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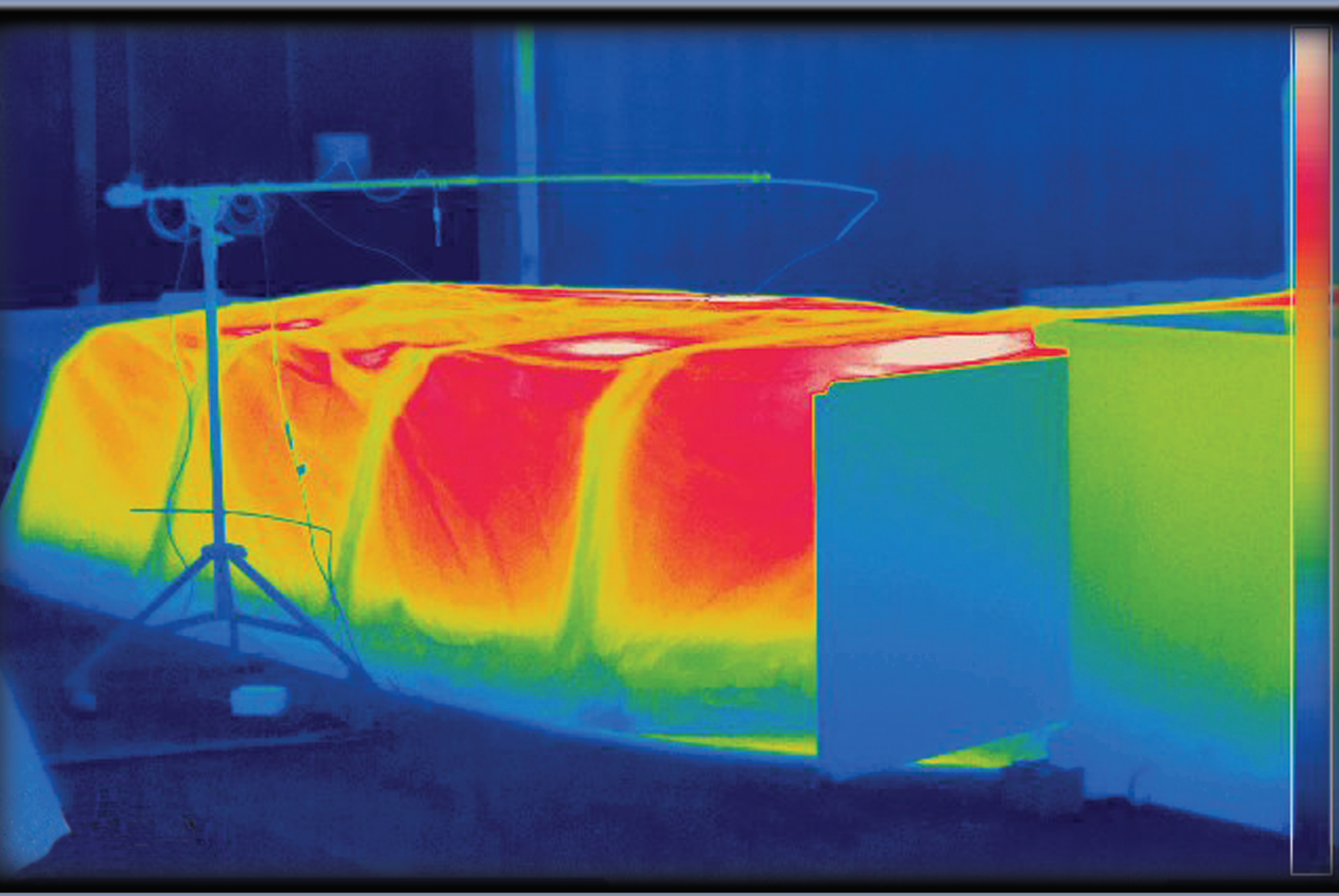
Investigation of Temperature Rise in Mobile Refuge Alternatives



Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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Investigation of Temperature Rise in Mobile Refuge Alternatives

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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
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ACRONYMS AND ABBREVIATIONS

AMB, amb	ambient
AVG, Avg, avg	average or averaging
Bx	box
CFR	Code of Federal Regulations
Cntr	center
CO_2	carbon dioxide
DBT	dry-bulb temperature
FOIA	Freedom of Information Act
H_2O	water
HVAC	heating, ventilation, and air conditioning
Int	interior or internal
IRB	Institutional Review Board
loc	location
Lt	left
Mid	middle or midheight
Midht	midheight
MSHA	Mine Safety and Health Administration
NA	not applicable
NIOSH	National Institute for Occupational Safety and Health
OMSHR	Office of Mine Safety and Health Research
PVC	polyvinyl chloride
RA	refuge alternative
RH	relative humidity
RTD	resistance temperature detector
Sk	skin (surface)
SRCM	Safety Research Coal Mine
Std Dev	standard deviation
Temp, temp	temperature
Tnt	tent
TOT, Tot	total
Und	under
WBGT	wet-bulb globe temperature

UNITS OF MEASURE

BTU/hr	British thermal units per hour
BTU/lb-°F	British thermal units per pound degree Fahrenheit
cm	centimeters
ft^3	cubic feet
ft^3/hr	cubic feet per hour
ft^3/min	cubic feet per minute
m^3	cubic meters
m^3/hr	cubic meters per hour
°C	degrees Celsius
°F	degrees Fahrenheit
ft	feet
ft/min	feet per minute
gal	gallons
g/m^3	grams per cubic meter
hr	hours
in	inches
kg	kilograms
kg/m^3	kilograms per cubic meter
kJ/kg-K	kilojoules per kilogram Kelvin
L	liters
L/day	liters per day
MPa	megapascal
m	meters
m/s	meters per second
mm	millimeters
min	minutes
%	percent
%RH	percent relative humidity
lb	pounds
lb/ft^3	pounds per cubic foot
PSI	pounds per square inch
ft^2	square feet
m^2	square meters
W/m-K	watts per meter Kelvin

Investigation of Temperature Rise in Mobile Refuge Alternatives

David S. Yantek[1]

Executive Summary

Background

One of the initial and persistent concerns over the use of mobile refuge alternatives (RA) 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 as the occupants lose water through respiration and perspiration. The National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) in its 2007 report to Congress on refuge alternatives recommended that refuge alternatives be designed and deployed to ensure that a temperature-humidity metric[2] known as *apparent temperature* not exceed 95°F [NIOSH 2007]. Subsequently the Mine Safety and Health Administration (MSHA) adopted this recommendation.[3]

Notwithstanding the above process, a standard method to determine compliance with this metric does not exist. The heat transfer process in an RA, including the contributions of the human occupants, is highly complex, and is not easily defined analytically or experimentally. Initially, regulatory agencies accepted the certification of registered professional engineers that the manufactured RAs met the apparent temperature requirement. In 2007, NIOSH tested four mobile RAs in its Lake Lynn Experimental Mine, and found that two failed to meet the apparent temperature criterion by a wide margin. These tests used artificial heat and humidity sources to simulate the heat and humidity loading of human occupants.

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[2] The body's core temperature is a standard to assess heat stress on the human body. However, the apparent temperature is easier to use since it is based on the relative humidity and dry bulb temperature of the air, and does not require a direct measurement of the body's core temperature. The apparent temperature scale is highly nonlinear. For example, at a relative humidity level of 95%, a dry bulb temperature of 80°F results in an apparent temperature of 86°F; a dry bulb temperature of 85°F results in an apparent temperature of 103°F; and a dry bulb temperature of 90°F results in an apparent temperature of 126°F. While the degree of heat stress in an individual may vary with age, health, and body characteristics, prolonged exposure to apparent temperatures approaching or exceeding 105°F are considered dangerous and could be life-threatening.

[3] 30 CFR 7.504 (b)(1): "When used in accordance with the manufacturer's instructions and defined limitations, the apparent temperature in the fully occupied refuge alternative shall not exceed 95 degrees Fahrenheit."

Another approach to testing the apparent temperature criterion would be to place an RA into mine ambient conditions, fill the RA to its rated occupancy with human subjects, and record the interior ambient temperature and relative humidity over the 96-hour period mandated in 30 CFR[4] 7.506 for breathable air sustainability. In consideration of this approach, a team of experts including physicians, biomedical researchers, and engineers endeavored to develop and obtain approval of a human subjects protocol for such testing. Ultimately it was determined that the experiment would place the subjects at an unacceptably high risk, and was not approvable by a Human Subjects Institutional Review Board (IRB).[5] Thus, it became necessary to develop experimental and analytical methods to determine if refuge alternatives, as built and deployed, meet the apparent temperature requirement.

NIOSH initiated research in 2008 with the goal of developing a technical foundation for such analytical and experimental procedures. Based on a significant amount of preliminary work at the Lake Lynn Experimental Mine, at NIOSH's Pittsburgh Research Laboratory, and at manufacturer facilities, the project was focused to address four research questions.

The first and likely most significant question is: *Does the mine behave as an infinite heat sink*? The engineering assumption that a mine does behave as an infinite heat sink was applied in the calculations originally used to certify mobile RAs, and is being applied in the design of tests to the present. If a mine can be assumed to behave as an infinite heat sink, then the temperature rise within an RA would be significantly less for a given configuration than if the mine does not behave as an infinite heat sink.

The second question is: *Does the facility in which the test is conducted impact the resulting temperature rise*? The manufacturers of RAs conduct tests to demonstrate that their RAs meet the 30 CFR 7.504 apparent temperature requirement, but they do so under varying conditions. The ability of an RA to dissipate heat could be different in a large open room (i.e., a high bay) as compared to a confined space, and accordingly the temperature rise predicted would be different.

The third question is: *Will the moisture generated by the occupants reduce the air temperature within the RA*? It has been suggested that condensation on the interior surfaces of the RA could significantly increase the heat loss, which would in turn reduce the internal air temperature.

The fourth question is: *Could occupancy derating values be used for RAs that are rated and approved for use at one mine ambient temperature,*[6] *but are deployed in a mine with a higher ambient temperature*?

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[4] Code of Federal Regulations. See CFR in references.

[5] 45 CFR 46—Protection of human subjects. These regulations provide direction on the treatment of human subjects, research protocol preparation, informed consent, review board procedures, and so on; and this regulation applies to all research involving human subjects conducted or supported by NIOSH (and other federal agencies).

[6] The geothermal gradient of surrounding rock will drive the air temperature. Ventilating air from the outside can cool or heat the ambient air in the mine, depending on the outside air temperature, rate of flow, and so forth. However, it must be assumed that forced ventilation will be disrupted after an explosion or other catastrophic event, and therefore, for the purposes of RA deployment, the ambient temperature will be different from the air temperature while the ventilation system is operating.

Experimental and analytical studies, described in this report, were designed to answer these questions. Each of the studies contributed incrementally to the overall understanding of the problem, and the knowledge gained in one step was applied in the next to further the understanding of temperature rise in RAs. A recently completed “capstone” study provided data to answer the research questions and to validate the numerical model developed in the project.

The in-mine component of this capstone study was conducted in an underground coal mine using a 10-person tent-type RA in a test area that was isolated from the mine ventilation system using brattice cloth and plastic sheeting to prevent airflow through the test area. The RA, the mine air, and the mine strata were instrumented to measure temperatures and other relevant parameters. The heat input from human occupants was simulated with specially designed containers that mimicked the heat and humidity loading equivalent to a 165-pound male.[7] Two additional heat sources were placed in the RA to account for heat that would be generated by the CO_2 scrubbers.[8] To examine the effect of including moisture generation on the RA interior environment, the in-mine tests were conducted both dry (without moisture generation) and wet (with moisture generation). Lastly, an additional experiment was performed with the RA located in a large high bay to determine if the measured RA internal temperature rise was affected by the test facility. All tests were conducted for 96 hours.

Summary of Findings

The mine strata temperatures were observed to increase throughout the 96-hour in-mine tests. The strata temperatures near the surface of the roof, rib, and floor increased more than the temperatures deeper into the strata, and, as depth into the strata increased, the strata temperature and its rate of change decreased. The strata temperature beneath the RA was observed to increase to a depth of 48 in (121.9 cm) into the mine floor. *These findings demonstrate that the mine cannot be assumed to behave as an infinite heat sink, and provide a definitive answer to the first research question.*

This 96-hour test was repeated with the RA placed inside of a large high bay. The internal air temperature rise for the dry tests[9] conducted in the high bay was compared to the internal air temperature rise for the dry tests conducted in the underground mine. The air temperature rise in the RA for the tests in the high bay was 21.0°F, whereas for the in-mine tests, the rise was 25.2°F. These findings demonstrate that the test location can have a significant impact on the results. In this case, the test conducted in the high bay underestimated the temperature rise by approximately 20%. This aligns well with the finding that the mine strata will not behave as an infinite heat sink—if it did, the in-mine results would have closely matched those from the high bay. *The answer to the second research question is that the test location will affect the observed temperature rise.*

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[7] Each “simulated miner” emitted 117 watts (metabolic heat) and 1 liter of water per day to mimic the moisture lost through respiration and perspiration. In one set of experiments, the humidity generation capability was not used so that the effect of not accounting for moisture generation during the tests could be better examined.

[8] 50 watts of heat was added for each of the miners to account for the exothermic CO_2 scrubbing process.

[9] The tests in which the emitted moisture capability of the simulated miners was deactivated are referred to as “dry” tests in the report, and those in which the moisture generation capability was activated are referred to as “wet” tests.

Significant condensation and pooling occurred within the RA during the in-mine wet test. Water puddled at every low spot on the tent floor and a layer of water that was roughly one-half-inch deep covered the bottom of the metal section of the RA. For the in-mine wet test, the temperature rise for the air inside the RA was 22.4°F, which represents a 2.8°F, or an 11% decrease compared to the in-mine dry test. The mine air temperature increased more during the wet test than during the dry test, whereas the temperature increase in the mine strata was less. These results indicate that condensation within the RA could indeed reduce the air temperature, but the results are confounded by the way in which the moisture from the “simulated miners” was injected into the RA. On subsequent examination, it was observed that the location of the injection tubes may have “short circuited” the heat transfer path from the interior of the RA to the RA roof to the mine air. The close proximity of the tubes to the roof of the RA may have resulted in the warm moisture condensing directly on the roof of the RA. *Thus, it is impossible from the findings of this study to provide a definitive answer for the third research question.* Notwithstanding, the indication is that the moisture contributed by the miners to the RA environment should be accounted for experimentally or analytically because it may have a small limiting effect on the temperature rise within the RA.

A thermal simulation model, developed in this project, was evaluated using the actual parameters of the RA and the in-mine conditions under which it was tested. The model correctly predicted the observed temperature rise to within 1°F (0.6°C). The validation of this model increases the confidence that it can be used to study temperature rise characteristics as well as to evaluate and certify RAs, as long as appropriate steps are taken to benchmark the model. This model was also used to develop derating tables for the RA used in this study. *The answer to the fourth research question is, given a properly validated model that has been benchmarked for baseline conditions, tables can be developed to define the reduced occupancy to ensure that the apparent temperature criterion is not exceeded when the RA is placed in mines with ambient temperatures that are higher than the ambient temperature in which the RA was originally tested*.

Summary of Discussion and Recommendations

The four research questions posed at the beginning of the study were addressed, and this new knowledge and understanding can be used to improve the procedures used to determine if an RA meets the apparent temperature criterion specified in 30 CFR 7.504.

RA apparent temperature determinations should be based on a standardized and published experimental method and supplemented by the use of validated and benchmarked numerical models. The experimental and analytical methods should not employ an assumption that mines will behave as an infinite heat sink. Moreover, the original engineering calculations that assumed this characteristic will underestimate the temperature rise in the RA. Furthermore, experimental tests must be conducted in a setting that will approximate the heat transfer characteristics found in a mine. A large and open room with a high ceiling will tend to behave as an infinite heat sink, and any tests conducted in such a high bay will significantly underestimate the air temperature rise in the RA. In addition, tests conducted in a test facility that attempts to mimic an infinite heat sink by using an HVAC system to maintain the air or the interior walls of the test facility at a constant temperature will also underestimate the air temperature rise within an RA.

The apparent temperature in the tent-type RA tested in this study will exceed the statutory limit at a mine ambient temperature of 60°F (15.6°C), and consequently, the number of occupants would have to be reduced.[10] It has been widely assumed that derating due to ambient conditions is of concern only for “hot” mines. The finding in this study indicates that occupancy derating could become necessary at temperatures lower than previously considered. It should be emphasized that this finding strictly applies only to the tested RA. However, based on first principles, similar results would be expected for RAs with comparable volumes and surface areas per miner. The exact ambient temperature at which an RA will exceed the 95°F apparent temperature limit will depend on the manufactured characteristics of the RA and characteristics of the mine strata, and therefore these would need to be determined experimentally, analytically, or both.

The experimental methods used in the capstone study establish a foundation for a standardized test method. The thermal simulation model is a powerful tool to predict temperature rise, and its use, in conjunction with the standardized test method, is recommended. This will allow a limited number of experimental tests to be leveraged analytically so that a wide range of RAs and operating conditions can be evaluated. Occupancy derating tables could be developed and used to account for the use of mobile RAs in varying mine ambient temperatures.

Introduction

In 2007, following the 2006 Sago and Alma mine disasters, the West Virginia Office of Miners’ Health, Safety and Training mandated refuge alternatives (RA) for underground coal mines according to the recommendations made by the West Virginia Mine Safety Technology Task Force [Harris 2006]. In 2008, the Mine Safety and Health Administration (MSHA) subsequently passed regulations requiring the use of RAs in underground coal mines. Both MSHA and the state of West Virginia require that RAs provide an environment with breathable air for entrapped miners. The state of West Virginia requires that this environment must be provided for up to 48 hours, while MSHA mandates a 96-hour period.

For underground coal mines, 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 CO_2 scrubbing systems, the temperature and humidity inside RAs could lead to severe discomfort or heat stress depending on the starting mine ambient temperature. In 30 CFR 7.504, the Mine Safety and Health Administration (MSHA) has specified a maximum apparent temperature of 95°F (35°C) inside an occupied RA. The apparent temperature is calculated using both the temperature and relative humidity [Steadman 1984].

Manufacturers have been conducting laboratory testing to demonstrate the ability of their RAs to maintain an RA environment that meets MSHA’s apparent temperature limit. In lieu of using human subjects for their apparent temperature tests, manufacturers are using various methods of generating heat to represent that of the miners and the scrubbing system. For each

[10] The capacity of the tested RA would be reduced by two miners, or 20% of the tested RA’s capacity, for every 5°F (2.8°C) above a baseline mine ambient temperature of 55°F (12.8°C)

simulated miner, a heat input of 400 BTU/hr (117 watts) is used to represent metabolic heat [Harris 2006]. With respect to the heat generated by the RA's CO_2 scrubbing system, 170 BTU/hr (50 watts) of heat per miner is used for a lithium hydroxide scrubbing system or 100 BTU/hr (30 watts) of heat per miner is used for a soda lime scrubbing system [Shumaker 2013]. Some manufacturers have conducted tests dry (all heat is input as sensible heat), while others have used a combination of dry (sensible) and moist (latent) heat. The type of test facility used also varies from manufacturer to manufacturer. One manufacturer has conducted tests in the high bay of a building. A few manufacturers have built special test facilities with the ability to adjust and/or maintain the temperature of the outer shell or the air temperature within the test facility. Another manufacturer tests in an underground facility with 3-foot-thick (0.9-meter-thick) concrete walls. Some of these facilities are designed such that the inner surface of the test facility is held constant in temperature, which mimics an infinite heat sink, while others are allowed to heat up during testing.

To determine the internal apparent temperature that would result in an RA, theoretical heat transfer and/or thermodynamic models can be used. In some cases, theoretical calculations have been made assuming the mine strata behaves as an infinite heat sink that carries heat away while remaining at a fixed temperature [Raytheon 2007; Gillies et al. 2012; Brune 2012]. Using this assumption, the air temperature inside an RA will tend to reach steady state in a relatively short time period (less than a day). Models that use the infinite heat sink assumption will tend to predict internal temperatures that are lower than models that account for a temperature increase of the mine strata. In order to improve the ability of theoretical models to predict RA temperatures, it is critical to determine if the mine behaves as an infinite heat sink, or if the mine temperatures increase, when subjected to heat from an occupied RA.

The National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) has conducted a series of apparent temperature tests to gain a better understanding of the factors involved with heat buildup inside RAs. Specifically, NIOSH OMSHR performed tests to attempt to answer the following questions:

- Does the mine behave as an infinite heat sink?
- Does the facility in which the test is conducted impact the resulting temperature rise?
- Will the moisture generated by the occupants reduce the air temperature within the RA?
- Could occupancy derating values be used for RAs that are rated and approved for use at one mine ambient temperature, but are deployed in a mine with a higher ambient temperature?

NIOSH OMSHR conducted a series of apparent temperature tests on an RA training unit (refer to Figure 1) to examine some of the differences in test results due to using different test venues and heat input methods (dry heat versus dry heat combined with moist heat). This 10-person tent-type RA was selected because its small size allowed it to be moved into the NIOSH OMSHR Safety Research Coal Mine (SRCM); this would have been impossible with a larger RA. Two test facilities were used to conduct these tests: the high bay of a building and 10 Room of the SRCM. Due to time constraints, the testing in the high bay was conducted with dry heat input only. However, the tests in the SRCM were conducted with both dry heat and a combination of dry and moist heat.

This report focuses on the temperature increase that occurred within the RA throughout the 4-day-long tests. In the following discussion of the test setup, a complete description of the actual test setup is given. While this description provides details on all of the sensors used during OMSHR's testing, the data measured using some of the sensors will not be discussed within this report. The intent is to write a second document in the future that will discuss heat transfer from the RA to the mine. The outputs of these sensors will be used in this future publication.

(a) Photo by NIOSH

(b) Photo by NIOSH

Figure 1. Photographs of the tested RA (a) from outside and (b) inside the tent end.

Test Setup and Procedures

Tests were conducted in a building high bay and in the SRCM. The tests in the high bay were conducted dry, while the tests in the mine were conducted dry and wet. For all tests, the same heat input devices were used at the same locations inside the tent. Unless otherwise noted, 4-wire resistance temperature detectors (RTDs) were used for all temperature measurements to eliminate the effects of lead wire resistance. For the high bay tests, all data were acquired using a single Data Translation DT9874 data acquisition system. Due to the number of sensors used for the in-mine testing, two Data Translation DT9874 data acquisition systems were used for the in-mine testing. In both venues, all data were acquired at a rate of 1 sample every 100 seconds with 24-bit resolution.

