Published in final edited form as:

J Therm Sci Eng Appl. 2020 April ; 12(2): . doi:10.1115/1.4044345.

Underground Mine Refuge Alternatives Heat Mitigation

Lincan Yan, **David Yantek**, **Timothy Lutz**, **Jeffrey Yonkey**, **Justin Srednicki**

The National Institute for Occupational Safety and Health (NIOSH), 626 Cochrans Mill Road, Pittsburgh, PA 15236

Abstract

In case of an emergency in an underground coal mine, miners who fail to escape from the mine can enter a refuge alternative (RA) for protection from adverse conditions, such as high carbon monoxide levels. One of the main concerns with the use of both portable and built-in-place (BIP) RAs, especially for hot or deep mines, is the interior temperature rise due to the occupants' metabolic heat and the heat released by devices such as the carbon dioxide (CO_2) scrubbing system. The humidity within the RA will also increase through occupants' respiration and perspiration and from the chemical reaction within the CO_2 scrubbing system. Heat and humidity buildup can subject the occupants to hazardous thermal conditions. To protect RA occupants, Mine Safety and Health Administration regulations mandate a maximum apparent temperature of 95 °F within an occupied RA. The National Institute for Occupational Safety and Health (NIOSH) tested both an air-conditioned borehole air supply (BAS) and a cryogenic air supply for RAs in the NIOSH Experimental Mine in Bruceton, PA. The BAS was tested on a 60-person BIP RA, while the cryogenic air supply was tested on a 30-person BIP RA and a portable 23-person tent-type RA. Multiple tests were conducted with both air supplies to assess their ability to cool RAs. The test results show that the BAS and the cryogenic air supply were able to maintain the apparent temperature within the tested RAs under the 95 °F limit. The BAS and the cryogenic air supply are potential RA heat mitigation strategies that mines could use to prevent heat/humidity buildup within RAs.

Keywords

experimental techniques; heat transfer enhancement

Lyan1@cdc.gov; jjy9@cdc.gov.

Contributed by the Heat Transfer Division of ASME for publication in the JOURNAL OF THERMAL SCIENCE AND ENGINEERING APPLICATIONS.

1 Introduction

If an accident occurs in an underground coal mine, miners who fail to escape from the mine can enter an refuge alternative (RA) for protection from adverse conditions, such as high carbon monoxide levels. One of the main concerns with the use of portable RAs is the temperature rise inside the RA from the metabolic heat of the occupants and the heat released by the CO_2 scrubbing system. Moreover, the humidity within the RA will increase through occupants' respiration and perspiration and from the chemical reaction within the CO_2 scrubbing system. The accumulation of heat and humidity could result in miners suffering heat stress, heat stroke, or even death. Previous researches have been conducted to predict a miner's core temperature response and moisture loss in environments that may be encountered in a coal mine refuge alternative [1] and to estimate the metabolic heat input for occupied refuge alternatives [2]. In those researches, the effects of metabolic heat rate (activity level), miner size (height and weight), and pose (sitting or lying) on body core temperature rise were also examined.

Mine Safety and Health Administration (MSHA) regulations require that RAs should be designed to ensure that the internal apparent temperature does not exceed 35 °C (95 °F) when the RA is fully occupied [3]. In this paper, evaluations of two potential heat mitigation devices for RAs—an air-conditioned borehole air supply (BAS) and a cryogenic air supply —are discussed.

RAs must be supplied with compressed oxygen from cylinders, compressed air from cylinders, or air from an air compressor, centrifugal fan, or alternative air source such as a cryogenic air supply. MSHA requires that breathable air supplied by compressed air from cylinders, fans, or compressors shall provide a minimum flow rate of 12.5 ft^3/min of breathable air for each person. MSHA also requires that the mines should provide oxygen at a minimum flow rate of 1.32 ft^3/h per person [4]. There are several methods used for heat mitigate for underground mine refuge alternatives. Those methods include battery-powered AC or ventilation cooling, ice storage cooling, and phase change material (PCM) cooling systems. National Institute for Occupational Safety and Health (NIOSH) has conducted multiply 96-h testing on using a battery-powered AC system for refuge alternative in hot mine conditions [5]. The tests demonstrate that the cooling system was effective in controlling the air temperature inside the RA. However, the battery drained out and did not last for the entire 96-h test. Optimizing the cooling cycle would reduce battery usage and extend cooling cycle time. PCM including ice storage cooling system mitigates the RA interior heat when the material changes phase from solid to liquid [6,7]. Xu et al. investigated a method that places the encapsulated ice plates directly in the chamber to control the RA interior temperature [8]. That system does not require any electrical power or battery. However, the cooling efficiency and capacity limits its application.

A BAS can supply breathable air and cooling for an RA. Another advantage of using a BAS is that it could dilute the CO_2 expelled by occupants and eliminate the need for CO_2 scrubbers. A cryogenic air supply could also be used to supply breathable air and cooling for an RA. An advantage of a cryogenic air supply is that a borehole is not required.

All testing to evaluate the BAS and cryogenic air supply was conducted in the NIOSH Experimental Mine in Bruceton, PA. The BAS was tested on a 60-person built-in-place (BIP) RA, while the cryogenic air supply was tested on a 30-person BIP RA and a portable 23-person tent-type RA. These occupancy ratings are based on the space requirement of 15 ft^2 per miner.

Two 60-person BIP RA tests were conducted to evaluate the cooling capability of the BAS. One test was conducted with cooling (conditioned air) and one test was conducted without cooling (unconditioned air). Both tests were conducted with warm outside air.

For the purpose of evaluating the cryogenic air supply, the 60-person BIP RA was partitioned in half to create a 30-person BIP RA. NIOSH also performed one heat and humidity test on a 23-person tent-type RA using the cryogenic air supply. The cryogenic air supply (Fig. 1), or cryogenic refuge alternative supply system (CryoRASS), provides gaseous air to the chamber through an air handler box that relies on environmental and human heat to expand the liquid air source into a gas. Therefore, this liquid air source could be used for RA cooling and dehumidification, which would reduce the human heat stress. One advantage of a cryogenic air supply is that it does not require electrical power in the refuge chamber postdisaster. Another potential benefit with the using cryogenic air instead of oxygen cylinders is the dilution of CO_2 in portable RAs. If the air flow rate delivered by the cryogenic air supply is high enough, the provided air would displace existing RA air and force occupant-–generated CO_2 to leave the RA through its relief valves. One of the challenges for using the cryogenic air system for underground refuge alternatives is the storage capacity. Electrical power is required to run the cryo cooler to maintain the liquid air inside the tank before it is being used. The larger the size of the RA, the larger the size of the cryo tank will be needed. However, the size of mine portal limits the cryogenic unit size that will be transported into the mine. It is important to note that only the cooling and dehumidification capabilities of the CryoRASS were evaluated. No testing was done to assess the ability of the CryoRASS to provide breathable air.

