*Underground Ventilation – Tukkaraja (Ed)*


# Occupancy derating for underground coal mine refuge alternatives

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ABSTRACT: Federal regulations require refuge alternatives (RAs) to be installed in underground coal mines in the United States. The thermal environment of RAs is a concern because trapped miners could experience heat exhaustion or heat stroke, which is deadly. To prevent exposing RA occupants to heat stress, regulations for RAs in underground coal mines mandate an apparent temperature (AT) limit of 35°C (95°F). To examine occupancy derating to meet the AT limit, researchers at the National Institute for Occupational Safety and Health (NIOSH) conducted RA thermal simulations with validated thermal simulation models using actual mine strata and temperature data. NIOSH examined occupancy derating for a portable 23-person tent-type RA and a portable 6-person rigid RA across a range of initial temperatures for the NIOSH Experimental Mine strata. Occupancy derating was necessary for mine air dry-bulb temperatures as low as 15.6°C (60°F). NIOSH also examined occupancy derating for each RA in five mines across the United States using the measured worst-case temperatures and mine strata of each mine. The results showed occupancy derating would be necessary for the mines with relatively warm initial temperatures. RA manufacturers and mines can use this information to ensure that RAs do not exceed the AT limit.

## 1 INTRODUCTION

On December 31, 2008, the Mine Safety and Health Administration (MSHA) published its final rule "Refuge Alternatives for Underground Coal Mines" (Federal Register, 2008), which became effective on March 2, 2009. This rule mandates underground coal mines to install refuge alternatives (RAs) so that all miners, contractors, and visitors have access to an RA in case of an inescapable mine emergency. The RA regulations require RAs to provide a breathable air environment, food and water, and supplies needed to sustain trapped miners for up to 96 hours. The regulations also provide requirements for the breathable air environment, available space and volume, and thermal conditions.

Due to human metabolic heat, carbon dioxide (CO2) scrubber system heat, and a limited ability to dissipate heat, the thermal environment of an occupied RA can become severe enough to cause heat exhaustion or heat stroke, which can be deadly (OSHA, 2003, Bernard, 2011). RA regulations for U.S. underground coal mines specify a maximum apparent temperature (AT) of 35°C (95°F) (Steadman, 1979). For indoor environments without solar loading, the AT is calculated using dry-bulb temperature and percent relative humidity (%RH) (Rothfusz, 1990). The regulations require RA manufacturers to conduct testing to determine an RA's maximum occupancy without exceeding the AT limit.

Many factors affect the resulting RA thermal conditions including the number of RA occupants, the mine air and strata temperature, and the mine strata thermal properties (Yan et al., 2020, Yantek et al., 2017). As the number of occupants increases, the heat input also increases, and the resulting RA thermal conditions become more severe. Higher initial mine air and strata temperatures also increase the severity of an occupied RA's thermal conditions. Mine strata materials have low thermal conductivity, which limits conductive heat transfer from an RA to the mine.

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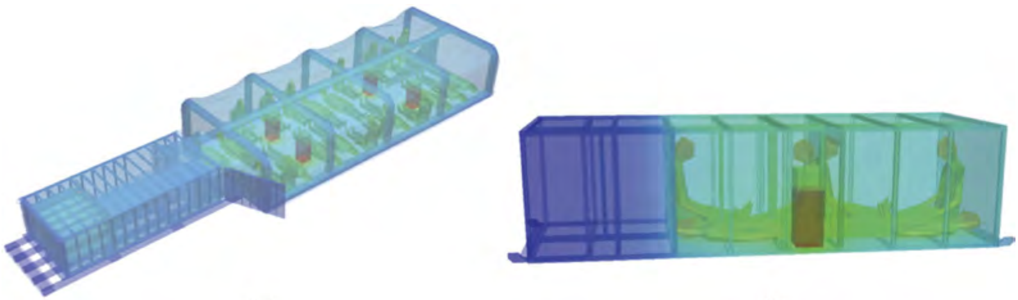
To ensure that the AT limit is not reached, heat mitigation devices or occupancy derating could be necessary for warm or hot mines. The National Institute for Occupational Safety and Health (NIOSH) used test-result-validated RA thermal simulation models with actual mine temperatures, %RH values, and strata compositions to examine occupancy derating for two portable RAs: a 23-person portable tent-type RA and a 6-person portable steel RA. The stated occupancies are based on the space and volume requirements of the RA regulations for underground coal mine RAs (CFR, 2019). This paper discusses the results of the occupancy derating simulations.

