SME Annual Meeting
Feb. 19 - 22, 2017, Denver, CO

Preprint 17-069

HEAT/HUMIDITY TESTS OF A BUILT-IN-PLACE REFUGE ALTERNATIVE

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ABSTRACT

Federal regulations require the installation of refuge alternatives (RAs) in underground coal mines. Of the in-use RAs, over 95% are mobile RAs with the remainder being built-in-place (BIP) RAs. Heat/humidity buildup has been one of the major concerns with mobile RAs. For BIP RAs, however, there is a lack of in-mine heat/humidity test data to determine the extent of heat and humidity buildup. To quantify heat/humidity buildup in BIP RAs, the National Institute for Occupational Safety and Health (NIOSH) performed a series of heat/humidity tests on a 60-person BIP RA with and without a borehole air supply. At various times during the year, tests were performed with cooled, heated, or unconditioned borehole air to examine how various outdoor temperatures may affect the thermal conditions inside a BIP RA. The results show that the air supplied to a BIP RA may require heating and cooling, depending on the outside air temperatures and the temperature of the mine. For example, during tests with an external ambient temperature above 70°F and a humidity that reached 90 %RH, providing 55°F dew point air was able to keep the internal apparent temperature below the mandated 95°F. Results for each test case are presented.

INTRODUCTION

The Mine Safety and Health Administration (MSHA) has required the installation of refuge alternatives (RAs) in underground coal mines since 2008 [1]. MSHA requires that RAs provide an environment with breathable air for entrapped miners for a 96-hour period. Heat buildup inside an occupied RA is a serious concern. Without a means to dissipate the heat and humidity generated by the occupants and the carbon dioxide scrubbing system, the temperature and humidity inside RAs could lead to severe discomfort or heat stress depending on the mine ambient temperature before and during occupation of the RA. In its 2006 report, the West Virginia Mine Safety Technology Task Force recommended an apparent temperature limit of 95°F for RAs [2]. In 30 CFR 7.504, MSHA specifies a maximum apparent temperature of 95°F inside an occupied RA [3]. The apparent temperature is calculated using both air temperature and relative humidity [4].

To determine if their RAs meet the apparent temperature limit, RA manufacturers have been performing 96-hour-long heat and humidity tests in laboratories. During these tests, a heat input of 117 W (400 BTU/hr) per person is used to represent the metabolic heat of a single miner [2]. The heat generated by the RA's carbon dioxide system is also accounted for in testing. To account for this heat, 50 W (170 BTU/hr) of heat per miner is used for a lithium hydroxide scrubbing system, or 30 W (100 BTU/hr) of heat per miner is used for a soda lime scrubbing system [5]. In these tests, air velocities around the RA are minimized to represent the worst-case scenario of an interruption in mine ventilation that might occur in a mine disaster.

In addition to the laboratory research conducted by mobile RA manufacturers, NIOSH has conducted in-mine heat and humidity testing on mobile RAs. To date, NIOSH has tested three mobile RAs at its research facility in Bruceton, PA. In 2013, NIOSH tested a 10-person training tent-type RA in its Safety Research Coal Mine [6, 7]. In 2014, NIOSH tested a 23-person tent-type RA in its Experimental Mine [8, 9]. NIOSH tested a 6-person metal RA beginning in 2015 and continuing through 2016 [10]. For all of these RAs, the stated capacity is in accordance with MSHA's requirement to provide an unencumbered floor space of 15 ft^2 per miner. In order to simulate worst-case conditions of an interruption to a mine's ventilation system, NIOSH's tests were conducted with the mine ventilation blocked from the test areas. Multiple tests were conducted on each of the aforementioned RAs. During these tests, NIOSH-developed simulated miners (SMs) were used to input a nominal 117 W of heat each to represent the metabolic heat input of miners. For some of the tests, the heat input was purely sensible (dry) heat; for other tests, the heat was split between sensible and latent (moist) heat. For the tests conducted with latent heat, the moisture input was roughly 1 to 1.5 L per SM per day. The tests results showed that, for the tests conducted with both sensible and latent heat, the temperature increase was roughly 15°F to 20°F and the relative humidity (RH) within the RAs reached roughly 85 to 95 %RH.

From 2015 through the present, NIOSH has performed several heat and humidity tests on a 60-person BIP RA that NIOSH built in its Experimental Mine. This capacity is based on the space requirement of 15 ft^2 per miner. As with prior testing, NIOSH-developed SMs were used to provide 117 W of heat to represent the metabolic heat of miners and 1 to 1.5 L of moisture input per SM per day. In October of 2015, NIOSH conducted the first heat and humidity tests on its BIP RA. NIOSH performed one test with the BIP RA partitioned to create a 30-person BIP RA for the purpose of evaluating a prototype RA cryogenic air supply [11]. NIOSH also performed one BIP RA heat and humidity test with its BIP RA at full capacity during evaluations of a borehole air supply [12]. During these initial tests with the borehole air supply, the supplied air was conditioned to a nominal 55°F dew point temperature.

