Report on Miner Refuge Chamber Thermal Analysis
Raytheon UTD
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Contract Number: 254-2008-M-23921
Task I Deliverable Item

Objective:

There are three objectives to this task:
1. For a given set of conditions, mine temperatures, and rock types, determine the potential effect of different rock types on heat dissipation based on observations made during the LLEM simulation tests.
2. Provide written summary of results from 1.
3. Develop and deliver a numerical model that would allow NIOSH to estimate the point, if any, when the apparent temperature inside the chamber would begin to adversely impact inhabitants.

Executive Summary:

Model results calibrated to the reported LLEM test conditions indicate that strata type has negligible effect on the conduction of heat away from tested refuge chambers for the given LLEM environmental conditions. Given these conditions heat is actually being transferred from the rock surface to the mine airway, not the opposite.

Procedure:

The following section describes the development of the model and tools used. It basically describes the process we defined in Matlab® to determine the internal chamber conditions, consisting of a script file and several function files used to perform calculations.

In order to create the model, we created a heat balance between the interior chamber conditions and the mine rock thermal conditions resulting in a series of equations to be modeled and solved for different parameters. These parameters are discussed hereafter.

To estimate the interior chamber humidity and temperature for a given set of LLEM experimental airway conditions and chamber, the model needs to determine the wet bulb temperature of the mine airway based on the input humidity and dry bulb temperature of the mine airway. With these two input values, the vapor pressure of moisture in the airway is determined. With an estimate of the wet bulb temperature of the airway, the calculated vapor pressure of moisture and the thermal properties of the rock, a heat balance between the airway and the rock surface is iterated until the error in the balance is zero. The result is the wet bulb temperature of the mine airway. Also given in these iterations is the latent heat and sensible heat transfer between the rock surface and mine airway as well as the heat conducted through the rock.

The next step is to perform a heat balance on the air in the mine airway external to the chamber. This gives the amount of heat conducted through the chamber walls. Knowing the heat conducted through the walls and using the assumed heat transfer coefficient for still air, the outside surface temperature of the chamber is calculated.

From here the inside chamber surface temperature is determined with knowledge of the chamber material thermal conductivity. Now with the inside surface temperature calculated, a heat balance on the chamber surfaces provides the internal dry bulb temperature, the internal vapor pressure and humidity. The sensible and latent heat transferred across the chamber surface is also found.

This is where the heat balances should end, but the model still needs to account for the cool moisture that was supplied to the chamber during the LLEM tests. Without this accounting, modeled chamber temperatures would be 20-30% higher than the actual LLEM experimental values. Knowing the thermodynamic properties of the internal chamber air and making some assumptions about the incoming moisture, the model yields a close approximation to the experimentally observed internal chamber temperatures.

Assumptions:

1. Heat transfer coefficient for the air is 10W/m-K and is the same inside and outside the chamber. This is an average value for still air.
2. Heat conducted through the floor of the chambers is small compared to the heat carried away by convection and is ignored in this application. From preliminary analysis, the thermal gradient within the rock is very small and only a few percent of the heat can be conducted away through the floor.
3. The construction materials of the Strata Products and ChemBio chambers was not supplied by NIOSH. Material was likened to “rubberized canvas”. Therefore, thermal conductivity of the Strata Products and ChemBio inflatable chambers is that of rubber, .04 W/m-K.
4. The wall thickness of the Strata Products and ChemBio chambers is equivalent to the Kennedy chamber, .105in.
5. The age of the airway is 30 years.
6. Virgin rock temperature (original unmined rock temperature), VRT, is 15C, or 59F.
7. The temperature and humidity values supplied by NIOSH are steady-state values for this analysis.
8. Moisture output of “men”= rate of condensation on walls of chamber.
9. Effect of windows is negligible.
10. Thermal conductivity of limestone is similar to concrete. An average value of 2.7 W/m-K is used.
11. Thermal conductivity of bituminous coal is .33W/m-K.

12. Thermal conductivity of shale in the mine roof and floor is similar to limestone and is taken as the same value, 2.67 W/m-K.
13. Atmospheric pressure in the mine airway and chamber is 100kPa.
14. Moisture supplied in the LLEM tests is supplied at the local mine airway temperatures, 16C, and not at the average temperature of expired air from a miner at rest, 35C.

Results Discussion:

The assumptions made above appear to be justified in the following summary and model discussion.

