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Organismo Supervisor de la Inversión en Energía y Minería

Mine Ventilation Challenges in Deep Underground Mines with High Temperatures

Philip Dirige, PhD, PEng
Workplace Safety North (WSN)

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Outline

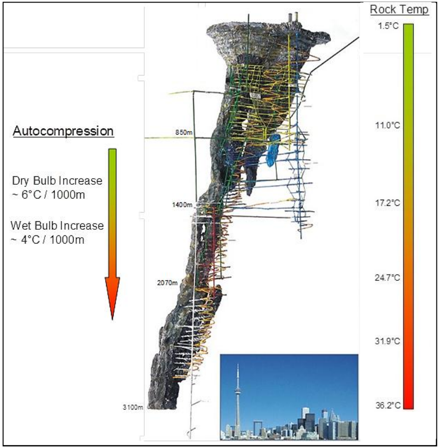
- Mining at depth challenges - focus on mine ventilation and high temperature environments
- Health and safety concerns of working in deep underground mines with high temperature environments
- Control strategies
- Control strategies applied in Ontario's underground mines with high temperature environments
- Emerging technologies for underground mine ventilation, cooling and sustainable ventilation system control
- Summary

Mining at depth challenges

- Mining at depth creates new challenges not only in extracting the ore but also in maintaining the working environment within safe working air quality and temperatures.
- Depth can affect the economics of ventilation in three ways:
  - First, as the distance that ventilation must be supplied lengthens the associated cost can increase linearly;
  - Second, depth can result in increased air loss within the system; and
  - Third, and most importantly for deep mines, is that with increasing depth, air temperatures in a mine would tend to increase.

Mining at depth challenges

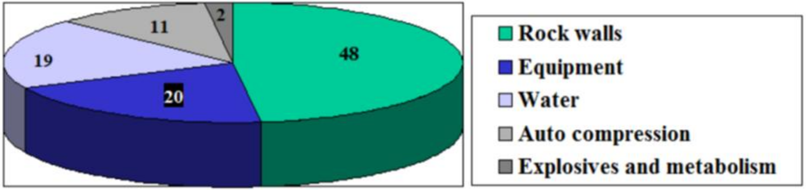
- Heat sources in underground mines includes:
  - Intake ventilation air increases in temperature as it auto-compresses on its way down the shaft.
  - Rock temperature increases with depth or “geothermal gradient”.



Primary heat source (adapted from Mining Magazine, 2007).

Mining at depth challenges

- Heat sources (continued…)
  - Also contributing to the heat load are diesel and electrical equipment, broken rock movement and, to a lesser, extent, consolidated backfilling process and oxidation of sulphide rock.



Heat sources in deep underground mines (source: Hartman, 1982).

Mining at depth challenges

- Deep mining requires significant ventilation and cooling infrastructure not only to meet regulatory requirements for air quality but also to achieve acceptable workplace temperatures.
- Ventilation and cooling system can be one of the highest costs in underground mines - contributes to about 30 to 40% of the total energy operating costs.
- Properly designed and operating mine ventilation system increases safety and can dramatically reduce costs.

Mining at depth challenges

- Nevertheless, “every mine is different - each one has unique requirements, operates in a slightly different environment and requires a customized, tailored installation for their respective operation.”
- Since each mine is unique, the method of heat control in underground mines with high temperature and prevention of workers exposure to high temperature while performing work, varies.

Safety and health concerns

- Worker’s exposure to high temperature environment while performing work can cause safety and health concerns.
- Safety concerns:
    - When a worker’s body continues to store heat while performing work, the worker can to lose concentration and has difficulty focusing on a task.
    - Increase the risk of injuries because of sweaty palms, fogged-up safety glasses, dizziness, etc.