## 2 OCCUPANCY DERATING ANALYSIS METHOD

The concept of occupancy derating of an RA is to limit its occupancy to less than full capacity in order to ensure that the conditions within the RA remain below the 35°C (95°F) AT limit. The resulting thermal conditions within an RA are a function of the number of occupants, the RA design, the mine strata thermal properties, and the mine air and strata temperatures. For a given RA, it would be impractical to conduct testing to represent the conditions in all mines.

In order to examine the need for occupancy derating, NIOSH used validated thermal simulation models (refer to Figure 1) of a 23-person portable tent-type RA and a 6-person portable steel RA that were tested in the NIOSH Experimental Mine (EM) (Yan et al., 2016a, Bissert et al., 2016, Yan and Yantek, 2018, Yan et al., 2020, Klein et al., 2017, Klein and Hepokoski, 2017) (Yan et al., 2016b) (Klein, 2017a) (Klein, 2017b). In these models, the mine strata were modeled as twenty-four 7.62-cm-thick (3-in-thick) layers up to a modeling depth of 1.83 m (6 ft). The models included transient heat conduction into the mine roof, rib, and floor. The mine strata thermal properties for each mine were used for the layers in the models. Human thermal models (HTMs) were used to input the heat of actual occupants (Bernard et al., 2018, Klein and Hepokoski, 2017). The HTMs model the complex nature of heat transfer from the human body and account for all manners of body heat transfer including vasodilation, perfusion, and evaporation of sweat. The $CO_2$ scrubber system heat input was set to 27.5 W per person (Shumaker, 2013). For each RA, the mine dry-bulb air temperature, %RH, and mine strata temperatures were used as initial conditions. A 96-hour transient thermal analysis was conducted with the maximum RA occupancy to determine the final RA air temperature and %RH. The AT limit was calculated from the predicted RA air temperature and %RH (Rothfusz, 1990). If the AT limit was reached, the number of HTMs was reduced and the analysis was repeated. The maximum number of occupants was then found by iteratively increasing or decreasing the number of HTMs.

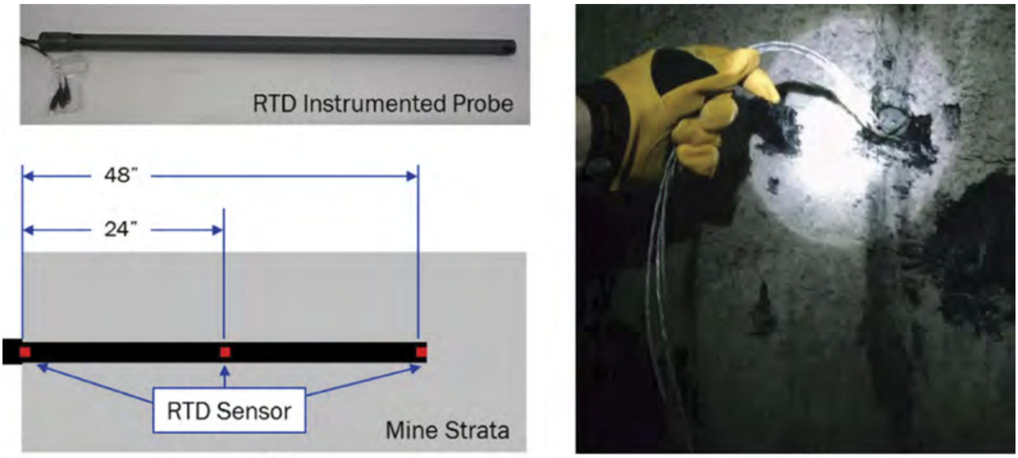


(a) (b)

Figure 1. Thermal simulation models used for occupancy derating analysis (a) 23-person portable tent-type RA and (b) 6-person portable steel RA.

