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EFFECTS OF THE CONSTANT MINE STRATA TEMPERATURE ASSUMPTION AND INITIAL MINE AIR AND STRATA TEMPERATURES ON REFUGE ALTERNATIVE INTERNAL AIR TEMPERATURE

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ABSTRACT

Federal regulations require the installation of refuge alternatives (RAs) in underground coal mines. Mobile RAs have a limited ability to dissipate heat, and heat buildup can lead to a life-threatening condition as the RA internal air temperature and relative humidity increase. The National Institute for Occupational Safety and Health Office of Mine Safety and Health Research performed heat testing on a 10-person tent-type training RA and contracted ThermoAnalytics, Inc. to develop a validated thermal simulation model (TSM) of the tested RA. The TSM was used to examine the effects of the constant mine strata temperature assumption, initial mine air temperature (MAT), initial mine strata surface temperature (MSST), initial mine strata temperature at depth (MSTD), and mine strata thermal behavior on RA internal air temperature using 117 W of sensible heat input per simulated miner. For the studied RA, when the mine strata temperature was treated as a constant, the final predicted RA internal air temperature was 12.8°F lower than it was when the mine strata thermal behavior was included in the model. A 10°F increase in the initial MSST resulted in a 7.1°F increase in the final RA internal air temperature, whereas a 10°F increase in the initial MSTD yielded a 2.5°F increase in the final RA internal air temperature.

INTRODUCTION

Since 2008, the Mine Safety and Health Administration (MSHA) has required the installation of refuge alternatives (RAs) in underground coal mines (1). MSHA requires that RAs provide an environment with breathable air for entrapped miners for a 96-hour period. Heat buildup inside an occupied RA is a serious concern. Without a means to dissipate the heat and humidity generated by the occupants and the carbon dioxide scrubbing system, the temperature and humidity inside RAs could lead to severe discomfort or heat stress depending on the mine ambient temperature before and during occupation of the RA. NIOSH recommended an apparent temperature limit of 95°F in its 2007 report to Congress (2). In 30 CFR 7.504, MSHA has specified a maximum apparent temperature of 95°F inside an occupied RA (3). The apparent temperature is calculated using both air temperature and relative humidity (4).

Calculations could be used to determine if the air within an occupied RA will reach the apparent temperature limit. In these calculations, in order to simplify the problem, the mine temperature could be assumed to remain constant. With this assumption, the effects of the mine strata thermal mass and thermal conductivity on the heat buildup in an RA are ignored. OMSHR research has shown that the mine air and strata temperatures surrounding an RA increase when subjected to the heat of an occupied RA (5). Thus, calculations performed with the assumption that the mine temperature is constant would under-predict the resulting dry-bulb temperature and apparent temperature for a given RA occupancy. The mine air temperature has been used as the basis for RA temperature calculations. However, research has not been used to confirm that the mine air temperature is the appropriate basis.

In order to demonstrate that their mobile RAs meet the apparent temperature limit, RA manufacturers have been performing 96-hour-long heat and humidity tests in laboratories. A heat input of 117 W (400 BTU/hr) per person is used during these tests to represent the metabolic heat of a single miner (6). To account for the heat generated by the RA's carbon dioxide scrubbing system, 50 W (170 BTU/hr) of heat per miner is used for a lithium hydroxide scrubbing system, or 30 W (100 BTU/hr) of heat per miner is used for a soda lime scrubbing system (7). In these tests, air velocities around the RA are minimized to represent the worst-case scenario of an interruption in mine ventilation that might occur in a mine disaster. In many cases, these test facilities were designed using air conditioning systems to keep the air within the test facility at a constant temperature during the tests. However, none of the tests conducted within these facilities have been benchmarked against tests conducted in an underground mine.

In addition to the laboratory research conducted by manufacturers, the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) has been conducting research on heat and humidity buildup in RAs. In 2013, OMSHR tested a 10-person training RA[1] in its Safety Research Coal Mine (SRCM) in Bruceton, PA (5). During these tests, ten OMSHR-developed simulated miners (ODSMs) were used to input a nominal 117 W of heat each to represent the metabolic heat input of miners. In addition, a heated water tank and a heated aluminum core from an ODSM were used to input the heat to represent that of the carbon dioxide scrubber system (refer to Figure 1). In order to simulate worst-case conditions of an interruption to a mine's ventilation system, OMSHR's tests were conducted with the mine ventilation blocked from the test area using plastic sheeting on one end and a brattice cloth on the other (refer to Figure 2). OMSHR's tests showed that the mine strata temperature does not remain constant during testing. The mine strata temperatures near the surface began to increase almost immediately, while temperatures at depths of 1.2 m (4 ft) or more were nearly constant for the 96-hour tests.

