# IN-MINE EXPERIMENTAL INVESTIGATION OF TEMPERATURE RISE AND DEVELOPMENT OF A VALIDATED THERMAL SIMULATION MODEL OF A MOBILE REFUGE ALTERNATIVE

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## 1. 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 the RA. The accumulation of heat and humidity can result in miners suffering heat stress or even death. To investigate this issue, the National Institute for Occupational Safety and Health (NIOSH) conducted testing on a training ten-person, tent-type, RA in its Safety Research Coal Mine (SRCM) in a test area that was isolated from the mine ventilation system. The test results using sensible and latent heat showed that the average measured air temperature within the RA increased by 20.6°F (11.4°C) and the relative humidity approached 90 %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 1°F (0.6°C) of the measured average air temperature.

## 2. INTRODUCTION

If an accident occurs in an underground coal mine, miners who fail to escape from the mine can enter the RA for protection from adverse conditions, such as high carbon monoxide levels. One of the main concerns with the use of mobile RAs is the thermal environment inside the RA 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) does not exceed 95°F (35°C) when the RA is fully occupied. However, a standard method to determine compliance with this metric does not exist. The heat transfer process within and surrounding a RA is very complex, and is not easily defined analytically or experimentally.

OMSHR conducted heat and humidity testing on a ten-person tent-type RA in its Safety Research Coal Mine (SRCM) in a test area that was isolated from the mine ventilation system. Tests were conducted with sensible heat only and with a combination of sensible and latent heat. During the testing, numerous parameters were measured: heat input to the chamber, the air temperature and relative humidity inside the RA, the heat flux through the tent's surfaces, the air temperature in the mine, the mine strata temperatures versus depth, and the airflow inside and outside the chamber. RadTherm 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. Sensible and latent heat were used in wet model, and sensible only heat was used in dry model. The barrels were modeled with and without moisture input. We only present results for dry model in this paper.

## 3. HEAT PRODUCTION AND TRANSFER WITHIN A RA

There are various levels of research needed to quantify the heat production and transfer within a confined space such as a refuge chamber. 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 96.8°F (36°C) and 100.4°F (38°C) [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 a RA include metabolic activity and heat contributed from equipment, such as the carbon dioxide ($CO_2$) scrubbing system. Heat within a RA can also be dissipated thro ugh mechanisms like conduction, convection, radiation, evaporation from people, 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 kg will deliver 117 W of heat to the environment. The experimental setup and thermodynamic model proposed in this paper will use this value as the input rate.

Heat transfer to and from the body occurs from convective transfer (air movement), radiant transfer, and respiration (heat in exhaled/inhaled air). Since 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 allows heat to move from the body's core to the skin, where it can be lost through convection, radiation, conduction, and perspiration. Sweating occurs when convection, radiation, and respiration become insufficient to dissipate the accumulation of heat from metabolic and environmental sources. Evaporation of sweat absorbs significant amounts of heat from the skin--far more than convection, radiation, and respiration combined--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 at 50% RH to ~1.3 L/hr at 80% RH at air temperature of 95°F (35°C) [5]. Therefore, high humidity will reduce the effectiveness of the body's most effective heat-loss mechanism.

## 4. IN-MINE EXPERIMENTS

Tests were conducted underground in the SRCM at the NIOSH research laboratory in Pittsburgh, PA. A tent-type RA with a 42-inch-high tent, an internal volume of roughly 540 $ft^3$ (15 $m^3$), and a floor surface area of about 150 $ft^2$ (14 $m^2$) (Fig. 1) was used for these tests. This RA meets the unrestricted surface area requirement of 15 $ft^2$ per miner specified in 30 CFR 7.505 for up to 10 people, and it meets the unrestricted volume criteria of 60 $ft^3$ per miner for seam heights up to 54 in (137 cm), mandated for RA manufacturers by 2018. Both tested RA and production RAs have a metal box attached to the tent to serve as mechanical room and airlock. The metal box portion of the RA was 82 in (208 cm) wide by 78 in (198 cm) long.

(a)

(b)

(c)

Fig. 1. Ten-person tent-type RA (a) during being deployment,
(b) after being deployed, and (c) interior view.

Importantly, even though the testing was conducted on a training model, the test results are expected to be similar to those observed for similar production tent-type mobile RAs. As with production RAs, the capacity for this model was determined using MSHA's volume and surface area requirements. In addition, the materials and construction of the training RA are similar to production models. The most significant difference between them is that the metal box of the tested RA was shortened by one compartment and, thus, did not include the steel cylinders which contain compressed air. It should be noted that the thermal mass of the steel box of the tested RA is lower than that of the steel box that would be used with a production RA. However, this is expected to have only a minimal effect on the measured data. At the end of a 96-hour test period, it is expected that the final temperature of a production RA with the same tent and a production-sized steel box containing the cylinders would be slightly lower than the temperature observed for the training RA. However, the difference in temperature rise at the end of the mandated 96 hours would be expected to be on the order of only 10% to 15% [6].