After performing the tests on the 60-person BIP RA with the borehole air supply delivering 55°F dew point air, NIOSH conducted several additional tests to examine the thermal conditions inside its BIP RA for a range of outside ambient temperatures and RH values with the borehole air supply delivering air. In August 2016, one test was conducted when high air temperatures and humid outside ambient conditions were expected. One test was conducted in January of 2016 when low outside air temperatures and dry outside ambient conditions were expected. Each of these tests was conducted with 60 SMs. The other was conducted in April when low outside air temperatures and humid outside ambient conditions were expected. This final test was performed using 6 SMs to determine if the resulting thermal conditions inside the BIP RA might be cool enough to cause discomfort if an RA is not fully occupied and the outside air temperature is low with high humidity.

TEST SETUP

Built-in-place RA

In the spring of 2015, NIOSH constructed a BIP RA in an entry in the NIOSH Experimental Mine. Two stoppings were built using two layers of solid 8-inch-thick concrete blocks. The dimensions of the

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constructed BIP RA are 45 feet long by approximately 20 feet wide and roughly 6.5 feet high (Figure 1).

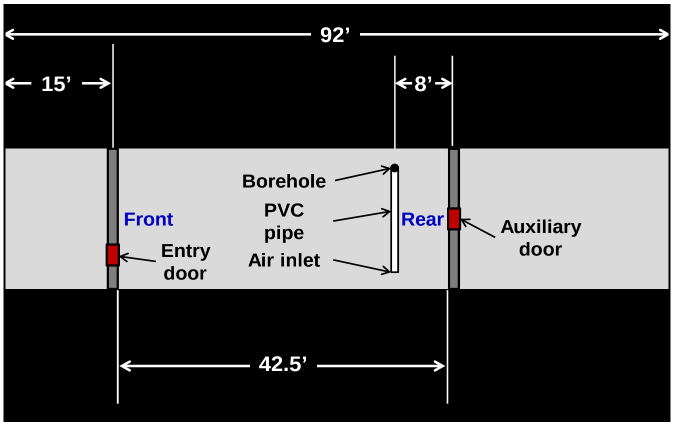

Figure 1. Overhead view of NIOSH 60-person BIP RA.

The floor within the test area is covered with a nominally 8-inch-thick layer of concrete, and the roof and ribs are covered with a roughly 1-inch-thick layer of shotcrete. The BIP RA is approximately 100 feet below the surface. A borehole located near the left rear corner (when viewed from the entry door) is used to provide air to the BIP from the surface. An approximately 8-feet-long 8-inch-diameter PVC pipe is 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 delivers the air near the right rear corner (when viewed from the entry door) of the BIP RA.

Borehole Air Supply

A borehole air supply constructed using a rotary blower powered by a 460 V electric motor with a power rating of 18.6-kW (25-hp) was positioned near the top of the borehole [12]. The borehole air supply incorporates a heating/cooling system consisting of a 39.3-kW (134,000 BTU/hr) air conditioner and a 45-kW (154,000 BTU/hr) heater. The borehole air supply has been demonstrated to be capable of providing a maximum airflow of 1,200 CFM at a pressure of 3 psi. During all tests discussed within this paper, air was delivered at a nominal volume flow rate of 775 SCFM, which exceeds the MSHA-required 12.5 SCFM of fresh air for 60 miners.

Heat Input

For each of the tests, SMs were used to provide the metabolic heat of actual miners. The SMs were arranged to apply a uniform heat input within the BIP RA (refer to Figure 2). The SMs were built using 0.11-m^3 (30-gallon) steel drums. Inside each SM, a thin-walled aluminum pipe is attached to a baseplate to create a "core" that is filled with water. Two silicone-encapsulated electrical resistance heaters rated at 120 W at 120 volts are attached to the outside of the aluminum core. One of these heaters is only used at the beginning of tests to preheat the SMs; the other heater is used for the entire test. To help achieve a reasonably uniform surface temperature, the SMs use an internal aquarium air pump to circulate the air within the annular area between the core and the drum. The internal air pump is positioned just under the lid so that warm air from the top of the drum is pumped to the bottom of the drum through tubes that are connected to the internal air pump. To generate moisture, the SMs use another aquarium air pump to force air through a roughly 3-inch air space atop the water-filled aluminum core. When the water level inside decreases by about 0.2 inches, a float switch inside the core actuates an aquarium water pump to refill the core from make-up water tanks.

During testing of mobile RAs that supply oxygen from cylinders, in addition to the representative metabolic heat for miners, the representative heat generated by mobile RA's carbon dioxide scrubbing system must be included. NIOSH has used immersible heaters inside the make-up water tanks to provide this heat during its mobile RA heat and humidity tests. Because the BIP RA tests discussed in this work were conducted using a borehole air supply delivering fresh air, it was assumed that it would be unnecessary to use a carbon dioxide scrubbing system. Thus, only the representative metabolic heat of actual miners was provided by the SMs during the test. For each of the tests, the SMs were powered using automatic variable AC transformers, or variacs, to control the input power. For the tests with 60 SMs, three automatic variacs were used; for the test with 6 SMs, one automatic variac was used.

