Published in final edited form as:

Int J Min Sci Technol. 2019 May ; 29(3): 343–355. doi:10.1016/j.ijmst.2019.01.004.

A test method for evaluating the thermal environment of underground coal mine refuge alternatives

D.S. Yantek[*],

L. Yan,

N.W. Damiano,

M.A. Reyes,

J.R. Srednicki

CDC NIOSH, Pittsburgh, PA 15236, USA

Abstract

Since 2009, the Mine Safety and Health Administration (MSHA) has required mines to install refuge alternatives (RAs) in underground coal mines. One of the biggest concerns with occupied RAs is the possible severity of the resulting thermal environment. In 30 CFR 7.504, the maximum allowable apparent temperature (AT) for an occupied RA is specified as 35 °C (95 °F). Manufacturers must conduct heat/humidity tests to demonstrate that their RAs meet the 35 °C (95 °F) AT limit. For these tests, heat input devices are used to input the metabolic heat of actual miners. A wide variety of test methods, sensors, and heat input devices could be used when conducting such tests. Since 2012, the National Institute for Occupational Safety and Health (NIOSH) has conducted over thirty 96-hour heat/humidity tests on four different RAs. This paper discusses the test equipment and procedures used during these investigations. This information is useful for RA manufacturers conducting RA heat/humidity tests, for other researchers investigating RA heat/humidity buildup, and for those who need to assess the thermal environment of any confined space where people may be trapped or are seeking refuge.

Keywords

Refuge chamber; Refuge alternative; Confined space; Thermal environment; Test method; Temperature

1. Introduction

In 2009, the Mine Safety and Health Administration (MSHA) mandated the installation of refuge alternatives (RAs) in underground coal mines [1]. MSHA requires that RAs

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[*] Corresponding author. dyantek@cdc.gov (D.S. Yantek).

provide an environment with breathable air for entrapped miners for a 96-hour period. Heat buildup inside an occupied RA is a serious concern. Without a means to dissipate the heat/humidity generated by the occupants and by the carbon dioxide (CO_2) scrubbing system, the temperature and humidity inside RAs could lead to severe discomfort or heat stress, depending on the mine ambient temperature before and during occupation of the RA.

In its 2006 report, the West Virginia Mine Safety Technology Task Force recommended an apparent temperature (AT) limit of 35 °C (95 °F) for RAs [2]. In 30 CFR 7.504 [3], MSHA has specified a maximum AT of 35 °C (95 °F) inside an occupied RA. The AT is calculated using both air temperature and relative humidity [4]. RA approvals for 30 CFR Part 75 [5] require that testing is performed to determine the maximum RA occupancy as a function of mine ambient temperature.

In order to demonstrate that their mobile RAs meet the AT limit, RA manufacturers have been performing 96-hour-long heat/humidity tests in laboratories. A heat input of 117 W (399 BTU/hr) per person is used during these tests to represent the metabolic heat of a single miner [2]. To account for the heat generated by the RA's CO_2 scrubbing system, 50 W (171 BTU/hr) of heat per miner is used for a lithium hydroxide scrubbing system, or 30 W (102 BTU/hr) of heat per miner is used for a soda lime scrubbing system [6]. In these tests, air velocities around the RA are minimized to represent the worst-case scenario of an interruption in mine ventilation that might occur in a mine disaster. In some cases, these test facilities were designed using air conditioning systems to keep the air within the test facility at a constant temperature during the tests. However, none of the tests performed within such facilities have been benchmarked against tests conducted in an underground mine.

NIOSH has conducted numerous in-mine heat/humidity tests on both portable and built-in-place (BIP) RAs. To date, NIOSH has tested three portable RAs [7]. In 2013, NIOSH tested a 10-person training unit tent-type RA in its Safety Research Coal Mine [8,9]. In 2014, NIOSH tested a 23-person tent-type RA in its Experimental Mine [10,11]. Beginning in 2015 and continuing through 2016, NIOSH also tested a 6-person metal RA in its Experimental Mine [12]. NIOSH has also tested a 60-person BIP RA that was constructed in its Experimental Mine. From 2015 through 2016, NIOSH performed several heat/humidity tests on its BIP RA at full capacity [13,14]. In the same time frame, for the purpose of evaluating a prototype RA cryogenic air supply, NIOSH also completed several tests with its BIP RA partitioned to create a 30-person BIP RA [15]. Note that the occupancy numbers stated above follow the space and volume requirements as specified in 30 CFR 7.505 [16], which requires 1.4 m^2 (15 ft^2) of unencumbered floor space per person and 1.5 m^3 (52.5 ft^3) of volume per person for mine heights greater than 1.22 m (48 in) but less than or equal to 1.37 m (54 in).

While RA heat/humidity test data can be used to learn a great deal about the thermal behavior of an occupied RA, simulation can be used to explore RA thermal behavior beyond the scope of physical measurements. In addition, thermal simulation models could be used to examine the maximum RA occupancy so that the AT limit is satisfied across a broad range of mine ambient temperatures, strata properties, and dimensions. NIOSH RA heat/humidity test data has been used to develop and validate several thermal simulation models

[9,11,17] and a thermal simulation software tool [18]. The RA thermal simulation models have been used to examine a variety of aspects related to RA heat/humidity, including heat loss mechanisms for occupied RAs [19], the effect of mine strata thermal behavior and initial mine temperatures [14], and the effect of seasonal temperatures on RA heat/humidity and occupancy [20]. Thermal simulation models could be used to examine mine-specific occupancy limits as a function of mine composition, mine ambient temperatures, and mine size, provided that the models are benchmarked against test data and the input parameters, such as mine strata thermal properties, adequately represent the mine.

When collecting RA heat/humidity test data, NIOSH followed a consistent test method. This applies to the devices used to provide the representative heat input of actual miners and the heat generated by an RA's CO_2 scrubber system and to the process used to conduct the tests. NIOSH also used similar instrumentation procedures across all tests. This paper provides information on all of the equipment and instrumentation used by NIOSH during RA heat/humidity testing and discusses the test procedures followed during these tests. While specific products may be mentioned, there are numerous vendors of all of the types of equipment discussed here. Any mention of company names should not be construed as an endorsement by NIOSH.

2. Heat input method

In RA heat/humidity testing, heat must be input into the RA to represent the metabolic heat input of actual miners and the heat input by the RA's CO_2 scrubber system. Depending on the specifics of an RA, a CO_2 scrubber system may be unnecessary. For example, if a BIP RA uses a borehole air supply to provide breathable air at 5.9 L/s (12.5 SCFM) per person as specified in 30 CFR 7.506 [21], the CO_2 exhaled by the miners would be diluted so that CO_2 scrubbing would be unnecessary. However, if an RA uses compressed oxygen cylinders to provide oxygen at 0.010 L/s (1.32 ft^3/hr) as specified in 30 CFR 7.506 [21], CO_2 scrubbing would be necessary. In the following section, the devices used by NIOSH to provide the representative metabolic heat of actual miners and the heat due to a CO_2 scrubber are described. In addition, the following section discusses the details on how these heat input devices were controlled during testing, using a combination of programmable variable autotransformers (PVAs) and manual variable autotransformers (MVAs).

2.1. Simulated miners for metabolic heat input

In 2012, NIOSH developed its first generation of simulated miners (SMs) to provide the representative heat input of actual miners (refer to Fig. 1). The design of the NIOSH-developed SMs was based on the idea that a heat input device used to represent actual miners should have a surface area that is approximately 75% of the surface area of the 2.0 m^2 (21.5 ft^2) body surface area for an average person [22]. Additional details on the first-generation SM can be found in NIOSH RI-9695 [8].

In an occupied RA, natural convection from the occupants to the RA air and radiation heat transfer from the occupants to the surroundings are important heat transfer mechanisms. Because convection coefficients depend on temperature, it is important for the SMs to have a surface temperature that is similar to the mean human skin temperature. To ensure that radiation heat transfer from SMs is representative of radiation heat transfer from actual miners, the SMs should also have an emissivity that is similar to the emissivity of human skin, which has a value of 0.98 [23,24]. If the SMs approximate the surface area of a person that is in contact with the ground, the heat lost to the ground via conduction, the surface area of a person that is exposed to the air, and the emissivity of human skin, the surface temperature of the SMs will likely be similar to human skin temperature, which varies from about 31.7–35 °C (89–95 °F) across an ambient temperature range from 23.9–32.2 °C (75–90 °F) [25].

To construct the SMs, NIOSH used commonly available 114-liter (30-gallon) steel drums that have a surface area of roughly 1.35 m^2 (14.5 ft^2), which is 68% of the surface area of an average person. With a slightly lower than recommended surface area, the surface temperatures of the SMs are slightly higher than they would have been if the recommended surface area was used.

The NIOSH heat/humidity tests have used SMs to provide the 117 W (399 BTU/hr) of representative metabolic heat input of actual miners. The SM design uses two heaters that are affixed to a water-filled core. One of these heaters is used only to preheat the SM, while the other heater is used throughout the entire test. Because the SMs use several components that are designed to operate on a standard 120-V circuit, the SMs must be operated at voltages from about 110–130 V. Across this voltage range, the SMs can provide 101–141 W (345–481 BTU/hr) of heat, if a heat input other than the “standard” 117 W (399 BTU/hr) is desired.