Safety and health concerns

- Health concerns:
  - Heat stress related disorders
    - Heat rash - red cluster of pimples or small blisters
    - Heat cramps - muscle cramps, pain, spasms in the abdomen, arms, legs
    - Heat syncope (fainting) - fainting, dizziness, or light-headedness
    - Heat exhaustion - headache, nausea, dizziness, weakness, heavy sweating, elevated body temperature, etc.
    - Heat stroke - confusion, altered mental status, slurred, speech, loss of consciousness, hot, dry skin or profuse sweating, seizures, very high body temperature, etc.

Control strategies

- **Acclimatization** - to help workers adapt to working in high temperature environments.
- **Engineering controls** - controls to reduce workers' exposure to high temperature environments:
  - reduce temperature and humidity through air cooling - natural or mechanical (refrigeration) means
  - air conditioning (air-conditioned cabs and break rooms)
  - increase general ventilation and air movement - use auxiliary ventilation fans
  - exhaust hot air produced by operation or local exhaust ventilation
  - reduce physical demands of work task - through mechanical assistance

Control strategies

- **Administrative and work practice controls** - employer should:
  - assess the demands of all jobs and have monitoring and control strategies in place for high temperature environments
  - increase the frequency and length of rest breaks – program for work-rest regimen
  - provide cool drinking water close to the work area to workers to stay hydrated
  - assign additional workers or slow down the pace of work
  - ensure workers are properly acclimatization

Control strategies

- **Administrative and work practice controls** - employer should (continued…):
  - train workers to recognize factors which may increase the risk of developing a heat related illness and the signs and symptoms of heat stress
  - start a "buddy system" since workers are not likely to notice their own symptoms
  - investigate any heat-related incidents
  - ensure that trained First Aid providers are available and an emergency response plan are in place in the event of a heat related illness.

Control strategies

- **Protective clothing** - special cooling devices can protect workers in high temperature environments
  - For very high temperature environments, thermally conditioned clothing may be used
    - air, water or ice-cooled insulated clothing
    - garments with self-contained air conditioner in a backpack
    - garments with compressed air source that feeds cool air through a vortex tube
    - plastic jacket with pockets can be filled with dry ice or containers of ice

Control strategies

- **Awareness training** - workers and supervisors should be trained about the hazards of heat exposure and their prevention. Topics should include:
  - risk factors for heat-related illness
  - different types of heat-related illness, including how to recognize common signs and symptoms
  - heat-related illness prevention procedures
  - importance of drinking small quantities of water often
  - Importance of acclimatization, how it is developed, and how workplace procedures address it
  - Importance of immediately reporting signs or symptoms of heat-related illness to the supervision

Control strategies

- **Awareness training** (continued…)
  - procedures for responding to possible heat-related illness
  - procedures to follow when contacting emergency medical services
  - procedures to ensure that clear and precise directions to the work site will be provided to emergency medical services
- **Combination of various control strategies** -

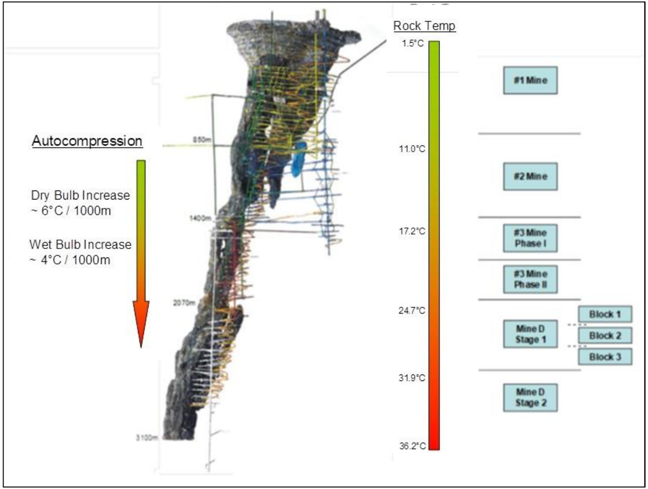
Control strategies implemented by Ontario's underground mines with high temperature environments

Case example #1 - Combined application of natural and mechanical cooling, work-rest regimen and others

- The predominant heat load at this deep underground mine is due to the effects of auto-compression and rock temperature (geothermal gradient).
- To a lesser extent, diesel and electrical equipment, and broken rock movement also all contribute some heat load.
- Minor heat load comes from backfilling (paste fill) process and sulphide rock oxidation.

