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Estimation of metabolic heat input for refuge alternative thermal testing and simulation

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Abstract

Refuge alternatives provide shelter to miners trapped underground during a disaster. Manufacturers must demonstrate that their refuge alternatives meet the U.S. Mine Safety and Health Administration (MSHA) requirements for oxygen supply, carbon dioxide removal, and management of heat from the occupants and mechanical/chemical systems. In this study, miner size and activity level were used to determine the metabolic heat rate, oxygen requirements and carbon dioxide generation that are representative of miners in a refuge situation. A convenience sample of 198 male miners was used for the distribution of current U.S. coal miners, and the composite 95th percentile height and weight were determined to be 193 cm (76 in.) and 133 kg (293 lb). The resting metabolic rate (RMR) was determined to be representative of activity level in a refuge alternative. The highest likely metabolic heat generation ranged from 113 to 134 W, depending on occupancy. The highest required oxygen supply and carbon dioxide removal were estimated to be 23 L (0.81 cu ft) of oxygen per hour per person and 20 L (0.71 cu ft) of carbon dioxide per hour per person, which means the margin of safety is 50 percent or more compared with the MSHA requirements. The information on metabolic heat generation can be used to assess refuge alternative thermal environments by testing or simulation. The required oxygen supply and carbon dioxide removal can be used to assess refuge alternative requirements.

Introduction

Refuge alternatives provide shelter to miners trapped underground during a disaster. Manufacturers must demonstrate that their refuge alternatives meet U.S. Mine Safety and Health Administration (MSHA) requirements for the supply of oxygen (O_2), removal of carbon dioxide (CO_2) and management of heat resulting from the refuge alternatives' occupants and mechanical/chemical systems (MSHA, 2008).

The MSHA requirements are based on a standard 70-kg (168-lb) male with an assumed allocation of activity of 80 percent rest and 20 percent moderate activity level. The purpose of this paper is to reexamine the metabolic heat generation and O_2 and CO_2 requirements of miners in a refuge alternative based on actual miner size and more realistic activity levels based on current refuge-alternative designs. Researchers took the following steps to estimate the metabolic demands and associated heat generation, O_2 requirements and CO_2 production:

1. Established the anthropometric characteristics of the miner population.
2. Described the metabolic rate profile of refuge alternative occupants.
3. Characterized the maintenance demands of refuge alternatives.
4. Summarized O_2 supply and CO_2 removal volumes.

Anthropometric characteristics

The weight, height and age distributions for the adult male population based on several studies are summarized in Table 1. For each data set, the reported mean and standard deviation are provided. The 95th percentile value for height and weight for each population was the mean plus 1.64 times the standard deviation.

The first set of data was collected in 2016 from a convenience sample of 34 male miners attending a United Mine Workers of America (UMWA) meeting plus 164 coal miner self-reports of height, weight and age from a mail-in survey. The data were pooled for a sample size of 198 males. The data, collected in four waves of responses, were similar, which supported the internal validity of the data.

The International Organization for Standardization (ISO, 2010) data in Table 1 are for the U.S. population. The sample representing the United States was collected between April 1998 and July 2000 from 10 states with additional data from Ottawa, Ontario, Canada using the adult population between 18 and 65 years of age who were volunteers for the CAESAR study. The National Health and Nutrition Examination Survey (NHANES) sample is for white, non-Hispanic males recorded between 2007 and 2011 (Centers for Disease Control and Prevention, 2016). The NHANES data were collected to represent the U.S. population and followed a rigorous sampling procedure. This sample was stratified by age, so the average age is not provided in the table. It is clear from the UMWA data that the average miner is heavier than the average adult U.S. male. The last two samples, which are for underground coal miners in low coal and high and medium coal, were taken about 1980 by investigators at Texas Tech University (Ayoub, Bethea et al., 1981; Ayoub, Selan et al., 1984).

