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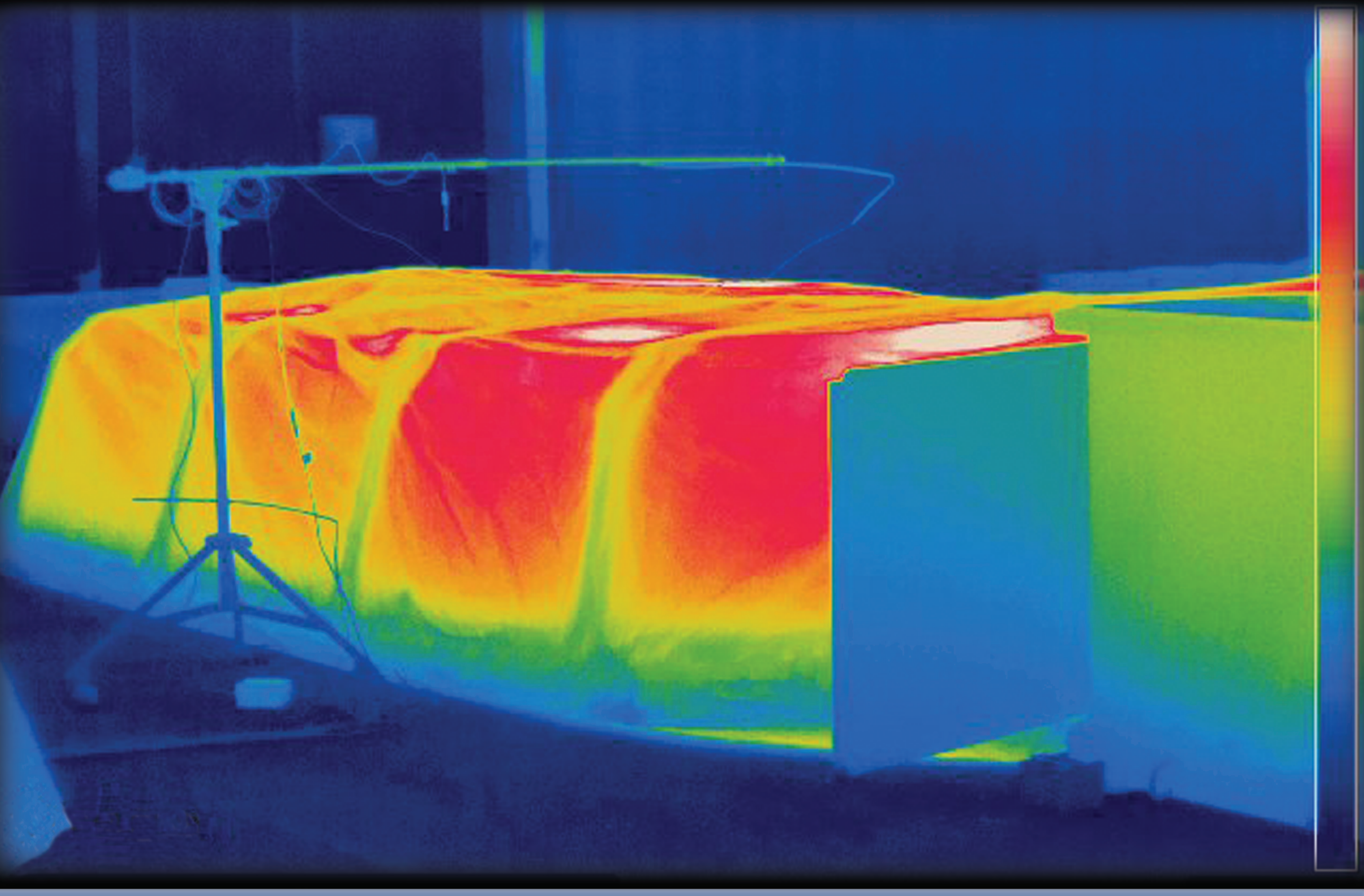
Investigation of Temperature Rise in Mobile Refuge Alternatives



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
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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

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[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.