Case example #1

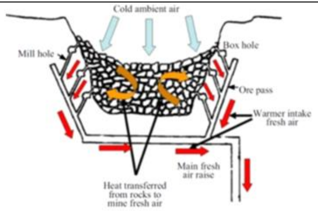
- Heat load source:
  - Auto-compression accounts for an increase of about 6^{o}C (dry bulb) and about 4^{o}C (wet bulb) for every 1,000 m of depth.
  - Geothermal gradient increase averages 11^{o}C for every 1,000 m of depth.



Long-section showing the different mining areas and primary heat sources (source: Mining Magazine, 2007).

Natural refrigeration system or “Cold Stope”

- Used primarily to cool #3 Mine, Phase I and II fresh air supply.
- Initial airflow was at 150 m³/s (318,000 cfm).
- Cold stope expanded further to 90 m³/s (191,000 cfm) of air.
- The “Expanded Cold Stope” air was used to complement the mechanically refrigerated airflow for the lower portion of the mine - 25% of total mine air intake.



#2 Mine

#3 Mine Phase I
(~1400-1750 m Level)

#3 Mine Phase II
(~1750-2050 m Level)

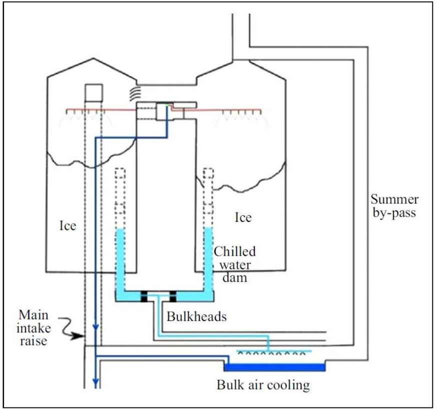
Mine D Stage 1
Blocks 1, 2 and 3
(~2050-2550 m Level)

Mine D Stage 2
(~2550-3000 m Level)

Natural refrigeration system or "Cold Stope"

Surface Ventilation Infrastructure
(source: Mining Magazine, 2007).

Natural refrigeration system or "Cold Stope"



Schematic diagram of the ice stope, with summer by-pass (source: Trapani et al., 2016).

Cold stope drawpoint access (source: Mining Magazine, 2007 and D. Counter, 2014).

Mechanical refrigeration system

- Refrigeration plant - utilizes ammonia as the refrigerant; and Bulk Air Cooler (BAC).
- For the heat loads at the lower portion of the mine.

Refrigeration plant interior (source: Mining Magazine, 2007).

Refrigeration plant exterior (source: Mining Magazine, 2007).

Mechanical refrigeration system

Exterior view of Bulk Air Cooler (source: Mining Magazine, 2007).

Mechanical refrigeration system

- Provides cooling for Mine D and a portion of #3 Mine - Phase II.

#2 Mine

#3 Mine Phase I
(~1400-1750 m Level)

#3 Mine Phase II
(~1750-2050 m Level)

Mine D Stage 1
Blocks 1, 2 and 3
(~2050-2550 m Level)

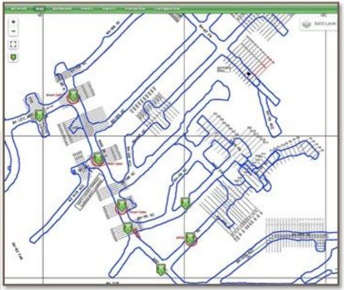
Mine D Stage 2
(~2550-3000 m Level)