According to Bauer and Kohler [4], each simulated miner dissipates 117 watts (metabolic heat) at steady state. An additional 170 BTU/hr (50 watts) of heat per simulated miner was input to represent the heat generated by a lithium hydroxide scrubbing system for all testing [6]. So the total heat input will be 1670 watts for all ten miners at steady state.

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 19.4 $ft^2$ (1.8 $m^2$) surface area of the human body [7]. NIOSH OMSHR developed its own simulated miners (Fig. 2) using commonly available 30-gallon (0.11-$m^3$) steel drums, thin-walled aluminum pipes, two aquarium air pumps, an aquarium water pump, and two silicone encapsulated electrical resistance heaters with a nominal power rating of 120 watts at 120 volts 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 14.5 $ft^2$ (1.35 $m^2$), 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].


Fig. 2. Inside view of a simulated miner.

The simulated miners were arranged to distribute the heat as evenly as possible within the deployed tent (Fig. 3). Due to the limited height within the tent, the simulated miners had to be positioned with an uneven spacing so they would not touch the inflatable support tubes. For all testing, the actual heat input was measured using 2-watt transducers (Flex-Core, model PC5-019CX5), one for each group of five simulated miners. The ten-person tent-type RA was deployed underground in the SRCM. 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.

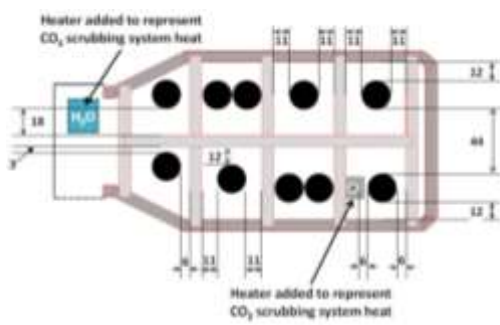


Fig. 3. Layout of simulated miners and heaters to represent
carbon dioxide scrubber heat (all dimensions in inches).

Two Data Translation DT9874 data acquisition systems were used to record all sensor/transducer channel data. During the test, all data was acquired at a rate of 1 sample every 100 seconds with 24-bit resolution.

### 4.1 Test Setup

The RA was positioned in the SRCM 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. A brattice cloth was installed to prevent bulk airflow into the test area. The encapsulated test area was approximately 150 ft. (45.7 m) long, 100 ft. (30.4 m) wide and 71 inch (1.8 m) high (Fig. 4).

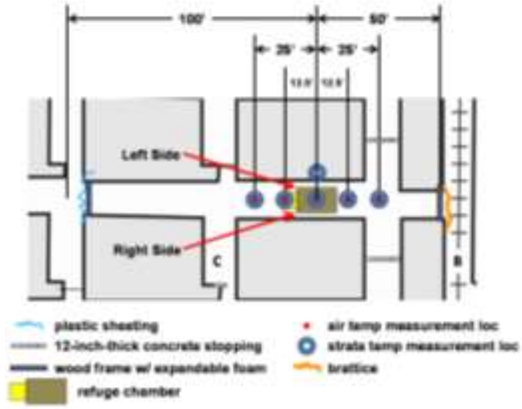


Fig. 4. Schematic of test area in the SRCM showing RA and mine air and strata measurement locations.

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, RA surface temperature, and the heat flux through the surface of the RA (Fig. 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 10 ft/min (0.05 m/s) and are not sensitive to flow direction. Measuring the airflow is important because any heat transfer simulation requires the specification of the convection coefficient which is directly related to the air velocity.

