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Temperature Rise Within a Mobile Refuge Alternative—Experimental Investigation and Model Validation

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Abstract

Mine Safety and Health Administration (MSHA) regulations require underground coal mines to install refuge alternatives (RAs). In the event of a disaster, RAs must be able to provide a breathable air environment for 96 h. The interior environment of an occupied RA, however, may become hot and humid during the 96 h due to miners' metabolic heat and carbon dioxide scrubbing system heat. The internal heat and humidity may result in miners suffering heat stress or even death. To investigate heat and humidity buildup with an occupied RA, 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 showed that the average measured air temperature within the RA increased by 11.4°C (20.5 °F) 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 h to within 0.6 °C (1.1 °F) of the measured average air temperature.

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1 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 thermal environment inside the RA. The metabolic heat of the occupants and the heat released by the CO_2 scrubbing system will cause the interior air temperature to increase. 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 internal thermal conditions can result in miners suffering heat stress, heat stroke, or even death. MSHA regulations require that RAs should be designed to ensure that the internal apparent temperature does not exceed 35 °C (95 °F) when the RA is fully occupied [1]. Apparent temperature is a temperature-humidity metric for the perceived temperature caused by the combined effects of air temperature, relative humidity, and wind speed. It is used to assess the perception of indoor temperatures when workplaces are not sufficiently heated, cooled, or insulated to provide comfortable or healthy conditions.

An RA is a protected, secure space with an isolated atmosphere and integrated components that create a life-sustaining environment for persons trapped in an underground coal mine. The primary function of an RA is to provide safe refuge for miners unable to escape their work area immediately after a disaster due to toxic gases or a blocked escapeway. To be effective, the RA must survive the initiation of the disaster, whether it is an explosion or fire. Furthermore, it would also be beneficial if the miners inside the RA were protected from the blast impacts of a secondary explosion.

Before a mobile RA can be deployed at an underground mine for emergency usage, it must be tested so that its internal apparent temperature when occupied will not exceed the 95 °F limit. However, for practical reasons, RA manufacturers usually can only conduct their tests at facilities different from the mining environment. NIOSH conducted its heat and humidity testing on a ten-person tent-type RA in its SRCM in a test area that was isolated from the mine ventilation system. Tests were conducted with sensible heat only (without moisture generation) and with a combination of sensible and latent heat (with moisture generation). During the testing, a number of 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 (comprised of rock, clay, coal, etc.) temperatures versus depth, and the airflow inside and outside the chamber.

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. Although tests were conducted for both wet and dry conditions (with and without moisture generation), we only present simulation results for the dry model in this paper.

2 Heat Production and Transfer Within an RA

The heat transfer process within and surrounding an RA is very complex, and is not easily defined analytically or experimentally. 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 can also be dissipated through mechanisms such as conduction, convection, radiation, evaporation of sweat from RA occupants, and condensation on the RA interior.

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 [2]. The human body maintains a normal core temperature between 36 °C (97 °F) and 38 °C (100 °F) [3]. In hot environments, the body is able to cool itself via the evaporation of sweat to maintain a viable core temperature.

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 [4,5]. According to Bauer and Kohler [5], a person weighing 75 kg will deliver 117 W of heat to the environment. The experimental setup and thermal simulation model proposed in this paper used this value as the input rate.

Heat transfer to and from the body occurs from convective transfer (air movement), radiant transfer, evaporation of sweat, 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 to the floor can be significant, provided that the value of thermal resistance and thickness of the tent material is low. 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/h at 50% RH to ~1.3 L/h at 80% RH at an air temperature of 35 °C [6]. Therefore, high humidity will reduce the effectiveness of the body's most effective heat loss mechanism.

3 In-Mine Experiments

3.1 Tested RA

Tests were conducted underground in the SRCM at the NIOSH research laboratory in Pittsburgh, PA. 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 (the side of a pillar or the wall of an entry). A brattice cloth was installed to prevent bulk airflow into the test area. The encapsulated test area was approximately 45.7 m long, 30.4 m wide, and 1.8 m high (150 × 100 × 5.9 ft) (Fig. 1).

A tent-type RA with a 1.07-m-high (3.5 ft) tent, an internal volume of roughly 15 m^3 (530 ft^3), and a floor surface area of about 14 m^2 (151 ft^2) (Fig. 2) were used for these tests. This RA meets the unrestricted surface area requirement of 1.4 m^2 (15 ft^2) per miner specified in 30 CFR 7.505 for up to ten people, and it meets the unrestricted volume criteria of 1.7 m^3 (60 ft^3) per miner for seam heights up to 137 cm (4.5 ft), mandated for RA manufacturers by 2018. The tested RA has a metal box attached to the tent to serve as mechanical room and airlock. The metal box portion of the RA was 208 cm (6.8 ft) wide by 198 cm (6.5 ft) long.

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 compressed air cylinders which would be included in production RAs. 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-h 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. At the end of the mandated 96 h, it is estimated that the difference in temperature rise between the training RA and a production RA would be only 10–15% [7].

3.2 Simulated Miners

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 ft^2) surface area of the human body [8]. NIOSH developed its own simulated miners (Fig. 3) 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 at 120 V to represent human metabolic heat [9]. 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. During testing, each simulated miner provided a nominal 117 W of heat at steady state. A heated water tank and a heated aluminum pipe were used to input an additional 50 W of heat per simulated miner to represent the heat of the RA's carbon dioxide scrubbing system (assuming that a lithium hydroxide scrubbing system was used) [7]. So, the total heat input will be 1670 W for all ten miners at steady state. More details on the design of simulated miners can be found in Ref. [7].

The simulated miners were arranged to distribute the heat as evenly as possible within the deployed tent (Fig. 4). The heated water tank was positioned within the metal box and the added aluminum core was positioned near the tent end of the RA to simulate CO_2 scrubbing system heat. 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.

3.3 Sensors

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 speed, 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 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.

Seven resistance temperature detectors (RTDs) were used to monitor the mine floor temperature beneath the tent (Fig. 6). Three 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.

Another four RTDs were installed in the mine floor to monitor mine strata temperature at various depths. An assumption made by prior research efforts was that a mine does not change its temperature when subjected to heat by an occupied RA [8,10]; hence, the mine strata would behave as an infinite heat sink. To check this assumption, the floor strata temperature beneath the center of the tent was measured at depths of 30.5, 61.0, 91.4, and 121.9 cm (12, 24, 36, and 48 in.) by installing a polyvinyl chloride (PVC) rod with four RTDs attached to its outside and covered with thermally conductive epoxy. To install the instrumented PVC rod, a 2.54-cm-diameter (1-in.-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 the midheight of the mine. The mine roof strata temperature was measured directly above the center of the tent. At each of these locations, the strata temperature was measured on the surface and at depths of 30.5 and 121.9 cm (12 and 48 in.).

The air temperatures within the test area were measured using 122-cm-long (48-in.-long) RTDs by averaging their readings at eight locations (Fig. 7).

3.4 Test Procedure

For all testing, the actual heat input was measured using 2W 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. Two data translation DT9874 data acquisition systems were used to record all sensor/transducer channel data. During the test, all data were acquired at a rate of one sample every 100 s with 24-bit resolution.

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.

Unlike a real miner, who is at body temperature when he or she enters an 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-h time period could be affected by this additional heat as the simulated miners are allowed to reach their operating temperature.

To address this issue, NIOSH 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, 1-in.-thick fiberglass insulating blanket (*R*-value of ~3.14) and the top of each was covered with a 1-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 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. 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 preheaters were turned off and the insulation was removed. Using this method, the simulated miners approached their steady state temperature within a few hours. Once the simulated miners were near their steady state temperature, most of the heat generated by their internal heaters was transferred to the RA atmosphere instead of contributing toward raising their temperatures.

3.5 Test Results

The RA internal temperatures during the 96-h test period are the temperatures of the most interest. Because the measured temperatures were observed to change very slowly, less than 0.4 °C (0.7 °F) over the final 24-h 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 were reduced from a sample rate of one sample per 100 s to a sample rate of one sample per 15 min.