VALIDATED THERMAL SIMULATION MODEL

As the 10-person training RA was being tested by OMSHR in the SRCM, OMSHR also contracted ThermoAnalytics, Inc. to develop and validate a thermal simulation model of the 10-person training RA (8). In the model, the mine strata was modeled in 75-mm-thick layers up to depths of 1.8 m for the roof, ribs, and floor (refer to Figure 2 and Figure 3). The roof was modeled as a combination of slate, bituminous coal, and shale; the rib was modeled as bituminous coal; and the floor was modeled as siltstone. The strata temperature at a depth of 1.8 m was modeled to be constant because temperatures at this depth changed by only a few tenths of a °F during 96-hour heat and humidity tests conducted in OMSHR's SRCM. For the shallower strata layers, the thermal simulation model calculated temperature changes. To

[1] The tested RA had a floor space of 151 ft^2, which meets the space requirement of 15 ft^2 per person for 10 occupants, and a volume of 540 ft^3, which meets the volume requirement of 52.5 ft^3 per person for mine heights between 48 and 54 inches as specified in 30 CFR 7.505.

represent an interruption in the mine ventilation system, the model assumed natural convection on the outside of the RA.

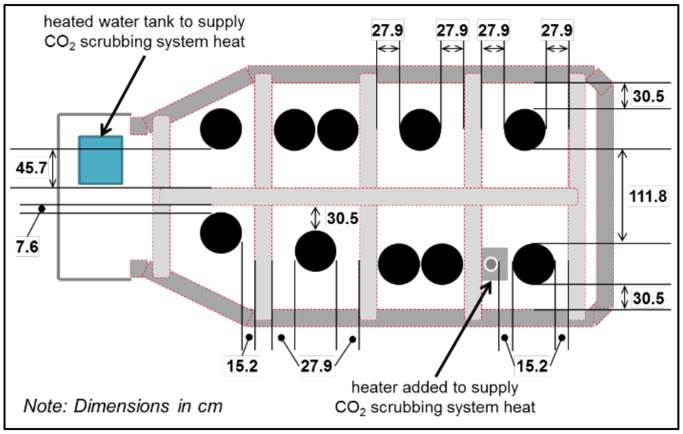

Figure 1. Layout of ten simulated miners, heated water tank, and heated aluminum cylinder used to perform heat and humidity testing on a 10-person tent-type training RA.

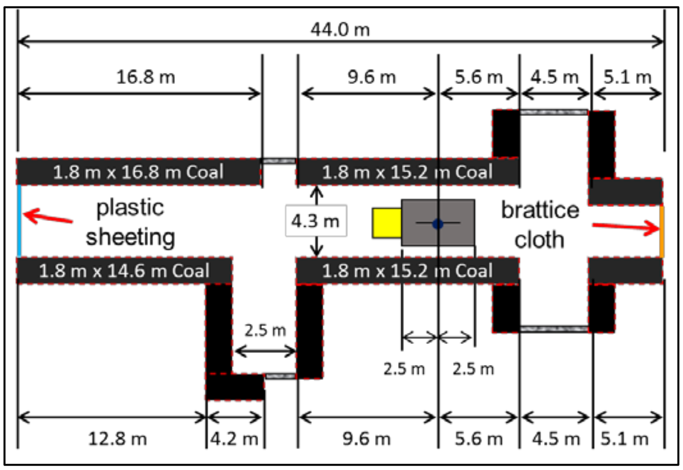

Figure 2. Overhead view of underground test area for heat and humidity tests on a 10-person tent-type RA.

In the model, hollow cylinders were used to provide the same heat input that was provided by the ODSMs during tests. For this initial model, the heat input was considered as sensible (dry) heat. The model also included the heated water tank and the heated aluminum core used to represent the carbon dioxide scrubbing system heat (refer to Figure 4). Because the voltage used to power the ODSMs during testing was lower than the 120V rating for the heaters within the ODSMs, the average heat input from the ODSMs during testing was 107 W. This lower heat input value was used in the model validation process so that the model results could be directly compared to the measured results. Because the heat input was about 10% lower, the measured temperature increases in the model were also about 10% lower than if the heat input was 117 W. However, this does not impact the validity of the model.

