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TEMPERATURE AND HUMIDITY TESTS FOR MOBILE REFUGE ALTERNATIVES

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ABSTRACT

Federal regulations require refuge alternatives (RAs) in underground coal mines to sustain life for 96 hours while maintaining an apparent temperature (AT) below 35°C (95°F). NIOSH research has shown that heat and humidity buildup is a major concern with RAs because they have a limited ability to dissipate heat, and high internal air temperature and relative humidity (RH) may expose occupants to heat stress. The heat transfer process within and surrounding an RA is very complex and is not easily defined analytically nor experimentally. To investigate heat and humidity buildup in RAs, NIOSH conducted multiple in-mine 96-hour tests on a 6-person metal-type RA, a 23-person tent-type RA, and a 10-person tent-type RA. The test results show that when moisture was introduced into the tests to represent perspiration and respiration from miners (wet tests), the average measured internal air temperature at midheight increased by 7.7°C, 9.4°C, and 10.5°C, and the RH approached 95%, 94%, and 88%, respectively. For the dry tests when no moisture was introduced, the average internal temperature increased by 8.4°C, 10.3°C, and 12.6°C, respectively.

INTRODUCTION

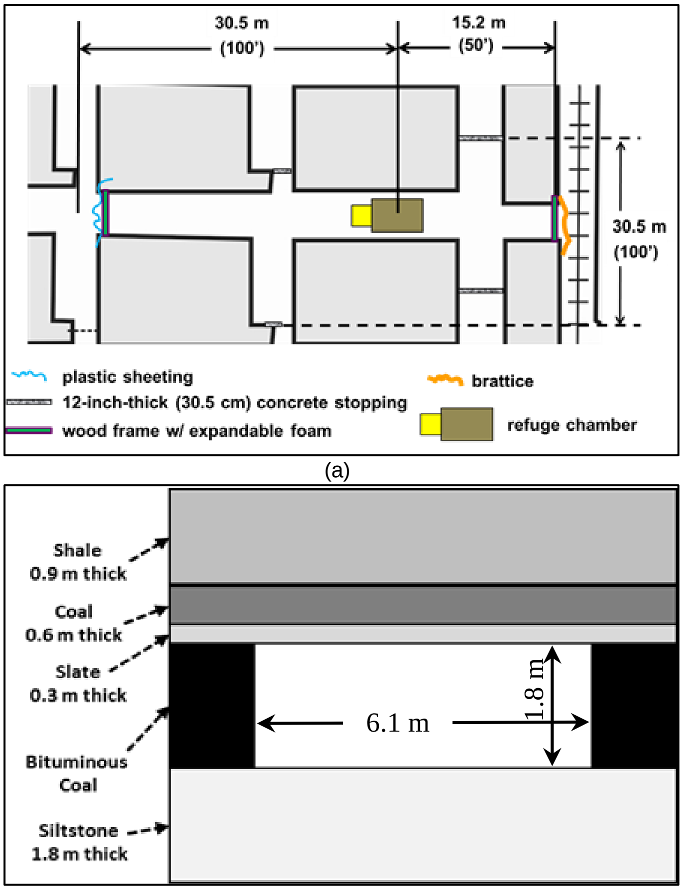
If an accident occurs in an underground coal mine, miners who cannot escape from the mine can enter an RA for protection from adverse conditions, such as high carbon monoxide levels. One of the main concerns with the use of mobile RAs is the thermal environment inside the RA. The metabolic heat of the occupants and the heat released by the CO_2 scrubbing system will cause the interior air temperature to increase. 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 internal thermal conditions can subject miners to heat stress, which can lead to heat exhaustion, heat stroke, or even death depending on duration and magnitude of exposure. MSHA regulations require that RAs must be designed to ensure that the internal apparent temperature does not exceed 35°C (95°F) when the RA is fully occupied **[1]**. Apparent temperature (AT) is a temperature-humidity metric for the perceived temperature caused by the combined effects of air temperature, relative humidity (RH), and wind speed. It is used to assess the perception of indoor temperatures when workplaces are not sufficiently heated, cooled, or insulated to provide comfortable or healthy conditions.