Initially, NIOSH examined occupancy derating for both RAs based on the EM. This analysis was conducted using the thermal simulation models of the RAs with the mine strata thermal properties and thermal conditions of the EM. The EM floor strata was modeled as a 15.2-cm-thick (6-inch-thick) layer of concrete over 168 cm (66 in) of siltstone, the EM rib strata was modeled as a 2.5-cm-thick (1-inch-thick) layer of shotcrete over bituminous coal, and the EM roof strata was modeled as 31 cm (12 in) of slate, 61 cm (24 in) of bituminous coal, and 91 cm (36 in) of shale. To simplify the model, the 2.5-cm-thick (1-in-thick) layer of shotcrete on the EM roof was ignored in the analysis. Thermal simulations were conducted across a range of initial mine air, mine strata, and RA temperatures from 12.8°C–23.9°C (55°F–75°F) in 2.8°C (5°F) increments. The initial %RH for these simulations was 85% based on measured data from the RA tests in the EM.

Next, NIOSH examined occupancy derating for the portable tent-type and metal RAs for five U.S. mines located in the Southwestern, Midwestern, Southern, Western, and Eastern regions of the U.S. NIOSH collaborated with these mines to determine the mine temperatures, %RH values, and mine strata properties to be used in the simulations (Bissert et al., 2016, Yantek et al., 2017). The mine air temperature, %RH, and strata temperatures near existing RAs were measured by mine personnel using air-temperature-measurement resistance temperature detector (RTD) probes, a %RH instrument, RTD-instrumented PVC rods (refer to Figure 2), and RTD thermometers provided by NIOSH. The mine strata temperatures were measured at the surface and at depths of 0.61 m (24 in) and 1.22 m (48 in). Mine personnel documented the temperatures at least once per month for an entire year. The worst-case combination of mine air temperature, %RH, and mine strata temperatures were used as initial conditions in the thermal simulations (see Table 1). Through conversations with mine personnel and NIOSH ground control researchers, the mine strata composition and layer thicknesses were assumed based on the geographic location of each mine (see Table 2). The strata properties used in the thermal simulations are shown in Table 3.




(a) (b)

Figure 2. (a) RTD-instrumented PVC rod for measuring strata temperatures and (b) picture showing RTD-instrumented rod installed into the mine rib.

## 3 RESULTS

### 3.1 *Results for NIOSH Experimental Mine*

The analysis of the 23-person portable tent-type RA with the EM strata properties showed that occupancy derating would be necessary for an initial temperature of 21.1°C (70°F) or greater (see Table 3). At an initial temperature of 21.1°C (70°F), the occupancy would have to be decreased from 23 to 16, a 30% reduction. For an initial temperature of 23.9°C (75°F), the occupancy would have to be reduced from 23 to 9, a 61% reduction.

Table 1. Mine dimensions and worst-case combinations of %RH, mine air temperature, and mine strata temperatures for five mines across the U.S.