In the model, the initial mine air, RA structure, RA internal air, and mine strata temperatures are defined as initial conditions. The thermal simulation model was shown to predict the measured air temperature within the RA to within 0.3°F. Therefore, the validated thermal simulation model of the 10-person mobile RA can be seen as a valuable tool for examining numerous factors that may influence the final RA internal air temperature.

Using the validated thermal simulation model, this paper will examine the effect of the constant mine strata surface temperature assumption on the resulting temperature within the 10-person tent-type RA. In addition, this paper will discuss the effect of initial mine air temperature, the initial mine strata surface temperature, and initial mine strata temperature at depth on the resulting air temperature within the tent-type RA.

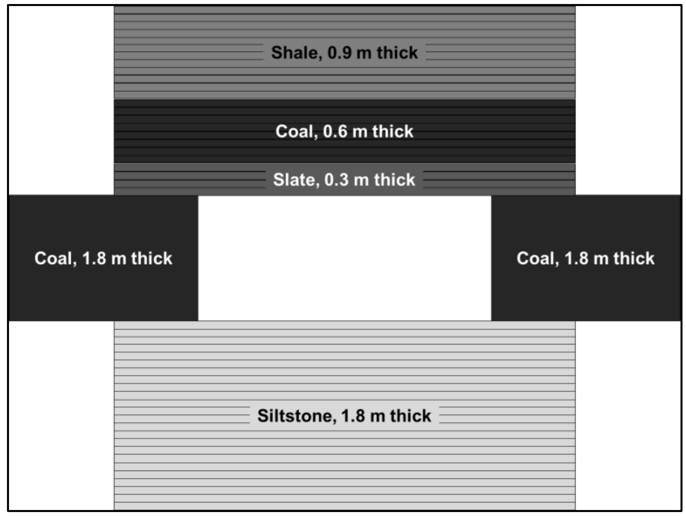

Figure 3. Mine strata composition used for thermal simulation model of a 10-person tent-type refuge alternative.

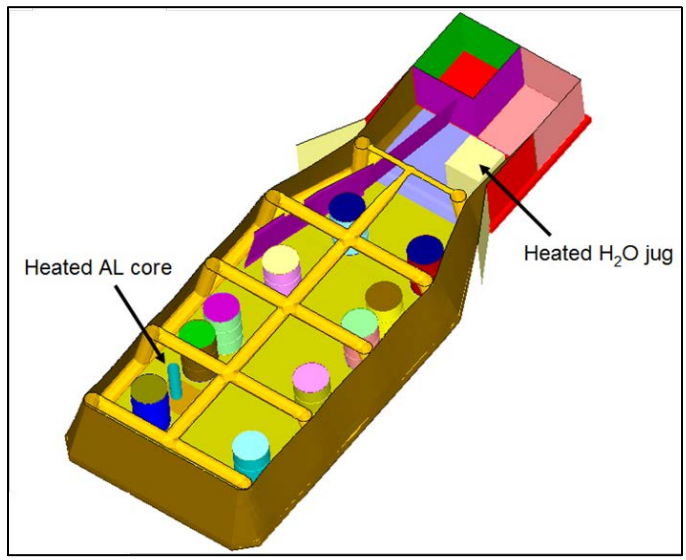

Figure 4. Layout of simulated miners, heated water tank, and heated aluminum core in the thermal simulation model of a 10-person tent-type RA.

METHODS

Effect of Constant Mine Strata Surface Temperature Assumption on Final RA Internal Air Temperature

The validated thermal simulation model of the 10-person tent-type RA was used to calculate the air temperature inside the RA after a period of 96 hours. The heat input for this analysis was applied using models of ten ODSMs set to input 117 W of sensible (dry) heat. Two thermal simulation cases were used. For the first case, the temperature increase for each layer of mine strata was calculated by the model. For the second case, the surface temperature of the mine strata was assumed to remain constant at its initial temperature. Thus, the second case ignores heating of the mine strata. The initial temperatures used for each analysis are shown in Table 1. The values for Case 1 are based on the measured data from OMSHR's tests on the 10-person tent-type RA. The initial mine strata temperatures from a depth of 1.2 m (4 ft) to a depth of 1.8 m (6 ft) were assumed to be the same because temperature measurements were not performed at depths greater than 1.2 m (4 ft). In Case 2, the temperatures at depth are not needed to define the initial conditions because the mine strata surface temperatures were considered to be constant.

Table 1. Initial temperatures used to evaluate the effect of the constant mine strata surface temperature assumption on the final RA internal air temperature.

