibility in underground coal mines. As tested, the BPAC was not evaluated subject to these requirements.

The CAS was able to provide enough cooling to keep the 20-person portable RA below the AT limit, but it had issues with ice buildup on the heat exchanger, and it ran out of liquid air prior to the end of the 96-hour test. The heat exchanger design must be capable of having ice buildup removed easily without risking damage. For the 20-person portable RA test, the CAS 2000-liter dewar had about 1850 liters of liquid air inside at the beginning of the test. During the test, the CAS was set to deliver liquid air to the heat exchanger inside the tent at a nominal rate of 220 liters/min. However, the CAS had limited flow rate control capability, so the actual flow rate exceeded the target amount. Better flow control capability would be needed for a final product.

The CAS tests on the 30-person 29.4°C (85°F) BIP RA showed promising results. With the heat input of 24 occupants, the unit was able to keep the AT below 37.8°C (100°F) for 91 hours. A small increase in liquid airflow rate and a larger volume of liquid air would have allowed the unit to provide enough cooling to bring the AT below 35°C (95°F) and to last the full 96 hours with 24 occupants. The tests with the heat input of 16 occupants showed the CAS would have kept the AT below 35°C (95°F) with a slight increase in liquid airflow rate. The tests highlighted the importance of having good flow control.

One of the challenges with the CAS is that this is a novel technology for mining applications. Because gas suppliers do not currently offer liquid air, mines would have to mix their own liquid air, or a supplier would need to be convinced to provide this commodity. Another challenge is the maintenance of a CAS in a mining environment. This would require the development of a maintenance schedule and instructions. It is likely that a vendor would need to provide maintenance services.

6 CONCLUSIONS

All three devices were able to reduce heat buildup within the RAs. The BAS would need to be tested in more severe thermal conditions like those in southern mines to ensure the device would be capable of keeping the apparent temperature (AT) below 35°C (95°F). Both the BPAC and CAS were able to keep the AT under 35°C (95°F), but both devices had issues. The BPAC needs improved battery capacity. In addition, the BPAC would need to pass permissibility testing. The CAS would benefit from a heat exchanger design that is less prone to ice buildup and has improved flow control.

To ensure hot mines can be kept under the AT limit without occupancy derating, cooling devices would need to be used with RAs. The devices tested here could all serve this need. The BAS is closest to being a usable product. The BPAC and CAS need some additional improvements before they are ready to be used to provide cooling to RAs in productions mines.

7 LIMITATIONS

The heat mitigation devices were evaluated only in the NIOSH Experimental Mine. If an actual mine has less conductive strata, the resulting ATs would be higher. The BAS evaluation was not conducted with hot outside ambient conditions or a preheated mine, both of which would be more severe than the tested conditions. All of the devices described in this publication would require additional development prior to implementing them in commercial mines.

8 DISCLAIMER

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

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6 LIMITATIONS

Because the analysis presented here was performed on only two RAs with conditions from only five mines across the U.S. and one nonproduction mine, the results should not be assumed to directly apply to mine-specific RA installations. Additional testing or analysis would be necessary to determine occupancy derating percentages for a specific RA installation.

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