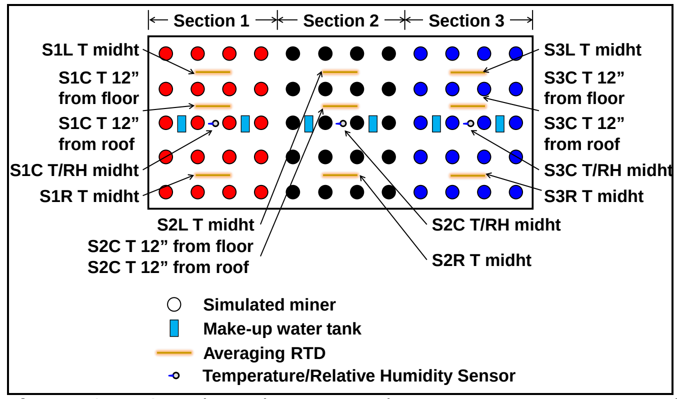

Figure 2. SM, heated water tank, temperature sensor, and temperature/RH sensor positions.

Instrumentation

Two separate data acquisition systems were used to collect data during the BIP RA tests. Above ground, a Graphtec Data Logger was used to collect data at the borehole air supply. The data logger was set up to collect data at a rate of 1 sample per minute. In the mine, three Data Translation DT-9874 instruments were used to collect data in the BIP RA. The in-mine data acquisition system was set up to collect data at rate of 1 sample per 100 seconds. Due to limitations of the setup software, this could not be matched with that of the surface data logger. Because the measured data changes very slowly for these tests, this mismatch of sample rates is unimportant.

On the surface, the airflow, blower outlet air temperature, blower outlet air dew point temperature, blower air pressure, outside ambient temperature, and outside ambient RH were measured. Refer to reference 12 for more information on the surface data measurements.

In the mine, numerous sensors were used to measure the heat input, water tank levels, borehole volumetric airflow, borehole air temperature and RH, BIP RA interior air temperatures and RH, and BIP RA mine strata temperatures. The heat input was measured using Ohio Semitronics watt transducers. The water tank levels were measured using Omega PX329 pressure sensors. The borehole volumetric airflow was measured using a Fluid Components International ST98 thermal-dispersion flow meter installed in the PVC pipe connected to the borehole (refer to Figure 1). For the first three tests, the borehole air temperature and RH were measured using a duct-mounted Greystone CDD5B201 carbon dioxide/RH/temperature transducer installed in the PVC pipe connected to the borehole. Due to a problem with the Greystone transducer, a Lascar Electronics EL-USB-2-LCD+ temperature/RH data logger was used to measure the air temperature and RH at the outlet of the borehole for the final test. The BIP RA interior air temperatures were measured at the locations indicated in Figure 2. The temperature and RH at the center of Section 2 at midheight was measured using a Vaisala HMP155 temperature/RH sensor. The temperature and RH at the centers of Section 1 and Section 3 at midheight were measured using Vaisala HMP110 temperature/RH sensors. At the other locations shown in Figure 2, the air temperature was measured using 4-foot-long averaging resistance temperature detectors (RTDs). Temperature probes constructed of PVC rods with attached RTDs were inserted into the roof, rib, and floor at various locations to measure the mine strata temperatures on the surface and at various depths.

TEST PROCEDURE

All NIOSH RA heat and humidity testing has been conducted using the following procedure. Prior to beginning each test, to minimize heat loss to the RA internal air so that the input heat will increase the temperature of the SMs more quickly, the SMs are wrapped with quilted 1-inch-thick fiberglass blankets and their lids are covered with 1-inch-thick polystyrene discs. For the first 2 to 4 hours of each test, both of the heaters on the aluminum core are used to raise the temperature of the SMs. The goal is to raise the surface temperature of the SMs to roughly 90°F to approximate human skin temperature. Once the SMs reach this temperature, the power to the SMs is temporarily shut off, the fiberglass blankets and polystyrene discs are removed, and the power to one of the internal heaters is turned on. After the preheat process, each SM provides a nominal 117 watts of heat as controlled by the automatic variacs. Each 96-hour test is started on a Monday at roughly 7 AM.

For the tests described in this paper, the following procedure was used. First, the above preheat procedure was used. After the preheat procedure was completed, the borehole air supply was turned on and it was adjusted to deliver a nominal 775 SCFM of outside air as verified by the BIP RA airflow sensor reading. Heat and humidity tests were conducted with unconditioned air, cooled air, and heated air with various outside ambient conditions as described below.

October 2015 Test with 60 SMs w/ High Outside Air Temperatures and Borehole Air Supply Delivering Cooled Air

In October of 2015, NIOSH performed a heat and humidity test with 60 SMs to examine the case of high outside air temperatures with a conditioned air supply. The borehole air supply was set to cool the supplied air to a dew point temperature of 55°F at the outlet of the blower.

August 2016 Test with 60 SMs w/ High Outside Air Temperatures and Borehole Air Supply Delivering Unconditioned Air

In August of 2016, NIOSH performed a heat and humidity test with 60 SMs to examine the case of high outside air temperatures with an unconditioned air supply. The purpose of this test was to gather data for comparison with the test conducted with cooled air.