2 In-Mine Tests

2.1 Heat Input.

For all tests, NIOSH-developed simulated miners (SMs) were used to represent the metabolic heat input of actual miners. Each SM provided 117 W of heat. In addition, each SM generated ~1.3 l–1.5 l of moisture per day to simulate the moisture generated by miners due to sweating and respiration. More details on the design of the SMs can be found in Ref. [9]. SMs are composed of 0.11 m^3 (30 gallon) steel drums, thin-walled aluminum pipes, two aquarium air pumps, an aquarium water pump, and two silicone-encapsulated electrical resistance heaters. Each of the heaters has a nominal power rating of 120 W at 120 V. At the beginning of a test, both heaters are used to preheat the SMs. After the preheat time period of 2–4 h, only one of the heaters is used.

If an RA uses oxygen cylinders to provide a breathable environment or if the RA cannot adequately dilute the CO_2 generated by its occupants, the heat generated by an RA's CO_2 scrubbing system must be accounted for during testing. For the tests on the cryogenic air supply with the 30-person BIP RA and the 23-person portable tent-type RA, NIOSH accounted for the heat of a CO_2 scrubbing system by using immersible heaters inside water tanks for the SMs. The immersible heaters were used to provide 27.5 W of heat per SM during these tests. Because the 60-person BIP RA test was conducted using a BAS delivering fresh air, it was assumed that it would be unnecessary to use a CO_2 scrubbing system in this situation. Thus, during the 60-person BIP RA tests with the BAS, only the representative metabolic heat of actual miners was provided by the SMs. For each of the tests, the total heat input was controlled using an automatic variable AC transformer to compensate for line voltage fluctuation.

2.2 60-Person and 30-Person Built-in-Place Refuge Alternative.

The BIP RA is located in an entry in the NIOSH Experimental Mine approximately 100 ft below the surface. To create the BIP RA, two stoppings were built using two layers of solid 8-in.-thick concrete blocks. The dimensions of the constructed BIP RA are approximately 45 ft long by 20 ft wide and 6.5 ft high (Fig. 2). The floor within the test area is covered with a nominally 8-in.-thick layer of concrete, and the roof and ribs are covered with a roughly 1-in.-thick layer of shotcrete.

Air is provided to the BIP RA via a borehole that enters the BIP RA near its left rear corner (when viewed from the entry door). An approximately 8-ft-long 8-in.-diameter PVC pipe is connected to the borehole to provide a long straight section to allow for accurate measurement of the delivered air flow. The outlet of the PVC pipe delivers the air near the right rear corner (when viewed from the entry door) of the BIP RA.

The SMs were arranged to apply a uniform heat input within the BIP RA. For the 60-person tests, the BIP RA was split into three sections for reference purposes (refer to Fig. 3(a)). For the 30-person tests, the BIP RA was split into two sections for reference purposes (refer to Fig. 3(b)). Water tanks were positioned along the middle of the BIP RA (Fig. 3). Each water tank provided water for 10 SMs.

For the 30-person BIP RA tests with the cryogenic air supply, the CryoRASS was positioned outside the BIP RA. The air handler box for the cryogenic air supply was positioned near the entry door at the front right corner of the BIP RA (Fig. 3(b)). Thus, the liquid air tank delivered gaseous air to the heat exchanger of the air handler box inside the BIP RA using a tube through the stopping wall.

2.3 23-Person Tent-Type Refuge Alternative.

The 23-person RA had a height of 1.7 m (5.5 ft), an internal volume of roughly 55.3 m^3 (1881 ft^3), and a floor surface area of about 31.8 m^2 (342 ft^2). This RA meets MSHA’s unrestricted surface area and volume criteria requirement for 23 people. Twenty-three SMs and four heated water tanks were arranged to distribute the heat as evenly as possible within the deployed tent (Fig. 4). More details on additional NIOSH heat/humidity testing on this 23-person RA can be found in Ref. [10]. Similar to the 30-person BIP RA test, the CryoRASS was positioned outside the RA tent. The liquid air tank delivered gaseous air to the air handler box inside the RA through a flexible duct.

2.4 Test Procedure.

During the first 2–4 h of each test, NIOSH uses a preheat procedure to bring the SMs from mine temperature to operating temperature, which is approximately the skin temperature of the human body. The SMs are wrapped in quilted fiberglass blankets and covered with 1-in.-thick polystyrene lids. By using insulation around the SMs, the heat lost to the RA is reduced, so that the temperature of the SMs increases relatively quickly. During this preheat period, both heaters inside each SM are powered. After the preheat period, the fiberglass blankets are removed, and only one of the internal SM heaters is powered.

Tests were conducted to examine the cooling capability of the BAS and the CryoRASS. The BAS was evaluated by testing a 60-person BIP RA. For this test, after the preheat procedure was completed, the BAS was turned on and adjusted to deliver air conditioned to a dew point temperature of 55 °F at a nominal flow rate of 775 standard cubic feet per minute (SCFM) to meet with the 12.5 SCFM air flowrate standard. The CryoRASS was evaluated by testing the 30-person BIP RA and the 23-person tent-type RA tests. The CryoRASS liquid air flow was set to 13.5 l/h for the 30-person BIP RA test and 10.5 l/h for the 23-person tent-type RA test. During the conversion from liquid to gas, the cryogenic (liquid) air volume expands by a factor of 728. The purposes of those tests were to examine the temperature and humidity reduction by the CryoRASS.

3 Results

3.1 60-Person Built-in-Place Refuge Alternative With Borehole Air Supply.