For 2010, the U.S. National Mining Association reported some demographic information on coal miners that indicated the mean age was 45 years. This was the same as the mean age for the convenience sample age, and both sources were greater than the Texas Tech values of 30 and 35 recorded in 1980, and the ISO sample of 40. This suggests that the current population of miners is older than in previous sample years. The 1980s data from Texas Tech may be confounded by the change in body composition over more than 30 years.

The NHANES and UMWA samples both point to an overall increase in weight from the Texas Tech data. This is not surprising, given the overall increase in weight reported over the last 20 years for the U.S. population (CDC, 2016). The ISO data suggest a lower rate of weight gain. Some of this increased weight may also be due to an increase in average height based on the 1980 to more recent data.

In this report, the UMWA data were used to represent the mining population for the analysis of resting metabolic rate (RMR). For the mean and 95th percentile miner, the UMWA data represented the highest values among the data sources available. Based on these data, for modeling and other representational purposes, the composite 95th percentile height and weight are 193 cm (76 in.) and 133 kg (293 lb).

Resting metabolic rate

RMR, also known as resting energy expenditure, is a measure of the metabolic demands of a resting individual who is typically sitting. This is in contrast to basal metabolic rate (BMR), which is a measure of the basic metabolic energy demands to maintain life with no added activity, simply maintaining posture or minimal movements. There is extensive literature on RMR and BMR due to the need to understand these demands in illness and weight management.

The RMR depends primarily on height, weight, age and gender. Any effect on RMR due to fitness or other personal factors that are not height, weight or age has not been reported. During exercise and exposures to heat stress, there may be an increase in metabolic rate. Effects due to ambient temperature and body temperature were not included in the analysis because the overall change in RMR would be small assuming the environment of the refuge alternative is sustainable for 96 hours and the changes in body temperature and physiological demands of thermal regulation are not taxed. Because most miners in underground coal are men, RMR predictions for men were used in this study. The oldest prediction equation to calculate RMR was by Harris and Benedict (1919):

$$RMR = 66.47 + 13.75 * WT + 5.0 * HT - 6.75 * AGE \quad (1)$$

More recently, Mifflin and et al. (1990) offered the Mifflin-St Jeor prediction equation:

$$RMR = 5.0 + 9.99 * WT + 6.25 * HT - 4.92 * AGE \quad (2)$$

The Owen formulation for men (Owen et al., 1987) calculates RMR as follows:

$$RMR = 879 + 10.2 * WT \quad (3)$$

For men aged 31 to 60, the World Health Organization's (WHO, 1985) formulations to calculate RMR using weight alone and using both weight and height are:

$$RMR = 879 + 11.6 * WT \quad (4)$$

$$RMR = 901 + 11.3 * WT + 0.16 * HT \quad (5)$$

In Eqs. (1) to (5), the calculated RMR is in kilocalories per day; the weight, WT, is in kilograms; the height, HT, is in centimeters; and the age, AGE, is in years.

To compare among these methods, the effects of height, weight and age based on the UMWA data are provided in Table 2 as the means and standard deviations of the RMR distributions. At this point, there is no allowance for prediction error associated with the formulation.

In Table 2, the mean values for each method are based on the mean data for the miner convenience sample. The standard deviations represent the contributions to the overall standard deviation from the standard deviation of each of the variables in the RMR prediction equations. The practical implication is that the 95th percentile for an RMR method is not simply the 95th percentile values of each of the variables. The 95th percentile RMR, or the RMR for the 95th percentile person, over the population is determined from:

$$RMR_{\mathrm{95th}} = RMR_{\mathrm{mean}} + 1.64 RMR_{\mathrm{sd}} \quad (6)$$

where RMR_{mean} is the mean value for the model and RMR_{sd} is the standard deviation of the model.

As a matter of practical design, any computer or physical simulation of a refuge alternative should include one person who represents the likely high value for RMR. This will allow the simulation to account for the potential of the environment to support heat dissipation for a worst-case individual.