Tested RA

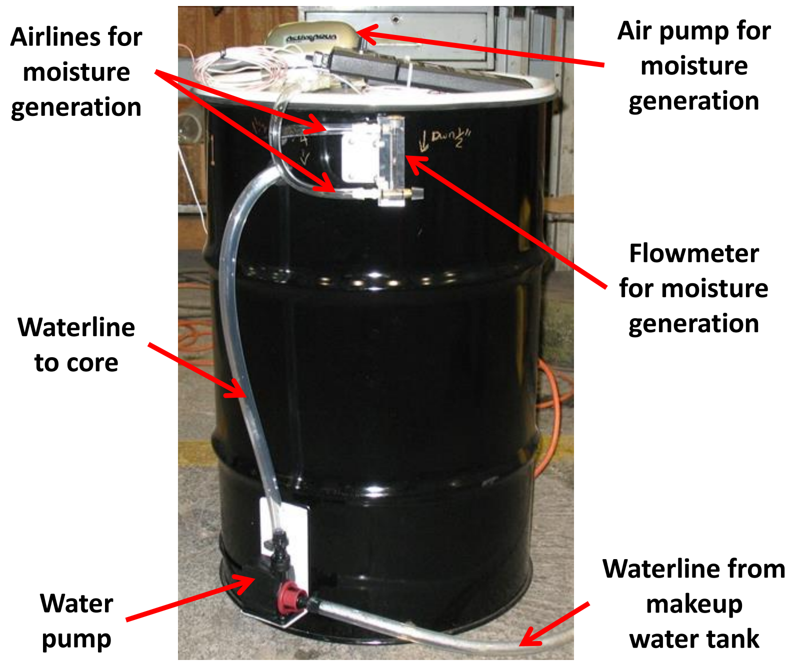
The tent of the tested RA was 42 in (107 cm) high with an internal volume of roughly 540 ft^3 (15 m^3) and a floor surface area of about 150 ft^2 (14 m^2). This RA meets the unrestricted surface area requirement of 30 CFR 7.505 for up to 10 people and it would also meet the unrestricted volume criteria for seam heights up to 54 in (137 cm), mandated for RA manufacturers by 2018. The metal box portion of the RA was 82 in (208 cm) wide by 78 in (198 cm) long and it did not include the air cylinders that are normally used with RAs.

Even though the testing was conducted on a training model, the results are expected to be similar to those observed for similarly sized, production tent-type mobile RAs. As with production RAs, the capacity for this model was determined using MSHA's volume and surface area requirements. In addition, the materials and construction of the training RA are similar to production models. The most significant difference between the tested RA and production RAs is that the metal box of the tested RA was shortened by one compartment and, thus, did not include the steel cylinders. The thermal mass of the steel box of the tested RA is lower than that of the steel box that would be used with a production RA. At the end of a 96-hour test period, it would be expected that the final temperature of a production RA with the same tent and a production-sized steel box containing the cylinders would be lower than the temperature observed for the training RA. However, the difference in temperature rise at the end of the mandated 96 hours would be expected to be on the order of only 10% to 15%.

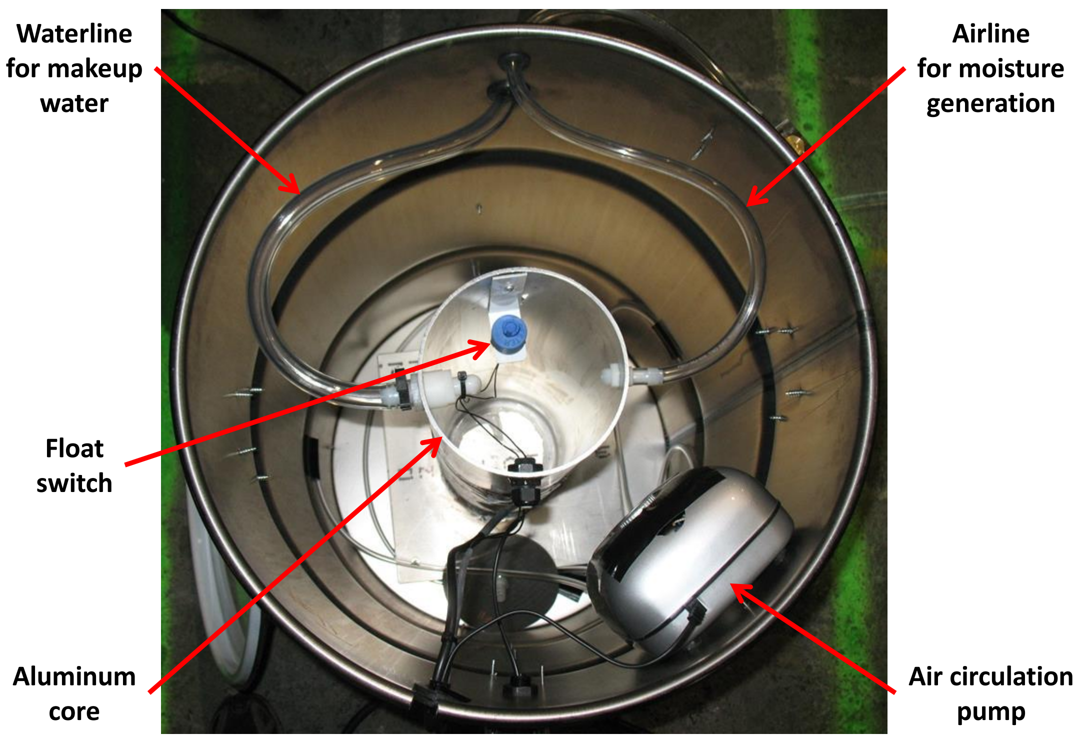
Heat Input Devices

When conducting apparent temperature tests, heat and/or moisture must be input by some artificial means. It is assumed that miners in a tent-type RA will be in a seated or lying position directly on the floor of the RA in that tent-type RAs are not provided with benches, cots, or pads to sit or lie upon. In order to approximate the heat transfer area of a seated or lying miner, the heat input devices should have a surface area of approximately 75% of the 19.4 ft^2 (1.8 m^2) surface area of the human body [Bernard 2012]. While most of the manufacturers use some type of plastic water jugs with “ice melter” cable strung from jug to jug, NIOSH OMSHR developed its own simulated miners (refer to Figure 2) using commonly available 30-gallon (0.11-m^3) steel drums, thin-walled aluminum pipe, two aquarium air pumps, an aquarium water pump, and two silicone-encapsulated electrical resistance heaters with a nominal power rating of 410 BTU/hr (120 watts) at 120 volts. The simulated miners were constructed of 30-gallon steel drums because 30-gallon steel drums are commonly available and have a surface area of 14.5 ft^2 (1.35 m^2), which is exactly 75% of the surface area of the human body.

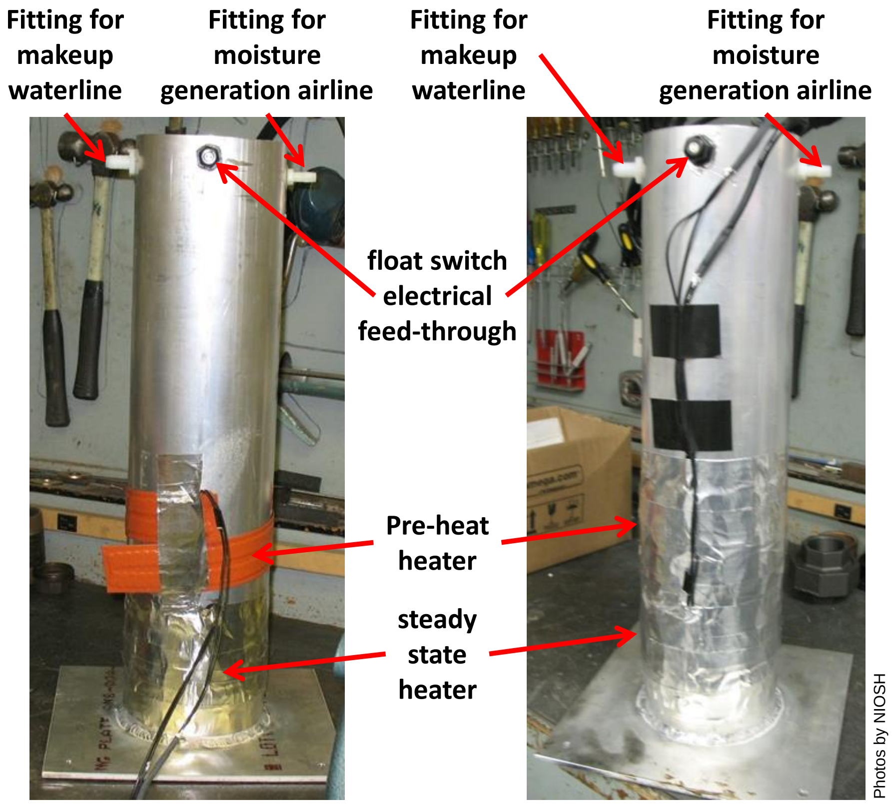
The simulated miners were designed to provide heat input from a heated, hollow aluminum core within the steel drum. The aluminum core was fabricated from thin-walled aluminum pipe by welding a length of it to an aluminum plate. The heaters were applied directly to the bottom third of the core using adhesive and were covered in aluminum reflective tape to ensure they were securely attached to the core. This core was attached to the bottom of the steel drum with spacers to prevent conduction of heat to the bottom of the drum. For each simulated miner, one of the heaters was used as a steady state heater that was powered for the entire duration of the 96-hour tests while the other was only used as a preheater for the first few hours of testing. During the tests, measures were taken to bring the simulated miners to steady state during the first 2 to 4 hours of the test. It is expected that their thermal mass would have a negligible effect on the results. Because real miners would be at nearly a steady state temperature when entering an RA, their thermal mass would also have no impact on the temperature rise within an RA.



(a) Photo by NIOSH



(b) Photo by NIOSH



(c)

Figure 2. Simulated miner construction: (a) outside, (b) inside, and (c) aluminum core.

Each simulated miner used one aquarium air pump to redistribute the air inside the annular region between the inside surface of the steel drum and the outside surface of the aluminum core. Hot air was pumped from the top of the drum to the bottom of the drum so that the exterior temperature of the drum would be more uniform. One of the shortcomings of using a water jug heated by a submerged resistance heater is that, as the water heats up, a thermal gradient is developed in the water; the water near the top of the jug is relatively hot while the water near the bottom of the jug is relatively cool. This results in a device that does not deliver the same amount of heat from its top and bottom surfaces as shown in Figure 3, depicting an infrared image of a water-filled jug heated by an immersion heater similar to the devices used by some manufacturers. The bottom of the water jug is at the same temperature as the floor it is resting on. Because heat transfer is driven by a temperature difference, no heat is delivered to the floor by the heated jug.

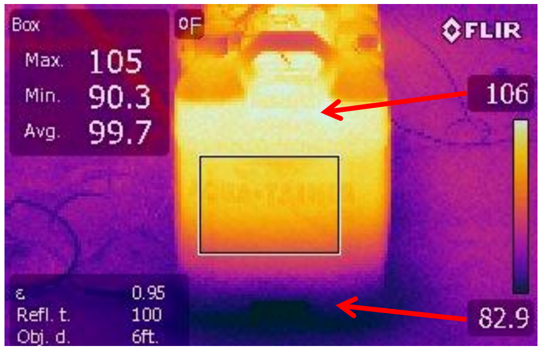


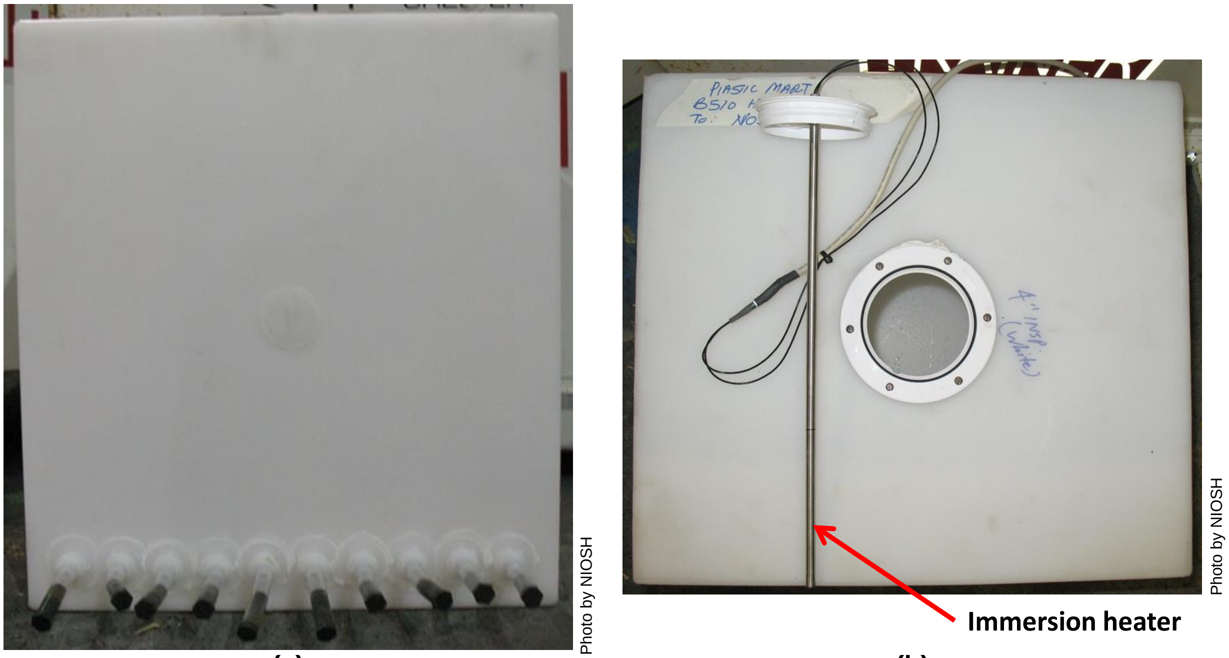
Photo by NIOSH

Figure 3. Infrared image of a water-filled jug heated by an immersion-style cartridge heater.

A miner sitting directly on a surface would surely deliver heat to that surface. Therefore, in order to simulate the heat transfer paths from a miner to a refuge chamber and a mine, the devices used for RA heat and humidity testing should transfer heat from their bottom surfaces to the RA floor. NIOSH OMSHR tests of the simulated miners show that the top and bottom surfaces of the simulated miners are within 1°F to 2°F (0.6°C to 1.1°C) after the temperatures have stabilized, and that these temperatures are about 30°F to 35°F (16°C to 19°C) higher than the ambient temperature [Yantek 2013]. The simulated miners would transfer heat through their bottom surfaces into the surface they are resting on, while the heated water jugs would not. This would result in a more realistic simulation of a real miner as heat would be delivered into the surface that the simulated miners are resting on.

One of the features of the NIOSH OMSHR simulated miners is that the hollow core can be filled with water so that the simulated miner can generate solely sensible (dry) heat or a combination of sensible and latent (moist) heat. In order to generate moisture, an aquarium pump is used to force air through the gap above the water inside the aluminum core so that water vapor is emitted into the atmosphere. In order to replenish the water in the core, the simulated miners use an aquarium water pump to fill the core from water stored in a 40-gallon (0.15-m^3) makeup water tank. The water tank has 10 bulkhead fittings to enable the aquarium water pumps to be connected to the tank (see Figure 4a). A float switch is used to shut the water flow off once the core is filled (see Figures 2a and 2b).

For all testing, an additional 170 BTU/hr (50 watts) of heat per simulated miner was input to represent the heat generated by a lithium hydroxide scrubbing system. To provide the scrubbing system heat, some RA manufacturers string additional heater cables within the RA. However, in OMSHR's testing, this would have made it difficult to position all the sensors inside the tent. To generate the scrubbing system heat for all ten simulated miners, an immersible heater rated at 1190 BTU/hr (350 watts) at 120 volts was inserted through the cap of the makeup water tank (refer to Figure 4b), and two heaters rated at 410 BTU/hr (120 watts) at 120 volts were affixed to an additional aluminum core (see Figure 2c). The locations of the heated water tank and additional aluminum core are shown in Figure 5. Using the heated water tank and the extra aluminum core to add the scrubber system heat eliminated the extra wires inside and enabled the test equipment to be positioned within the tent.



(a) (b)

Figure 4. Makeup water tank from (a) front and (b) top.

Ten simulated miners were used for all of the heat and humidity tests. The simulated miners were arranged to distribute the heat as evenly as possible within the deployed tent. The total heat input for all tests was nominally 5700 BTU/hr (1670 watts). Due to the limited height within the tent, the simulated miners had to be positioned with an uneven spacing so they would not touch the inflatable support tubes (refer to Figure 5). The heated water tank was positioned within the metal box and the added aluminum core was positioned near the tent end of the RA. The added aluminum core was placed on top of a 2-inch-thick (50-mm-thick) layer of Styrofoam insulation to prevent direct heat transfer from the aluminum core to the mine strata via conduction. Prior to deploying the tent and installing the simulated miners, all ten simulated miners were positioned in an area that was marked with field marking paint to check the spacing (see Figure 6). For all testing, the actual heat input, which would vary according to the supply voltage, was measured using two watt transducers, one for each group of five simulated miners.

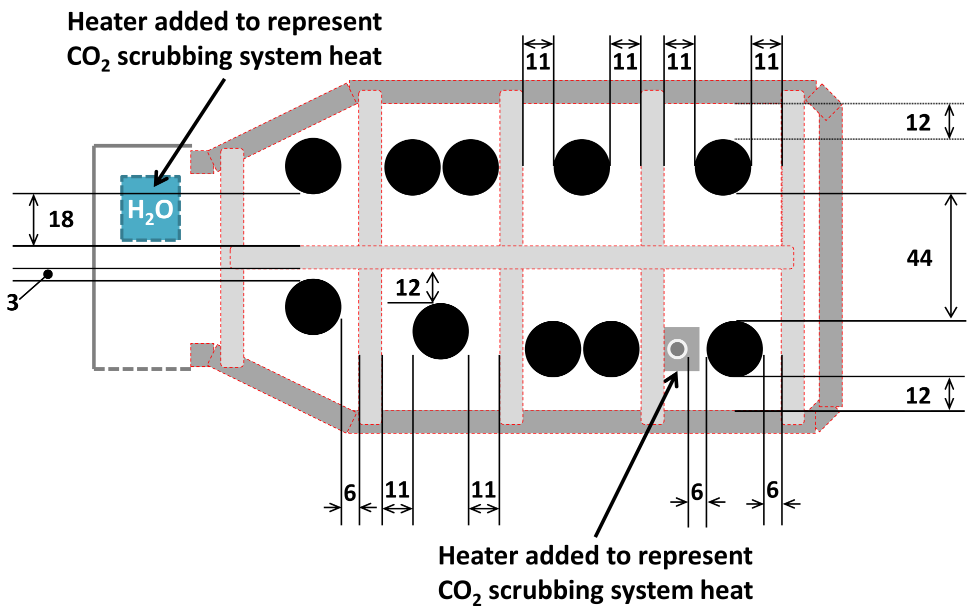


Figure 5. Layout of simulated miners and heaters to represent carbon dioxide scrubber heat (all dimensions in inches).

Figure 6. Layout of simulated miners within outline representation of the tested RA (lines represent support tubes).

The cooling effect due to the flow of oxygen into an RA was estimated to determine if the amount of cooling would be significant. In 30 CFR 7.506, MSHA specifies that oxygen should be delivered at a rate of 1.32 ft^3 per hour per miner. In order to supply this quantity of oxygen for 96 hours, manufacturers use oxygen cylinders pressurized to 4500 PSI (31 MPa). When the oxygen is delivered to the RA, it expands due to the reduction in pressure from 4500 PSI in the cylinders to atmospheric pressure, 14.7 PSI (0.101 MPa). This expansion causes the temperature of the oxygen to decrease as it is delivered to the RA. As the cooled oxygen flows through the RA, it absorbs heat until it reaches the temperature of the air inside the RA. Assuming a full capacity of 10 miners, the sensible cooling due to the flow of oxygen was approximated using an oxygen flow rate of 13.2 ft^3/hr (0.374 m^3/hr) according to the following equation [The Engineering ToolBox 2013]:

$$Q = 60\rho\dot{v}C_p\Delta T \quad (1)$$

where Q is the heat loss in BTU/hr,

ρ is the density in lb/ft^3,

$\dot{v}$ is the volume velocity in ft^3/min,

C_p is the specific heat in BTU/lb-°F, and

ΔT is the temperature change in°F.

Equation 1 was used to estimate the cooling due to the flow of oxygen with a density of 0.0843 lb/ft^3 (1.35 kg/m^3), a flow rate of 0.22 ft^3/min (0.374 m^3/hr), and a specific heat of 0.219 BTU/lb-°F (0.915 KJ/kg-K). In applying Equation 1, the temperature of the oxygen as it enters the RA must be known. According to one RA manufacturer, as it enters the RA, the temperature of the oxygen drops by roughly 30°F (16.7°C) from the cylinder temperature. Assuming the oxygen in the cylinders starts at 55°F (12.8°C), and drops by 30°F (16.7°C), the oxygen would enter the RA at 25°F (3.9°C). If the air in the RA is assumed to stabilize at 83°F (28.3°C), the oxygen would also increase to 83°F (28.3°C) and the temperature change for the oxygen would be 58°F (32.2°C). The aforementioned values lead to an estimated cooling of 13.6 BTU/hr (4 watts), which is negligible when compared to the 5700 BTU/hr (1670 watts) of heat input that represents the miners and CO_2 scrubbing system. Therefore, the cooling effect due to the oxygen supply was ignored during testing.

Setup for High Bay Tests

The tent-type RA was set up in the high bay to conduct apparent temperature testing (refer to Figure 7). Two 48-inch-long (122-cm-long) averaging RTDs, two temperature/RH sensors, an omnidirectional airflow sensor, and a wet bulb globe temperature (WBGT) sensor array were used inside the tent (see Figure 8) to measure temperature, relative humidity, and airflow due to natural convection. The averaging RTDs in the center of the tent were attached to a tripod with one positioned 8 in (20 cm) from the underside of the tent and the other positioned 8 in above the floor (see Figure 9). The temperature/RH sensors, the WBGT sensor array, and the airflow sensor were positioned at midheight. Two RTDs were used to measure the air temperature close to the tent. One 48-inch-long (122-cm-long) averaging RTD was positioned 12 in (30 cm) above the center of the tent with its long axis parallel to that of the tent. Another 48-inch-long (122-cm-long) averaging RTD was centered alongside the tent at midheight with its long axis parallel to that of the tent. The high bay ambient temperature was monitored using a 48-inch-long (122-cm-long) averaging RTD oriented vertically and positioned 12 ft (3.7 m) to the side of the metal box and 12 in (30 cm) from the floor.

Photo by NIOSH

Figure 7. RA setup for apparent temperature testing in a high bay.