The sensor location within the RA tent and measured temperature are shown in Fig. 8. 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. 8(*b*)). The reason for the initial rapid change in interior tent air temperature is that the temperature difference between interior tent air and heat sources (the simulated miners and heated water tanks) was at a maximum at the beginning of the test. Meanwhile, both the steady state heater and preheater were used during that time period. The heat transfer from heat sources to tent air decreased gradually when that temperature difference was getting smaller. The initial temperature of tent air and mine air was ~12.8 °C (55 °F). At the end of the fourth day of testing, the temperature rise was approximately 13.3 °C (24 °F)[2]. The temperatures at midheight at the box end, tent end, and center of the tent were within about 0.8 °C 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 1.4 °C (2.5 °F) higher than the temperature at midheight, and about 3.2 °C (5.8 °F) higher than the temperature near the tent floor.

Note that the interior tent air temperatures have a spike where a rapid increase and then a rapid decrease exist as shown in Fig. 8(*b*). During the test, the simulated miners were heated up to reach their operating temperature (human body temperature) using both their internal steady state heaters and their internal preheaters at a nominal total of 234 W per simulated miner. As the simulated miners were heated to the operating temperature, the tent air is heated up as well. Once the simulated miners reached their desired steady state operating temperature, the power to both of the internal heaters was turned off, the fiberglass wraps and Styrofoam lids were removed, and the power to the simulated miners' steady state heaters was restored. During this process, the air temperature within the RA decreased as shown as a spike in Fig. 8(*b*).

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. 9). 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 5.6 °C (10.1 °F) in the first 24 h. By the end of 4 days, the temperature between the tent and the surface of the mine floor strata increased by 8.1 °C (14.6 °F); the temperature at 12 in. deep increased by 3.4 °C (6.1 °F); the temperature at 24 in. deep increased by 1.4 °C (2.5 °F); the temperature at 36 in. deep increased by 0.8 °C (1.4 °F); and the temperature at 48 in. deep increased by 0.5 °C (0.9 °F).

As Figs. 8 and 9 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 1.7 °C (3.1 °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 show that the strata temperatures at a depth of 1.2 m. remained nearly constant throughout the tests. Therefore, thermal simulation models of an 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 [7].

[2]Temperature change conversion formula Δ°C = Δ°F × 0.5556.

4 Thermal Simulation

4.1 Model Description

A TAITherm 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 the heaters that represent the CO_2 scrubbing system heat. 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.

TAITherm is a validated heat transfer prediction software tool. TAITherm applies a multiphysics approach to solve for thermal conduction, radiation, convection, and moisture transport under both steady state and transient conditions. The model is capable of performing large-scale transient thermal simulations that account for the thermal behavior of the surrounding mine strata and is able to account for the moisture input from simulated miners. Regardless of the heat input, the model can predict the relative humidity inside the chamber and the effects of air movement due to natural ventilation via a coupled computational fluid dynamics analysis.

Figure 10 shows a cut-away view of the tent-style training RA. The ten cylinders inside of the RA are the simulated miners that were used in testing to represent actual miners. The heated water tank and the heated aluminum core were used to simulate the CO_2 scrubbing system heat. The mine strata were represented in TAITherm with a shell element mesh, while the thickness (volume) was defined virtually. The mine strata were modeled as a 1.8-m-thick (5.9-ft) layer that was discretized into 24 7.6-cm-thick (3.0-in.) 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 NIOSH.

4.2 Validation

To validate the accuracy of temperature prediction of the TAITherm mine shelter model, the transient thermal response predicted by the model was compared to the physical measurements collected by NIOSH [7]. A plot comparing the transient temperatures predicted by the model to the experimental data is shown in Fig. 11. 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 in. 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 shelter interior. For the mine floor temperature, an average of predicted element temperatures over a 72-in. (183-cm) distance was used to compare the model results to the 72-in.-long averaging RTDs used in the physical test.

Table 2 summarizes the results of the TAITherm model validation at the end of the 96-h test. The predicted average air temperature within the shelter is only 0.1 °C (0.18 °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 underpredicts 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. Figure 12 shows an infrared image taken during a preliminary test in a high bay at NIOSH. The image shows significant hot spots where the hot air from the barrels impinges on the tent. The hotspots are due to the warm air from barrels, which heat up the tent roof above. The high temperature difference between hotspots and ambient air results in a certain heat transfer rate. However, such hotspots may not be as strong or not present when real humans occupy the RA. In that case, most of the heat generated would be added to the RA interior air. As a contrast, Fig. 13 shows a contour plot for the simulated tent surface temperature at the end of the 96-h test.

4.3 Uncertainty

As shown in Table 2, the mine strata temperature predictions may be off 1–2 °C (1.8–3.6 °F) from the measurement data. The primary sources of error are uncertainty in mine strata properties such as rock type, thickness, and thermal properties. Uncertainties in the rock properties could also be addressed by taking core samples and performing conductivity, density, and specific heat measurements. The maximum prediction error was 2.5 °C (4.5 °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 computational fluid dynamics models coupled with the TAITherm thermal model.

5 Conclusions and Remarks

In this paper, the use of 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 11.4 °C (20.5 °F) and the relative humidity approached 90% RH. The transient thermal response predicted by the TAITherm model was compared to physical measurements collected in the NIOSH in-mine dry test. The TAITherm model predicted the average tent interior air within 0.1 °C (0.18 °F) of the physical measurements after the 96-h dry test.

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

Further studies on heat loss mechanisms, the effect of mine dimensions, sensitivity to strata composition, and the effect of initial mine air and mine strata temperatures could also help to provide insight into RA thermal characteristics under adverse environments.

Acknowledgments

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Nomenclature

CO_2 carbon dioxide

MSHA Mine Safety and Health Administration

NIOSH The National Institute for Occupational Safety and Health

***R*-value** a measure of thermal resistance

RAs refuge alternatives

RH relative humidity

RTDs resistance temperature detectors

SRCM safety research coal mine

30 CFR title 30 Code of Federal Regulations

References

1. MSHA. Regulatory Economic Analysis for Refuge Alternatives for Underground Coal Mines. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration, Office of Standards, Regulations, and Variances; 2008.
2. Johnson, D. Assessment of Thermal Environment of Mine Refuge Chamber. Carrollton, TX: Industrial Hygiene and Safety Technology, Inc.; 2008.
3. Macpherson, MJ. Subsurface Ventilation and Environmental Engineering. The Netherlands: Springer, Dordrecht; 1993. Physiological Reactions to Climatic Conditions; p. 1-42.
4. Williams WJ. 2009 personal communication.
5. Bauer ER, Kohler JL. Update on Refuge Alternatives: Research, Recommendations, and Underground Deployment. Min. Eng. 2009; 61(12):51–57.
6. Foundation, Z. How Much Sweat Can Evaporate. Tulsa, OK: The Zunis Foundation; 1998. http://www.zunis.org/Sweat_page_4.htm [accessed Aug. 2015]
7. Yantek, D. Investigation of Temperature Rise in Mobile Refuge Alternatives. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Office of Mine Safety and Health Research; 2014.
8. Brune, J. Dissipating the Heat Inside Mine Refuge Chambers. 14th U.S./North American Mine Ventilation Symposium, Society for Mining, Metallurgy, and Exploration; June 17–20; Salt Lake City, UT. 2012. p. 297-304.
9. Randall, H. Charleston, WV: Safety and Training by the West Virginia Mine Safety Technology Task Force; 2006. “Mine Safety Recommendations,” Report to the Director of the Office of Miners’ Health.
10. Fasouletos, M. Parametric Design of a Coal Mine Refuge Chamber. Morgantown, WV: ProQuest; 2007.