The SM can be used to conduct testing with purely sensible (dry) heat input or with a combination of sensible and latent (moist) heat. The SM design generates moisture using a small air pump to force air through a gap atop its water-filled core. The moisture generated by the SMs is a function of the ambient temperature and relative humidity (RH) and is not readily adjustable. Depending on the temperature and RH of the ambient environment, the SMs generate roughly 1 L to 2 L per SM per day. The moisture output increases with increasing ambient temperature.

A recent study determined the appropriate representative metabolic heat for miners entrapped in an RA [26]. The study found that the activities within an RA are insignificant and the resting metabolic rate (RMR) determines the heat input of a person entrapped in an RA. A convenience sample of miners was used to determine the appropriate height, weight, and age to represent the population of miners. The appropriate representative heat input for RA testing and analysis was determined using miner size to calculate the RMR based on standard RMR equations with consideration given to statistical variation in miner size within an RA. The study found that the previously used 117 W (399 BTU/hr) is a reasonable estimate. However, the study recommended that the heat input used should be based on the number of miners assumed to be inside an RA as shown in Table 1.

2.2. CO_2 scrubber heat input

Except for the test of the 10-person tent-type RA, NIOSH used heated water tanks to provide the heat input to represent the heat input of an RA CO_2 scrubber system for tests that required simulation of CO_2 scrubbing systems. When tests were performed on the 10-person tent-type RA, NIOSH used a heated water tank and a spare SM core to provide the CO_2 scrubber heat input. For convenience, the CO_2 scrubber heat was input by heating the water tanks. The SMs must have a source of water, and this water must be contained within the RA throughout the test. If water would be pumped in from outside the RA, the water would absorb heat from the RA, assuming that the RA air temperature is higher than the water temperature. It is necessary to have water tanks within the RA to replenish the water used for moisture generation. Some RAs use soda lime curtains distributed throughout the RA. Therefore, it was decided that using uniformly spaced, heated water tanks within the RA would be a reasonable representation of the heat input generated by an RA's CO_2 scrubber system. Note that when NIOSH tested a 10-person tent-type RA, to represent the CO_2 scrubber system heat input, one heated water tank was located in the RA's metal box and the aforementioned SM core was located within the tent. For all other tests involving the addition of CO_2 scrubber heat, multiple, uniformly positioned, heated water tanks were used.

Rather than developing another complicated device to generate the representative heat of a CO_2 scrubber system, NIOSH simply added a flanged immersion-type electrical resistance heater to each water tank (refer to Fig. 2). Each immersion-type heater was installed by drilling a hole in either the water tank lid or the water tank top surface and then simply inserting the heater. The flange around the top of each heater provides the support, and no additional attachment is necessary. The heating element of the heaters is 76.2 mm (3 in) long and is located at the end of the heater that is in the water. The remaining length of the heater is not heated.

Depending on the needs of a specific test, NIOSH has generally connected 5 or 6 SMs to each water tank. The water tanks were sized so that more than enough water would be available than is necessary for a 4-day-long test. Assuming that each SM would generate at most 2 L per day over a 4-day-long test and that 6 SMs are connected to a water tank, each tank would need about 50 L (13 gallons) of water for a single test. However, the tanks were oversized so that 0.1–0.15 m (4–6 in) of water would remain in the bottom of the tank at the end of the test to keep the tip of the immersion-style heater covered with water. This was done to prevent failure of the heater due to overheating. Tanks with volumes from about 75 L to 95 L (20 gallons to 25 gallons) were used for the tests. In addition, the shape of the tanks used varied from tanks shaped like a cube to tall rectangular tanks with small footprints. It should be noted that for tests with the original SMs, the water level within the water tanks had to be kept below the height of the water-filled core within the SMs to prevent overfilling and leakage of water from the SMs via the SM's moisture generation tube.

The electrical specifications of the immersion-style heater were based on the assumption that one heated water tank would provide water to 6 SMs and the equivalent CO_2 scrubber heat for 6 actual miners. For design purposes, a CO_2 scrubber heat input of 30 W (102 BTU/hr) per person was assumed [6]. Therefore, the immersion-style heater would have to provide 180 W (614 BTU/hr) of heat to the water tanks. Recall that the original SMs require roughly 120 V to operate. Immersion-style heaters rated at 180 W (614 BTU/hr) of heat input at 120 V could have been used to provide the equivalent CO_2 scrubber heat of 6 real miners. However, this would have resulted in less flexibility during testing as 120 V would be necessary to generate the required heat input. Instead, NIOSH used heaters rated at 250 W (853 BTU/hr) at 120 V with a nominal resistance of 57.6 Ω. With these heaters, a voltage of only 102 V is necessary to provide the required 180 W (614 BTU/hr) of CO_2 scrubber heat for 6 people.

If a situation would occur that would cause the water level within a tank to be low enough to reach the heated tip of the immersion-type heater, the heater would be in danger of overheating. As a safeguard, NIOSH uses immersion-type heaters that were manufactured with Type J thermocouples located just above the heating elements within the bodies of the heaters. During testing, the temperature at this location is monitored. When the water level covers the heating element, the temperature at the thermocouple location is usually about 66 °C (150 °F). However, the temperature rapidly increases to 93 °C (200 °F) or more if the water level reaches the height of the heating element.

2.3. Arrangement of simulated miners and heated water tanks

For all NIOSH testing, the SMs were arranged as uniformly as possible within the area of the RA that is intended to be occupied because it is assumed that actual miners would spread out within an RA. For some tests of tent-type RAs, deviation from uniform spacing was necessary to accommodate test equipment, the heated water tanks, and other equipment, and to prevent the tops of the SMs from touching the air-filled support tubes of the RA’s tent. With the exception of the heat/humidity tests NIOSH performed on the 10-person tent-type RA, NIOSH has also arranged the heated water tanks in a uniform fashion. For the 10-person tent-type RA, as previously mentioned, the heated water tank was positioned within the metal box. For the 10- and 23-person tent-type RAs, the SMs were arranged in two columns separated by about 0.9–1.5 m (3–5 ft) to allow researchers to move within the RA to position sensors, connect water lines, run electrical power, and perform other setup tasks. For the tests on the metal 6-person RA, the space between the SMs had to be decreased to 0.3–0.6 m (1–2 ft) due to the support structure within the RA. For the BIP RA tests, the SMs were spaced in a grid with about 0.6–0.9 m (2–3 ft) between them. Fig. 3 shows the arrangement of the heat input devices for each NIOSH RA test.

3. Electrical power for simulated miners and heated water tanks

3.1. Programmable variable autotransformers and manual variable autotransformers

The NIOSH tests performed on the 10-person tent-type RA in 2012 were performed with the SMs and heated water tanks plugged directly into the electrical outlets within the NIOSH Safety Research Coal Mine. It was initially assumed that the line voltage and resulting heat input would be steady enough that the test results would not be affected. Note that these tests were performed assuming a CO_2 scrubber heat input of 50 W (171 BTU/hr) per person for lithium hydroxide CO_2 scrubbing. Therefore, the nominal heat input for the test was 1670 W (5700 BTU/hr) based on 167 W (570 BTU/hr) per person, which includes a metabolic heat input of 117 W (399 BTU/hr) per person and a CO_2 scrubber heat input of

50 W (171 BTU/hr) per person. However, during the tests, line voltage fluctuations caused higher-than-expected variations in the heat input (refer to Fig. 4).

The measured input power roughly followed a sinusoidal pattern with a period of about 24 h. Each day, the heat input reached a minimum between 1:30 PM and 5:30 PM and a maximum between 1:30 AM and 5:30 AM. As a result, the temperatures measured during the test also exhibited a sinusoidal behavior superimposed on an exponentially increasing curve. The sinusoidal variation of the input power thus made data analysis very challenging. In addition, because the average line voltage was less than 120 V, the average heat input across the 96-hour test was 1590 W (5430 BTU/hr), 80 W (273 BTU/hr) below the target heat input of 1670 W (5700 BTU/hr). If the heat input did not exhibit the sinusoidal nature, the measured temperature change could have been scaled to make up for the low input heat. However, this was not easily done because of the sinusoidal input power fluctuations.

Prior to conducting further in-house RA heat/humidity testing, NIOSH talked with several RA manufacturers about their RA heat/humidity test facilities and procedures. When discussing the sinusoidally varying heat input observed during NIOSH testing with A.L. Lee Corporation, NIOSH was made aware of commercially available programmable variable autotransformers (PVAs) that can be used to maintain a steady output power instead of maintaining a constant output voltage, as is the norm for PVAs.

For all the RA heat/humidity tests that NIOSH completed after the tests conducted on the 10-person tent-type RA, NIOSH used Staco MV15M6020E-F8059 PVAs to control the heat input (refer to Fig. 5). To maintain constant power output, these units use custom-programmed closed-loop control. Each PVA has a keypad on the front which allows the desired electrical power (heat input) setpoint to be entered. The PVAs use an internal watt transducer to measure their output power, which is a function of the load and the line voltage—a change to either would cause the power to change. As the line voltage (or load) fluctuates, the controller examines the power output measured by the internal watt transducer. If the measured wattage is outside of the wattage setpoint plus a tolerance band, the control board sends a signal to adjust the windings of the PVA using a stepper motor. NIOSH has set the tolerance band to ±100 W (±341 BTU/hr) to avoid excessive adjustment of the PVA windings and possible wear of the internal components.