Using the 95th percentile person to represent all of the occupants can substantially overestimate the total heat generation in the refuge alternative from the occupants. In this case, it is worthwhile to consider a reasonable upper limit for a group of occupants. Following this approach, for a reasonable upper limit on an individual, the reasonable upper limit for the mean of a group of occupants, or the 95th percentile mean, is determined from:

$$RMR_{\mathrm{95thmean}} = RMR_{\mathrm{mean}} + 1.64 RMR_{\mathrm{sd}} / \sqrt{n} \quad (7)$$

where RMR_{mean} is the mean value for the model, RMR_{sd} is the standard deviation of the model, and $\sqrt{n}$ is the square root of the number of occupants. As the number of occupants becomes large, the upper limit on the mean approaches the mean value.

Table 3 reports the 95th percentile value of RMR for each prediction method for the 95th percentile person and for increasing numbers of occupants. As expected, the 95th percentile mean predicted RMR value decreases with the number of occupants, because there is a tendency for the mean of larger sample sizes to move toward the mean for the population.

Two recent evaluations of prediction equations for RMR (Frankenfield, Roth-Yousey and Compher, 2005; Hasson et al., 2011) informed the specification of RMR in this report. While Hasson et al. found minor differences between measured and predicted mean values for all methods, virtually all of the predicted values were within a range of ± 500 kcal/d. They also reported that the Harris-Benedict equation was most likely to predict within ±10 percent of the measured value. Frankenfield, Roth-Yousey and Compher (2005), reviewed validation studies and reported that the Mifflin-St Jeor prediction provided the narrowest error band at 10 percent of predicted, which would be on the order of ± 200 kcal/d. They did note that the validation applied primarily to non-Hispanic whites.

From the discussion above, it is clear that a reasonable upper limit on RMR was approximately 2,300 kcal/d before factoring in estimation error. None of the reported studies provided an estimate of the standard error, or similar variance measure. To select a high representative value, the maximum estimate for each row in Table 3 was identified and then 10 percent of the value was added. This value is noted in the column labeled 1.1*Highest. Finally, the RMR in watts is reported in the last column.

Among the various RMR prediction methods presented above, the weight multiplier is approximately 10. If there were a systematically higher weight of 10 kg, the increase in RMR would be about 100 kcal/d, which is under 10 percent of the upper limit value. From Eqs. (1) and (2), a change of ±3 cm in height among the sources of anthropometric data would account for less than 20 kcal/d, which would be negligible. Similarly, according to Eqs. (1) and (2), each year of age decreases RMR by about 6 kcal/y, so a 10-year age difference would only account for 60 kcal/d. Further, the estimated values should be overestimated because age, height and weight are treated as independent variables. In reality, they are collinear and the dependence would reduce the estimated standard deviation. Overall, the highest values multiplied by 1.1 likely represent a value greater than 95 percent of the population.

The practical application of Table 3 is the prediction of a likely high RMR for any one person — represented by the first value in the last column — of 134 W, and the prediction of a likely high average RMR for any group of people. The high group average depends on the number of members of the group. Thus, the values in the last column decrease with increasing number of occupants. With a high-occupancy refuge alternative, the average RMR is closer to 113 W.