Fully automated ventilation system

- As a result of the cooling system during summer months and heating during winter months, energy consumption increased, hence ventilation cost.
  - Energy is the 2nd largest cost – can range from 25% to 40% of the total energy requirements of the mine.
  - 225 ventilation fans using 25,000 HP, producing 900 m^3/s (1,900,00 cfm) of fresh air
- A new fully automated ventilation-on-demand system was implemented.
  - Equipment and personnel location tracking, airflow, gas, temperature, and proximity warning

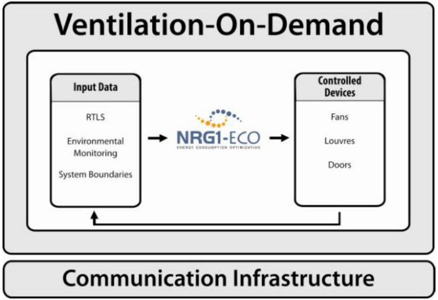
Fully automated ventilation system

- Fully automated ventilation-on-demand (VOD) system



Fully automated ventilation system

- Personnel and equipment tracking
  - WiFi based RFID tags for VOD control via
  - Coverage - ramps, level access, main drifts and shops



Ventilation-On-Demand

Input Data

RTLS

Environmental Monitoring

System Boundaries

→ NRG1-ECO ENERGY CONSUMPTION OPTIMIZATION →

Controlled Devices

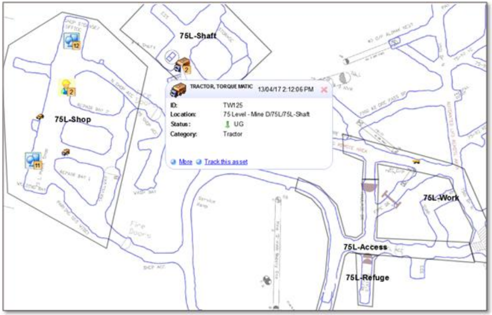
Fans

Louvres

Doors

Communication Infrastructure

VOD System Components (source: Allen and Tran, 2011).



TRACTOR, TORQUE MATIC 13/04/17 2:12:06 PM

ID: TW125
Location: 75 Level - Mine D/75L/75L-Shaft
Status: UG
Category: Tractor

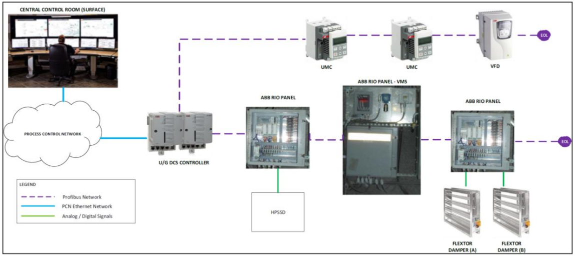
Fully automated ventilation system

- Safety benefits
  - Accountability for all employees location and rapid accountability during emergencies
  - Live tracking
  - Location of critical emergency equipment
  - Combined gas, airflow and temperature monitoring

Fully automated ventilation system

- Variable frequency drive (VFD) technology for fan motor control for improved operating performance and system control, reduction in current peak demand, and optimized power usage.

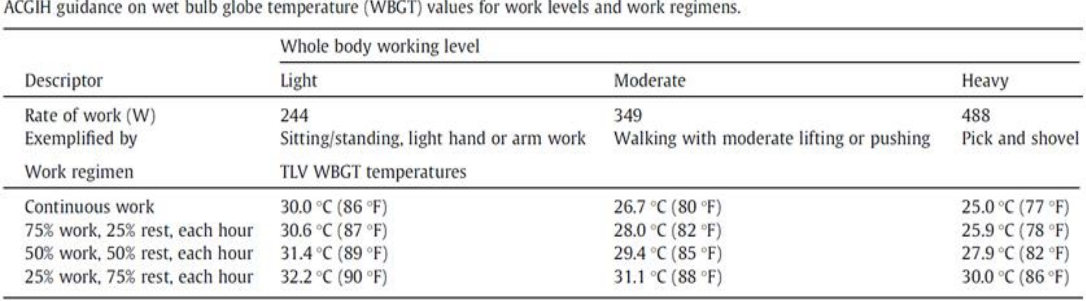
- Ventilation where it is needed
  - Tailored schedule
  - Flushing inactive headings
  - Optimized flows