During tests, the PVAs provide power to both the SMs and the heated water tanks. Typically, from 6 to 10 SMs and 1 or 2 heated water tanks are connected to a single PVA. The PVAs are powered from a 480-V, three-phase, high-voltage mine power center that is connected to an Ericson Mobile Temporary Power Distribution Center (MTPDC). The Ericson MTPDC then steps down from 480 V to 240 V using a single-phase transformer. The 240-V legs from the MTPDC feed power to the Ericson Temporary Power Distribution Centers (TPDC), which split the 240-V circuit into 120-V circuits (see Fig. 6). The PVAs are then powered from the 120-V output of the TPDCs.

The SMs are connected to the PVAs through dedicated multiple-outlet power cables or by plugging 10- or 12-gauge extension cords into receptacles on the front of the PVAs and then connecting multiple-outlet extension cords to the 10- or 12-gauge extension cords inside the

RA. The heated water tanks are connected to manual variable autotransformers (MVAs) that are plugged into receptacles on the PVAs. The MVAs are used as step-down transformers to reduce the voltage outputs of the PVAs to power the heated water tanks. For each PVA, one watt transducer is used to measure the total power delivered to the SMs and heated water tanks, and a separate watt transducer is used to measure the power delivered to only the heated water tanks via the MVA.

Each PVA is typically set to deliver the total heat input that corresponds to the number of SMs connected to it. The target heat input includes both the metabolic heat input of 117 W (399 BTU/hr) per SM and the CO_2 scrubber heat input of 27.5 W (93.8 BTU/hr) per SM. (Note that this assumes that soda lime is used for the CO_2 scrubber.) As an example, if 6 SMs are connected to a PVA, the PVA is set to deliver a total of 867 W (2960 BTU/hr). Once the PVA setpoint is entered, the MVA, which controls the power to the heated water tanks, is slowly adjusted while monitoring the water tank watt transducer output until the desired water tank heat input is met. As the MVA is adjusted, the controller and stepper motor of the PVA adjust the total power delivered to maintain the setpoint value.

As a result of implementing the PVAs, the input power for each test no longer resembles a sine wave with a 24-hr period. Fig. 7 shows the heat input (electrical power) for tests on a 23-person tent-type RA that were performed using a PVA. The target heat input for these tests was 3323.5 W (11,340 BTU/hr). Note that these tests were conducted assuming a soda lime CO_2 scrubbing system with 27.5 W (93.8 BTU/hr) of heat input per person. The heat input exhibits frequent variations that result from the PVA adjusting to keep the output power within the tolerance limits. However, because thermal systems, such as an occupied RA in a mine, respond relatively slowly, the rapid fluctuations in heat input do not affect the logarithmic nature of the temperature curve.

The PVAs have a limit to the power they can provide. Each PVA can deliver a total current of 30 A split equally into two 15-A circuits. For the original SMs, a single SM requires about 1 A of current at 120 V. The rated power output of the water tank heaters is 250 W (853 BTU/hr) at 120 V, which would require a current of 2.1 A. Therefore, if the water tank heaters are operated at their rated power, each water tank heater can provide the representative CO_2 scrubber system heat for 9 SMs. This value is calculated by dividing 250 W (853 BTU/hr) by 27.5 W (93.8 BTU/hr) per SM and rounding down. Thus, the total current to provide both the representative metabolic heat and CO_2 scrubber heat for 9 SMs would be 11.1 A (1 A per SM plus 2.1 A for the water tank heater). Therefore, if both 15-A PVA circuits are used, a single PVA could be used to provide the total heat input of 18 SMs. It should be noted that these numbers are specific to the original SM design and water tank heaters rated at 250 W (853 BTU/hr).

3.2. Electrical cables

When setting up the power (heat input) for RA heat/humidity tests, another factor that must be considered is the gauge and length of the electrical cables used to power the SMs [27]. All power cords, extension cords, multi-tap adapters, etc. used in the test setup must be able to handle the required current. In addition, the voltage drop associated with the power/extension cords should be considered. Each power cord will cause a voltage drop depending on the length of the cord, the wire gauge, and the current passing through the cord [28]. This voltage drop is associated with heating of the extension cord, and for the length of the cord outside the RA, this voltage drop does not contribute to the RA heat input.

To minimize the voltage loss associated with SM power cables that are external to the RA, larger gauge, shorter power/extension cords are recommended. Consider the scenario outlined above with 9 SMs connected to one of the 15-A circuits of a PVA via one 15.2-m-long (50-foot-long) extension cord that is external to the RA. For this extension cord, the current is 9 A. For a length of 15.2 m (50 ft), at least a 16-gauge power cord is necessary to carry a current of 9 A [27]. However, using a larger gauge cord is advisable due to the voltage drop associated with smaller gauge cords. Table 2 shows the voltage drop and power reduction at the SMs, assuming 9 A of current for 15.2-m-long (50-ft-long), 16-gauge to 8-gauge power cords. As the data show, larger gauge cords result in less reduction in the power delivered to the SMs. NIOSH has used 10-gauge and 12-gauge power cords to connect SMs to the PVAs as this was determined to be a reasonable compromise when considering cost, availability, and power reduction.

4. Instrumentation

Numerous engineering parameters were measured during NIOSH RA heat/humidity testing. Most sensors were connected to a data acquisition system, which is discussed below. In some cases, data loggers with built-in sensors were used. The information below discusses the parameters measured, the sensors or data loggers used, and considerations for measuring these parameters. Although information on the specific test equipment that NIOSH used is provided, there are numerous devices available that could be used to perform the measurements.

The electrical power for the SMs and heated water tanks was measured to ensure the heat input was correct. The water tank levels were measured to determine the moisture input rate. The temperature and RH were measured within the RA and outside the RA when a test involved a portable RA. For portable RAs, the RA surface temperatures were measured in several locations. For some tests, moisture sensors were used to determine if condensation was present on the interior surfaces of the RA. Air velocity within the RA was also measured. The mine strata surface temperatures and mine strata temperatures at depths up to 1.2 m (4 ft) were also measured.

4.1. Data acquisition system

Several factors are important when considering the data acquisition system to be used for heat/humidity testing. First, the data acquisition system must be able to handle the types of sensors that will be used for testing. In addition, the accuracy and resolution of the data acquisition system must be considered. Simply stated, accuracy is how closely a measurement is to the real value, and resolution refers to the smallest change in a parameter that can be detected. Finally, the sampling rate must be appropriate for the sensors and type of system to be tested, which is a thermal system in this case. The sample rate refers to the number of samples collected per unit of time.

RA heat/humidity testing can involve a wide variety of sensors. Sensors such as thermocouples and resistance temperature detectors (RTDs) are often used to measure temperatures. Both thermocouples and RTDs require special signal conditioning. Other sensors may require an excitation voltage. Most sensors that use an excitation voltage generate an output signal within a range of ±10 V. The data acquisition must be able to handle the voltage generated by the sensors used for testing.

Data acquisition systems should have a voltage accuracy of less than 0.1% of the full-scale range. In most cases, the data acquisition systems of today will have better accuracy than this, and the sensors will determine the measurement accuracy. For thermocouple and RTD channels, the accuracy should be ±0.1 °C (±0.2 °F) or better. In most cases, the thermocouple itself will have far worse accuracy than the data acquisition system. RTDs are typically far more accurate than thermocouples, and RTDs can have an accuracy on the order of ±0.1 °C (±0.2 °F), depending on the class of RTD used.

Today, data acquisition systems with 16- and 24-bit resolution are commonplace, and either are sufficient for thermal testing. A 16-bit input will divide its range (span) into 65,536 steps (2^{16}), while a 24-bit input will divide its range into 16,777,216 steps (2^{24}). As an example, a 16-bit voltage input with a range of ±10 V (span of 20 V) will have a maximum resolution of 0.305 mV (20 V divided by 65,536). To assess this accuracy in terms of engineering measurements, consider a temperature sensor with a 0–10-V output from 0–100 °C (32–212 °F). This sensor would have a sensitivity of 10 °C/V (18 °F/V), or 0.01 °C/mV (0.018 °F/mV). In this case, the measurement would have a resolution of 0.0031 °C (0.0055 °F). Of course, in most cases, the accuracy limits of the sensor and data acquisition system will prevent this resolution from being achieved. In summary, the 16- and 24-bit resolution data acquisition systems available today have more than enough resolution to yield accurate measurements.

When choosing a data acquisition system or data logger, the response speed of the system to be measured must be considered. Sample rates are measured in units of samples/sec or Hz. Communications systems may require sample rates of 10 GHz; electrical systems may require sample rates of several MHz; acoustic systems may require sample rates of up to 100 kHz; mechanical systems may require sample rates of up to 10 kHz. However, because the thermal responses of confined spaces, such as RAs, are relatively slow, a sample rate of 10 Hz is more than adequate in most cases. In fact, during RA heat/humidity testing, NIOSH has used a sample rate of 1 sample per 100 s to acquire data. Typically, this has been digitally decimated to 1 sample per 5 min or 1 sample per 15 min when post-processing the data. Because the data change so slowly, the sample rate can be very low.

