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Parametric Design of a Coal Mine Refuge Chamber

Michael A. Fasouletos

**Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Mechanical Engineering**

**Kenneth Means, Ph.D., Chair
James Smith, Ph.D.
Scott Wayne, Ph.D.**

Department of Mechanical and Aerospace Engineering

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ABSTRACT

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Michael A. Fasouletos

In 2006 several coal mine tragedies led to safety legislation to provide post accident protection to coal miners. One of the key aspects of this legislation was providing refuge areas where miners could await rescue if they could not escape the mine. These refuge areas were to be designed to sustain life for four days, providing the miners with adequate oxygen, carbon dioxide scrubbing, food, water, and reasonable temperature control. A parametric study has been performed to provide further definition of the requirements in order to design an optimal portable refuge chamber with little or no electricity to enhance the comfort level of the trapped miners. The specific areas of interest concentrate on the amount and method of supplying oxygen and carbon dioxide scrubbing per miner along with the method of cooling necessary for sustaining the miners. Temperature inside the chamber becomes a vital concern when the outside ambient temperature rises in conjunction with internally generated heat from carbon dioxide scrubbing and metabolic body heat, causing internal temperatures to become elevated above safe levels. The maximum ambient temperature to sustain miners without air conditioning and the maximum ambient temperature with air conditioning was investigated to provide the best protection for the miners after an accident. The following work describes the complete calculations and design of the parameters using fundamentals from Thermodynamics, Heat Transfer, and Heating, Ventilating, and Air Conditioning.

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Chapter 1: Introduction

1.1 Background

In the last year legislation has swept the nation in the coal mining industry calling for major reforms in coal mine safety. A disastrous year in the mining industry in which 47 coal miners died in tragedies such as the Sago Mine Explosion and the Aracoma Alma Mine fire, both in West Virginia, and the Darby No. 1 Mine explosion in Kentucky, prompted the Miner Act of 2006 to be signed into law on June 15, 2006. The Miner Act called for major reform in the areas of post-accident communications, tracking, breathable air, lifelines, training and local coordination. In all of these areas technology needs to be developed to be able to better protect the industry's most valuable resource, the miner.

The Mine Safety and Health Administration (MSHA) is the federal enforcement agency responsible for the health and safety of the nation's miners. MSHA was formed in 1977 when Congress passed the Federal Mine Safety and Health Act of 1977, known as the Mine Act. The Mine Act amended the 1969 Coal Act in a number of significant ways, and consolidated all federal health and safety regulations of the mining industry, coal as well as non-coal mining, under a single statutory scheme. The Mine Act strengthened and expanded the rights of miners, and enhanced the protection of miners from retaliation for exercising such rights [19]. MSHA is responsible for inspecting underground and surface mining installations to ensure the protection of the workforce.

The concentration of this report deals with the post-accident breathable air portion of the Miner Act. MSHA has required that post-accident breathable air be provided for all miners underground for 96 hours [1]. This could be accomplished by drilling boreholes from the surface, burying compressed air lines throughout the mine or in the form of refuge chambers. The most practical and economic of the three choices above would be the refuge chamber in that it is easily accessible and can be transported and moved as mining progresses. These units would utilize compressed air bottles for purging contaminants, oxygen bottles to sustain the miner's oxygen requirements and carbon dioxide scrubbing to prevent contamination of the isolated environment from exhaled carbon dioxide. Before the design of the refuge chamber could commence, the parameters of such a system would need to be defined. A minimum life sustaining atmosphere would need to be developed to design any sort of refuge chamber for entrapped miners to await mine rescue teams. Parameters such as oxygen consumption rate, carbon dioxide exhalation rate, and maximum allowable temperatures inside such a chamber for human survival had to be defined.

1.2 Current Chambers

Soon after the legislation was passed many companies started designing and building refuge chambers to be put on the market. Many of the current refuge chambers available do not consider sustaining life in an elevated external temperature caused by fire or explosion. Some chambers have been designed only for the body heat generated by the miners and do not take into consideration the heat generated by the chemical

reaction required for the scrubbing of carbon dioxide. Many of the refuge chambers are constructed of a vinyl or rubber material that is inflatable and the only means of cooling is provided through heat transfer to the outside. An example of this type of shelter is shown in its storage skid in Figure 1 and shown deployed in Figure 2. This will only protect miners when the outside of the chamber is cooler than the inside so that the carbon dioxide scrubbing generated heat and body heat generated by the miners will be able to be conducted out of the chamber and thus not accumulate and cause heat exhaustion. Some have included air conditioning that requires an external power source, which may not always be available as many mining accidents disable the power source and thus an independent system would be necessary for backup.

Figure 1: Inflatable Chamber not Deployed

Figure 2: Inflatable Shelter Deployed

1.3 Proposal of New Parameters

The current refuge chambers are sufficient when there are not any elevated external temperatures and thus the heat generated inside can be dissipated to the outside through the thin walls of the refuge chambers. Although these chambers would have saved the lives of the twelve miners that perished in the Sago Mine explosion, many times high temperatures will be present after the initial accident and thus hinder the dissipation of the internally generated heat. The need for additional consideration into an air conditioning source that requires little energy should be a priority when designing a safe and reliable refuge chamber.

The primary goal of this thesis was to develop the oxygen, carbon dioxide scrubbing, and temperature parameters to sustain miners for 96 hours. The oxygen and carbon dioxide scrubbing parameters were designed around the activity level of trapped miners. It was assumed the miners would be at rest with minimal activity $\frac{4}{5}$'s of the time and at moderate activity levels the other $\frac{1}{5}$ of the time. The temperature design

had many considerations that needed to be investigated. The heat generation inside the chamber including the body heat from the miners and the heat produced from the chemical reaction of the soda lime or lithium hydroxide used in the carbon dioxide scrubbers was researched to determine the total amount of heat that might be generated inside the chamber. From these temperature considerations a study was performed to decide what outside temperatures would be sufficient to maintain a livable environment on the inside without air conditioning. If the outside temperature could not keep the inside temperature livable, then an air conditioning system would need to be implemented.

Chapter 2: Literature Review

2.1 Carbon Monoxide Physiological Effects

Carbon Monoxide is often referred to as the silent killer because it is a colorless, odorless, and tasteless gas that can be lethal if exposed to in large quantities or long durations. Carbon Monoxide is the product of incomplete combustion and is commonly formed from unvented gas space heaters, leaking chimneys and furnaces, gas water heaters, wood stoves, gas stoves, automobile exhaust, and any type of fire or explosion. Symptoms of mild poisoning include headaches, dizziness, disorientation, nausea and fatigue at concentrations less than 100 ppm. Concentrations as low as 667 ppm can cause up to 50% of the body's hemoglobin to be converted to carboxy hemoglobin, which inhibits oxygen intake [10]. Exposures of this level can be life-threatening. Many people that die of carbon monoxide poisoning do not even realize what is taking place and silently slip into unconsciousness. Table 1 describes the various effects of carbon monoxide at different exposure levels.

Table 1: Effects of Carbon Monoxide Concentrations

<u>Concentration of CO in air</u>	<u>Inhalation time and toxic developed</u>
50 parts per million (ppm)	Safety level as specified by the Health and Safety Executive
200 PPM	Slight headache within 2-3 hours
400 PPM	Frontal headache within 1-2 hours, becoming widespread in 3 hours
800 PPM	Dizziness, nausea, convulsions within 45 minutes, insensible in 2 hours

It is paramount to consider carbon monoxide poisoning in refuge chambers, because in the event that a fire or explosion occurs, carbon monoxide will often be present. After entering the chamber, the system should be flushed or purged to dilute any harmful gases that might have entered as the miners were entering.

2.2 Carbon Dioxide Physiological Effects

In closed environments carbon dioxide can be just as lethal as the well known killer, carbon monoxide. Carbon dioxide is naturally occurring in the earth's atmosphere at a concentration of 0.03 percent and is produced from naturally occurring human and animal metabolisms [7]. In confined spaces with no ventilation to the outside, the buildup in the concentration of carbon dioxide can dramatically influence major vital processes, including the control of breathing, vascular dilation or constriction, and body fluid pH.