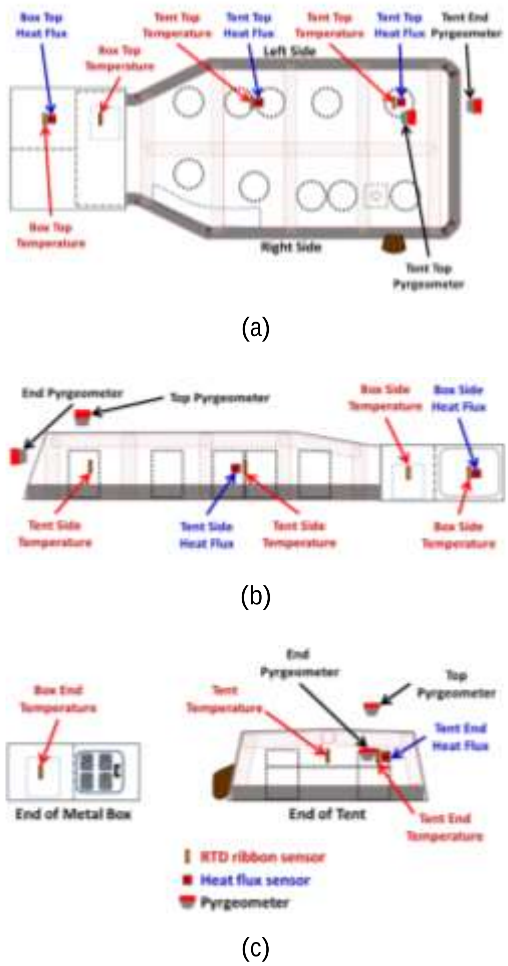


Fig. 5. Sensor location of RTD ribbon, heat flux, and pyrgeometers: (a) top view, (b) left side view, and (c) end view.

Seven resistance temperature detectors (RTDs) were used to monitor the heat transfer into the mine floor beneath the tent (Fig. 6). Three 72-inch-long (183-cm-long) averaging RTDs were positioned between the tent bottom and the mine floor. One was positioned beneath the simulated miners on the right side of the tent, one was placed beneath the simulated miners on the left side of the tent, and one was located beneath the center of the tent. Each of these was oriented with its long axis parallel to that of the tents


Fig. 6. Sensor location of 72-inch-long averaging RTDs between tent bottom and mine floor strata.

An assumption made by prior research efforts was that a mine does not change its temperature when subjected to heat by an occupied RA [7] [9]--hence the mine strata behaves as an infinite heat sink. To check this assumption, the floor strata temperature beneath the center of the tent was measured at depths of 12, 24, 36, and 48 in (30.5, 61.0, 91.4, and 121.9 cm) by installing a PVC rod with four RTDs attached to its outside and covered with thermally conductive epoxy. To install the instrumented PVC rod, a 1-inch-diameter (2.54-cm-diameter) hole was drilled into the mine floor, the outside of the PVC rod was coated with thermally conductive paste, and the rod was pushed into the hole.

The temperatures on and within the mine roof and rib strata were also measured using RTD-instrumented PVC rods as described above. The mine rib strata temperature was measured next to the center of the tent at midheight of the mine on the rib surface and at depths of 12 and 48 in (30.5 and 121.9 cm). The mine roof strata temperature was measured directly above the center of the tent. At each of these locations, the roof strata temperature was measured on the surface and at depths of 12 and 48 in (30.5 and 121.9 cm). The air temperatures within the test area were measured using 48-inch-long (122-cm-long) RTDs by averaging their readings at eight locations.

### 4.2 Test procedure

Unlike a real 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.

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, one-inch-thick fiberglass insulating blanket (R-value of ~3.14) and the top of each was covered with a one-inch-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 410 BTU/hr (120 watts) at 120 volts. At the beginning of the tests, both the steady state heater and the preheater for each simulated miner were turned on and the surface temperatures at the midheight of two of the simulated miners were monitored. The preheaters were turned off and the insulation was removed when the temperatures mentioned above reached approximately 95°F (35°C)--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 RA atmosphere.

## 5. 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 1°F (0.56°C) 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 100 seconds to a sample rate of 1 sample per 15 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 (Fig. 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 was approximately 24°F. The temperatures at midheight at the box end (labeled X19-Bx End Temp on Fig. 7), tent end (labeled X21-Tnt End Temp), and center of the tent (labeled X8-DBT) were within about 1.5°F of each other throughout the test. At the center of the tent, the data show the air temperature near the top of the tent was about 2.5°F higher than the temperature at midheight, and about 5.8°F higher than the temperature near the tent floor.

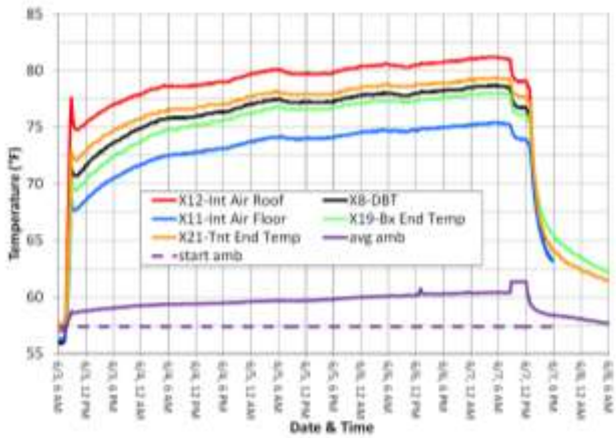


Fig. 7. RA internal air temperatures at various spots and average mine air temperature.