Location	Case 1	Case 2
ODSM Surfaces	95.0°F (35.0°C)	95.0°F (35.0°C)
Mine air, RA metal case, RA tent, and RA internal air	57.0°F (13.9°C)	57.0°F (13.9°C)
Mine roof surface	56.4°F (13.6°C)	56.4°F (13.6°C)
Mine roof at 1.2 to 1.8 m deep	55.1°F (12.8°C)	does not apply
Mine rib surface	56.4°F (13.6°C)	56.4°F (13.6°C)
Mine rib at 1.2 to 1.8 m deep	53.5°F (11.9°C)	does not apply
Mine floor surface	56.0°F (13.3°C)	56.0°F (13.3°C)
Mine floor at 1.2 to 1.8 m deep	52.9°F (11.6°C)	does not apply

Effect of Initial Mine Temperature on Final RA Internal Air Temperature

The validated thermal simulation model was modified to increase the width of the mine entry from 4.3 m (14 ft) to 6.1 m (20 ft) so that its dimensions would be more representative of production underground coal mines in the United States. Because the spacing between an RA and the mine strata affects the temperature rise within an RA, increasing the mine width makes the results more applicable to production underground coal mines. This modified model was used to examine the effect of initial mine air temperature, initial mine strata surface temperature, and initial mine strata temperature at depth on the final air temperature within the RA. As with the analysis using the constant mine strata surface temperature assumption, the heat input for this analysis was applied using models of ten ODSMs without moisture input.

First, the effect of the initial mine air temperature on the final RA internal air temperature was examined using two test cases. To prevent confusion with the previously discussed cases, these will be referred to as Case A and Case B (refer to Table 2). For Case A, the initial mine air and RA temperatures were set to 70°F, while the initial mine strata temperatures at the surface and throughout the modeled depth were set to 60°F. For Case B, the initial temperatures of the mine air, RA metal case, RA tent, RA internal air, and mine strata temperatures were set to 60°F.

Next, to examine the effect of initial mine strata surface temperature on the final RA internal air temperature, a fixed initial mine strata temperature of 60°F was assumed at a depth of 1.8 m (6 ft), and the final RA internal air temperature was calculated for initial mine strata surface temperatures of 50°F, 60°F, and 70°F. In these analyses, the initial mine air and RA temperatures were set to the same value as the initial mine strata surface temperature.

Table 2. Initial temperatures used to evaluate the effect of the initial mine air temperature on the final RA internal air temperature.

Location	Case A	Case B
ODSM Surfaces	95.0°F (35.0°C)	95.0°F (35.0°C)
Mine air, RA metal case, RA tent, and RA internal air	70.0°F (21.1°C)	60°F (15.6°C)
Mine roof, rib, and floor strata surfaces	60°F (15.6°C)	60°F (15.6°C)
Mine roof, rib, and floor strata at 1.8 m deep	60°F (15.6°C)	60°F (15.6°C)

Then, to investigate the effect of initial mine strata temperature at depth on the final RA internal air temperature, the initial mine strata temperature at a depth of 1.8 m (6 ft) was assumed to be 50°F, 60°F, and 70°F, while the initial mine air, RA, and mine strata surface temperatures were set to 60°F.

Finally, the initial mine air temperature, RA temperature, mine strata surface temperature, and mine strata temperature at a depth of 1.8 m (6 ft) were all assumed to be 50°F, 60°F, and 70°F. For each of these simulations, the mine strata temperature was assumed to vary linearly from its surface to a depth of 1.8 m (6 ft).

In an actual mine, the mine strata surface temperature would be slightly higher or lower than the mine air temperature due to daily and/or seasonal variations in mine air temperature, and the temperature variation from the surface to a depth would not necessarily be linear as it would tend to depend on the mine strata composition. However, these assumptions are sufficient to allow the effect of initial mine air and strata temperatures on the final RA internal air temperature to be examined qualitatively.

RESULTS

Effect of Constant Mine Strata Surface Temperature Assumption on Final RA Internal Air Temperature

The analyses related to the evaluation of the constant mine strata surface temperature assumption show that assuming the mine strata temperature is constant results in a much lower final air temperature within the RA, and also results in a much shorter time to reach steady state (refer to Figure 5). When the model included the mine strata temperature increase, after 96 hours the air temperature inside the RA increased by 21.5°F, from 57°F to 78.5°F. When the mine strata temperature was assumed to remain constant, after 96 hours the air temperature inside the RA increased from 57°F to 65.7°F, a difference of only 8.7°F, (40% lower than when the model included the mine strata temperature increase). The temperature rise per miner was 2.2°F when the model calculated the temperature increase of the mine strata, and 0.9°F when the mine strata temperature was assumed to remain constant. With the mine strata temperature treated as a constant, steady state is reached by the end of the second day, as indicated by the lack of a substantial change in the RA internal air temperature beyond the second day. However, when the mine strata temperature increase is included in the thermal simulation model, steady state is not reached within 96 hours, as demonstrated by an increase in the RA internal air temperature for the entire duration (refer to Figure 5).