January 2016 Test with 60 SMs w/ Low Outside Air Temperatures and Borehole Air Supply Delivering Unconditioned Air and Heated Air

To examine the case of low outside air temperatures with both an unconditioned and a heated air supply, NIOSH performed a heat and humidity test with 60 SMs in January 2016. For this test, unconditioned air was used for the first 2 days. Then the borehole air supply heater was turned on for the remainder of the test. The purpose of this test was to determine if heating the borehole air is warranted when the outside air temperature is low, and to examine if the borehole heater for the tested air supply is capable of providing sufficient heat to maintain comfortable BIP RA interior temperatures.

April 2016 Test with 6 SMs w/ Low Outside Air Temperatures and Borehole Air Supply Delivering Unconditioned Air

At the request of MSHA, to examine the case of low outside air temperatures with an unconditioned air supply and less-than-maximum occupancy, NIOSH performed a heat and humidity test with six SMs in April of 2016. For this test, six SMs located along the ribs in Section 2 were used. The purpose of this test was to examine the BIP RA thermal environment when an unconditioned air supply is used, the outside temperatures are low, and the BIP RA is not fully occupied to see if the interior temperatures could be low enough that hypothermia is a possibility.

RESULTS

October 2015 Test with 60 SMs w/ High Outside Air Temperatures and Borehole Air Supply Delivering Cooled Air

For the tests with high outside air temperatures using a cooled borehole air supply, the outside air temperature ranged from 48.6°F to 77.5°F with an average of 63.8°F, the outside RH ranged from 36.8 to 95.2 %RH with an average of 72.0 %RH, and the outside apparent temperature ranged from 47.4°F to 77.1°F with an average of 72.0°F (refer to Figure 3). The maximum outside RH occurred when the outside air temperature was at a minimum at the beginning of each day. The blower outlet air temperature averaged 70.4°F and the borehole outlet temperature inside the BIP RA averaged 69.3°F, indicating that the air temperature remained essentially unchanged as it traveled down the borehole. The RH of the air at the borehole outlet ranged from 39.2 to 73.1 %RH with an average of 58.3 %RH.

The time-varying apparent temperature was calculated for each of the midheight measurement locations inside the BIP RA. The location to the left of Section 1 (labeled S1L T midht in Figure 2) had the highest apparent temperature (refer to Figure 4). At this location, the air temperature ranged from 68.4°F to 75.2°F with an average of 72.7°F, the RH ranged from 54.4 to 80.7 %RH with an average of 62.9 %RH, and the apparent temperature ranged from 68.3°F to 75.5°F with an average of 72.7°F.

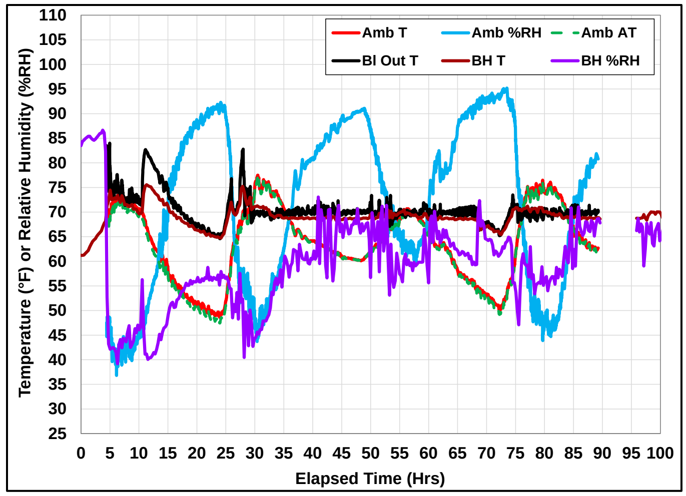

Figure 3. Outside ambient temp. and RH, blower outlet temp., and borehole outlet temp. and RH for Oct. 2015 tests conducted with 60 SMs and with the borehole air supply delivering 55°F dew point air.

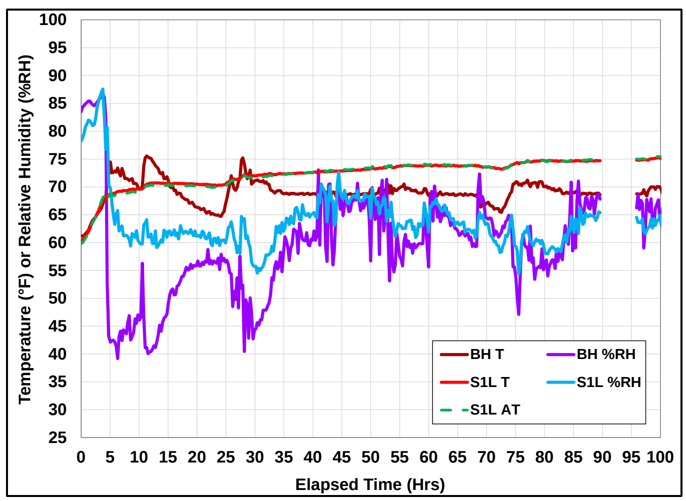

Figure 4. Borehole outlet temp. and RH, and BIP RA air temp., RH, and apparent temp. measured at the left of Section 1 for Oct. 2015 tests conducted with 60 SMs and with the borehole air supply delivering 55°F dew point air.

