# Critical Evaluation of Current Environmental Comfort Conditions of Bogala Underground

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**Abstract**

Ventilation is a basic part of all underground mine operations as fresh, cool air is required to remove stale, affected air from the workings. The inadequate ventilation often is the cause of lower worker efficiency leading to decreased productivity and increased accident rates. This study focuses on the evaluation of environmental comfort conditions in Bogala Underground, a medium-depth underground graphite mine located in Aruggammana, Sri Lanka. A detailed ventilation survey was carried out taking measurements of dry bulb temperatures, wet bulb temperatures, Dry Kata and Wet Kata thermometer values, air velocities, surface air temperature and barometric pressures at strategic points covering the entire mine. All results were compared with corresponding standard values which describe the standard conditions to be met for working underground. Recommendations were made to improve the present environmental comfort conditions by installing auxiliary fans in stopes where necessary which will enhance the immediate mine environment contributing to health and safety aspects of the underground working environment.

**Keywords:** Auxiliary Fan, Heat Indices, Mine Environment, Mine Ventilation

## 1. Introduction

The main objective of mine ventilation is to provide environmental comfort conditions conducive to optimum efficiency of work in the mini-environment of a mine. Ventilation practices also have made great strides with advances gained in science and technology in the world. Mines have become safer and comfort level enhanced over the years compared with that of the past. Without advances made in ventilation and safety, mining at ultra-deep levels reaching 4 km depth would not have been possible. Quest for minerals at depth will have to be continued to ensure the existence of the human race itself.

Compared to the surface environment, it is difficult to maintain underground comfort conditions without artificial flow of air. Fresh Air supply should be maintained continuously, to ensure acceptable health conditions leading to higher efficiency and productivity of the mines. A number of factors such as the virgin rock temperature, human physiology, heat balance (combined effects of evaporation, radiation, convection-conduction), metabolism, type of clothing directly affect the comfort of workers [1].

The environmental determinants, namely, the dry-bulb temperature, humidity, mean radiant temperature and air velocity should satisfy the accepted standard levels, otherwise, the mine mini environment can be termed as uncomfortable [2]. When there is no proper comfortable conducive environment provided for the mine workers in the long term, it will be harmful to their health. Mainly due to heat, there is the possibility of a number of illnesses such as heat rash, heat cramps with symptoms such as, dizziness and fainting and heat exhaustion leading to a heat stroke too [1].

Therefore, taking effective actions to overcome these barriers and finding technical solutions is essential. High temperatures encountered underground create conditions which have an adverse effect on comfort, efficiency and safety. The environmental determinants, namely, the air velocity, relative humidity and dry bulb temperature, wet-bulb temperature, barometric pressure, mean radiant temperature, effective temperature are parameters to be considered [1].

Bogala mine is the largest and second deepest underground graphite mine in Sri Lanka and the current operating depth is 506 m. The history of the mine which goes back to 150 years with the development strategy hinging on lateral and deeper development, a proper environmental comfort study has to be conducted for the proper evaluation of current environmental conditions for the mine after the last study conducted in 1993 [3].

## 2. Methodology

### 2.1 Selecting the Strategic Locations

The mine has a complicated underground network with lateral and depth-wise expansions. Alfred Shaft and Gabriel Shaft, the two main shafts providing access to personnel, serves ore transportation, and intake ventilation. The two auxiliary shafts, the ventilation shaft (with ventilation discharge side) and Karandawatta Shaft serve as emergency exits.

Development of the deepest level of Gabriel Shaft at 275 fathom level (476m) has been completed in the year 2005 and other major lateral developments have been completed in the year 2008. Due to the mechanical limitations of the winder, management has decided not to deepen the Gabriel shaft any further. However further development work has to be continued up to the sub level (506m) from 275 fathom level (476m) to provide access to deeper-lying vein extensions.

