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TEMPERATURE AND HUMIDITY RISE FOR 23-PERSON TENT-TYPE MOBILE REFUGE ALTERNATIVE

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ABSTRACT

Mine Safety and Health Administration (MSHA) regulations require underground coal mines to use refuge alternatives (RAs) to provide a breathable air environment for 96 hrs. One of the main concerns with the use of mobile RAs is the heat and humidity buildup inside an RA. The accumulation of heat and humidity can result in miners suffering heat stress or even death. MSHA regulations require that the apparent temperature in a fully occupied RA must not exceed 95°F. To investigate this issue, the National Institute for Occupational Safety and Health (NIOSH) conducted testing on a 23-person tent-type RA in its Experimental Mine (EM) in a test area that was isolated from the mine ventilation system. The test results showed that the average measured air temperature within the RA increased by 9.4°C (17°F) and the relative humidity (RH) approached 94 %RH. The test results were used to benchmark a thermal simulation model of the tested RA. The validated thermal simulation model predicted the average air temperature inside the RA at the end of 96 hours to within 0.6°C (1.0°F) of the average measured air temperature.

INTRODUCTION

If an accident occurs in an underground coal mine, miners who fail to escape from the mine can enter an RA for protection from adverse conditions, such as high carbon monoxide levels. One of the main concerns with the use of mobile RAs is the potentially adverse thermal environment inside an RA from the metabolic heat of the occupants and the heat released by the carbon dioxide (CO_2) scrubbing system. Moreover, the humidity within the RA will increase through occupants' respiration and perspiration and from the chemical reaction within the CO_2 scrubbing system. The accumulation of heat and humidity can result in miners suffering heat stress, heat stroke, or even death.

In its 2007 report to Congress, the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) recommended that RAs should be designed to ensure that the internal apparent temperature (a temperature-humidity metric) in an occupied RA does not exceed 35°C (95°F). However, a standard method to determine compliance with this metric does not exist. The heat transfer process within and surrounding an RA is very complex, and is not easily defined analytically or experimentally.

To investigate the related issues, OMSHR conducted heat and humidity testing on a 23-person tent-type RA in its Experimental Mine (EM) in a test area that was isolated from the mine ventilation system. During the testing, numerous parameters were measured: heat input to the chamber, the air temperature and relative humidity inside the RA, the air temperature in the mine, the mine strata temperatures versus depth, and the airflow inside and outside the chamber. The focus of this paper is on the temperature rise within an RA. TAITherm heat transfer analysis software was used to develop a thermal simulation model of the RA as it was tested in the mine, using the test results as the benchmark. Both sensible and latent heat were used in the test and the model.

HEAT PRODUCTION AND TRANSFER WITHIN AN RA

There are various levels of research needed to quantify the heat production and transfer within a confined space such as an RA. The control of temperature and humidity within a confined space is critical because of the relatively narrow range in which the unprotected human body can operate without developing heat stress [1]. The human body maintains a normal core temperature between 36.0°C (96.8°F) and 38.0°C (100.4°F) [2]. In hot environments, the body is able to cool itself via the evaporation of sweat to maintain a viable core temperature. The heat sources within an RA include metabolic activity and heat contributed from equipment, such as the CO_2 scrubbing system. Heat within an RA is dissipated through conduction, convection, radiation, evaporation from occupants, and condensation on the RA interior.

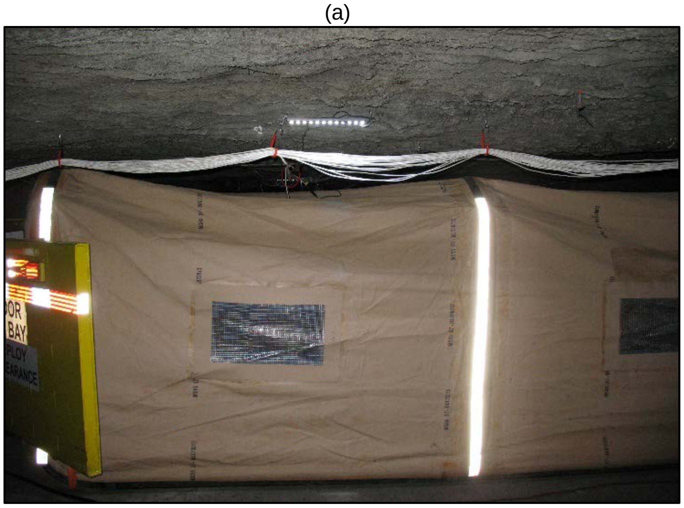
The heat produced by metabolic activity increases as the level of activity increases. Several standard values can be found for the heat produced by human metabolism [3] [4]. According to Bauer and Kohler [4], a person weighing 75.0 kg (165.3 lb) will deliver 117 W (399.2 BTU/hr) of heat to the environment at rest state. The physical testing and thermal simulation model discussed in this paper use this value as the input heat rate.