Carbon dioxide inhalation has various effects including: headaches, dizziness, tremors, convulsions, unconsciousness, and may even lead to death depending on the concentration levels and the activity level of the exposed person. Starting at lower end concentrations, exposure to 1 to 1.5 percent carbon dioxide can be tolerated comfortably and little noticeable respiratory stimulation occurs until the carbon dioxide concentration is above 2 percent. When carbon dioxide levels reach 3 percent, noticeable effects such as headaches, diffuse sweating, and dyspnea were recorded among patients at complete rest after a period of several hours [7]. Concentrations from 3 to 10 percent can lead to more severe effects such as unconsciousness and tremors within a short amount of time. Any levels of carbon dioxide concentration above 10 percent can lead to unconsciousness,

coma, convulsions, and death within several minutes. Table 2 presents the physiological effects of carbon dioxide at various concentration levels.

Table 2: Effects of Carbon Dioxide at Several Concentrations [7]

Carbon Dioxide Concentration (Percent)	Time	Effects
17 - 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death
>10 - 15	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
7 - 10	Few minutes 1.5 minutes to 1 hour	Unconsciousness, near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
6	1 - 2 minutes ≤16 minutes Several hours	Hearing and visual disturbances Headache, dyspnea Tremors
4 - 5	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnea
3	1 hour	Mild headache, sweating, and dyspnea at rest
2	Several hours	Headache, dyspnea upon mild exertion

The information above shows how vitally important it is to have carbon dioxide scrubbing capabilities inside a refuge chamber. With several miners and the small amount of volume it would not take very long for the carbon dioxide concentration to reach 3 percent. For example, a 15 man chamber with the dimensions of 25'x 8'x 5', would only take 110 minutes before the concentration would exceed the 3 percent concentration limit defined by MSHA. The only solutions to keeping the carbon dioxide below 3 percent would be to increase the volume of the chamber or introduce carbon dioxide scrubbing. The volume increase to keep the concentration below 3 percent would be so drastic it

would not be applicable in coal mines where space can be very limited. This leads to the introduction of carbon dioxide scrubbing through the use of chemicals such as lithium hydroxide or soda lime, commonly used aboard submarines and spacecraft.

2.3 Oxygen Deficiency Effects

The earth's atmosphere contains approximately 20.8 percent oxygen. When oxygen levels fall below 19.5 percent, the atmosphere is considered oxygen deficient. The effects of low oxygen can be serious and lead to permanent central nervous system damage or even result in death depending on the time exposed and the level of oxygen. Oxygen concentrations below 16 percent are considered unsafe for human exposure because of harmful effects on bodily functions, mental processes and coordination. If exposure to low oxygen is limited, the effects can usually be reversed. The following are the likely effects of oxygen deficient levels in air:

Table 3: Effects of Oxygen Deficiency [8]

<u>Percent Oxygen in Air</u>	<u>Effect</u>
17	Faster, deep breathing
15	Dizziness, buzzing in ears, rapid heartbeat
13	May lose consciousness with prolonged exposure
9	Fainting, unconsciousness
7	Life endangered
6	Convulsive movements, death

Oxygen deficiency is one of the more important concerns when designing refuge chambers. With the small volumes of the refuge chambers, oxygen can be displaced by carbon dioxide relatively quickly. With each miner breathing 1.32CFH of oxygen, a need to supply oxygen is evident. The most common and simplistic method has been to utilize compressed oxygen bottles to support the 1.32CFH per person requirement. Although this is the preferred method some precautions should be taken when storing oxygen bottles as they can be highly flammable.

2.4 Heat Stroke

Heat stroke is a condition which occurs when the body produces or absorbs more heat than it can dissipate and is usually due to excessive exposure to heat. The heat-regulating mechanisms of the body eventually become overwhelmed and unable to effectively deal with the heat, and body temperature climbs uncontrollably [9]. Normal progression of heat stroke starts with heat exhaustion which is characterized by mental confusion, muscle cramps, and often nausea or vomiting. Without treatment this often leads to heat stroke when internal body temperatures reach 104F and becomes life threatening. Skin temperatures associated with comfort at sedentary activities are 91.5 to 93F and decrease with increasing activity [2]. The degree of heat stress may vary with age, health, and body characteristics.

MSHA has set the maximum sustaining temperature limit in refuge chambers at an apparent temperature of 95F. The apparent temperature is a measure of relative discomfort due to combined heat and high humidity. It is based on physiological studies

of evaporative skin cooling for various combinations of ambient temperature and humidity. Apparent temperatures greater than 80F are generally associated with some discomfort while values approaching or exceeding 105F are considered life-threatening, with severe heat exhaustion or heat stroke possible if exposure is prolonged or activity levels are high [13]. Table 4 below presents various apparent temperatures as a function of relative humidity and dry bulb temperature.

Table 4: Apparent Temperature [13]

REL	TEMPERATURE (°F)													
HUM (%)	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									

An apparent temperature of 95F will allow the body to naturally dissipate the heat and cool itself through sweating and the evaporation of the sweat. Even with the maximum temperature set at 95F, design of the chamber should aim at making the chamber as comfortable as possible because higher temperatures will cause strain on the body and in return will increase respiration rates and the amount of water intake needed. It is also vitally important that the buildup of heat inside the chamber due to carbon dioxide scrubbing and human metabolism be considered.

2.5 Previous Technology in other fields

There has been numerous research conducted on the life support and ventilation systems for isolated environments such as used in naval submarines and spacecraft. It is necessary to eliminate carbon dioxide produced by the metabolisms of crew members and to regenerate the air by supplying oxygen. If carbon dioxide is not removed from an enclosed environment, in time the ambient carbon dioxide partial pressure will rise and cause detrimental physiological effects to the crew members. When humans are in space for short durations, it is advantageous to adsorb carbon dioxide with chemicals such as lithium hydroxide or soda lime and supply oxygen from tanks for atmospheric control [5]. The US Navy has long used lithium hydroxide curtains as an emergency backup for the main operating system while the British Royal Naval utilizes soda lime contained in canisters.

2.6 Carbon Dioxide Scrubbing Reactions

The adverse effects of high carbon dioxide levels require stored chemicals, usually lithium hydroxide or soda lime, aboard the refuge chambers. Both chemicals require a series of chemical reactions to absorb carbon dioxide. The heat generated from the overall process complicates the temperature design of the chamber. The following describes the chemistry involved for lithium hydroxide and soda lime.

The removal of carbon dioxide from the atmosphere utilizing soda lime is achieved by the use of canisters filled with soda lime and fitted to an absorption unit where air is drawn through the canister by the means of an electronically powered fan and is thus an “active system” [6]. The total amount of heat generated from the carbon dioxide reaction with soda lime was found to be 32 BTU/Hr per person of sensible heat found from tests run by Strata [18]. Soda lime removes carbon dioxide in a series of three reactions. The first reaction combines the carbon dioxide with water to get carbon dioxide in solution. The second reaction combines the carbon dioxide solution with sodium hydroxide to form sodium bicarbonate. The sodium bicarbonate is then reacted with calcium hydroxide to form calcium carbonate, sodium hydroxide, and water. The series of reactions are shown below with the overall reaction shown at the end.

The removal of carbon dioxide from the atmosphere utilizing lithium hydroxide is achieved by the use of curtains filled with lithium hydroxide to hang inside the chamber. The curtains absorb the carbon dioxide out of the air without forcing the air through them with the use of a fan, thus a “passive system”. Lithium hydroxide removes carbon dioxide from the atmosphere in a series of two reactions. The first reaction is with the lithium hydroxide and water while it is the second reaction that actually reacts with carbon dioxide to remove the carbon dioxide from the air. The following reactions are shown below along with the total reaction.

The heat generated in the first step is exothermic and generates 29.04Kcal/2moles of LiOH, while the second reaction is endothermic and absorbs the heat at a rate of 7.65Kcal/2 moles of LiOH·H₂O. Thus the total heat generated from the overall reaction becomes exothermic at a rate of 21.39Kcal/ 2 moles of LiOH or 1 mole of CO₂ [15]. Assuming 1.08CFH of carbon dioxide is generated per man and multiplying by 0.1144lb/Ft³, the density of carbon dioxide at 70 F and 1atm, yields approximately 0.1 lbs CO₂/ man-hr generated.

With 100 percent removal, the heat generated is equivalent to 87.5 BTU/Hr per man as shown in equation (3) below.

$$BTU / Hr = \left(\frac{0.1lbs}{ManHr} \right) \left(\frac{21.39Kcal}{1molCO_2} \right) \left(\frac{1molCO_2}{44g} \right) \left(\frac{1g}{0.0022lbs} \right) \left(\frac{3.96BTU}{1Kcal} \right) = 87.5BTU / ManHr \quad (3)$$

This assumes complete reactions with both water and carbon dioxide which is not likely to occur in actual events. Also from the above reactions it should be noted that the first reaction of lithium hydroxide and water will produce a spike in heat when the curtains are initially deployed until carbon dioxide is produced to complete the reaction and lower the overall heat gained from the entire reaction. Thus the miners should not deploy more curtains than is needed as more heat would be generated than anticipated. Figure 3 depicts the lithium hydroxide curtains that can be utilized to remove the carbon dioxide.