Two tests were conducted on the 60-person BIP RA with the BAS. For one test, the BAS was set up to supply air without cooling. For the other test, the BAS was set to cool the ambient air to a dew point temperature of 55 °F at the outlet of the blower. The purpose of these tests was to examine the resulting apparent temperature in the BIP RA with and without a conditioned air supply with high outside air temperatures.

The time-varying temperature and relative humidity (RH) at the borehole outlet and the temperature and RH at the midheight of each section (Sections 1–3) were measured. Figure 5 shows these results for the test conducted with the BAS supplying cooled air. Section 1 (labeled S1C AirT@MH) had the highest temperature compared with Sections 2 and 3. The air temperature at the center of Section 1 ranged from 60.6 °F at the beginning of the test to 75.0 °F (apparent temperature, 79.3 °F) at the end of the test. Note that the borehole outlet is located within Section 3. As shown in Fig. 5, the RHs at the borehole outlet and in Sections 1–3 have similar patterns. The temperature and %RH for the test conducted with unconditioned BAS (no cooling) are plotted in Fig. 6. During that test, the borehole air temperature remained at ~122 °F. Note that the %RH of the blown air decreased during the test.

3.2 30-Person Built-in-Place Refuge Alternative With CryoRASS.

For comparison purposes, two tests were conducted for the 30-person BIP RA—a baseline test with no heat mitigation and the CryoRASS test. The temperature and RH results for these tests are plotted in Fig. 7. For the baseline test, the temperature and RH at Sections 1 and 2 were very close to each other. The temperature increased from 60.0 °F at the beginning to 84.0 °F at the end, while the RH was nearly constant during most of the test (~88 % RH). For the CryoRASS test, the temperature at the midheight of Section 1 ranged from 62.0 °F to 81.0 °F. The temperature at the mid-height of Section 2 was about 1 °F lower than the temperature at the midheight of Section 1. The RH for both sections was nearly constant during most of the test. The RH for Section 1 was about 81 %RH and the RH for Section 2 was about 83 %RH. Note that a power outage occurred during the test with the CryoRASS. This power outage caused the jump in data at about 50 h. elapsed time in Fig. 7(b). The power outage lasted about 8 h. During the power outage, all SMs lost power. However, this would only affect the temperature at the end of the test by a few tenths of a degree.

3.3 23-Person Tent-Type Refuge Alternative With CryoRASS.

Temperature and RH were measured in the RA. For reference purposes, the tent was divided into three parts referred to as tent 1 (near the entrance), tent 2 (near the middle), and tent 3. The temperature and RH for the baseline test (no CryoRASS) and the test with the CryoRASS are shown in Figs. 8 and 9.

With the CryoRASS, the RH was reduced. At the center of the tent, the RH was 95 %RH without the CryoRASS and 88 %RH with the CryoRASS. With the CryoRASS, about two third of the tent floor was dry at the end of the test. During these tests, the SMs generated about 30 gallons of water. For the CryoRASS test, the condensate tank under the air handler box collected approximately 11 gallons of water during the 96-h test.

The temperature at the center of tent 2 was about 3 °F cooler at the end of the test when the CryoRASS was used. At the end of the tests, the apparent temperature at the center of tent 2 was 71.9 °F with the CryoRASS, compared with the value of 75.6 °F without the CryoRASS.

During testing, the temperature of the air delivered by the CryoRASS was monitored at the inlet and outlet of the air handler box. The temperature measurements in the air handler box typically showed a drop of 6–7 °F throughout the test. It is estimated that air handler flow was slightly less than 150 SCFM.

4 Discussion

During the 60-person BIP RA test with the BAS with cooling, the outside air temperature ranged from 48.6 °F to 77.5 °F with an average of 63.8 °F and the outside RH ranged from 36.8 to 95.2 % RH with an average of 72.0 %RH. The maximum outside RH occurred when the outside air temperature was at a minimum at the beginning of each day. The RH of the air at the borehole outlet ranged from 39.2 to 73.1 %RH with an average of 58.3 %RH (Fig. 5). During the 60-person BIP RA test with the BAS without cooling (unconditioned air), the outside air temperature ranged from 57.0 °F to 88.6 °F with an average of 71.4 °F and the outside RH ranged from 31.4 to 94.6 %RH with an average of 72.0 %RH. The RH of the air at the borehole outlet ranged from 19.5 to 100.0 %RH with an average of 59.8 %RH (Fig. 6).

For both of the tests on the 60-person BIP RA with the BAS, the time-varying apparent temperature was calculated for the midheight of the center of each section (Sections 1–3) inside the BIP RA. For the 60-person BIP RA test with the BAS with cooling, Section 1 had the highest apparent temperature (Fig. 5). At this location, the air temperature ranged from 60.5 °F to 74.4 °F with an average of 71.6 °F, the RH ranged from 54.4 to 87.6 %RH with an average of 63.9 %RH, and the apparent temperature ranged from 59.9 °F to75.1 °F with an average of 71.5 °F (Table 1). For the 60-person BIP RA test with the BAS without cooling, Section 3 had the highest apparent temperature. At this location, the air temperature ranged from 59.6 °F to 81.7 °F with an average of 76.5 °F, the RH ranged from 48.9 to 99.0 %RH with an average of 68.1 %RH, and the apparent temperature ranged from 57.3 °F to 84.4 °F with an average of 77.8 °F. If the outside air temperature was a few degrees higher, or if the outside RH was a few percent higher, the apparent temperature limit could have been reached. However, the data indicate that the BAS with cooling was able to keep the apparent temperature about 20 °F below the 95 °F apparent temperature limit. In contrast, the interior BIP RA apparent temperature with BAS without cooling may approach to the 95 °F limit, especially for hot ambient air. Another observation is that when outside air temperature changes during the day, the air temperature and the strata temperature will remain relatively constant. The mine air temperature and strata temperature were kept at about 60 °F. When outside air was sent to BIP RA through borehole by BAS, its temperature will increase a little through the contact with the warmer pipe/strata (greater than 55 °F).