In the study, the complexity of the access network has affected the selection of strategic locations. Main focus in the survey was on locations where man-rock interaction taken place such as stopes, shaft landings, hoist chamber etc. to evaluate prevailing environmental comfort conditions. After giving due consideration to the above mentioned factors, Surface-Alfred Shaft Pit-Head, 072 fm Shaft Landing, Underground Hoist Room, Gabriel Shaft Landing, 090 fm Shaft Landing, 109 fm Shaft Landing, Stope No. 10, 126 fm Shaft Landing, 142 fm Shaft Landing, Stope No. 11, Stope No. 16, 170 fm Shaft Landing, Stope No. 6, Stope No. 7, Stope No. 21, 205 fm Shaft Landing, 240 fm Shaft Landing, Stope No. 30, Stope No. 9, 275 fm Shaft Landing, Stope No. 3, Stope No. 5, Stope No. 15, Workplace No. 4(Drive), Stope No. 12-1, Stope No. 12-2 and Bottom of Ventilation Shaft location were selected as ventilation stations.

## 2.2 Measurements at Each Stations

After identifying the 27 locations, dry bulb temperatures, wet bulb temperatures, Dry Kata thermometer values, air velocities and barometric pressures both underground and on surface at Alfred Shaft head were recorded. In the study, wet and dry bulb hygrometer (whirling hygrometer) was used to measure the temperatures and humidity. As the mechanism of heat transfer from the human body is similar to the mechanism of heat transfer from Kata thermometer, it was used to measure the rate of heat transfer from the human body. Air velocity was measured using the fixed point method with Digital Anemometer (Model-LCA301). Aneroid Barometer was employed to measure the absolute barometric pressure in every location with several readings repeated to obtain an average value.

## 2.3 Calculation of Indices of Heat Stresses

Indices of heat stresses were calculated with the input of the measured data,namely, dry bulb temperature, wet bulb temperature, air velocity, barometric pressure and Kata values.

**Effective Temperature**

Effective Temperature (ET) can be taken approximately equal to 90 % of wet-bulb temperature and 10 % of dry bulb temperature [1]. Some scales were defined to calculate effective temperature by American Society of Heating and Ventilating Engineers (ASHVE). It is more accurate than the above mentioned approximation.

Effective temperatures were calculated using the basic effective temperature scale for every strategic location.

**Dry Kata Cooling Power**

In order to calculate Dry Kata Cooling Power, time taken for the alcohol level to fall between two marks inscribed on the stem and Kata factor were used [4]. Dry Kata cooling power of each strategic location were calculated using equation (1).

Dry Kata Cooling Power = $F/t$ ......(1)

Where,

F – Kata factor (526 $mcal/cm^2$)
t - Time taken for the alcohol level to fall between two marks (s)

**Wet Kata Cooling Power**

Wet Kata readings may be approximated from measurements of air velocity, u and wet bulb temperature, $t_w$ [4]. Wet Kata Cooling Power is given by equation (2).

Wet Kata Cooling Power =

$$(0.7 + u^{0.5})(36.5 - t_w) \qquad (2)$$

Where,

u - Air velocity (m/s)
$t_w$ - Wet bulb temperature (°C)

**Air Cooling Power (ACP)**

The summation of radiation, R; convection, C; and evaporation, E may be considered as a quantified measure of the ACP. Respiratory cooling, conducive heat transfers per square meter of skin surface area was assumed to be negligible [4].

The components of ACP were computed using the following relationships [4],

$$R = 4.93\,(t_s - t_r) \qquad (3)$$

$$C = 0.608P^{0.6}u^{0.6}\,(t_s - t_d) \qquad (4)$$

$E = 965\frac{P^{1.6}u^{0.6}}{(P-e)^2}(e_{sk}-e)$........................(5)

Where,

$t_s$ - Average skin temperature (°C)
$t_r$ - Average radiant temperature of the surroundings (°C) (This may approximated to the dry bulb temperature except when in close proximity to machine surfaces)
P - Barometric pressure (kPa)
u - Air velocity (m/s)
$t_d$ - Dry bulb temperature (°C)
e - Actual vapour pressure in the airstream (kPa)
$e_{sk}$ - Saturated vapour pressure at the skin temperature (kPa)
w - Skin wetness fraction

The vapour pressure was calculated using the following psychrometric equations [4],