Heat transfer to and from the body occurs from conduction, convection, radiation, respiration, and evaporation. Because miners in a tent-type RA will sit or lie directly on the floor, heat loss through conduction can be significant. The differential between skin and core temperature results in heat transfer from the body's core to the skin, where it can be lost through convection, radiation, conduction, and perspiration. Sweating occurs when conduction, convection, radiation, respiration, and evaporation become insufficient to dissipate the accumulation of heat from metabolic and environmental sources. Evaporation of sweat absorbs significant amounts of heat from the skin; hence it allows the body to lose heat rapidly. As the ambient temperature approaches or exceeds skin temperature, sweating becomes the body's primary mechanism of heat loss. However, the rate of sweat evaporation is limited by the relative humidity of the surrounding air. As the relative humidity increases, the rate of sweat evaporation slows, reducing the body's ability to cool itself. Evaporation of sweat becomes very slight at high relative humidity. For example, the maximum sweat evaporation rate drops from ~2.5 L/hr (84.5 oz/hr) at 50% RH to ~1.3 L/hr at 80% RH at air temperature of 35°C (95°F) [5]. Therefore, high humidity will reduce the effectiveness of the body's most effective heat loss mechanism.

IN-MINE EXPERIMENTS

Tests were conducted underground in the EM at the NIOSH research laboratory in Pittsburgh, PA. A tent-type RA with a 1.7-m-high (5.5-ft-high) tent, an internal volume of roughly 55.3 m^3 (1881 ft^3), and a floor surface area of about 31.8 m^2 (342 ft^2) (Figure 1) was used for these tests. This RA meets the unrestricted surface area requirement of 1.4 m^2 (specified as 15 ft^2) per miner specified in 30 CFR 7.505 for up to 23 people, and it meets the unrestricted volume criteria of 1.7 m^3 (60 ft^3) per miner for seam heights up to 1.37 m (4.5 ft), as mandated by the Mine Safety and Health Administration (MSHA) for RA manufacturers to comply with by 2018.

(a)



(b)

(c)

Figure 1. 23-person tent-type RA (a) during deployment, (b) after deployment, and (c) interior view.

A metal box was attached to the tent to serve as mechanical room. The metal box portion of the RA was 1.98 m (6.5 ft) wide by 4.72 m (15.5 ft) long.

According to Bauer and Kohler [4], the metabolic heat generated by an RA occupant is 117 W (399.2 BTU/hr) at steady state. In addition to the sensible heat applied to the barrel surfaces, 1.3L/barrel/day of water was added to the tent interior air as latent heat. This amount of heat was input for each simulated miner. An additional 27.5 W (93.8 BTU/hr) of heat per simulated miner was input to represent the heat generated by a lithium hydroxide scrubbing system for all testing [6]. Thus the total heat input was for all 23 miners at steady state. For the tests conducted with 23 simulated miners, the total steady state heat input was nominally 3323.5 W (11,340.3 BTU/hr).

Miners in a tent-type RA will sit or lie directly on the floor of the RA since tent-type RAs are not provided with benches, cots, or pads. 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 1.8-m^2 (19.4-ft^2) surface area of the human body [7]. NIOSH OMSHR developed its own simulated miners (Figure 2) using commonly available 0.11 m^3 (30 gal) steel drums, thin-walled aluminum pipes, two aquarium air pumps, an aquarium water pump, and two silicone-encapsulated electrical resistance heaters with a nominal power rating of 120 W (409.5 BTU/hr) at 120 V to represent human metabolic heat [8]. The heated water tank was positioned within the metal box and the added aluminum core was positioned near the tent end of the RA. The simulated miners have a surface area of 1.35 m^2 (14.5 ft^2), which is exactly 75% of the surface area of the human body. More details on the design of simulated miners can be found in [6].