| Mine | Width | Height | Mine Air Temp. | Mine Air % RH | Strata Temperatures | | |
|---|---|---|---|---|---|---|---|
| | | | | | Surface | 0.61 m (24 in) Depth | 1.22 m (48 in) Depth |
| Southwestern | 5.94 m (19.5 ft) | 2.90 m (9.5 ft) | 18.9°C (65.6°F) | 69 | 18.3°C (65.2°F) | 18.9°C (65.6°F) | 18.9°C (66.0°F) |
| Midwestern | 5.49 m (18 ft) | 1.68 m (5.5 ft) | 20.6°C (69.4°F) | 92 | 19.4°C (67.2°F) | 18.3°C (65.2°F) | 17.8°C (64.1°F) |
| Southern | 6.40 m (21 ft) | 2.93 m (9.6 ft) | 27.2°C (81.3°F) | 92 | 28.3°C (82.8°F) | 26.7°C (80.1°F) | 26.1°C (78.7°F) |
| Western | 4.88 m (16 ft) | 2.59 m (8.5 ft) | 17.2°C (62.7°F) | 59 | 15.0°C (58.7°F) | 15.0°C (58.5°F) | 13.9°C (57.1°F) |
| Eastern | 5.79 m (19 ft) | 2.21 (7.25 ft) | 18.9°C (66.4°F) | 96 | 17.2°C (63.4°F) | 17.2°C (62.9°F) | 17.2°C (62.5°F) |

Table 2. Mine strata composition of five mines used in occupancy derating study. Note: If only one material is listed, the entire 1.8-m-thick (6-ft-thick) strata layer is assumed to consist of the listed material.

| Mine | Strata Composition | | |
|---|---|---|---|
| | Floor | Ribs | Roof |
| Southwestern | mudstone | bituminous coal | 72 cm (2.5 ft) bituminous coal, 49 cm (1.6 ft) shale, 18 cm (0.6 ft) bituminous coal, 9.1 cm (0.3 ft) mudstone |
| Midwestern | 122 cm (4 ft) claystone, 61 cm (2 ft) sandstone | bituminous coal | shale |
| Southern | shale | 91 cm (3 ft) bituminous coal, 91 cm (3 ft) shale | shale |
| Western | bituminous coal | 5.1 cm (2 in) shotcrete, 89 cm (35 in) bituminous coal, 89 cm (35 in) mudstone | 30 cm (1 ft) bituminous coal, 122 cm (4 ft) sandstone, 30 cm (1 ft) bituminous coal |
| Eastern | shale | bituminous coal/shale composite | 91 cm (3 ft) bituminous coal, 91 cm (3 ft) shale |

Table 3. Mine strata thermal properties used in the occupancy derating studies.

| Material | Density (kg/m$^3$) | Thermal Conductivity (W/m-K) | Specific Heat (J/kg-K) |
|---|---|---|---|
| shale, mudstone, claystone | 2600 | 1.0 | 1000 |
| bituminous coal (non-EM) | 1346 | 0.33 | 1380 |
| Sandstone | 2500 | 1.7 | 920 |
| Siltstone | 2600 | 2.7 | 1000 |
| concrete, shotcrete (measured) | 2039 | 1.3 | 1088 |
| EM bituminous coal (measured) | 1500 | 0.58 | 1297 |

Note: For measured values, core samples collected by NIOSH were tested by Decagon Devices, Inc., 2365 NE Hopkins Court, Pullman, WA 99163.

The analysis of the 6-person portable steel RA with the EM strata properties also showed that occupancy derating would be necessary for an initial temperature of 21.1°C (70°F) or greater (see Table 4). At an initial temperature of 21.1°C (70°F), the occupancy would have to be decreased from 6 to 4, a 33% reduction. For an initial temperature of 23.9°C (75°F), the occupancy would have to be reduced from 6 to 2, a 67% reduction.