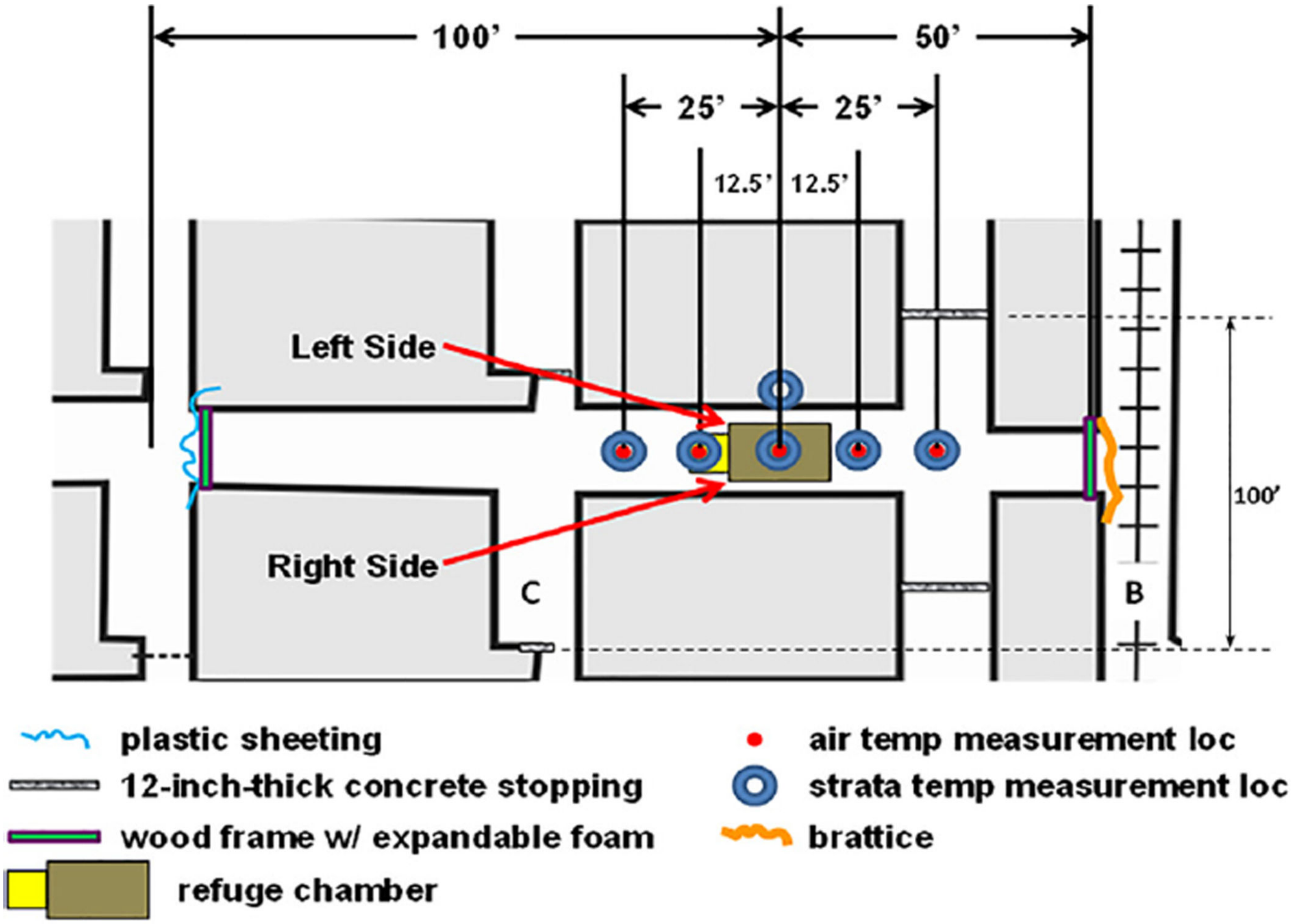

Fig. 1.
Schematic of test area in the SRCM showing RA and mine air and strata measurement locations

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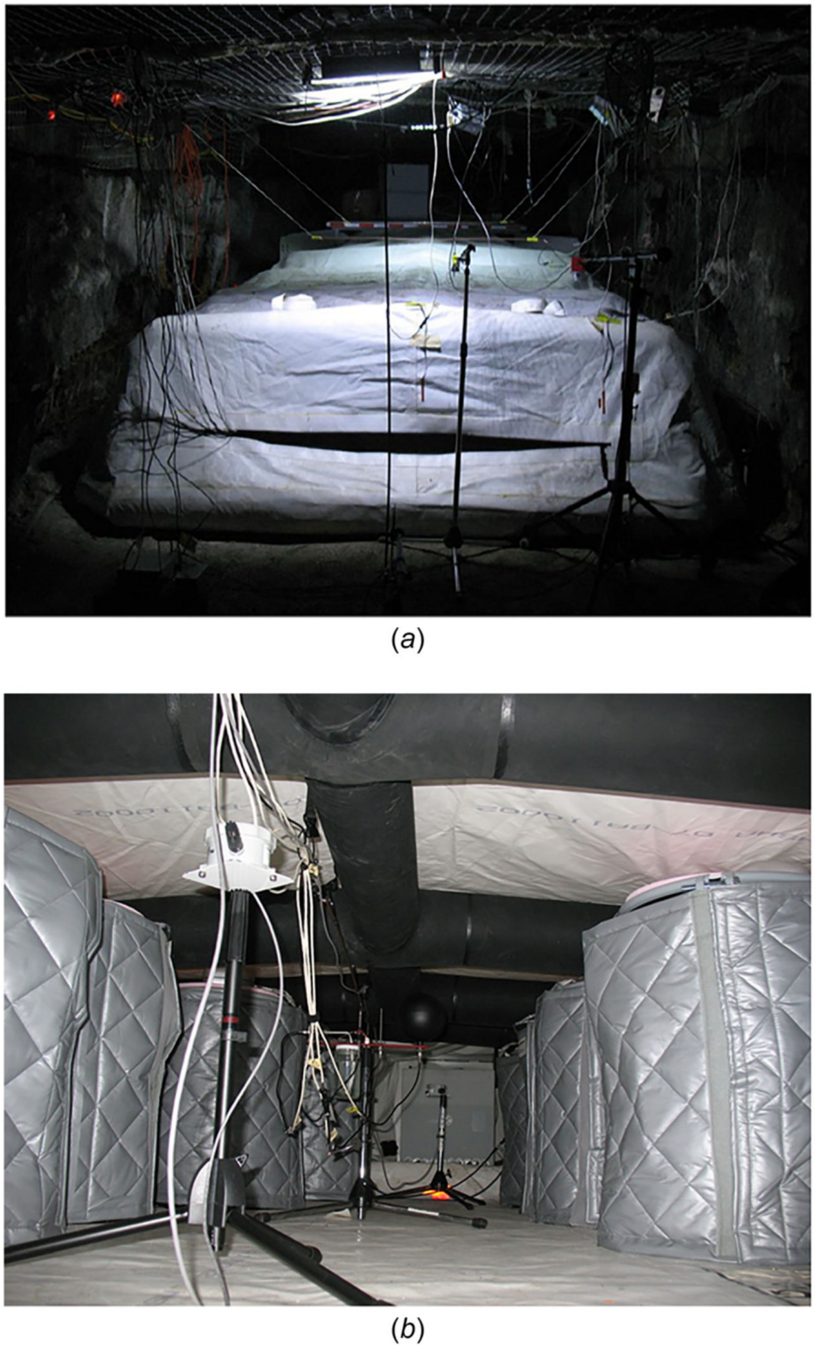


Fig. 2.

Deployed ten-person tent-type RA (*a*) and interior view (*b*)