Task 1 Summary:

The results of the first objective are that strata type has negligible effect on the conduction of heat away from the refuge chamber for the given LLEM environmental conditions. Given these conditions heat is actually being transferred from the rock surface to the mine airway, not the opposite. This latent heat is absorbed by water on the rock face. Additionally, sensible heat is being transferred from air in the mine airway to the rock surface since it is warmer than the rock surface temperature. The sensible heat also contributes to evaporation of water from the rock surface and cools the rock surface to below VRT.

In order for the rock to conduct the heat from the mine airway two things must occur. First, the temperature gradient through the rock must be large. Coal mines are typically shallow compared to other mines, such as gold mines that extend thousands of feet into the Earth. The average ground temperature fluctuates daily and seasonally but is constant between 10-13C at 4m below the ground surface. From here, VRT increases linearly with depth as demonstrated in Figure 1. For shallow coal mines, the VRT is not greater than the average ground surface temperature by more than a few degrees. At 75 meters, the approximate depth of LLEM, the VRT is therefore about 12-15C. The result is a very small temperature gradient between the VRT and the local mine conditions which limits the amount of heat the rock can conduct. Second, the rock surface temperature must be greater than VRT. For the LLEM experiments, the rock surface temperature is a few degrees below VRT. Thus, heat is conducted into the airway as latent heat. See Figure 2 for clarification of terms. The model demonstrates changes of VRT in either direction by a few degrees does not affect the results of the LLEM experimental tests.

However, there may be situations in which the rock surface temperature may be greater than the VRT. In this situation, heat will be conducted through the rock, but it could potentially have an adverse impact on the internal chamber temperature. The Matlab® -based model can be employed to represent situations whereby the mine airway temperatures and humidities are varied to yield heat transfer through the rock and the internal chamber thermodynamic conditions.