For mines where it would be difficult to install boreholes, an alternative way of providing cooling and breathable air is necessary. The cryogenic air supply is one option for such mines. The CryoRASS relies on cryogenic air and does not require electric power during use. For the 30-person BIP RA tests, the interior temperature ranged from 62.6 °F to 81.8 °F with the CryoRASS and from 60.0 °F to 84.2 °F without the CryoRASS (baseline test). The RH within the BIP was maintained at about 83.3 %RH with the CryoRASS, compared with 87.9 %RH without CryoRASS. The apparent temperature reduction inside the RA was obvious (Table 2).

The use of the CryoRASS with the 23-person tent-type RA was the first successful demonstration of cooling and dehumidifying an RA during 96-h tests. For the 23-person tent-type RA test with the CryoRASS, the RH averaged about 85 %RH. This was a bit higher than expected, but this test revealed that the air handler box could be improved with the addition of a second cold plate that will likely greatly reduce “freeze out” of circulated humid air from the refuge. Approximately 11 gallons of water were removed during this test with about 1 more gallon of frost still in the air handler at test termination. Without the CryoRASS, the RH inside the RA was over 90 %RH. At the end of the test without the CryoRASS, the interior surfaces of the tent were covered with moisture and pools of water were observed on the floor. For the test with the CryoRASS, there was less moisture on the interior surfaces, and the water pools on the floor were nearly eliminated.

The air temperature for the 23-person tent-type RA with the CryoRASS ranged from 59.3 °F to 62.9 °F, the RH ranged from84.1 to 96.0 %RH, and the apparent temperature ranged from58.8 °F to 73.3 °F (Table 3). For the 23-person tent-type RA without the CryoRASS (baseline test), the air temperature ranged from 57.2 °F to 74.2 °F, the RH ranged from 92.3

to 97.3 %RH, and the apparent temperature ranged from 57.1 °F to 75.9 °F. The cooling effect of the CryoRASS is not significant in this test. However, a higher cryogenic air flow rate would have increased cooling and dehumidification. Note that this would require additional liquid air and a larger container for storage.

5 Conclusion

The purpose of the 60-person BIP RA tests was to evaluate the need for cooling the BAS-supplied air when the outside air temperature is high. The test with high outside air temperatures and the BAS delivering air conditioned to a dew point temperature of 55 °F showed that the maximum apparent temperature within the BIP RA was well under the 95 °F apparent temperature limit. The test data show that the interior apparent temperature of the 60-person BIP RA with BAS with cooling was about 9 °F lower than that of 60-person BIP RA with BAS without cooling.

The tests results show that with the use of cryogenic air supply, both the 30-person BIP RA and the 23-person tent-type RA interior temperature and humidity were reduced. For example, the temperature at the mid-point of the 23-person tent-type RA was about 3 °F cooler at test end when the cryogenic air supply was used. The improvement in RH was even larger with the use of the CryoRASS (88 %RH versus 97 %RH). For the 30-person BIP RA tests, the interior temperature rise was about 19 °F with the CryoRASS compared with 24 °F for the baseline test (no CryoRASS). However, posttest liquid air quantity assessment indicated that further cooling effect can be achieved by increasing the actual liquid air flow. It is important to note that only the cooling capabilities of the CryoRASS were evaluated during the tests discussed within this report. The ability of the CryoRASS to supply miners with sufficient oxygen was not part of this evaluation.

Both the BAS and the CryoRASS were shown to reduce heat and humidity buildup in the tested RAs. These findings indicate that warm mines could use these systems to prevent the interior of occupied RAs from reaching the maximum apparent temperature limit.

This effort focused on evaluating only the heat mitigation capability of the cryogenic air supply. Prior to using cryogenic air supplies for RAs, the ability of cryogenic air supplies to supply breathable air must be evaluated.

Nomenclature

BIP	built-in-place
RA	refuge alternative
RH	relative humidity

References

[1]. Klein M, Yantek D, and Hepokoski MAYL, 2017, “Prediction of Human Core Temperature Rise and Moisture Loss in Refuge Alternatives for Underground Coal Mines,” Trans. Soc. Min. Metall. Explor, 342(1), pp. 29–35.

[2]. Bernard T, Yantek D, and Thimons E, 2018, "Estimation of Metabolic Heat Input for Refuge Alternative Thermal Testing and Simulation," Min. Eng,70(8), pp. 50–54.

[3]. MSHA, 2008, "30 CFR Parts 7 and 75; Refuge Alternatives for Underground Coal Mines; Final Rule," U.S. Department of Labor, Mine Safety and Health Administration.

[4]. MSHA, 2014, "30 CFR Part 7: Testing, Evaluation, and Approval of Mining Products," U.S. Department of Labor, Mine Safety and Health Administration.

[5]. Yan L, Yantek D, Reyes M, Damiano N, Srednicki J, Bickson J, and Whisner B, 2018, "Cooling Systems for Refuge Alternatives in Hot Mine Conditions," ASME 2018 International Mechanical Engineering Congress and Exposition, Pittsburgh, PA, 11 9–15, Paper No. IMECE2018–87507.

[6]. Wu B, Lei B, Zhou C, and Zhao Z, 2012, "Experimental Study of Phase Change Material's Application in Refuge Chamber of Coal Mine," Procedia Eng, 45(1), pp. 936–941.

[7]. Wang S, Jin L, Han Z, Li Y, Ou S, Gao N, and Huang Z, 2017, "Discharging Performance of a Forced-Circulation Ice Thermal Storage System for a Permanent Refuge Chamber in an Underground Mine," Appl. Therm. Eng, 110(1), pp. 703–709.

[8]. Xu X, You S, Zheng X, Zhang H, and Liu S, 2017, "Cooling Performance of Encapsulated Ice Plates Used for the Underground Refuge Chamber," Appl. Therm. Eng, 112(1), pp. 259–272.

[9]. Yantek D, 2014, "Investigation of Temperature Rise in Mobile Refuge Alternatives," U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Office of Mine Safety and Health Research.

[10]. Yan L, Yantek D, Klein M, Bissert P, and Matetic R, 2016, "Validation of Temperature and Humidity Thermal Model of 23-Person Tent-Type Refuge Alternative," Min. Eng. Mag, 68(9), pp. 97–103.