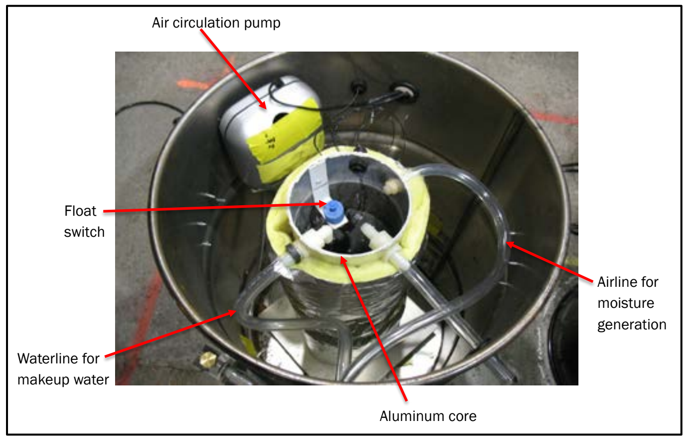


Figure 2. Inside view of a simulated miner.

The simulated miners were arranged to distribute the heat as evenly as possible within the deployed tent (Figure 3). For all testing, the actual heat input was measured using two watt transducers (Flex-Core, model PC5-019CX5), one for a group of 11 simulated miners and one for a group of 12. The RA was isolated from the mine ventilation system to prevent bulk airflow into the test area without having a significant impact on heat loss from the ends of the test area. This represents a worst-case scenario—a loss of the mine ventilation fans. Two Data Translation DT9874 data acquisition systems were used to record all sensor/transducer data. During the test, all data was acquired at a rate of 1 sample every 20 seconds with 24-bit resolution.

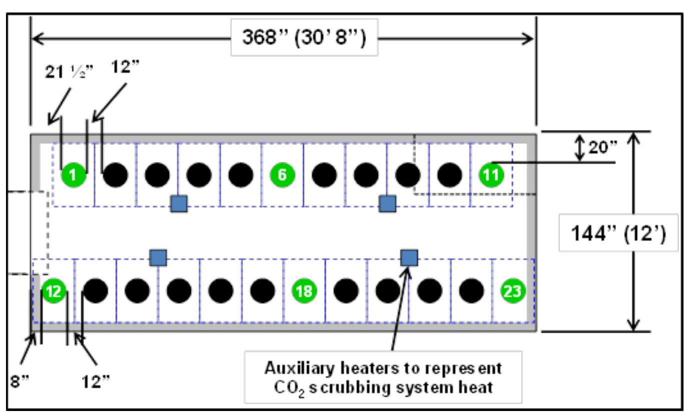


Figure 3. Layout of simulated miners and heaters to represent carbon dioxide scrubber heat (all dimensions in inches).

Test Setup

The RA was positioned in the EM with the center of the tent located at the center of the room so that the sides of the RA were equidistant from the ribs. The encapsulated test area was approximately 44.2 m (145.0 ft) long and 1.8 m (5.9 ft) high (Figure 4).

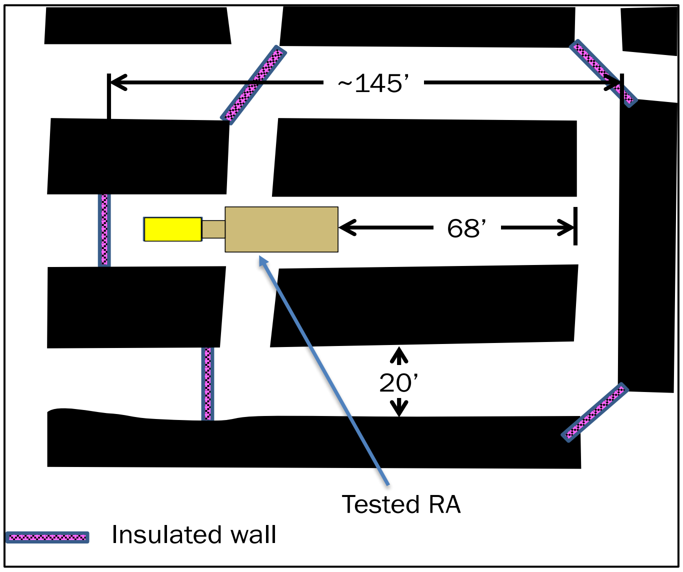


Figure 4. Schematic of test area in the EM.