Because NIOSH measured a wide variety of parameters during RA heat/humidity testing, a data acquisition system that could be used with a wide variety of sensors was needed. Some data acquisition systems can only be used with one type of sensor input. For example, some data acquisition systems have only voltage inputs, thermocouple inputs, or resistance temperature detector (RTD) inputs. Due to the need to accommodate voltage, thermocouple, and RTD signals, NIOSH used multiple Data Translation DT9874 data acquisition systems connected to a single computer [29].

The DT9874 is factory-configured per customer specifications with voltage, thermocouple, and RTD inputs. A single DT9874 chassis can be configured with up to 48 channels, using six boards with 8 channels each. As an example, a DT9874 can be configured to have a single 8-channel thermocouple board, three 8-channel RTD boards, and two 8-channel voltage input boards for a total of 8 thermocouple channels, 24 RTD channels, and 16 voltage input channels. Multiple DT9874 chassis can be connected to one PC, and all channels will be acquired simultaneously. For BIP RA heat/humidity testing, NIOSH used one DT9874 with 48 voltage channels, one DT9874 with 48 RTD channels, and one DT9874 with 16 thermocouple channels, 16 RTD channels, and 16 voltage channels. This setup had a total capacity of 108 channels, though not all were used.

4.2. Watt transducers

In order to measure the heat input for the SMs and heated water tanks, two watt transducers were used per programmable variable autotransformer (PVA). One watt transducer was integrated with the PVA to measure its total power. The other watt transducer was set up to measure the power delivered to the heated water tanks via the manual variable autotransformer (MVA). The watt transducers are powered directly from the voltage delivered to the SMs and water tank heaters, so no external power supply is required. Each watt transducer provides a voltage output that is directly proportional to the measured wattage

During testing, the desired total heat input (SMs and heated water tanks) is entered into the PVA controller. Then, the MVA is adjusted until the wattage delivered to the heated water tanks matches the desired value. The PVA controller adjusts its output to maintain the desired total power output (heat input to the RA).

4.3. Water tank level sensors

In order to determine the moisture input during testing, the water tank level must be measured. In early testing, NIOSH simply checked the initial and final water tank level by visual inspection and calculated the total water consumption during the entire 4-day test. Although this may be adequate, measuring the moisture input in real time allows the moisture input to be used to determine if the moisture generation circuit of the SMs is working properly. In addition, the SM moisture generation rate is not fixed or controllable. The moisture generated by the SMs increases at the beginning of the test before leveling off for the last day or so. To accurately simulate the RA test results using a computer model, the time-varying moisture input throughout the tests must be known.

After the initial testing where only visual inspection was used to determine moisture input, NIOSH attempted to use ultrasonic level sensors to measure the water tank levels. At first, the ultrasonic level sensors seemed to work well. However, during the tests, the readings from the ultrasonic level sensors were erratic and could not be used for their intended purpose. The readings before and after a test appeared to be accurate, but during a test the indicated level would increase and decrease without the expected downward trend. Because the water tanks are heated, water vapor tends to accumulate above the water level within the tanks. The erratic behavior of the ultrasonic sensor readings during the tests is thought to be caused by reflections off the water vapor.

After investigating other ways to measure water tank level, NIOSH decided to use a pressure transducer installed in a port at the bottom of the water tank. The pressure due to the height of a fluid can be calculated by multiplying the density of the fluid, the gravitational constant, and the height of the fluid. For a volume of water with a height of 0.6 m (24 in), the pressure would be 6.0 kPa (0.87 psi), so a pressure sensor with a maximum pressure of 6.9 kPa (1 psi) was selected. The selected transducer has a 0–5-V output and requires a 9–30-V DC power supply. The pressure transducers were installed at the bottom of the water tank and then calibrated in terms of tank volume. To calibrate the pressure transducer in terms of liters per volt, the tank was filled with water, using a graduated cylinder, and the output voltage was recorded at several tank volumes. The slope of the line in terms of liters per volt and the offset voltage were entered into the data acquisition system setup so that the volume of water per tank could be measured in real time. The pressure sensors have proven to be a reliable way to measure the water level, and the accuracy is sufficient for our purposes.

4.4. RA air temperature and RH

Perhaps the most important parameters to measure during RA heat/humidity testing are the air temperature and RH inside the RA. NIOSH has used air temperature/RH (T/RH) transducers connected to the data acquisition system, as well as stand-alone T/RH data loggers. In addition, NIOSH has also used various types of RTDs connected to the data acquisition system to measure air temperature. Care should be taken to position the temperature and RH sensors so that they are more than a few centimeters away from the heat input devices. In addition, preventative steps, such as installing a rain cap, should be taken to prevent moisture from dripping directly on RH sensors, and the sensors should not be placed near the outlet of the moisture generation circuit of the SMs.

Because the AT is a complex function of both air temperature and RH, the impact of the accuracy of both the temperature and RH measurements must be considered when selecting T/RH sensors. Air temperature sensors can be found with accuracies of ±0.3 °C to ±1.1 °C (±0.5 °F to ±2 °F) across the temperature range of roughly 15–35 °C (59–95 °F), which is expected in RA heat/humidity testing. RH can be difficult to measure accurately at the high RH values that may occur during RA heat/humidity testing. In NIOSH testing, the RH in the tested RAs has often exceeded 90% RH. Care must be taken to scrutinize the RH measurement range and accuracy specifications of RH sensors. Some RH sensors are only usable up to 80% RH. Others are usable above 90% RH, but become inaccurate as the RH exceeds 90% RH. Some RH sensors have an accuracy of ±2% RH to ±3% RH for lower RH values, but their accuracy may be as poor as ±5% RH for higher RH values.

In order to examine the impact of temperature sensor accuracy on the calculated AT, a few temperature measurements of 27.8 °C (82.0 °F) using sensors with a range of accuracies from ±0.11 °C to ±1.1 °C (±0.2 °F to ±2.0 °F) were considered with a perfectly measured 90% RH (see Table 3). To examine the effect of RH sensor accuracy on the calculated AT, a few RH measurements of 90% RH, using sensors with a range of accuracies from ±1.0% RH to ±5% RH were evaluated (Table 4). As expected, the data in the tables show that inaccuracies in both the temperature and RH measurements adversely affect the calculated AT. Inaccurate temperature measurements appear to have more of an adverse effect than inaccurate RH measurements.

The types of temperature sensors that could be used include thermocouples, RTDs, and thermistors. The most accurate type of thermocouple—a Type T thermocouple made from special limits of error wire—has an accuracy of ±0.5 °C (±0.9 °F), while the more common Type J and Type K thermocouples have an accuracy of ±1.1 °C (±2.0 °F), even when made from special limits of error wire [30]. A variety of RTD designs are available. One of the most common RTDs is a platinum sensing element RTD. The accuracy of RTDs is determined by the “class” of RTD. Class A and Class B RTDs are readily available. At a temperature of 25 °C (77 °F), a Class A RTD has an accuracy of ±0.2 °C (±0.36 °F), while a Class B RTD has an accuracy of ±0.43 °C (0.77 °F) [31]. Thermistors are available that have accuracies of ±0.1 °C (±0.18 °F) or ±0.2 °C (±0.36 °F) [32].

Because errors in temperature measurement have a large effect on the calculated AT, thermistors and Class A RTDs are recommended for measuring the RA internal air temperature during RA heat/humidity tests due to their superior accuracy. T/RH sensors are available that use thermistors for measuring temperature. Many instruments are available that can provide the necessary signal conditioning for RTDs.

As an alternative to using RTDs and thermistor-based T/RH transducers connected to a data acquisition system, T/RH data loggers are available that can measure and store data on internal memory for subsequent download via a USB connection or that can transmit data to a computer via Wi-Fi or Bluetooth. Many of these devices have temperature accuracies that are comparable to that of Class A RTDs and thermistors. In addition, T/RH data loggers that have RH accuracies of ±2% to ±3% RH are available. If T/RH data loggers are used, care should be taken to select ones that are suitable for the high humidity (~ 90 %RH) environment encountered during RA heat/humidity testing.

NIOSH has used Class A RTDs, thermistor-based T/RH sensors, and stand-alone data loggers to measure the internal RA temperature and RH during heat/humidity testing. For each test, the length of the RA interior has been split into two or three equal-length sections. For most tests, one T/RH transducer with a temperature accuracy of ±0.11 °C (±0.2 °F) and RH accuracy of ±1.7 %RH has been used at the center of the RA at midheight, and a T/RH transducer with a temperature accuracy of ±0.22 °C (±0.4 °F) and an RH accuracy ±2.5% RH has been used at the center of the other sections at midheight. In addition, 2 to 4 additional RTDs or T/RH data loggers have been used to measure the temperature and/or RH within each section. These sensors have been positioned either 0.30 m (12 in) from the RA floor, 0.30 m (12 in) from the RA roof, or at midheight. In some cases, these sensors were positioned along the RA midline, while in other cases they were positioned to the left and right side of each section. Generally, the measurements at the center of each section have been the focus of the data analysis with respect to calculating the AT because of the high accuracy of the sensors used at these locations.