Before a mobile RA can be deployed at an underground mine for emergency usage, it must be tested to show that its internal AT when fully occupied will not exceed the 35°C (95°F) limit. For practical reasons, RA manufacturers usually conduct their tests at above-ground test facilities. To investigate RA thermal response in an in-mine environment, NIOSH conducted multiple 96-hour tests on a 6-person metal-type RA, a 23-person tent-type RA, and a 10-person tent-type RA in its underground coal mine facility. The work described in this paper could be used by RA manufacturers to determine a final temperature rise based solely on dry and time-reduced testing.

TEST SETUP

Test Venues

Safety Research Coal Mine (SRCM). Tests on 10-person tent-type RA were conducted in NIOSH's Safety Research Coal Mine (SRCM) in Bruceton, PA (Fig. 1a). To prevent bulk airflow into the test area, the RA was isolated from the mine ventilation system using plastic sheeting on one end and brattice cloth on the other as shown in the figure. This represents a worst-case scenario—a loss of the mine ventilation fans. The RA was positioned in the SRCM with the center of the tent located at the center of the entry so that the sides of the RA were equidistant from the ribs. The encapsulated test area was approximately 45.7 m long, 30.4 m wide, and 1.8 m high (150 × 100 × 5.9 ft). The strata composition for the roof, rib, and floor nearby the test area is shown in Fig. 1b. The thickness of each layer was determined by using ground penetrating radar. The strata composition materials include a layer of 0.9-m-thick shale, a layer of 0.6-m-thick coal, a layer of 0.3-m-thick slate, a layer of 1.8-m-thick bituminous coal, and a layer of 1.8-m-thick siltstone.

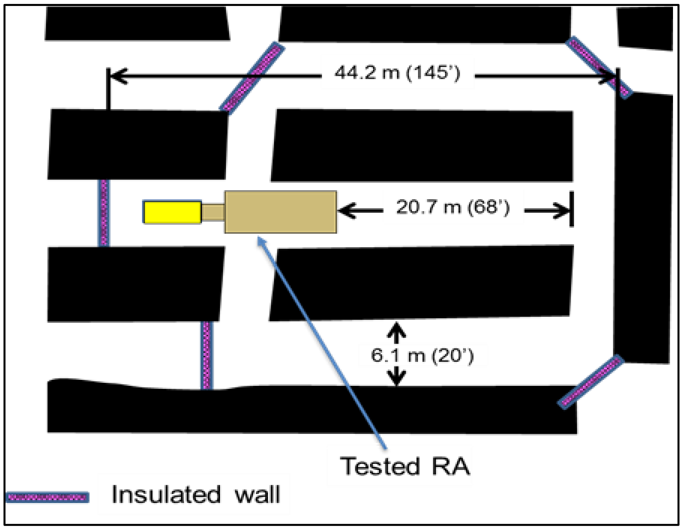


(a)

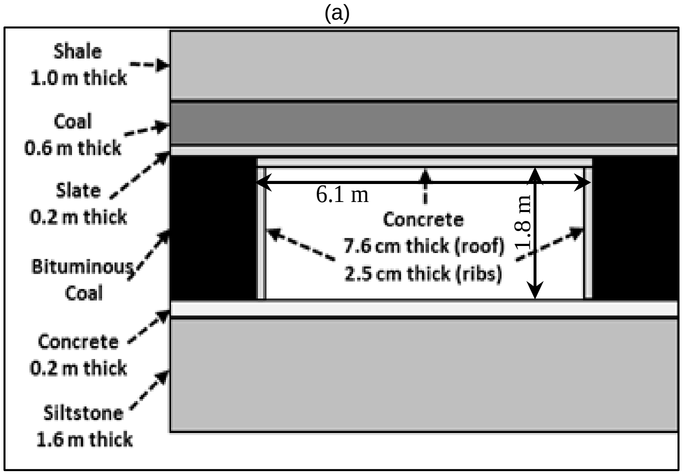
(b)

Figure 1. Test area (a) and entry cross section (b) in the SRCM.