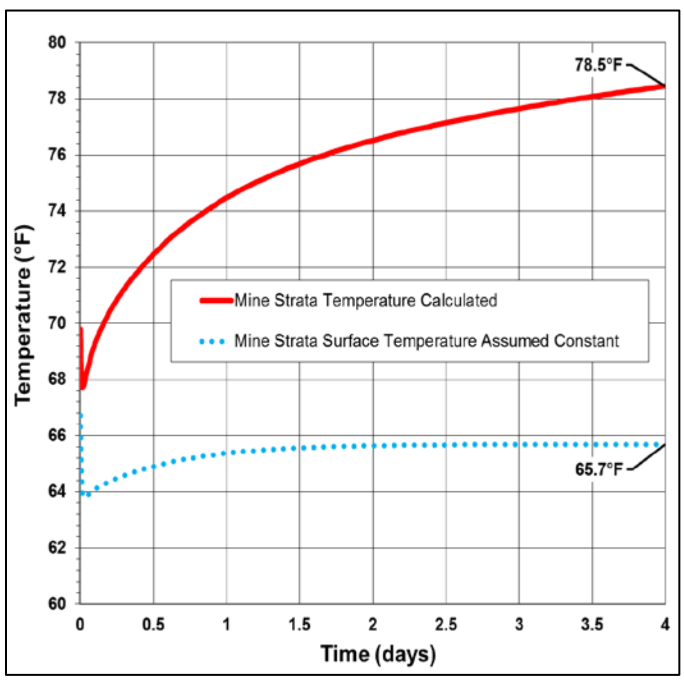

Figure 5. Predicted air temperature inside RA with the mine strata temperature increase calculated by the model (red solid line) and with the mine strata surface temperature assumed to remain constant (blue dotted line).

Effect of Initial Mine Temperature on Final RA Internal Air Temperature

The analyses used to examine the effect of the initial mine air temperature on the final RA internal air temperature (refer to Table 2) showed that the initial mine air temperature does not have much of an effect on the final RA internal air temperature across a 10°F (5.6°C) range of initial mine air temperatures. For the analyses performed here, the final RA internal air temperature was found to be 80.09°F when the initial mine air temperature was 70°F (Case A) and 80.06°F when the initial mine air temperature was 60°F (Case B), a 0.03°F difference.

The analyses used to examine the effect of initial mine strata temperature on the RA internal air temperature show that changes in the initial mine strata surface temperature have more of an effect on the final RA internal air temperature than changes in the initial mine strata temperature at depth (refer to Figure 6 and Figure 7). For the modeled tent-type RA and mine strata thermal properties, a 10°F change in the initial mine strata surface temperature resulted in a 7.1°F change in the final RA internal air temperature, while a 10°F change in the initial mine strata temperature at a depth of 1.8 m yielded a 2.5°F change in the final RA internal air temperature. Figure 6 shows that the RA internal air temperature for the three initial mine strata surface temperatures are nearly parallel over the course of four days, while Figure 7 shows that the RA internal air temperature for three different initial mine strata temperatures at a depth of 1.8 m appear to diverge over the course of four days. When the initial mine strata surface temperature and the initial mine strata temperature at a depth of 1.8 m were both changed by 10°F, the RA internal air temperature changed by 9.6°F, which demonstrates that the changes due to variations in initial mine strata surface temperature and initial mine strata temperature at 1.8 m depth are additive for the modeled situation. Table 3 summarizes the initial mine air and mine strata temperatures used for the simulations and the corresponding final RA internal air temperatures.