Table 4. Derating results for 23-person portable tent-type RA from simulations of the EM. Red indicates the AT exceeded 35°C (95°F). Note: The initial %RH for these simulations was 85 %RH.

| Initial Temperature | Number of Occupants | Final RA Air-Temperature | Final RA %RH | Final AT |
|---|---|---|---|---|
| 12.8°C (55°F) | 23 | 22.8°C (73.0°F) | 85.2 | 22.2°C (72.0°F) |
| 15.6°C (60°F) | 23 | 25.1°C (77.1°F) | 85.7 | 25.9°C (78.6°F) |
| 18.3C (65°F) | 23 | 28.1°C (82.5°F) | 90.2 | 33.9°C (93.1°F) |
| 21.1°C (70°F) | 23 | 30.8°C (87.5°F) | 90.2 | 44.1°C (111.4°F) |
| | 17 | 28.5°C (83.3°F) | 92.8 | 36.0°C (96.8°F) |
| | 16 | 27.8°C (82.1°F) | 93.9 | 33.9°C (93.0°F) |
| 23.9°C (75°F) | 17 | 31.2°C (88.2°F) | 92.4 | 46.6°C (115.8°F) |
| | 11 | 28.8°C (83.9°F) | 94.9 | 37.7°C (99.9°F) |
| | 9 | 27.9°C (82.2°F) | 97.0 | 34.6°C (94.3°F) |

Table 5. Derating results for 6-person portable steel RA from simulations of the EM. Red indicates the AT exceeded 35°C (95°F). Note: The initial %RH for these simulations was 85 %RH.

| Initial Temperature | Number of Occupants | Final RA Air-Temperature | Final RA % RH | Final AT |
|---|---|---|---|---|
| 12.8°C (55°F) | 6 | 22.9°C(73.2°F) | 83.9 | 22.5°C (72.5°F) |
| 15.6°C (60°F) | 6 | 25.3°C (77.6°F) | 84.0 | 26.5°C (79.7°F) |
| 18.3C (65°F) | 6 | 27.4°C (81.3°F) | 90.0 | 31.9°C (89.4°F) |
| 21.1°C (70°F) | 5 | 28.5°C (83.3°F) | 94.5 | 36.3°C (97.4°F) |
| | 4 | 27.4°C (81.3°F) | 93.3 | 32.2°C (90.0°F) |
| 23.9°C (75°F) | 3 | 28.7°C (83.6°F) | 96.1 | 37.4°C (99.3°F) |
| | 2 | 27.3°C (81.2°F) | 95.6 | 32.5°C (90.5°F) |

### 3.2 *Results for five mines across the U.S.*

The analysis of the 23-person portable tent-type RA for the five mines across the U.S. showed that some mines would not require derating, while others would require derating (see Table 5). The Midwestern mine and the Southern mine would require derating. The Midwestern mine would require the occupancy to be reduced from 23 to 21, a 9% reduction. The Southern mine would require the occupancy to be reduced from 23 to 1, a 96% reduction. The Southwestern, Western, and Eastern mines would not require derating. It should be noted that, if the initial temperature was a few degrees higher, the Southwestern mine would also require derating as the predicted final air temperature would likely exceed the AT limit.

The analysis of the 6-person portable steel RA for the five mines across the U.S. showed that only the Southern mine exceeded the AT limit (see Table 6). For the Southern mine, the AT limit would be exceeded even with only a single occupant. Therefore, the Southern mine would need to implement cooling to use the 6-person portable steel RA. At full occupancy, the Midwestern mine was just below the AT limit. If the initial temperature of the Midwestern and Southwestern mines were a degree or two higher, the number of occupants for the 6-person portable metal RA would need to be reduced for each mine.

Table 6. Derating results for 23-person portable tent-type RA from simulations of five mines across the U.S. Red indicates the AT exceeded 35°C (95°F).