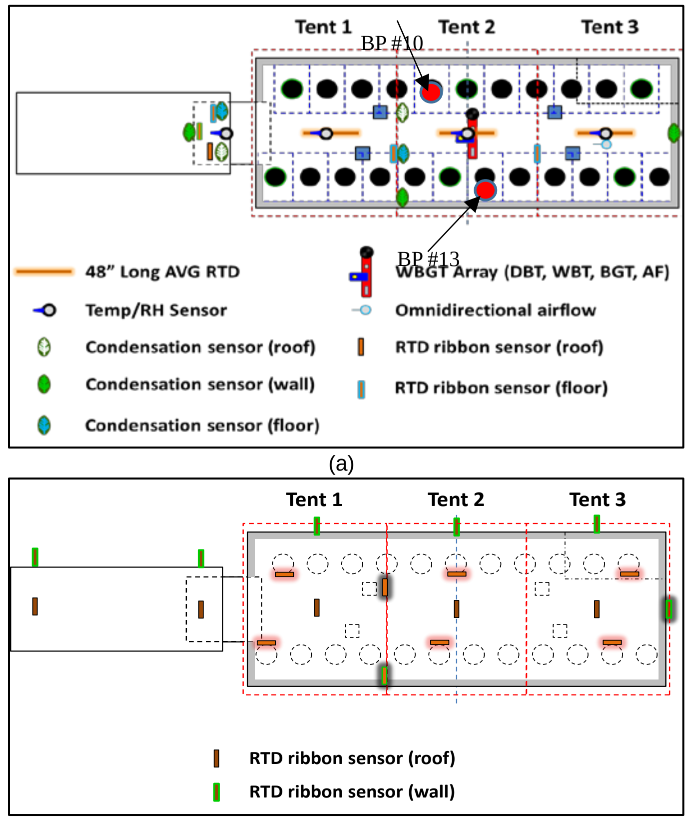
Numerous transducers were used to measure a variety of parameters. Sensors were used inside and outside the tent to record the internal and external air temperature, relative humidity, airflow, and RA surface temperature (Figure 5). To determine the airflow speed near the RA, three omnidirectional airflow sensors were positioned near the tent. These particular airflow sensors were chosen because they can accurately measure flow speeds as low as 0.05 m/s (10.0 ft/min) and are not sensitive to flow direction. Measuring the airflow is important because any heat transfer simulation requires the specification of the convection coefficient which is directly related to the air velocity. Two resistance temperature detector (RTD) instrumented PVC rods were positioned between the tent bottom and the mine floor at junctions of different parts (Figure 5a) and were used to measure the temperature of the mine floor beneath the tent.

The floor and rib strata temperature beneath the center of the tent was measured at depths of 0, 15.2, 61.0, and 121.9 cm (0, 6, 24, and 48 in) by installing a PVC rod with four RTDs attached to its outside and covered with epoxy (Figure 6). To install the instrumented PVC rod, a 2.54-cm (1.0-in) diameter hole was drilled into the mine floor and the rod was pushed into the hole. The temperatures on and within the mine roof strata were also measured on the surface and at the same depths as the ribs using RTD-instrumented PVC rods as described above. The air temperatures within the test area were measured using 182.9-cm-long (72-in-long) RTDs by averaging their readings at eight locations.

Test procedure

Unlike a human miner, who is at body temperature when he or she enters a RA, a simulated miner is "cold" when it is first powered and may take up to a day to reach its steady state temperature. As the simulated miner is allowed to reach its operating temperature, the surroundings in the test area heat up, effectively preheating the RA. So the final air temperature measured inside the RA at the end of the 96-hour time period could be affected by this additional heat as the simulated miners are allowed to reach their operating temperature.

To address this issue, OMSHR used an approach that would decrease the time for the simulated miners to reach steady state and to minimize heating of the RA and surroundings while the simulated miners were not yet at their steady state temperatures, as described below. At the beginning of the test, all of the simulated miners were wrapped in a quilted, 2.54-cm-thick (1.0-in-thick) fiberglass insulating blanket (R-value of ~3.14) and the top of each was covered with a 2.54-cm-thick (1.0-in-thick) Styrofoam disk. By using insulation around the simulated miners, the heat lost to the RA can be minimized so that the temperature of the simulated miners increases relatively quickly. In addition to being insulated, the simulated miners were designed to use two heaters: a steady state heater and a preheater, each with a rating of 120 W (410 BTU/hr) at 120 V. At the beginning of the tests, both the steady state heater and the preheater for each simulated miner were turned on and the surface temperatures at the midheight of two of the simulated miners were monitored. The preheaters were turned off and the insulation was removed when the temperatures mentioned above reached approximately 35°C (95°F)—roughly the expected steady state temperature of the simulated miners and the skin temperature of the human body. The simulated miners approached their steady state temperature within a few hours and, at this time, most of the heat generated by the heaters was transferred to the RA atmosphere.



(a)

(b)

Figure 5. Sensor locations: (a) interior and (b) exterior.

