# DESIGN ASPECTS OF UNDERGROUND RESCUE CHAMBERS

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## Abstract

The use of refuge chambers for use in handling underground emergencies is an issue of topical relevance within the US mining industry. Chamber design is of importance to meet some new safety requirements of US federal and some state government mine regulations. A review has been undertaken of a steel mine refuge chamber design to predict what will be internal temperature within the chamber over an extended period with miners present? The design has been examined for the situation when the chamber is sited in still mine air. Spreadsheets have been developed to allow various design assumptions to be tested.

The evaluation has been undertaken using thermodynamic heat transfer models with some assumptions specified to produce a model of appropriate simplicity but with adequate degree of accuracy. Under normal still air conditions it can be seen that internal chamber conditions rise quickly to often arduous conditions. There will always be quite a few assumptions necessary in complex heat transfer process evaluations.

Some important refuge chamber design parameters are:

- External surface area of the chamber, its wall thickness and construction.
- Metabolic heat generated and number of persons making use of the chamber.
- The temperature of the external mine atmosphere to the chamber over the year and the influence of geothermal gradient on temperature at depth.
- The maximum internal chamber Apparent Temperature considered safe.
- The distance inside the underground mine and adjacent ventilation conditions.

Keywords: Rescue chamber, heat stress and strain, mine heat sources

## Introduction

In the event of an underground coal mine disaster, mine workers are taught to attempt to escape and exit the mine by whatever means and as quickly as possible. They are also instructed to don a self-contained self-rescuer (SCSR) to provide breathable air because post-disaster mine air is likely to be contaminated with high concentrations of CO and other explosion or fire generated toxic gases.

US regulations requiring mines to provide an improved survival system has been implemented since the 2006 Sago WV mine disaster when 11 miners attempted to barricade themselves at their working place but 10 miners lost their lives behind the barricade due to CO poisoning. The result was the adoption of portable refuge chambers as the means of providing protection for miners who cannot escape a mine disaster. Miners are now instructed to go to the nearest refuge chamber if escape is not possible.

In the US a portable refuge chamber is an enclosed structure that provides a breathable atmosphere, food, and water with 96 hours of life support for the number of occupants for which the chamber was intended. These chambers, which are currently portable and are moved forward as the mine face advances, are either a steel box or an inflatable tent-type structure. Refuge chamber capacities generally range from 12 (one section crew of miners and possibly a few more) to 36 occupants. Once inside the chamber, miners seal the door, activate the oxygen, assemble and activate the carbon dioxide scrubbing system, and then wait for rescue. The hope is that rescuers reach the chamber within the 96 hours life support window.

One issue of importance in chamber design involves understanding the heat and humidity generated within an occupied refuge alternative and the heat transfer mechanisms between the refuge chamber and mine environment. Heat is generated mainly by the occupants but also the carbon dioxide scrubbing system and any light sources in the chamber. Humidity is also produced as the occupants exhale. Important relevant questions include:

- How much heat refuge chamber occupants generate;
- How best to simulate human heat;
- The heat transfer process within, through, and to outside the chamber;
- What controls the heat transfer (i.e. the mine air temperature or the temperature of the surrounding coal ribs, roof, and mine floor);
- The effect of chamber wall material on heat transfer;

- How an increase in ambient mine air enhances or retards the heat transfer from inside the chamber to outside the chamber;
- Does direct contact with the mine floor promote heat transfer; and
- Does the mine structure (roof, ribs, and floor) act as an infinite heat sink?

The reason a thorough understanding is needed is that all portable refuge chambers currently in underground coal mines in the U.S. were designed, modeled, tested, and approved to a standard of an ambient mine temperature of 13-16 °C (55-60 °F) and were demonstrated to remain below 35 °C (95 °F) apparent temperature inside the chambers while fully occupied according to the Steadman Apparent Temperature criteria (see Appendix 1). There are, however, some mines in the U.S. where the ambient mine temperature is greater than 16 °C (60 °F), and even as high as 24-27 °C (75-80 °F). In addition, the temperature of post-disaster mine air may be higher as well. This reduces the amount of heat that transfers out of a refuge chamber, resulting in higher internal temperature and possibly a greater than 35°C (95 °F) apparent temperature. Apparent temperatures above 35 °C (95 °F) can lead to a number of unwanted medical problems including heat strain, dehydration and even death.

There is a need to establish engineering specifications and practical guidelines for designing refuge alternatives and dealing with heat and humidity inside an occupied refuge alternative. Establishment of these requires as a first step a description of the heat-transfer mechanisms associated with refuge chamber occupation. A concise attempt at this is the objective of this paper.

## Technical Approach

A review has been undertaken of a specified mine refuge chamber design to predict what will be internal temperatures within chambers over extended periods with miners present. These have been examined for the situation when the chambers are sited in still mine air. The exercise to achieve this required the development of spreadsheets to allow various design assumptions to be tested. The discussion mentions a number of aspects of the heat-transfer mechanisms/processes associated with refuge alternative occupation in an underground mine.