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 (Fig. 8). As depth into the floor strata increased, the temperature increased less and at a lower rate. The temperature measured between the tent and mine floor increased by almost 10°F in the first 24 hours. By the end of four days, the temperature between the tent and the surface of the mine floor strata increased by 14.5°F; the temperature at 12 inches deep increased by 6.2°F; the temperature at 24 inches deep increased by 2.6°F, the temperature at 36 inches deep increased by 1.5°F, and the temperature at 48 inches deep increased by 0.9°F.

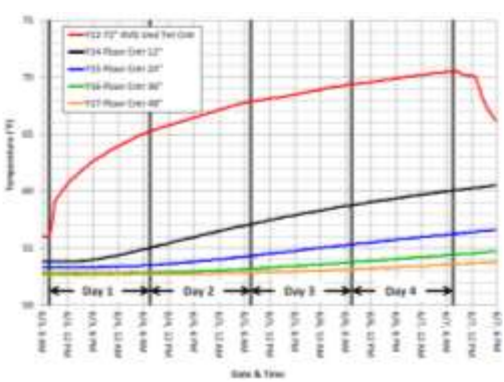


Fig. 8. Mine floor strata temperatures under the tent during the 96-hour test.

As Fig. 7 and Fig. 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 average mine air temperature computed from the eight sensors in the test area increased by just over 3°F for the test. Because the mine strata temperatures increased, it is clear that the mine does not act as an infinite heat sink. The in-mine test data showed that the strata temperatures at a depth of 4 ft. remained nearly constant throughout the tests. Therefore, thermal simulation models of a RA in an underground coal mine should include at least a four-foot-thick layer of mine strata. The temperature at a depth of 4 ft. can then be assumed to remain constant at the temperature corresponding to the mine that the model is to represent [6].

## 6. THERMAL SIMULATION MODEL DESCRIPTION

A RadTherm model of the SRCM 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. The 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. RadTherm is a validated heat transfer prediction software tool. RadTherm applies a multi-physics approach to solve for thermal conduction, radiation, convection, and moisture transport under both steady-state and transient conditions.

Fig. 9 shows a cut-away view of the tent-style training RA. The ten steel barrels inside of the RA are the simulated miners that were used to represent people in the testing. The mine strata was represented in RadTherm with a shell element mesh, while the thickness (volume) was defined virtually. The mine strata was modeled as a six-foot layer that was discretized into 24 three-inch-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. Two 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.

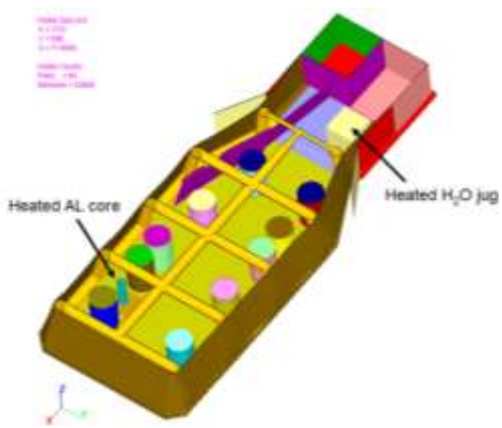


Fig. 9. Cut-away view of mine shelter with ten barrels (simulated miners) and two auxiliary heaters.

Table 1. Material properties used in the model1.

| Material | Location | Thermal conductivity (W/m-K) | Density (kg/m3) | 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 |

### 7. MODEL VALIDATION

To validate the accuracy of temperature prediction of the RadTherm mine shelter model, the transient thermal response predicted by the model was compared to physical measurements collected by NIOSH [6]. A plot comparing the transient temperatures predicted by the model to the experimental data are shown in Fig. 10. The figure shows comparisons for one of the simulated miners, the RA interior air, and the mine floor under the tent at two different locations. An average of the two 48" RTDs (x11 and x12) was used for the tent interior air temperature because the RadTherm model calculates a single average air temperature for the entire shelter interior. For the mine floor temperature, an average of predicted element temperatures over 1 Provided by RA manufacturer. a 72-inch distance was used to compare the model results to the 72-inch-long averaging RTDs used in the physical test.