Experimental Mine (EM). Tests on a 23-person tent-type RA and 6-person metal-type RA were conducted in NIOSH's Experimental Mine (EM) in Bruceton, PA (Fig. 2a). The RAs were installed at the intersection of an entry and a crosscut. To prevent bulk airflow into the test area, the RA was isolated from the mine ventilation system using polystyrene walls. The RAs were centered within the entry so that the sides of the chamber were equidistant from the ribs. The strata composition for the roof, rib, and floor nearby the test area is shown in Fig. 2b. The strata composition materials include a layer of 1.0-m-thick shale, a layer of 0.6-m-thick coal, a layer of 0.2-m-thick slate, a layer of 1.8-m-thick bituminous coal, a layer of 0.2-m-thick concrete, and a layer of 1.6-m-thick siltstone.



(a)



(b)

Figure 2. Test area (a) and entry cross section (b) in the EM.

Heat Input

Simulated miners were used during the testing to represent the heat input of actual miners. The simulated miners are comprised of commonly available 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 with a nominal power rating of 120 watts at 120 volts. Both of the heaters are used to preheat the simulated miners at the beginning of a test. Only one of the heaters is used after the preheat time period of 2 to 4 hours.

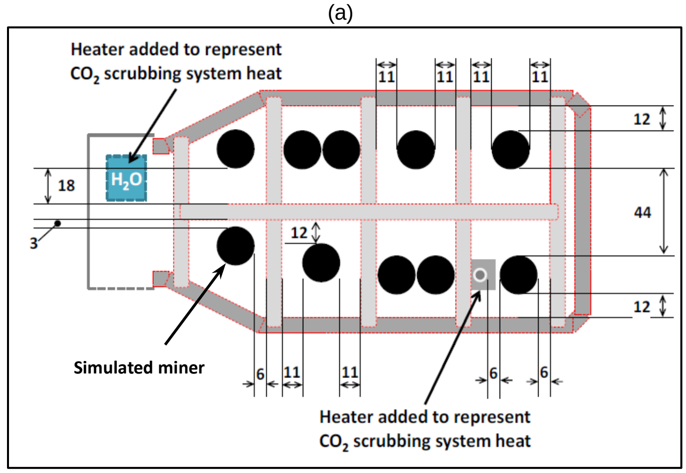
During testing, each simulated miner provided a nominal 117 watts of heat at steady state. For the 10-person tent-type RA, to represent the heat of a lithium hydroxide carbon dioxide scrubbing system, a heated water tank and a heated aluminum pipe were used to input an additional 50 watts of heat per simulated miner. For the 23-person tent-type RA and the 6-person metal-type RA, additional heated water tanks were used to input 27.5 W of heat for each simulated miner to represent the heat that would be generated by a soda lime CO_2 scrubbing system. All input power was controlled using an automatic variable AC transformer to compensate for voltage fluctuation.

The simulated miners were modified to increase the moisture generation prior to the tests in EM. Each simulated miner outputted ~1.1 to ~1.3 L/day for the 10-person tent RA wet tests in the SRCM, and ~1.3 L/day to ~1.5 L/day for the 23-person tent RA and 6-person metal RA wet tests in the EM. More details on the design of the simulated miners can be found in [2].

Tested RAs

10-Person Tent. A training model 10-person tent-type RA was placed in the SRCM at the location as specified in Fig. 1 (Fig. 3a). The RA had a height of 1.07 meters (3.5 ft), an internal volume of roughly 15 m^3 (530 ft^3), and a floor surface area of about 14 m^2 (151 ft^2). This RA meets the unrestricted surface area requirement of 1.4 m^2 (15 ft^2) per miner as specified in 30 CFR 7.505 for up to 10 people, and it meets the unrestricted volume criteria of 1.7 m^3 (60 ft^3) per miner for seam heights up to 137 cm (4.5 ft), mandated for RA manufacturers by 2018. Tent-type RAs, such as the tested RA, use a metal box to store their tent prior to its deployment, to store the compressed air cylinders that are used to inflate the tent, and to store compressed oxygen cylinders that are used to provide occupants with oxygen. The metal box portion of the RA was 208 cm (6.8 ft) wide by 198 cm (6.5 ft) long. More details on testing on that type of RA can be found in **[3]**.