The key or principal question under review is what will be the internal temperature within a refuge chamber over an extended period with miners present? The design exercise follows mathematically developed designs based on various conditions. This approach in particular considers the influence of condensation moisture on internal chamber steel walls in heat transfer calculations. Chamber internal temperatures have been examined for the normal situation where the chamber is sited in still mine air. This assumes that the chamber is out of the main mine air flow (such as in a crosscut) or the mine fans are off due to a mine fire or explosion. An example using one chamber design and construction but with varying size has been examined within this illustration. Spreadsheets have been given as examples that can allow extrapolation to various design assumptions to be tested.

### *Refuge Chamber Design Assumptions*

A steel refuge chamber with nominal dimensions of - External L: 6369.06mm; W: 2217.74mm; H: 1168.40mm has been selected for analysis. Some design parameters are as follows.

- The chamber is of steel of 6.3mm thickness. This steel is assumed to have a heat conductivity of 45 W/m $^{o}$C.
- Metabolic heat generated is 117W (400 Btu) per person. This assumes no activity by miners 80 percent of time and moderate activity for the remaining time.
- Additional sensible heat from conversion of $CO_2$ using soda lime chemical is 8W (28 Btu) per person.
- The chambers hold up to 12 persons for base calculations. Number of persons has been increased for later comparison calculations.
- External mine atmosphere to the chamber is 13$^{o}$C (55 $^{o}$F). This is the average external underground atmosphere temperature throughout the year for the state with the largest number of underground coal mines, West Virginia. US Regulatory authorities have set an Apparent Temperature of 35$^{o}$C (95$^{o}$F) as the maximum safe condition.
- It has been assumed that the chamber sits in a crosscut, that there is no positive airflow and the area surrounding the chamber is sufficiently large that it functions as an infinite heat sink.
- Ongoing fires are not anticipated to increase ambient temperature near the refuge chamber.
- The mine workings are relatively shallow and there is no significant geothermal gradient.
- The chamber has a system of chemicals for neutralising respiration $CO_2$ and bottled oxygen for providing breathable air.

### *Engineering Assumptions*

Various engineering assumptions have been made for these design exercises.

- Bottled compressed oxygen is released at the rate of uptake of the occupants within the chamber (0.5 liters/minute). This air will initially have a low humidity level. The very low rate of release will mean the air will very quickly become saturated from addition of breathed out respiration air. Some of this air will be lost through cracks around the chamber door while providing a positive pressure to keep out the external toxic environment.

- Compressed oxygen in the chamber will adjust to the ambient temperature. Although it will initially start with a low absolute humidity on release it will quickly move to saturation due to the excess humidity present.
- Surface temperatures in West Virginia can vary from a daily average of about 0°C in mid winter to 27°C in mid-summer. However the air entering the mine will be quickly tempered from these extremes as the surrounding strata acts as a heat sink or source. Reference to Gillies and Aughenbaugh (1981)[1] for mine temperatures taken in Missouri (Missouri has an approximately similar climate to West Virginia and is at about the same latitude) indicates that the air ventilation Sensible or Dry Bulb (DB) temperature 600m from the coal face will be damped and fluctuate through a range of no greater than 8°C (46°F) to 20°C (68°F). This variation will depend on a number of factors including tunnel air velocity and in most cases will probably be less than the range given.
- The comfort of refuge chamber personnel will be influenced by air sensible temperature, absolute humidity and air velocity. Persons entering the chamber will find the internal temperature initially across the range of say 8°C to 20°C depending on the season, depth and other considerations. Air velocity will be very low. Relative Humidity will generally be high as is normal in most parts of all underground mines. As such it will very quickly move towards 100 percent or saturated conditions as respiration adds moisture from breathing into the confined chamber atmosphere. For calculations it has been assumed that the chamber atmosphere will reach saturation quickly and excess humidity will condense on the chamber walls (this assumption may not be precisely correct particularly when the external temperature is low and the chamber is located close to a fresh air source)**.**
- Heat transfer processes examined have been restricted to thermal conduction and convection and moisture latent heat phase changes. The latent heat generated by the influence of condensation moisture on internal chamber steel walls has been taken into account in heat transfer calculations. Radiant heat transfer effects have been considered to be negligible. The relatively low heat levels generated from exothermic processes from chemical reactions in scrubbing $CO_2$ from air have been ignored in the calculations in this paper although for precise calculations it would be worthwhile including them.

### *Examination of Heat Transfer from the Chamber*

The thermodynamic theory that calculations are based on principally relies on Whillier (1974)**[2]**. The model developed assumes flow through flat solid surfaces. Figure 1 shows a model of the heat transfer conditions. It is assumed the chamber is mounted on skids or wheels with air underneath.

### *Refuge Chamber External Dimension (12 person model as an example)*

Height: 1.168 m; Internal Height: 1.068 m
Width: 2.218 m; Internal Width: 2.118 m
Length: 6.369 m; Internal Length: 6.269m

(This assumes the steel frame supporting the chamber structure is about 50 mm wide. To allow for this 100mm has been deducted from external dimensions).

