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Analysis of heat loss mechanisms for mobile tent-type refuge alternatives

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Abstract

Federal regulations require that refuge alternatives (RAs) be located within 305 m (1,000 ft) of the working face and spaced at one-hour travel distances in the outby area in underground coal mines, in the event that miners cannot escape during a disaster. The Mine Safety and Health Administration mandates that RAs provide safe shelter and livable conditions for a minimum of 96 hours while maintaining the apparent temperature below 35 °C (95 °F). The U.S. National Institute for Occupational Safety and Health used a validated thermal simulation model to examine the mechanisms of heat loss from an RA to the ambient mine and the effect of mine strata composition on the final internal dry bulb temperature (DBT) for a mobile tent-type RA. The results of these studies show that 51 percent of the heat loss from the RA to the ambient mine is due to radiation and 31 percent to conduction. Three mine width and height configurations and four mine strata compositions were examined. The final DBT inside the RA after 96 hours varied by less than 1 °C (1.8 °F) for the three mine width/height configurations and by less than 2 °C (3.6 °F) for the four mine strata compositions.

Keywords

Refuge alternatives; RAs; Mine strata; Apparent temperature; NIOSH

Disclaimer

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Introduction

Following a mine disaster, workers will try to escape the mine. If escape is not possible, they can take shelter in a refuge alternative (RA). In 2009, the Mine Safety and Health Administration (MSHA) mandated RAs in mines to ensure that a safe and livable shelter is provided for a minimum of 96 hours, and that the apparent temperature (AT) does not exceed 35 °C (95 °F) inside the RA (MSHA, 2012). An ongoing concern with RAs is the potential to exceed this limit. The temperature rise inside an RA is due to the metabolic heat released by the occupants as well as heat released by the carbon dioxide scrubbing system.

The U.S. National Institute for Occupational Safety and Health (NIOSH) tested a 10-person tent-type training unit RA (Fig. 1) in its Safety Research Coal Mine (SRCM) in Bruceton, PA, to investigate heat buildup in RAs. The 10-person capacity for the tested RA is based on 1.4 m^2 (15 ft^2) of floor space per miner. NIOSH-developed simulated miners, which are heat input devices that generate both sensible and latent heat, were used to represent the metabolic heat generation of an average miner for testing in the SRCM. It was found that the number of occupants in an RA may need to be reduced based on the ambient mine temperature, which varies from mine to mine (Yantek, 2014). To further research on the temperature rise inside an RA, NIOSH contracted ThermoAnalytics Inc. (Calumet, MI) to perform thermal simulations of the tested 10-person mobile tent-type RA. Thermo-Analytics developed a thermal model of the SRCM using its TAITherm software, which can incorporate a human thermal model (HTM) to represent the equivalent metabolic heat loss of a miner within the RA's enclosed environment. The thermal model was previously validated by comparing simulation results with test results (Yan et al., 2015). During a mine disaster in which miners have to take shelter in an RA, mine ventilation may not be available. As such, mine ventilation was off for both the testing in the SRCM as well as in the simulations. For the tested 10-person tent-type RA, this paper discusses the heat loss mechanisms, and the effects of mine strata composition and mine width and height on the air temperature rise within the RA.

Heat loss mechanisms

Over the course of 96 hours, occupants will emit sensible and latent (humidity) heat to the RA through metabolic processes. The heat transfer from the RA to the ambient mine was examined to quantify how much heat is lost through the three primary RA-to-mine heat transfer mechanisms: (1) conduction into the mine floor, (2) natural convection from the RA and (3) radiation from the RA. These heat loss mechanisms are driven by temperature difference. Conduction to the mine floor is a function of the RA floor's thermal conductivity, thickness, density, specific heat, the contact area of the occupants, and the temperature difference between the bottom of the RA and the mine floor surface. Natural convection from the RA to the ambient mine is a function of the density difference in the air, the RA's effective convection heat transfer coefficient, the exposed surface area, and the temperature difference between the outer surface of the RA and the mine air. Radiation heat transfer from the RA to the ambient mine is the heat transferred due to electromagnetic waves, and is a function of the RA's thermal emissivity and surface area, as well as the difference between the RA's outer surface temperature raised to the fourth power and the mine wall temperature

raised to the fourth power. The initial mine air and strata temperatures and heat were measured in the SRCM and used as inputs to the TAITherm model. The model was used to calculate final temperatures of the RA and mine. The heat loss magnitudes for each of the aforementioned heat loss mechanisms were calculated from these simulation results. Two heat input cases were used with the model. The first case used models of the simulated miners to supply the input heat, and the second case used people modeled with the HTM to supply the input heat. The heat input for the simulated miners was set at a fixed value of 117 W, as was used during testing. For the case with the HTM-modeled humans, the heat input was based on a specified activity level for the humans. The activity level for the HTM-modeled humans was specified so that the initial heat input was 117 W. Because the heat input by the HTM-modeled humans is also a function of body core temperature, the heat input for the HTM-modeled humans will change slightly throughout the simulation. The heat lost due to each heat loss mechanism and the total heat lost were compared for the two heat input cases.