August 2016 Test with 60 SMs w/ High Outside Air Temperatures and Borehole Air Supply Delivering Unconditioned Air

During the tests with high outside air temperatures using an unconditioned borehole air supply, the outside air temperature ranged from 57.0°F to 88.6°F with an average of 71.4°F, the outside RH ranged from 31.4 to 94.6 %RH with an average of 72.0 %RH, and the outside apparent temperature ranged from 56.6°F to 88.8°F with an average of 71.7°F (refer to Figure 5). Similar to the October 2015 test conducted with a cooled borehole air supply, at the beginning of each day, the maximum outside RH occurred when the outside air temperature was at a minimum. In addition, the outside RH was at its minimum when the air temperature was at its maximum. The blower outlet air temperature averaged 88.5°F and the borehole outlet temperature inside the BIP RA averaged 81.8°F, indicating that the supplied air cooled as it traveled down the borehole. The RH of the air at the borehole outlet ranged from 26.8 to 81.0 %RH with an average of 52.3 %RH.

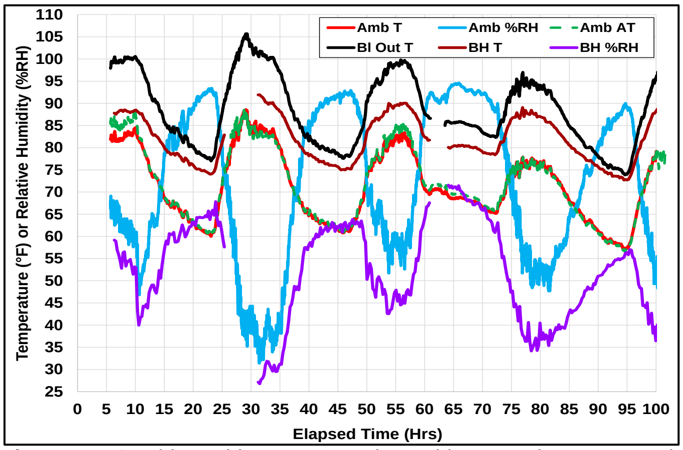

Figure 5. Outside ambient temp. and RH, blower outlet temp., and borehole outlet temp. and RH for Aug. 2016 tests conducted with 60 SMs and with the borehole air supply delivering unconditioned air.

Again, the time-varying apparent temperature was calculated for each of the midheight measurement locations inside the BIP RA. The location to the right of Section 3 (labeled S3R T midht in Figure 2) had the highest apparent temperature (refer to Figure 6). At this location, the air temperature ranged from 59.5°F to 83.2°F with an average of 77.4°F, the RH ranged from 48.9 to 99.0 %RH with an average of 67.7 %RH, and the apparent temperature ranged from 59.8°F to 87.0°F with an average of 78.7°F. Figure 6 shows that the BIP RA air temperature was generally lower than the borehole air temperature, which indicates that the borehole air was heating rather than cooling the BIP RA air.

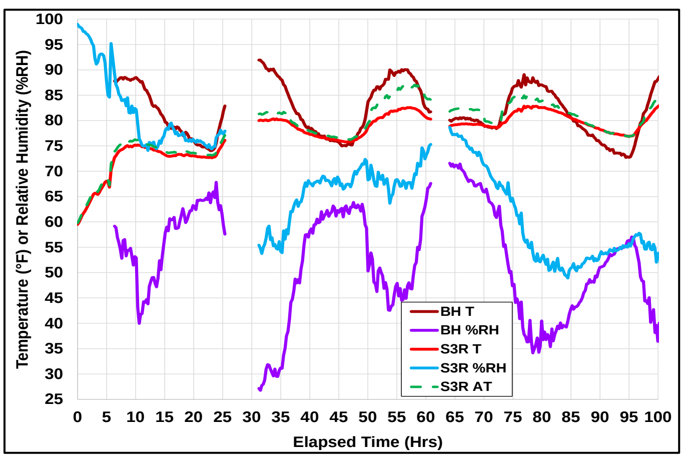

Figure 6. Borehole outlet temp. and RH, and BIP RA air temp., RH, and apparent temp. measured at the right of Section 3 for Aug. 2016 tests conducted with 60 SMs and with the borehole air supply delivering unconditioned air.

January 2016 Test with 60 SMs w/ Low Outside Air Temperatures and Borehole Air Supply Delivering Unconditioned Air and Heated Air

For the tests conducted in January 2016, the borehole air was unconditioned for the first half of the test. During the first half of the test, the outside air temperature ranged from 5.4°F to 31.5°F with an average of 20.0°F, and the outside RH ranged from 51.8 to 74.9 %RH with an average of 74.9 %RH (refer to Figure 7). The blower outlet air temperature ranged from 20.6°F to 46.4°F with an average of 35.3°F, and the borehole outlet temperature inside the BIP RA ranged from 32.6°F to 68.4°F with an average of 45.1°F, indicating that the air was heated by the surrounding earth as it traveled down the borehole. The RH of the air at the borehole outlet ranged from 21.2 to 88.3 %RH with an average of 39.0 %RH.