The effect of the T/RH sensors' accuracy on the calculated AT was examined (refer to Table 5). The effect of the accuracy of both T/RH sensors used in NIOSH tests on the calculated AT was examined, assuming an actual temperature of 27.8 °C (82.0 °F) and an actual RH of 90 %RH, which would yield a calculated AT of 33.5 °C (92.3 °F). Of course, the sensor with better temperature and RH accuracies yields calculated AT values that are closer to the "true" value. However, the cost of a sensor relative to its benefit on measurement accuracy must be considered. The more accurate T/RH sensor costs over $1,000, while the less accurate T/RH sensor costs less than $400.

The temperature and RH variability inside the tested RAs has been relatively low. When comparing temperatures at different heights within the RAs, the temperatures measured near the floor were the lowest, and the temperatures measured near the roof were the highest. This is expected because warm air rises. In addition, for tent-type RAs, the RH in the tent section closest to the metal box was lower than the RH in the other sections in the tent. This is because the metal box tends to act as a large condenser. During heat/humidity tests on a 23-person tent-type RA, water condensed within the metal box almost immediately after beginning the test. Because there were no heat sources in the metal box, the surface of the metal box remained relatively cool as compared to the surface of the tent, and moisture built up on the interior of the metal box.

As an example of RA temperature and RH variation, the temperature and RH measurements for a 23-person tent-type RA heat/humidity test are shown in Table 6. The data show that the range of temperatures for the measurements near the floor, at midheight, and near the roof varied by 0.3 °C (0.5 °F), 0.4 °C (0.7 °F), and 0.9 °C (1.7 °F), respectively. For RA tests with uniform heat input, the temperature and RH do not vary much from location to location. Therefore, the temperature and RH only need to be measured at a few locations.

For the example test data, the temperature variation is relatively low because the heat sources within the RA were evenly distributed. If the heat sources were not evenly distributed, or if a cooling source with a localized cooling effect was used, the temperature and RH would probably vary much more than the values reported here. In these cases additional T/RH measurements are warranted.

4.5. RA surface temperature and mine strata temperature

During RA heat/humidity testing, NIOSH measured surface temperatures on the RA, and surface temperatures and temperature with depth for the mine roof, rib, and floor. The main use of this data was for benchmarking thermal simulation models. Thus, accuracy was less important for these measurements. However, because the data acquisition system used could accommodate RTDs, Class A RTDs were used for convenience and accuracy. Type T thermocouples made from special limits of error wire would have been accurate enough for measuring RA surface and mine strata temperatures.

Ribbon-type, silicone-encapsulated Class A RTDs were bonded to the RA to measure surface temperatures. Rods instrumented with multiple Class A RTDs were used to measure the strata temperature with depth (Fig. 8). Flat spots were machined into the sides of the rods at the desired measurement locations, and channels were machined along the lengths of the rods to run wires from the RTDs to the tops of the rods. Class A RTDs were affixed along the lengths of PVC rods, and the wires connected to each were installed in the machined slots. Potting compound was used to protect both the RTDs and the wires. A hole slightly larger than the rod was drilled into the strata, and the RTD-instrumented rod was inserted into the drilled hole. Typically, the strata temperatures were measured at the surface and at depths up to 1.2 m (48 in). PVC rods were used to attach the RTDs because the thermal conductivity of PVC is similar to that of mine strata materials. This is desirable to prevent temperature measurement errors due to heat being conducted along the length of the rod. If a highly conductive material—such as aluminum, copper, or steel—is used, heat conducted from the surface along the length of the rod could cause significant strata temperature measurement errors.

4.6. Air velocity inside an RA

NIOSH measured air velocity inside the RA and in the mine air during RA heat/humidity testing. Because there is no significant air movement in the RA, and the ventilation fans in the test mine were turned off during testing, the air velocity inside the RA and in the mine air were expected to be very low—on the order of 0.05 m/s (10 ft/min)—because air movement is primarily due to convection currents that arise from temperature differences. The only sensors NIOSH found that could be used to measure this low air velocity were omnidirectional airflow sensors from Kanomax and TSI Alnor. Other suitable products may be available. These omnidirectional airflow sensors use a heated sphere to determine the airflow. Due to their construction, these airflow sensors are delicate and must be handled with caution. The air velocity was primarily used for determination of the heat convection coefficients in thermal simulation models.

4.7. Wet-bulb globe temperature

Because wet-bulb globe temperature (WBGT) is often used to assess heat stress [33], NIOSH measured the WBGT during RA heat/humidity tests. Because commercially available WBGT sensors are expensive and not widely available, NIOSH constructed its own WBGT measurement device (refer to Fig. 9). The WBGT measurement device consists of a black globe temperature sensor, a natural wet-bulb thermometer, and a dry-bulb thermometer [33,34]. The black globe temperature sensor was constructed by installing a compression-fitting-mounted, tube-encapsulated Class A RTD inside a matte-black-painted, 152-mm-diameter (6-in-diameter) copper toilet float. The natural wet-bulb temperature sensor was constructed using a distilled-water-filled glass jar and a tube-encapsulated Class A RTD with a cotton wick covering the RTD and dipping into the water. Another tube-encapsulated RTD was used as the dry-bulb temperature sensor. During data collection, the RTDs for the WBGT device were connected to the data acquisition system for later calculation of the WBGT. Although the MSHA regulation is based on AT rather than WBGT, some may want to measure WBGT for comparison with heat stress standards.

5. Test procedures

5.1. Preheat procedure

Because the SMs are at mine temperature at the beginning of a test and they have significant thermal mass, as long as an entire day would be required for the SMs to warm up to steady-state, or operating, temperature. Recall that, at steady state, all of the heat input to an object is lost to the environment. Prior to reaching steady state, a portion of the heat input goes to raising the temperature of the object and the remainder is lost to the environment. During the time required for the SMs to reach a steady-state temperature, part of the heat delivered to the SMs would heat the SMs, and the remainder would be lost to the RA and surroundings.

Decreasing the time for the SMs to reach steady state is desirable because the time required for the SMs to reach operating temperature adds to the test time. In addition, because only a portion of the heat delivered to the SMs during this time is lost to the RA, the 96-hour test cannot really be considered to start until the SMs reach operating temperature. Furthermore, some heat is lost to the RA and surroundings before the SMs reach operating temperature. So, the surroundings and RA temperature are increasing during this period. If the 96-hour test is considered to be started at the end of the time required for the SMs to reach operating temperature, the final temperatures at the end of the test will be higher than would be observed if the SMs could be brought to operating temperature in a very short time.

For all RA heat/humidity tests performed with the original SMs, NIOSH has followed the same preheat procedure to shorten the time required for the SMs to reach operating temperature from nearly one day to four hours or less. To reduce the preheat time, NIOSH insulates the SMs prior to starting a test. Quilted fiberglass blankets and polystyrene lids are used to insulate the SMs. NIOSH also increases the heat input to the SMs at the beginning of a test. Each SM has a preheat heater and a steady-state heater attached to its core. To preheat the SMs, the preheat heaters are powered by line voltage until the sides of the SMs reach about 32.2–35.0 °C (90–95 °F). At this time, power to the preheat and steady-state heaters is turned off, the insulating materials are removed, and power is restored to the steady-state heaters.

Because the SMs rest directly on the floor and the bottoms of the SMs are not insulated, some heat is lost into the mine floor during this preheat procedure. However, this is thought to have only a small effect on the test results. Due to the large thermal mass of the mine strata, the mine strata temperatures increase very slowly throughout the tests. In addition, the temperatures near the end of a 96-hour RA heat/humidity test change only a few tenths of a degree during the last 12 to 24 h of the test, so the preheat process has a minimal effect on the final data.

If a preheat procedure is not used and the test starting point is taken as the time when the SMs reach steady state, the final temperatures would be higher because, as discussed above, some heat would be lost to the inside of the RA as the SMs are reaching operating temperature. Because this would yield higher temperatures at the end of the test, the RA would be “penalized” if these results would be used to assess the occupancy limits of the RA subject to the AT limit.

5.2. Heat input

Both the metabolic heat of miners and the CO_2 scrubber system heat must be accounted for in testing. As previously mentioned, prior NIOSH testing has been conducted with 117 W (399 BTU/hr) of representative metabolic heat. The research by Bernard et al. [26] shows that the heat input should be based on the number of miners assumed to be within an RA (see Table 1). For more than 10 occupants, 117 W (399 BTU/hr) would be slightly higher than the recommended values. However, considering that 117 W (399 BTU/hr) is only about 4% higher than the 113 W (386 BTU/hr) recommended for 25 or higher occupants, the difference in test results would be minimal. The CO_2 scrubber heat input per miner should be determined based on the scrubber material used. A value of 27.5 W (93.8 BTU/hr) per person would be representative of a soda-lime-based scrubbing system.

It is recommended that the SMs are arranged to uniformly distribute the heat within the tested RA. This simplifies the analysis and provides the ability to do a check on the data because, with a uniform heat input, the temperatures measured throughout an RA should not vary much.