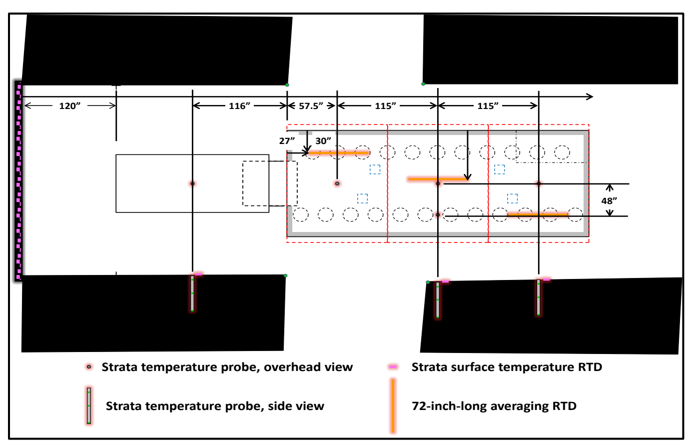


Figure 6. Sensor location of 72-inch-long averaging RTDs and mine strata temperature sensors.

EXPERIMENTAL RESULTS

The RA internal temperatures during the 96-hour test period are the temperatures of the most interest. Because the measured temperatures were observed to change very slowly, less than 0.6°C (1.0°F) over the final 24-hour time period, the sample rate used to acquire the data was much higher than necessary and reducing the dataset would not affect the characteristics of the data. The raw test data was reduced from a sample rate of 1 sample per 20 seconds to a sample rate of 1 sample per 5 minutes. The air temperatures within the tent rose relatively quickly during the first day before leveling off with a slow, steady rise for the remainder of the test (Figure 7). The temperatures in the tent varied slightly with the input heat, and the mine ambient temperature steadily rose. At the end of the fourth day of testing, the temperature rise in tent part was approximately 10.0°C (18.0°F). The temperatures at midheight at tent 1 (labeled X28-I-Tnt1-AT-MH), tent 2 (labeled X33-I-Tnt2-AT-MH), and tent 3 (labeled X36-I-Tnt3-AT-MH) were within about 0.83°C (1.5°F) of each other throughout the test. At the box end of the tent (labeled X26-I-MB-AT-MH), the data shows that the interior air temperature at midheight of the tent was about 5.6°C (10°F) lower than the temperature at other locations mentioned above. An average of four RTDs (X-26, X-28, X-33, and X-36) was used for the tent interior air temperature because the TAITherm model calculates a single average air temperature for the entire shelter interior. The test results showed that the average measured air temperature within the RA increased by 9.4°C (17°F).

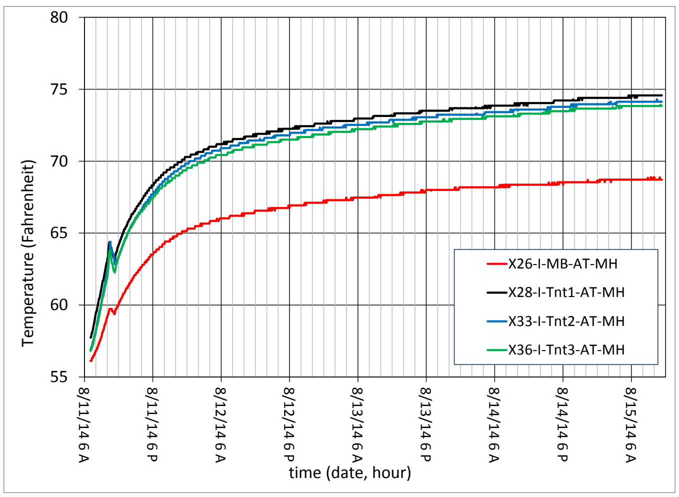


Figure 7. RA internal air temperatures at various locations.

As mentioned previously, the strata temperatures were also monitored during the tests. The temperature between the bottom of the tent and the mine floor surface increased almost immediately after beginning the test (Figure 8). As depth into the floor increased, the temperature increased less and at a lower rate. The temperature measured between the tent and mine floor increased by about 3.1°C (5.5°F) in the first 24 hours. By the end of four days, the temperature between the tent and the surface of the mine floor increased by 6.1°C (11.0°F); the temperature at 15.2 cm (6 in) deep increased by 5.3°C (9.5°F); the temperature at 61.0 cm (24 in) deep increased by 1.9°C (3.5°F), and the temperature at 122 cm (48 in) deep remained constant.