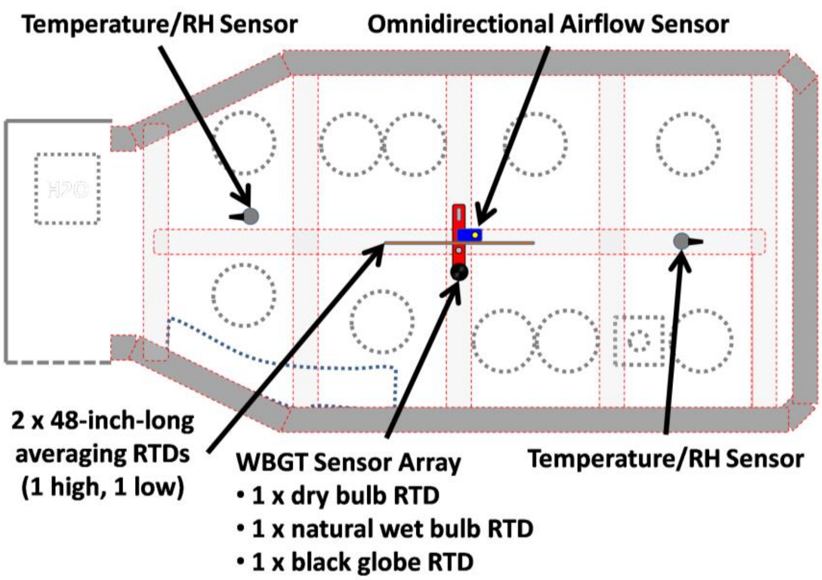
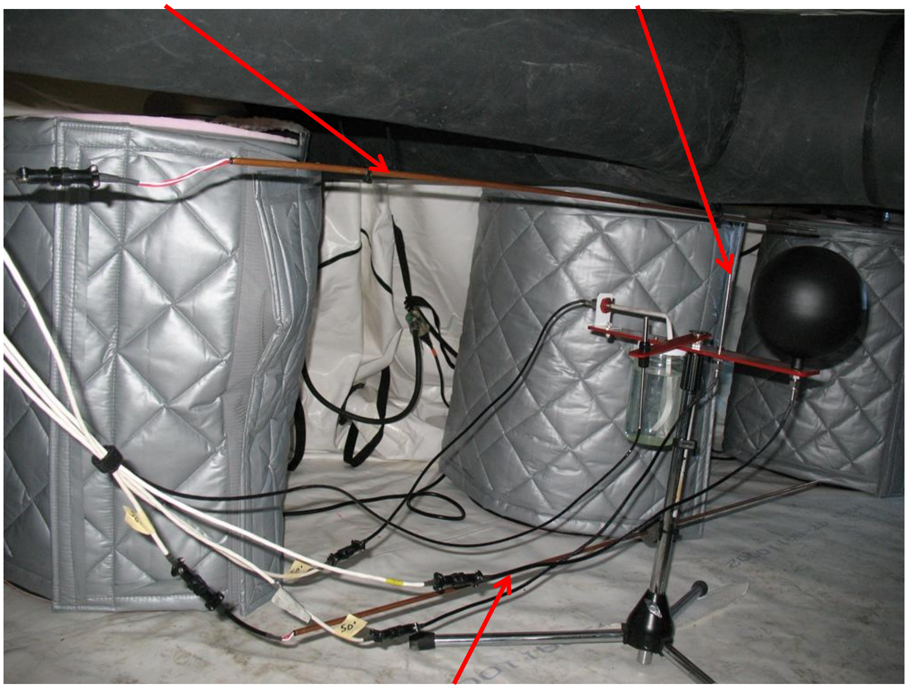


Figure 8. Locations of interior temperature and relative humidity sensors for high bay testing.



(a)

(b)

Figure 9. Photographs of (a) RTDs at tent center and (b) temperature/RH sensors at tent end and box end.

Setup for In-Mine Tests

For the in-mine testing, the RA was positioned in 10 Room of the SRCM with the center of the tent located approximately 50 ft (15.2 m) from B Butt (see Figure 10) so that the sides of the RA were equidistant from the ribs (see Figure 11). A brattice cloth was stapled to a wooden frame at the beginning of B Butt and a thin layer of plastic sheeting was attached to a wooden frame near C Butt. This was done to prevent bulk airflow into the test area without having a significant impact on heat loss from the ends of the test area, and it represents a worst-case scenario (a loss of the mine ventilation fans). The encapsulated test area was approximately 150 ft (45.7 m) long.

Inside the tent, the same sensors and sensor locations were used as in the high bay tests to document the internal air temperature, relative humidity, and airflow. In addition to the aforementioned sensors, two condensation sensors were positioned near the tent end of the RA. One of these was positioned on the roof and the other was positioned on the side wall (refer to Figure 12). When the tests were performed with added moisture, the output of these sensors was examined to determine if and when condensation had occurred.

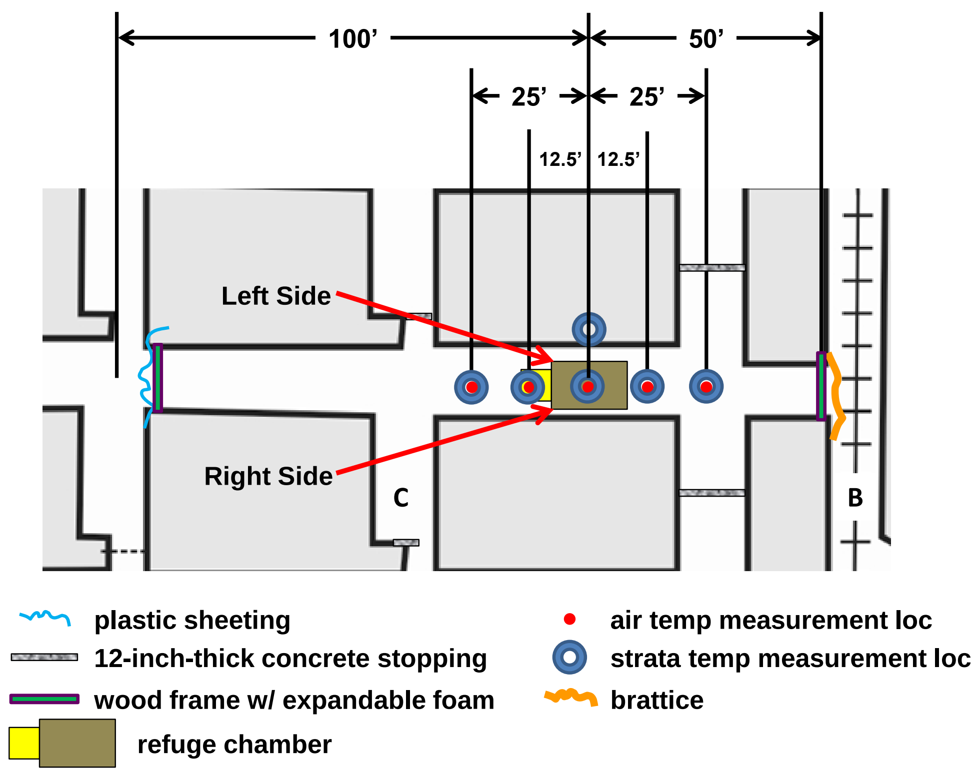


Figure 10. Schematic of test area in the SRCM showing RA and mine air and strata measurement locations.

Photo by NIOSH

Figure 11. RA set up for apparent temperature testing in the SRCM.

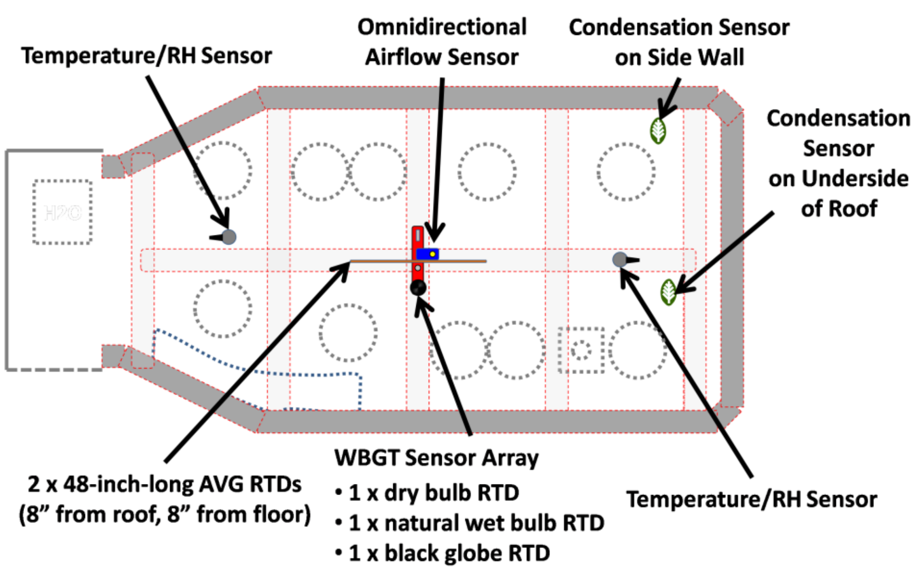


Figure 12. Locations of interior temperature and relative humidity sensors for in-mine testing.

For the in-mine tests, additional sensors were used to measure the exterior surface temperature of the RA and the heat flux through the surface of the RA (refer to Figure 13). Surface temperatures were measured on the tent using two ribbon RTDs on the top of the tent (Figure 13a), two ribbon RTDs on the left side of the tent (Figure 13b), and two ribbon RTDs on the end of the tent (Figure 13c). On the metal box, surface temperatures were measured using two ribbon RTDs on the top of the box (Figure 13a), two ribbon RTDs on the side of the box (Figure 13 b), and one ribbon RTD on the end of the box (Figure 13 c). In addition to the ribbon RTDs for measuring temperatures, heat flux sensors were added to the RA at the following locations: two on top of the tent and one on top of the metal box (Figure 13a); one on the side of the tent and one on the side of the metal box (Figure 13b); and one on the end of the tent (Figure 13c). The heat flux sensors measure the total heat flow through the sensor from conduction, convection, and radiation. To measure the radiation heat transfer from the tent, one pyrgeometer was positioned so that it pointed at the area adjacent to one of the heat flux sensors atop the tent and a second pyrgeometer was aimed at the area adjacent next to the heat flux sensor on the end of the tent (refer to Figure 13). While the heat flux sensors measure total heat transfer, the pyrgeometers measure only radiation heat transfer.

To determine the airflow speed near the RA, three omnidirectional airflow sensors were positioned near the tent as shown in Figure 14. These particular airflow sensors were chosen because they can accurately measure flow speeds as low as 10 ft/min (0.05 m/s) and are not sensitive to flow direction. Measuring the airflow is important because any heat transfer simulation requires the specification of the convection coefficient which is directly related to the air velocity.

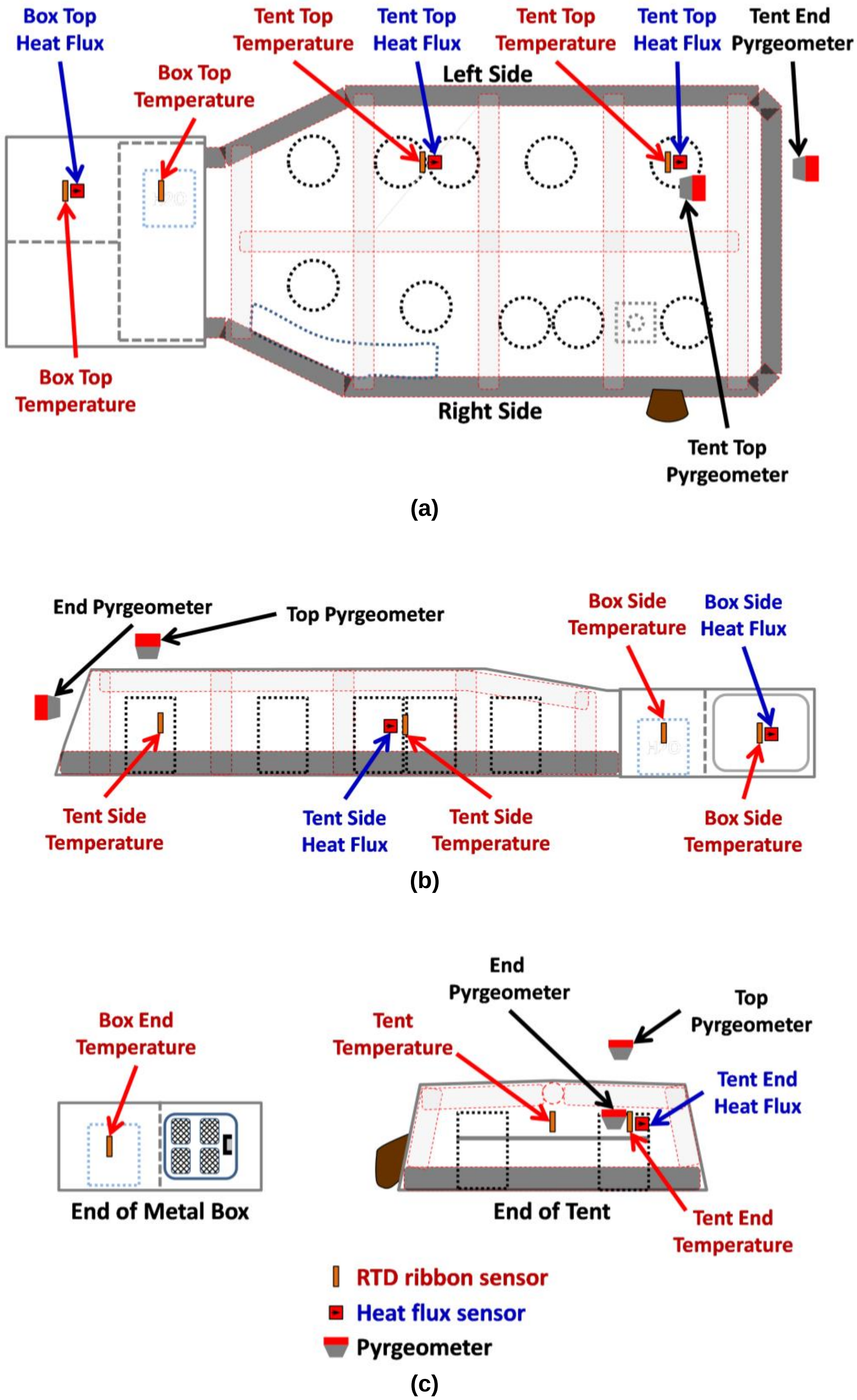


Figure 13. Locations of RTD ribbon sensors, heat flux sensors, and pyrgeometers for in-mine testing: (a) top view, (b) left side view, and (c) end view.

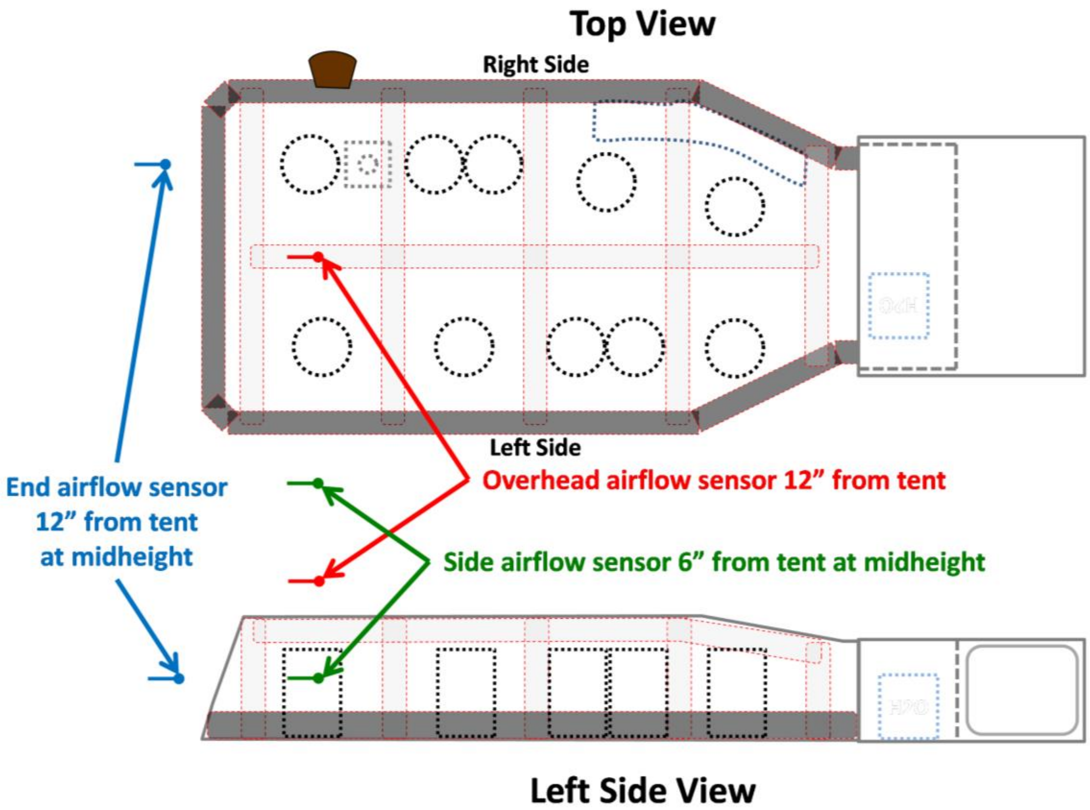


Figure 14. Locations of omnidirectional airflow sensors for measuring air speed near the RA.

Seven RTDs were used to examine the heat transfer into the mine floor beneath the tent. Three 72-inch-long (183-cm-long) averaging RTDs were positioned between the tent bottom and the mine floor (see Figure 15). One was positioned beneath the simulated miners on the right side of the tent, one was placed beneath the simulated miners on the left side of the tent, and one was located beneath the center of the tent. Each of these was oriented with its long axis parallel to that of the tent. The floor strata temperature beneath the center of the tent was measured at 12, 24, 36, and 48 in (30.5, 61.0, 91.4, and 121.9 cm) deep by installing a PVC rod with four RTDs attached to its outside and covered with thermally conductive epoxy. Flat spots were machined onto the outside of the PVC rod at each desired sensor location and slots were machined along the outside of the rod so that the RTD wiring could be protected. To install the instrumented PVC rod, a 1-inch-diameter (2.54-cm-diameter) hole was drilled into the mine floor, the outside of the PVC rod was coated with thermally conductive paste, and the rod was pushed into the hole.

The temperatures on and within the mine roof and rib strata were also measured using RTD-instrumented PVC rods as described above. The mine rib strata temperature was measured next to the center of the tent at midheight of the mine on the rib surface and at depths of 12 and 48 in (30.5 and 121.9 cm) as shown in Figure 10. The mine roof strata temperature was measured directly above the center of the tent, 12.5 ft (3.8 m) from the center of the tent towards B Butt and C Butt, and 25 ft (7.6 meters) from the center of the tent towards B Butt and C Butt. At each of these locations, the roof strata temperature was measured on the surface and at depths of 12 and 48 in (30.5 and 121.9 cm).

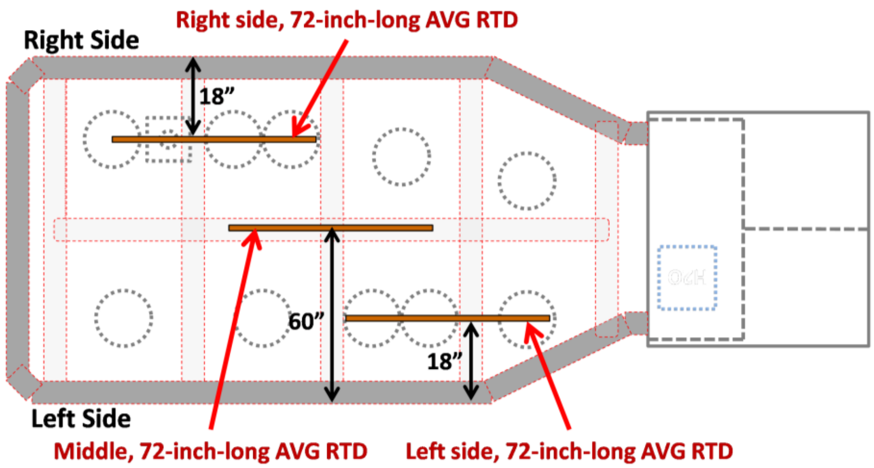


Figure 15. Location of 72-inch-long averaging RTDs between tent bottom and mine floor strata.

The air temperatures within the test area were measured using 48-inch-long (122-cm-long) averaging RTDs at eight locations (see Figure 16). Five RTDs were positioned near the RA as follows: two RTDs oriented horizontally and located between the side of the tent and the rib at the tent’s midheight approximately 21 in (53 cm) above the mine floor; two RTDs oriented horizontally and located 12 in (30 cm) above the tent; and one RTD oriented horizontally and located 12 in (30 cm) above the metal box 12.5 ft (3.8 m) from the center of the tent towards C Butt. Three additional RTDs were oriented vertically and positioned equidistant from the mine floor and roof as follows: 12.5 ft (3.8 m) from the center of the tent towards B Butt; 25 ft (3.8 m) from the center of the tent towards B Butt; and 25 ft (3.8 m) from the center of the tent towards C Butt. The average mine air temperature was computed using all eight of the aforementioned RTDs.

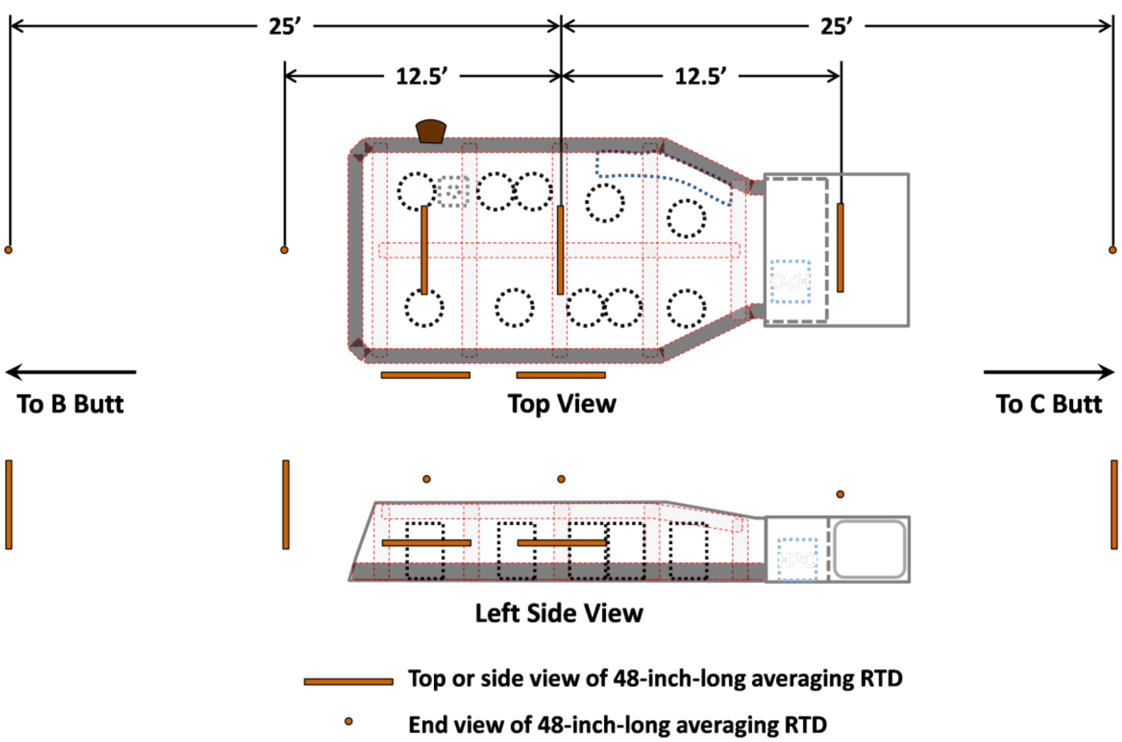


Figure 16. Locations of 48-inch-long averaging RTDs used to measure the mine air temperature.

Test Start-up Procedure

One of the difficult issues with RA heat and humidity testing is how to initiate the tests with respect to simulating the heat generated by real miners. If real miners were to enter an RA, their body heat would immediately begin to deliver heat. However, when some sort of device is used to generate heat that is representative of the real miners' metabolic heat, the device is "cold" when it is first supplied with power. Initially, most of the power supplied to the device serves to heat the device. As the device nears its steady state temperature, the majority of the power supplied is dissipated to the environment. If un-insulated heated water jugs are used, it can take up to a day or longer for the heated water jugs to approach steady state due to the relatively high specific heat of water. While waiting for the water jugs to heat up, the surroundings in the test area heat up, effectively preheating the RA. Unless measures are taken to remove the heat input as the water jugs are coming up to temperature, the final air temperature measured inside the RA at the end of the 96-hour time period could be affected by this additional heat. We used a different approach to decrease the time for our simulated miners to reach steady state and to prevent heating the RA and surroundings while the simulated miners were not yet at their steady state temperatures, as described below.