(a)



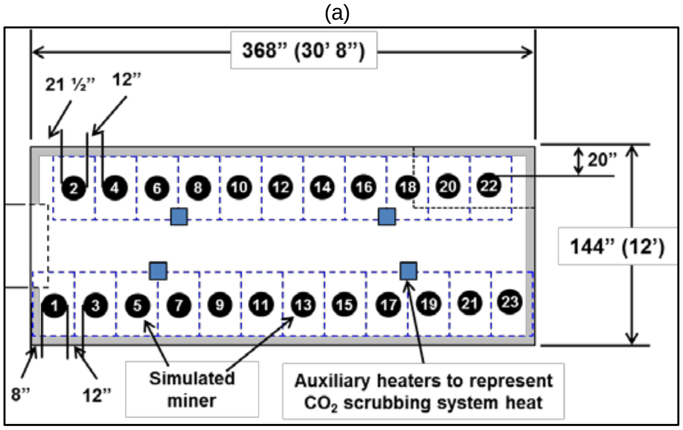
(b)

Figure 3. Ten-person tent-type RA (a) and schematic of the RA with ten (10) simulated miners and heaters to represent carbon dioxide scrubber heat (all dimensions in inches) (b).

23-Person Tent. A 23-person tent-type RA was placed in the EM at the location as specified in Fig. 2 (Fig. 4a). The 23-person RA had a height of 1.7 m (5.5 ft), an internal volume of roughly 55.3 m3 (1881 ft3), and a floor surface area of about 31.8 m2 (342 ft2). This RA also meets the unrestricted surface area and unrestricted volume criteria requirement mentioned early as mandated by MSHA for up to

23 people. The metal box for this tested RA was 1.98 m (6.5 ft) wide by 4.72 m (15.5 ft) long. Twenty-three simulated miners and four heated water tanks were arranged to distribute the heat as evenly as possible within the deployed tent (Fig. 4b). More details on testing on that type of RA can be found in [4].

(a)



(b)

Figure 4. Twenty-three-person tent-type RA (a) and layout of simulated miners to represent miner metabolic heat and heated water tanks to represent carbon dioxide scrubber heat (all dimensions in inches) (b).

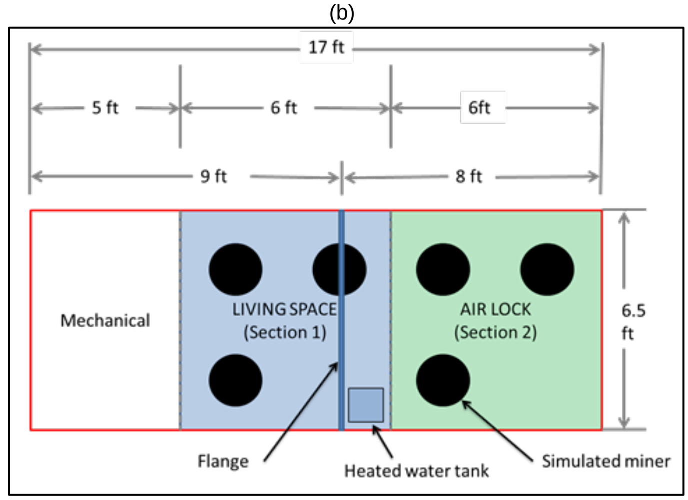
6-Person Metal. The 6-person metal RA was positioned in the EM at the same location as the 23-person tent-type RA—i.e., the 23-person tent RA was replaced by the 6-person metal RA. The 6-person metal RA is 5.2 m long by 2.0 m wide by 1.4 m high (17 x 6.5 x 4.6 ft), with an internal volume of ~18 m^3 (619 ft^3) and a floor surface area of ~10 m^2 (111 ft^2) (Fig. 5). The chamber consists of two parts that were bolted together through a flange (Fig. 5c). It was internally divided into three sections: the mechanical room, the living space (Section 1), and the air lock (Section 2). Ordinarily, the mechanical room would be used to store compressed oxygen cylinders that would be used to provide occupants with oxygen. Section 1 and Section 2 would be the areas occupied by miners. Section 2 would also serve as an air lock. The six simulated miners and heated water tank were arranged to distribute the heat as evenly as possible within the deployed RA.