As Figure 7 and Figure 8 show, the mine strata and mine air temperatures increased throughout the in-mine tests. The temperatures of the mine floor strata beneath the tent showed the largest increases because the simulated miners were in direct contact with the tent floor. The in-mine test data showed that the strata temperatures at a depth of 1.2 m (4.0 ft) remained nearly constant throughout the tests. Therefore, thermal simulation models of a RA in an underground coal mine should include at least a 1.2-m-thick (4.0-ft-thick) layer of mine strata. The temperature at a depth of 1.2 m (4.0 ft) can then be assumed to remain constant at the temperature corresponding to the mine that the model is to represent [6]. The RA, nevertheless, may perform differently in mines that have different strata with different thermal conductivity properties. Hence, the validation of the thermal simulation model of a particular RA may need to provide a baseline strata model against which the RAs performance can be compared.

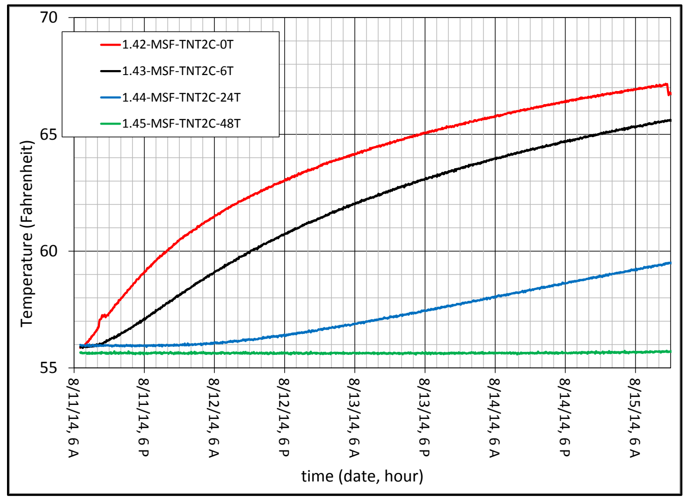


Figure 8. Mine floor strata temperatures under the tent during the 96-hour test.

THERMAL SIMULATION MODEL DESCRIPTION

There are several thermal models used to simulate and predict the temperature and humidity within an occupied RA [7] [9]. A TAITherm model of the EM test was developed to account for the RA and mine geometry, RA and mine strata thermal properties, and heat generated by the simulated miners and auxiliary heaters. With the ability to simulate human thermal behavior using its Human Thermal Model, the TAITherm model predicts the transient thermal response of the simulated miners, RA surfaces, RA interior air, mine strata, and mine air. Inputs to the model are initial mine and chamber temperatures and simulated miner heat rates. TAITherm is a validated heat transfer prediction software tool. TAITherm applies a multi-physics approach to solve for thermal conduction, radiation, convection, and moisture transport under both steady state and transient conditions. The thermal model was created from 3D CAD geometry of a 5.5' tall tent-style RA. The geometry was modified so that a finite element shell mesh could be applied. Figure 9 shows a cut-away view of the tent-style RA. The 23 simulated miners inside of the RA were used to represent people in the testing. The mine strata was represented in TAITherm with a shell element mesh, while the layer thickness volume was defined virtually. The mine strata was modeled as a 1.8-m (6.0-ft) thick layer that was discretized into 24 7.62-cm-thick (3.0-in-thick) layers.

Heat rate and initial temperature data from the test were used as inputs to the model. Table 1 lists the various material properties applied in the model. The thermal properties listed in Table 1 were estimated based on information provided by the RA manufacturer and OMSHR. Four auxiliary heaters were also modeled inside the tent to represent the heat generated by a CO_2 scrubbing system, as was done in the mine tests.

MODEL VALIDATION

To validate the accuracy of temperature prediction of the TAITherm mine RA model, the transient thermal response predicted by the model was compared to physical measurements collected by NIOSH. A plot comparing the transient temperatures predicted by the model to the experimental data is shown in Figure 10. The figure shows comparisons for temperature at top of one of the simulated miners (BP #13), the RA interior air, and the tent floor at the junction of part 2 and part 3. An average of the two 1.2-m (4.0-ft) RTDs (x11 and x12) was used for the tent interior air temperature because the TAITherm model calculates a single average air temperature for the entire RA interior. For the mine floor temperature, an average of predicted element temperatures over a 1.8-m (6.0-ft) distance was used to compare the model results to the 1.8-m-long (6.0-ft-long) averaging RTDs used in the physical test. Moisture was included for the model results shown in table 2. Figure 11 shows comparison for the tent interior relative humidity. The final modeled RH was 92.5% while measured average RH of 93.9%.