Fig. 1.
Cryogenic refuge alternative supply system (CryoRASS) in experimental mine

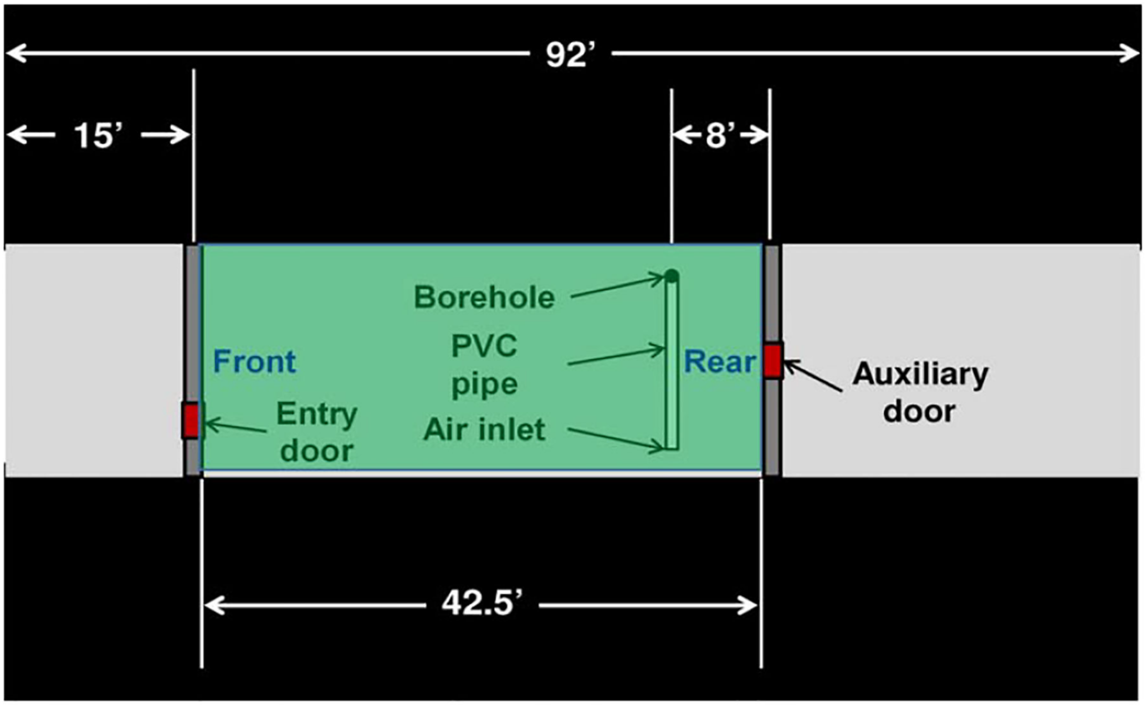


Fig. 2.
Overhead view of NIOSH 60-person BIP RA

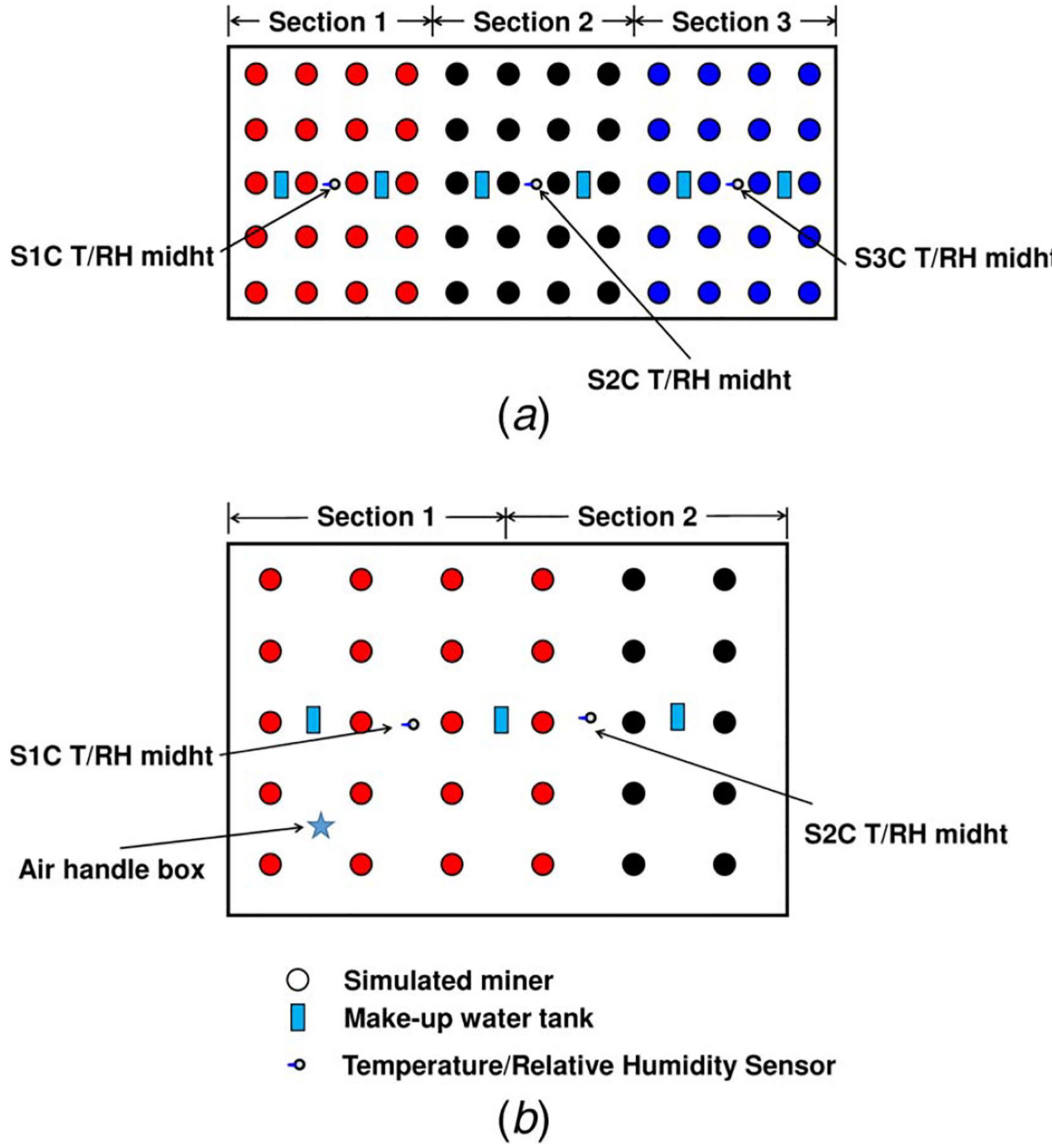


Fig. 3.