At the beginning of each test, all of the simulated miners were wrapped in a quilted, one-inch-thick fiberglass insulating blanket and the top of each was covered with a one-inch-thick Styrofoam disk (see Figure 8). By using insulation around the simulated miners, the heat lost to the inside of the RA can be minimized so that the temperature of the simulated miners increases relatively quickly. In addition to being insulated, the simulated miners were designed to use two heaters: a steady state heater and a preheater, each with a rating of 410 BTU/hr (120 watts) at 120 volts. At the beginning of the tests, both the steady state heater and the preheater for each simulated miner were turned on and the surface temperatures at the midheight of two of the simulated miners were monitored until each reached approximately 95°F, roughly the expected steady state temperature of the simulated miners. Once this temperature was reached, the preheaters of all the simulated miners were turned off and the insulation was removed. The end result was that within a few hours, the simulated miners were close to their steady state temperature and the power supplied to the steady state heaters was thus delivered to the RA.

For the in-mine tests, fresh air had to be blocked off from the test area prior to beginning the tests. Each in-mine test was started on a Monday at approximately 7 AM. For each in-mine test, a function check of the heat input devices was conducted during the morning of the Friday prior to beginning the tests on Monday. Upon completing the function check of the heat input devices, the test area was sealed off on both ends and a data recording was begun. The trapped air inside the test area was allowed to cool over the weekend prior to beginning the tests.

Data Analysis and Normalization

To make the resulting test data more manageable, the raw test data were reduced from a sample rate of 1 sample per 100 seconds to a sample rate of 1 sample per 15 minutes. Because the measured temperatures were observed to change very slowly (less than a degree over the final 24-hour time period), reducing the dataset did not affect the characteristics of the data. For each of the three tests, the temperature rise for the air inside the tent was calculated. For the tests in the high bay, the high bay ambient temperature and the internal air temperature at a specific time were used to compute the internal air temperature rise at that time. For the in-mine tests, the internal air temperature rise at a specific time was calculated using the internal air temperature at that time and the initial temperature at that sensor location. Different references were used to calculate the temperature rise because the behaviors of the ambient air temperatures were different for each test. In the case of the high bay tests, the heat input due to the RA testing had a negligible effect on the high bay ambient temperature. However, the high bay temperature fluctuated due to the outside environmental temperature and activity within the building. The air temperature inside the RA was observed to increase and decrease with the fluctuating high bay temperature. For the in-mine tests, the heat input from the RA testing caused the mine ambient temperature to increase from its initial temperature by several degrees. In this case, the initial mine ambient temperature must be used when calculating a temperature rise.

The temperatures at the end of the 96-hour test period are the temperatures of interest. To account for small fluctuations in input heat due to changes of the supply voltage, all data were normalized to an input power of 5700 BTU/hr (1670 watts). For the high bay testing, the RA internal temperature was observed to follow the high bay ambient temperature beginning sometime during the second day of the tests. For the in-mine testing, the temperature changes occurred very slowly, with near steady state conditions reached during the fourth day of testing. For both test venues, small changes in input heat were observed to cause small changes in the RA internal air temperature. Because air has a very low thermal mass—the product of density and specific heat—the air temperature changed nearly as rapidly as the heat input. However, because the materials that make up the RA, the high bay, and the mine strata have relatively high specific heat values (more than 1,000 times that of air), the temperatures of the high bay, strata, and RA lagged behind changes in the input heat. To minimize the effects of this lag on the computed temperature changes, the average value for each measured channel was calculated for the final six hours of the tests. All values were changing very slowly towards the end of the tests and the input power was relatively constant for the final 6-hour time period. To be consistent, the initial value for each channel was averaged for the 6-hour time period prior to providing power to the simulated miners.

The temperature rise for each measured channel was then computed by

$$\Delta T_{M,i} = T_{fin,i} - T_{0,i} \tag{2}$$

where $\Delta T_{M,i}$ is the measured temperature rise for the i^{th} channel,

$T_{fin,i}$ is the average temperature of the i^{th} channel during the final six hours of the test, and

$T_{0,i}$ is the initial temperature of the i^{th} channel averaged for the six hours just prior to powering the simulated miners.

The temperature changes based on an average of the final six hours of data and the initial temperatures averaged over the six hours prior to powering the simulated miners were used to compute the normalized temperature changes for each channel by

$$\Delta T_{N,i} = \Delta T_{M,i} \frac{5700}{\dot{q}_{avg}} \tag{3}$$

where $\Delta T_{M,i}$ is the temperature rise for the i^{th} channel based on Equation 2,

5700 is the desired input heat in BTU/hr,

$\dot{q}_{avg}$ is the average heat input for the final six hours of the test in BTU/hr, and

$\Delta T_{N,i}$ is the temperature rise for the i^{th} channel normalized to a heat input of 5700 BTU/hr (1670 watts).

Temperature and Humidity Results: As-Measured Test Data

High Bay, Dry

For the tests in the high bay, the heat input varied throughout the day (refer to Figure 17). In the evening hours (after work) the power increased and remained relatively high throughout the night. Then, at around 6 AM, as the workday began, the power decreased and stayed relatively low until the end of the workday. The average heat input for the full 96 hours was 1718 watts, 2.9% more than the target heat input of 1670 watts, and the standard deviation was 29.6 watts. The variation in the heat delivered makes it necessary to normalize the results based on the input heat. The average heat input for the final six hours of the test was 1738 watts—4.1% higher than the target heat input. For the dry high bay tests, the average daily heat input changed by less than 2% as shown in Table 1.

The tests in the high bay showed that the air temperature within the RA increased rapidly and began to track the high bay ambient temperature within the first day of testing (refer to Figure 17). The high bay ambient temperature varied by as much as 10°F each day, with the maximum temperature occurring between 4 and 6 PM and the minimum temperature occurring at roughly 6 AM each day. On days three and four, a diesel-powered engine was being run on the other side of the high bay. This increased the ambient temperature significantly. Regardless of the actual high bay ambient temperature, the RA internal air temperatures were observed to closely follow the high bay ambient temperature. Even though the ambient temperature and power delivered varied, the temperature rise based on the top temperature sensor inside the RA and the high bay ambient temperature was roughly 20°F from the beginning of day 2 until the end of the test.

Table 1. Average heat input for each day of testing

Day	Average Heat Input (watts)	% Change In Average Heat Input Versus Previous Day
1	1688	NA
2	1721	+1.9%
3	1708	-0.8%
4	1720	+0.7%

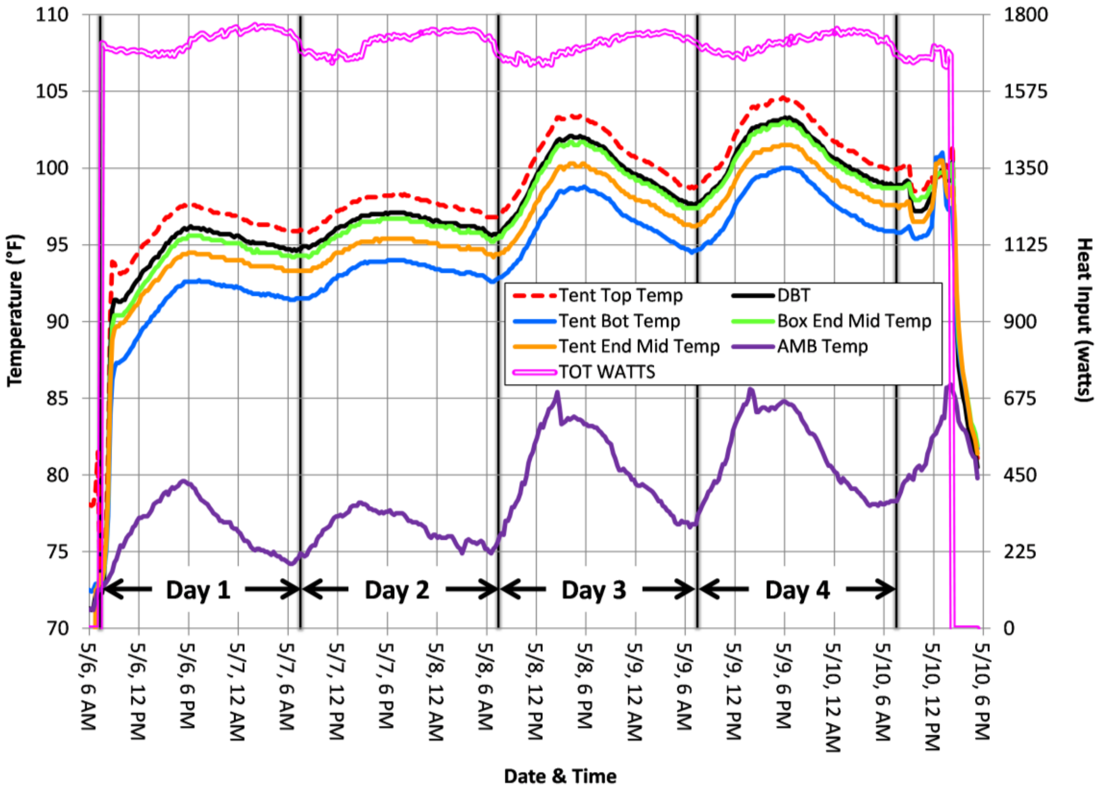


Figure 17. Tent internal air temperatures, high bay ambient temperature, and heat input for high bay testing.

SRCM, Dry

For the dry tests in the SRCM, the heat input fluctuated each day (refer to Figure 18) in a manner similar to what was observed in the high bay testing, but with less variation. From 6 AM to roughly 6 PM, the input power was lower than it was for the 6 PM to 6 AM time period. The average heat input for the full 96 hours was 1589 watts—4.9% less than the target heat input of 1670 watts—with a standard deviation of 19.3 watts. The average heat input for each day is shown in Table 2. As the data show, the average heat input changed by 1% or less from day to day. The average heat input for the final six hours of the test was 1597 watts—4.4% less than the target heat input. Once again, in order to interpret the results properly, the temperature rise must be normalized according to the input power.

The air temperatures within the tent rose relatively quickly during the first day before leveling off with a slow, steady rise for the remainder of the test (refer to Figure 18). The temperatures in the tent varied slightly with the input heat and the mine ambient temperature steadily rose. At the end of the fourth day of testing, the temperature rise computed using the internal air temperature near the roof and the starting internal air temperature near the roof was approximately 24°F. The temperatures at midheight at the box end, tent end, and center of the tent (labeled X8-DBT on Figure 18) were within about 1.5°F of each other throughout the test. At the center of the tent, the data show the air temperature near the top of the tent was about 2.5°F higher than the temperature at midheight, and about 5.8°F higher than the temperature near the tent floor.

Table 2. Average heat input for each day of testing

Day	Average Heat Input (watts)	% Change In Average Heat Input Versus Previous Day
1	1579	NA
2	1595	+1.0%
3	1580	-1.0%
4	1587	+0.4%

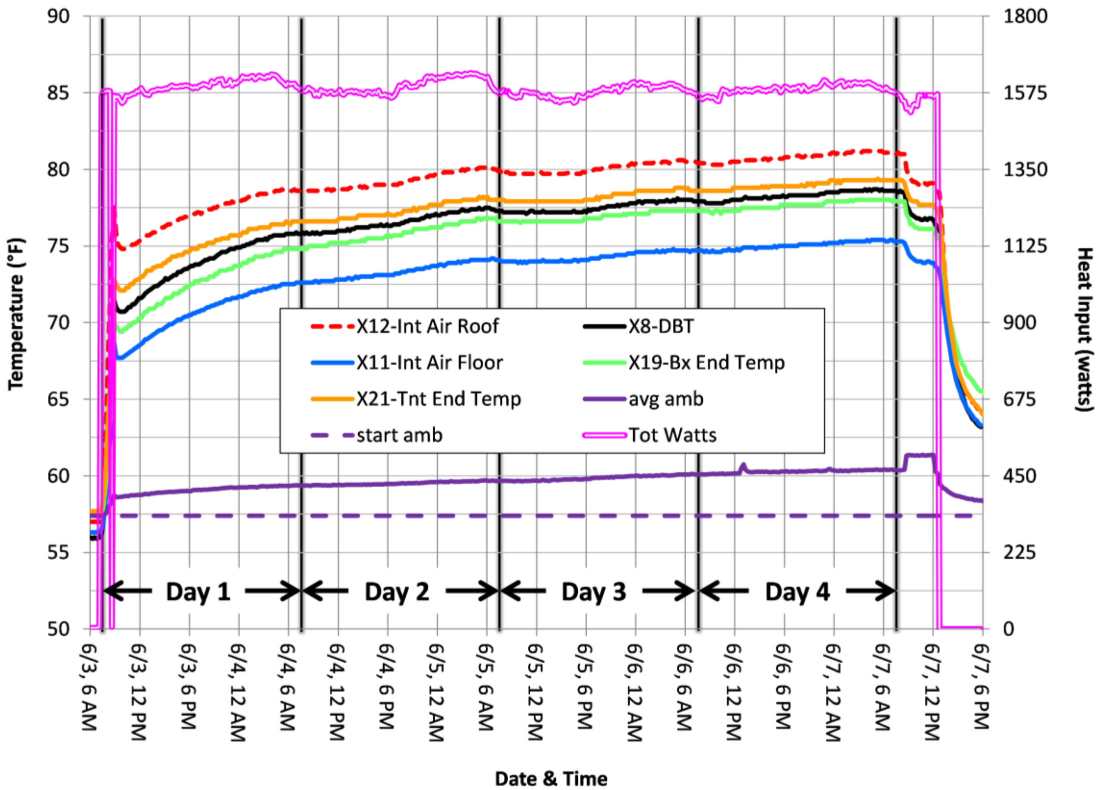


Figure 18. RA internal air temperatures, average mine air temperature, and heat input for dry testing in the SRCM.

During the dry in-mine testing, the relative humidity measured at each end of the tent decreased throughout the test as the internal air temperature rose (see Figure 19). This is expected as the amount of water vapor in the air should not have changed. However, as air temperature increases, it has a higher water-holding capacity. So, in this case, the decrease in relative humidity is expected.

The temperature between the bottom of the tent and the mine floor surface increased almost immediately after beginning the test (see Figure 20). As depth into the floor strata increased, the temperature increased less and at a lower rate. The temperature between the tent and mine floor increased by almost 10°F in the first 24 hours. By the end of four days, the temperature between the tent and the mine floor strata increased by 14.5°F; the temperature 12 in deep increased by 6.2°F; the temperature 24 in deep increased by 2.6°F, the temperature 36 in deep increased by 1.5°F, and the temperature 48 in deep increased by 0.9°F.

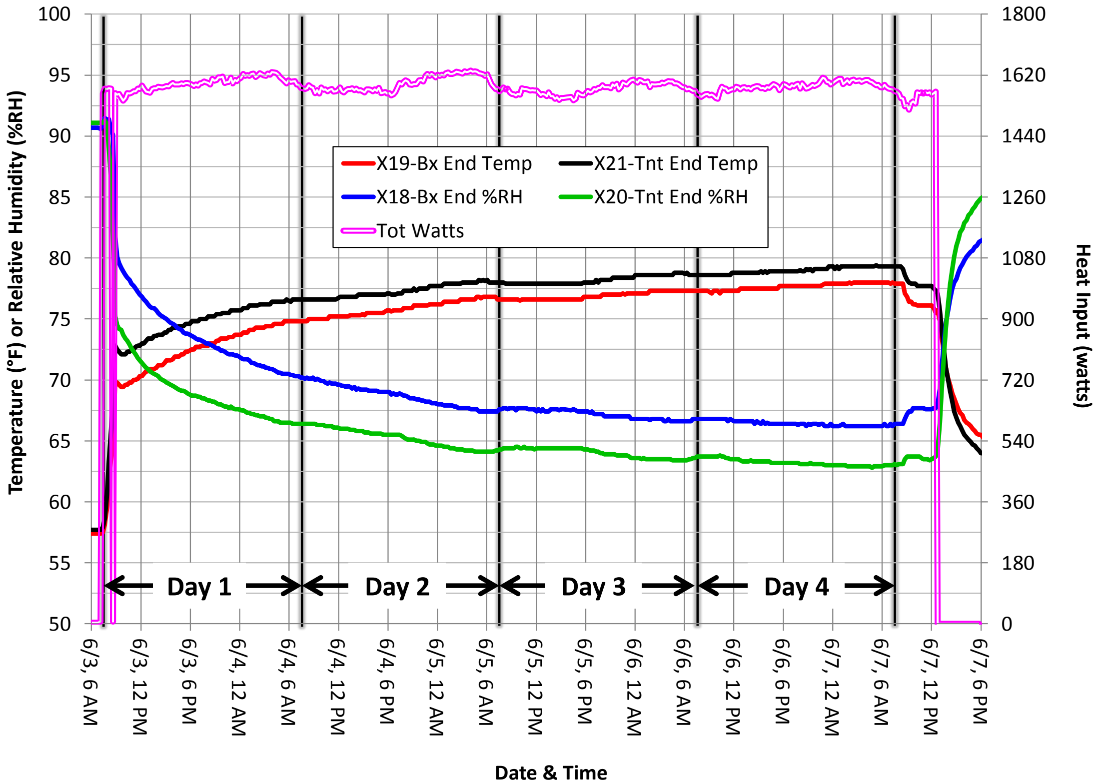


Figure 19. Temperature and relative humidity at the box end and tent end at midheight for the dry in-mine tests.

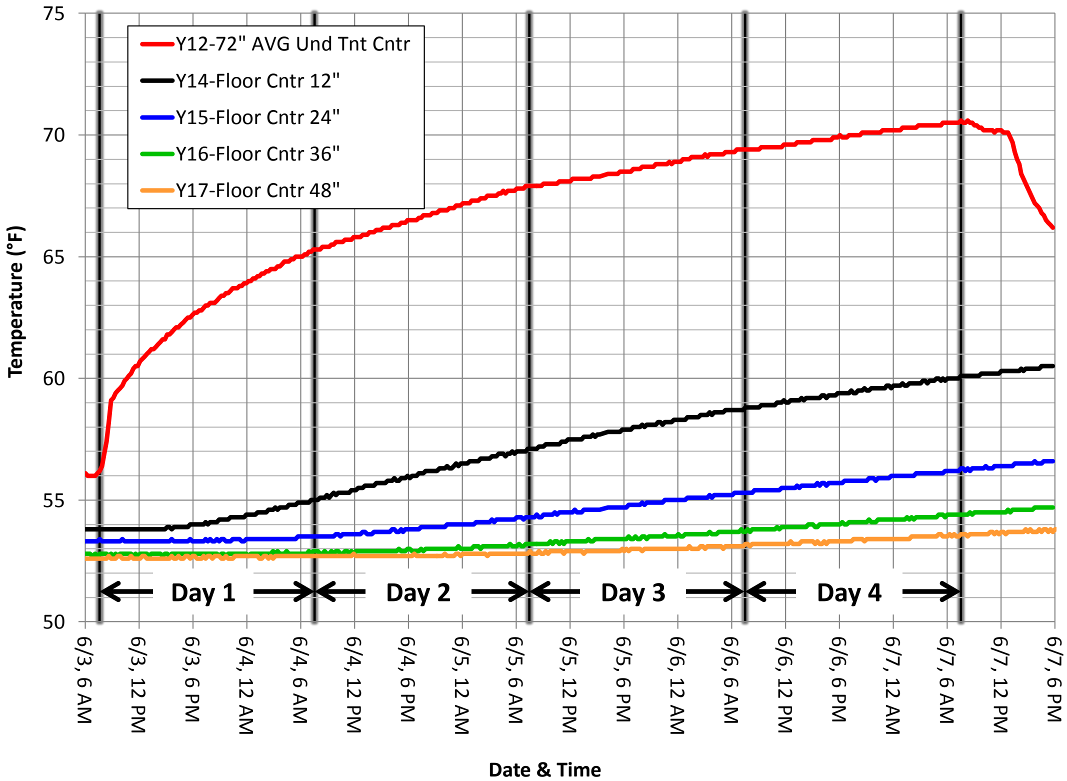


Figure 20. Mine floor strata temperatures under the tent during dry in-mine testing.

In the SRCM, the average mine air ambient temperature computed from the eight averaging RTDs located near the RA (refer to Figure 16), was observed to steadily increase throughout the test (refer to Figure 18). The mine air temperatures at the sensors around the RA increased almost immediately after beginning the test as shown in Figure 21. The rapid temperature rise for the sensor above the tent towards B Butt at roughly 1 PM on day 4 corresponds with a time when the test area was entered briefly to inspect the test setup. The air at the sensor above the tent end increased more rapidly than the air at the other air temperature sensor locations. This is probably because the sensor above the tent end was near the aluminum core that was used to input roughly half of the heat of the CO_2 scrubbing system. It was expected that the aluminum core temperature would increase much more rapidly than the water tank inside the metal box or the simulated miners. After quickly rising for the first few hours of the test, the air temperatures increased slowly for the remainder of the test. Over a 96-hour time period, the mine air temperatures between the tent and rib at the midheight of the tent increased roughly 2°F; and the mine air temperatures above the tent and metal box increased roughly 3 to 5 degrees Fahrenheit.

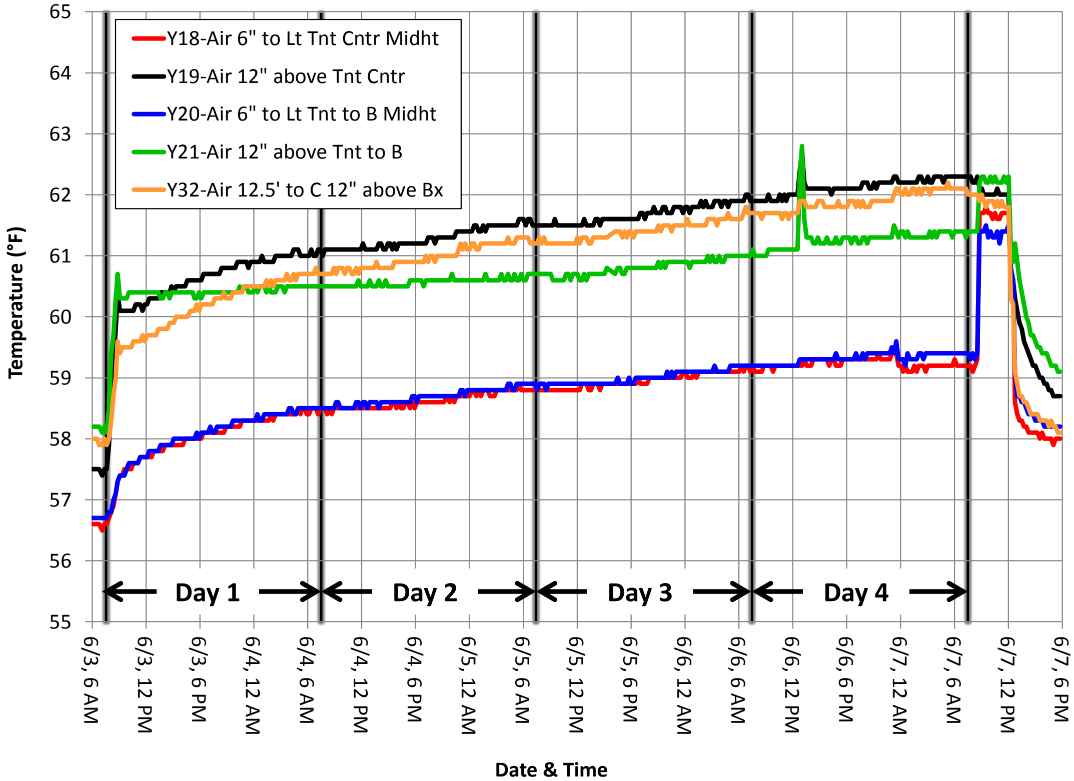


Figure 21. Mine air temperatures near the RA during the dry in-mine testing.