Figure 3: Lithium Hydroxide Curtains [15]

2.7 MSHA Regulations

The guidance provided by the Mine Safety and Health Administration regarding post accident breathable air for coal miners describes the respiratory quotient, which is the ratio of carbon dioxide expelled to oxygen consumed, as 0.8 [1]. This was calculated by assuming activity levels of rest for 4/5 of the time and moderate activity for the other 1/5 of the time. The breathing rate at rest was found to be 0.01 cubic feet per minute of oxygen per person, while at moderate activity the breathing rate was found to be 0.07 CFM of oxygen per person. Taking the respective weighted average of these numbers yields the assumed breathing rate of 0.022 CFM of oxygen per person.

$$OxygenConsumption = (4/5)*0.01cfm + (1/5)*0.07cfm = 0.022cfm \quad (4)$$

The carbon dioxide generation at the assumed breathing rate yields 0.018 CFM per person.

$$CarbonDioxideGeneration = 0.022cfm * 0.8 = 0.018cfm \quad (5)$$

These guidelines will be used throughout the design to calculate the oxygen and scrubbing capabilities for various size refuge chambers.

2.8 Summary

The conditions cited in the previous sections show that survival is dependent on all of atmospheric gases and temperature conditions. A single failure in one of the systems will result in a total loss of the objective; therefore it is of the utmost importance to carefully design and account for all parameters when designing the atmospheric controls. Parameters must carefully take into account the number of miners, their activity levels, and the surrounding environment that is continuously changing around them. The unlimited possibilities of scenarios present a complicated analysis that should define the performance limitations on refuge chambers.

Chapter 3: Problem Identification

3.1 Introduction

When designing any engineering application all possible scenarios have to be considered with some minor assumptions that will simplify the problem without significantly altering the results. The coal mine refuge chamber presents endless possible scenarios that could happen in the event an accident occurred underground. Three of the several possible scenarios will be examined in full detail. The first scenario deals with trapped miners under constant lower ambient temperature conditions. The second scenario is just the opposite and deals with trapped miners in constant elevated ambient temperatures due to an ongoing fire. The third scenario being considered is a transient problem where the ambient temperature starts at a higher level and lowers as the explosive gases cool or the fire is quenched and cooled. While these problems are similar, all have unique aspects that need to be considered.

These three different scenarios all affect the heat either conducted into the chamber from the elevated temperatures or the ability to conduct heat out of the chamber due to the carbon dioxide scrubbing and metabolic body heat. If there are no extreme temperatures present throughout the entrapment to increase respiration rates, the oxygen and carbon dioxide scrubbing material are independent from the temperature and can be calculated according to the quantity of people and the duration of their stay.

3.2 Lower Ambient Temperature Entrapment

While no entrapment is good, this first scenario is the best case for the miner. Although trapped and possibly surrounded by deadly gases, once inside the chamber, the heat generated can escape through the walls of the chamber. The temperature inside the chamber will be dependent on the surrounding ambient temperature, thermal conductivity of the material to build the chamber, heat transfer area, number of miners, and amount of heat generated from the carbon dioxide scrubbing requirements.

The oxygen supply, carbon dioxide scrubbing chemicals, and desiccant to absorb water released through sweat and natural human breathing will all be dependent on the amount of miners expected to use the shelter. With the considerations above, the maximum ambient temperature and required materials to sustain a breathable atmosphere will be investigated.

3.3 Elevated Ambient Temperatures

In this scenario, the only change will be designing the cooling loads that present the challenge of designing a chamber with low thermal conductivity to keep the heat from entering the chamber while cooling the inside with little or no energy source. In this scenario, the heat will be traveling through the walls of the chamber from the outside as well as building up inside from body heat and the carbon dioxide scrubbing. One of the goals of the design is exploring the elevated temperatures to find the maximum ambient mine temperature that will allow for practical cooling loads.

3.4 Transient Temperatures

Transient temperatures present a plethora of different situations that could happen after a fire or explosion. The ambient temperature could fluctuate throughout the mine and sustaining fires or reoccurring explosions could keep temperatures elevated.

Sustaining high elevated temperatures for very long will not be explored, as mine rescue teams would not be able to perform any type of rescue mission in these conditions.

However, a quick spike in temperature at the beginning with cooling ambient temperatures will be explored to determine a method of simulating the inside temperature of the refuge chamber with time to be able to model several scenarios.

3.5 Problem Summary

In all of the above scenarios the amount of oxygen, carbon dioxide scrubbing chemicals, desiccant, and cooling loads to maintain a sustainable atmosphere will be studied to find the worst case scenario and design a sustainable atmosphere for the refuge chamber. In some cases, practical temperature control will not be feasible and these upper limits need to be defined as well.

Chapter 4: Design Constants

The chamber is designed to hold fifteen average men for a sustained period of 96 hours. Each of these average males will generate heat at 400 BTU/Hour and consume oxygen at the rate of 1.32CFH and exhale carbon dioxide at the rate of 1.08CFH. Lithium Hydroxide curtains to scrub the carbon dioxide produced generate heat at a rate of 87.5 BTU/Hour per person. The total heat generated inside the chamber due to metabolic body heat and carbon dioxide scrubbing reactants was assumed to be 500BTU/Hour to provide a slight safety factor for extra heat generated inside the chamber depending on the activity level of the miners.

Chapter 5: Parametric Design

5.1 Oxygen, Food, and Water Sustenance

Oxygen can be supplied to the miners in numerous ways such as from chemically generated oxygen by the thermal decomposition of chlorate compounds. This method will not be used, as it adds unneeded heat that will either need to be dissipated to the outside of the chamber or be removed with the use of an air conditioning system. The simplest and most reliable way to provide oxygen will be supplied to the miners in the form of compressed oxygen bottles stored inside the refuge chamber. These bottles will be “K-sized” bottles that contain 282 cubic feet of oxygen at 2400psi. These tanks are 9.25 inches in diameter and 60 inches high. The oxygen tanks will be fitted with an easy to use regulator that will only allow the release of oxygen at the required flow rate so that the oxygen supply lasts the entire 96 hours. The calculation for the number of oxygen tanks is below, with Table 9 in Appendix A displaying the amount of tanks needed for different occupancy rates.

$$NumberTanks = \frac{1.32 \text{ ft}^3 / \text{ManHour} * 15 \text{ Miners} * 96 \text{ Hours}}{282 \text{ ft}^3 / \text{Tank}} = 6.7 = 7 \text{ Tanks} \quad (6)$$

The amount of food and water to sustain an average male was researched. It was found that an average male needs approximately 2,000 calories and 1 gallon of water per day [11]. The food was researched and the best available option was the MRE. The Meal, Ready-to-Eat, or MRE is a self-contained, individual field ration in lightweight packaging developed by the United States military for its service-members for use in combat or other field conditions where organized food facilities are not available. The MRE's are designed to have long lasting shelf life. The table below illustrates the shelf life of MRE's at various temperatures.

Table 5: MRE Shelf Life [12]

Degrees in F	Months
120	1
110	5
100	18
90	30
80	48
70	66
60	84
50 or less	96

The shelf life above was determined by taste and can actually be eaten after the shelf life has been expired as long as the person does not mind the taste [12]. Each MRE contains around 1200 calories and thus 2 meals per day per person would need to be stored inside the shelter. Thus a total of 120 meals would be supplied for 15 miners for

four days. The MRE meals come in 16" x 9" x 11" boxes that contain 12 meals and thus ten of these boxes shall be stored. A total of 60 gallons of water shall be stored to supply each miner with a gallon a day. The tank to hold this amount of water will be 8 Ft³.