Layout of SMs, heated water tanks, and temperature/relative humidity sensors within (a) 60-person BIP RA and (b) 30-person BIP RA

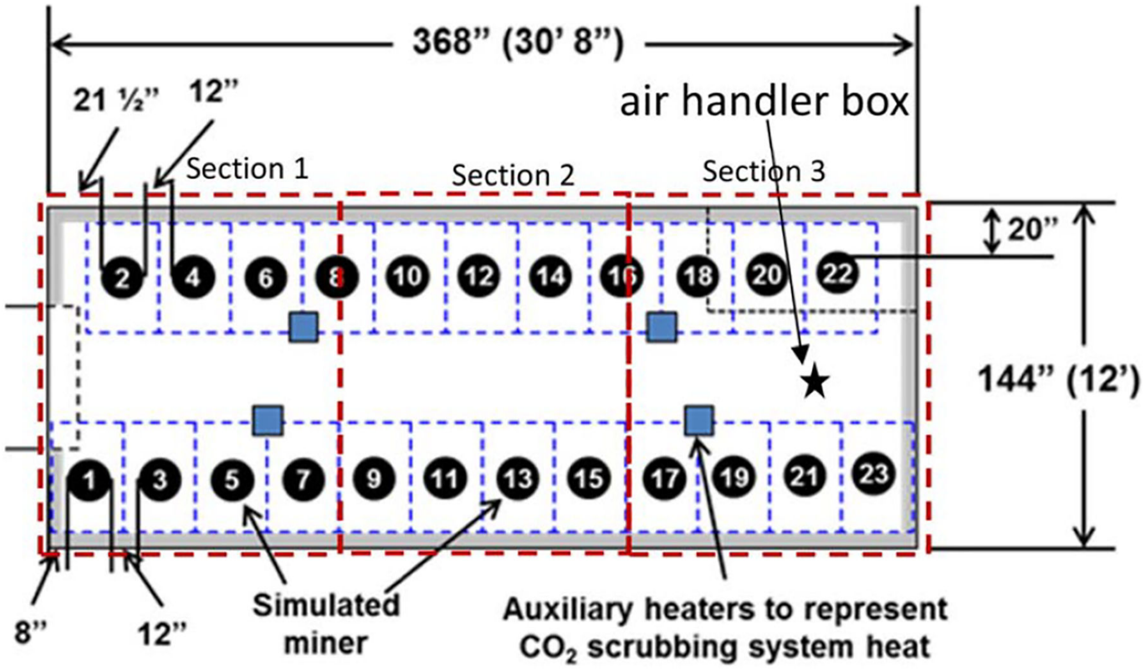


Fig. 4.

Layout of simulated miners to represent miner metabolic heat and heated water tanks to represent CO_2 scrubber heat (all dimensions in inches). The RA was divided into four parts labeled as tent 1 (near the entrance), tent 2 (near the middle), tent 3, and metal box (the storage container for the un-inflated chamber), which is not shown in this figure.

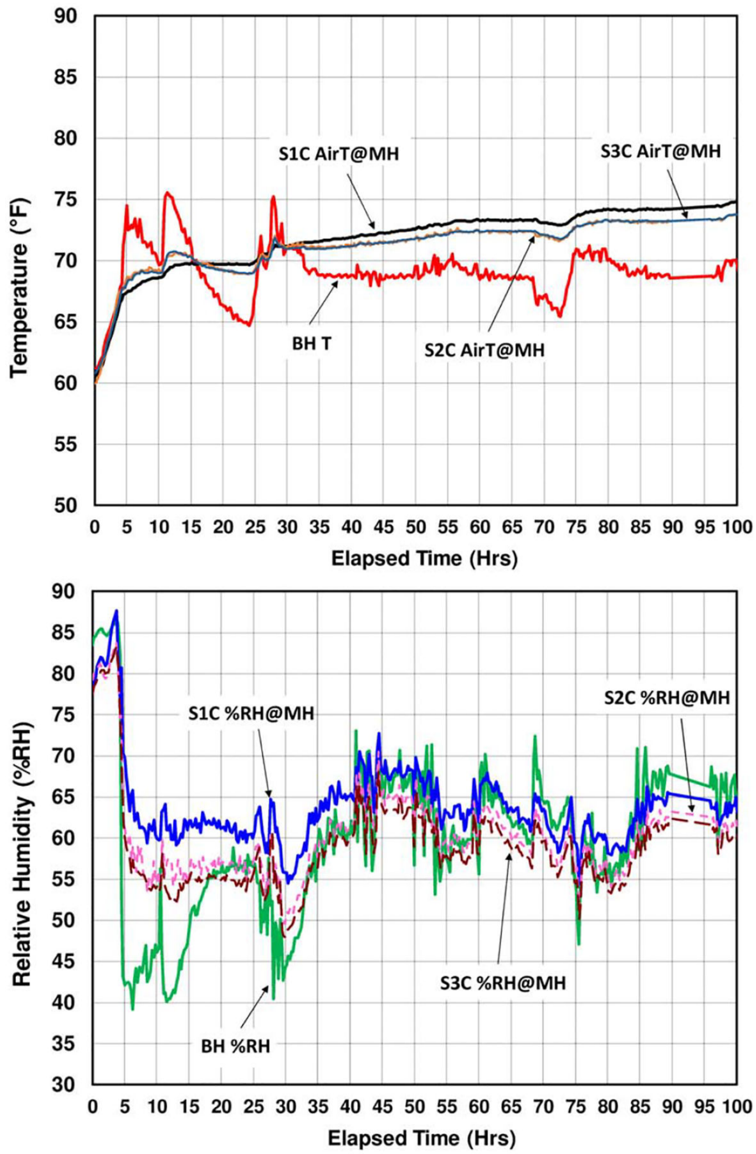


Fig. 5.