Away from the footprint of the RA, the mine air temperature also increased at the sensors (refer to Figure 16) located 12.5 ft from the tent center towards B Butt, 25 ft from the tent center towards B Butt, and 25 ft from the tent center towards C Butt (see Figure 22). Once again, the spikes in the temperatures at 12.5 ft and 25 ft towards B Butt at roughly 1 PM on day 4 correspond to an inspection of the test area. The air temperature at 25 ft towards C Butt started at about 2°F lower temperature than the air at the other locations. The temperature at this location increased by about 3°F and the temperatures at the other two locations increased by nearly 2°F. The data show that the air temperatures at these locations continued to increase throughout the tests.

The roof and rib strata temperatures near the center of the tent increased throughout the test (refer to Figure 23). The surface temperatures increased rapidly for the first several hours of the test and then began to level off for the rest of the first day. For the second, third, and fourth days, the surface temperatures increased gradually, but steadily. By the end of the fourth day, the roof surface temperature increased by 5.4°F and the rib surface temperature increased by 4.7°F. The temperatures 12 in into the roof and rib began to change near the beginning of the second day of testing. During the second, third, and fourth days, the temperatures 12 in into the roof and rib increased slowly, but steadily. During the 96-hour test, the temperature 12 in into the roof changed by 1.3°F and the temperature 12 in into the rib changed by 1.2°F. The temperatures 48 in into the roof and rib changed by only a few tenths of a degree during the 96-hour tests.

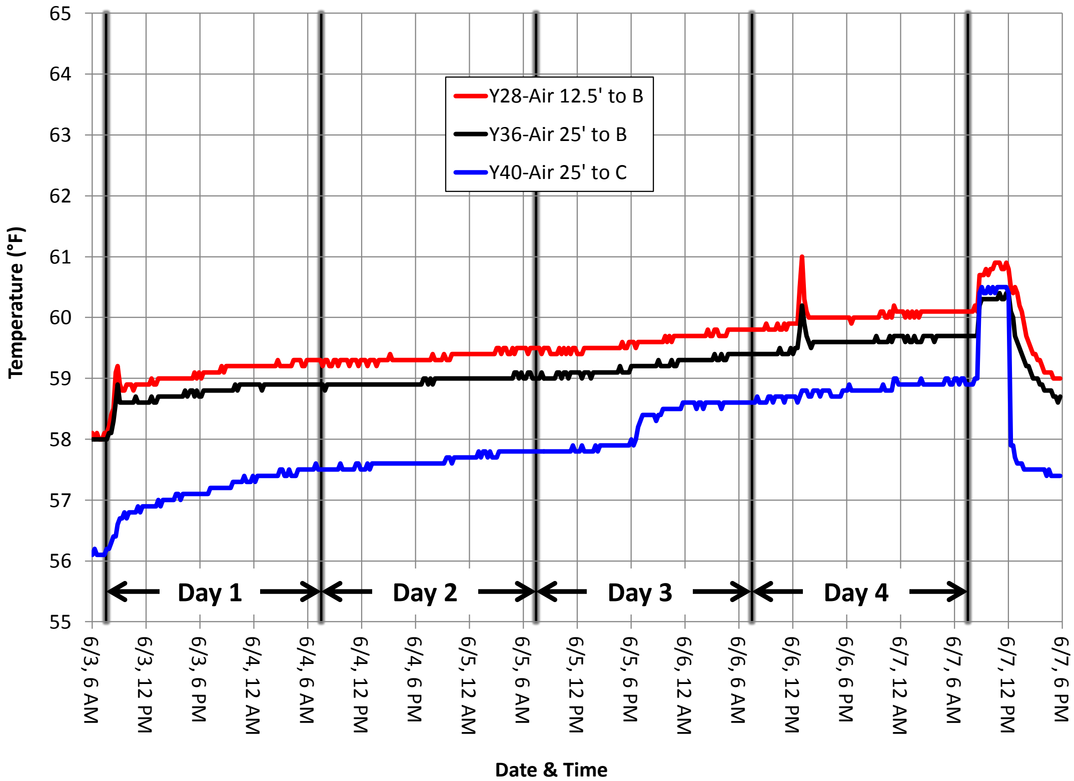


Figure 22. Mine air temperatures outside the footprint of the RA during the dry in-mine testing.

The roof strata temperatures 12.5 ft from the center of the tent towards B Butt and C Butt increased throughout the test (refer to Figure 24). Similar to the strata temperatures near the center of the tent, the roof strata surface temperatures 12.5 ft from the center of the tent increased quickly for the first few hours of the test and then climbed slowly and steadily for the remainder of the test. The measurement location 12.5 ft towards C Butt was over the metal box whereas the location 12.5 ft towards C Butt was outside of the footprint of the RA. The roof strata surface temperature 12.5 ft towards B Butt increased by 3.2°F while the roof strata surface temperature 12.5 ft towards C Butt increased by 4.3°F. At a depth of 12 in, the temperatures began to change after the first day and they increased gradually for the remainder of the test. The roof strata temperature 12.5 ft towards B Butt increased by 0.6°F and the temperature 12.5 ft towards C Butt increased by 0.7°F. The roof strata temperatures 48 in deep changed by only a few tenths of a degree.

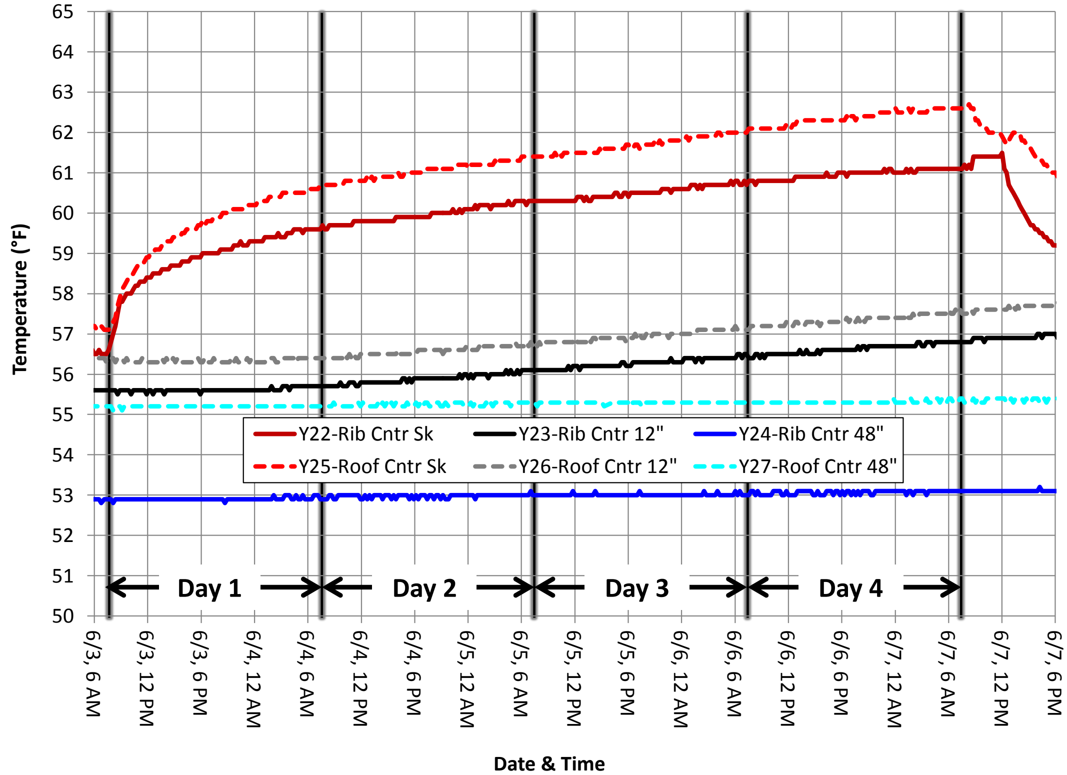


Figure 23. Rib and roof strata temperatures near the tent center on the surface and at 12 and 48 in depth for dry in-mine testing.

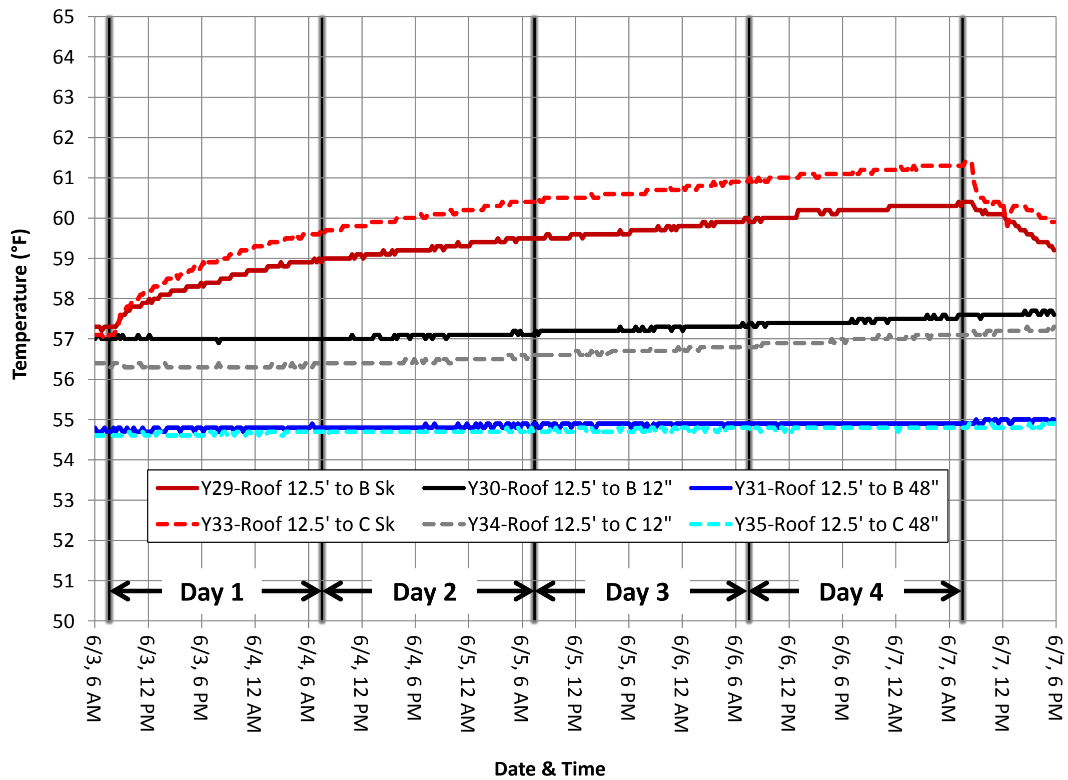


Figure 24. Roof strata temperatures on the surface and at 12 and 48 in depth measured 12.5 ft towards B Butt and C Butt during the dry in-mine testing.

The roof strata surface temperatures measured 25 ft from the center of the tent towards B Butt and C Butt increased gradually, but steadily during the 96-hour tests (see Figure 25). The temperature 25 ft towards B Butt increased by 1.3°F and the temperature 25 ft towards C Butt increased by 2.4°F. It should be noted that the measurement location 25 ft towards C Butt was closer to the RA than the measurement location 25 ft towards B Butt (refer to Figure 16). The roof strata temperatures 12 in and 48 in into the roof changed less than a few tenths of a degree over the 96-hour tests.

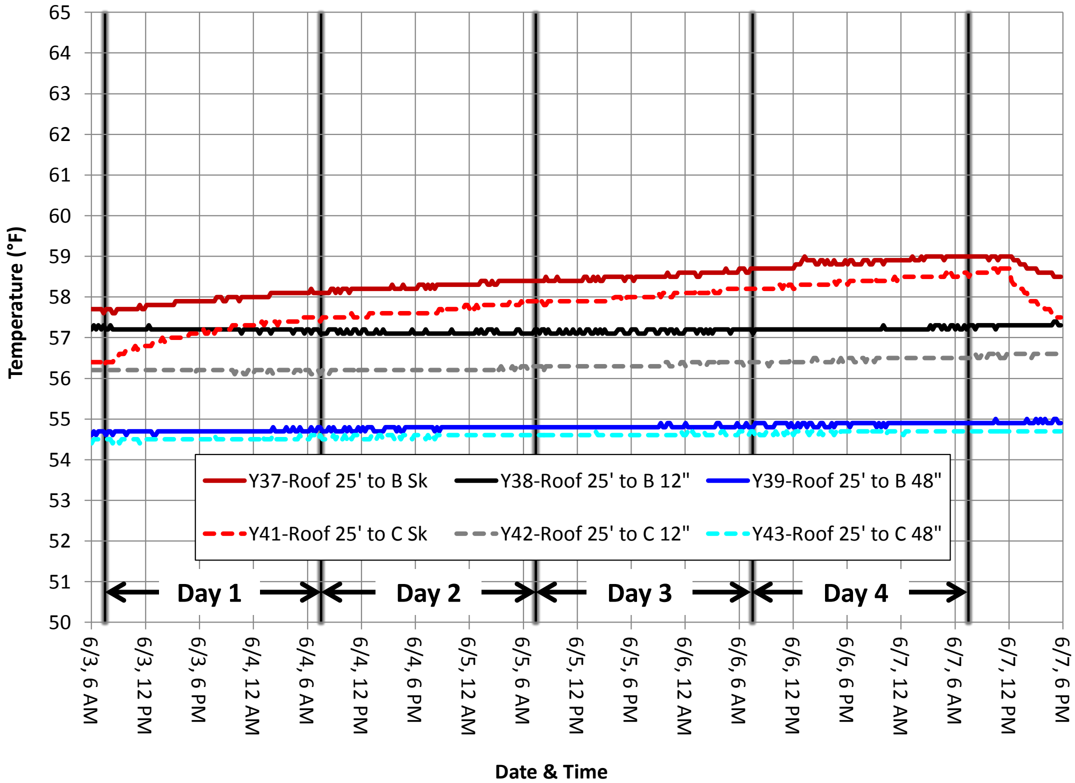


Figure 25. Roof strata temperatures on the surface and at 12 and 48 in depth measured 25 ft towards B Butt and C Butt during the dry in-mine testing.

SRCM, Wet

For the wet tests in the SRCM, the heat input fluctuated each day (refer to Figure 26) in a manner similar to what was observed for the dry in-mine testing. From 6 AM to roughly 6 PM, the input power was lower than it was for the 6 PM to 6 AM time period. The average heat input for the full 96 hours was 1592 watts—4.7% less than the target heat input of 1670 watts—with a standard deviation of 34.7 watts. The average heat input for each day and the percent change from day to day is shown in Table 3. As the data show, the average heat input changed by only a few percent from day to day. During the wet in-mine tests, the average heat input for the final six hours of the test was 1597 watts—4.4% less than the target heat input. Once again, in order to interpret the results properly, the temperature rise of each channel must be normalized according to the input power.

Within the tent, the air temperatures rose relatively quickly during the first day before leveling off. On the second day, the average input heat increased 2.8% above the average input heat from the first day, causing a slight hump in the internal air temperatures. On the third and fourth days, the average heat input decreased by just over 1% compared to each of the previous days. As a result, the air temperatures on the third and fourth days appeared to level off (refer to Figure 26). At the end of the fourth day of testing, the temperature rise computed using the final internal air temperature near the roof and the starting internal air temperature near the roof was approximately 21°F. The temperatures at midheight at the box end, tent end, and center of the tent (labeled X8-DBT on Figure 26) were within about 1.5°F of each other throughout the test. At the center of the tent, the data show that the air temperature near the top of the tent was about 2.5°F higher than the temperature at midheight, and about 5°F higher than the temperature near the tent floor.

Table 3. Average heat input for each day of testing

Day	Average Heat Input (watts)	% Change In Average Heat Input Versus Previous Day
1	1571	NA
2	1615	+2.8%
3	1594	-1.3%
4	1572	-1.4%

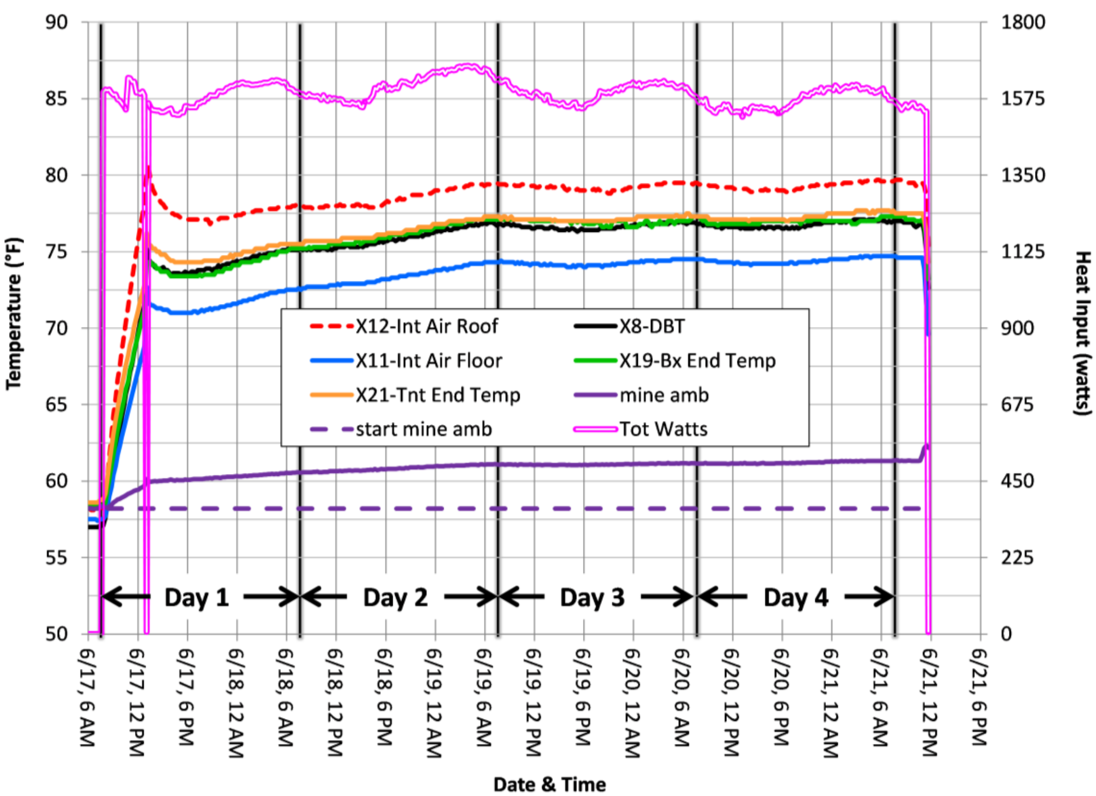


Figure 26. RA internal air temperatures, average mine air temperature, and heat input for wet testing in the SRCM.

At the beginning of the wet in-mine tests, the relative humidity at each end of the tent dropped slightly from roughly 90 %RH to about 88 %RH (refer to Figure 27). During the dry in-mine tests, the relative humidity dropped by more than 20% as the internal temperatures increased (refer to Figure 19). However, during the wet in-mine tests, the relative humidity at each end of the tent remained above 85 %RH throughout the tests. At the tent end, the relative humidity dipped slightly during the first 12 hours of the test and then it stayed constant at roughly 88 %RH for the remainder of the test. The relative humidity at the metal box end of the tent decreased for roughly the first two days of the test and then it leveled off at about 86% until the middle of the third day. During the final 36 hours of the test, the relative humidity at the box end of the tent jumped by 3% or more several times with each occurrence lasting 2 to 8 hours. Two of these excursions exceeded 90 %RH for 6 to 8 hours. The highest measured relative humidity was 93 %RH during the final 6 hours of the fourth day.

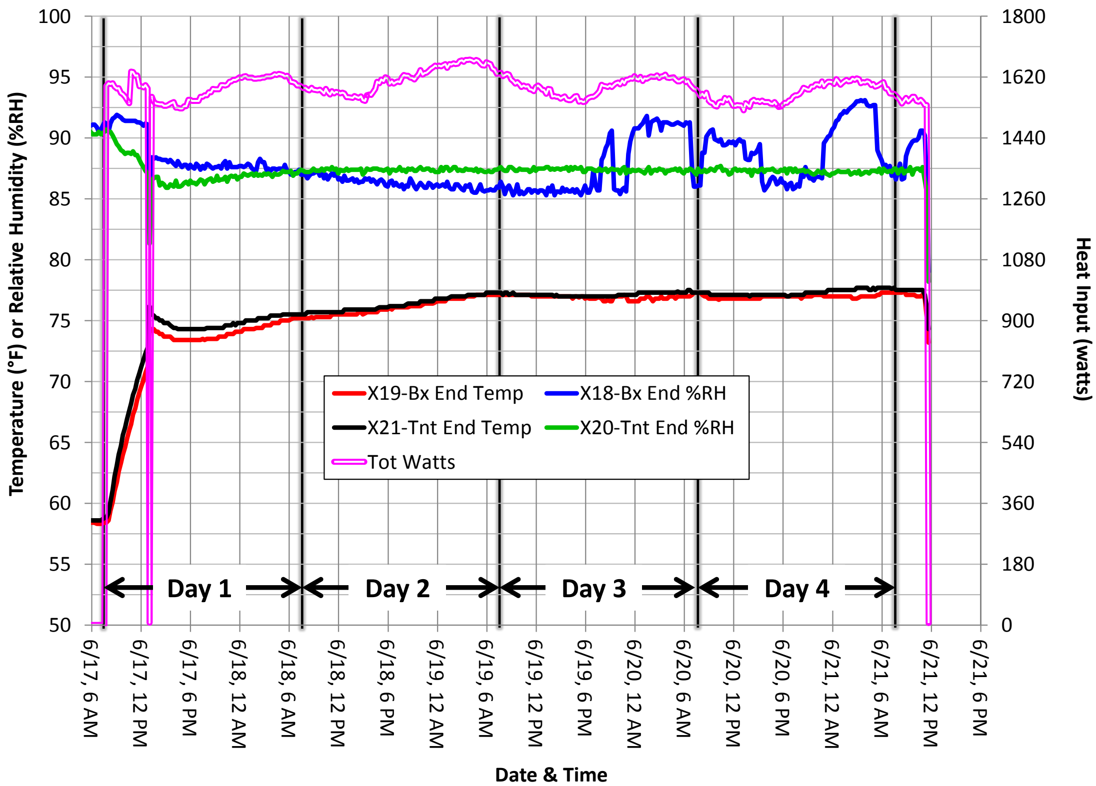


Figure 27. RA internal air temperatures and relative humidity at box end and tent end and heat input for the wet in-mine testing.