5.2 Carbon Monoxide Design

To keep carbon monoxide and other contaminants produced from an explosion from entering the refuge chamber there will be an airlock section in the refuge chamber for entering. This section will be able to hold all of the miners so that the air can be purged with compressed air until the contaminants are diluted enough for safe breathing. This will be accomplished with enough compressed air to have a purge three times the volume of the airlock in less than 30 minutes. The air tanks will be used in conjunction with a one way pressure valve that will let air escape the airlock as it is being purged to let the contaminants out and avoid creating high pressure inside the chamber. The number of air tanks is calculated below.

$$NumberTanks = \frac{10Ft * 5Ft * 5.5Ft * 3}{282FT^3} = 2.9 = 3Tanks \quad (7)$$

Inside the airlock will be a multi-gas detector capable of measuring CO, CO₂, O₂, and CH₄, to allow the miners to be able to determine when the atmosphere inside the airlock is breathable. This will allow them to remove their temporary breathing devices called Self Contained Self Rescuers, SCSRs, and save as much compressed air as possible.

5.3 Carbon Dioxide Design

The carbon dioxide scrubbing system chosen utilizes lithium hydroxide in the curtain form. Lithium hydroxide was chosen over soda lime because it is a “passive system” that does not require energy to be effective. The soda lime would have required a fan to blow the atmosphere through the canister in order for it to operate efficiently. Conserving any energy at all is vital to save for air conditioning purposes. The amount of lithium hydroxide needed to sustain 15 miners for four days is shown below and also in Table 9 in Appendix A, displaying the amount required for various occupancies.

$$CO_2 Generated = 1.08 Ft^3 / ManHr * 15men * 96Hr = 1,555 Ft^3 CO_2 \quad (8)$$

Convert this volume of carbon dioxide generated to pounds of lithium hydroxide needed when 1 pound of lithium hydroxide absorbs 0.794 pounds of carbon dioxide.

$$lbsLiOH = 1,555 Ft^3 CO_2 * 0.1144 \frac{lbsCO_2}{Ft^3} * \frac{1lbLiOH}{0.794lbsCO_2} = 224lbsLiOH \quad (9)$$

The amount of lithium hydroxide needed to sustain 15 miners for four days is 224 pounds. This material comes packaged in boxes that contain 5.7 pounds of lithium hydroxide per box from the ExtendAir Company. This means a total of 40 boxes with the dimensions of 11” x 10” x 6” would need to be stored in the chamber. The lithium

hydroxide boxes come with everything needed to be deployed, including devices for distributing the curtains.

The ExtendAir curtains have been designed so that curtains are hung every 12 hours which the following figure illustrates. From the above equations five boxes of lithium hydroxide would need to be hung every twelve hours to produce results as shown in Figure 4 below.

Source: NSMRL Report TR1228 dated 27 Aug 2003

Figure 4: Concentration of CO₂ [15]

5.4 Temperature Design without Powered Air Conditioning

Without an air conditioning system the heat generated inside the refuge chamber from the miners and carbon dioxide scrubber would need to be conducted out of the chamber. The heat generated from an average male, seated while performing light work was found to be 400BTU/Hr [2]. The amount of heat from the scrubber, 87.5BTU/Hr per miner, combined with the heat from a miner comes up with a conservative estimate of 500BTU/Hr per miner. With 15 miners in the refuge area the total heat generated becomes 7500BTU/HR.

The rate at which the heat could be dissipated out of the chamber, assuming a maximum temperature of 90F inside the chamber, was found for varying outside temperatures to find the maximum outside temperature that would allow the heat to escape. This was done with heat transfer and heating, ventilation, and air conditioning principles. The total heat transfer rate, Q , was found from the following equation [3]:

$$Q = UA(\Delta T), \quad (10)$$

where:

Q = total heat transfer rate,

U =Overall Heat Transfer Coefficient,

A =Area of heat transfer surface, and

ΔT =(T_i - T_o) Temperature difference.

To solve for the total heat transfer, the first calculation that had to be made was calculating the thermal resistance or overall heat transfer coefficient from the individual heat transfer coefficients of the inside air film, wall, and outside air film from the following equation [3]:

$$R = \frac{1}{U} = \frac{1}{h_{c,i}} + \frac{L_A}{K_A} + \frac{1}{h_{c,o}}, \quad (11)$$

where

R=Total Resistance,

U=Overall Heat Transfer Coefficient,

$h_{c,i}$ = Inside Convective Heat Transfer Coefficient,

L_A = Thickness of Wall,

K_A = Thermal conductivity of Wall Material, and

$h_{c,o}$ =Outside Convective Heat Transfer Coefficient.

For a chamber without cooling, it is preferable to have the largest heat transfer rate as possible to allow the heat to transfer to the outside easily. Also a larger surface area, thin walls, and a material with a high thermal conductivity will provide a higher heat transfer rate. Although a material with a high thermal conductivity is desired the convective heat transfer coefficients on the inside and outside walls will ultimately govern and limit how much heat can be dissipated. This can be seen in Appendix B where various materials yield approximately the same heat transfer rates and maximum ambient temperatures that can be sustained. In this scenario, an inflatable or thin steel

chamber will provide comparable results. The inflatable material can be made of any durable, flame retardant nylon based material that has a thermal conductivity value around 0.14 BTU/FtHrF [3]. Using this value at a thickness of 1/8 in. for strength, along with a convective heat transfer coefficient of 1.5 BTU/Ft²HrF on the inside and outside walls, since there will not be much air movement, yields an overall heat transfer coefficient of 0.71 BTU/ Ft²HrF from equation (9). Next, the area of the heat transfer surfaces was to be calculated. Only the roof, the front, and the two side walls should be used for this calculation since the floor will be in contact with the ground and the back will be used for storage preventing heat transfer from these surfaces. Thus, for a refuge area with the dimensions of 25 feet long, 10 feet wide and 5.5 feet high the heat transfer area is 580Ft². Note that the airlock door must be left open after the initial purge since the area of its walls are counted as heat transfer surfaces. With the previous calculations, an Excel sheet was made to find the highest outside temperature that could dissipate the 7500BTU/Hr generated by the 15 miners and lithium hydroxide curtains. As can be seen in Table 6 below, anything above 71F does not allow the heat to be conducted out of the chamber faster than it is created inside.

Table 6: Maximum Outside Ambient Temperature-No Air Conditioning

Outside Temp	Delta T	Q (Heat Transfer rate out of chamber) (BTU/Hr)	Heat generated-Heat Transferred out (BTU/Hr)
60	30	12353.89	-4853.89
61	29	11942.09	-4442.09
62	28	11530.29	-4030.29
63	27	11118.50	-3618.50
64	26	10706.70	-3206.70
65	25	10294.91	-2794.91
66	24	9883.11	-2383.11
67	23	9471.31	-1971.31
68	22	9059.52	-1559.52
69	21	8647.72	-1147.72
70	20	8235.92	-735.92
71	19	7824.13	-324.13
72	18	7412.33	87.67

Another concern related to temperature and comfort inside the refuge chamber is the removal of moisture produced from the miners. A build-up of moisture inside the chamber will prevent the miners sweat from evaporating, making it uncomfortable and possibly deadly if temperature and humidity levels rise simultaneously. For this reason a desiccant will be required to remove humidity from the air. An average male loses 1.32 pounds of water per day, giving a total of approximately 80 pounds of water that needs to be absorbed [16]. Silica gel desiccant in the form of 2-5mm beads will hold 23% of its weight in water at a relative humidity of 50% [17]. The required amount of desiccant required for the miners for four days will then become 348 pounds. This will be stored inside the chamber and will require 10Ft³ of space.

5.5 Temperature Design with Powered Air Conditioning Unit

If the conditions outside the refuge chamber are unknown or expected to be above the limit where heat cannot be dissipated outside the chamber a more proactive approach may be necessary to cool the inside of the chamber and keep any heat from entering the chamber from the outside. Some of the methods of cooling considered were chemical cooling, storing liquid nitrogen, storing ice to cool the chamber, and finally the use of a split system heat pump in conjunction with stored power supply to operate the air conditioning system.

Chemical cooling is not practical as it required large amounts of chemicals and water to be stored and liquid nitrogen presents the problem of maintaining its low temperature so that it does not evaporate. Ice could be used, but then again it would require a freezer to store the large amounts of ice to be kept frozen. Using ice would also introduce more humidity into the chamber which is already a problem. The most practical cooling method would utilize a heat pump in conjunction with a power supply.