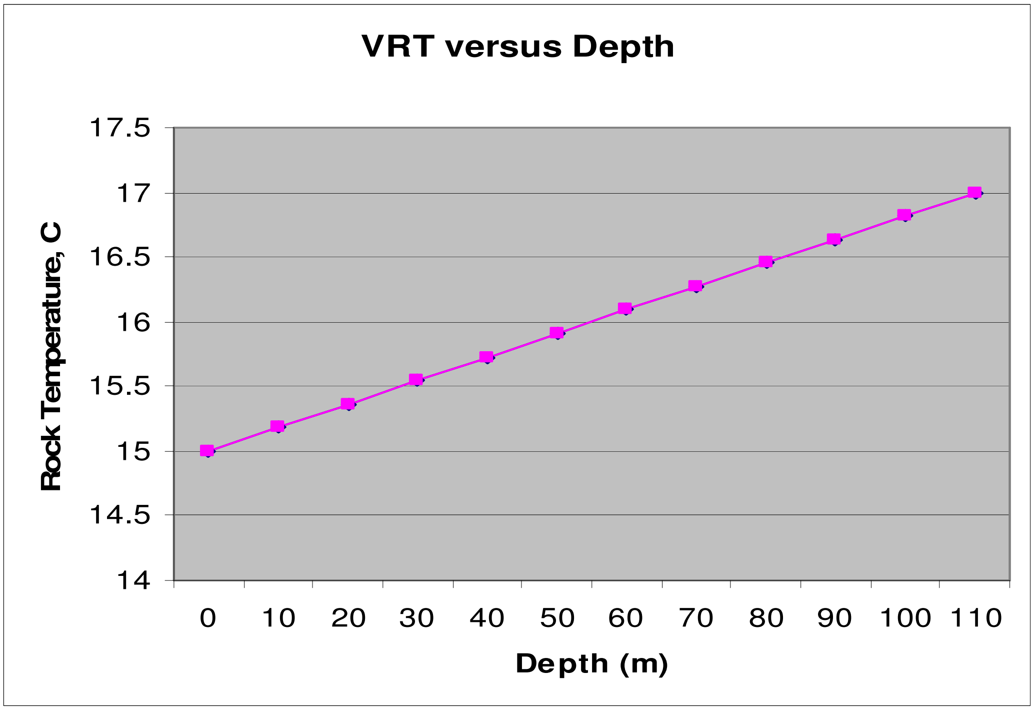

Figure 1. Variation in rock temperature with depth

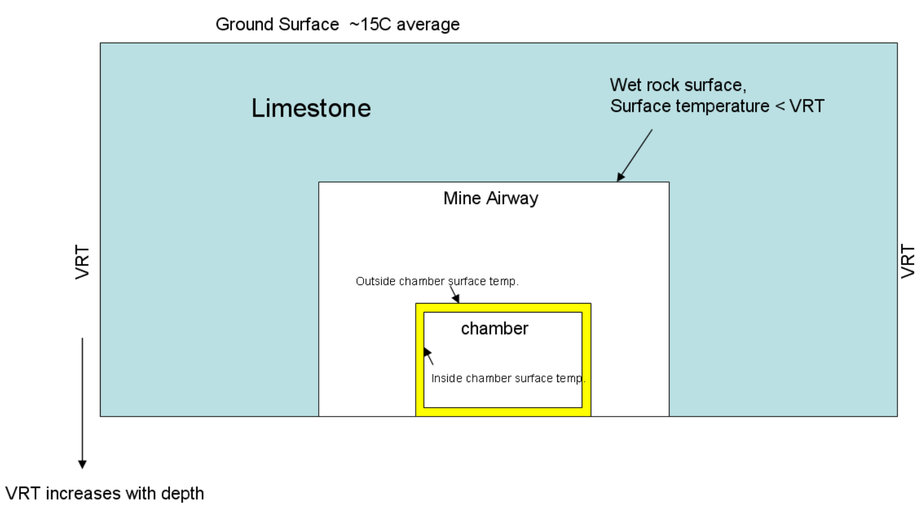

Figure 2. Example cross-section of mine shaft airway and refuge chamber [Note: not to scale]

Model Discussion:

The model is able to run different scenarios by changing the input parameters. The input parameters are the VRT, rock thermal properties, rock age, chamber dimensions and thermal properties, airway temperatures, humidities, and cross-section.

Tabulated below is the model output for each chamber used in the LLEM tests. Values were obtained first for limestone and then coal strata. A comparison is made between the LLEM experimental values and the model output. All model values are within 4% of the experimental values.

Manufacturer	ChemBio			Strata Products			Kennedy		
Strata	LLEM Experiment	Lime. Model	Coal Model	LLEM Experiment	Lime. Model	Coal Model	LLEM Experiment	Lime. Model	Coal Model
Internal Chamber Temperature F	73	73	73	76	73	73	87	84	84
Internal Chamber humidity %	62	60	60	60	59	59	42	43	43

Comparing the average values in the ChamberData spreadsheet provided by NIOSH on November 19, 2007 to the recorded time-dependent temperature and humidity experimental test values supplied on December 4, 2007 by NIOSH for the experiments at LLEM, there is a discrepancy in the Strata Products test data. The internal chamber temperature in the recorded data averages around 76F rather than the 70F in the spreadsheet. Also, the inside humidity averages around 60% rather than 69%. Lastly, the mine airway humidity is closer to 66% rather than 63%. For the model airway humidity of 66% was used. The model is able to verify the internal chamber humidity of 60% as well as the internal chamber temperature of 76F. These results are reflected in the table above. The assumption of steady state (#7 in the list of Assumptions) may not be perfectly accurate, but the recorded time-dependent experimental values suggest that for all practical purposes and the time period of interest it is a valid assumption.

Based on the listed assumptions #1 through #13, the initial model was able to validate the chamber humidity values in the LLEM experiments but not the internal chamber temperatures. The modeled temperature values were 25%, 18% and 31% greater than the NIOSH temperatures for the ChemBio (inflatable), Strata Products (inflatable) and Kennedy (rigid) chambers, respectively.

There are several possibilities for the temperature differences. First, the assumptions made for the heat transfer coefficient inside and outside the chamber may be incorrect. Second is that heat conduction through the floor may be more significant, which would bring down the chamber temperature. Third, if the humidity injected into the chamber wass at a lower temperature than that expired by mine workers, it will have the effect of reducing the chamber temperature. However, it is suspected that the reason for the discrepancy is due to the third possibility, that input moisture temperature is less than the moist air expired by a resting miner. This suspicion was verbally confirmed by Eric Bauer of NIOSH in a telephone conversation with Steve Cotten on December 6.

Assumption #14 was introduced in order to correct for these cooler moisture temperatures in the LLEM experiments. The revised model now verifies the LLEM experimental humidity and temperature values for each chamber to within 4%, as stated previously. This suggests that internal refuge chamber temperatures could be up to 30% higher, or 104F for the Kennedy chamber, with real miners in an actual refuge situation.

Chamber construction material seems to have very little effect on inside conditions due to the small wall thickness of each of the chambers. The difference in thermal conductivities between the two inflatable chambers and the rigid steel chamber is three orders of magnitude yet this difference has only a minute effect on internal chamber temperature. This is verified by the modeled inside and outside surface temperatures of the chamber being the same to two decimal places for all chambers evaluated in the LLEM tests.