During the wet tests, the simulated miners delivered a total of 10.6 gal (40 L) of water into the interior of the RA, or 1 liter per simulated miner per day. This was documented by marking the initial and final water level on the makeup water tank (see Figure 28a). Saturated air was delivered to the interior of the tent at a rate of 1 liter per simulated miner per day. This is within the range of values of humidity generation for people indoors quoted by TenWolde and Pilon—0.8 to 1.7 L/day [TenWolde and Pilon 2007]. In the case of miners within an RA, it is likely that the moisture added by the miners would be towards the upper end of this range due to higher than normal sweat rates. In addition, the temperature of the water vapor exiting the simulated miners was measured to be from 95°F to 100°F at an ambient temperature of 75°F. This is representative of the water vapor exhaled by humans when breathing and evaporated from skin due to sweating.

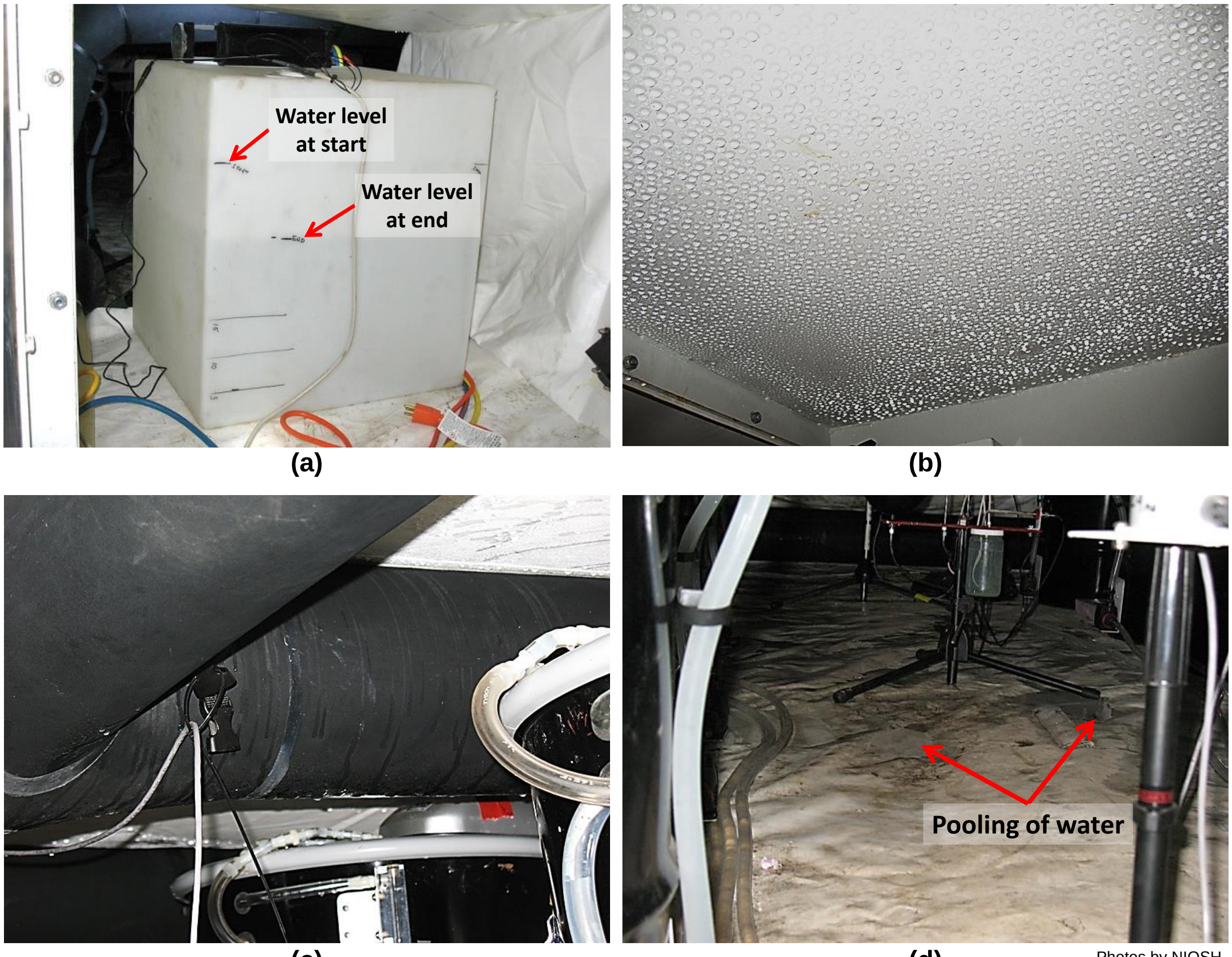
The condensation sensor on the side of the tent indicated that condensation began on the tent sidewall approximately five hours after beginning the test. However, the condensation sensor on the underside of the roof did not indicate the presence of condensation at any time during the test. Using an infrared camera, the temperature at this location was measured to be about 82°F to 85°F while the calculated dew point temperature for the air inside the RA was about 73°F to 74°F. Because the temperature at the roof condensation sensor location exceeded the dew point temperature, no condensation occurred at this specific location.

At the completion of the test, an access panel on the metal box was removed to examine the inside of the RA. The underside of the roof of the metal box was coated with droplets of condensation about ¼ inch in diameter (see Figure 28b). The bottom of the metal box was covered in about an inch-deep layer of water so that water ran out of the bolt holes after a bolt-on access panel was removed. It is estimated that this accounted for about half of the water input into the RA by the simulated miners. In the tent, signs of condensation appeared on the tent walls, on the underside of the roof, and on the support tubes (see Figure 28c). Finally, pools of water were observed at low spots on the tent floor (see Figure 28d).

As previously mentioned, over the course of the tests, the simulated miners delivered 40 L of water into the RA. Calculations were performed to determine how much of the added water went into the air inside the chamber and how much condensed on the chamber walls (refer to the Appendix). Using a value of 999 kg/m^3 for the density of water, the mass of water input into the RA was 39.96 kg. The absolute humidity for the air inside the RA was calculated to be 0.113 kg/m^3 at the beginning the test and 0.207 kg/m^3 at the end of the test. Using the RA volume of 15 m^3, the mass of water vapor in the air increased from 0.17 kg to 0.31 kg. This equates to only 0.35% of the input water going towards raising the humidity of the air. Assuming that no water vapor leaked from the RA, 39.82 kg or 39.86 L of water condensed on the interior of the RA. This means that nearly all of the water emitted by the simulated miners condensed on the interior surfaces of the RA.

During the wet in-mine testing, the average mine air ambient temperature computed from the eight averaging RTDs located near the RA (refer to Figure 16) increased throughout the tests (refer to Figure 26). As expected, the mine strata beneath the tent behaved very similarly to the dry in-mine testing. The temperature between the bottom of the tent and the mine floor surface increased almost immediately after beginning the test (see Figure 29). As depth into the floor strata increased, the temperature increased less and at a lower rate. The temperature between the tent and mine floor increased by almost 9°F in the first 24 hours. By the end of four days, the temperature between the tent and the mine floor strata increased by 12.7°F; the temperature 12 in deep increased by 5.0°F; the temperature 24 in deep increased by 2.1°F, the temperature 36 in deep increased by 1.0°F, and the temperature 48 in deep increased by 0.5°F.

As with the dry in-mine test, the mine air temperatures at the sensors around the RA (refer to Figure 16) increased almost immediately after beginning the test as shown in Figure 30. The air temperatures began to level off after roughly the first two days, but the air temperatures at these sensors continued to rise for the entire 96-hour test. By the end of the 96-hour test, the mine air temperatures between the tent and rib at the midheight of the tent increased roughly 3°F, and the mine air temperatures above the tent and metal box increased approximately 3 to 5 degrees Fahrenheit. The air temperature changes near the tent were similar to those observed for the dry in-mine testing.



Photos by NIOSH

Figure 28. Photographs of interior after stopping test: (a) picture of water tank showing initial and final water level; (b) condensation on underside of roof of metal box; (c) condensation on underside of tent roof and on support tubes; and (d) pooling of water on tent floor.

Away from the footprint of the RA, the mine air temperature also increased at the sensor locations (refer to Figure 16) as shown in Figure 31. The air temperature measured 25 ft towards C Butt from the center of the tent started at about 1°F lower than the other two locations. For the wet in-mine testing, the temperatures measured 12.5 ft towards B Butt, 25 ft towards B Butt, and 25 ft towards C Butt increased by about 2°F. The data show that the air temperatures at these locations continued to increase throughout the tests. However, from the beginning of the third day to the end of the fourth day, the temperature changes at each of these locations were only a few tenths of a degree.

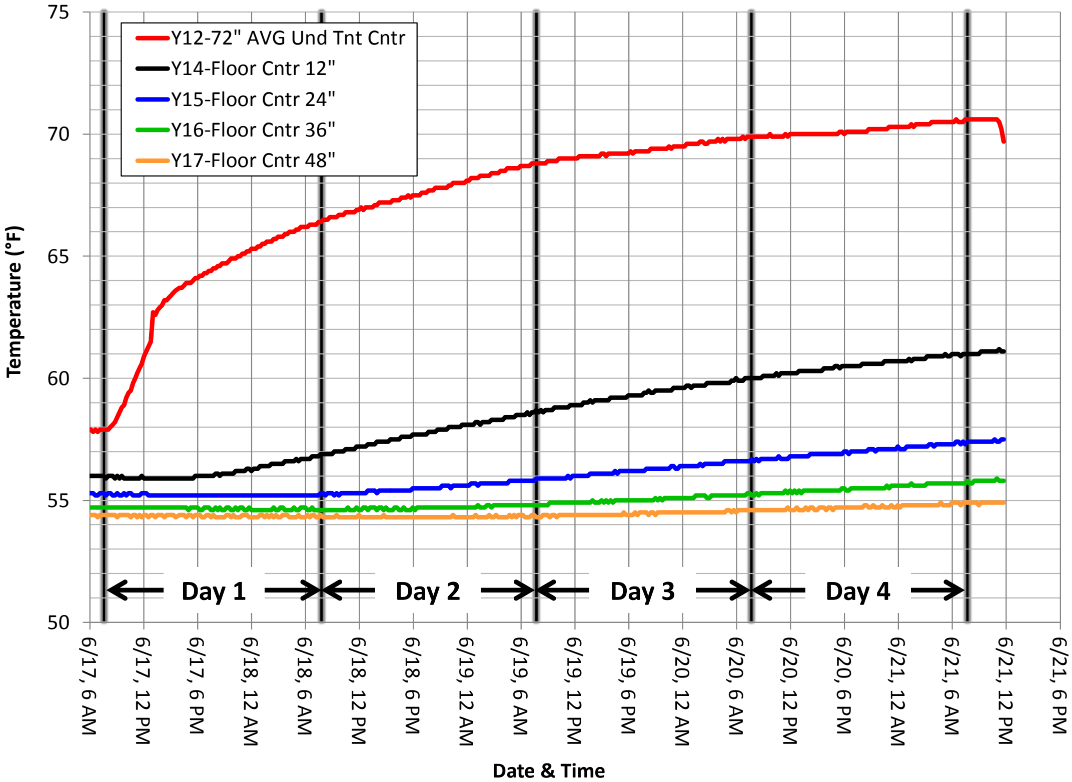


Figure 29. Mine floor strata temperatures under the tent during wet in-mine testing.

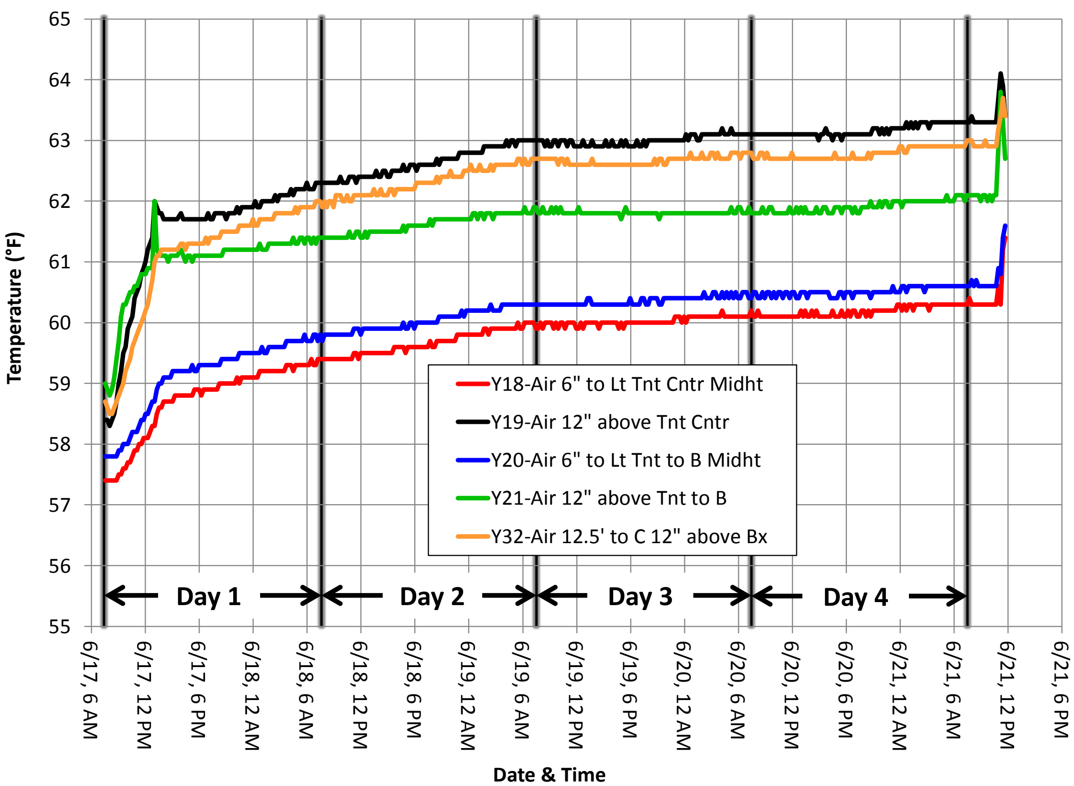


Figure 30. Mine air temperatures near the RA during the wet in-mine testing.

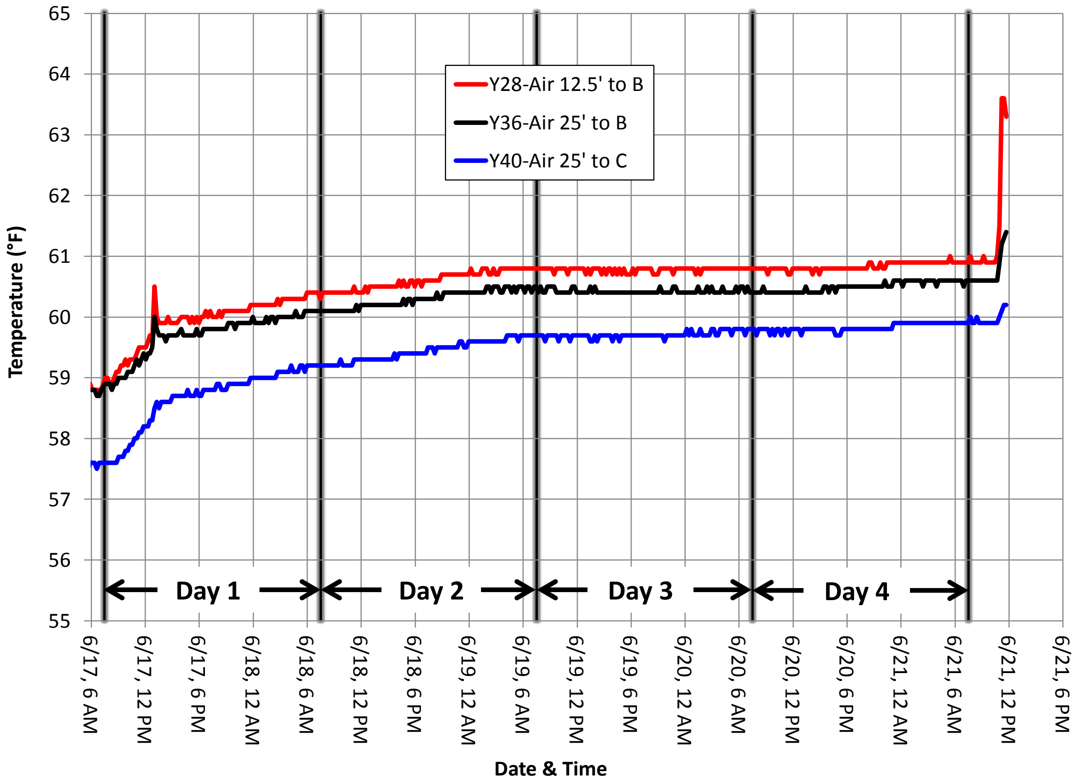


Figure 31. Mine air temperatures outside the footprint of the RA during the wet in-mine testing.

The roof and rib strata temperatures near the center of the tent showed similar behavior to that of the dry in-mine testing. The roof and rib strata temperatures near the center of the tent increased throughout the test (refer to Figure 32). The surface temperatures increased rapidly for the first several hours of the test and then began to level off after the first two days. Beyond the second day, the surface temperatures increased gradually, but steadily. During the third and fourth days, the surface temperatures changed by only a few tenths of a degree each day. However, this could have been due to the input power decreasing from day two to day three and from day three to day four. By the end of the fourth day, the roof surface temperature increased by 5.5°F and the rib surface temperature increased by 4.7°F. The temperatures 12 in into the roof and rib began to change near the beginning of the second day of testing. During the second, third, and fourth days, the temperatures 12 in into the roof and rib increased slowly, but steadily. During the 96-hour test, the temperatures 12 in into the roof and rib changed by 1.1°F. Near the center of the tent, the temperatures 48 in into the roof and rib changed by only a few tenths of a degree over the 96-hour tests.

For the wet, in-mine tests, the roof strata temperatures 12.5 ft from the center of the tent towards B Butt and C Butt increased throughout the test (refer to Figure 33) in a manner similar to the dry in-mine tests. As with the strata temperatures near the center of the tent, the roof strata surface temperatures 12.5 ft from the center of the tent increased quickly for the first few hours of the test and then began to level off after the second day. Recall, the measurement location 12.5 ft towards C Butt was over the metal box whereas the location 12.5 ft towards C Butt was outside of the footprint of the RA. The roof strata surface temperature 12.5 ft towards B Butt increased by 3.3°F while the roof strata surface temperature 12.5 ft towards C Butt increased by

4.7°F. At a depth of 12 in, the temperatures began to change near the end of the second day and they increased gradually for the remainder of the test. The roof strata temperature 12.5 ft towards B Butt increased by 0.6°F and the temperature 12.5 ft towards C Butt increased by 0.8°F. Similar to the dry in-mine test results, the roof strata temperatures 48 in deep changed by only a few tenths of a degree.

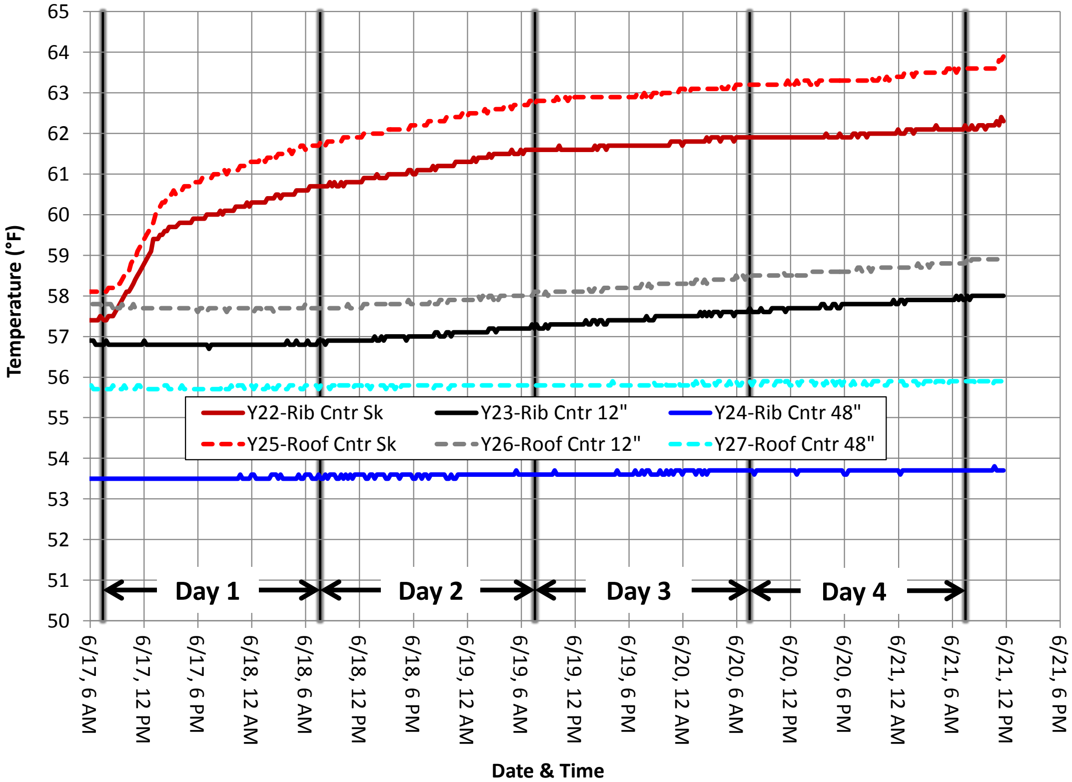


Figure 32. Rib and roof strata temperatures near the center of the tent on the surface and at 12 and 48 in depth during the wet in-mine testing.

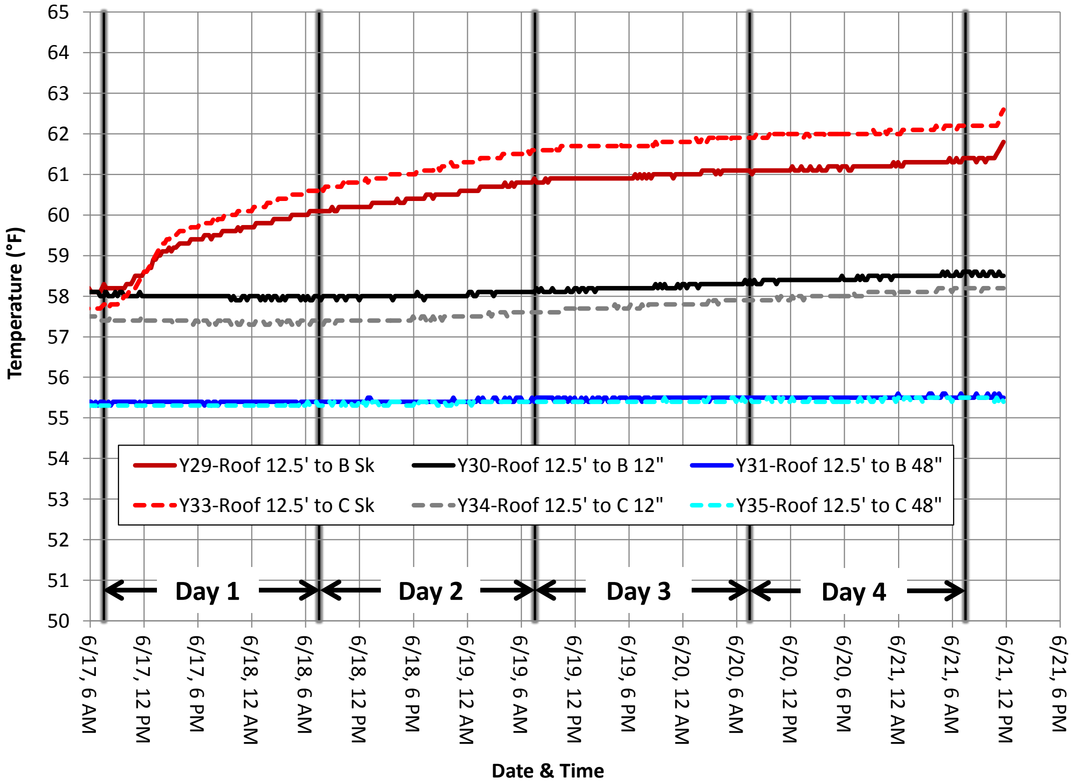


Figure 33. Roof strata temperatures on the surface and at 12 and 48 in depth measured 12.5 ft towards B Butt and C Butt during the wet in-mine testing.