$e_{sk} = 0.6106\ exp\left\{\frac{17.27t_s}{237.3+t_s}\right\}$ .....................(6)

$e = 0.6106\ exp\left\{\frac{17.27t_w}{237.3+t_w}\right\} - 0.000644(t_d-t_w)$ ……………………..(7)

## 3. Results

**Table 1 - Wet bulb temperature, dry bulb temperature and relative humidity**

| Location | Wet Bulb Temperature (°C) | Dry Bulb Temperature (°C) | Relative Humidity (%) |
|---|---|---|---|
| Surface | 22.5 | 31.5 | 44 |
| Bottom of Ventilation Shaft | 28.5 | 28.5 | 100 |
| 072 fm Shaft Landing | 23.5 | 28.5 | 64 |
| Top of Gabriel Shaft | 24.5 | 28.0 | 76 |
| Underground Hoist Room | 19.0 | 25.0 | 54 |
| 090 fm Shaft Landing | 24.0 | 27.5 | 74 |
| 109 fm Shaft Landing | 24.5 | 27.5 | 76 |
| Stope No. 10 | 30.0 | 30.5 | 96 |
| 126 fm Shaft Landing | 24.0 | 26.5 | 80 |
| 142 fm Shaft Landing | 24.0 | 27.0 | 77 |
| Stope No. 16 | 29.5 | 29.5 | 100 |
| Stope No. 11 | 31.0 | 31.0 | 100 |
| 170 fm Shaft Landing | 25.5 | 28.0 | 82 |
| Stope No. 7 | 31.5 | 32.0 | 98 |
| Stope No. 6 | 28.0 | 29.0 | 92 |
| Stope No. 21 | 31.0 | 31.5 | 97 |
| 205 fm Shaft Landing | 30.5 | 31.0 | 97 |
| 240 fm Shaft Landing | 27.3 | 29.5 | 83 |
| Stope No. 30 | 30.0 | 30.5 | 97 |
| Stope No. 9 | 30.5 | 31.0 | 97 |
| 275 fm Shaft Landing | 27.5 | 28.5 | 92 |
| Stope No. 5 | 32.0 | 32.0 | 100 |
| Stope No. 3 | 31.0 | 31.0 | 100 |
| Stope No. 15 | 31.3 | 31.5 | 98 |
| Stope No. 12-1 | 31.5 | 31.5 | 100 |
| Stope No. 12-2 | 33.0 | 33.0 | 100 |
| Workplace No. 4 (Drive) | 30.5 | 31.3 | 94 |

**Table 2 - Effective temperature**

| Location | Effective Temperature (°C) |
|---|---|
| Surface | 25.0 |
| Bottom of Ventilation Shaft | - |
| 072 fm Shaft Landing | 21.9 |
| Top of Gabriel Shaft | 25.8 |
| Underground Hoist Room | - |
| 090 fm Shaft Landing | 24.0 |
| 109 fm Shaft Landing | 23.8 |
| Stope No. 10 | 30.0 |
| 126 fm Shaft Landing | 22.5 |
| 142 fm Shaft Landing | 23.5 |
| Stope No. 16 | 29.5 |
| Stope No. 11 | 31.0 |
| 170 fm Shaft Landing | 25.0 |
| Stope No. 7 | 31.5 |
| Stope No. 6 | 28.3 |
| Stope No. 21 | 31.1 |
| 205 fm Shaft Landing | 29.5 |
| 240 fm Shaft Landing | 27.2 |
| Stope No. 30 | 30.1 |

| | |
|---|---|
| Stope No. 9 | 30.5 |
| 275 fm Shaft Landing | 26.6 |
| Stope No. 5 | 32.0 |
| Stope No. 3 | 31.0 |
| Stope No. 15 | 31.3 |
| Stope No. 12-1 | 31.5 |
| Stope No. 12-2 | 33.0 |
| Workplace No. 4 (Drive) | 30.7 |