The devices used to provide the representative CO_2 scrubber heat input should be positioned at the locations of the CO_2 scrubber(s) for the RA under test. Some RAs use hanging CO_2 scrubber curtains, while other RAs use an air-motor-driven fan with scrubbing material cartridges atop a frame that is positioned in a nearly central location in the RA. If the RA’s CO_2 scrubber system concentrates heat in one location, the temperatures near the CO_2 scrubber will likely be increased.

5.3. Cool-down period between tests

Between individual tests, a cool-down period of a few weeks may be required to allow the temperatures of the test facility and RA to return to their initial temperatures. Because the materials of a laboratory or coal mine have high thermal mass, the laboratory or coal mine will heat up and cool off slowly. Table 7 shows the RA internal air temperature at the center of the tent at midheight; the average mine air temperature near the RA, the mine strata floor temperatures at 0 mm, 152 mm, and 610 mm (0 in, 6 in, and 24 in) depth under the center of the tent; and the mine strata roof temperature at 0 mm, 152 mm, and 610 mm (0 in, 6 in, and 24 in) depth above the center of the tent for a 96-hour heat/humidity test performed on a 23-person tent-type RA in the NIOSH Experimental Mine. The table lists the temperatures at the beginning of the test, at the end of the test, and after a cool-down period of 92 h. The data show that after almost 4 days without input heat, the temperatures remained elevated by about 1.0–2.9 °C (2–5 °F) compared to their initial values. The time required for the facility to cool could be reduced by using an air conditioning system. However, the temperatures for the test facility would have to be monitored to ensure that the temperatures returned to their pretest values.

6. Limitations

The temperature, RH, and AT in an occupied RA depend on the mine air and strata temperature, the mine strata composition, and the heat input from miners and the CO_2 scrubbing system. NIOSH research on RA heat/humidity has been conducted in the NIOSH Experimental Mine and Safety Research Coal Mine. In the NIOSH mines, the temperature of the mine strata at a depth of 1.2 m (4 ft) stays in the range of about 12.8–14.4 °C (55–58 °F) throughout the year. In addition, the NIOSH mines have strata compositions that are typical of the Pittsburgh Coal Seam. The results obtained from RA heat/humidity tests conducted in the NIOSH mines have not been compared to results from tests in other test facilities. However, it is expected that the results would be similar if the temperatures and thermal properties of the facilities are similar. In addition, the SMs have not been validated by direct comparisons with real miners inside an RA. However, RA thermal simulations show that the temperature and RH inside an RA were similar when comparing results from simulations that used models of the SMs to the results from simulations that used models of real people [35].

7. Conclusions and recommendations

When conducting refuge alternative (RA) heat/humidity testing, some type of heat input devices must be used to provide the representative metabolic heat of actual miners and that of the RA's CO_2 scrubbing system. To yield similar results to what would be observed with actual humans, the heat input devices used for the testing should be designed so that the amount of heat transferred to the ground via conduction, to the RA air via convection, and to the RA surroundings via radiation closely matches the human heat transfer via each heat loss mechanism. In order for the interior environment of the RA to reach the temperature and relative humidity (RH) that would be observed with actual humans, some of the heat must be input as latent heat. If this latent heat is input by a device such as the simulated miners (SMs), a moisture input rate of about 1.5 L/day (0.53 Gal/day) per SM is appropriate. The latent heat input could be in the form of water vapor or via simulated sweat.

Programmable variable autotransformers (PVAs) can be used if line voltage fluctuations are severe enough to cause the heat generated by the heat input devices and the resulting RA air temperature to vary to the point where analysis becomes difficult. Small temperature variations of a few tenths of a degree may not be cause for concern. However, if the line voltage follows a similar sinusoidal trend to that observed during the initial NIOSH heat/humidity tests, PVAs can be used to eliminate this issue.

When connecting heat input devices inside an RA to their power sources, consideration should be given to the voltage drop and power loss associated with the power cord. These are a function of the length, wire gauge, and current of a power cord.

Many data acquisition systems are available that could be used for RA heat/humidity testing. Because thermal systems respond slowly, a data acquisition system with a sample rate on the order of a few samples per second is adequate. Therefore, consideration should be given to the types of sensors that will be used for measurements. Some data acquisition systems have thermocouple, RTD, and voltage inputs, while others do not.

When selecting sensors, attention should be given to their accuracy. This is especially true for sensors used to measure air temperature and RH within the RA because these sensors are used to calculate apparent temperature. Thermistor-based T/RH sensors and Class A RTDs are recommended for RA air temperature measurement due to their superior accuracy compared to thermocouples. The specifications of RH sensors should be closely examined to verify that their accuracy is sufficient when measuring RH above 90% RH.

The heat input devices used to simulate actual miners should be uniformly arranged within the RA. It is assumed that miners would spread out within an RA. In addition, with a uniform heat input, the temperature variation within an RA would be small, and only a few temperature measurements would be needed to capture the air temperature within the RA.

A preheat procedure should be used so that the heat input devices reach operating temperature within a few hours or less. If a preheat procedure is not implemented, the RA internal temperature measured at the end of the test will be higher than it would be if the heat input devices are preheated. In effect, this would penalize an RA with respect to occupancy limits subject to the 35 °C (95 °F) AT limit.

Finally, for successive tests, a cool-down period may be necessary. During a 96-hour heat/humidity test, the test facility temperature will increase several degrees. After testing stops, more than a week may be required for the temperatures to return to their initial values. Use of air conditioning could reduce this time. However, the temperatures of the facility should be checked before conducting additional tests.

Repeatable, reliable data can be collected using well-planned test methods. The resulting data can be used by RA manufacturers to examine RA occupancy as a function of ambient temperature. In addition, such results can be used for comparison with thermal simulation models.

Acknowledgments

The authors gratefully acknowledge Jason Wilkerson of A.L. Lee Corp. for his guidance on using PVAs for heat/humidity testing.

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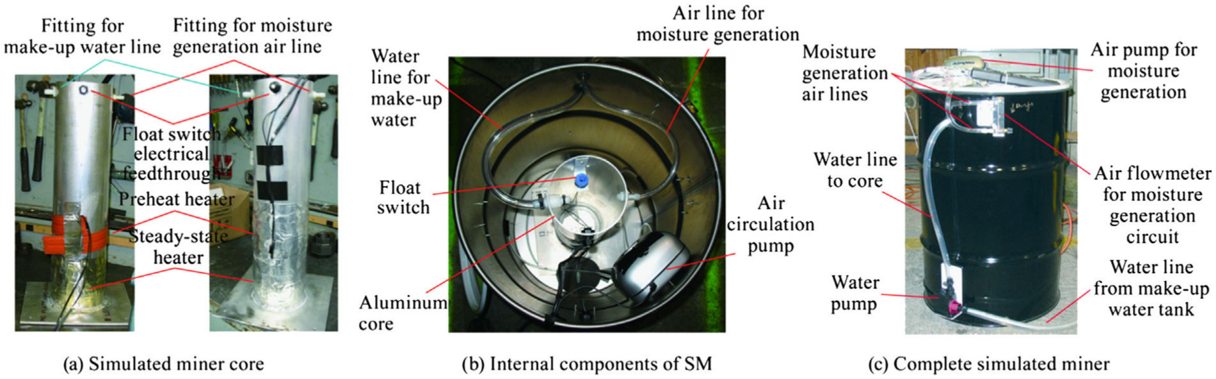
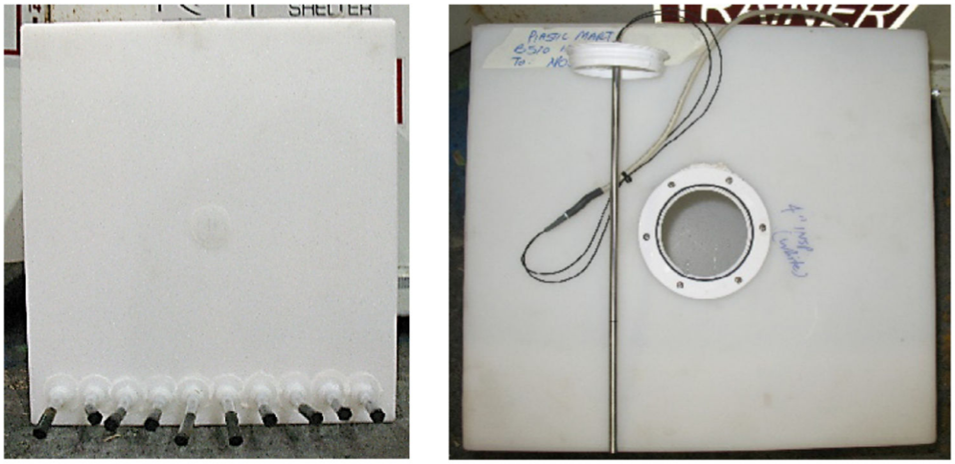


Fig. 1.

Simulated miners used for heat input.



(a) Photo of water tank from front (b) Photo of water tank from above

Fig. 2.

Photo of water tank and immersion-type heater.