Temperature (upper) and relative humidity (lower) at midheight of Sections 1–3 and borehole outlet for testing with BAS (conditioned air)

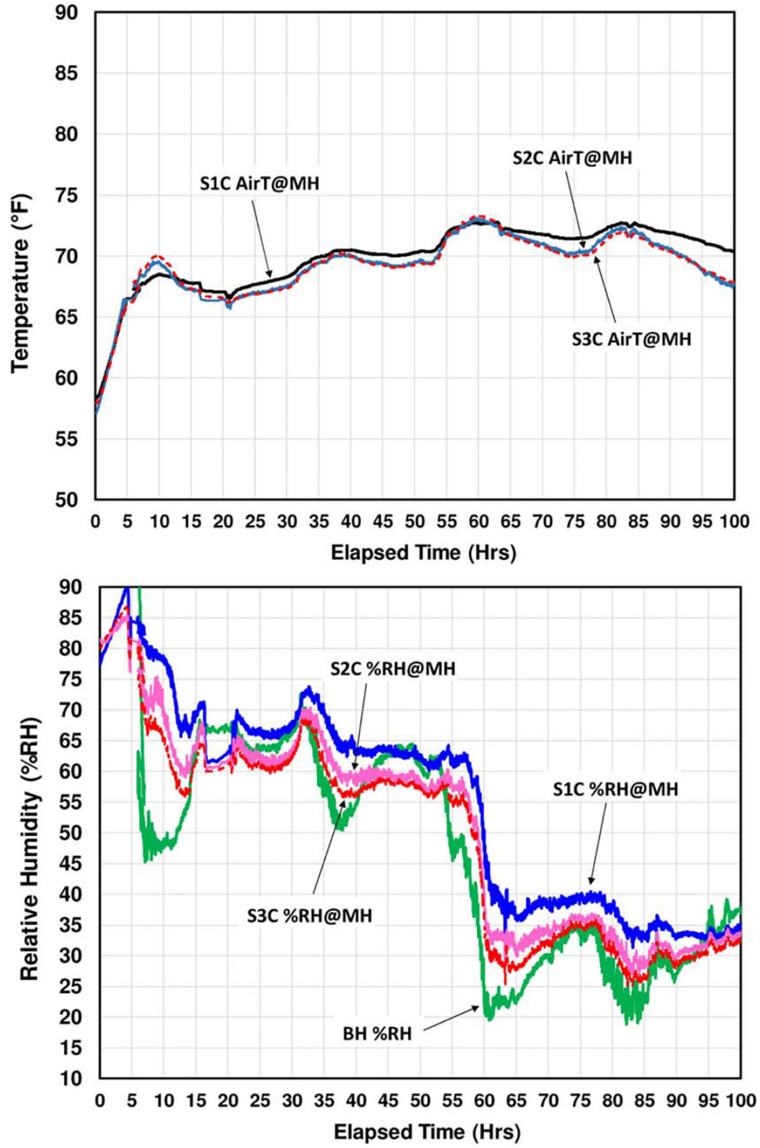


Fig. 6.

Temperature (upper) and relative humidity (lower) at midheight of Sections 1–3 and borehole outlet for testing with BAS (unconditioned air)

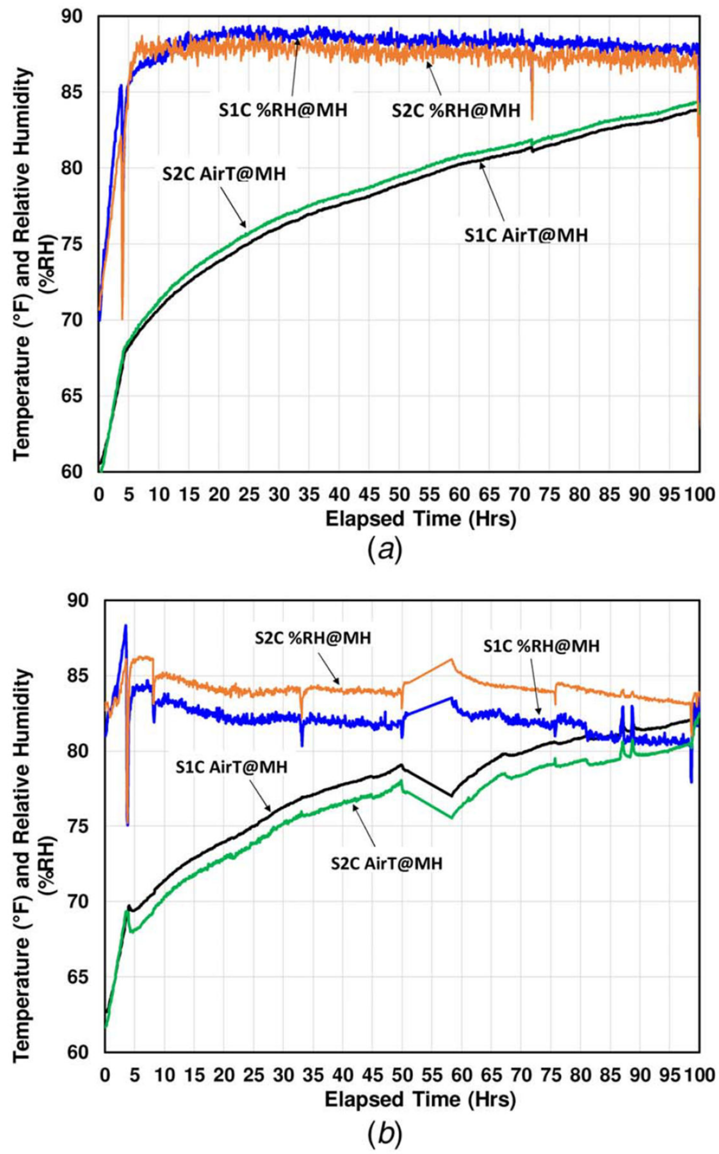
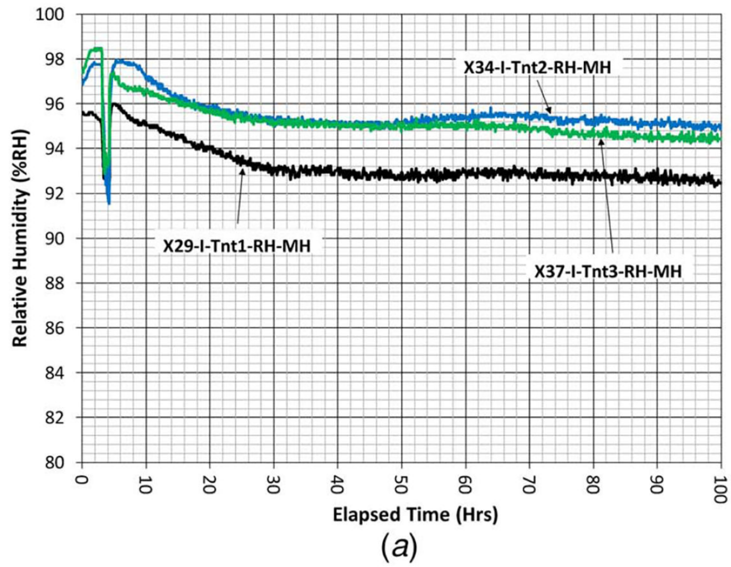