During the second half of the test, the supplied air was heated by the borehole air supply. The outside air temperature ranged from 8.5°F to 47.1°F with an average of 31.5°F, and the outside RH ranged from 47.3 to 77.9 %RH with an average of 62.8 %RH (refer to Figure 7). The blower outlet air temperature ranged from 50.7°F to 91.6°F with an average of 77.0°F, and the borehole outlet temperature inside the BIP RA ranged from 48.4°F to 79.2°F with an average of 69.0°F, indicating that the air cooled as it traveled down the borehole. The RH of the air at the borehole outlet ranged from 15.4 to 88.3 %RH with an average of 37.1 %RH.

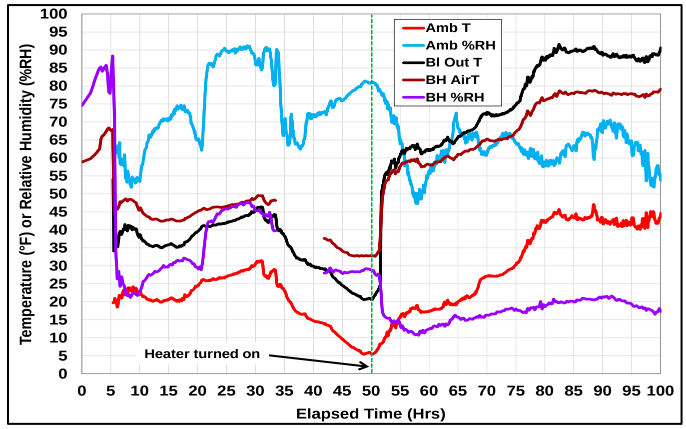

Figure 7. Outside ambient temp. and RH, blower outlet temp., and borehole outlet temp. and RH for Jan. 2016 tests conducted with 60 SMs and with the borehole air supply delivering unconditioned or heated air.

Because the concern for this test was exposure to low temperatures when unheated air is supplied, the BIP RA air temperatures at midheight were compared to determine the lowest temperature for the first half of the test. The temperature at the center of Section 3 at midheight (labeled S3C T midht in Figure 2) had the lowest temperature (refer to Figure 8). At this location, for the first half of the test with unheated air, the air temperature ranged from 54.8°F to 67.3°F with an average of 59.4°F, and the RH ranged from 29.3 to 86.7 %RH with an average of 40.3 %RH. After the borehole air supply heater was turned on for the second half of the test, the air temperature at this location ranged from 57.1°F to 73.7°F with an average of 67.8°F, and the RH ranged from 25.4 to 86.7 %RH with an average of 38.9 %RH.

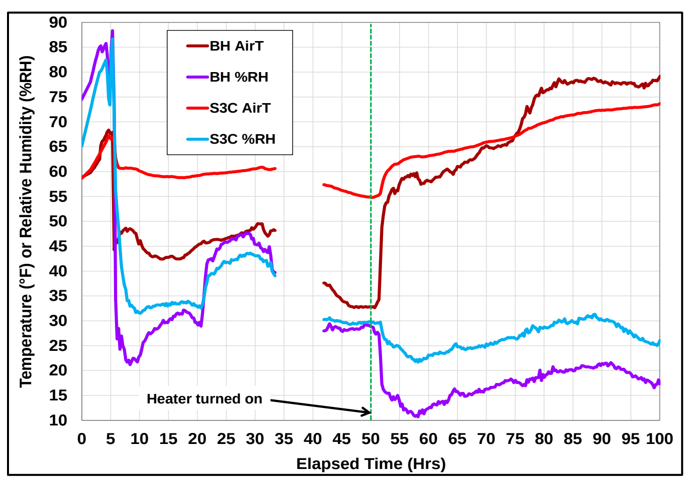

Figure 8. Borehole outlet temp. and RH, and BIP RA air temp. and RH measured at the center of Section 3 for Jan. 2016 tests conducted with 60 SMs and with the borehole air supply delivering unconditioned or heated air.

April 2016 Test with 6 SMs w/ Low Outside Air Temperatures and Borehole Air Supply Delivering Unconditioned Air

NIOSH performed a test with 6 SMs with low outside air temperatures with an unconditioned air supply in April of 2016. During this test, the outside air temperature ranged from 23.3°F to 67.5°F with an average of 40.7°F, and the outside RH ranged from 15.8 to 89.5 %RH with an average of 62.3 %RH (refer to Figure 9). The air temperature at the blower outlet ranged from 39.1°F to 83.5°F with an average of 56.6°F, and the air temperature at the borehole outlet ranged from 45.0°F to 72.0°F with an average of 56.7°F. Except for the range of elapsed times from 15 to 25 hours and 55 to 65 hours, Figure 9 shows that the blower outlet temperature and the temperature at the borehole outlet are similar for the majority of the test. This indicates that most of the time the air temperature remained essentially unchanged as it traveled down the borehole. At the borehole outlet, the RH ranged from 18.5 to 82.0 %RH with an average of 39.3 %RH.

