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ANALYSIS OF HEAT LOSS MECHANISMS FOR MOBILE TENT-TYPE REFUGE ALTERNATIVES

P. T Bissert, Office of Mine Safety and Health Research, Pittsburgh, PA
D. S Yantek, Office of Mine Safety and Health Research, Pittsburgh, PA
M. D. Klein, ThermoAnalytics Incorporated, Calumet, MI
L. Yan, Office of Mine Safety and Health Research, Pittsburgh, PA

ABSTRACT

Federal regulations require that refuge alternatives (RAs) are located within 305-m (1000-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 (AT) below 35°C (95°F). The National Institute for Occupational Safety and Health used a validated thermal simulation model to examine the mechanisms of heat loss from the RA to the ambient mine and the effect of mine strata composition on the final internal dry bulb temperature (DBT) for mobile tent-type RAs. The results of these studies show that most of the heat loss from the RA to the ambient mine is due to radiation (51%) and conduction (31%). Three mine width/height configurations and three mine strata compositions were examined. The final DBT inside the RA after 96 hours varied less than 1°C (1.8°F) for the three mine width/height configurations and less than 2°C (3.6°F) for the three mine strata compositions.

INTRODUCTION

Following a mine disaster, workers will try to escape the mine. If their escape is futile, they can take shelter in a refuge alternative (RA). In 2008, 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 [1]. 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 National Institute for Occupational Safety and Health (NIOSH) tested a 10-person tent-type training unit RA in its Safety Research Coal Mine (SRCM) 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 (117 W) 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 [2]. To further research temperature rise inside an RA, ThermoAnalytics, Inc. (TAI) was contracted by NIOSH to perform thermal simulations of the tested 10-person mobile tent-type RA. TAI developed a thermal model of the SRCM using RadTherm software, which incorporates 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 [3]. During a mine disaster in which miners would 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. This paper discusses the heat loss mechanisms and the effects of mine strata composition and mine width and height associated with a ten-person tent-type RA.

HEAT LOSS MECHANISMS

Over the course of 96 hours, occupants will emit heat and humidity to the RA through metabolic processes. The heat transfer outside of the RA was examined to quantify how much heat is lost to the ambient mine. The three primary heat loss mechanisms include conduction into the mine floor, convection from the RA due to ventilation airflow, and 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, and the contact area of the occupants. Convection from the RA to the ambient mine is a function of ventilation airflow, the RA's effective convection heat transfer coefficient and the exposed surface area. Radiation 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 surface temperatures of the RA and mine walls. The heat input and corresponding temperature buildup were measured in the SRCM and used as inputs to the RadTherm model from which the heat loss magnitudes were calculated. The heat generated by the simulated miners (barrel models) in the SRCM was compared to the heat generated by the HTMs in the thermal simulations.

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 were examined, as listed in Table 1 and shown in Figure 1, to determine the effect of mine strata composition on heat buildup. For all cases, the ribs were considered as bituminous coal. Strata near the surface of the floor and roof will experience temperature rise much earlier in the 96 hour 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 due to the large thermal mass.

Table 1. Mine strata compositions that were tested.

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

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. Thermal properties for each of the materials are shown below in Table 2. Material properties were reviewed [4, 5, 6, 7, 8] and the values shown in Table 2 were selected to cover a range of thermal conductivities.

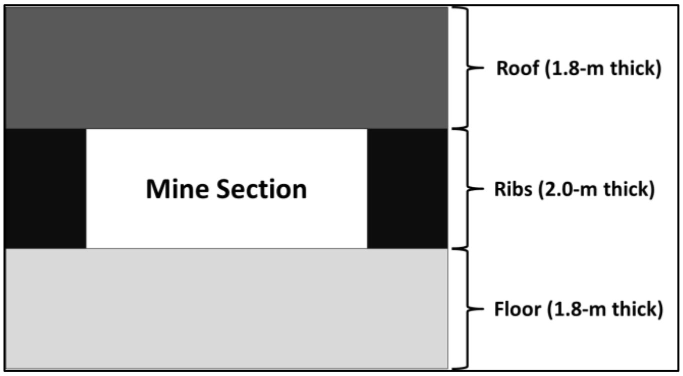

Figure 1. Cross sectional view of the thermal model used to examine different mine strata compositions.

Table 2. Thermal properties of the mine strata materials that were tested.