Internal surface area: 44.47 $m^2$
Internal volume: 14.18 $m^3$
Chamber Steel Thickness (1/4"): 6.35 mm

Chamber Steel Thermo Conductivity: 45.0 W/m °C
Constant external temperature: 13.0°C
Absolute Pressure: 100.3 kPa
Air Density: 1.24 $kg/m^3$
Air Mass inside the Chamber: 17.3 kg

Chamber Capacity: 12 person
Starting Metabolic Heat Rate: 117 W per person
Total Metabolic Heat Generated: 1404W or J/s or 1.40 kJ/s

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[1] A.D.S. Gillies and N.B. Aughenbaugh, Passive air conditioning: Flow through rock-lined tunnels tempers air, Underground Space, 6, Pergamon Press, October 1981,pp.114-120.

[2] A. Whillier. Introduction to steady state heat transfer *The Ventilation of South African Gold Mines,* pp138-163, Ed: The Mine Ventilation Society of South Africa, 1974.

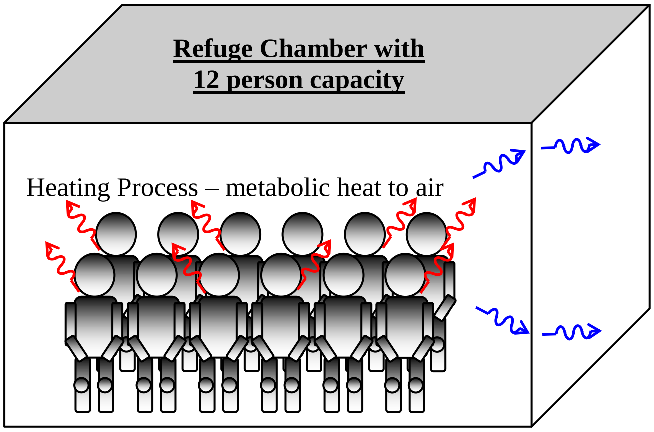

**Figure 1.** Model of the heat transfer conditions inside and outside the refuge chamber.

### *Heating Process*

It is assumed that all metabolic heat generated by the 12 persons inside the Refuge Chamber will be transferred to air inside the Chamber without any losses. It is assumed for each person that metabolic heat output is constant at 117 kW and for instance does not increase with human agitation as body temperature increases.

Initial heat content (at time = 0 minutes) in the air inside the chamber at 13°C (55°F) can be calculated as follows.

### *Chamber initial internal conditions*

Vapor Pressure, $P_{WS}$

$= 0.6105 \text{ Exp } (17.23 \times DB/(237.3 + DB)$

$= 0.6105 \text{ Exp } (17.23 \times 13/(237.3 + 13)$

$= 1.497$ kPa

Moisture content, r

$= 0.622 \times Pws/P$

$= 0.622 \times 1.497/100.3$

$= 0.00928$ kg/kg

Enthalpy, H

$= 1.005 \times DB + r \times (1.80 \times DB + 2501)$

$= 1.005 \times 13 + 0.00928 \times (1.80 \times 13 + 2501)$

$= 36.86$ kJ/kg

### *Chamber internal conditions after 1 minute*

Heat added from Metabolic energy per minute = (1.404 kJ/s × 60 s/min)/ 17.3 kg = 4.86 kJ/kg

Enthalpy with Heat added = 36.86 + 4.86 = 41.72 kJ/kg

This gives a temperature of 14.8°C (saturated).

The assumption has been made that the amount of moisture breathed out by the persons inside the chamber would make the air inside the chamber saturated very quickly.

### *Cooling Processes*

The Heat transfer (cooling) processes from the air inside the chamber through the steel structure and then to outside air can be divided into three processes. These are

- Natural convective heat transfer from air inside to water condensed on the internal surface (assuming water condenses and covers the whole internal surface in a short time).
- Conductive heat transfer within the steel structure.
- Natural convective heat transfer from the steel structure external face to the air outside.

Convective heat transfer coefficient for process 1 is between air/condensation water and steel and can be calculated as follows.

Convective heat transfer coefficient, $hc_1 = 190 \times (1 + 0.012 \times T_W) \times (\Delta T)^{1/3}$

Conductive heat transfer through the 6.35mm steel for process 2 can be ignored as the steel can transfer the heat from inside to outside of chamber almost freely due to its high thermal conductivity (it effectively has no insulating capability).

Convective heat transfer coefficient for process 3 under natural convection conditions can be calculated as follows.

Convective heat transfer coefficient, $hc_3 = 1.4 \times (\Delta T)^{1/3}$

Therefore the overall coefficient of heat transfer,

$UA = 1/(1/(hc_1 \times A) + 1/(hc_3 \times A))$

$= 1/(1/(1.4 \times (\Delta T)^{1/3} \times A) + 1/(190 \times (1 + 0.012 \times T_W) \times (\Delta T)^{1/3} \times A))$

where $\Delta T$ is air temperature difference between internal and external air. $T_W$ is the condensed water temperature which lies between the dew point temperature $T_{Wdp}$ for the internal condition of the chamber and the constant external temperature which can be calculated as

$T_{Wdp} = 237.3 \times LN(P_{WS}/0.6105)/(17.27-LN(P_{WS}/0.6105))$

Therefore, for the first minute UA = 75.15 W/ °C (or 1.69 W/m² °C)

Thus, the convective heat transfer (loss) from inside air to outside air is

Overall convective heat transfer amount

$= UA \times \Delta T$

$= 75.15 \times (14.8 – 13)$

$= 135.27$ W

Therefore, in the first minute, the total heat loss from inside to outside of the Chamber can be calculated as follows.