Instrumentation

Sensors were used inside and outside the RAs to record the internal and external air temperature, RH, and RA surface temperature. During each test, resistance temperature detectors (RTDs) were used to monitor the strata surface temperatures. In addition, RTDs were attached to PVC rods that were installed within the strata to monitor the strata temperatures with depth.

(a)

(b)



(c)

Figure 5. The external (a) end view, (b) side view, and (c) dimension of a 6-person metal-type RA.

To monitor the internal temperature and RH, two temperature/RH sensors and one wet bulb globe temperature (WBGT) sensor array were evenly placed at midheight of the 10-person tent RA; three temperature/RH sensors and one WBGT sensor array were evenly placed at midheight of the 23-person tent RA; two temperature/RH sensors and one WBGT sensor array were evenly placed at midheight of the 6-person metal RA.

The mine air temperatures within the test area were measured using 122-cm-long (48-inch-long) RTDs by averaging their readings at eight locations around the RA chamber. More details on sensor and RTD locations can be found in [4].

All data were recorded using a Data Translation DT9874 data acquisition system. The sampling rates were set to 1 sample every 20 seconds or 100 seconds with 24-bit resolution. For all testing, the actual heat input was measured using watt transducers (Flex-Core, model PC5-019CX5).

Test Procedure

At the beginning of each test, NIOSH used a procedure to bring the simulated miners from mine temperature to operating temperature (the skin temperature of the human body). The simulated miners were wrapped in quilted fiberglass blankets and covered with 1-inch-thick polystyrene lids. By using insulation around the simulated miners, the heat lost to the RAs could be minimized so that the temperature of the simulated miners increased relatively quickly. During the first 2 to 4 hours of each test, both heaters inside each simulated miner were powered to raise the simulated miner temperatures from mine temperature to operating temperature. One of the heaters was turned off and the insulation was removed once the RA internal temperature reached approximately 35°C (95°F)—the miner skin temperature or the operation temperature.

All tests were conducted in either wet or dry conditions. For the wet test, moisture was generated to simulate the moisture generation by actual miners. No moisture was generated in the dry test.

TEST RESULTS

10-Person Tent

The RA internal temperatures during the 96-hour test period are the temperatures of the most interest. Fig. 6 shows the average measured internal air temperature and RH at midheight of the RA during the wet and dry tests. The internal air temperatures rose relatively quickly during the first half-day before leveling off with a slow, steady rise for the remainder of the test. The initial temperatures of tent air and mine air were ~15°C (59°F) and ~ 13.3°C (56°F) for the wet test and dry test, respectively. At the end of the 96-hour test, the average temperatures at tent midheight were approximately 25.3°C (77.5°F) and 25.9°C (78.6°F) for the wet test and dry test, respectively. The RH approached ~88% at the end of the wet test.