	Density (kg/m^3)	Specific Heat (J/kg-K)	Conductivity (W/m-K)
Bituminous coal	1346	1380	0.33
Shale	2600	1000	1.00
Siltstone	2600	1000	2.70
Slate	2700	760	1.16
Sandstone	2300	920	4.60

MINE HEIGHT AND WIDTH

The original thermal model was developed to reflect the size of the SRCM: 1.8-m (6-ft) tall x 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 x 5.5-m (18-ft) wide. A third mine size, 1.4-m (4.5-ft) tall x 3.7-m (12-ft) wide, was modeled to gather an additional data set.

RESULTS

The thermal simulation results were used to determine which of the heat loss mechanisms is most prevalent. Table 3 shows the total heat input with the three mechanisms of heat loss (convection, radiation, conduction) for both the physically tested barrel models and the simulated HTMs used in RadTherm. For both test cases, the primary mechanisms for heat loss are radiation from the RA to the ambient mine and conduction into the mine floor. Conduction for the human thermal model was slightly lower than that of the barrel model because the barrels heat a larger area on the floor than the HTMs. The HTMs were modeled with only their butt and feet in contact with the floor (i.e. less surface area). The results of the thermal simulations indicate that the most heat is lost due to radiation (~51%) and conduction (~31%).

Table 3. RA heat loss at 48 hours.

			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%

The total heat input between the barrel models and the human thermal models was close at the midway point of the 96-hr test. As such, the results in Table 3 represent the 48-hr point in the test. The total imposed heat for the human thermal model (1694-1703 W) is slightly greater than that of the barrel models (1670 W) since the metabolic heat rate is a function of core temperature.

The results for 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% across all cases as shown in Table 4, for different strata compositions. 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 x 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 based on the equation [9] shown below, where T_{AT} is the apparent temperature, T_{DBT} is the DBT temperature inside the RA, RH is the relative humidity inside the RA,

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

Table 4. Final temperature parameters inside the RA for the different mine strata composition cases.

Strata Composition	Air DBT (°C)	RH (%)	Avg. Floor Temp (°C)	AT (°C)
1	28.7	91.0	25.0	36.9
2	28.3	90.1	24.6	35.3
3	27.6	88.5	23.1	33.1
4	26.7	86.2	21.7	30.4

The apparent temperatures over 96 hours for the four strata compositions are shown in Figure 2. The apparent temperature at the end of the 96-hour 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).

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 Figure 3. The SRCM strata composition was used for the mine size simulations (Floor: 1.8-m (6-ft) siltstone, Roof: 0.3-m (1-ft) slate, 0.6-m (2-ft) coal, 0.9-m (3-ft) shale). The initial temperature for each test was 13.9°C (57°F), and for all cases the final temperature varied by less than 1°C (1.8°F).

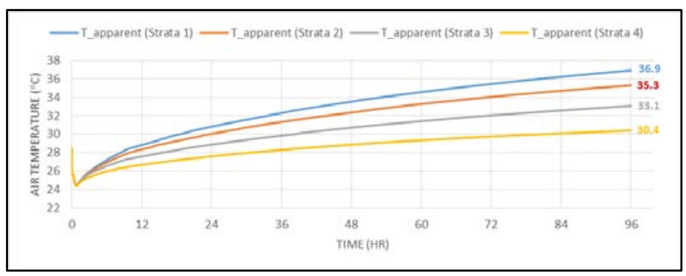

Figure 2. Apparent temperatures for the four different mine strata compositions over 96 hours.

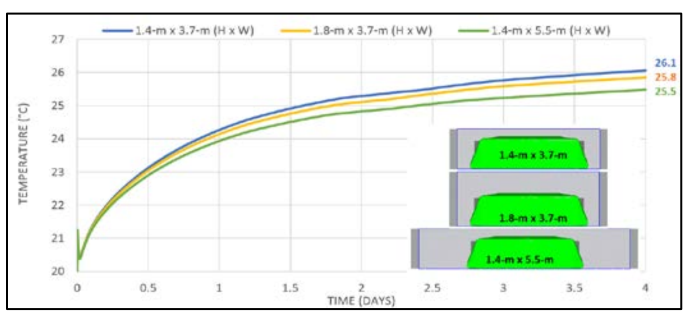

Figure 3. Average air DBT for three different mine sizes.

DISCUSSION

In this paper, a validated thermal simulation model was used to examine the effects of mine strata composition and mine size on the final temperature inside a 10-person tent-type RA. The thermal simulation model was developed and validated by TAI using RadTherm software.