Maintenance and other demands

To support the proper functioning of the refuge alternative and to monitor the environment, there is a metabolic cost that will add to the heat load. One support function that the occupants are likely to perform is the periodic changing out of CO_2 absorbents. For one manufacturer's refuge alternatives, all of the CO_2 sorbents are deployed when miners activate the refuge alternative, and there is no further maintenance required. Another manufacturer's refuge alternatives require daily replacement of the sorbents. Assuming one person is responsible for sorbent maintenance, the overall metabolic cost to retrieve the 20-kg fresh cartridge from storage (lifting/lowering of 1 m), move it 10 m to the location, remove the spent cartridge (lifting/lowering of 1 m) and move it 10 m away, stow the old cartridge away (lifting/ lowering of 1 m), and place the new cartridge (lifting/lowering of 1 m) can be estimated. The cost to lift or lower 20 kg over 1 m four times is less than 2 kcal/ cartridge. The highest metabolic demand would be dragging the cartridge. Assuming a coefficient of friction of 1.0 between the cartridge and the refuge alternative, the cost would be 4 kcal/cartridge for the 20-m distance. The most efficient way to move the cartridge is to pass it along from one to another as in a bucket brigade, which would add very little to the two costs mentioned so far. Assuming one person crawling over the 20-m distance, the added cost would be twice that of walking, or about 3 kcal/cartridge. The total per cartridge is nominally 10 kcal/cartridge. Even at 10 cartridges per day, the energy demand would be only 100 kcal. This is small compared to the RMR of nearly 2,300 kcal/d.

Several other refuge alternative maintenance activities would have low metabolic demands. One such task is periodically monitoring the O_2 concentration and adjusting the flow. Other metabolic demands would include other surveillance activities, bathroom breaks, and simple movement to change postures. If these collective activities were described as the equivalent of walking a mile, the equivalent incremental increase in metabolic demands would be less than 100 kcal/d. Again, this is a very low metabolic demand compared to the more than 2,000 kcal/d for the RMR. The analysis did not include other factors such as injury, anxiety and exhaustion. These are difficult to assess but, based on the primary author's experience, would likely also have a small effect. As a balancing point, the occupants are also likely to have periods in which the lower basal metabolic rate would apply because they would be sleeping.

Oxygen/carbon dioxide removal volumes

To support 5 kcal of energy expenditure, 1 L of O_2 is required (Hoeger and Hoeger, 2016). This number is biased high. The amount of CO_2 generated in a mixed carbohydrate and fat metabolism is 0.85 L of CO_2 per liter of O_2. Table 4 provides the total expected high volumes of O_2 and CO_2 per person and the totals by number of occupants based on 96-hour occupancy. The values are derived from those in Table 3.

The MSHA standard (2008) requires 1.32 cu ft of O_2/h/ person, which is equivalent to 37.4 L of O_2/h/person. With likely high values from 19 to 23 L of O_2/h/person, the MSHA standard provides a margin of safety of more than 50 percent. While it is generally assumed that CO_2 generation is about 80 percent of O_2 consumption (Foster-Miller Inc., 2007), the data presented in Table 4 were based on 85 percent. Thus, the estimates of CO_2 removal requirements are somewhat higher than suggested by the project O_2 requirements, but well below the designs of refuge alternatives.

Summary of findings

To represent the distribution of height and weight of current coal miners, the UMWA data in Table 1 were selected because they best represented the target population. These data were primarily used to estimate the RMR. Any systematic differences in RMR due to errors in estimating height, weight and age were relatively small compared to the overall variation. A composite 95th percentile miner was 193 cm (76 in.) for height and 33 kg (293 lb) for weight.

The metabolic costs of miners operating and maintaining a refuge alternative during actual usage are small, and RMR is clearly the dominant source of metabolic heat. For the 95th percentile of the range of individuals, the RMR is about 135 W. In computer or physical simulations, one simulated occupant should have this level of heat generation. The likely high mean heat generation across all occupants in the simulation decreases from 134 W and approaches 113 W for 35 occupants. It should be noted that there were systematic assumptions about the representative high value that would make the stated metabolic rates higher than the real 95th percentile value of the population of miners.

The O_2 supply and CO_2 removal volumes based on the estimated high values were provided to help the mining community to understand the O_2 demands, CO_2 scrubbing load and the heat generation, and to put a margin of safety on the statutory requirements of refuge alternatives. Specifically, the volumes per person per day decreased from the single high person at 23 L (0.81 cu ft) of O_2 per hour per person and 20 L (0.71 cu ft) of CO_2 per hour per person as the projected number of occupants increased. These estimated demands are two-thirds or less of the MSHA requirements, which means the margin of safety is 50 percent or more.