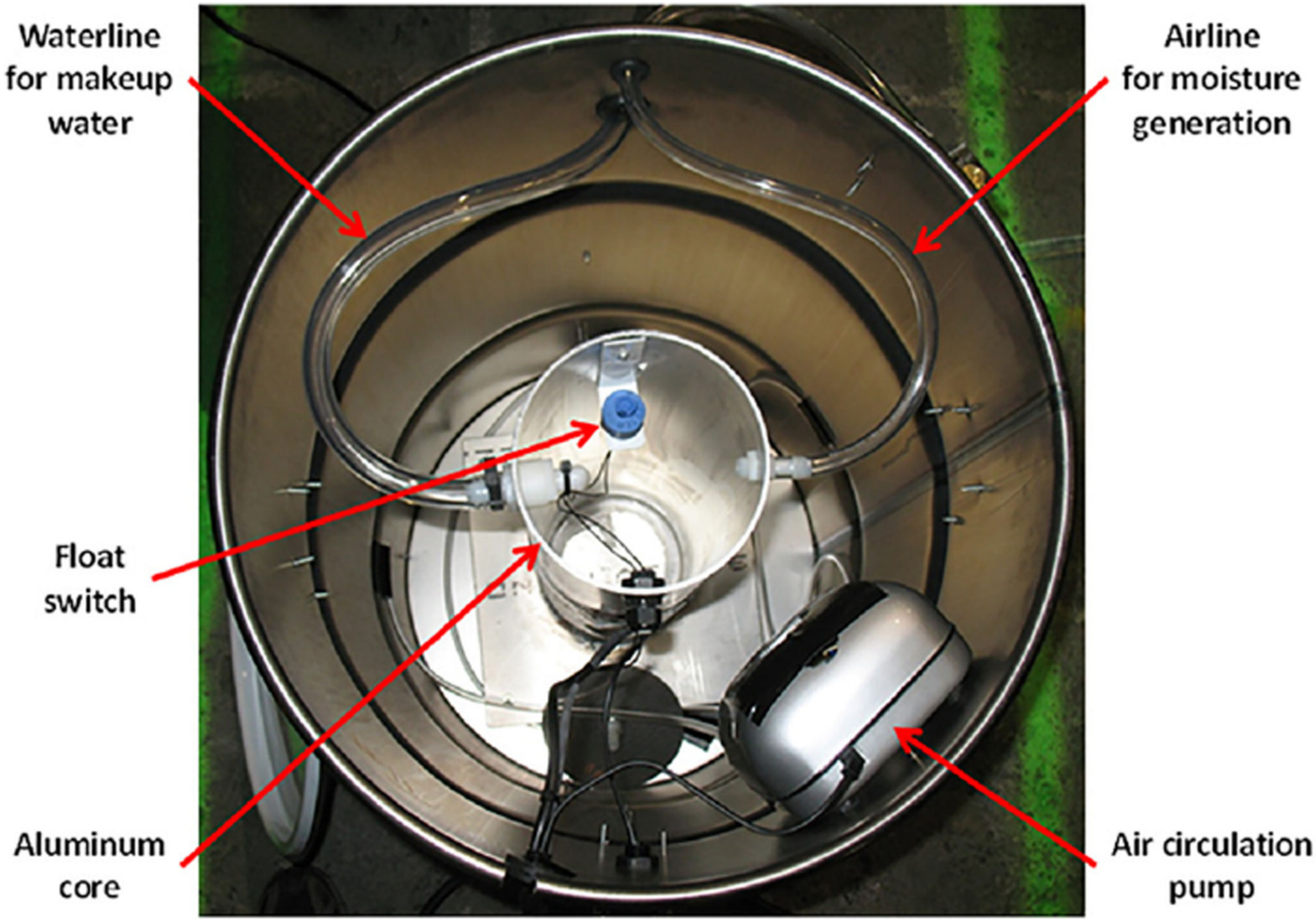


Fig. 3.
Inside view of a simulated miner

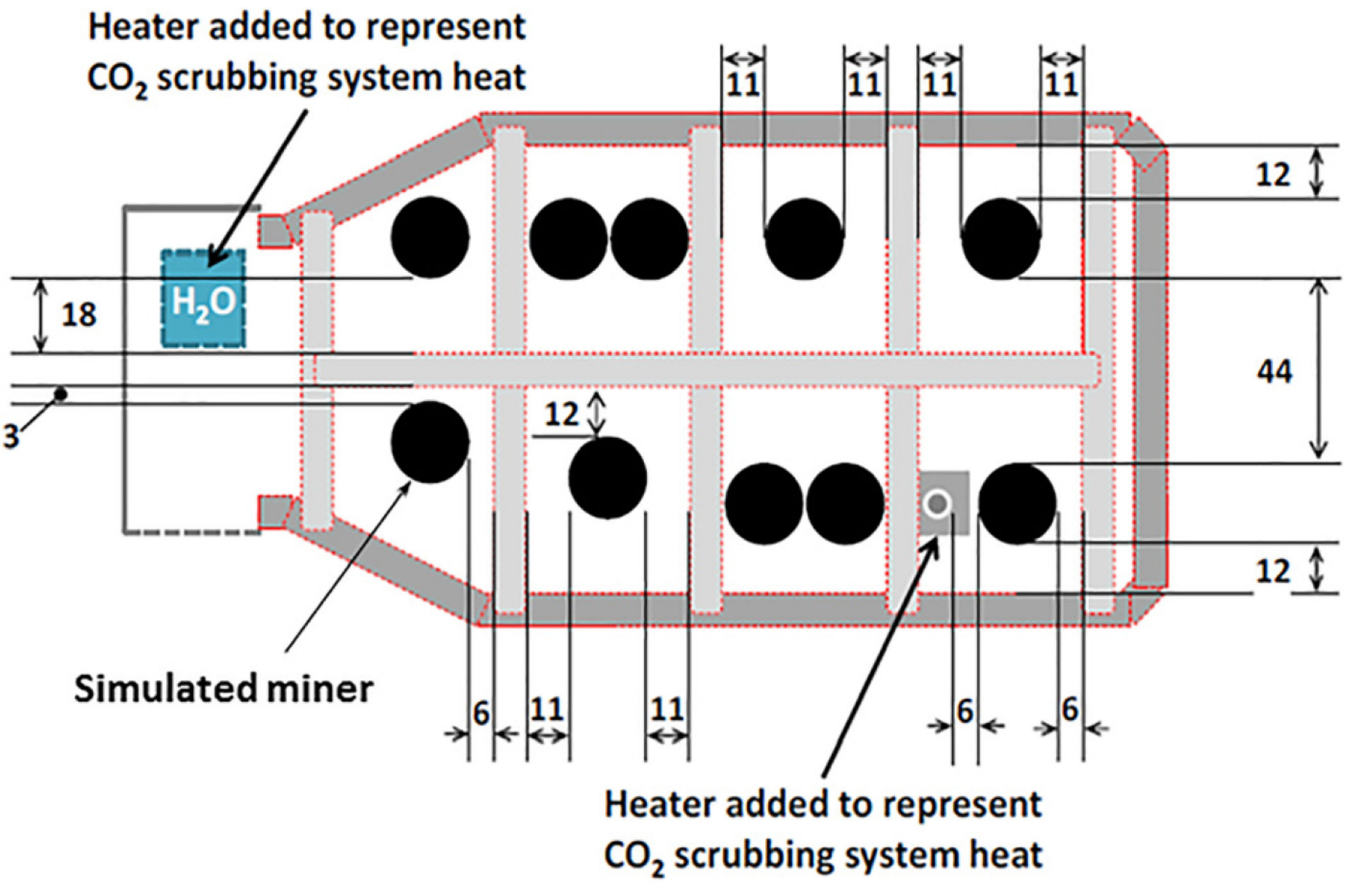


Fig. 4.

Layout of simulated miners and heaters to represent carbon dioxide scrubber heat (all dimensions in inches). The strips are the air-pressurized tubes acting as a frame for the tent RA.