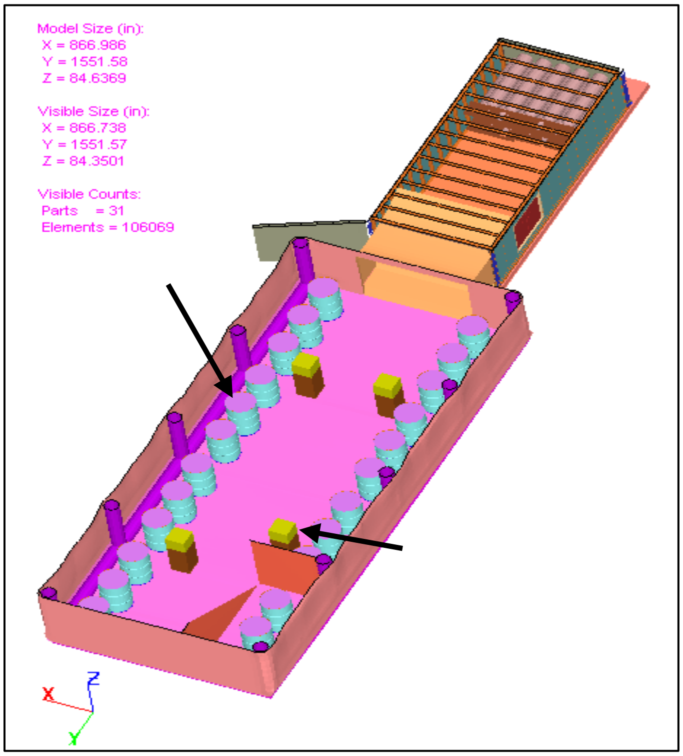


Figure 9. Cut-away view of RA tent with 23 simulated miners and four auxiliary heaters.

Table 1. Material properties used in the model[1].

Material	Location	Thermal conductivity, (W/m-K)	Density, (kg/m^3)	Specific heat, (J/kg-K)
Slate	Mine Roof	1.16	2700	760
Shale	Mine Roof	0.95	2500	1100
Siltstone	Mine Floor	2.5	2600	1000
Bituminous Coal	Mine Ribs, Roof	0.33	1346	1380
Polyvinyl Chloride	Tent	0.15	1380	960
Mild Steel	Tent case, barrels	52.02	7769	461

Table 2 summarizes the results of the TAITherm model validation at the end of the 96-hour test. The predicted average air temperature within the RA is very close to the measured air temperature, with only a 0.3°C (0.6°F) over-prediction. The temperatures on the barrel and tent side also match very closely. Results for the various mine rock surfaces are mixed due to uncertainty in rock thermal properties and lack of air stratification in the model.

Figure 12 shows examples of elements that were selected for comparison with measured data (see numbered callouts). TAITherm calculates temperatures at the centroid of each surface mesh element.

As shown in Table 2, the mine strata temperature predictions may vary 1.1-1.6°C (2.0-3.0°F) due to uncertainty in rock thermal properties such as the rock types, thickness, and their specific thermal properties.

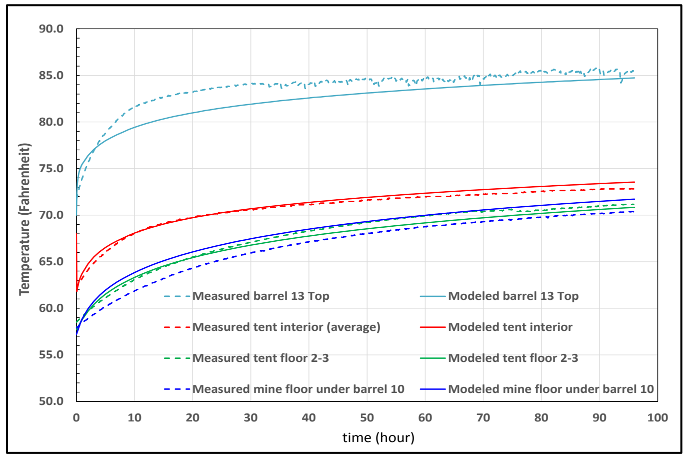


Figure 10. Simulated (solid line) vs. measured (dot line) temperature results for the top of one simulated miner (BP #13), interior (midheight), and floor (underneath conjunction of Tent 2 and Tent 3) of the tested RA, and mine floor under BP #10.