Mine strata composition

The mine strata surrounding an RA will vary from mine to mine and will be different for every geographic region. It is expected that the heat buildup within the RA will be greater for mine strata with lower thermal conductivity. Four different mine floor and roof strata compositions (Table 1 and Fig. 2) were examined to determine the effect of mine strata composition on heat buildup. For all cases, the ribs were considered as consisting of bituminous coal. Strata near the surfaces of the floor and roof will experience temperature rise much earlier in the 96-h test than deeper strata. Mine strata at depths beyond what are described in Table 1 will have little to no effect on the resultant heat buildup because, due to the large thermal mass of the subsequent mine strata layers, the deeper strata temperatures will not begin to change within 96 hours.

The compositions were selected to examine a range of mines with the lowest conductivity to the highest conductivity. It is expected that most mines will fall in between these extreme cases. The thermal properties of each of the materials are shown in Table 2. Material properties were reviewed (Gilliam and Morgan, 1987; Robertson, 1988; Herrin and Deming, 1996; Jones, 2003; Railsback, 2011), and the values shown in Table 2 were selected to cover a range of thermal conductivities.

Mine height and width

The original thermal model was developed to reflect the size of the SRCM: 1.8 m (6 ft) tall and 3.7 m (12 ft) wide. In order to quantify the effects of mine size on the heat buildup within an RA, the mine model used for thermal simulations was modified to be representative of a typical coal mine: 1.4 m (4.5 ft) tall and 5.5 m (18 ft) wide. A third mine size, 1.4 m (4.5 ft) tall and 3.7 m (12 ft) wide, was modeled to gather an additional data set.

Results

Thermal simulations

The thermal simulation results were used to determine which of the heat loss mechanisms is most prevalent across a range of initial mine temperatures from 12.8°C to 18.3°C (55°F to 65°F). Table 3 shows the total heat input with the heat lost due to conduction, convection and radiation for both a model of the physically tested simulated miners (barrel models) and the HTM-modeled humans used in TAITherm (human models). For both simulation cases, the primary mechanisms for heat loss are radiation from the RA to the mine surroundings and conduction into the mine floor. Conduction for the simulations that used the HTM-modeled humans to provide the input heat was slightly lower than that of the simulations that used models of the simulated miners to provide the input heat because the simulated miners heat a larger area on the floor than the humans modeled with the HTM. The HTM-modeled humans were modeled with only their butt and feet in contact with the floor, resulting in less surface area in contact. The results of the thermal simulations indicate that the most heat is lost due to radiation, at about 51 percent, and conduction, at about 31 percent.

The total heat input for both heat input cases was close at the midway point of the 96-h simulation. As such, the results in Table 3 represent the 48-h point in the test. The total imposed heat for the HTM-modeled humans is 1,694–1,703 W, slightly greater than the 1,670 W of the simulated miner models because the metabolic heat rate for the HTM-modeled humans is a function of core temperature.

Mine strata composition analysis

The results of the mine strata composition analysis show that the RA air temperature varied by up to 2.0 °C (3.6 °F) and the relative humidity varied by up to 4.8 percent across all strata compositions (Table 4). For all of the test cases, the mine width and height were modeled to match the SRCM dimensions of 1.8 m (6 ft) tall by 3.7 m (12 ft) wide, the initial mine air and mine strata temperatures was 15.6 °C (60 °F), and the final temperature for the four test cases varied by less than 1.2 °C (2 °F). The apparent temperature was calculated using the following equation (Rothfusz, 1990):

$$\begin{aligned} T_{AT} = & -42.379 + (2.04901523)T_{DBT} + (10.14333127)RH \\ & -(0.22475541)T_{DBT}RH - (6.83783 \times 10^{-3})T_{DBT}^2 \\ & -(5.481717 \times 10^{-2})RH^2 + (1.22874 \times 10^{-3})T_{DBT}^2 RH \\ & +(8.5282 \times 10^{-4})T_{DBT}RH^2 - (1.99 \times 10^{-6})T_{DBT}^2 RH^2 \end{aligned}$$

where T_{AT} is the apparent temperature, T_{DBT} is the DBT temperature inside the RA, and RH is the relative humidity inside the RA.