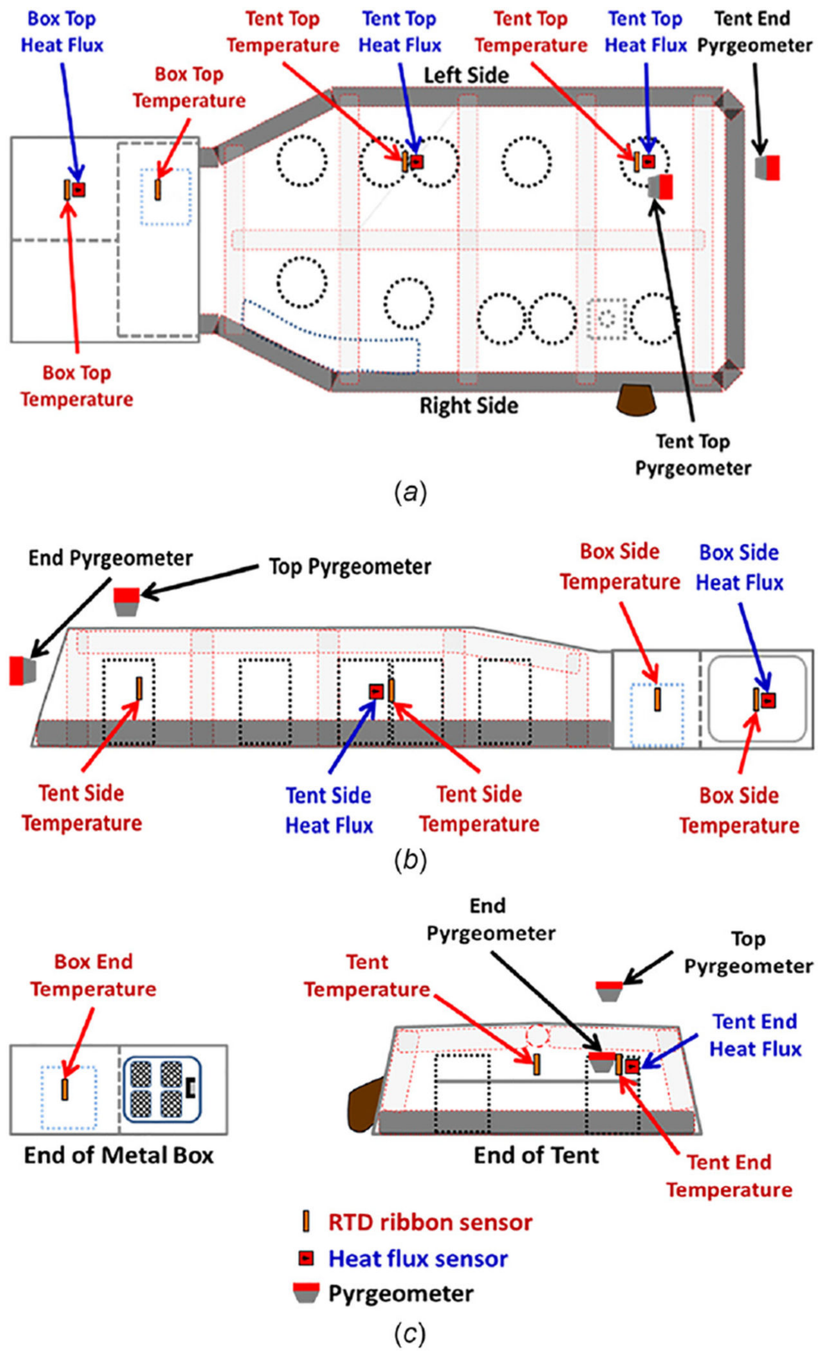


Fig. 5.
Sensor location of RTD ribbon, heat flux, and pyrgeometers: (*a*) top view, (*b*) left-side view, and (*c*) end view

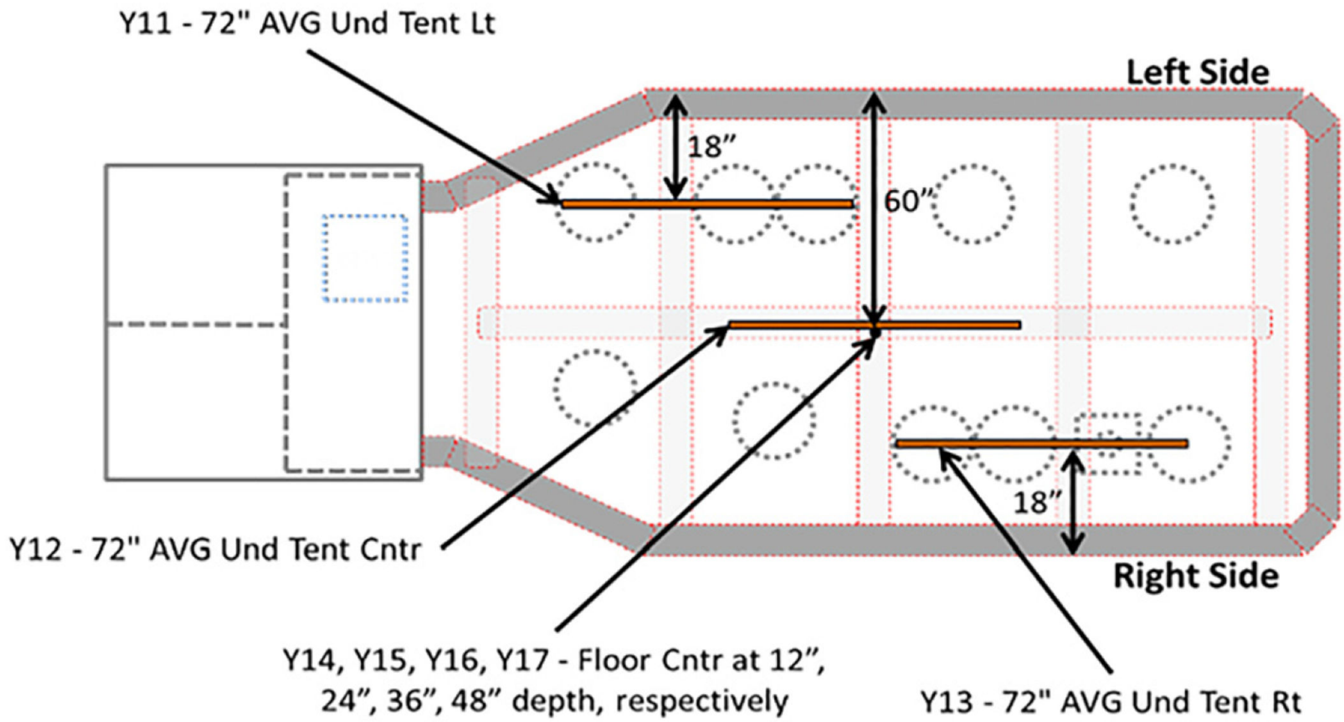


Fig. 6.

Sensor locations of 72-in.-long averaging RTDs between tent bottom and mine floor strata, and 48-in.-long RTDs measuring mine floor strata temperature at various depths