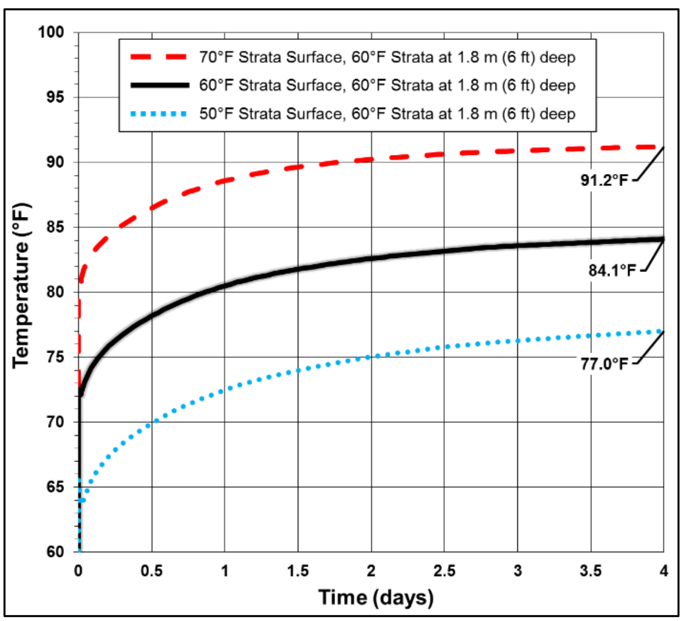

Figure 6. RA internal air temperature versus time for initial mine strata surface temperatures of 50°F, 60°F, and 70°F with a mine strata temperature of 60°F at a depth of 1.8 m.

DISCUSSION

The results clearly show that treating the mine strata temperature as a constant results in a much lower air temperature rise within an RA. For the 10-person training RA that was tested and modeled in OMSHR's SRCM, the difference in final RA internal air temperature for purely sensible (dry) heat was 12.8°F. This temperature difference is specific to the 10-person training RA, the SRCM strata, the initial mine air and mine strata temperatures, and the assumption that the heat input was purely sensible heat. In an occupied RA, a significant portion of the heat input would be via latent (wet) heat due to evaporation of sweat, and this would affect the air temperature rise within the RA. With a portion of the heat input as latent heat, the RA internal air temperature increase calculated either with or without the constant mine strata temperature assumption would be less than it would be using purely sensible heat. However, the tendency for analyses that use the constant mine strata temperature assumption to under-predict the final air temperature within a mobile RA would apply to all RAs and all mine strata conditions.

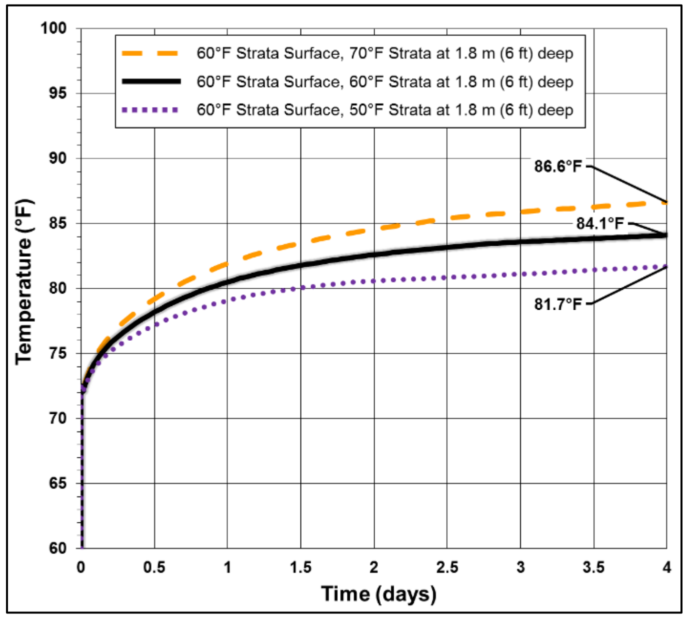

Figure 7. RA internal air temperature versus time with an initial mine strata surface temperature of 60°F for initial mine strata temperatures of 50°F, 60°F, and 70°F at a depth of 1.8 m.

Table 3. Predicted final RA internal air temperature for a range of initial mine strata surface temperatures and initial mine strata temperatures at a depth of 1.8 m from 50°F to 70°F.

Initial Mine Air Temperature	Initial Mine Strata Temperature at 1.8 m (6 ft)	Final RA Internal Air Temperature
50.0°F (10.0°C)	50.0°F (10.0°C)	74.5°F (23.6°C)
50.0°F (10.0°C)	60.0°F (15.6°C)	77.0°F (25.0°C)
60.0°F (15.6°C)	50.0°F (10.0°C)	81.7°F (27.6°C)
60.0°F (15.6°C)	60.0°F (15.6°C)	84.1°F (28.9°C)
60.0°F (15.6°C)	70.0°F (21.1°C)	86.6°F (30.3°C)
70.0°F (21.1°C)	60.0°F (15.6°C)	91.2°F (32.9°C)
70.0°F (21.1°C)	70.0°F (21.1°C)	93.6°F (34.2°C)