**Table 3 - Dry Kata cooling power and Wet Kata cooling power**

| Location | Dry Kata Cooling Power (mcal/(cm²s)) | Wet Kata Cooling Power (mcal/(cm² s)) |
|---|---|---|
| Surface | 4.52 | 17.21 |
| Bottom of Ventilation Shaft | 13.84 | 27.24 |
| 072 fm Shaft Landing | 8.03 | 25.28 |
| Topof Gabriel Shaft | 4.13 | 8.40 |
| Underground Hoist Room | 6.34 | 12.25 |
| 090 fm Shaft Landing | 9.92 | 16.35 |
| 109 fm Shaft Landing | 5.84 | 16.89 |
| Stope No. 10 | 2.08 | 4.55 |
| 126 fm Shaft Landing | 5.42 | 19.21 |
| 142 fm Shaft Landing | 5.84 | 16.66 |
| Stope No. 16 | 2.72 | 4.90 |
| Stope No. 11 | 2.02 | 3.85 |
| 170 fm Shaft Landing | 3.67 | 14.21 |
| Stope No. 7 | 1.93 | 3.50 |
| Stope No. 6 | 3.31 | 5.95 |
| Stope No. 21 | 2.45 | 3.85 |
| 205 fm Shaft Landing | 3.59 | 8.69 |
| 240 fm Shaft Landing | 3.03 | 11.30 |
| Stope No. 30 | 2.36 | 4.55 |
| Stope No. 9 | 2.55 | 4.20 |
| 275 fm Shaft Landing | 7.79 | 11.23 |
| Stope No. 5 | 1.47 | 3.15 |
| Stope No. 3 | 2.53 | 3.85 |
| Stope No. 15 | 4.33 | 3.68 |
| Stope No. 12-1 | 2.13 | 3.50 |
| Stope No. 12-2 | 1.93 | 2.45 |
| Workplace No. 4 (Drive) | 3.17 | 4.20 |

**Table 4 - Air cooling power (ACP)**

| Location | Air Cooling Power(ACP) (W/m²) |
|---|---|
| Surface | 216.82 |
| Bottom of Ventilation Shaft | 789.65 |
| 072 fm Shaft Landing | 468.67 |
| Top of Gabriel Shaft | 26.16 |
| Underground Hoist Room | 37.48 |
| 090 fm Shaft Landing | 205.24 |
| 109 fm Shaft Landing | 237.61 |
| Stope No. 10 | 16.61 |
| 126 fm Shaft Landing | 277.17 |
| 142 fm Shaft Landing | 210.34 |
| Stope No. 16 | 20.44 |
| Stope No. 11 | 14.69 |
| 170 fm Shaft Landing | 194.75 |
| Stope No. 7 | 10.83 |
| Stope No. 6 | 22.35 |
| Stope No. 21 | 12.76 |
| 205 fm Shaft Landing | 164.81 |
| 240 fm Shaft Landing | 163.12 |
| Stope No. 30 | 16.61 |
| Stope No. 9 | 14.69 |
| 275 fm Shaft Landing | 160.21 |
| Stope No. 5 | 10.83 |
| Stope No. 3 | 14.69 |
| Stope No. 15 | 12.76 |
| Stope No. 12-1 | 12.76 |
| Stope No. 12-2 | 6.96 |
| Workplace No. 4 (Drive) | 13.73 |

## 4. Discussion

### 4.1 Wet Bulb Temperature

At every shaft landing, wet bulb temperature values measured were less than the acceptable limit as they are located in the main fresh air way.

Wet bulb temperatures are less than the acceptable limit in every stope. There being no air movement through most of the stopes.

The temperature 32°C is regarded as the upper limit of acceptable for hot mines [4]. In Bogala mine all stopes and shaft landing wet bulb temperatures are less than the upper limit except in stope No. 12-2.

A high wet bulb temperature implies the high average skin temperature, then the potential of evaporative cooling of body surface decreases rapidly.

## 4.2 Effective Temperature

As same as wet bulb temperature, conditions of shaft landings are much comfortable than the stopes. Effective temperatures of every stope are higher than the acceptable limit of standard effective temperature value.

The reason for increased effective temperature at stopes is the lack of air movement (Air velocity = 0 m/s). The parameter may properly be regarded as a comfort index rather than a heat stress index.