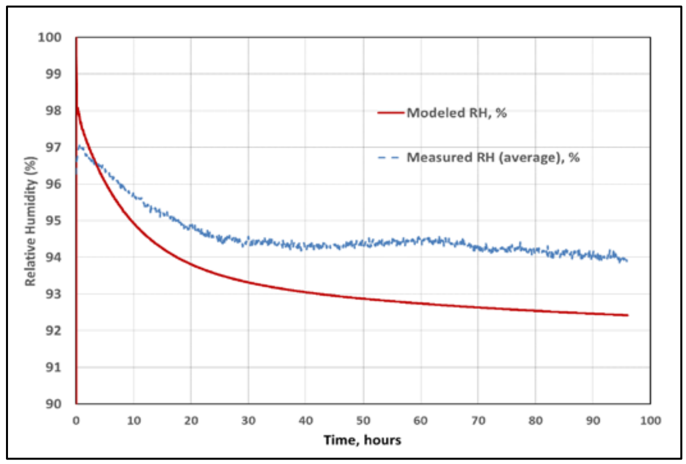


Figure 11. Modeled (solid line) vs. measured (dot line) interior relative humidity.

Table 2. Model error summary at 96 hours (positive value means over-prediction by model, negative means under-prediction).

Sensor location	Sensor #	Prediction Error (^{0}F)
Tent Air	x-26, x-28, x-33, x-36	0.6
Mine Air	2-31 to 2-40	0.1
BP10 Bottom	x-8	0.3
BP10 Side	x-9	0.3
BP10 Top	x-10	-2.5
BP13 Bottom	x-11	-4.0
BP13 Side	x-12	1.6
BP13 Top	x-13	-0.9
Tent Side 1	1-18	-0.02
Tent Side 2	1-24	0.3
Tent Side 3	1-28	-0.9
Tent Top 1 (middle)	1-20	-1.1
Tent Top 2 (middle)	1-26	-1.6
Tent Top 3 (middle)	1-30	-0.9
Tent Floor 1-2	1-5	1.3
Tent Floor 2-3	1-11	-0.5
Mine walls (rib) 2	2-13	2.1
Mine walls (rib) 3	2-17	2.2
Mine roof over tent	2-26	-0.1
Mine roof over case	2-21	1.0
Mine floor under tent 1 - under barrels	1-41	1.1
Mine floor under tent 2 - middle	2-4	1.5

[1] Provided by RA manufacturer.

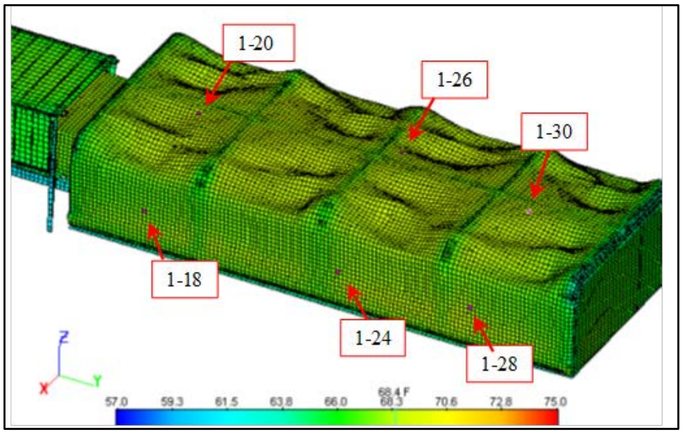


Figure 12. 3D view of the simulated RA model at the end of the 96-hour test.

CONCLUSIONS AND REMARKS

In this paper, the use of the test results to validate a thermal simulation model was discussed. The test results showed that the average measured air temperature within the RA increased by 9.4°C (17°F). The transient thermal response predicted by the TAITherm model was compared to physical measurements collected in the NIOSH in-mine test. The TAITherm model predicted the average tent interior air within 0.3°C (0.6°F) of the physical measurements after 96 hours. The maximum prediction error was 2.2°C (4.0°F) for a point on the bottom of BP #13. A similar error was not seen on the bottom of BP #10. Uncertainties in the rock types and their thermal properties are likely the largest source of error in the model. This could be dealt with by taking core samples and performing thermal conductivity and specific heat measurements.

The validated model has also been used to extend the analysis to include TAITherm models of humans instead of models of simulated miners (not discussed in this paper). The TAITherm human thermal model could then be used to predict the transient core temperature response of RA occupants. Further studies could use the core temperature response to determine safety limits for mine ambient temperature and number of RA occupants.

DISCLAIMER

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