In this scenario the overall heat transfer coefficient should be kept as low as possible to keep high outside temperatures from conducting inside while a split system air conditioning unit can be sized for the heat load of the people, carbon dioxide scrubber, and any heat that may conduct to the inside. A temperature of 125F was assumed to be the highest outside ambient temperature that would reasonably support life because higher temperatures would inhibit the rescue process where it would not be feasible to rescue the miners. With this maximum temperature, the heat conducted into the chamber with a wall resistance of 16.3, formed from the outside air layer, $\frac{1}{4}$ inch 1010 steel

outside wall, 3.5 inch mineral fiber insulation, ¼ inch 1010 steel inside wall, and the inside air layer, was to be determined. At a steady state temperature of 125F the maximum heat conducted into the chamber was approximately 1,400BTU/Hr as shown in Table 7 below.

Table 7: Maximum Outside Ambient Temperatures with Air Conditioning

Outside Temp (F)	Delta T (F)	Heat Transfer into Chamber (BTU/Hr)
90	0	0.00
95	5	194.37
100	10	388.75
105	15	583.12
110	20	777.50
115	25	971.87
120	30	1166.25
125	35	1360.62
126	36	1399.50
127	37	1438.37
128	38	1477.25
129	39	1516.12

In this scenario an air conditioner will be sized according to the internal heat load of 7,500 BTU/Hr broken into its sensible and latent heat loads and an allowance for heat conducting into the chamber of 1,500BTU/Hr for a total load of 9,000BTU/Hr.

To size an air conditioning unit, the first calculation that had to be made was splitting up the different loads into sensible and latent heat to come up with the sensible heat ratio (SHR). To calculate the total sensible and latent loads, the 400BTU/Hr per miner was split up into 205BTU/Hr latent and 195BTU/Hr sensible [2]. Also the heat from the carbon dioxide scrubber was considered all sensible heat since the reaction required water vapor to start the reaction and used the water produced from the reaction

to remain self sustaining. The 1,500BTU/Hr conducting into the chamber was also part of the sensible load. For 15 miners the total sensible load was determined to be 5,925BTU/Hr while the latent load was 3,075BTU/Hr. From this information the sensible heat ratio was calculated in equation (12) below.

$$SHR = \frac{SensibleHeat}{TotalHeat} = \frac{5925}{9000} = 0.65 \quad (12)$$

Next a psychrometric chart was utilized to analyze an air conditioning unit and make sure the unit could remove the moisture from the air. A point was plotted at 90F dry bulb and 40 percent relative humidity, the design condition of the room (R). Next utilizing the sensible heat ratio calculated above, a line was drawn with the same slope down to where it intersected the 70F dry bulb line. This point was called (S), as it is the quality at which the supply air would be needed to be brought into the chamber to maintain the room conditions. This process line also showed that the moisture could be removed from the air by the air conditioner since the line would intersect the saturation line if it continued past the 70F dry bulb line. The processes described above can be seen on the psychrometric chart in Figure 5 below.

Figure 5: System Psychrometric Chart

The psychrometric analysis program that produced the process above also gave the specific properties relating to each of the state points shown in Table 8 below:

Table 8: State Point Data

1. R

STATE POINT DATA

Air Flow (Standard) (cfm)	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Humidity Ratio (lb/lb)	Specific Volume (cu.ft./lb)	Enthalpy (Btu/lb)	Dew Point (°F)	Density (lb/cu.ft.)	Vapor Pressure (in.Hg)	Absolute Humidity (gr/cu.ft.)
271	90.000	71.188	40.0	0.01211	14.122	34.938	62.4580	0.0717	0.5694	6.005

2. S

STATE POINT DATA

Air Flow (Standard) (cfm)	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Humidity Ratio (lb/lb)	Specific Volume (cu.ft./lb)	Enthalpy (Btu/lb)	Dew Point (°F)	Density (lb/cu.ft.)	Vapor Pressure (in.Hg)	Absolute Humidity (gr/cu.ft.)
271	70.000	61.500	62.1	0.00974	13.557	27.439	56.4609	0.0745	0.4597	5.030

Process: Connect States

Start Point Name	Total Energy (Btu/hr)	Sensible Energy (Btu/hr)	Latent Energy (Btu/hr)	Moisture Difference (lb/hr)	Sensible Heat Ratio	Enthalpy/ Humidity Ratio (Btu/lb / lb/lb)
R	-9,145	-5,960	-3,185	-2.9	0.652	N/A

Utilizing the enthalpy values of the two states the air quantity could be calculated as shown below. First the mass of air had to be found from the following equation:

$$m_a h_s + q_t = m_a h_r \quad (13)$$

Rearranging and solving for m_a yields:

$$m_a = \frac{q_t}{h_r - h_s} = \frac{9000 \text{ BTU} / \text{Hr}}{34.94 - 27.44 \text{ BTU} / \text{lb}} = 1200 \text{ lbs} / \text{Hr} \quad (14)$$

Converting to cubic feet per minute to calculate the flow rate:

$$Q = m_a v / 60 = \frac{1200 \text{ Lb} / \text{Hr} * 13.56 \text{ ft}^3 / \text{Lb}}{60 \text{ min} / \text{Hr}} = 271 \text{ cfm} \quad (15)$$

The equation to solve for the mass of water condensing out as a result of the air conditioning can be found from the humidity ratio as shown below:

$$m_a W_R - m_w = m_a W_s \quad (16)$$

Rearranging and solving for the mass of the water yields:

$$m_w = m_a (W_R - W_s) = 1200 \text{ Lb} / \text{Hr} (0.01211 - 0.00974) = 2.84 \text{ Lb} / \text{Hr} = 2.72 \text{ Pints} / \text{Hr} \quad (17)$$

This significant source of water could be recycled into a separate water tank so that the miners could utilize this water if their drinking water supply had been depleted.

The following air conditioner was sized from the above specifications to be able to supply the minimum quantity of air and remove the moisture from the air while cooling the chamber by the specified amount, keeping efficiency a concern. The Pace 9,000 BTU wall mounted ductless split system air conditioning unit was chosen for this purpose. It can provide cooled air at 295 CFM, while removing water at 3.4 pints per hour, above the required amounts. It has a seasonal energy efficiency ratio (SEER) of 13

and requires 115 volts at 8 amps. The dimensions of the unit is relatively small with the inside unit measuring 31" x 11" x 7" and the outside unit measuring 31" x 21" x 13". The unit is picture in the Figures 6 and 7 below.

Figure 6: Inside AC Unit

Figure 7: Outside AC Unit

5.6 Transient Analysis

An analysis was performed to determine the reaction of the inside temperature of the refuge chamber with varying fluctuations in ambient temperature. Both the low ambient temperature design and the high ambient temperature design was explored to determine which chamber could best resist temperature fluctuations due to an initial spike in temperature due to the fire or explosion. To perform the analysis the total heat generated from the miners and carbon dioxide scrubber had to be combined with the heat transferred into the chamber to calculate the net heat produced per time unit. In the calculations the time was broken down into minutes to get a smooth inside temperature curve. The heat transferred in was calculated from equation 10 and converted into BTU/min instead of BTU/Hr. This value was then added to the 125BTU/min produced from the miners and lithium hydroxide. In the case where an air conditioning system was used, 150BTU/min was subtracted from the previous calculations to get a net value. With the net heat value, a difference in air temperature could be found from the following equation.

$$Q = m_a * c_p * \Delta T \quad (18)$$

Rearranging and solving for ΔT ,

$$\Delta T = \frac{Q}{m_a * c_p} \quad (19)$$

where

Q=Net Heat,

m_a =Air Mass Flow Rate, and

c_p =Specific Heat.

The change in temperature calculated above was then added to the previous inside temperature, for a new inside temperature value to use during the next calculation, creating an iterative process. The excel sheets can be found in Appendix C.

The current chambers designed for lower ambient mine temperatures provide protection that meet West Virginia state law requiring the chambers to be able to withstand 300F for 3 seconds before returning to ambient levels as can be seen in Figure 8 below.

Figure 8: Current Chamber Transient Response-300F for 3 seconds

Although these chambers perform satisfactorily under the required conditions, the chambers do not respond well to more realistic temperature spikes that last longer than 3 seconds before returning to ambient levels. This is evident when a spike of 300F lasts for five minutes as can be seen below in Figure 9. As can be seen, these chambers do not provide protection against high ambient temperatures as the inside temperature is heavily dependent on the ambient temperature.

Figure 9: Current Chamber Transient Response-300F for 5 minutes

The design to provide protection against elevated temperatures was also investigated to see how well it responds to the spike in temperature. It was modeled with an initial spike in temperature of 300F for 5 minutes and then an additional 5 minutes at 150F before returning to the maximum ambient temperature of 125F that was found previously. In this scenario, the air conditioner was run from the start and continued to run for the duration of the model to produce the results shown in Figure 10 below. As can be seen, the ambient mine temperature has little effect on the inside of the chamber. The high thermal resistance of this chamber provides protection from the surrounding atmosphere providing a higher degree of protection for the miner.