RA modeling and testing must replicate the effect of the mine strata temperature increase so that simulation or test results will represent real-world RA behavior. Each mine will, in general, have a different mine strata composition, initial mine air temperature, initial mine strata surface temperature, and initial mine strata temperature at depth, and each of these will affect the final air temperature and relative humidity inside an occupied RA. If a validated thermal model is used to examine RA heat buildup, each of these effects could be accounted for easily. However, if the results of physical testing are to be used directly without correction, the test facility would have to be constructed of materials that have thermal conductivity and specific heat similar to typical coal mine strata. In addition, the facility would have to incorporate the ability to control the initial air temperature and the initial temperatures within its walls up to the depth within the walls where the temperature would not change over the test duration.

As an alternative, and probably a more economical choice, to developing a mine-like test facility, test results obtained in a constant temperature test facility could be used with a correction factor to predict in-mine performance. This correction factor would have to be developed to account for the mine strata temperature increase and the resistance to heat transfer provided by the mine strata that would be observed in actual mines. It is expected that this correction factor would be a function of the mine strata thermal properties and the mine strata temperatures, and that it would be determined using heat transfer principles. With this approach, the test facility could be constructed so that its interior is maintained at a constant temperature throughout the tests using a heating or cooling system, and the correction factor could be applied to predict the in-mine thermal performance of an RA. For such a facility, the thermal conductivity of the materials used for its construction would not impact RA heat and humidity test results; when the interior surface temperature is held constant, the thermal properties of the materials beyond the interior surface are not part of the mathematical equations that govern heat transfer.

To this point, the mine air temperature has been considered as the key input when examining heat buildup within occupied RAs. However, the results presented above show that both the initial mine strata surface temperature and the initial mine strata temperature at depth will affect the final air temperature within an occupied RA, whereas a 10°F change in initial mine air temperature had almost no effect on the final RA internal air temperature. Therefore, models and tests used to examine heat buildup with RAs should include the ability to account for the initial mine strata surface temperature and the initial mine strata temperature at depth.

Effect of the constant strata temperature assumption, initial mine air temperature, and initial mine strata temperature on apparent temperature

To examine how much of an impact the constant strata temperature assumption, initial mine strata surface temperature, and initial mine strata temperature at depth have on the apparent temperature within an RA, simulation results were used to determine the apparent temperature for the 10-person RA for several combinations of initial temperatures using the strata composition of the SRCM. Because the testing and simulations were conducted with purely sensible heat, a value for relative humidity must be assumed for the calculation of apparent temperature. Prior OMSHR tests using simulated miners and thermal simulations using models of real miners have resulted in RA relative humidity values of 85 to 95 %RH; for the purposes here, 90 %RH has been used. In a real situation, the heat input would be split between sensible and latent heat, and the split between sensible and latent heat would depend on the severity of the thermal environment within the RA (9). If a portion of the heat is input as latent heat, the air temperature rise would be less than the values determined using purely sensible heat. In prior analyses and tests, when the latent heat input is 25% to 55% of the total heat input, the RA internal air temperature rise is roughly 85% to 95% of the RA internal air temperature rise for purely sensible heat. Therefore, the analysis here will tend to somewhat over-predict the final RA internal air temperature and the resulting apparent temperature. Nevertheless, this analysis is sufficient to examine the trends.

Implications of results for apparent temperature predictions

RA apparent temperatures calculated using RA internal air temperatures from analyses or testing performed with the constant strata temperature assumption are much higher than those computed from RA internal air temperatures resulting from simulations that calculate the mine strata temperature increase. As the data in Table 4 (see page 6) show, for the tested 10-person RA, the apparent temperature for a 60°F initial mine strata surface temperature and a 60°F initial mine strata temperature at a depth of 1.8 m would be 75.6°F if the constant strata temperature assumption is used (refer to Case 4). However, for the same initial temperatures, the apparent temperature would be 98.4°F if the mine strata temperature increase is included in the model (refer to Case 5). The latter value exceeds the 95°F apparent temperature limit, while the former value does not.