135.27 J/s × 60 s / 17.3 kg /1000 = 0.47 kJ/kg

Thus Enthalpy with metabolic heat added and convective heat loss subtracted within the first minute would be 36.86 + 4.86 - 0.47 = 41.25 kJ/kg

This gives a temperature of 14.6$^{o}$C (saturated). This means that the cooling effect at these internal and external temperature differences is small. The cooling effect becomes more pronounced as temperature differences rise.

The predicted chamber internal conditions after 1 minute then become the initial internal condition in the second minute and the calculations are repeated iteratively as demonstrated above for a given time period.

***Chamber internal conditions at beginning of the second minute***

Vapour Pressure, $P_{WS}$

= 0.6105 Exp (17.23 × 14.6/(237.3 + 14.6)

= 1.661 kPa

Moisture content, r

= 0.622 × 1.661/100.3

= 0.01047 kg/kg

Enthalpy, H

= 1.005 × 13 + 0.01047 ×(1.80 × 14.6 + 2501)

= 41.20 kJ/kg

***Chamber internal conditions after 2 minutes***

Heat added from Metabolic energy per minute = (1.404 kJ/s × 60 s/min)/ 17.3 kg = 4.86 kJ/kg

Enthalpy with Heat added = 41.20 + 4.86 = 46.06 kJ/kg

This gives a temperature of 16.3$^{o}$C (saturated).

For the second minute UA = 80.94 W/ $^{o}$C (or 1.82 W/m$^{2}$ $^{o}$C)

Thus, the convective heat transfer (loss) from inside air to outside air is

Overall convective heat transfer amount

= 80.94 × (16.3 – 13)

= 267.09 W

Therefore, in the second minute, the total heat loss from inside to outside of the Chamber can be calculated as follows.

267.09 J/s × 60 s / 17.3 kg/s /1000 = 0.92 kJ/kg

Thus Enthalpy with metabolic heat added and convective heat loss subtracted at the second minute would be

41.20 + 4.86 - 0.92= 45.14 kJ/kg

This gives a temperature of 16.0$^{o}$C (saturated). This means that the cooling effect (reducing 0.3$^{o}$C) at these internal and external temperature differences is becoming more pronounced as temperature difference rises.

## Predictions of Chamber Internal Temperatures

***The 12 person Chamber***

From the basis of this thermodynamic modeling and assumptions, Table 1 gives the predicted internal temperature within a 12 person chamber for an underground sensible temperature of 13$^{o}$C over an extended period with 12 miners present in a spreadsheet form.

**Table 1.** Predicted internal temperature within the refuge chamber Model CSLS-12 over an extended period with 12 miners present under constant external temperature of 13$^{o}$C.