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Table 1

Demographic characteristics of U.S. men as mean, standard deviation and 95th percentile.

Metric	**Mean**	**Standard dev. (SD)**	**95th percentile (mean + 1.64 SD)**
UMWA sample (2016)			
Height (cm)	180.0	8.1	193
Weight (kg)	100.5	19.5	133
Age (y)	45.5	11.0	
ISO, U.S. males (2010) (Sample dates: 1998-2000)			
Height (cm)	177	8.1	190
Weight (kg)	83.2	17.4	112
Age (y)	39.3	11.9	
NHANES (CDC, 2016) (Sample dates: 2007-2011)			
Height (cm)	177.4	9.9	194
Weight (kg)	90.4	22	127
Texas Tech, low coal (Ayoub et al., 1981)			
Height (cm)	174.4	6.5	185
Weight (kg)	81.9	16.8	110
Age (y)	34.5	11.4	
Texas Tech, high and medium coal (Ayoub et al., 1984)			
Height (cm)	174.3	6.9	186
Weight (kg)	80.4	12.2	101
Age (y)	31.6	9.3	

Table 2

Distributions of RMR from prominent estimation methods based on the ISO distribution of age, height and weight.

Metric	**Mean RMR (kcal/d)**	**Standard deviation of RMR**
Harris-Benedict (H-B), Eq. (1)	1,830	244
Mifflin-St Jeor (M-SJ), Eq. (2)	1,749	190
Owen for men (Owen), Eq. (3)	1,728	178
WHO without height, Eq. (4)	1,844	202
WHO with height, Eq. (5)	1,869	197

Table 3

RMR predictions for the 95th percentile value based on five predication models, the highest value for a given population size plus 10 percent, and the equivalent highest RMR in watts.

No. of occupants	RMR predicted using various methods (kcal/d)					1.1*Highest (kcal/d)[a]	RMR (W)
	H-B, Eq. (1)	**M-SJ, Eq. (2)**	**Owen, Eq. (3)**	**WHO without height, Eq. (4)**	**WHO with height, Eq. (5)**		
95th percentile person	2,519	2,264	2,239	2,426	2,437	2,771	134
2	2,376	2,158	2,138	2,310	2,324	2,614	126
3	2,313	2,111	2,093	2,259	2,275	2,545	123
4	2,276	2,083	2,066	2,229	2,245	2,503	121
5	2,250	2,064	2,048	2,208	2,225	2,475	120
10	2,186	2,017	2,002	2,156	2,174	2,405	116
15	2,158	1,996	1,982	2,134	2,152	2,374	115
20	2,141	1,984	1,970	2,120	2,139	2,355	114
25	2,129	1,975	1,962	2,111	2,130	2,343	113
30	2,121	1,969	1,956	2,104	2,123	2,335	113
35	2,114	1,964	1,951	2,099	2,118	2,330	113

[a] The highest value across all of the RMR estimation methods is increased by 10 percent to allow for an upper limit on the prediction error.

Table 4

High values (95th percentile) of RMR in kilocalories per day, the equivalent RMR in watts, volumes of oxygen and carbon dioxide per hour per person, and the total for 96 hours.

No. of occupants	RMR (kcal/d)	RMR (W)	L_{O2}/h/person	L_{CO2}/h/person	Total O_2 (L)	Total CO_2 (L)
1	2,771	134	23	20	2,217	1,884
2	2,614	126	22	19	4,182	3,555
3	2,545	123	21	18	6,107	5,191
4	2,503	121	21	18	8,010	6,808
5	2,475	120	21	18	9,899	8,414
10	2,405	116	20	17	19,237	16,351
15	2,374	115	20	17	28,482	24,210
20	2,355	114	20	17	37,680	32,028
25	2,343	113	20	17	46,855	39,826
30	2,335	113	19	17	56,049	47,642
35	2,330	113	19	17	65,230	55,446