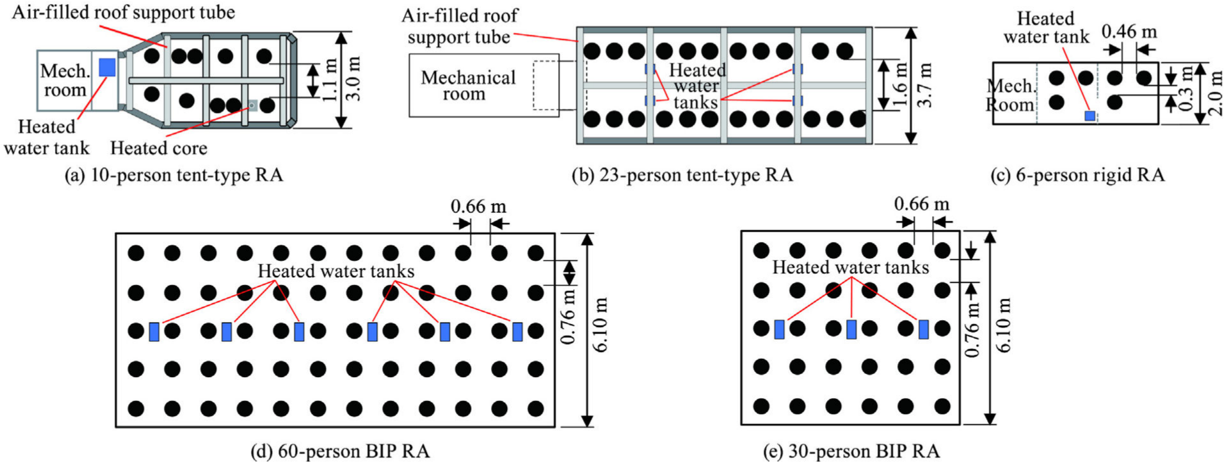


Fig. 3.

Arrangement of heat input devices for RA heat/humidity tests on a 10-person tent-type RA, a 23-person tent-type RA, a 6-person rigid RA, a 60-person BIP RA, and a 30-person BIP RA.

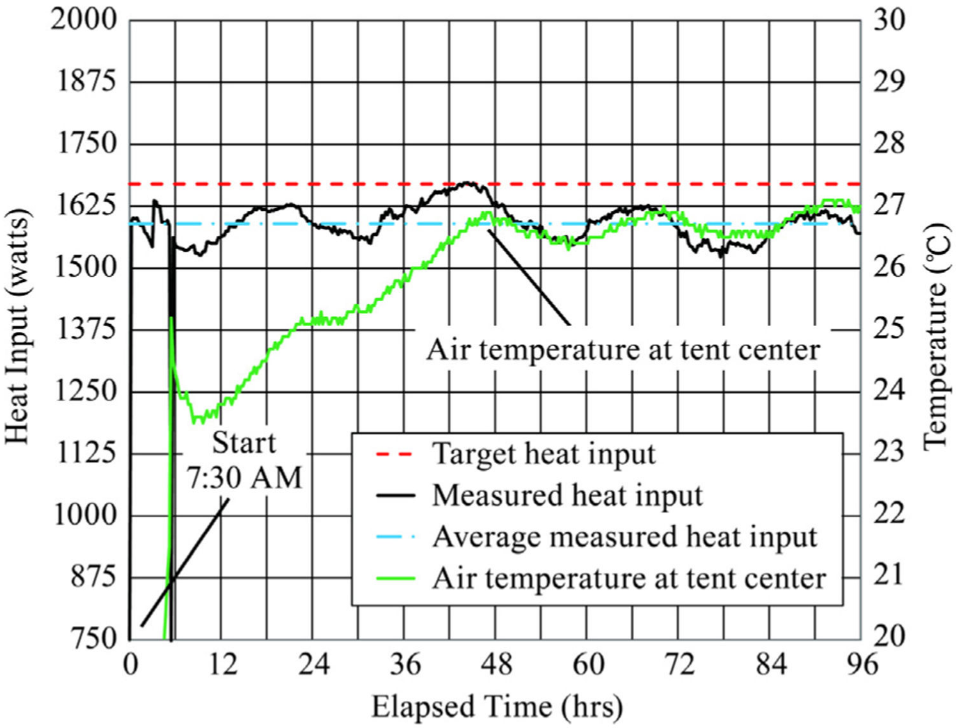


Fig. 4.

Heat input and RA internal air temperature at the center of the tent for heat/humidity tests of a 10-person tent-type RA that were conducted with the SMs and heated water tanks powered directly from a 120-V circuit, showing sinusoidal heat input fluctuations.

Fig. 5.
Programmable variable autotransformer used to control input power (heat) during NIOSH RA heat/humidity testing.

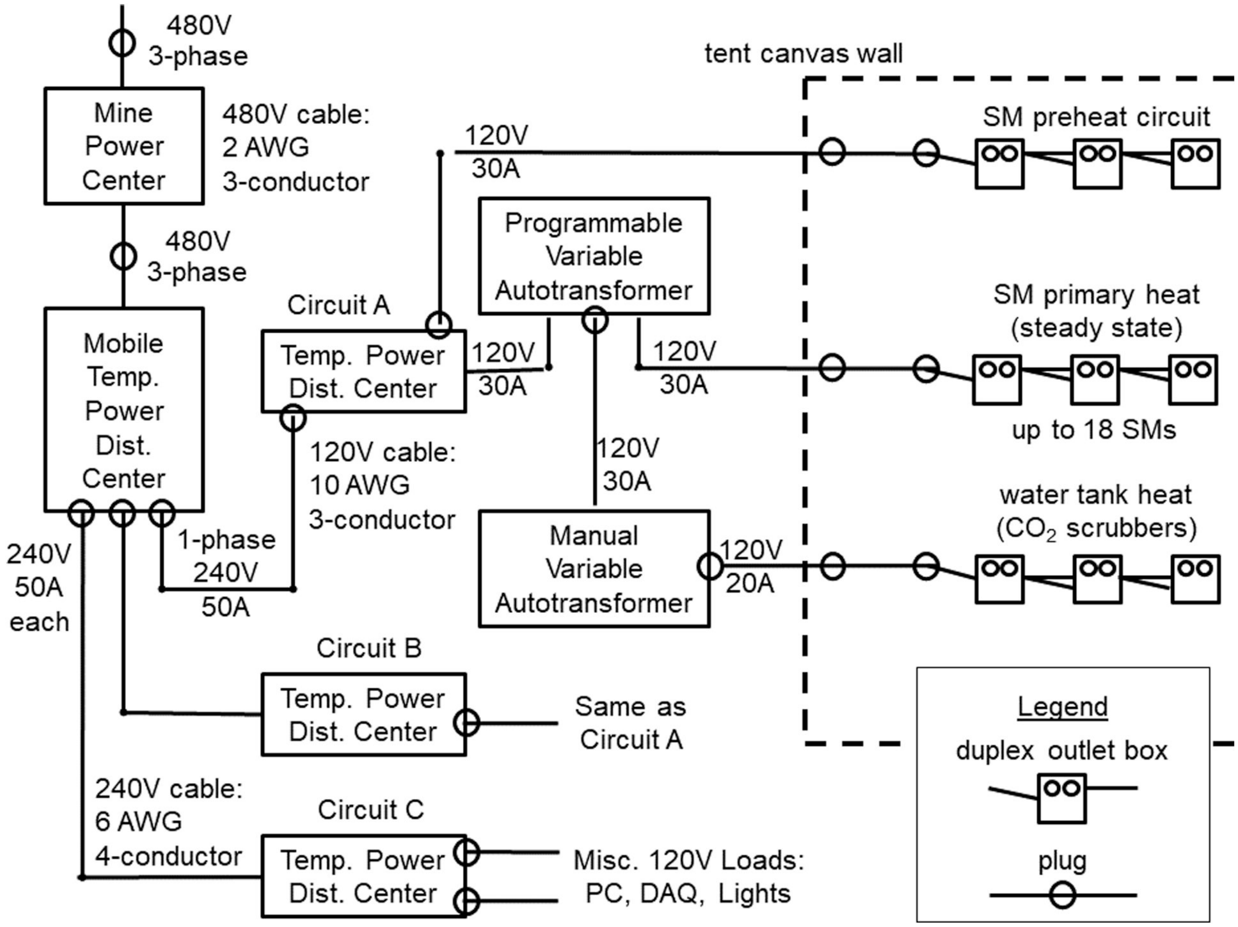


Fig. 6.

Electrical schematic for circuit used to power SMs and heated water tanks during RA heat/ humidity testing.