| Mine | Initial AirTemperature | Initial % RH | Number of Occupants | Final AirTemperature | Final % RH | Final AT |
|---|---|---|---|---|---|---|
| Southwestern | 18.7°C (65.6°F) | 69 | 23 | 28.1°C (82.5°F) | 92.5 | 34.3°C (93.7°F) |
| Midwestern | 20.8°C (69.4°F) | 92 | 23 | 28.6°C (83.4°F) | 93.3 | 36.3°C (97.4°F) |
| | | | 22 | 28.2°C (82.8°F) | 92.6 | 35.1°C (95.1°F) |
| | | | 21 | 27.9°C (82.2°F) | 91.9 | 33.8°C (92.8°F) |
| Southern | 27.4°C (81.3°F) | 92 | 9 | 30.7°C (87.2°F) | 99.4 | 47.1°C (116.8°F) |
| | | | 4 | 29.0°C (84.2°F) | 98.7 | 39.4°C (103.0°F) |
| | | | 3 | 28.6°C (83.5°F) | 98.8 | 37.9°C (100.2°F) |
| | | | 2 | 28.2°C (82.8°F) | 99.0 | 36.3°C (97.3°F) |
| | | | 1 | 27.8°C (82.1°F) | 99.3 | 34.7°C (94.5°F) |
| Western | 17.1°C (62.7°F) | 59 | 23 | 26.1°C (78.9°F) | 84.9 | 27.9°C (82.3°F) |
| Eastern | 19.1°C (66.4°F) | 96 | 23 | 31.4°C (80.6°F) | 88.6 | 30.6°C (87.1°F) |

Table 7. Derating results for 6-person portable metal RA from simulations of five mines across the U.S. Red indicates the AT exceeded 35°C (95°F).

| Mine | Initial AirTemperature | Initial % RH | Number of Occupants | Final RA AirTemperature | Final % RH | Final AT |
|---|---|---|---|---|---|---|
| Southwestern | 18.7°C (65.6°F) | 69 | 6 | 27.7°C (81.8°F) | 90.0 | 32.7°C (90.8°F) |
| Midwestern | 20.8°C (69.4°F) | 92 | 6 | 28.2°C (82.7°F) | 91.6 | 34.6°C (94.2°F) |
| Southern | 27.4°C (81.3°F) | 92 | 2 | 30.0°C (86.0°F) | 98.6 | 43.6°C (110.4°F) |
| | | | 1 | 28.6°C (83.5°F) | 98.3 | 37.7°C (99.9°F) |
| Western | 17.1°C (62.7°F) | 59 | 6 | 24.3°C (75.8°F) | 83.3 | 24.7°C (76.4°F) |
| Eastern | 19.1°C (66.4°F) | 96 | 6 | 26.6°C (79.8°F) | 85.7 | 29.1°C (84.4°F) |

## 4 DISCUSSION

The derating simulation results show that the occupancy derating percentages depend on the initial mine temperature and mine strata composition based on geographical location. For the portable tent-type RA, the predicted AT was just under the AT limit when the mine initial temperature was 18.3°C (65°F) for the EM and for the Southwestern mine. If the mine strata thermal conductivity was slightly lower, the AT limit would have been reached because the final RA air temperature would have been higher. At an initial mine temperature of 21.1°C (70°F), the portable tent-type RA needed to be derated by 30% and the portable metal RA needed to be derated by 33% for the EM. In addition, for the Midwestern mine with a mine initial temperature of just under 21.1°C (70°F), the portable tent-type RA needed to be derated by 10% and the portable metal RA was almost at the AT limit. For the EM, at an initial mine temperature of 23.9°C (75°F), the portable tent-type RA and portable metal RA would have to be derated by 60% and 67%, respectively. For the EM at an initial mine temperature of 26.7°C (80°F), using the dry-bulb temperature rise per occupant and relative humidity for the 23.9°C (75°F) initial mine temperature, the occupancy of the portable tent-type RA would have to be derated by 90% and the portable steel RA would not be able to be used without cooling. For the Southern mine, which had an initial mine temperature of about 26.7°C (80°F), the derating analysis showed that the portable tent-type RA would have to be derated by 96% and the portable metal RA would require cooling.