| Time (min) | Metabolic Heat (W or J/s) | Heat Gain (kJ/kg) | Temp Initial (°C) | Vapour Pressure (kPa) | Moisture Content (kg/kg) | Enthalpy Initial (kJ/kg) | Enthalpy with Heat (kJ/kg) | Temp with Heat (°C) | Convec Heat Transfer Coeff (W/m2 °C) | Convec Heat loss (kJ/kg) | Enthalpy Final (kJ/kg) | Temp Final (°C) | Temp Final (°F) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1404 | 4.86 | 13.0 | 1.497 | 0.00942 | 36.9 | 41.7 | 14.8 | 1.69 | 0.47 | 41.2 | 14.6 | 58.3 |
| 2 | 1404 | 4.86 | 14.6 | 1.663 | 0.01049 | 41.2 | 46.1 | 16.3 | 1.82 | 0.93 | 45.1 | 16.0 | 60.8 |
| 3 | 1404 | 4.86 | 16.0 | 1.817 | 0.01148 | 45.1 | 50.0 | 17.6 | 1.91 | 1.35 | 48.6 | 17.2 | 62.9 |
| 4 | 1404 | 4.86 | 17.2 | 1.957 | 0.01237 | 48.6 | 53.4 | 18.7 | 1.99 | 1.75 | 51.7 | 18.2 | 64.7 |
| 5 | 1404 | 4.86 | 18.2 | 2.084 | 0.01320 | 51.7 | 56.5 | 19.6 | 2.05 | 2.10 | 54.5 | 19.0 | 66.2 |
| 6 | 1404 | 4.86 | 19.0 | 2.196 | 0.01393 | 54.4 | 59.3 | 20.4 | 2.10 | 2.39 | 56.9 | 19.7 | 67.5 |
| 7 | 1404 | 4.86 | 19.7 | 2.297 | 0.01458 | 56.8 | 61.7 | 21.1 | 2.14 | 2.66 | 59.0 | 20.4 | 68.6 |
| 8 | 1404 | 4.86 | 20.4 | 2.390 | 0.01518 | 59.0 | 63.8 | 21.7 | 2.17 | 2.92 | 60.9 | 20.9 | 69.6 |
| 9 | 1404 | 4.86 | 20.9 | 2.471 | 0.01571 | 60.9 | 65.7 | 22.2 | 2.20 | 3.12 | 62.6 | 21.4 | 70.5 |
| 10 | 1404 | 4.86 | 21.4 | 2.544 | 0.01619 | 62.6 | 67.5 | 22.7 | 2.23 | 3.32 | 64.1 | 21.8 | 71.2 |
| 11 | 1404 | 4.86 | 21.8 | 2.611 | 0.01662 | 64.1 | 69.0 | 23.1 | 2.25 | 3.49 | 65.5 | 22.2 | 71.9 |
| 12 | 1404 | 4.86 | 22.2 | 2.669 | 0.01700 | 65.5 | 70.3 | 23.4 | 2.27 | 3.63 | 66.7 | 22.5 | 72.5 |
| 13 | 1404 | 4.86 | 22.5 | 2.721 | 0.01734 | 66.7 | 71.5 | 23.7 | 2.28 | 3.76 | 67.8 | 22.8 | 73.0 |
| 14 | 1404 | 4.86 | 22.8 | 2.768 | 0.01765 | 67.7 | 72.6 | 24.0 | 2.29 | 3.88 | 68.7 | 23.0 | 73.4 |
| 15 | 1404 | 4.86 | 23.0 | 2.808 | 0.01792 | 68.7 | 73.5 | 24.2 | 2.31 | 3.98 | 69.5 | 23.2 | 73.8 |
| 16 | 1404 | 4.86 | 23.2 | 2.846 | 0.01816 | 69.5 | 74.4 | 24.4 | 2.32 | 4.07 | 70.3 | 23.4 | 74.2 |
| 17 | 1404 | 4.86 | 23.4 | 2.880 | 0.01839 | 70.3 | 75.2 | 24.6 | 2.33 | 4.16 | 71.0 | 23.6 | 74.4 |
| 18 | 1404 | 4.86 | 23.6 | 2.908 | 0.01857 | 70.9 | 75.8 | 24.8 | 2.33 | 4.22 | 71.6 | 23.7 | 74.7 |
| 19 | 1404 | 4.86 | 23.7 | 2.936 | 0.01876 | 71.6 | 76.4 | 24.9 | 2.34 | 4.30 | 72.1 | 23.9 | 75.0 |
| 20 | 1404 | 4.86 | 23.9 | 2.961 | 0.01892 | 72.1 | 77.0 | 25.0 | 2.35 | 4.35 | 72.6 | 24.0 | 75.2 |
| 30 | 1404 | 4.86 | 24.6 | 3.092 | 0.01978 | 75.1 | 79.9 | 25.7 | 2.38 | 4.67 | 75.3 | 24.6 | 76.4 |
| 60 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 90 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 120 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 150 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 180 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 210 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 240 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 270 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 300 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 330 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 360 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 720 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 1080 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 1440 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 1800 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 2160 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 2520 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |
| 2880 | 1404 | 4.86 | 24.9 | 3.140 | 0.02010 | 76.2 | 81.0 | 26.0 | 2.39 | 4.78 | 76.2 | 24.9 | 76.7 |

Figure 2 shows how these predicted internal temperatures rise over the first 8 hour period with miners present in the 12 person Chamber.

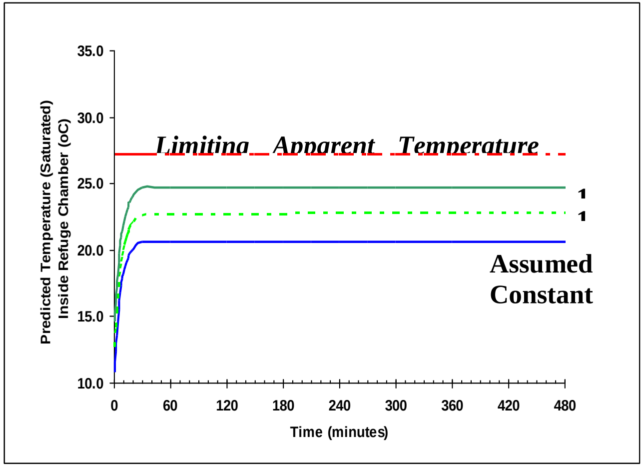

**Figure 2.** Predicted internal temperature rise over the first 8 hour period for a 12 Person Chamber for external temperatures 9 to 13$^{o}$C.

These calculations assume that there is no internal air movement or external airflow across the Chamber location. Air velocity across the chamber walls would increase surface heat transfer and provide some reduction to high and uncomfortable internal temperatures. Provision of significant air velocity would be difficult in many mine locations. In the case of a mine explosion main mine fans are likely to be inoperable for some time.

Table 2 shows that with a constant external temperature of 13$^{o}$C and 12 persons in the chamber the internal saturated temperature within the chamber stabilises at 24.6$^{o}$C over 48 hours. This internal saturated temperature without any external change will remain constant for a long period as the miners wait to be rescued. A saturated air temperature of 27.2 $^{o}$C is equivalent to an Apparent Temperature of 35 $^{o}$C (95 $^{o}$F).