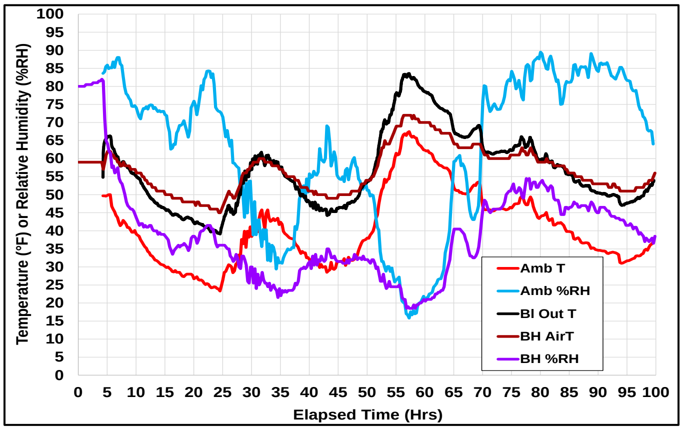

Figure 9. Outside ambient temp. and RH, blower outlet temp., and borehole outlet temp. and RH for Apr. 2016 tests conducted with 6 SMs and with the borehole air supply delivering unconditioned air.

The concern for this test was exposure to low temperatures when unheated air is supplied with much less than full occupancy, so the BIP RA air temperatures at midheight were compared to determine the lowest temperature. The temperature at the center of Section 2 at midheight (labeled S2C T midht in Figure 2) had the lowest temperature (refer to Figure 10). At this location, the air temperature ranged from 53.5°F to 62.5°F with an average of 57.7°F, and the RH ranged from 18.5 to 72.7 %RH with an average of 31.9 %RH. Figure 10 shows that, except for elapsed times from about 50 to 70 hours, the supplied borehole temperature was lower than the temperature within the BIP RA. This indicates that the supplied air would be cooling the BIP RA.

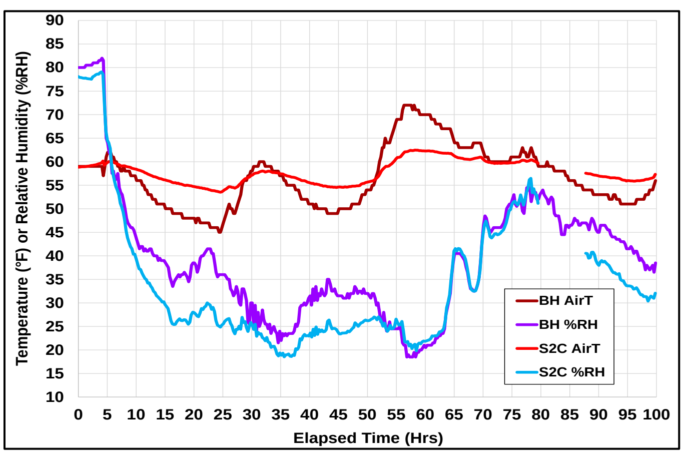

Figure 10. Borehole outlet temperature and RH, and BIP RA air temperature and RH measured at the center of Section 2 for Apr. 2016 tests conducted with 6 SMs and with the borehole air supply delivering unconditioned air.

DISCUSSION

Tests Conducted with High Outside Air Temperatures

The purpose of the tests with high outside air temperatures was to determine if the borehole air supply needs to be cooled when the outside air temperature is high. The tests conducted in October of 2015 with high outside air temperatures with the borehole air supply delivering air conditioned to a dew point temperature of 55°F showed that the resulting maximum apparent temperature within the BIP RA was well under the 95°F apparent temperature limit. The purpose of the tests conducted in August of 2016 was to determine if the apparent temperature limit would be exceeded in the BIP RA if the borehole air supply was not conditioned for similar outside ambient conditions.

For the August 2016 tests with 60 BP and unconditioned air, at 58 hours of elapsed time, the maximum apparent temperature inside the BIP RA for the tested conditions was 87°F (refer to Figure 6). This apparent temperature value was calculated from the BIP RA air temperature of 82°F and RH of 70 %RH measured near the borehole outlet (labeled S3R T midht in Figure 2). If the temperature at the location in question was 86°F (only 4°F higher), and the RH was the same, the apparent temperature limit of 95°F would have been reached.

It is important to understand that the air temperature at the blower outlet and the air temperature at the borehole outlet inside the BIP RA are a function of the ambient air temperature. The air temperature at the borehole outlet also depends on the temperature of the strata, which depends on the depth of the mine and RA. If the outside air temperature increases, the blower outlet air temperature increases, and the borehole outlet temperature also increases. The relationship between these temperatures will be specific to the BIP RA installation including the depth of the mine.