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, which is related to the ventilation flow rate, has the smallest effect on heat loss in an RA for the case modeled here, where it is assumed that mine ventilation is interrupted.

Strata compositions were varied to include strata of both high and low thermal conductivity. While there was little variation in the final temperature inside the RA over the range of tested strata compositions, the simulations showed that the apparent temperature limit of 35°C (95°F) would be exceeded for the first two strata compositions, which was the least conductive case that consisted of a shale floor and a combination of coal and shale on the roof.

The temperature rise per miner was calculated for the four strata compositions by taking the difference between the simulated final and initial dry bulb temperatures inside the RA and dividing by the occupancy (ten-person RA). The temperature rise per miner results are shown in Table 5.

Table 5. Temperature rise per miner in a ten-person RA assuming an initial DBT of 15.6°C (60.0°F).

Strata Composition	Final DBT (°C)	Temperature Rise (°C)	Temperature Rise per Miner (°C)
1	28.7	13.1	1.31
2	28.3	12.7	1.27
3	27.6	12.1	1.21
4	26.7	11.2	1.12

Since 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 ten-person tent-type RA that does not have any type of cooling system. Assuming that the temperature rise per miner would remain constant with the values shown in Table 5, and the final RH would reach 90%, 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 ten-person tent-type RA down to nine-person RA would comply with the AT limit.

The initial temperature that would exceed the apparent temperature limit for a ten-person RA 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% RH based on the range of values found during simulations. The results are shown in Table 6.

Table 6. Initial temperature that would cause the AT limit to be reached assuming a final RH of 90%.

Strata Composition	AT (°C)	Initial DBT (°C)
1	35.0 (95.0 °F)	15.3
2	35.0 (95.0 °F)	15.7
3	35.0 (95.0 °F)	16.3
4	35.0 (95.0 °F)	17.2

For the least conductive case (shale floor, combination of coal and 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 (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.

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%.

Strata Composition	Occupants	Final Air DBT (°C)	AT (°C)
1	7	27.5	32.3
2	7	27.2	31.4
3	8	28.0	33.7
4	8	27.3	31.5

As described in this paper, simulations were performed with three mine sizes to represent the SRCM (1.8-m (6-ft) high x 3.7-m (12-ft) wide), a typical underground coal mine in the U.S. (1.4-m (4.5-ft) high x 5.5-m (18-ft) wide), and a smaller mine (1.4-m (4.5-ft) high x 3.7-m (12-ft) wide). 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) so 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 variation in strata composition and 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 case, 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 complies with the apparent temperature limit. The final apparent temperature was calculated for the four mine strata compositions using a higher initial temperature. The results indicate that two of the strata compositions would require a derating of three miners while the other two would require a derating of two miners. These results are only applicable to the ten-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.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Reference to specific brand names does not imply endorsement by the National Institute for Occupational Safety and Health.

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REFERENCES

[1] U.S. Government, 2012. “Subpart L - Refuge Alternatives.” 30 CFR 7.5.

[2] Yantek, D., 2014. "Investigation of Temperature Rise in Mobile Refuge Alternatives." Publication 2014–117, RI 9695. 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. Pittsburgh, PA.

[3] Yan, L., Yantek, D., Bissert, P., Klein, M., 2015. “In-Mine Experimental Investigation of Temperature Rise and Development of a Validated Thermal Simulation Model of a Mobile Refuge Alternative.” Proceedings of the 2015 International Mechanical

Engineering Congress & Exposition. November 13-19, 2015. Houston, Texas.

[4] Railsback's Petroleum Geoscience and Subsurface Geology, 2011. "Heat flow, geothermal gradient, and the thermal conductivity of sedimentary rocks."

[5] Gilliam, T, Morgan, I, 1987. "Shale: Measurement of Thermal Properties." Oak Ridge National Laboratory, ORNL/TM-10499.

[6] Robertson, E, 1988. "Thermal Properties of Rocks." United States Department of the Interior Geological Survey. Open-File Report 88-441.

[7] Jones, M, 2003. "Thermal properties of stratified rocks from Witwatersrand gold mining areas." The Journal of the South African Institute of Mining and Metallurgy, April 2003, pp 173-186.

[8] Herrin, J., Deming, D., 1996. "Thermal conductivity of U.S. coals." Journal of Geophysical Research, Vol 101, No. B11, Pages 25,381 – 25,386, November 10, 1996. Paper number 96JB01884.

[9] Rothfusz, L., 1990. "The Heat Index Equation." SR 90-23. Fort Worth, TX.