Table 1. Predicted internal chamber saturated air temperature over an extended period with 12 miners present under various constant external temperatures

| External Temp | | 9$^{o}$C | 11$^{o}$C | 13$^{o}$C |
|---|---|---|---|---|
| Time | | Internal Temp ($^{o}$C) | Internal Temp ($^{o}$C) | Internal Temp ($^{o}$C) |
| (min) | (hour) | | | |
| 1 | | 10.8 | 12.7 | 14.6 |
| 2 | | 12.3 | 14.2 | 16.0 |
| 3 | | 13.6 | 15.4 | 17.2 |
| 4 | | 14.6 | 16.4 | 18.2 |
| 5 | | 15.5 | 17.2 | 19.0 |
| 6 | | 16.2 | 18.0 | 19.7 |
| 7 | | 16.8 | 18.6 | 20.4 |
| 8 | | 17.3 | 19.1 | 20.9 |
| 9 | | 17.8 | 19.6 | 21.4 |
| 10 | 0.2 | 18.2 | 20.0 | 21.8 |
| 12 | | 18.8 | 20.6 | 22.5 |
| 14 | | 19.2 | 21.1 | 23.0 |
| 16 | | 19.6 | 21.5 | 23.4 |
| 18 | | 19.8 | 21.8 | 23.7 |
| 20 | 0.3 | 20.0 | 22.0 | 24.0 |
| 30 | 0.5 | 20.4 | 22.5 | 24.6 |
| 60 | 1.0 | 20.6 | 22.7 | 24.6 |
| 90 | 1.5 | 20.6 | 22.7 | 24.6 |
| 120 | 2.0 | 20.6 | 22.7 | 24.6 |
| 150 | 2.5 | 20.6 | 22.7 | 24.6 |
| 180 | 3.0 | 20.6 | 22.7 | 24.6 |
| 210 | 3.5 | 20.6 | 22.7 | 24.6 |
| 240 | 4.0 | 20.6 | 22.7 | 24.6 |
| 270 | 4.5 | 20.6 | 22.7 | 24.6 |
| 300 | 5.0 | 20.6 | 22.7 | 24.6 |
| 330 | 5.5 | 20.6 | 22.7 | 24.6 |
| 360 | 6.0 | 20.6 | 22.7 | 24.6 |
| 720 | 12.0 | 20.6 | 22.7 | 24.6 |
| 1080 | 18.0 | 20.6 | 22.7 | 24.6 |
| 1440 | 24.0 | 20.6 | 22.7 | 24.6 |
| 2160 | 36.0 | 20.6 | 22.7 | 24.6 |
| 2880 | 48.0 | 20.6 | 22.7 | 24.6 |

## The 16 and 20 Person Chambers

Adoption of the same approach and assumed design situations allows calculations that demonstrate that an equilibrium internal temperature of 26.1 $^{o}$C within a chamber filled with 16 persons will be achieved from an underground sensible temperature of 13$^{o}$C over an extended period.

Figure 3 shows how these predicted internal temperatures rise over the first 8 hour period with miners present in a 16 Person chamber. It shows results graphically over external temperature ranges of 9 to 13$^{o}$C.

Figure 3 shows that with a constant external temperature of 13$^{o}$C and 16 persons in the chamber the internal temperature within the chamber will stabilizes at 26.1$^{o}$C. This internal saturated temperature without any external change will remain constant for a long period as the miners wait to be rescued. A saturated air temperature of 27.2 $^{o}$C is equivalent to an Apparent Temperature of 35 $^{o}$C (95 $^{o}$F); 26.1$^{o}$C is significantly below this.

Figure 4 shows that with a constant external temperature of 13$^{o}$C and 20 persons in the chamber the internal temperature within the chamber will stabilises at

27.1$^{o}$C. As discussed above this internal saturated temperature without any external change will remain constant for a long period as the miners wait to be rescued. A saturated air temperature of 27.2 $^{o}$C is equivalent to an Apparent Temperature of 35 $^{o}$C (95 $^{o}$F). The temperature of 27.1$^{o}$C is effectively at the saturated air temperature of 27.2 $^{o}$C (equivalent to an Apparent Temperature of 35 $^{o}$C (95 $^{o}$F)) but not above it. The difference has no theoretical and measurable significance. Figure 4 as with the previous results has been extended to show results graphically over external temperature ranges of 9 to 13$^{o}$C.

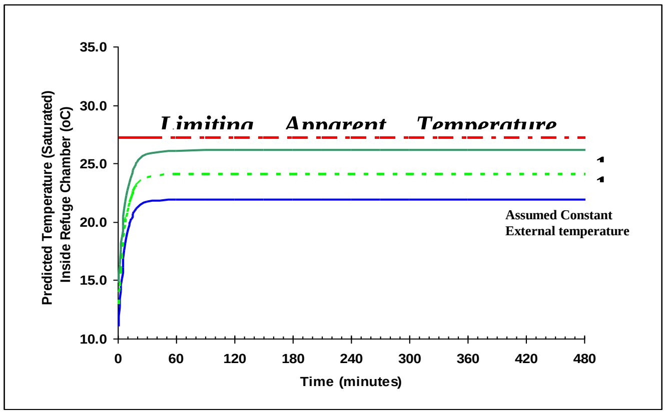

**Figure 3.** Predicted internal temperature rise over the first 8 hour period for a 16 Person Chamber for external temperatures of 9 to 13$^{o}$C