Figure 10: Air Conditioned Transient Response

5.7 Power Sources for the Air Conditioning Unit

To run an air conditioning unit of this size for the worst case scenario of four days would require a considerable amount of power. A continuous power source supplied from the mine will not be available and thus an alternative form of power such as from batteries or a diesel generator will be explored. The air conditioning unit requires 115 volts and 8 amps of alternating current. This requires approximately 920 watts of power to run the air conditioning system.

A battery system will need to be used in conjunction with an inverter to convert the DC power supplied by the batteries to AC power required by the air conditioning unit. The inverter converts the 12V direct current batteries to 120V alternating current at an efficiency of 90 percent. Considering the efficiency of the inverter the batteries will now need to supply approximately 1,100 Watts of power for 96 hours. The inverter selected will be able to supply 1500 watts of continuous power to meet the load of the air

conditioner and has the dimensions 11.2" x 3.9" x 16.3". The lead acid batteries utilized are capable of supplying 250 amp hours at 12 volts for a total energy of 3 kWh with dimensions of 21" x 11" x 10". The air conditioner will require a total of 105.6 kWh during the 96 hour period. Utilizing these two values, the air conditioning unit will require 36 batteries wired in a parallel. The cost of the inverter is \$500 and the batteries are \$460 a piece for a total of \$17,000. Not only is the price high, but the batteries will require a large amount of space and will require a charging station to maintain their energy. The inverter and batteries are shown in Figure 11 below.

Figure 11: Inverter and Battery

The battery, inverter and all other necessary electrical wiring and equipment will need to be designed and approved according to state and federal regulations. MSHA requires electrical equipment to be permissible, which means that the equipment must be encased such that any spark that may be created from the electrical equipment cannot ignite methane in the mine atmosphere. This is accomplished by having a sealed

enclosure around all electrical equipment. Some of the other requirements deal with the examination, testing, and maintenance of the equipment.

A diesel generator is a relatively cheap alternative to batteries and will not require an inverter since it produces alternating current. A diesel 4000 watt generator is capable of supplying 3300 W of continuous power for 8 hours on 3.7 gallons of fuel. The generator will operate for 12 hours on 50% of the rated output. Since only 1.0 kW is required, the generator will be able to run for 12 hours on 3.7 gallons. For the generator to run the entire 96 hours, roughly 30 gallons or 4 cubic feet of fuel will be required to operate the air conditioning system and other electronics such as lights if desired. The generator shown in Figure 12 below will not require much space as the dimensions of the generator are 28" x 22" x 26".

Along with the fuel consideration, the generator must have an adequate supply of oxygen to run as well. Conventional diesel engines require a minimum of 16-17% oxygen concentrations in the atmosphere to adequately run at normal loads. Studies have found that oxygen concentrations below 16-17% significantly impede the ability for combustion to be maintained and hydrocarbon fuels become completely inert in environments with oxygen concentration levels lowered to 12-13% at standard temperature and pressure [20]. Although the oxygen concentration may not fall that low after an accident, storing oxygen for the combustion process should be taken into consideration. To calculate the amount of oxygen needed the air to fuel ratio (AFR) needs to be found. Because the amount of air in the combustion chamber is relatively constant and the amount of fuel is variable, diesel engines run at varying air to fuel ratios. The AFR depends on what your goals are, but often AFR for a diesel is set in the neighborhood of 28-32:1 under typical

partial loading conditions [21]. Using the information above, the amount of oxygen required can be found by knowing diesel fuel weighs approximately 7 pounds per gallon for a total of 210 pounds of fuel that will need oxygen. Next, using an AFR of 28:1, the amount of air required is 5,880 pounds or 78,400Ft³ of air which is only 21% oxygen by volume, thus the amount of oxygen is actually 16,464Ft³. Knowing that we only need 16% oxygen, the minimum amount of oxygen needed becomes 12,544Ft³. Assuming that the post-accident mine atmosphere never dipped below 8% oxygen, the supply of oxygen should be approximately 6,272Ft³, requiring 22 oxygen tanks that hold 282Ft³ of oxygen in each. The total volume the oxygen tanks will occupy was calculated to be approximately 100Ft³.

Figure 12: Diesel Generator

All of these components will need to be altered to conform to state and federal requirements for use in coal mines. To be able to be used underground MSHA standards require specific limitations on external temperatures, safety shutdown systems, fire suppression systems, and permissibility requirements on all electrical components.

From the two power supplies above, the diesel generator would be the preferred method. It is considerably cheaper and would require less maintenance while increasing the portability of the refuge chamber. With the batteries, the system would need recharged often, which would require running electricity to the chamber, sometimes from as far as 2,000 feet away. The diesel system would simplify the installation as the air conditioner could be plugged straight into the generator without the additional expense of the inverter. With the above considerations, both systems would need to be altered to be able to meet MSHA and state standards.

5.8 Other Necessary items inside Shelter

Other items that should be included in the shelter for the comfort of the miners should include items such as first aid kits, blankets, permissible flashlights, multi-gas detectors, batteries, toilet bags, toilet paper, tools, drinking cups, and some reading material or other form of low activity level entertainment. All of these supplies can be stored under the bench except for the toilet as it will be utilized in the air lock portion for privacy. The airlock will also serve as the restroom area and a small portable toilet with disposable bags is provided so that it can be reused numerous times. There will be a compartment to dispose of the waste bags along the wall of the airlock as well.

Figure 13: Example of Toilet and Disposable Bags [14]

Chapter 6: Results

6.1 Chamber Layout without AC Unit

With all of the above considerations for food, water, carbon dioxide scrubbing, air and oxygen bottles, and the rest of the supplies, the most challenging aspect was making sure all the items would fit. Thus a modeled chamber was drawn with Pro-Engineer Software to scale with all the packaging shown inside. All of the chambers will be similar and the only changes will be made to the air conditioning design. The first chamber in Figure 14 is the chamber without an actual air conditioning unit and thus requires a lower outside temperature to conduct the heat to the outside. As is shown desiccant is added to this design to absorb moisture.

Figure 14: Top View of Chamber

Figure 15: Front View of Chamber

As can be seen in Figure 15, the miners will all enter the chamber and be in the air lock section with both doors closed. They will then activate the 3 air tanks on the left to purge the airlock. Once the contaminant levels have dropped to acceptable levels, the miners will shut the air tanks off and proceed into the main living area of the chamber while leaving the door open to maximize heat transfer area. They will then proceed to the oxygen bottles and open the regulator to a preset position and open and hang 5 boxes of lithium hydroxide curtains. They will then await their rescue, hanging 5 boxes of curtains every 12 hours and keeping activity levels minimal and conserving food and water.

6.2 Chamber with AC Unit

The next chamber shown in Figure 16 will have a split type air conditioning system in conjunction with an independent power supply that will be able to handle a maximum load of 9,000BTU/Hr. The design of this chamber is the same as the previous chamber with the exception of the air conditioner shown in purple and the power source shown in red and the removal of the desiccant material.

Figure 16: Top and Front Views of Chamber

The procedure for entering this chamber is the same as the previous except that it would benefit the miners if they left the airlock door closed, except for entering and exiting for bathroom purposes so that heat transfer area is kept minimal. After entering the chamber the air conditioner should be enabled to keep the room cool as well as turning the oxygen regulator on and hanging the lithium hydroxide curtains.

Chapter 7: Conclusions

When designing a refuge chamber there are endless possibilities of scenarios to consider but with basic heat transfer principles and HVAC guidelines, a model can predict the heat loads associated with the material properties and internal and external environments. The design of the chamber should first consider what level of protection from outside temperatures the design must achieve. This will be the basis for choosing the material to construct the chamber. If it is determined that high temperature levels are not a possibility or that they will be too high for human survival even with a chamber, the design should focus on maximizing heat transfer out of the chamber. If the goal is to sustain high ambient temperatures, the construction of the chamber should be much more rigid, designing the overall heat transfer coefficient as low as possible to keep the external heat out and only cool the heat being produced internally. After the chamber has been designed for temperature, the rest of the survival necessities, such as food, water, oxygen, and carbon dioxide scrubbing should be calculated according to the maximum number of miners expected to use the shelter in case of an emergency.