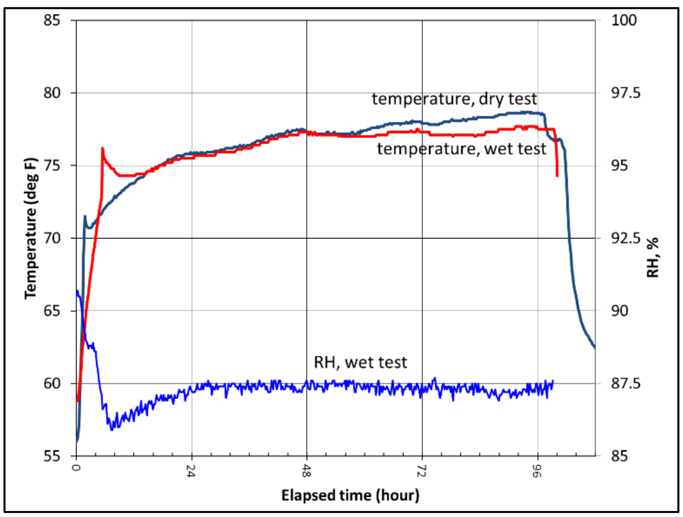


Figure 6. Average midheight internal air temperature and RH during the 96-hour test of the 10-person tent RA.

23-Person Tent

Fig. 7 shows the average measured internal air temperature and RH at midheight of the 23-person tent RA during the wet test and dry test. The initial temperature of tent air and mine air was ~14.4°C (58°F) for both the wet test and dry test. At the end of the 96-hour test, the average temperatures at midheight were approximately 23.3°C (74°F) and 24.8°C (76.7°F) for the wet test and dry test, respectively. The RH approached ~94% at the end of the wet test.

6-Person Metal

Fig. 8 shows the average measured internal air temperature and RH at midheight of the 6-person metal RA during the wet test and dry test. The initial temperature of tent air and mine air was ~14.4°C (58°F) for both the wet test and dry test. At the end of the 96-hour test, the average temperatures at the RA midheight were approximately 22.1°C (71.7°F) and 22.8°C (73°F) for the wet test and dry test, respectively. The sudden temperature drop at ~28 hours for the dry test was caused by a power outage. The RH approached ~95% at end of the wet test. Note that the RH increase at 72 hours was caused by a float switch stick during this testing. Based on the trend depicted in Fig. 8, the RH would probably have been 94% at the end of the test without that float switch stick.

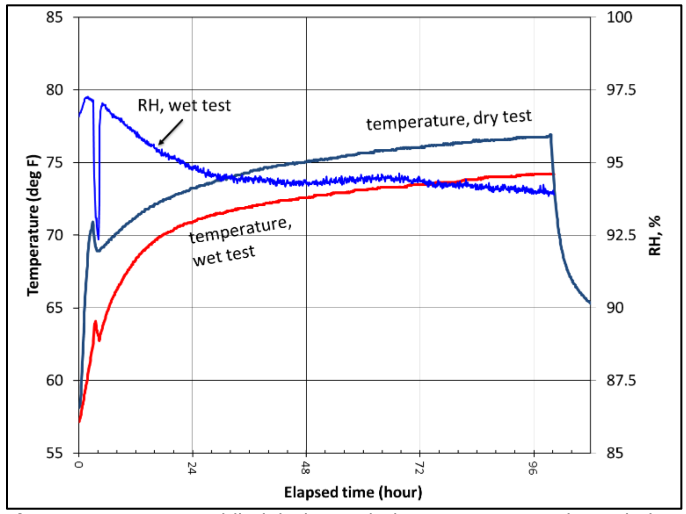


Figure 7. Average midheight internal air temperature and RH during the 96-hour test of the 23-person tent RA.

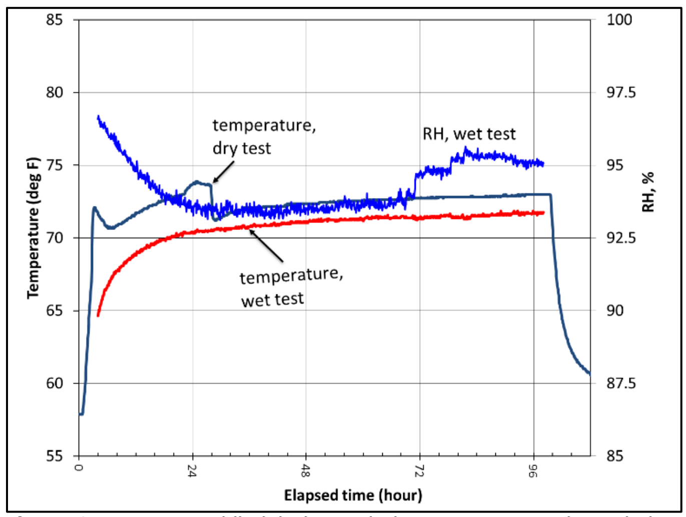


Figure 8. Average midheight internal air temperature and RH during the 96-hour test of the 6-person metal RA.