The NIOSH BIP RA is about 100 feet below the surface, and the strata surface temperatures for the BIP RA are about 58°F to 60°F. During the testing in August of 2016 with an unconditioned air supply, when the outside ambient temperature was near a peak, the air temperature at the borehole outlet was consistently about 10°F lower than the air temperature at the blower outlet (refer to Figure 5). The data indicates that at the 58-hour mark the blower increased the outside ambient air temperature by 18°F (from 78°F to 96°F). In addition, the air temperature decreased by 8°F (from 96°F to 88°F) as it traveled down the borehole. In addition, the data shows that the air temperature at the right of Section 3 followed the same trend as the borehole outlet temperature (refer to Figure 6) and, at 58 hours, the air temperature at this location was about 6°F less (82°F versus 88°F) than the air temperature at the borehole outlet. Overall, the temperature at the right of Section 3 was 4°F higher than the outside ambient air temperature at an elapsed time of 58 hours.

If the humidity in the supplied air was at the same level, and the outside air temperature had reached 82°F at the 58-hour mark, it is feasible that the temperature at the right of Section 3 would have reached 86°F. With this temperature and the same RH observed during testing, the 95°F apparent temperature limit would be reached. This demonstrates that the air in BIP RAs with unconditioned borehole air supplies could reach the apparent temperature limit if the outside air temperature is high.

Tests Conducted with Low Outside Air Temperatures

Hypothermia occurs when the body core temperature drops below 95°F [13]. In wet and windy conditions, hypothermia may occur at temperatures of 50°F or above [14]. The tests conducted in January of 2016 showed that for the NIOSH BIP RA, the lowest air temperature in the BIP RA was 55°F at an elapsed time of 50 hours (refer to Figure 8). At this time, the outside ambient air temperature was 5°F (refer to Figure 7) and the temperature of the air at the borehole outlet was 33°F. To guard against hypothermia, it would be advisable to provide blankets and towels in BIP RAs located in geographic areas where the outdoor air temperature is low.

It should be noted that the resulting air temperature in the BIP RA is a function of the air temperature at the borehole outlet, and the heat input by the SMs, or real miners in an actual refuge situation. If fewer

SMs were used for this test to represent an RA with less than full occupancy, the air temperature in the RA would have been lower.

The January 2016 data shows that after the borehole air supply heater was activated, the temperature of the air at the borehole outlet increased from about 33°F to 55°F in less than 4 hours (refer to Figure 8). The heated air increased the air temperature within the BIP RA from about 55°F to 60°F in the same time period, and the air temperature continued to increase throughout the remainder of the test, reaching a comfortable temperature of about 73°F at the end of the test. This demonstrates that the 45-kW (154,000 BTU/hr) heater built into the borehole air supply would be adequate to prevent conditions that could lead to hypothermia for the tested conditions.

A follow-up test to examine the possibility of conditions that could lead to hypothermia for less-than-fully occupied BIP RAs was conducted in April of 2016. These tests were conducted with only six SMs, but with the airflow delivered at the flow rate required for full occupancy. The air was not heated for this test. The outside ambient temperature for these tests was not as low as desired, so the test conditions were not as severe as the tests conducted in January of 2016.

In spite of this, the test data shows that the air temperature in the center of Section 2 of the BIP RA labeled S2C T midht in Figure 2) dipped below 55°F from 20 to 27 and from 42 to 48 hours of elapsed time (refer to Figure 10). During these time periods, the outside air temperature was 30°F or below (refer to Figure 9) and the air temperature at the borehole outlet was 50°F or below. With a lower outside air temperature, the air temperature inside the BIP RA would have been even lower. Again, it would be prudent to stock blankets and towels in BIP RAs located in geographic areas with low outside air temperatures.

CONCLUSIONS

The four tests described within this paper examined the resulting air temperature and RH in a BIP RA for high and low outside air temperatures both with and without a conditioned air supply. The results demonstrated that without air conditioning, it is plausible that the resulting thermal environment within a BIP RA could exceed the 95°F apparent temperature limit. For the tested BIP RA, this could be expected if the outdoor air temperature would reach 86°F or more. Supplying cooled/dehumidified air was shown to result in BIP RA conditions that were well below the apparent temperature limit. The tests conducted with low outside air temperatures showed that it is possible that the air inside the BIP RA could be low enough to cause hypothermia. Less-than-fully occupied BIP RAs and low outside air temperatures would result in the lowest BIP RA temperatures. The data from the January 2016 test showed that heating the air resulted in moderate BIP RA temperatures despite the low outside air temperature. If an air supply does not have heating capabilities, stocking blankets and towels in BIP RAs should be considered.

It is important to realize that the resulting temperatures inside any BIP RA with a borehole air supply are a function of the outside air temperature, the air temperature at the borehole outlet, the pre-disaster mine temperature, the RA occupancy, and numerous other factors. It is not a "given" that the resulting thermal environment will be satisfactory. Either testing or thermal simulation should be performed to ensure the safety of the thermal environment. Given the lack of ability to control the weather to examine the influence of extreme outside weather conditions on the resulting BIP RA thermal environment, use of a thermal simulation model that incorporates all heat sources, including that provided by borehole air, seems to be a better option than testing. Of course, such a simulation model would have to be validated using test data to ensure its predictions are accurate.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Reference to specific brand names does not imply endorsement by the National Institute for Occupational Safety and Health.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Tim Matty, Mary Ellen Nelson, Andrew Mazzella, Jim Addis, Paul Stefko, Joe Sabo, and other NIOSH researchers for their assistance in completing this work.

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