Process control network schematic (source: CIM Memo, Flores and Acuna, 2016).

Work-rest regimen

- When individual and combined surface and sub-surface cooling system cannot maintain the wet bulb global temperature (WBGT) below the work-rest temperature regimen threshold - a work-rest schedule is used.



ACGIH guidance on wet bulb globe temperature (WBGT) values for work levels and work regimens.

	Whole body working level		
Descriptor	Light	Moderate	Heavy
Rate of work (W)	244	349	488
Exemplified by	Sitting/standing, light hand or arm work	Walking with moderate lifting or pushing	Pick and shovel
Work regimen	TLV WBGT temperatures		
Continuous work	30.0 °C (86 °F)	26.7 °C (80 °F)	25.0 °C (77 °F)
75% work, 25% rest, each hour	30.6 °C (87 °F)	28.0 °C (82 °F)	25.9 °C (78 °F)
50% work, 50% rest, each hour	31.4 °C (89 °F)	29.4 °C (85 °F)	27.9 °C (82 °F)
25% work, 75% rest, each hour	32.2 °C (90 °F)	31.1 °C (88 °F)	30.0 °C (86 °F)

Other methods

- Air conditioned cabs for equipment
- Remote and autonomous operation of mucking and other equipment - removing the worker from high temperature workplaces.

Case example #2 - Diesel to Electric (battery-electric) - reducing underground ventilation and cooling requirements

- Facts - deep underground mines require significant ventilation and cooling infrastructure to:
  - Meet regulatory requirements for air quality - in jurisdictions where the ventilation volume is regulated by the operating power of the diesel fleet; and
  - Achieve sufficient air to limit contaminants to within safe working levels and acceptable workplace temperatures with the higher rock temperatures and increased auto-compression with depth.

“All-electric” equipment

- Advantages to battery-electric equipment include:
  - Reduced heat load from the mobile equipment fleet - significantly lower heat generation can be achieved (about 35% of an equivalent diesel)
  - Elimination of diesel particulate matter (DPM) from the workplace
  - Elimination vehicle produced NOX and other gases from the workplace
  - Reduced noise
  - Potential reduction in maintenance costs

Ventilation and cooling plant design

- The ventilation design is determined by the project and not governed by regulatory requirements.
- Workplace temperatures emerged as a critical factor in the design as the mine gets deeper in order to maintain the health and safety of the workers as well as productivity in the mine.
- Auto-compression and rock temperature represents a significant heat load at depth.

Ventilation and cooling plant design

- The ventilation design was based on the following parameters:
  - Combined diesel power rating - 5,000 kW
  - Maximum workplace WBGT - 28°
  - Diesel engine ventilation requirement - 0.06 m^3/s/kW power of engine