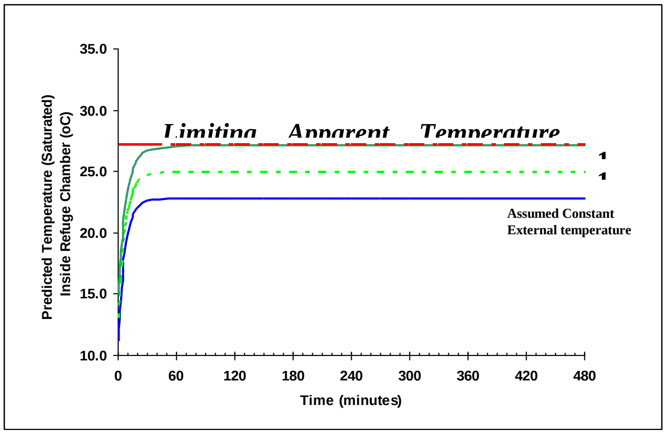

**Figure 4.** Predicted internal temperature rise over the first 8 hour period for a 20 Person Chamber for external temperatures of 9 to 13$^{o}$C

## Some Importance Issues

Recent research has highlighted some important issues and consequent important adjustments are as follows:

(a) The assumption for moisture in the occupants expired air and the resulting humidity increase in the chamber. The above analyses have assumed metabolic heat generation of 117W per person based on condition of no activity by miners with 100 percent of time at rest. Metabolic heat generation in some other refuge chamber studies had been based on activity of 15% low energy exercise and 85% at rest to give a rate of 140W per person.

(b) The cooling effect from the condensation against the steel inside the chamber.

(c) Estimation of heat build up inside the chamber from Metabolic heat generation and heat from soda lime in the scrubber cartridges.

### *(a) Moisture in the expired air and resulting humidity increase in the chamber.*

The average person's lung capacity is approximately 6.0 litres. As only approximately 7.5% of lung air is changed over in one breath at rest about 0.45 litres of air per breath is exchanged. With average 15 breaths per minute there are 0.081 m$^{3}$ per minute of lung air (saturated) breathed out by 12 persons inside a chamber (15 × 0.45 × 12).

The amount of moisture added by this expelled air can be calculated by assuming the breathed out air is at 36$^{o}$C saturated (body temperature) and the air inside the chamber is 13$^{o}$C initially.

From Psychrometric equations for air at sea level
Moisture content at 36$^{o}$C saturated is 39.14 g/kg
Moisture content at 13$^{o}$C saturated is 9.42 g/kg
Moisture from breathed out air from 12 persons per minute is (0.081 m$^{3}$ x 1.127 kg/m$^{3}$) × (39.14 – 9.42) = 153 g

For temperature rise from 13$^{o}$C to 14.7$^{o}$C saturated in the first minute, steady state psychrometric conditions require a moisture content increase from 9.42 g/kg to 10.54 g/kg.

Thus it would only require

21.1 kg × (10.54 – 9.42) = 23.63 g

in the first minute to keep the condition inside the chamber saturated while there are 153 g of moisture available having been breathed out by the persons inside the chamber.

The excess moisture will condense on the "cold" steel inner surfaces.

This calculation has been undertaken under the assumption of saturated conditions inside the chamber from beginning. If the initial conditions inside the chamber are not saturated then the excess moisture is sufficient to saturate the atmosphere in one extra minute if conditions are as low as 35% Relative Humidity or 6.2/13°C wet bulb and dry bulb temperature). Bottled oxygen or compressed air added to the chamber will likely be unsaturated (when expanded to atmospheric pressure) but likewise will quickly become saturated from the excess moisture breathed out.

With the assumption that the average breath at rest allows 0.45 litres of air exchanged then with average 15 breaths per minute there are 0.081 $m^3$ per minute of lung air (saturated) breathed out by the 12 persons inside the chamber. The amount of moisture added by this expelled air is calculated at about 153 g per minute.

### *(b) The cooling effect from the condensation against the steel inside the chamber*

The condensed water on the inside steel surface of the chamber assists the heat transfer from air inside the chamber to outside of the chamber through natural convective heat transfer processes between air/condensation water and steel. This is more efficient than air to steel natural convective heat transfer alone. Based on the thermodynamic heat transfer calculations, the overall heat transfer coefficient for the air/condensation water-steel-air case is about 30% more than that of air-steel-air case.

Cooling can be interpreted to occur in a number of ways.

- As sensible heat in the shelter's atmosphere is lost through transmission through the shelter's steel skin and radiated to the cooler atmosphere outside.
- As heat lost from the atmosphere in the process of condensation of the water vapor on the inside of the shelter's steel skin. This is a latent heat process as vapor changes state to liquid water. This heat is effectively seen as sensible heat that is transferred to the internal steel.
- The resultant sensible heat condition on the inside surface is transmitted through the shelter skin to the cooler atmosphere outside where it heats the cooler air.