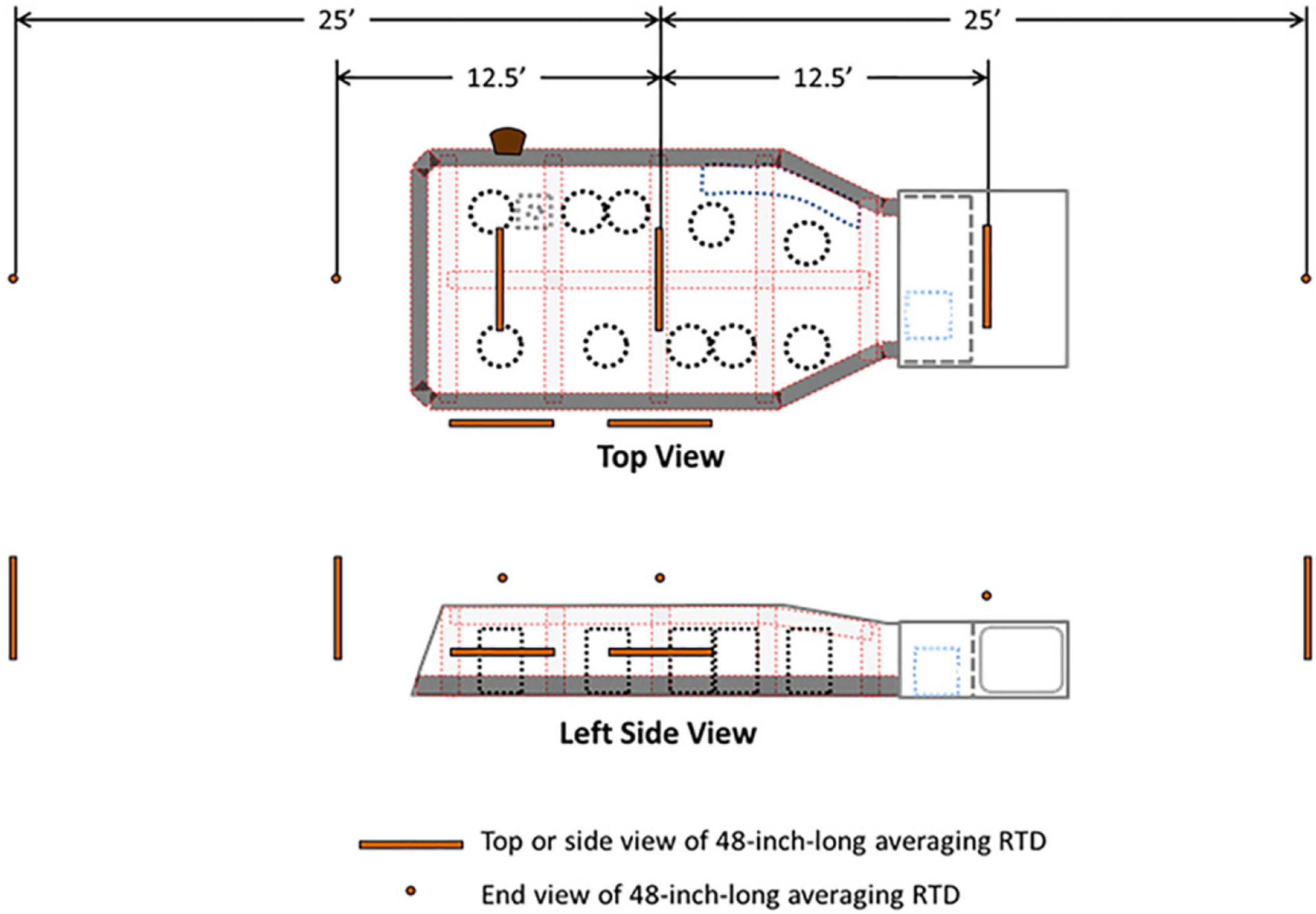
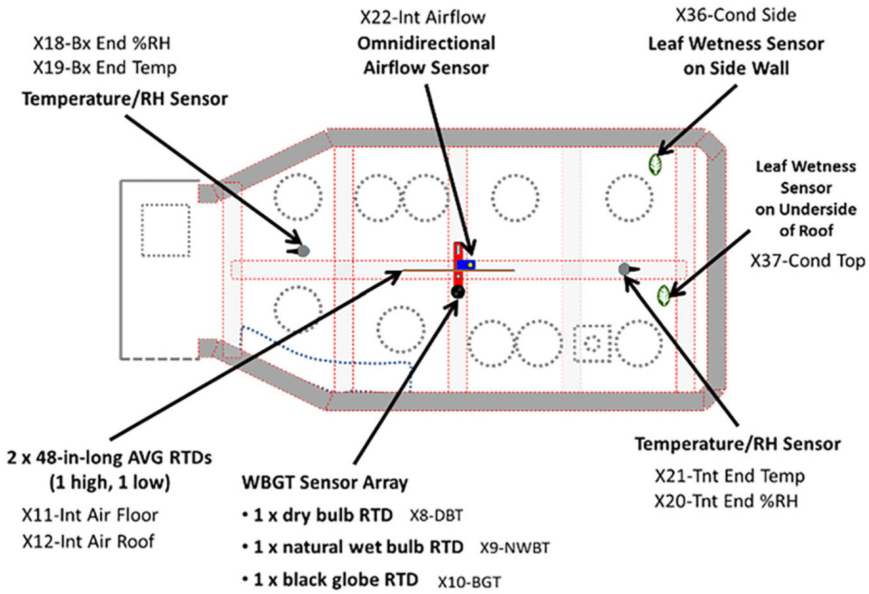
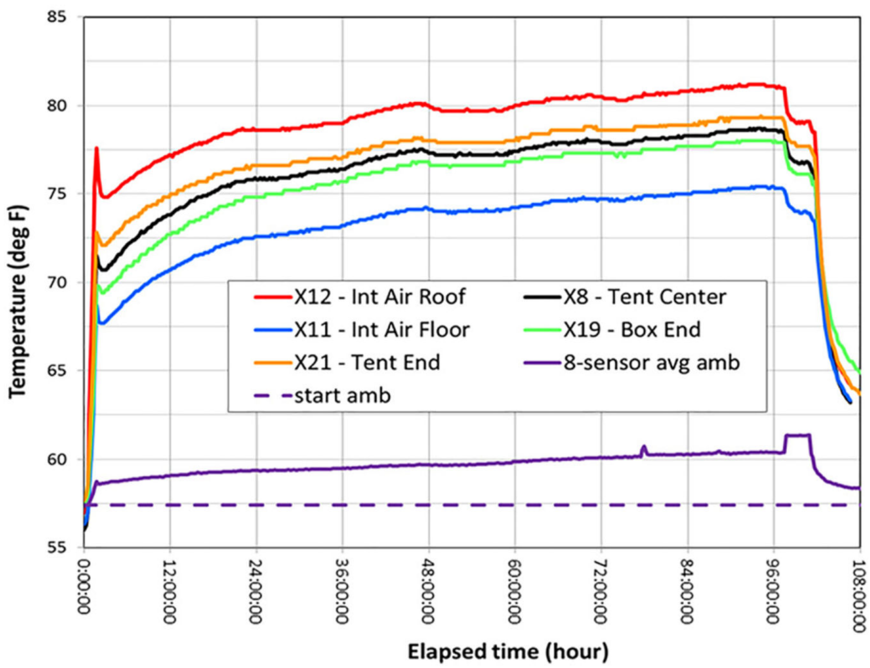


Fig. 7.

Locations of 122-cm-long (48-in.-long) averaging RTDs measuring mine air temperature within the test area



(*a*)



(*b*)

Fig. 8.

Sensor locations inside tent (*a*) and RA internal air temperatures at various spots and average mine air temperature (*b*)

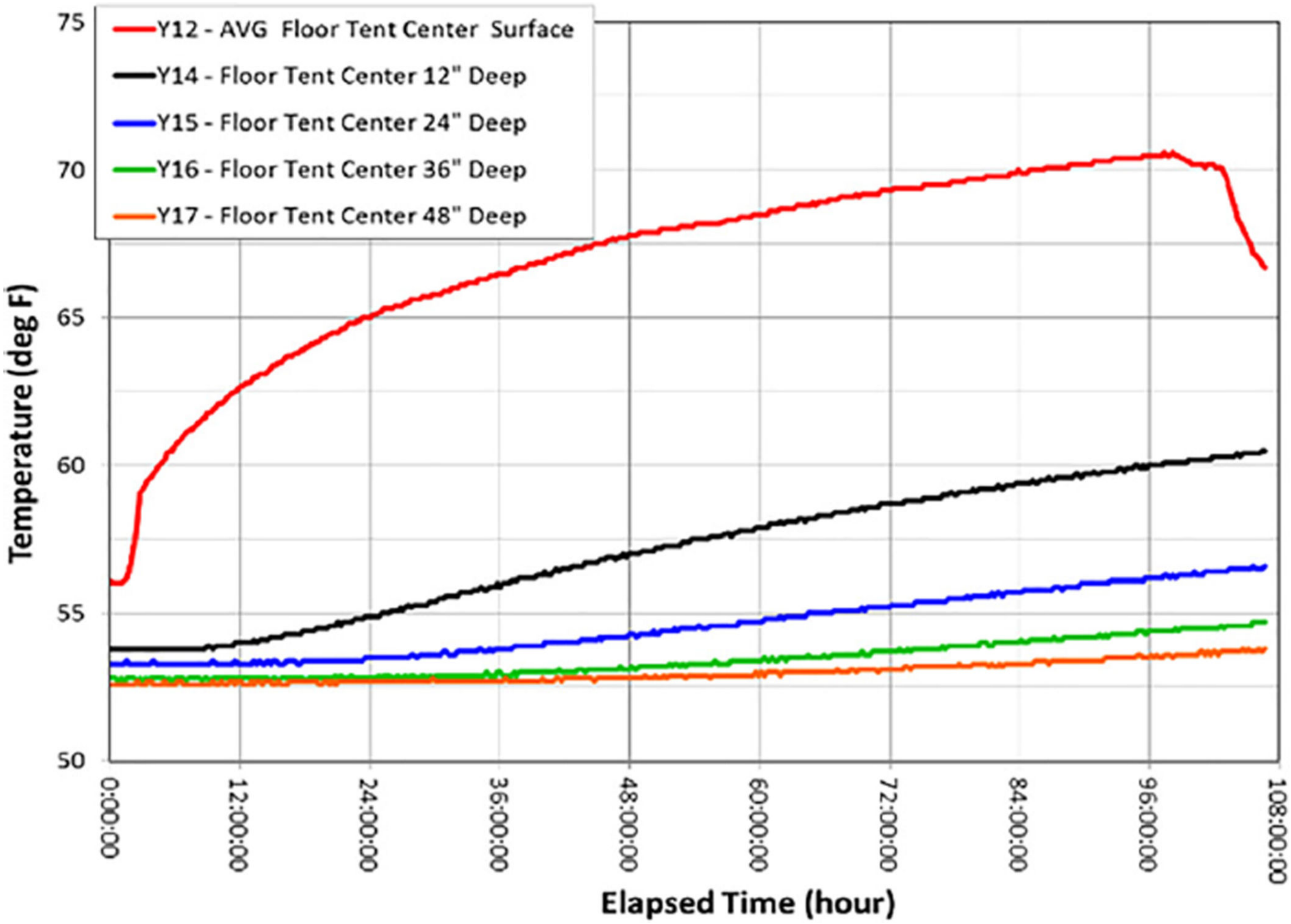


Fig. 9.
Mine floor strata temperatures under the tent during the 96-h test. The locations of the measuring sensors are shown in Fig. 6.