Chapter 8: Future Work

Future work on this topic should concentrate on obtaining more accurate results of the heat loads inside the chamber through experimentation as there have not been any studies done on this subject in particular. A prototype of the chamber should be setup to include a set number of average males to stay inside the chamber while under constant ambient conditions. In this experiment the dry bulb temperature should be monitored along with the relative humidity as a function of time. This will allow for the calculation of more accurate heat generation values from the miners and carbon dioxide scrubber. It will also allow for a more accurate measurement of the sensible and latent heat loads. There should also be gas detectors to measure the exact concentration of all gases present to make sure the system is functioning as desired and maintains livable conditions. Also the people in the study should be monitored to make sure that they are safe and correlate any change in the atmosphere with a change in a certain bodily functions such as an increase in heart or respiration rates.

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Appendix A

Oxygen Tanks and Lithium Hydroxide Curtains Required for Various Capacities

Table 9: Oxygen and LiOH Required

Oxygen Per Miner per hour			1.32	CFH	
Co2 Liberation per miner per hour			1.08	CFH	
Design Period			96	Hr	
No. of Miners	Oxygen Required (Ft^3)	No. of O2 Bottles	Co2 Liberation (Ft^3)	Lbs of LiOH	Boxes of LiOH
1	126.72	0.45	103.68	14.94	2.62
2	253.44	0.90	207.36	29.88	5.24
3	380.16	1.35	311.04	44.81	7.86
4	506.88	1.80	414.72	59.75	10.48
5	633.6	2.25	518.40	74.69	13.10
6	760.32	2.70	622.08	89.63	15.72
7	887.04	3.15	725.76	104.57	18.35
8	1013.76	3.59	829.44	119.51	20.97
9	1140.48	4.04	933.12	134.44	23.59
10	1267.2	4.49	1036.80	149.38	26.21
11	1393.92	4.94	1140.48	164.32	28.83
12	1520.64	5.39	1244.16	179.26	31.45
13	1647.36	5.84	1347.84	194.20	34.07
14	1774.08	6.29	1451.52	209.14	36.69
15	1900.8	6.74	1555.20	224.07	39.31
16	2027.52	7.19	1658.88	239.01	41.93
17	2154.24	7.64	1762.56	253.95	44.55
18	2280.96	8.09	1866.24	268.89	47.17
19	2407.68	8.54	1969.92	283.83	49.79
20	2534.4	8.99	2073.60	298.77	52.42
21	2661.12	9.44	2177.28	313.70	55.04
22	2787.84	9.89	2280.96	328.64	57.66
23	2914.56	10.34	2384.64	343.58	60.28
24	3041.28	10.78	2488.32	358.52	62.90
25	3168	11.23	2592.00	373.46	65.52
26	3294.72	11.68	2695.68	388.40	68.14
27	3421.44	12.13	2799.36	403.33	70.76
28	3548.16	12.58	2903.04	418.27	73.38
29	3674.88	13.03	3006.72	433.21	76.00
30	3801.6	13.48	3110.40	448.15	78.62
31	3928.32	13.93	3214.08	463.09	81.24
32	4055.04	14.38	3317.76	478.02	83.86
33	4181.76	14.83	3421.44	492.96	86.48
34	4308.48	15.28	3525.12	507.90	89.11
35	4435.2	15.73	3628.80	522.84	91.73

Appendix B

Maximum Ambient Temperatures

Table 10: ¼” 1010 Steel Chamber

k	36.97	BTU/hr ft F
h	1.50	BTU/hr ft ² F
k/L	1774.70	BTU/hr ft ² F
Rt	1.33	hr ft ² F/BTU
Ut	0.75	BTU/hr ft ² F
UA	476.05	BTU/Hr F

Outside Temp	Delta T	Q (Heat Transfer rate out of chamber)	Heat generated-Heat Transferred out
60	30	14281.46	-6781.46
61	29	13805.42	-6305.42
62	28	13329.37	-5829.37
63	27	12853.32	-5353.32
64	26	12377.27	-4877.27
65	25	11901.22	-4401.22
66	24	11425.17	-3925.17
67	23	10949.12	-3449.12
68	22	10473.07	-2973.07
69	21	9997.03	-2497.03
70	20	9520.98	-2020.98
71	19	9044.93	-1544.93
72	18	8568.88	-1068.88
73	17	8092.83	-592.83
74	16	7616.78	-116.78
75	15	7140.73	359.27
76	14	6664.68	835.32
77	13	6188.63	1311.37
78	12	5712.59	1787.41
79	11	5236.54	2263.46
80	10	4760.49	2739.51
81	9	4284.44	3215.56
82	8	3808.39	3691.61
83	7	3332.34	4167.66
84	6	2856.29	4643.71
85	5	2380.24	5119.76
86	4	1904.20	5595.80
87	3	1428.15	6071.85
88	2	952.10	6547.90
89	1	476.05	7023.95
90	0	0.00	7500.00

Table 11: ½” 1010 Steel Chamber

k	36.97284806	BTU/hr ft F
h	1.5	BTU/hr ft ² F
k/L	887.3483536	BTU/hr ft ² F
Rt	1.334460286	hr ft ² F/BTU
Ut	0.749366624	BTU/hr ft ² F
UA	475.8478064	BTU/Hr F

Outside Temp	Delta T	Q (Heat Transfer rate out of chamber)	Heat generated-Heat Transferred out
60	30	14275.43	-6775.43
61	29	13799.59	-6299.59
62	28	13323.74	-5823.74
63	27	12847.89	-5347.89
64	26	12372.04	-4872.04
65	25	11896.20	-4396.20
66	24	11420.35	-3920.35
67	23	10944.50	-3444.50
68	22	10468.65	-2968.65
69	21	9992.80	-2492.80
70	20	9516.96	-2016.96
71	19	9041.11	-1541.11
72	18	8565.26	-1065.26
73	17	8089.41	-589.41
74	16	7613.56	-113.56
75	15	7137.72	362.28
76	14	6661.87	838.13
77	13	6186.02	1313.98
78	12	5710.17	1789.83
79	11	5234.33	2265.67
80	10	4758.48	2741.52
81	9	4282.63	3217.37
82	8	3806.78	3693.22
83	7	3330.93	4169.07
84	6	2855.09	4644.91
85	5	2379.24	5120.76
86	4	1903.39	5596.61
87	3	1427.54	6072.46
88	2	951.70	6548.30
89	1	475.85	7024.15
90	0	0.00	7500.00

Table 12: Vinyl Chamber

k	0.14	BTU/hr ft F
h	1.50	BTU/hr ft ² F
k/L	13.31	BTU/hr ft ² F
Rt	1.41	hr ft ² F/BTU
Ut	0.71	BTU/hr ft ² F
UA	450.85	BTU/Hr F

Outside Temp	Delta T	Q (Heat Transfer rate out of chamber) (BTU/Hr)	Heat generated-Heat Transferred out (BTU/Hr)
60	30	13525.38	-6025.38
61	29	13074.53	-5574.53
62	28	12623.68	-5123.68
63	27	12172.84	-4672.84
64	26	11721.99	-4221.99
65	25	11271.15	-3771.15
66	24	10820.30	-3320.30
67	23	10369.46	-2869.46
68	22	9918.61	-2418.61
69	21	9467.76	-1967.76
70	20	9016.92	-1516.92
71	19	8566.07	-1066.07
72	18	8115.23	-615.23
73	17	7664.38	-164.38
74	16	7213.53	286.47
75	15	6762.69	737.31
76	14	6311.84	1188.16
77	13	5861.00	1639.00
78	12	5410.15	2089.85
79	11	4959.30	2540.70
80	10	4508.46	2991.54
81	9	4057.61	3442.39
82	8	3606.77	3893.23
83	7	3155.92	4344.08
84	6	2705.08	4794.92
85	5	2254.23	5245.77
86	4	1803.38	5696.62
87	3	1352.54	6147.46
88	2	901.69	6598.31
89	1	450.85	7049.15
90	0	0.00	7500.00