## 4.3 Dry Kata Cooling Power

Most of shaft landings show lower limit of comfort level except 170 fm, 205 fm and 240 fm shaft landings. The main reason is the increase in wet bulb temperature. It is observed that as the mine is getting deeper and deeper, temperatures become higher. However at the 275 fm shaft landing, Dry Kata cooling power is higher than the lower limit of comfort level as well as quite comfortable work level. Its dry and wet bulb temperatures are higher but there is considerable amount of air movement due to the booster fan.

On the other hand, at all stopes, Dry Kata cooling powers are less than the lower limit of comfort. The main reasons are lack of air movement and high temperature of wet and dry bulbs. Consequences of falling Dry Kata values below the lower limit of comfort level are profuse sweating and body surface temperature getting increased. It is observed that at all stopes Dry Kata cooling powers are higher than the extremely oppressive limit.

## 4.4 Wet Kata Cooling Power

Wet Kata cooling power at most stopes and shaft landings are less than the lower limit of comfort level. Because of air velocities in the working places and some shaft landings are generally low. In most working places, the air velocity is zero. In the regions with low air velocities, the Wet Kata cooling power is generally lower than the accepted 5 mcal/cm$^2$s.

All workers suffer from profuse sweating; rise in body temperature and heart rate in order to get some comfort especially when work is performed.

## 4.5 Air Cooling Power (ACP)

**Areas with Light Work**

Standards indicate that when performing light work, metabolic heat generation of a human is in the region of 115 W/m$^2$ [4]. Air cooling power at most of locations are higher than the metabolic heat generation of workers in those working areas except at the top of Gabriel Shaft and underground hoist chamber. Mini environments where light work is carried out have been shown to be capable of removing heat generated in the body. As the mine hoist chamber air conditioned, it provides proper comfort. Lack of air movement in Gabriel shaft top leads to less evaporation being the cause of low air cooling power.

According to previous research carried out, Air Cooling Power in underground mines should fall below 300 W/m$^2$ [4]. However in most areas in Bogala Underground, air cooling power is less than the recommended design value with light work.

**Areas with Hard Work**

As mentioned above, air velocity and wet-bulb temperatures are the most important environmental parameters affecting the air cooling power. In areas where hard work is carried out (stopes) air velocity is 0 m/s.

Therefore, the miners feel an excessive thermal sensation due to heat accumulation within the body, and a concomitant rise in body temperature, heat must be transferred from body to environment at least as fast as it is generated within the body. However those areas encountered underground do not have the capability to remove excessive heat generated within the body.

## 5. Conclusions

According to the statistical analysis conducted, wet bulb temperatures at areas with light work such as shaft landings, mine hoist chamber are below the acceptable limit of standard wet bulb temperature. But all stopes are above the accept limit of standard wet bulb temperature. Therefore, periods of continuous work in stopes should not be 8-hours at wet bulb temperature in excess of acceptable limit (28°C) [1].

According to the calculated effective temperatures, effective temperatures at shaft landings, mine hoist chamber are suitable for a 8-hour work shift. The period of continuous work in stopes should not be 8-hours at effective temperature in excess of acceptable limit (28°C) [1]. Work should be terminated in Stope No. 12 -2.

According to the analyses of Dry Kata cooling power, miners work under distinctly oppressive conditions with profuse sweating with skin flushed and wet. According to the calculated Wet Kata cooling power, miners are under extremely oppressive conditions.

According to the analyses, the average cooling power of the air in areas with light work such as shaft landings are greater than metabolic heat generation and personnel will be able to attain thermal equilibrium with the environment at that same rate of light work.

According to the analyses of air cooling power in areas with hard work, metabolic heat generation is greater than the average cooling power of the air and miners are under condition of excessive thermal sensation.

Considering all results and analysis, the periods of continuous work in all stopes should be less than 8-hours and work should be terminated in Stope No. 12 -2.

## 6. Recommendations

It is recommended that present environmental comfort conditions of Bogala Underground can be improved by installing auxiliary fans in stope which will enhance health and safety aspects of the underground working environment.

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