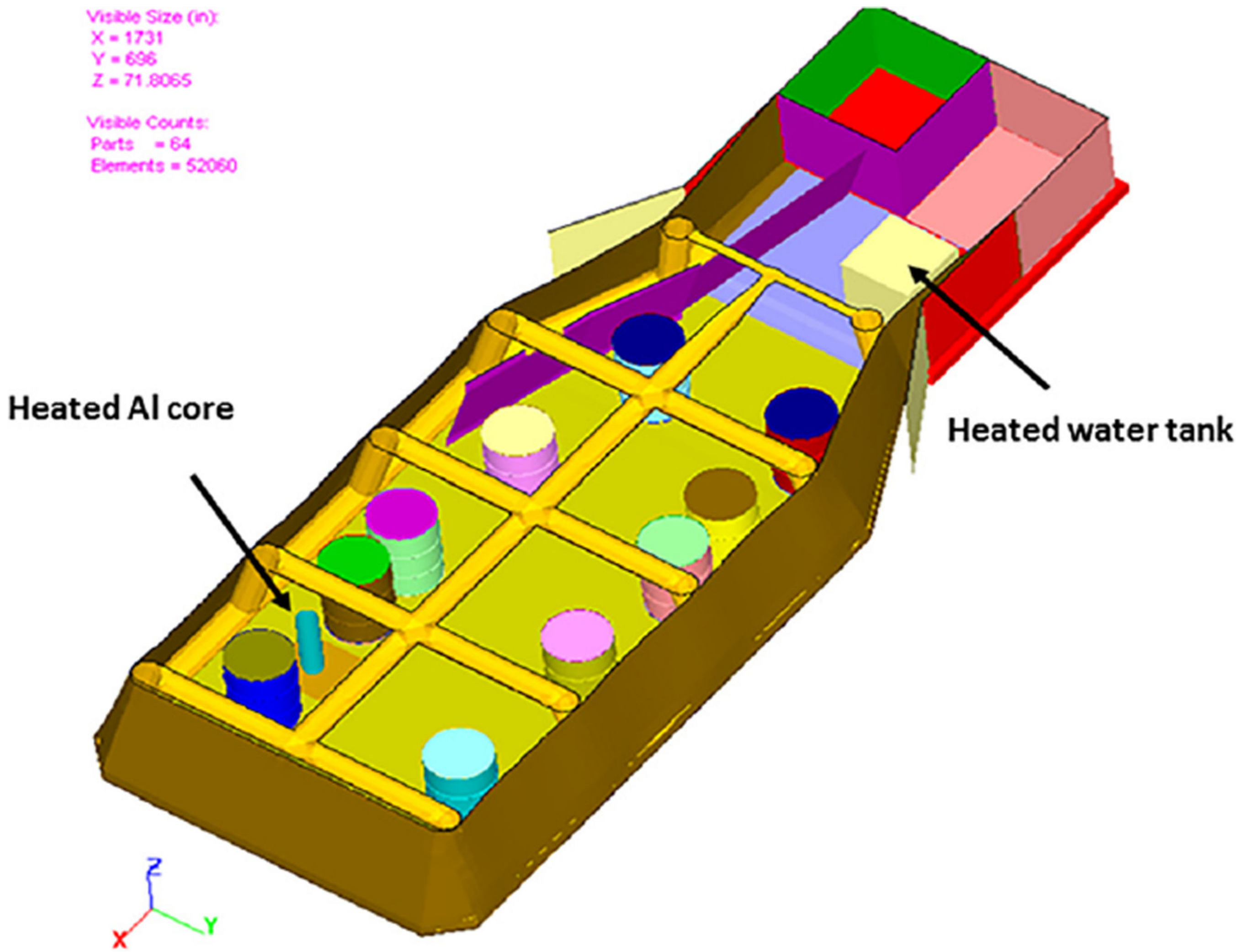


Fig. 10.
Cut-away view of mine shelter with ten barrels (simulated miners) and two auxiliary heaters

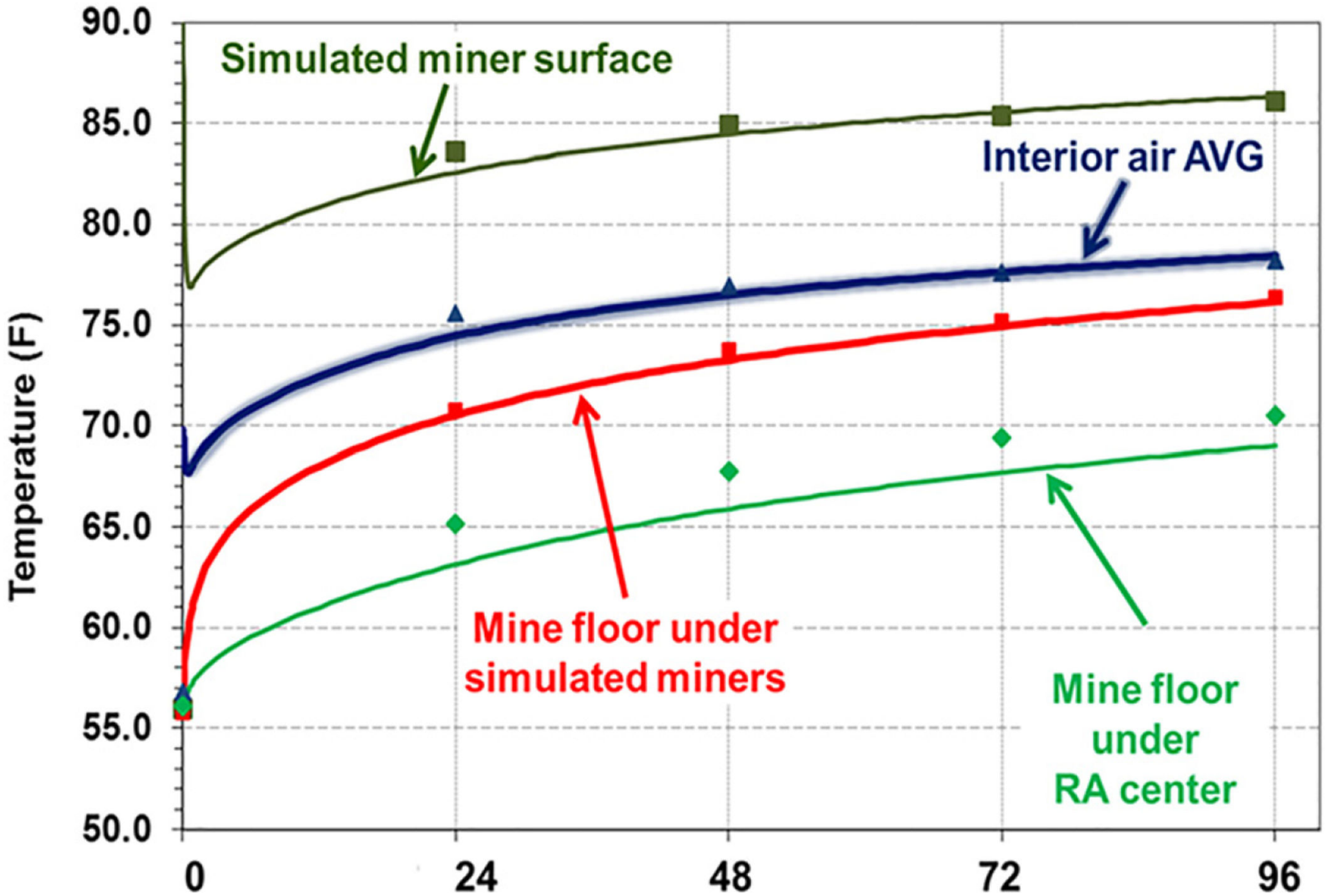


Fig. 11.