DISCUSSION

For each of the RAs, the temperature rise at the end of each complete day (ΔT_1, ΔT_2, and ΔT_3) was compared to the final temperature rise at the end of day four (ΔT_4). Table 1 shows the final temperature rise and RH at the end of the 96-hour test. The final temperature rise, ΔT_4, in the wet test is approximately 83% of that in the dry test for the 10-person tent RA tested in the SRCM. This value becomes approximately 91% and 93% for the 23-person tent RA and the 6-person metal RA, respectively, tested in the EM.

Table 1. Final temperature and humidity change for three types of RAs.

Tested RA	Test condition	Final ΔT (ΔT_4, °F)	Final RH (%)	$\frac{\text{Final } \Delta T\text{, wet}}{\text{Final } \Delta T\text{, dry}}$
10-p tent, SRCM	dry	+22.6	--	83%
	wet	+18.7	88	
23-p tent, EM	dry	+18.6	--	91%
	wet	+17.0	94	
6-p metal, EM	dry	+15.0	--	93%
	wet	+14.0	95	

The temperature rise at the end of each day during the test was compared to the final temperature rise for each test (refer to Table 2). For each type of RA, the ratio of temperature rise for each day to the final temperature rise was roughly the same for the dry test and wet test.

Those observations could be useful for RA manufacturers for their RA testing. As Table 1 shows, for the same type of 6-person metal RA used in the test, the dry testing temperature rise could be used by multiplying a coefficient of 0.93 with an assumed final RH of 95% to substitute for the wet tests. This would give RA manufacturers the option of using dry tests instead of wet tests. Also, the data in Table 2 suggests that for a particular RA and test location, ΔT for a particular day divided by the final ΔT is nearly constant. Therefore, if RA manufacturers determine these values, they would not have to run a full 96-hour test when developing the protocol for their AT tests. Instead, they could possibly run “trials” for 2-3 days to determine the optimum maximum mine air temperature for full occupancy to comply with the interior AT limit.

Table 2. Temperature rise for each day during the test compared to the final temperature rise.

Tested RA	Test condition	$\Delta T_1/\Delta T_4$ (%)	$\Delta T_2/\Delta T_4$ (%)	$\Delta T_3/\Delta T_4$ (%)
10-p tent, SRCM	dry	87	93	97
	wet	88	97	98
23-p tent, EM	dry	81	91	96
	wet	82	91	96
6-p metal, EM	dry	NA	96	98
	wet	91	95	98

CONCLUSION

Three types of mobile RAs were used in wet and dry tests to investigate the internal temperature and humidity rise. Those mobile RAs had different occupancy capacities and structural materials. The final temperature rise in the wet test was approximately 83%, 91%, and 93% of that in the dry test for the 10-person tent, 23-person tent, and 6-person metal RA, respectively. Based on these results, instead of conducting wet tests, RA manufacturers might be able to use the final temperature rise from their dry tests by multiplying a coefficient and assuming a final RH to estimate the final temperature rise that would result from wet tests. Our test results also show that for each type of RA, the ratio of temperature rise at the end for each day to the final temperature rise was roughly the same for the dry tests and wet tests. With that observation, a full 4-day test on an RA’s temperature limit might be reduced to a 2-day or 3-day test by compensating a ratio to the final temperature rise. Importantly, these factored 2-day or 3-day tests might be useful for RA design, test setup, and derating purposes *only*—i.e., this approach cannot be used to substitute for the full 96-hour tests required by MSHA for the purpose of certification.

DISCLAIMER

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