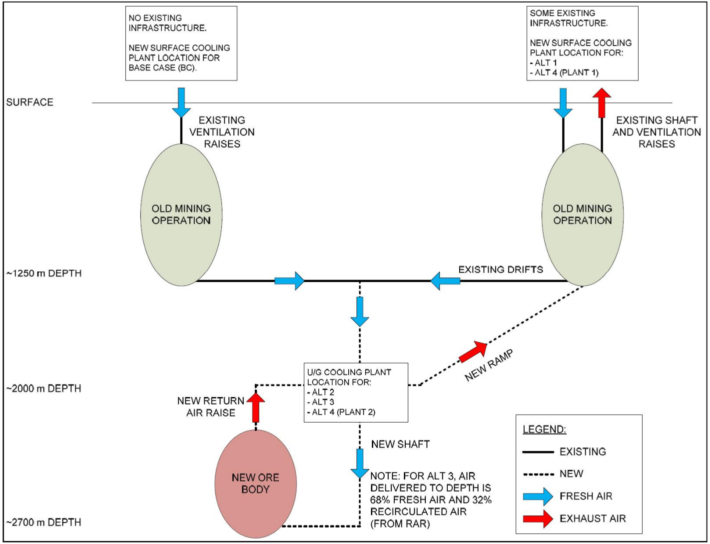
Diesel vs Battery Ventilation System Comparison (source: Deziel, 2016)

Parameter	**Diesel**	**Battery**
Ventilation Air (m^3/s)	300	180
Fan Power (MW_E)	10.9	6.1
Underground Cooling (MW_R)	25.4	13.3
Shaft Diameters (m)	6.5	5.0
Return Air Raise Diameter (m)	5.0	3.8

Ventilation and cooling plant design - options

- Design options considered:
  - Base Case (BC): Surface cooling and intake at the old workings with no surface infrastructure and exhausting through the nearby existing mine.
  - Alternative 1 (ALT 1): Surface cooling, intake and exhausting at the nearby existing mine
  - Alternative 2 (ALT 2): Underground cooling without recirculation, intake and exhaust through the nearby existing mine.
  - Alternative 3 (ALT 3): Underground cooling with recirculation, intake and exhaust through the nearby existing mine.
  - Alternative 4 (ALT 4): Surface cooling at the existing nearby mine and underground cooling without recirculation, make-up and exhaust through the nearby existing mine (once through).

Ventilation and cooling plant design



Ventilation and cooling design configurations (source: Harris et al., 2017).

Ventilation and cooling plant design - result

- Alternative 2 configuration represented both the lowest capital and operating costs of the options studied.

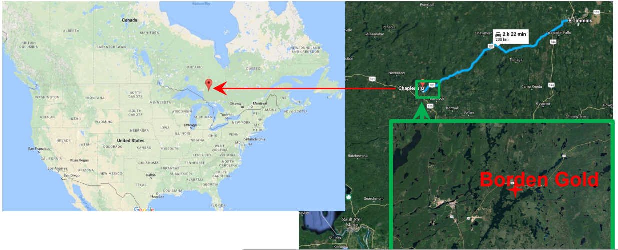
- For other mine configurations, it is possible that further cost savings could be achieved using a controlled air recirculation scheme.

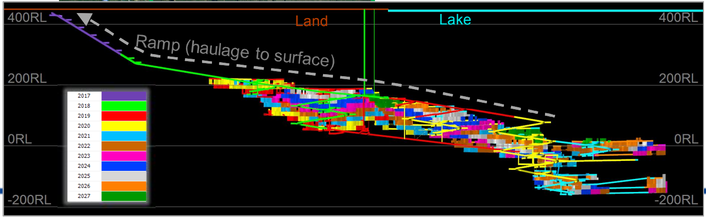
- The reduced airflows required to ventilate a battery powered fleet decrease the amount of cooling that can be delivered to the working areas of the mine.

- Refrigeration plant located on surface would require increased ventilation volumes to achieve the desired cooling as the air temperature increases with depth generally due to auto-compression.

Emerging technology - technologically feasible all-electric underground operation

- The Borden Mine is developed with a low carbon footprint and an “all- electric” mine equipment.





Source: Calnan and Young, 2017

Why electric mine?