The key to achieving a stable temperature inside appears to be ensuring there is sufficient surface area on the shelter's skin to allow for condensation and the transfer of heat to the outside.

### *(c ) Exothermic heat from use of chemicals for $CO_2$ scrubbing.*

Calculations in 12 person chambers have been undertaken anonymously and reported that "$CO_2$ chemicals" used during chamber evaluations add 364W (1,245 Btu/hr) of heat from removal of carbon dioxide by soda lime. The anonymous analysis also calculated heat removal of 1,470W (5,022 Btu/hr) from respiration and perspiration along with 1,470W (5,022 Btu) in sensible heat for at total of 3308W (11,298 Btu/hr) or 127W (434 Btu/hr) per occupant including the heat from chemicals. Chemical exothermic heat thus made up about 11% of the total. This heat source had not been included due to its marginal influence although for precise calculations it would be worthwhile including this source.

## Conclusions

A review has been undertaken of specified mine refuge chamber designs to predict what will be internal temperatures within chambers over extended periods with miners present. These have been examined for the situation when the chambers are sited in still mine air. Spreadsheets have been developed to allow various design assumptions to be tested.

The evaluation has been undertaken using thermodynamic heat transfer models with some assumptions specified to produce a model of appropriate simplicity but with adequate degree of accuracy.

There will always be quite a few assumptions necessary in complex heat transfer process evaluations. It would be beneficial if the models developed are calibrated against an empirical evaluation of a refuge chamber in a mine.

# Appendix 1. Apparent Temperature

University of Virginia
Climatology Office

## Apparent Temperature:

| **REL HUM (%)** | **TEMPERATURE (°F)** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **70** | **75** | **80** | **85** | **90** | **95** | **100** | **105** | **110** | **115** | **120** | **125** | **130** | **135** |
| **0** | 64 | 69 | 73 | 78 | 83 | 87 | 91 | 95 | 99 | 103 | 107 | 111 | 117 | 120 |
| **5** | 64 | 69 | 74 | 79 | 84 | 88 | 93 | 97 | 102 | 107 | 111 | 116 | 122 | 126 |
| **10** | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 | 105 | 111 | 116 | 123 | 131 | |
| **15** | 65 | 71 | 76 | 81 | 86 | 91 | 97 | 102 | 108 | 115 | 123 | 131 | | |
| **20** | 66 | 72 | 77 | 82 | 87 | 93 | 99 | 105 | 112 | 120 | 130 | 141 | | |
| **25** | 66 | 72 | 77 | 83 | 88 | 94 | 101 | 109 | 117 | 127 | 139 | | | |
| **30** | 67 | 73 | 78 | 84 | 90 | 96 | 104 | 113 | 123 | 135 | 148 | | | |
| **35** | 67 | 73 | 79 | 85 | 91 | 98 | 107 | 118 | 130 | 143 | | | | |
| **40** | 68 | 74 | 79 | 86 | 93 | 101 | 110 | 123 | 137 | 151 | | | | |
| **45** | 68 | 74 | 80 | 87 | 95 | 104 | 115 | 129 | 143 | | | | | |
| **50** | 69 | 75 | 81 | 88 | 96 | 107 | 120 | 135 | 150 | | | | | |
| **55** | 69 | 75 | 81 | 89 | 98 | 110 | 126 | 142 | | | | | | |
| **60** | 70 | 76 | 82 | 90 | 100 | 114 | 132 | 149 | | | | | | |
| **65** | 70 | 76 | 83 | 91 | 102 | 119 | 138 | | | | | | | |
| **70** | 70 | 77 | 84 | 93 | 106 | 124 | 144 | | | | | | | |
| **75** | 70 | 77 | 85 | 95 | 109 | 130 | 150 | | | | | | | |
| **80** | 71 | 78 | 86 | 97 | 113 | 136 | | | | | | | | |
| **85** | 71 | 78 | 87 | 99 | 117 | 140 | | | | | | | | |
| **90** | 71 | 79 | 88 | 102 | 122 | 150 | | | | | | | | |
| **95** | 71 | 79 | 89 | 105 | 126 | | | | | | | | | |
| **100** | 72 | 80 | 90 | 108 | 131 | | | | | | | | | |

**Explanation --** The apparent temperature is a measure of relative discomfort due to combined heat and high humidity. It was developed by R.G. Steadman (1979) and is based on physiological studies of evaporative skin cooling for various combinations of ambient temperature and humidity. The apparent temperature equals the actual air temperature when the dew-point temperature is 57.2°F (14°C). At higher dew-points, the apparent temperature exceeds the actual temperature and measures the increased physiological heat stress and discomfort associated with higher than comfortable humidities. When the dew-point is less than 57.2°F, on the other hand, the apparent temperature is less than the actual air temperature and measures the reduced stress and increased comfort associated with lower humidities and greater evaporative skin cooling. Apparent temperatures greater than 80°F are generally associated with some discomfort. Values approaching or exceeding 105°F are considered life-threatening, with severe heat exhaustion or heatstroke possible if exposure is prolonged or physical activity high. The degree of heat stress may vary with age and health.