Simulated (solid line) versus measured (dot marker) temperature results for RA interior and mine floor under the RA

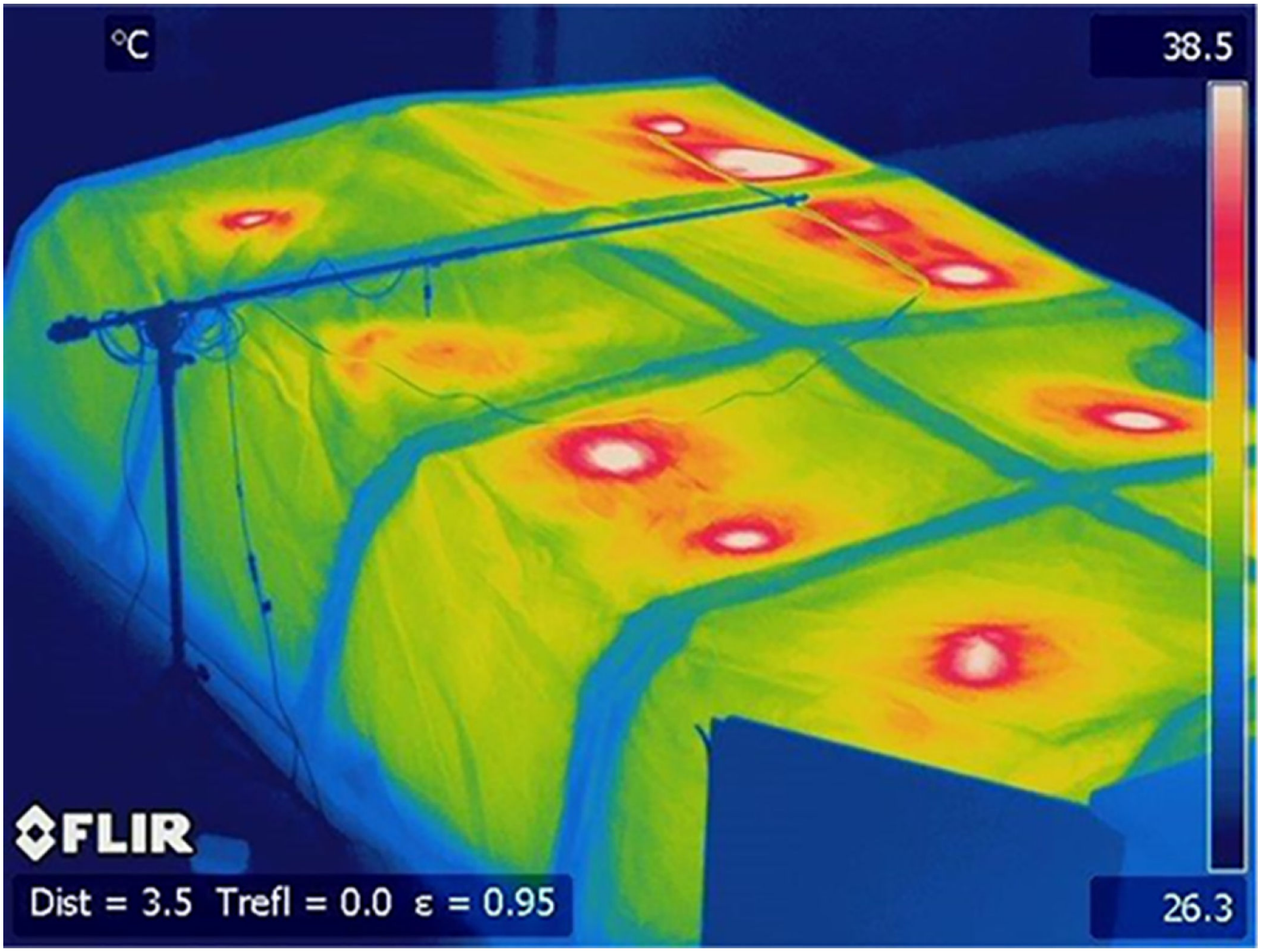


Fig. 12.
Infrared image of tent with hot spots due to warm air from barrels

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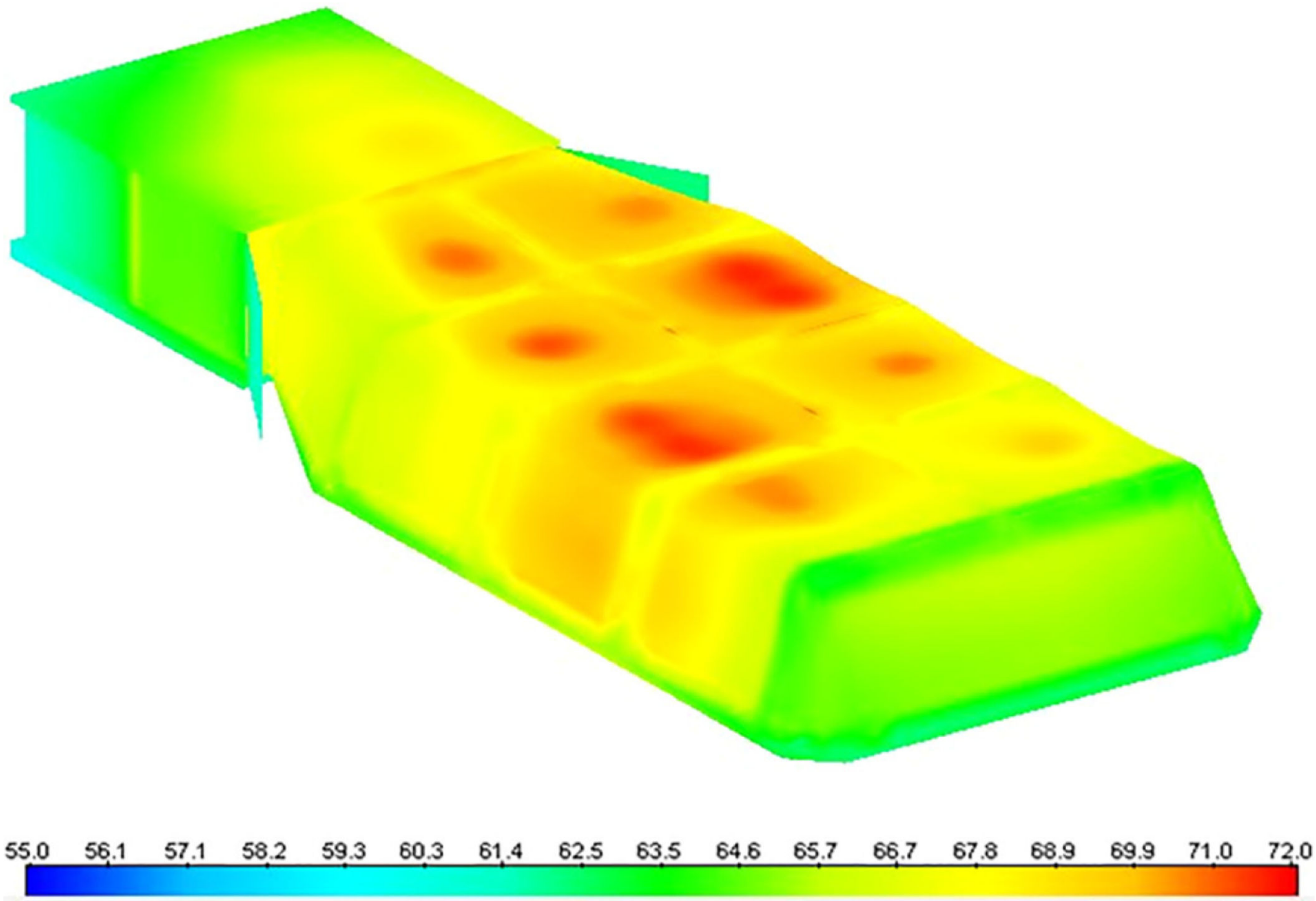

Fig. 13.
Final RA surface temperature contour plot (simulated)

Table 1

Material properties used in the model[3]

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

[3]Provided by RA manufacturer.

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Table 2

Model error summary at 96 h (positive value means over-prediction by the model, negative means under-prediction)

Sensor location	Sensor no.	Prediction error (Celsius)
Tent air average	X11 and X12	0.1
Simulated miner #5	X0	0.1
Tent top	Y6	−2.5
Tent side	Y7	0.2
Case top	Y2	−0.9
Mine floor under barrels, 72 in. average	Y11	−0.1
Mine floor under tent middle, 72 in. average	Y12	−0.8
Mine floor under tent middle, 12 in. depth	Y14	1.9
Mine rib surface adjacent to tent	Y22	1.6
Mine roof surface above tent	Y25	0.8
Mine roof surface above case	Y33	−0.3