In a manner similar to that of the dry in-mine testing, during the wet in-mine testing, the roof strata surface temperatures measured 25 ft from the center of the tent towards B Butt and C Butt increased gradually, but steadily during the 96-hour tests (see Figure 34). The temperature 25 ft towards B Butt increased by 1.5°F and the temperature 25 ft towards C Butt increased by 2.3°F. As was previously mentioned, the measurement location 25 ft towards C Butt was closer to the RA, and the heat sources inside, than the measurement location 25 ft towards B Butt (refer to Figure 16). As with the dry in-mine tests, the roof strata temperatures 12 in and 48 in into the roof changed less than a few tenths of a degree over the 96-hour tests.

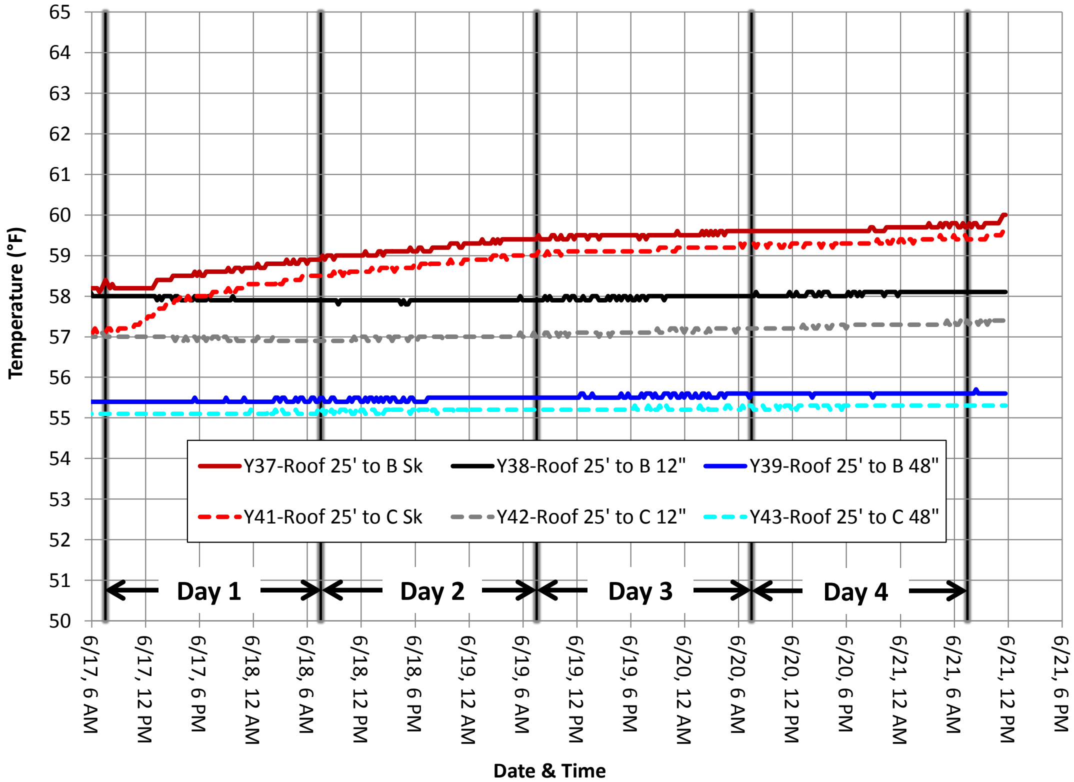


Figure 34. Roof strata temperatures on the surface and at 12 and 48 in depth measured 25 ft towards B Butt and C Butt during the wet in-mine testing.

Temperature Results: Normalized Temperature Rise

Average Heat Input

The average and the standard deviation of the heat input for the full 96-hour tests and for the final six hours of each test were computed (see Table 4). As the table shows, although the heat input was not constant during the tests, the heat input only varied by a few percent for the entire duration of all tests. For the final six hours of each test, the standard deviation of the heat input was less than 1% of the average value.

Table 4. Average heat input and standard deviation for full 96 hours and final 6 hours of each test

Test	Avg Heat Input for Full 96 Hours (watts)	Std Dev of Heat Input for Full 96 Hours (watts)	Avg Heat Input for Final 6 Hours (watts)	Std Dev of Heat Input for Final 6 Hours (watts)
High Bay, Dry	1718	29.6	1738	13.8
In-mine, Dry	1589	19.3	1597	8.9
In-mine, Wet	1592	34.7	1597	15.1

Normalized Temperature Rise

For each test, the average heat input for the final six hours of each test was used to normalize the temperature rise for the air inside the RA. These data are summarized in Table 5. The data show that the normalized temperature rise for the air inside the RA was highest for the dry in-mine testing. For each test, the temperature rise of the air near the roof was greater than those at the floor and at midheight and the temperature rise of the air near the floor was lower than those at the roof and at midheight. This is due to the stratification of the air inside the tent. The warmer (lower density) air rises to the top and the cooler (higher density) air sinks to the floor.

Table 5. Normalized temperature rise (°F) for the air inside the RA

Test	Near Roof	Near Floor	Center, Midheight	Box End, Midheight	Tent End, Midheight
High Bay, Dry	21.0	17.1	20.1	19.7	18.7
In-mine, Dry	25.2	19.9	23.8	21.5	22.6
In-mine, Wet	22.4	18.0	20.8	19.6	19.7

When comparing the results for the wet in-mine tests to those of the dry in-mine tests, the normalized temperature increases for each strata and air measurement location were similar for most of the measurement locations (refer to Table 6 for the mine strata and Table 7 for the mine air). However, the floor strata temperature increases under the tent were consistently lower for the wet tests than they were for the dry tests. The percentage differences for the floor strata under the tent were 12% lower at 0 in; 20% lower at 12 in; 28% lower at 24 in; 38% lower at 36 in; and 56% lower at 48 in.

Table 6. Normalized temperature rise (°F) of the mine strata by location for dry and wet in-mine tests

Location, Test Condition	0” Depth	12” Depth	24” Depth	36” Depth	48” Depth
Floor at Tent Center, Dry	15.0	6.4	2.9	1.6	0.9
Floor at Tent Center, Wet	13.2	5.1	2.1	1.0	0.4
Rib at Tent Center, Dry	4.7	1.2	-	-	0.2
Rib at Tent Center, Wet	4.9	1.1	-	-	0.2
Roof at Tent Center, Dry	5.6	1.2	-	-	0.2
Roof at Tent Center, Wet	5.6	1.0	-	-	0.2
Roof, 12.5’ to B Butt, Dry	3.1	0.5	-	-	0.2
Roof, 12.5’ to B Butt, Wet	3.3	0.4	-	-	0.1
Roof, 12.5’ to B Butt, Dry	4.3	0.7	-	-	0.2
Roof, 12.5’ to B Butt, Wet	4.6	0.7	-	-	0.2
Roof, 25’ to B Butt, Dry	1.2	0.0	-	-	0.3
Roof, 25’ to B Butt, Wet	1.6	0.1	-	-	0.2
Roof, 25’ to C Butt, Dry	2.2	0.3	-	-	0.2
Roof, 25’ to C Butt, Wet	2.4	0.3	-	-	0.2

Table 7. Normalized temperature rise (°F) of the mine air by location for dry and wet in-mine tests

Location	Dry	Wet
6" to Left of Tent Center at Midheight	2.7	3.1
6" to Left of Tent towards B Butt at Midheight	2.8	2.9
12" above Tent Center	5.0	5.3
12" above Tent towards B Butt	3.3	3.4
12" above Metal Box (12.5' towards C Butt)	4.3	4.6
12.5' towards B Butt	2.1	3.6
25' towards B Butt	1.8	1.9
25' towards C Butt	2.9	2.4
Mine air average (based on above eight sensors)	3.1	3.2

Discussion

Mine Behavior

In the case of an occupied RA, the mine strata can be a heat source, a heat sink, or a non-factor depending on the temperature difference between the RA and the mine strata. For the testing that is the subject of this report, the mine strata was at a lower temperature than the RA and the results obtained are different than what would be obtained if the mine strata were at a higher temperature than the RA. Of course, if the mine strata were at a higher temperature than the RA, the mine strata would be a heat source and the resulting air temperatures inside the RA would be higher than those observed here. In both cases, the mine would not act as an infinite heat sink. The following discussion is specific to the case where the mine strata acts as a heat sink (i.e. the mine strata temperature is lower than that of the RA) as in the tests conducted in the SRCM.

As heat is input into an RA, the air temperature inside the RA and the temperature of the RA itself begin to rise. Subsequently, heat is transferred into the mine strata and mine air and their temperatures increase. Heat is transferred into the mine strata beneath the tent primarily via conduction. The sides and top of the RA transfer heat to the mine air by natural convection. Heat is transferred to the mine rib and roof via radiation from the top and sides of the tent and by natural convection from the mine air. If the mine would behave as an infinite heat sink, the mine strata temperatures would not increase during the tests. For a given scenario, infinite heat sink behavior would result in the lowest possible temperatures within an RA. However, because heat transfer is driven by a temperature difference, if the mine strata temperatures increase, the heat lost from the RA would be reduced compared to the infinite heat sink situation. As the mine strata temperatures would increase, the mine air temperature would increase above the temperatures observed with infinite heat sink behavior. Finally, the RA internal air temperature would increase above the value observed if the mine were to behave as an infinite heat sink.

The mine strata and mine air temperatures increased throughout the in-mine tests. The temperatures of the mine floor strata beneath the tent showed the largest increases because the simulated miners were in direct contact with the tent floor. The normalized temperature rise at the tent/mine floor interface was 15.0°F for the dry tests and 13.2°F for the wet tests. At the center of the tent, the mine roof strata surface temperature increased by nearly 6°F and the rib strata surface temperature increased by nearly 5°F for both the wet and dry tests. The average mine air temperature computed from the eight sensors in the test area increased by just over 3°F for both the wet and dry tests. Because the mine strata temperatures increased, it is clear that the mine does not act as an infinite heat sink.

The in-mine test data showed that the strata temperatures at a depth of four ft remained nearly constant throughout the tests. In order for laboratory testing to show similar results to a real mine, the test facility should be designed to mimic the thermal behavior of four ft of mine strata. In addition, the exterior temperature of the facility should be maintained at the desired mine strata temperature by using an HVAC system. Similarly, thermal simulation models of an RA in an underground coal mine should include a four-foot-thick layer of mine strata. The temperature at a depth of four ft can then be assumed to remain constant at the temperature corresponding to the mine that the model is to represent.

Effect of Test Facility on Temperature Rise

As the data in Table 5 show, the normalized temperature rise of the air inside the RA was several degrees higher for the dry in-mine tests when compared to the data for the dry high bay tests. The normalized temperature rise for the air at the center of the tent near the roof was 25.2°F for the dry in-mine tests and 21.0°F for the dry high bay tests. The apparent temperature for each of these temperature rise values was calculated for several initial mine ambient temperatures with an assumed relative humidity of 95%. This value was used because the maximum observed relative humidity in the wet testing was 93%, and 2% was added to this value to account for the accuracy of the RH sensor and to err on the side of caution. These calculations show that the 95°F apparent temperature limit would be exceeded for the tested RA at an initial mine ambient temperature of 57.4°F based on the dry in-mine test data and at an initial mine ambient temperature of 61.6°F based on the dry high bay test data.

There are two key differences between the high bay test and the in-mine tests. One of these is the response of the air surrounding the RA. In the high bay, the heat transferred from the RA to the ambient air within the building does not have a significant impact on the ambient air temperature. In the mine, however, the heat transferred from the RA to the mine causes the temperature of the mine air to increase. The other potential difference is the amount of heat transferred into the floor beneath the simulated miners. In the high bay, the floor is made of concrete whereas the SRCM floor is made of siltstone. The thermal conductivity of siltstone (2 to 3 W/m-K) is higher than that of concrete (0.8 to 1.8 W/m-K). The resistance to heat transfer into the floor would be greater for the high bay test, and, if the thermal gradient between the bottom of the tent and the floor is similar to that which occurred in the mine, it is expected that less heat would be lost into the floor of the high bay.

The results for the high bay tests are similar to what would be observed with infinite heat sink behavior. The heat input within the RA had a negligible effect on the ambient temperature within the high bay, but the temperature at the interface between the tent and the high bay floor increased by about 20°F. As a result, the temperature rise values for the high bay testing are greater than those that would be observed with true infinite heat sink behavior. True infinite heat sink behavior would yield the lowest temperatures.

The results above suggest that test facilities that are used to conduct apparent temperature testing should not approximate an infinite heat sink if the data are to be used to certify that an RA is suitable for a particular mine ambient temperature. Instead, test facilities that mimic the behavior of a real coal mine should be used. The density, thickness, specific heat, and thermal conductivity of the materials used to construct the test facility will influence apparent temperature test results. Another critical factor is the means by which the test facility ambient temperature is controlled. If airflow is interrupted in a mine—the worst-case scenario—the temperature of the air surrounding an RA would increase. If an HVAC system is used to control the air temperature within the test facility, the measured temperature rise would be less than what would be observed in the worst-case in-mine scenario. The measured temperature rise will be dependent on the specifics of such test facilities.

In order to compare results across test facilities and RAs, standardized test facilities would have to be built and standardized test procedures would have to be followed. With regard to the test facilities, the best approach would be to design and build the facility so that the thermal properties of the walls, ceiling, and floor of the test facility reasonably represent those of a mine. The in-mine test results seem to indicate that over the course of a 96-hour time period, the temperatures four ft into the mine strata do not change much. Therefore, in order for laboratory test results to be comparable to in-mine results, the test facility needs to mimic the thermal mass and thermal conductivity of four ft of mine strata.

If testing must be conducted at multiple ambient temperatures, the temperature at the depth of four ft should be controlled via an HVAC system rather than at the air temperature within the test facility. As heat is input into the RA, the air temperature inside the test facility and the temperatures of the walls, ceiling, and floor of the test facility would begin to increase. If the facility design approximates the thermal properties of a mine, the measured temperature changes would be close to those that would be observed in a mine.

Effect of Moisture

The goal of conducting the wet and dry in-mine tests was to determine if including moisture would affect the final temperatures inside the RA, because it could be postulated that condensation of moisture on the inner walls and pooling of water on the floor would enhance heat transfer and significantly lower the final temperatures inside an RA. It should be noted that condensation on the interior surfaces of the RA will only occur if the interior surfaces of the RA are below the dew point temperature of the air inside the RA. This would be the case for mines that have a relatively low ambient temperature. However, if the mine temperatures are such that the interior surfaces of the RA exceed the dew point temperature, condensation would not occur.

After completing the dry and wet in-mine tests, the temperatures of the mine air and mine strata were examined beginning approximately 66 hours before the start of each test through the end of the second test. In spite of allowing ten days between tests, the temperatures at the beginning of the second test had not yet cooled to their "natural" temperatures. The floor strata temperatures below the tent had the greatest differences in starting temperatures (refer to Figure 35). As the figure shows, the starting temperatures at each depth were about 2°F higher for the tests conducted with added moisture. The roof and rib strata and the air inside the test area were also higher for the wet tests. The starting temperatures for each test are summarized in Table 8.

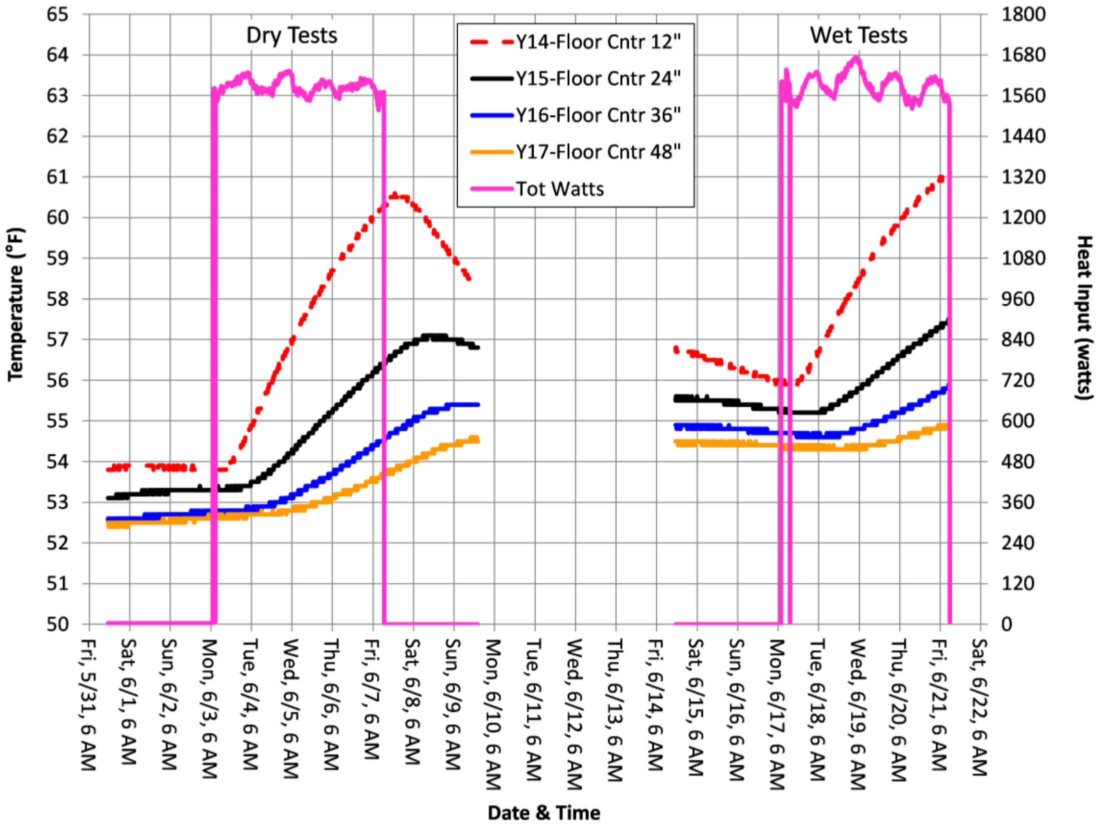


Figure 35. Mine floor strata temperatures for the dry and wet in-mine tests.

Table 8. Initial mine strata and air temperatures and differences in the initial mine strata and air temperatures for the dry and wet in-mine tests

Location	Dry (°F)	Wet (°F)	ΔT (°F)
Floor, 12" depth	53.8	55.9	2.1
Floor, 24" depth	53.3	55.3	2.0
Floor, 36" depth	52.8	54.7	1.9
Floor, 48" depth	52.6	54.4	1.8
Rib, 12" depth	55.6	56.9	1.3
Rib, 48" depth	52.9	53.5	0.6
Roof, 12" depth	56.4	57.8	1.4
Roof, 48" depth	55.2	55.7	0.5
Avg mine air temp	57.5	58.2	0.7

Because the starting temperatures for the wet tests had not yet reached their original temperatures, the temperature rise values that were calculated would tend to be somewhat lower than they would have been if the starting temperatures had reached their original values. As a result, it is difficult to determine the exact effect of moisture on the temperature rise. The normalized temperature rise values for the wet tests could be as much as 2°F lower than they would have been if the mine strata temperatures had been given sufficient time to reach their natural temperatures prior to beginning the wet tests due to the higher initial temperature for the mine floor strata beneath the tent.

The temperature data for the in-mine tests were examined to estimate the amount of time that should be allowed between tests so that the layers of the mine strata reach their initial temperatures. From the data, it appears that roughly three weeks would be needed for the strata to cool. This time could be reduced if cool air is forced through the test area. Prior to beginning a test, the strata temperatures should be carefully examined to ensure the temperatures have reached their initial values. For tests conducted in a specially designed test facility, the time between tests could be reduced significantly by using an HVAC system to cool the facility in between tests. Similar to in-mine tests, the temperatures of the test facility should be examined to ensure the pre-test temperatures are reached before initiating another test.

For both the dry and wet in-mine tests, Table 5 shows the normalized temperature rise for the air inside the tent, Table 6 shows the normalized rise for the mine strata, and Table 7 shows the normalized temperature rise for the mine air. For each interior temperature measurement location, the temperature rise was lower during the wet in-mine tests. The temperature rise values for the mine strata beneath the tent were also lower for the wet in-mine tests. For the roof and rib strata, the temperature rise values were similar for both tests. The temperature rise values for the mine air were similar at most of the locations. However, the temperature rise at 12.5 ft towards B Butt was 1.5°F higher for the wet tests. Near the tent roof in the center of the tent, the normalized temperature rise for the dry tests was 25.2°F and the temperature rise for the wet tests was 22.4°F.

Even though the final internal temperatures were found to be lower for the wet tests, the results cannot be used to confirm or refute the claim that including moisture in apparent temperature tests increases the heat loss from an RA and, thereby, lowers the resulting internal air temperatures. The fact that the mine had not cooled to its natural temperature prior to beginning the wet tests makes it difficult to use the wet test data to determine an accurate temperature rise. In addition, the design of the moisture generation portion of the simulated miners may have affected the results. The moisture outlet port at the top of each simulated miner was less than eight inches from the underside of the tent. As the moist air exits the simulated miner, it is directed at the underside of the tent. This would tend to "short circuit" the heat transfer path to the mine air. To avoid this problem, in future testing, the exit port for the moist air would be relocated to the side of the simulated miner so the moist air would be directed inward.

In order to determine the effect of including moisture on the temperatures inside an RA, additional testing would have to be performed with redesigned simulated miners and with the mine at its "natural temperature" at the beginning of the tests. For the tested RA, it can be said that including 1 liter of moisture per simulated miner reduced the temperature rise by 2.8°F at most. However, due to the elevated strata temperature and the aforementioned concern with "short circuiting" the heat transfer path by having the moist air impinge directly on the underside of the tent, this effect of the moisture on the internal air temperature could also be negligible.

The relative humidity for the wet tests was observed to stay within the range of 85 %RH to 88 %RH for most of the test duration (see Figure 27). However, at the box-end relative humidity sensor, the relative humidity was observed to increase to 93% for a sustained duration a few times during the last two days of the test. One possible reason for these excursions is that the interior of the metal box may have reached the dew point temperature. If this occurred, moisture would no longer condense on the inside of the metal box, which would cause the relative humidity to increase at the box end of the tent.

For cases where the initial mine temperature is low, it is doubtful that the %RH inside an RA would reach 100 %RH. In such situations, the interior surfaces of the RA will be at a lower temperature than that of the air inside the RA by some amount. In addition, the dew point temperature will be lower than the air temperature. To demonstrate, consider the wet in-mine tests where the air inside the RA reached 78°F and 90 %RH. For these conditions, the dew point temperature is 75°F. Any interior surface within the RA at or below 75°F would cause water to condense and the relative humidity would be somewhat limited due to this condensation.