The apparent temperatures over 96 hours for the four strata compositions are shown in Fig. 3. The apparent temperature at the end of the 96-h test for the first strata composition, which features a shale floor and 0.3 m (1 ft) of coal and 2.4 m (8 ft) of shale in the roof, exceeds the apparent temperature limit of 35 °C (95 °F).

Mine size analysis

Simulations were run with three mine sizes to study the effect of mine size on the average air temperature inside an RA. The results of these simulations are shown in Fig. 4. The SRCM strata composition was used for the mine size simulations, with floor consisting of 1.8 m (6 ft) of siltstone and roof consisting of 0.3 m (1 ft) of slate, 0.6 m (2 ft) coal and 0.9 m (3 ft) of shale. The initial temperature for each test was 13.9 °C (57 °F), and for all cases the final internal RA temperature varied by less than 1 °C (1.8 °F).

Discussion

In this work, a validated thermal simulation model was used to examine RA-to-mine heat loss mechanisms and the effects of mine strata composition and mine size on the final temperature inside a 10-person tent-type RA. ThermoAnalytics developed the thermal simulation model using its TAITherm software and validated this model using NIOSH in-mine test data.

The different heat loss mechanisms were studied to determine how RAs lose heat to a mine. It was found that most of the heat loss is due to radiation into the mine and conduction into the floor. This indicates that convection has the smallest effect on heat loss in an RA for the case modeled here, where it is assumed that mine ventilation is interrupted.

The effect of mine strata composition on heat buildup was examined using the thermal simulation model. Strata compositions were varied to include strata of both high and low thermal conductivities. While there was little variation in the final temperature inside the RA over the range of modeled strata compositions, the simulations showed that the apparent temperature limit of 35 °C (95°F) would be exceeded for the first two strata compositions, as shown in Table 4, which were the least conductive strata composition cases. From the simulations, the temperature rise per miner was calculated for the four strata compositions by taking the difference between the final and initial dry bulb temperatures inside the RA and dividing by the occupancy in a 10-person RA. The temperature rise per miner results are shown in Table 5.

Because the first two mine strata compositions exceeded an AT of 35.0 °C (95.0°F), as shown in Table 4, the RA would need to be derated in order to comply with the AT limit. This is only applicable to these two cases, and is based on the tested 10-person tent-type RA that does not have any type of cooling system. The maximum occupancy was determined for the first two strata compositions so that the AT would meet the 35.0 °C (95 °F) limit, assuming that the temperature rise per miner would remain constant with the values shown in Table 5, and that the final RH would reach 90 percent. The ten-person tent-type RA with only nine occupants would reach 27.4°C (81.3 °F) DBT with an AT of 31.8°C (89.2 °F) after 96 hours for the first mine strata composition, and would reach 27.0 °C (80.6°F) DBT with an AT of 30.7 °C (87.2 °F) for the second mine strata composition. Thus, for these two particular cases, derating the 10-person tent-type RA down to a nine-person RA would comply with the AT limit.

The initial mine temperature for which the 10-person RA would exceed the apparent temperature limit over the course of 96 hours can be calculated by assuming a constant temperature rise per miner and a constant final relative humidity for each strata composition. The final relative humidity was assumed to be 90 percent based on the range of values found during simulations. The results are shown in Table 6.

For the least conductive case of a shale floor with a combination coal-shale roof, the initial temperature in the RA would have to be below 15.3 °C (59.5 °F), while for the most conductive case of a sandstone floor and roof, the initial temperature in the RA would have to be below 17.2 °C (63.0 °F). Additionally, the allowable occupancy that would not exceed the apparent temperature limit was calculated for the four strata compositions with a raised initial temperature of 18.3 °C (65.0 °F). The results are shown in Table 7.

As described, simulations were performed with three mine sizes to represent the SRCM, a typical underground coal mine in the United States, and a smaller mine. These simulations were run using only sensible heat. The largest mine section resulted in the lowest temperature rise, while the smallest mine section resulted in the largest heat rise. However, the final temperature variation for the three cases was less than 1 °C (1.8 °F), indicating that temperature rise is not very sensitive to mine sizes.