Appendix C

Transient Response

Table 13: Current Chamber-300F for 3 seconds

Total Time	Period	Toutside(F)	Tinside(F)	Heat Transferred (BTU/Hr)	Heat Transferred (BTU/min)	Heat from miners (BTU/min)	ΔT (F)
0	0.05	300	60.00	103008.00	85.84	6.25	3.73
0.05	1	70	63.73	2693.09	44.88	125.00	6.87
1.05	1	70	70.60	-256.53	-4.28	125.00	4.88
2.05	1	70	75.48	-2352.60	-39.21	125.00	3.47
3.05	1	70	78.95	-3842.13	-64.04	125.00	2.47
4.05	1	70	81.42	-4900.62	-81.68	125.00	1.75
5.05	1	70	83.17	-5652.82	-94.21	125.00	1.25
6.05	1	70	84.42	-6187.34	-103.12	125.00	0.89
7.05	1	70	85.30	-6567.19	-109.45	125.00	0.63
8.05	1	70	85.93	-6837.12	-113.95	125.00	0.45
9.05	1	70	86.38	-7028.94	-117.15	125.00	0.32
10.05	1	70	86.69	-7165.25	-119.42	125.00	0.23
11.05	1	70	86.92	-7262.12	-121.04	125.00	0.16
12.05	1	70	87.08	-7330.96	-122.18	125.00	0.11
13.05	1	70	87.19	-7379.87	-123.00	125.00	0.08
14.05	1	70	87.28	-7414.64	-123.58	125.00	0.06
15.05	1	70	87.33	-7439.34	-123.99	125.00	0.04
16.05	1	70	87.37	-7456.89	-124.28	125.00	0.03
17.05	1	70	87.40	-7469.37	-124.49	125.00	0.02
18.05	1	70	87.42	-7478.23	-124.64	125.00	0.01
19.05	1	70	87.44	-7484.53	-124.74	125.00	0.01
20.05	1	70	87.45	-7489.01	-124.82	125.00	0.01
21.05	1	70	87.46	-7492.19	-124.87	125.00	0.01
22.05	1	70	87.46	-7494.45	-124.91	125.00	0.00
23.05	1	70	87.47	-7496.06	-124.93	125.00	0.00
24.05	1	70	87.47	-7497.20	-124.95	125.00	0.00
25.05	1	70	87.47	-7498.01	-124.97	125.00	0.00
26.05	1	70	87.47	-7498.58	-124.98	125.00	0.00
27.05	1	70	87.47	-7498.99	-124.98	125.00	0.00
28.05	1	70	87.47	-7499.29	-124.99	125.00	0.00
29.05	1	70	87.47	-7499.49	-124.99	125.00	0.00
30.05	1	70	87.47	-7499.64	-124.99	125.00	0.00
31.05	1	70	87.47	-7499.74	-125.00	125.00	0.00
32.05	1	70	87.47	-7499.82	-125.00	125.00	0.00
33.05	1	70	87.47	-7499.87	-125.00	125.00	0.00
34.05	1	70	87.47	-7499.91	-125.00	125.00	0.00
35.05	1	70	87.47	-7499.93	-125.00	125.00	0.00

Table 14: Current Chamber-300F for 5minutes

Total Time	Period	Toutside(F)	Tinside(F)	Heat Transferred (BTU/Hr)	Heat Transferred (BTU/min)	Heat from miners (BTU/min)	ΔT (F)
1	1	300	60.00	103008.00	1716.80	6.25	69.70
2	1	300	129.70	73091.61	1218.19	125.00	54.34
3	1	300	184.04	49770.47	829.51	125.00	38.61
4	1	300	222.65	33197.87	553.30	125.00	27.44
5	1	300	250.09	21420.95	357.02	125.00	19.50
6	1	70	269.59	-85664.03	-1427.73	125.00	-52.70
7	1	70	216.89	-63045.37	-1050.76	125.00	-37.45
8	1	70	179.44	-46971.96	-782.87	125.00	-26.61
9	1	70	152.83	-35549.79	-592.50	125.00	-18.91
10	1	70	133.92	-27432.90	-457.22	125.00	-13.44
11	1	70	120.48	-21664.83	-361.08	125.00	-9.55
12	1	70	110.93	-17565.89	-292.76	125.00	-6.79
13	1	70	104.14	-14653.08	-244.22	125.00	-4.82
14	1	70	99.32	-12583.16	-209.72	125.00	-3.43
15	1	70	95.89	-11112.23	-185.20	125.00	-2.44
16	1	70	93.46	-10066.94	-167.78	125.00	-1.73
17	1	70	91.72	-9324.13	-155.40	125.00	-1.23
18	1	70	90.49	-8796.28	-146.60	125.00	-0.87
19	1	70	89.62	-8421.17	-140.35	125.00	-0.62
20	1	70	89.00	-8154.61	-135.91	125.00	-0.44
21	1	70	88.56	-7965.18	-132.75	125.00	-0.31
22	1	70	88.24	-7830.57	-130.51	125.00	-0.22
23	1	70	88.02	-7734.91	-128.92	125.00	-0.16
24	1	70	87.86	-7666.93	-127.78	125.00	-0.11
25	1	70	87.75	-7618.63	-126.98	125.00	-0.08
26	1	70	87.67	-7584.30	-126.40	125.00	-0.06
27	1	70	87.61	-7559.91	-126.00	125.00	-0.04
28	1	70	87.57	-7542.57	-125.71	125.00	-0.03
29	1	70	87.54	-7530.25	-125.50	125.00	-0.02
30	1	70	87.52	-7521.50	-125.36	125.00	-0.01
31	1	70	87.51	-7515.28	-125.25	125.00	-0.01
32	1	70	87.50	-7510.86	-125.18	125.00	-0.01
33	1	70	87.49	-7507.71	-125.13	125.00	-0.01
34	1	70	87.49	-7505.48	-125.09	125.00	0.00
35	1	70	87.48	-7503.90	-125.06	125.00	0.00

Table 15: Air Conditioned Transient Response

Total Time	Period	Toutside(F)	Tinside(F)	Heat Transferred (BTU/Hr)	Heat Transferred (BTU/min)	Heat from miners (BTU/min)	Heat Removed by AC(BTU/min)	ΔT (F)
0	1	300	60.00	8539.88	142.33	125.00	150.00	4.75
1	1	300	64.75	8370.99	139.52	125.00	150.00	4.63
2	1	300	69.38	8206.15	136.77	125.00	150.00	4.52
3	1	300	73.90	8045.26	134.09	125.00	150.00	4.41
4	1	300	78.31	7888.24	131.47	125.00	150.00	4.31
5	1	150	82.62	2397.56	39.96	125.00	150.00	0.61
6	1	150	83.23	2376.02	39.60	125.00	150.00	0.59
7	1	150	83.82	2355.01	39.25	125.00	150.00	0.58
8	1	150	84.39	2334.50	38.91	125.00	150.00	0.56
9	1	150	84.96	2314.48	38.57	125.00	150.00	0.55
10	1	128	85.50	1512.11	25.20	125.00	150.00	0.01
11	1	128	85.51	1511.82	25.20	125.00	150.00	0.01
12	1	128	85.52	1511.54	25.19	125.00	150.00	0.01
13	1	128	85.53	1511.26	25.19	125.00	150.00	0.01
14	1	128	85.54	1510.99	25.18	125.00	150.00	0.01
15	1	128	85.54	1510.73	25.18	125.00	150.00	0.01
16	1	128	85.55	1510.47	25.17	125.00	150.00	0.01
17	1	128	85.56	1510.22	25.17	125.00	150.00	0.01
18	1	128	85.56	1509.98	25.17	125.00	150.00	0.01
19	1	128	85.57	1509.74	25.16	125.00	150.00	0.01
20	1	128	85.58	1509.50	25.16	125.00	150.00	0.01
21	1	128	85.58	1509.27	25.15	125.00	150.00	0.01
22	1	128	85.59	1509.05	25.15	125.00	150.00	0.01
23	1	128	85.60	1508.84	25.15	125.00	150.00	0.01
24	1	128	85.60	1508.62	25.14	125.00	150.00	0.01
25	1	128	85.61	1508.42	25.14	125.00	150.00	0.01
26	1	128	85.61	1508.21	25.14	125.00	150.00	0.01
27	1	128	85.62	1508.02	25.13	125.00	150.00	0.01
28	1	128	85.62	1507.82	25.13	125.00	150.00	0.01
29	1	128	85.63	1507.64	25.13	125.00	150.00	0.01
30	1	128	85.64	1507.45	25.12	125.00	150.00	0.01
31	1	128	85.64	1507.28	25.12	125.00	150.00	0.00
32	1	128	85.65	1507.10	25.12	125.00	150.00	0.00
33	1	128	85.65	1506.93	25.12	125.00	150.00	0.00
34	1	128	85.65	1506.76	25.11	125.00	150.00	0.00
35	1	128	85.66	1506.60	25.11	125.00	150.00	0.00