- Sustainability - safety, environment and community
- Significantly lower heat generation ~ 35% of an equivalent diesel engine
- Economic - energy and cost reduction
- “Greener” - lows carbon footprint
- Improved social acceptance
- Technologically feasible

Engineering trade-off: Diesel versus electric

- Challenge to establish engineering criteria
  - Ventilation requirements (not direct as with diesel)
  - No empirical data for new equipment
    - Power load estimation
    - Productivity
    - Maintenance
    - Safety requirements

Ventilation Criteria for Electric

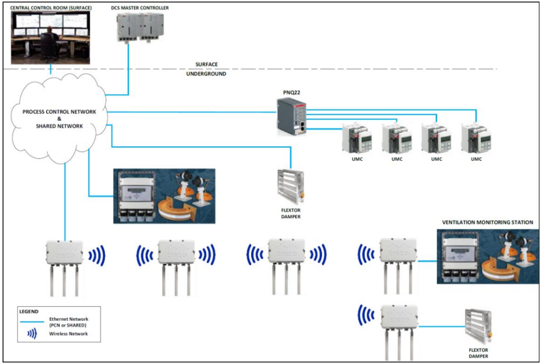
What determines requirement?

a. No DPM/NOx
b. No heat issues from estimation
c. Dust – min./max. air velocities
d. Other considerations?
e. Benchmark vent. regulations for non-diesel (interprovincial, international)

- 0.25 m/s under usual operation
- Sized larger for blast clearing & VOD
- Planned for VOD on contaminants

Emerging technologies - Automated or “Smart” ventilation system

- WiFi based ability to monitor mine personnel, mine environment and control ventilation equipment over Ethernet

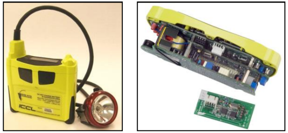


End state of monitoring and control hardware (source: CIM Memo, Flores and Acuna, 2016).

Different types of environmental monitoring sensors (source: International Mining, 2011).

Emerging technologies - Automated or “Smart” ventilation system

- Real-time monitoring data and control system for optimized delivery of air where, when and how much.
- Remotely measure the airflow rate and direction, blast gas concentrations and wet bulb temperature to ensure that the mine workers are safe.
- Automated ventilation control system can result in a significant energy savings - a mine with the system was able to achieve approximately $2 million per year of savings.

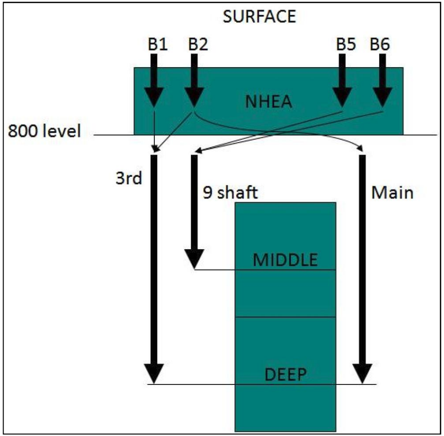


New ventilation control system to save Glencore – Kidd Mine millions every year.

Jan 21 Posted by Super User in News

Other methods

- Natural heat exchange area (NHEA) - a method of conditioning the incoming air from surface that goes into the fresh air system.



Fresh airflow distribution system (source: Acuna et al., 2010a).

Summary

- In deep and hot mines, ventilation is required to cool the workplace for miners.
- The primary sources of heat in underground hard-rock mines are virgin-rock temperature, machinery, auto compression and fissure water, while other to a lesser extent human body heat, consolidated backfill and blasting.
- Mine-ventilation system is a real-time process that requires excellent balancing of climate controls and the dilution of exhaust gases and hazardous substances to ensure a safe working environment for workers.

Summary (continued…)

- The primary heat load sources should be determined to be able to design appropriate cooling process.
- “Every mine is different - each one has unique requirements, operates in a different environment and requires a customized, tailored cooling process for their respective operation.”
- For a workplace with high temperature environment that cannot be controlled by available cooling process, a heat stress control plan (work-rest regimen) should be developed in accordance with the American Conference of Governmental Industrial Hygienists (ACGIH) guidance.

Acknowledgement

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Questions