Fig. 7.

Temperature and relative humidity at midheight of Sections 1 and 2 for (a) baseline test and (b) CryoRASS test



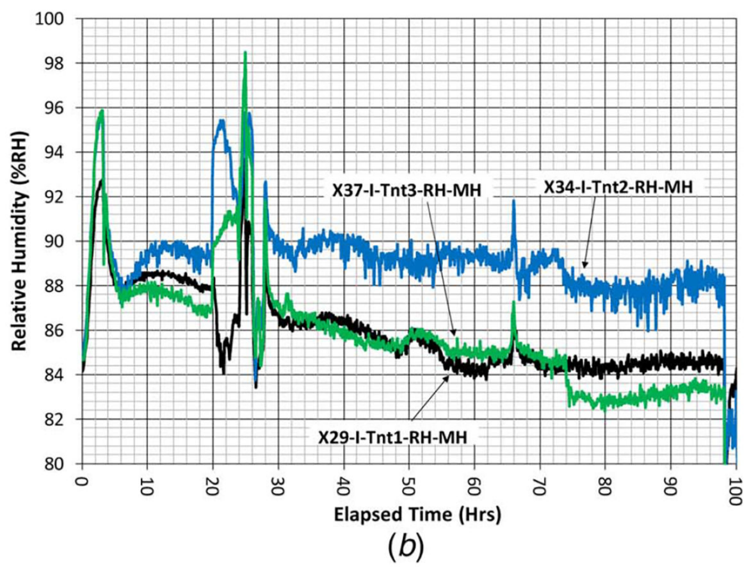


Fig. 8.

Relative humidity of tent 1–3 (labeled as X29, X34, and X37, respectively) of (a) baseline test and (b) CryoRASS test

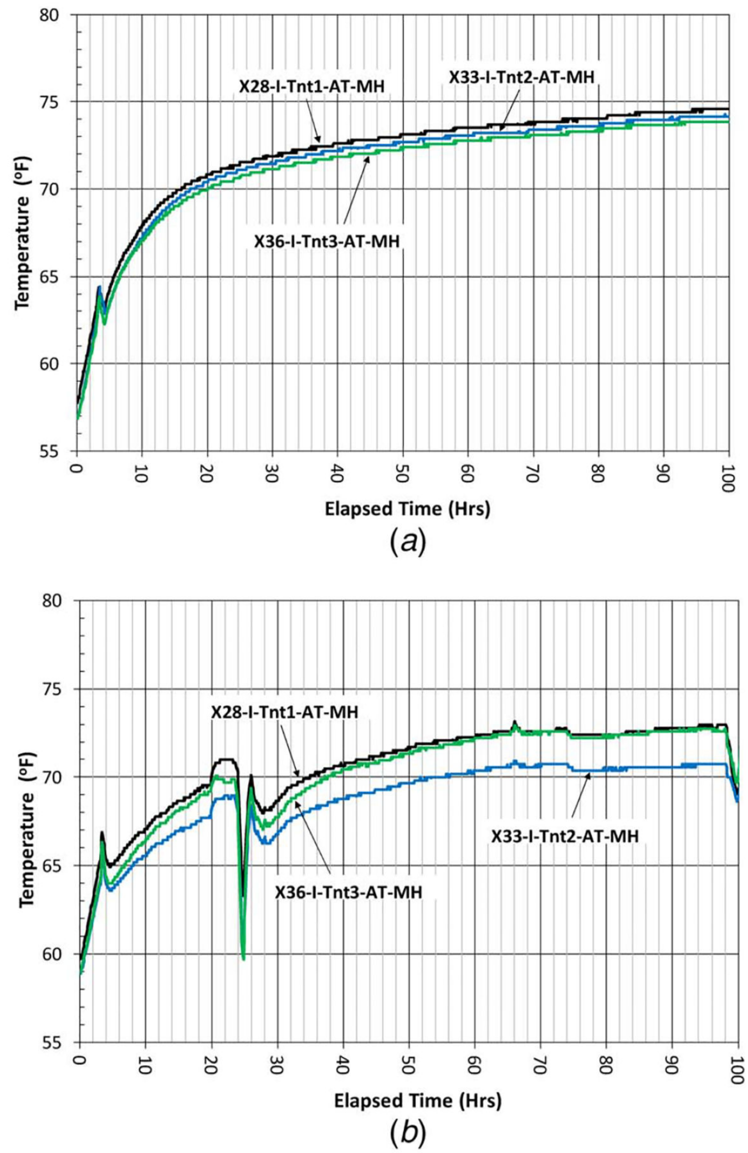


Fig. 9.

Temperature of tent 1–3 (labeled as X28, X33, and X36, respectively) of (a) baseline test and (b) CryoRASS test

Table 1

The apparent temperature (°F) for the BAS testing on a 60-person BIP RA

	BAS with cooling	BAS without cooling
Outside air	44.9–79.4	53.9–119.0
RA interior	59.9–75.1	57.3–84.4

Table 2

The apparent temperature (°F) for testing on a 30-person BIP RA

	With CryoRASS	Without CryoRASS
RA interior	62.5–88.7	60.0–96.8

Table 3

The apparent temperature (°F) for testing on a 23-person tent RA

	With CryoRASS	**Without CryoRASS**
RA interior	58.8–73.3	57.1–75.9