Conclusion

Thermal simulation models can be used to analyze heat buildup in RAs in different mines to account for variations in strata composition and in mine width and height. The results from these studies indicate that the mine strata composition can have a significant impact on the apparent temperature. From the case with the most conductive mine strata to the case with the least conductive mine strata, the apparent temperature increased by 6.5 °C (11.9 °F). For the first two mine strata composition cases, which were the two least conductive cases, the results show that the RA occupancy would have to be derated by one miner to comply with the apparent temperature limit. The initial temperature in the mine also plays a significant role in determining whether an RA will comply with the apparent temperature limit for a given occupancy. The final apparent temperature was calculated for the four mine strata compositions using a higher initial mine temperature of 18.3 °C (65.0 °F). The results indicate that the two least conductive strata compositions would require a derating of three miners while the two more conductive strata compositions would require a derating of two miners. These results are only applicable to the 10-person tent-type RA that was tested and the conditions that were simulated, and should not be interpreted as an ultimate derating factor to all RAs. As such, higher air temperatures and lower mine strata thermal conductivities could require that the allowable occupancy be derated in order to comply with the apparent temperature limit. These factors should be considered when implementing RAs into a mine.

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Figure 1.
(a) 10-person tent-type RA, (b) Instrumented RA as tested by NIOSH, (c) Interior of RA.

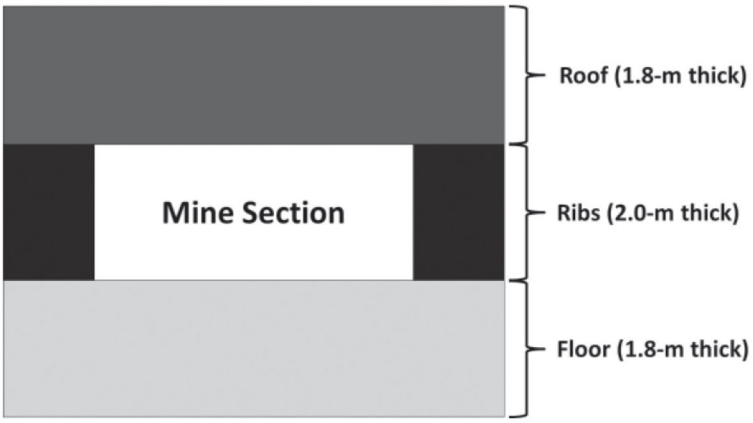

Figure 2.
Cross-sectional view of the thermal model used to examine different mine strata compositions.

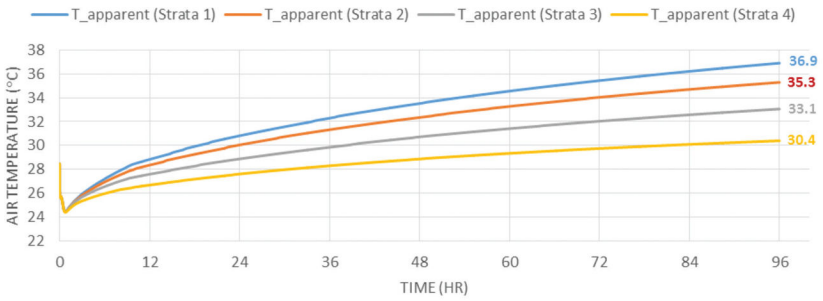

Figure 3.

Apparent temperatures for the four different mine strata compositions over 96 hours.

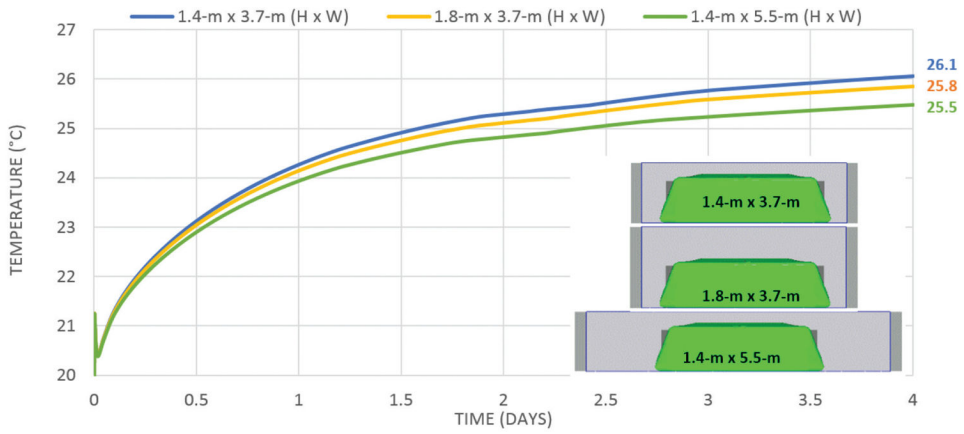

Figure 4.
Average air DBT for three different mine sizes.