The initial mine air temperature, the initial mine strata surface temperature, and the initial mine strata temperature at depth affect the final apparent temperature in an RA. In addition, for a single temperature value for the initial mine air and mine strata surface temperature, the final RA apparent temperature may be below the apparent temperature limit for lower initial mine strata temperatures at depth, but may exceed the apparent temperature limit for higher initial mine strata temperatures at depth. As shown in Table 4, for an initial mine air and mine strata surface temperature of 60°F, the final RA apparent temperature can exceed the 95°F apparent temperature limit depending on the initial mine strata temperature at depth. For initial mine air and mine strata surface temperatures of 60°F with an initial mine strata temperature of 50°F at 1.8 m depth, the calculated apparent temperature is 90.6°F (see Case 3). However, if the initial mine strata temperature at 1.8 m depth is 60°F, the apparent temperature would reach 98.4°F (see Case 5); if the initial mine strata temperature at 1.8 m depth is 70°F, the apparent temperature would reach 107.6°F (see Case 6).

CONCLUSIONS

The constant strata temperature assumption led to lower RA internal air temperatures and apparent temperatures for the conditions studied and reported here. This assumption would lead to situations where the actual apparent temperature would be much higher than predicted by calculations performed using this assumption. Therefore, this assumption should be used for preliminary analyses only. Also, the results demonstrate that the mine strata temperature increase has an important effect on the final temperature within an occupied RA. Therefore, it must be accounted for when determining RA occupancy either through testing or calculations.

Both the initial mine strata surface temperature and the initial mine strata temperature at depth affect the RA internal air temperature and apparent temperature. Neglecting to include the initial mine strata temperature at depth can result in under-predicting the apparent temperature by a large amount if the mine strata temperature at depth is significantly higher than the mine strata surface temperature. To ensure that apparent temperature limits are not exceeded, predictions of allowable occupancy of RAs for mines should include the initial mine air temperature, the initial mine strata surface temperature, and the initial mine strata temperature at depth. Tests to determine whether RAs meet the apparent temperature limit must be conducted so that the effects of the mine strata are either included in the test, or are accounted for with a correction factor that is computed based on heat transfer principles.

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. Federal Register [2008]. Refuge Alternatives for Underground Coal Mines; Final Rule. Department of Labor, Mine Safety and Health Administration, 30 CFR Parts 7 and 75, Wednesday, December 31, pp. 80656-80700. [http://www.msha.gov/REGS/FEDREG/FINAL/2008finl/E8-30669.pdf]

2. NIOSH [2007]. Research report on refuge alternatives for underground coal mines, Office of Mine Safety and Health, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Department of Health and Human Services, December 2007, 16 pp. [http://www.cdc.gov/niosh/docket/archive/pdfs/NIOSH-125/125-ResearchReportonRefugeAlternatives.pdf]

3. CFR. Code of Federal Regulations, Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

4. Steadman R.G., 1979, "The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science," *J. Appl. Meteor.* 18:861–873.

5. Yantek D.S., 2014, 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.

6. West Virginia Mine Safety Technology Task Force. 2006. Mine Safety Recommendations, Report to the Director of the Office of Miners' Health, Safety and Training by the West Virginia Mine Safety Technology Task Force. Charleston, WV: West Virginia Office of Miners' Health, Safety and Training.

7. Shumaker, W.A. 2013, Information relayed from Wesley Shumaker, Mechanical Engineer, MSHA, to Howard Epperly, Retired, MSHA, to Eric Bauer, Retired, OMSHR, regarding the heat used to represent the CO_2 scrubbing system heat during heat and humidity testing of refuge alternatives. U.S. Department of Labor, Mine Safety and Health Administration, Approval and Certification Center, Triadelphia, WV.

8. Yan, L., D. Yantek, P. Bissert, and M. Klein, 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, 2015 IMECE, November 13-19, 2015, Houston, Texas, USA.

9. US Department of Health, Education, and Welfare. 1966. Sensible and Latent Heat Losses from Occupants of Survival Shelters, Occupational Health Research and Training Facility. Washington, DC.

Table 4. Calculated final apparent temperature for a range of initial mine air and initial mine strata temperatures with an assumed 90% RH.

Case	Treatment of Mine Strata Temperature	Initial Mine Air and Strata Surface Temperature (°F)	Initial Mine Strata Temperature at 1.8 m depth (°F)	Final RA Internal Air Temperature (°F)	RA Internal Air Temperature Rise (°F)	Final RA Apparent Temperature Assuming 90% RH (°F)
1	Calculated	50	50	74.5	24.5	73.2
2	Calculated	50	60	77.0	27.0	78.2
3	Calculated	60	50	81.7	21.7	90.6
4	Held constant	60	60	75.8	15.8	75.6
5	Calculated	60	60	84.1	24.1	98.4
6	Calculated	60	70	86.6	26.6	107.6
7	Calculated	70	60	91.2	21.2	127.4