If the initial mine temperature is such that the interior surfaces of the RA approach the dew point temperature of the air inside the RA, the relative humidity inside could approach 100%. Based on the observed temperature rise of the tent and metal box, it is estimated that the interior surface of the tent for the tested RA would approach the dew point temperature if the initial mine temperature was 70°F or higher and that the interior surface of the metal box would approach the dew point temperature if the initial mine temperature was 75°F or higher. In these circumstances, the air inside the RA might approach 100 %RH. Additional testing at elevated mine ambient temperatures would be required to prove this.

Resulting Internal Temperatures and Estimated[11] Derated Capacity for Tested RA

In order to estimate the final internal air temperature of an RA, the temperature rise measured at one ambient temperature could be applied to a range of mine ambient temperatures. Then the apparent temperature could be computed based on a known or assumed relative humidity. Similarly, to determine the derated capacity of an RA for a mine ambient temperature, the temperature rise per miner could be computed from test results and used to estimate the apparent temperature in the RA based on a known or assumed relative humidity. The temperature increase of an object is directly related to the sensible heat input. For dry RA tests, the heat input by the simulated miners is purely sensible heat, while for wet RA tests the heat input is split between sensible and latent heat with the majority of the heat input as sensible heat. In each case, the sensible heat input is directly related to the number of simulated miners. If the sensible heat input is doubled by doubling the number of simulated miners, for example, the temperature increase would also double. Thus, it is expected that the temperature increase within the RA will be directly related to the number of miners or simulated miners inside. In addition, it is also assumed that across the small range of expected initial mine ambient temperatures, the heat transfer

[11] The proposed method of using the temperature rise on a per-miner basis to determine the derated capacity of an RA across a range of mine ambient temperatures should be proven through a series of carefully conducted experiments.

parameters are nearly constant. With these assumptions, the temperature rise per miner could be used across a range of initial mine ambient temperatures to determine the number of miners that would cause the apparent temperature inside an RA to exceed an apparent temperature of 95°F.

The aforementioned method was applied using the test data obtained for the tested RA in the SRCM. *It should be noted that all values mentioned hereafter are applicable to the tested RA in the tested mine.* For other RAs, tests would have to be conducted in a mine-like environment to determine the appropriate temperature rise per miner. Even though two RA designs may be similar, the specific design of an RA will have some effect on the heat loss and the resulting temperature inside the RA. A change in materials, geometry, and RA size will all have some effect on the heat transfer from an RA and the resulting temperatures.

For the tested RA, the resulting internal air temperatures and apparent temperatures were computed for the RA at full capacity using the measured temperature rise for the dry tests—25.2°F—and an assumed relative humidity of 95%. The dry test results were used because, as previously mentioned, for the wet tests there are some concerns about the initial mine strata temperatures and the possible “short circuit” of the heat transfer path from the simulated miners to the RA due to the proximity of the moisture generation outlet to the underside of the tent. Even though the maximum observed relative humidity was 93%, a relative humidity of 95% was used to account for the accuracy limitations of the RH sensor and to err on the side of caution. In addition, the moisture input by the simulated miners was towards the lower end of the range of moisture generation values expected to be emitted by real miners.

The internal air temperatures and apparent air temperatures were estimated for the tested RA at full capacity for a range of mine ambient temperatures from 55°F to 70°F as shown in Table 9. At a mine ambient temperature of 57.4°F, the tested RA would reach the apparent temperature limit. As the table shows, at higher mine ambient temperatures, the air inside the RA would exceed the apparent temperature limit.

Table 9. Estimated apparent temperature for the tested RA at full capacity for a range of mine ambient temperatures

Mine Ambient Temperature (°F)	Dry-Bulb Temperature of Air within RA (°F)	Apparent Temperature (°F)
55	80.2	87.0
57.4	82.6	95.0
60	85.2	105.0
65	90.2	127.6
70	95.2	154.8

Note: The data in Table 9 are applicable only to the OMSHR-tested RA. These values should not be applied to other RAs.

The values shown in Table 9 are specific to the tested tent-type RA and the test conditions used in the SRCM. However, it is expected that similar results would be observed for other tent-type RAs that do not have some means of improving heat loss. Furthermore, although a steel RA was not tested, it is expected that steel RAs without some form of air conditioning would also exceed the apparent temperature limit at some ambient temperature. In addition, it is expected that all RAs without air conditioning would have to be derated at some mine ambient temperature. Regardless of the manufacturer and the type of RA, i.e. steel or tent, the trends in temperature increase will be similar. Nonetheless, it is recommended that manufacturers conduct additional RA tests to establish derating tables for both steel- and tent-type RAs.

For the tested RA, the number of miners that would cause the internal temperature to exceed an apparent temperature of 95°F was calculated from

$$N = \frac{82.5 - T_{amb}}{\Delta T_m} \tag{4}$$

where N is the number of miners that would cause the apparent temperature to exceed the 95°F apparent temperature limit,

82.5°F is the temperature that results in a 95°F apparent temperature with 95% relative humidity,

T_{amb} is the initial ambient temperature of the mine, and

ΔT_m is the temperature change per miner—2.52°F for the tested RA as tested in the SRCM.

For calculations resulting in fractions, the result was rounded down. The estimated derated capacity for the tested RA as a function of mine ambient temperature is shown in Table 10. It is important to note that these values are specific to the tested RA and the test conditions used in this study. These values should not be applied to other makes or models of RAs.

Table 10. Estimated derated capacity for the tested RA as a function of mine ambient temperature

Mine Initial Ambient Temperature (°F)	Derated Capacity
60	8
65	6
70	4
75	2

Note: The data in Table 10 are applicable only to the OMSHR-tested RA. These values should not be applied to other RAs.

RAs are being used in mines with ambient temperatures above 60°F. The findings of this study highlight the need to develop some type of derating strategy based on existing tent- and steel-type RAs. The data in Table 10 were used to develop an example derating strategy as shown in Table 11. This derating table was developed as a series of 5-degree-Fahrenheit bands to account for differences in application, RA manufacturer, and experimental error. A table such as this would need to be developed for both tent-type and steel-type RAs based on multiple tests of each RA type.

Table 11. Example of derated capacity as a percentage of full capacity for the tested RA as a function of initial mine ambient temperature at the RA location

Initial Mine ambient Temperature at RA (°F)	Derating %
Below 60	No derating
60 to 65	40%
65 to 70	60%
70 to 75	80%

Note: The data in Table 11 are applicable only to the OMSHR-tested RA. These values should not be applied to other RAs.

Test Duration Required to Estimate Final Temperature

Due to the thermal mass of the mine strata, the temperatures measured during in-mine RA apparent temperature tests do not reach steady state very quickly, but rather continue to rise throughout the 96-hour tests. A steady state condition is really never reached within 96 hours due to the thermal mass of the mine. The temperatures increase relatively quickly during the first day of the test. As the test goes on, the temperatures increase much more gradually (refer to Figures 18 and 26). In order to explore the possibility of using a shortened test to estimate the final temperature inside an RA, the dry in-mine temperature data were used to determine the percentage of the final temperature increase versus elapsed time for the air inside the RA, the mine air and mine strata surfaces, and the mine ambient air near the RA (refer to Figure 36).

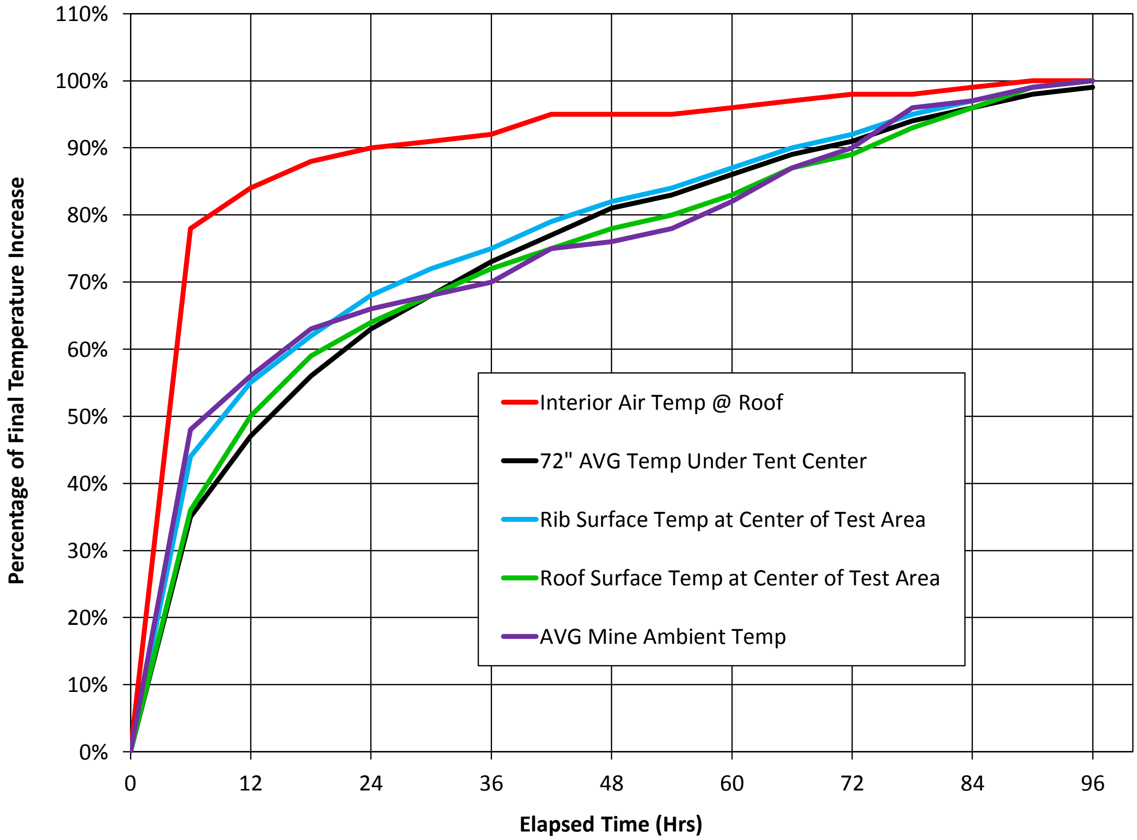


Figure 36. Percentage of final temperature increase versus elapsed time for RA interior air; mine roof, rib, and floor strata surfaces; and mine ambient air.

The data suggest that a shorter test duration could be used to estimate the final air temperature within the RA that occurs at 96 hours. The analysis shows that the air temperature increase in the RA occurs more rapidly than the mine air and mine strata surface temperatures. The air inside the RA reaches 90% of its final temperature increase at about 24 hours while the mine air and strata take about 72 hours to reach 90% of their final temperature increase. If apparent temperature tests were conducted in test facilities designed to mimic the behavior of a mine, it is expected that similar behavior would be observed. Manufacturer testing could be conducted in a much more time-efficient manner if the temperature increase for the air inside the RA at 24 hours could be used to calculate the final air temperature that would occur at 96 hours. Of course, to ensure this trend would hold true for a wide variety of cases, this type of analysis would need to be performed by manufacturers using multiple sets of test data.

Conclusions and Recommendations

The test results show that the mine does not act as an infinite heat sink when subjected to the heat input from an occupied RA. The mine air and strata temperatures increase throughout the tests. Furthermore, the RA temperatures determined through testing in a high bay are several degrees lower than those observed during in-mine tests. The effect of including moisture generation on the resulting RA internal air temperatures is still unknown. Although the temperature increases for the wet tests were about 2°F lower than those of the dry tests, two complicating factors could have contributed to this 2°F difference. First, in spite of waiting ten days between the dry and wet in-mine tests, the mine strata in the test area was still at a slightly elevated temperature when the wet tests were initiated. Next, the moisture generation nozzle of the simulated miners was very close to the underside of the tent, possibly “short circuiting” the heat transfer path from the simulated miners to the mine. Further testing would need to be performed to prove or disprove that including moisture generation has a measurable effect on the air temperatures within an RA. For the wet tests, significant pooling was observed on the RA floor and condensation was observed on all of the other interior RA surfaces.

A test standard for conducting apparent temperature testing should be developed. This standard should specify the test facility design that must be used when conducting such testing. The test facility must adequately simulate a coal mine environment with respect to the thermal properties of a mine. In addition, the means for adjusting the ambient temperature of the test facility should be defined. The test standard should define the exact means of generating heat to simulate that of entrapped miners and should also dictate how to begin the tests. For example, should the heat input devices be wrapped in insulation for a fixed amount of time at the beginning of each test, and should the heat input devices have pre-heaters run during this time? Conducting apparent temperature tests using standardized test facilities and procedures would allow the comparison of results amongst different RA types (e.g. tent and rigid) and manufacturers.

According to the tests results obtained here, derating would be necessary for the tested RA at mine ambient temperatures at and above 60°F. Even though derating values will depend on the specific RA design, it is expected that similar results would be observed for all RAs—that is to say that regardless of the RA design, a mobile RA without air conditioning would have to be derated at some mine ambient temperature. The temperature at which derating is necessary will depend on the specific RA design and application. In addition, when developing these tables, some consideration should be given to the value to be used for the relative humidity if dry tests are used and if the apparent temperature limit is used as the means to assess tolerability of the RA’s ambient environment.

It should be stressed that neither manufacturer nor OMSHR testing has indicated that the interior of an RA intended for use in an underground coal mine will reach 100 %RH, while it is common for relative humidity values of 85 %RH to 95 %RH to be observed in tests that account for moisture generation. In reality, if the actual relative humidity is assumed to reach 85 %RH, 90 %RH, or 95 %RH, the interior air dry-bulb temperature that would cause the 95°F apparent temperature limit to be reached would only vary by about 1°F over this range of relative humidity values. To demonstrate, if the interior air would reach 85 %RH, the apparent temperature limit would be reached at a dry-bulb temperature of 83.7°F; if the interior air would reach 90 %RH, the apparent temperature limit would be reached at a dry-bulb temperature of 83.1°F; if the interior air would reach 95 %RH, the apparent temperature limit would be reached at a dry-bulb temperature of 82.6°F. At this time, OMSHR cannot recommend a specific relative humidity value to use to calculate apparent temperature if tests are conducted dry. Additional data would be required to make such a recommendation.

Testing an RA at multiple ambient temperatures may be unnecessary provided that the temperature rise does not change much when tests are performed at a different initial ambient temperature. The temperature for an object subjected to a heat input is a function of the heat input, the initial temperature, and the heat loss mechanisms involved: conduction, convection, radiation, evaporation, etc. Conduction, convection, and radiation heat loss are driven by a temperature difference. Transient heat conduction is affected by the thermal conductivity, thickness, density, and specific heat of a body; convection is a function of the convection heat transfer coefficient and the exposed surface area of an object; and radiation is affected by the thermal emissivity and surface area of an object. The thermal conductivity, density, specific heat, convection coefficient, and thermal emissivity are a function of temperature. However, across a small range of temperatures, it is doubtful that the parameters affecting each of these heat transfer modes would change enough to make much of an impact on the heat loss. If this is the case, the temperature rise for one initial ambient temperature would be the same as the temperature rise measured for another initial ambient temperature. This could greatly reduce the testing that is needed to certify RAs for mines across a relatively narrow range of ambient temperatures. Prior to using this strategy, manufacturers should perform several tests at a range of ambient temperatures to ensure the temperature rise is constant. Of course, these tests should be conducted in a standardized test facility that mimics the thermal properties of a mine.

Performing tests with heat inputs corresponding to various reduced RA capacities in order to establish a derating table may also be unnecessary. As discussed above, for dry tests the temperature rise for an object is a function of the sensible heat input. If the heat input is doubled, the temperature rise will also be doubled. Because most of the heat input for wet tests is through sensible heat, it is expected that similar behavior would be observed for tests conducted with moisture input. Therefore, it is expected that the temperature increase within the RA will be directly related to the number of miners or simulated miners inside. If this is the case for RAs, once the temperature rise is established for a fully occupied chamber, the temperature rise per miner could be computed. The temperature rise per miner could be used with various initial mine ambient temperatures and an assumed percent relative humidity to determine maximum number of miners an RA could contain before exceeding the 95°F apparent temperature limit. Once again, manufacturers should conduct multiple tests with the heat input corresponding to multiple numbers of miners to prove that the temperature change per miner is constant. As above, these tests should be performed in a test facility that mimics the thermal properties of a mine.

The data appear to indicate that less-than-full-duration tests could be used to estimate the final air temperature inside an RA. For the in-mine tests, the test data indicate that 90% of the temperature rise for the air inside the RA occurred during the first 24 hours of testing. If further manufacturer testing shows that this relationship holds true for a variety of test cases, a 24-hour test could be used to estimate the final air temperature inside an RA instead of conducting 96-hour tests. This would greatly reduce manufacturers' costs to conduct apparent temperature tests.

To date, RA manufacturers have used laboratory testing to determine the apparent temperature that would occur in an occupied RA. Each test for a single set of conditions—RA model, mine ambient temperature, RA occupancy, etc.—can take more than a week to perform. In lieu of using laboratory testing, a validated thermal simulation of an RA in an underground coal mine could be used to determine the resulting apparent temperature for a wide variety of conditions[12]. Such a model could be used by RA manufacturers to evaluate their RAs across a wide range of mine ambient temperatures and for various mine strata compositions. Based on the observation that the mine roof, rib, and floor strata temperatures at a depth of 4 ft did not change significantly during our 96-hour in-mine tests, it is recommended that at least 4 ft of strata should be included in thermal simulation models. In addition, the temperature at a depth of 4 ft can be assumed to be constant. However, the air and strata layers at depths less than 4 ft should be allowed to heat up. Rather than using numerous laboratory tests to determine the derated capacity of an RA, the validated model could be used to develop derating tables. One significant advantage of using a thermal simulation model is that the mine-specific strata composition can be accounted for in the model, while doing so in a test laboratory would be difficult. If standardized test methods and test facilities that mimic a mine are used to perform laboratory tests, laboratory-generated test data could be used to validate such thermal simulation models. Ultimately, the best solution is to use a combination of test data and thermal simulation models to determine RA apparent temperatures as this will reduce costs and test time while providing the best possible apparent temperature estimates.

Another option is that manufacturers could develop their own mathematical model to convert the test results obtained in their existing test facilities to results that would be observed in an actual mine. If this approach is taken, in-mine test data should be used to ensure the developed models adequately convert the laboratory-acquired data to meaningful results that could adequately predict the resulting in-mine apparent temperature. Because each manufacturer's apparent temperature test facility is different, a universal model would not be applicable to all manufacturers' test facilities. It is expected that a specific mathematical model would have to be developed for each test facility. However, if all manufacturers standardized their apparent temperature test facilities, only one validated model would need to be developed. Once a validated model was developed, the model could be used with the in-lab results to predict the resulting apparent temperature for a mine based on the mine-specific strata and temperatures. Furthermore, such a model could be used to determine the derated RA capacity if the predicted apparent temperature would exceed the 95°F limit.

[12] Future efforts to demonstrate the suggested technique for establishing the derated capacity of a production RA are being considered. This work would consist of a series of tests of a production RA in an underground mine along with the development of a thermal simulation model of the production RA as tested in the mine. Once the model would be validated, it would be used to determine the derated capacity of the production RA for a range of mine ambient temperatures.

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APPENDIX

Normalization of Measured Data to Account for Variations in the Heat Input

The temperature rise for each measured channel was computed by

$$\Delta T_{M,i} = T_{fin,i} - T_{0,i} \tag{A1}$$

where $\Delta T_{M,i}$ is the measured temperature rise for the i^{th} channel,

$T_{fin,i}$ is the average temperature of the i^{th} channel during the final six hours of the test, and

$T_{0,i}$ is the initial temperature of the i^{th} channel averaged for the six hours just prior to powering the simulated miners.

The normalized temperature changes for each channel were computed by

$$\Delta T_{N,i} = \Delta T_{M,i} \frac{1670}{\dot{q}_{avg}} \tag{A2}$$

where $\Delta T_{M,i}$ is the temperature rise for the i^{th} channel based on Equation 2,

1670 is the desired input heat in watts, $\dot{q}_{avg}$ is the average heat input for the final six hours of the test, and

$\Delta T_{N,i}$ is the temperature rise for the i^{th} channel normalized to a heat input of 1670 watts.

Example:

For the dry in-mine testing, the interior air temperature measured near the roof of the RA averaged over the final six hours of testing was 81.1°F and the initial temperature averaged over the six hours prior to the beginning of testing was 57.0°F. The average power input for the final six hours of the dry in-mine testing was 1597 watts.

From Equation A1

$$\Delta T_{M,i} = 81.1°\text{F} - 57.0°\text{F} = 24.1°\text{F} .$$

From Equation A2

$$\Delta T_{N,i} = (24.1°\text{F})\left(\frac{1670 \ \ watts}{1597 \ \ watts}\right) = 25.2°\text{F} .$$

Calculation of Mass of Water Added to the Air During the Wet Tests

The relative humidity can be calculated by

$$RH = \frac{p_w}{p_{ws}} \tag{A3}$$

where RH is the relative humidity of the air,

p_w is the partial pressure of water vapor in the air, and

p_{ws} is the saturation pressure of water vapor [Vaisala 2013].

The saturation pressure of water vapor can be calculated by

$$p_{ws} = A \cdot 10^{\left(\frac{mT}{T+T_n}\right)} \tag{A4}$$

where p_{ws} is the saturation pressure of water vapor in hectopascal,

A is a constant equal to 6.116441,

m is a constant equal to 7.591386,

T_n is a constant equal to 240.7263, and

T is the temperature of the air in Kelvin [Vaisala 2013].

Rearranging Equation A3 and substituting Equation A4 for p_{ws} yields the following equation for the partial pressure of water vapor

$$p_w = RH \cdot A \cdot 10^{\left(\frac{mT}{T+T_n}\right)}. \tag{A5}$$

The absolute humidity can be found from

$$h_{abs} = Cp_w / T \tag{A6}$$

where h_{abs} is the absolute humidity in g/m^3,

C is a constant equal to 2.16679 g-K/J,

p_w is the partial pressure of water vapor in Pascal, and

T is the absolute temperature in Kelvin [Vaisala 2013].

At the beginning of the wet tests, the temperature was 14.4°C and the relative humidity was 91%. Using Equation A4, the partial pressure of water vapor, p_w, was found to be 1493 Pascal. Substituting this into Equation A5, the absolute humidity was found to be 11.25 g/m^3. Using the RA volume of 15 m^3, the mass of water in the air at the beginning of the test was found to be 0.17 kg.

At the beginning of the wet tests, the temperature was 25.6°C and the relative humidity was 87%. Using Equation A4, the partial pressure of water vapor, p_w, was found to be 2856 Pascal. Substituting this into Equation A5, the absolute humidity was found to be 20.71 g/m^3. Using the RA volume of 15 m^3, the mass of water in the air at the end of the test was found to be 0.31 kg.

The total volume of water input into the tent by the simulated miners was 40 L or 0.04 m^3. Using a value of 999 kg/m^3 for the density, the mass of water input into the RA was 39.96 kg. The water input from the simulated miners increased the mass of the water vapor in the air increased by 0.14 kg. Assuming that no water vapor leaked from the RA, 39.82 kg or 39.86 L of water condensed on the interior of the RA. This means that nearly all of the water emitted by the simulated miners condensed on the interior surfaces of the RA.

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