Table 1

Mine strata compositions that were used in simulations.

Case	Floor strata composition (1.8 m thick)	Roof strata composition (1.8 m thick)
1	Shale.	Coal (0.3 m), shale (1.5 m).
2	Shale.	Shale.
3	Siltstone.	Slate.
4	Sandstone.	Sandstone.

Table 2

Thermal properties of the mine strata materials that were used in simulations.

	Density (kg/m^3)	Specific heat (J/kg-K)	Conductivity (W/m-K)
Bituminous coal.	1,346	1,380	0.33
Shale.	2,600	1,000	1.00
Siltstone.	2,600	1,000	2.70
Slate.	2,700	760	1.16
Sandstone.	2,300	920	4.60

Table 3

RA heat loss at 48 hours for a range of initial mine temperatures from 12.8°C to 18.3°C (55°F to 65°F).

			Air temperature (°C)		
			12.8	**15.6**	**18.3**
Barrel models	Total heat input.	(W)	1670	1670	1670
		(%)	100%	100%	100%
	Convection.	(W)	272	266	261
		(%)	16.3%	15.9%	15.6%
	Radiation.	(W)	755	763	772
		(%)	45.2%	45.7%	46.2%
	Conduction.	(W)	644	641	637
		(%)	38.6%	38.4%	38.1%
Human models	Total heat input.	(W)	1694	1697	1703
		(%)	100%	100%	100%
	Convection.	(W)	315	310	303
		(%)	18.6%	18.3%	17.8%
	Radiation.	(W)	852	858	863
		(%)	50.3%	50.6%	50.7%
	Conduction.	(W)	528	529	537
		(%)	31.2%	31.2%	31.5%

Table 4

Final temperature parameters inside the RA for the different mine strata composition cases.

Strata composition	Air DBT	RH (%)	Avg. floor temp	AT
1	28.7 °C (83.7 °F)	91.0	25.0 °C (77.0 °F)	36.9 °C (98.4 °F)
2	28.3 °C (82.9 °F)	90.1	24.6 °C (76.3 °F)	35.3 °C (95.5 °F)
3	27.6 °C (81.7 °F)	88.5	23.1 °C (73.6 °F)	33.1 °C (91.6 °F)
4	26.7 °C (80.1 °F)	86.2	21.7 °C (71.1 °F)	30.4 °C (86.7 °F)

Table 5

Temperature rise per miner in a 10-person RA assuming an initial DBT of 15.6 °C (60.0 °F).

Strata composition	Final DBT	Temperature rise	Temperature rise per miner
1	28.7 °C (83.7 °F)	13.1 °C (23.6 °F)	1.31 °C (2.36 °F)
2	28.3 °C (82.9 °F)	12.7 °C (22.9 °F)	1.27 °C (2.29 °F)
3	27.6 °C (81.7 °F)	12.1 °C (21.8 °F)	1.21 °C (2.18 °F)
4	26.7 °C (80.1 °F)	11.2 °C (20.2 °F)	1.12 °C (2.02 °F)

Table 6

Initial temperature that would cause the AT limit to be reached assuming a final RH of 90 percent.

Strata composition	AT	Initial DBT
1	35.0 °C (95.0 °F)	15.3 °C (59.5 °F)
2	35.0 °C (95.0 °F)	15.7 °C (60.3 °F)
3	35.0 °C (95.0 °F)	16.3 °C (61.3 °F)
4	35.0 °C (95.0 °F)	17.2 °C (63.0 °F)

Table 7

Allowable number of occupants to remain below the AT limit for cases with a raised initial mine temperature of 18.3 °C (65.0 °F), assuming a final RH of 90 percent.

Strata composition	No. of occupants	Final air DBT	AT
1	7	27.5 °C (81.5 °F)	32.3 °C (90.1 °F)
2	7	27.2 °C (81.0 °F)	31.4 °C (88.5 °F)
3	8	28.0 °C (82.4 °F)	33.7 °C (92.7 °F)
4	8	27.3 °C (81.1 °F)	31.5 °C (88.7 °F)