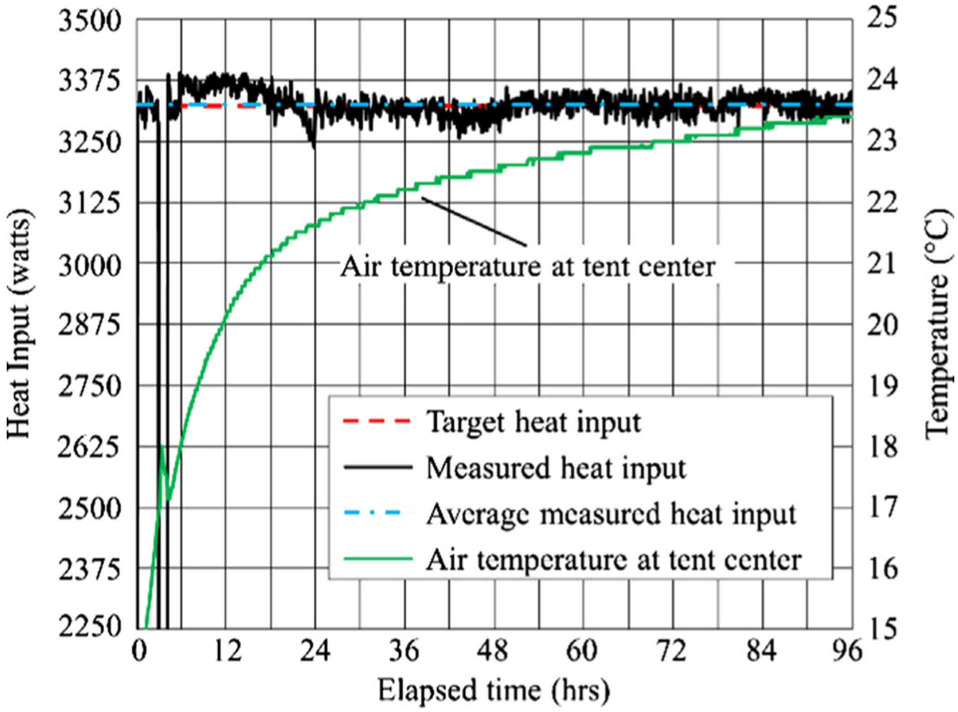


Fig. 7.

Heat input and RA internal air temperature at the center of the tent for a heat/humidity test of a 23-person training unit RA that was conducted with the SMs and heated water tanks powered by a programmable variable autotransformer.

Fig. 8.

RTD-instrumented PVC rod for measurement of strata temperatures.

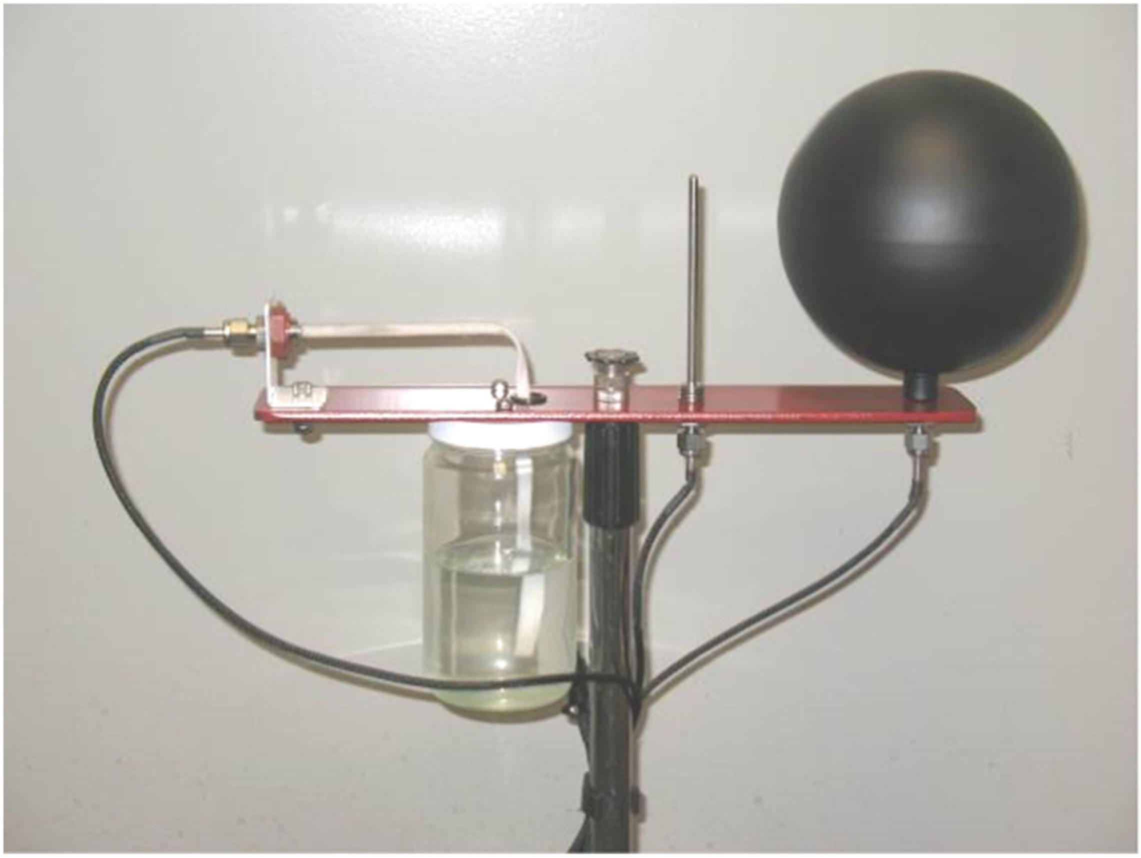


Fig. 9.

NIOSH-constructed wet-bulb globe temperature measurement device.

Table 1

Recommended metabolic heat input values based on number of miners in an RA.

Number of occupants	Heat input per miner (W)
1	134
2	126
3	123
4	121
5	120
10	116
15	115
20	114
25+	113

Table 2

Voltage drop and power reduction at SMs, assuming 9 A of current for various gauge 15.2-m-long (50-ft-long) power cords.

Power cord gauge	Voltage drop (V)	Power reduction (%)
16	3.61	5.9
14	2.27	3.7
12	1.43	2.4
10	0.90	1.5
8	0.57	0.95

Table 3

Impact of temperature sensor accuracy on calculated AT for an assumed 90% RH.

27.8 °C (82.0 °F) Temperature			**Calculated AT**		
Acc. (°C)	**Min. Meas. (°C)**	**Max. Meas. (°C)**	**Min. (°C)**	**Max. (°C)**	**Range (°C)**
±0.11	27.7	27.9	33.2	33.8	0.6
±0.28	27.5	28.1	32.8	34.2	1.4
±0.56	27.2	28.3	32.1	34.9	2.8
±1.1	26.7	28.9	30.9	36.5	5.6

Table 4

Impact of RH sensor accuracy on calculated AT for an assumed 27.8 °C (82 °F).

90 %RH			Calculated AT		
Acc. (%RH)	**Min. Meas. (%RH)**	**Max. Meas. (%RH)**	**Min. (°C)**	**Max. (°C)**	**Range (°C)**
±1.0	89.0	91.0	33.3	33.7	0.4
±2.0	88.0	92.0	33.1	33.8	0.7
±3.0	87.0	93.0	32.9	34.1	1.1
±5.0	85.0	95.0	32.6	34.4	1.8

Table 5

Effect of T/RH sensor accuracy on calculated AT.

27.8 °C (82 °F) Temperature		**90% RH**		**Calculated AT 33.5 °F**	
Acc. (°C)	**Min/Max Meas. (°C)**	**Acc. (%RH)**	**Min/Max Meas. (%RH)**	**Min/Max (°C)**	**Range (°C)**
±0.11	27.7/27.9	±1.7	88.3/91.7	32.9/34.1	1.2
±0.22	27.6/28.0	±2.5	87.5/92.5	32.5/34.6	2.1

Table 6

Air temperature and RH measurements for a 23-person tent-type RA test.

Measurement location	T (°C)	RH (%)
Center of metal box at midheight	20.4	98.0
Center of tent Section 1, 0.3 m from roof	24.4	
Center of tent Section 1 at midheight	23.6	92.6
Center of tent Section 1, 0.3 m from floor	22.2	
Center of tent Section 2, 0.3 m from roof	24.1	
Center of tent Section 2 at midheight	23.4	94.9
Center of tent Section 2, 0.3 m from floor	22.0	
Center of tent Section 3, 0.3 m from roof	24.2	
Center of tent Section 3 at midheight	23.2	94.3
Center of tent Section 3, 0.3 m from floor	22.9	
AVG of measurements 0.3 m from roof	24.2	
AVG of measurements at midheight	23.4	93.9
AVG of measurements 0.3 m from floor	22.4	
AVG of all measurements in tent	23.3	
Range of measurements 0.3 m from roof	0.3	
Range of measurements at midheight	0.4	2.3
Range of measurements 0.3 m from floor	0.9	
Range of all measurements in tent	2.4	2.3

Table 7

RA internal air temperature at the tent center, mine average air temperature; mine strata floor temperatures at 0 m, 0.15 m, and 0.61 m depth; and mine strata roof temperatures at 0 m, 0.15 m, and 0.61 m depth from a heat/humidity test on a 23-person tent-type RA.

Location	Temperature (°C)			
	T_0 (Initial)	T_1 (After 96-hr Test)	T_2 (After Cooling for 92 hrs)	T_2-T_0
RA internal air	13.8	23.4	16.3	2.5
Mine average air	13.4	15.6	14.4	1.0
Mine floor strata at 0 m	13.3	19.4	15.9	2.6
Mine floor strata at 0.15 m	13.3	18.6	16.2	2.9
Mine floor strata at 0.61 m	13.3	15.2	15.9	2.6
Mine roof strata at 0 m	13.3	17.9	15.5	2.2
Mine roof strata at 0.15 m	13.4	17.0	15.6	2.2
Mine roof strata at 0.61 m	13.2	14.0	14.4	1.2