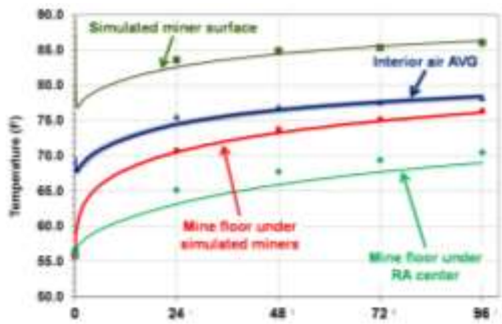


Fig. 10. Simulated (solid line) vs. measured (dot marker) temperature results for RA interior and mine floor under the RA.

Table 2 summarizes the results of the RadTherm model validation at the end of the 96-hour test. The predicted average air temperature within the shelter is only 0.25°F higher than the measured air temperature. The predicted temperatures on the simulated miner and tent side also match the measured temperatures very closely. The model under-predicts the temperatures on the top of the tent because warm air flowing out of the barrels was not accounted for in the model, and air stratification was not modeled within the tent.

Fig. 11 shows an infrared image taken during a preliminary test in a high bay at OMSHR. The image shows significant hot spots where the hot air from the barrels impinges on the tent. As a contrast, Fig. 12 shows a contour plot for the simulated tent surface temperature at the end of 96-hour test.

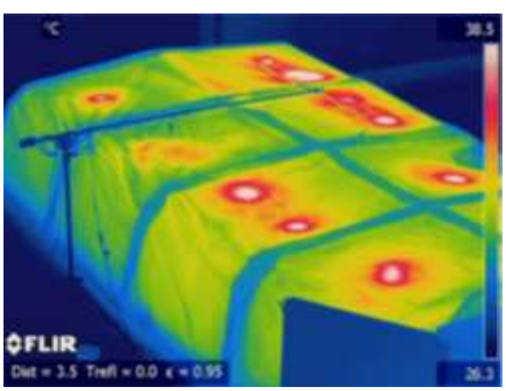


Fig. 11. Infrared image of tent with hot spots due to warm air from barrels.

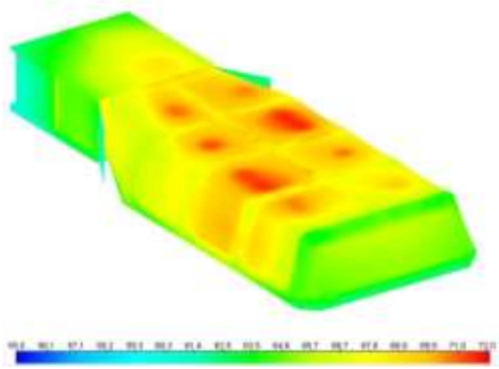

Fig. 12. Final RA surface temperature contour plot (simulated).

As shown in Table *2*, the mine strata temperature predictions may be off 3°C-4°C due to uncertainty in rock thermal properties such as the rock types, thickness, and their specific thermal properties.

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

| Sensor location | Sensor # | Prediction Error (°F) |
|---|---|---|
| Tent air average | x11 and x12 | 0.25° |
| Simulated miner #5 | x0 | 0.26° |
| Tent top | y6 | -4.44° |
| Tent side | y7 | 0.36° |
| Case top | y2 | -1.60° |
| Mine floor under barrels 72" average | y11 | -0.24° |
| Mine floor under tent middle 72" average | y12 | -1.47° |
| Mine floor under tent middle, 12" depth | y14 | 3.46° |
| Mine rib surface adjacent to tent | y22 | 2.94° |
| Mine roof surface above tent | y25 | 1.46° |
| Mine roof surface above case | y33 | -0.45° |

## 8. CONCLUSIONS AND REMARKS

In this paper, the use of the test results to validate a thermal simulation model was discussed. The test results using sensible and latent heat showed that the average measured air temperature within the RA increased by 20.6°F (11.4°C) and the relative humidity approached 90%RH. The transient thermal response predicted by the RadTherm model was compared to physical measurements collected in the OMSHR in-mine test. The RadTherm model predicted the average tent interior air within 0.25°F of the physical measurements after 96 hours. The maximum prediction error was 4.44°F for a point on the top of the tent. The error at this point can be explained by a lack of air stratification in the model, and not accounting for hot air flowing from the top of the barrels and impinging upon the top of the tent. The validation could be taken further by accounting for these air flow details with CFD models coupled with the RadTherm thermal model. Uncertainties in the rock properties could also be addressed by taking core samples and performing conductivity and specific heat tests.

The validated model could be used to extend the analysis to include RadTherm models of real humans instead of models of simulated miners. The RadTherm human thermal model could then be used to predict the transient core temperature response of shelter occupants. Further studies could use the core temperature response to determine safety limits for mine ambient temperature and number of shelter occupants.

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