Based on the occupancy derating analysis results for the EM and the actual mines, a table of expected percent occupancy derating needed for compliance was developed (refer to Table 7). In the development of this table, we considered the results from more than 30 in-mine tests of the portable 23-person tent-type and 6-person metal RAs. In addition, we considered simulation results that examined the resulting thermal conditions for mine strata compositions having "low" to "high" thermal conductivity and a range of mine entry sizes (Bissert et al., 2016). Furthermore, we considered simulation results that examined how initial mine air temperatures, initial mine strata surface temperature, and initial mine strata temperature at depth affects the resulting thermal conditions (Yantek et al., 2017). To account for variations in mine strata composition, entry size, and RA thermal properties, the lowest percent occupancy reductions from the analysis were decreased slightly, and the highest percent occupancy reductions from the analysis were increased slightly. This table should not be interpreted as a rigid set of percent occupancy reductions as it is based on thermal simulations and has not been validated by testing. Furthermore, the table is based on results from only one portable tent-type RA and one portable metal RA and a few mines with assumed mine strata composition based solely on geographical location. However, Table 7 can be used as a guide to provide an expected possible range of percent occupancy reductions. It should be noted that above 26.7°C (80°F), it is likely that cooling or dehumidification would be required because the buildup of moisture inside an RA would likely result in a relative humidity of greater than 90%. At this relative humidity, the 35°C (95°F) AT limit would be reached at an RA air temperature of 28.3C (83°F). For initial mine temperatures of 29.4°C (85°F), the AT limit would be reached for a relative humidity of 75%. Based on all NIOSH testing and thermal simulations, the relative humidity would exceed 90%. Therefore, cooling or dehumidification would be necessary for mine air temperatures above 29.4°C (85°F).

Table 8. Approximate percent occupancy derating needed for a 23-person portable tent-type RA and a 6-person portable steel RA.

| Range of Initial Mine Temperatures | % Occupancy Derating Needed for Compliance |
|---|---|
| < 15.6°C (60°F) | Derating unnecessary |
| 16.6°C–18.3°C (60°F–65°F) | 0%–10% |
| 18.3°C–21.1°C (65°F–70°F) | 0%–40% |
| 21.1°C–23.9°C (70°F–75°F) | 25%–75% |
| 23.9°C–26.7°C (75°F–80°F) | 50%–90% |
| 26.7°C–29.4°C (80°F–85°F) | 90%–100% |
| >29.4°C (85°F) | Cooling/dehumidification required |

## 5 CONCLUSIONS

Although it would be impractical to conduct testing for all possible mine temperatures and mine strata compositions, our analysis results can be used as a rough guide for planning purposes. In order to ensure compliance with the 35°C (95°F) AT limit, testing or simulations using validated thermal simulation models should be used to estimate the final AT, which primarily depends on initial mine temperature and mine strata composition.

In the absence of cooling or dehumidification, our analysis indicates that occupancy derating of RAs may be required for some mines. For mines below 18.3°C (65°F) with very low mine strata thermal conductivity, the occupancy may need to be slightly reduced. For mines between 18.3°C–21.1°C (65°F–70°F), occupancy derating would be necessary for mines with strata having low thermal conductivity. From 21.1°C–26.7°C (70°F–80°F), the results indicate that occupancy derating would be necessary. Above (80°F), occupancy derating would approach 100%, and cooling or dehumidification would be needed to ensure that the thermal conditions inside an RA stay below the 35°C (95°F) AT limit.

## 6 LIMITATIONS

Because the analysis presented here was performed on only two RAs with conditions from only five mines across the U.S. and one nonproduction mine, the results should not be assumed to directly apply to mine-specific RA installations. Additional testing or analysis would be necessary to determine occupancy derating percentages for a specific RA installation.

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# Underground Ventilation

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## 6 LIMITATIONS

Because the analysis presented here was performed on only two RAs with conditions from only five mines across the U.S. and one nonproduction mine, the results should not be assumed to directly apply to mine-specific RA installations. Additional testing or analysis would be necessary to determine occupancy derating percentages for a specific RA installation.

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