22nd ANNUAL MDEC CONFERENCE

Toronto Airport Hilton Hotel, Canada

October 4 – 6, 2016

MDEC DIESEL WORKSHOP

Mine Ventilation – Diesel & Alternative Equipment

PRESENTED BY

Brian Prosser (Mine Ventilation Services)
Cheryl Allen (Vale)
Jozef Stachulak (MIRARCO)
Michelle Levesque (Natural Resources Canada)

COORDINATED BY

David Young (Natural Resources Canada)

OCTOBER 4, 2016

MDEC Diesel Workshop

Mine Ventilation – Diesel & Alternative Equipment

Hilton Toronto Airport Hilton & Suites
Ontario, Canada

Tuesday, October 4, 2016

07:30 – 08:30 Breakfast and registration

08:30 – 12:00 Welcome – David Young, Co-chair MDEC Conference

Basic Principles – Design process
(Page 1-36)
Brian Prosser, PE, Principal Consultant, Mine Ventilation Services

12:00 – 13:00 Lunch

13:00 – 16:00 Case Study 1- Impact of alternative mobile equipment power sources
: **(Page 37-61)**
Cheryl Allen, P.Eng, Principal Engineer – Ventilation, Vale, and

Jozef Stachulak Ph.D; P.Eng, Manager, Strategic Ventilation & Diesel Research, MIRARCO Mining Innovation

Case Study 2 – Manage energy in auxiliary mine ventilation systems
(Page 62-79)
: Michelle Levesque, Senior Engineer in Mine/Mill Energy Efficiency and Underground Mine Environment, CanmetMINING, Natural Resources Canada

MDEC – 2016
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Ventilation Design Process
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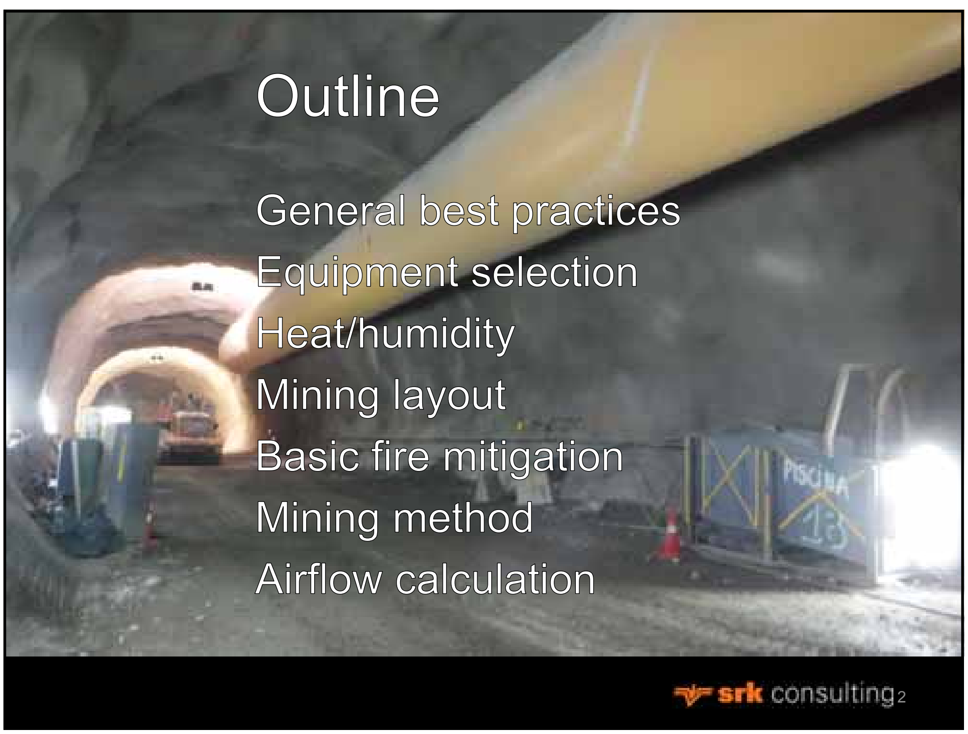
Outline
General best practices
Equipment selection
Heat/humidity
Mining layout
Basic fire mitigation
Mining method
Airflow calculation
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General Best Practices

Why do we ventilate mines?

The objective of underground ventilation is to provide airflows in sufficient quantity and quality to dilute contaminants to safe concentrations in all parts of the facility where personnel are required to work or travel. (McPherson)

We design ventilation systems to ensure health and safety, not just to meet minimum legislative requirements.

General Best Practices

What is "best" in a hot mine may not be "best" in a cold mine, what is "best" in potash may not be "best" in a stope mine, etc.

- Design and operating procedures and practices that are described as being correct and effective.
- Best practices are not the end all – be all of design development, but represent a good place to start.
- Each mine, mining method, location, and ore type requires different approaches and consideration.
- "Best Practices" will change from person to person, and/or place to place.

Best Practices and Regulations

Regulations should follow along the lines of “best practices” however, this is not always the case.

Meeting the regulatory requirements should represent a “minimum” design.

Following best practices will often create a design that is more robust than the regulatory requirements.

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General Examples

Air supplied to a working area can come from a haulage ramp (legally ok)

- *Best practice would be to supply air from an alternate source (risk avoidance, air quality)*

Emergency egress can be through an exhaust route (legally ok)

- *Best practice would be to egress through fresh air*

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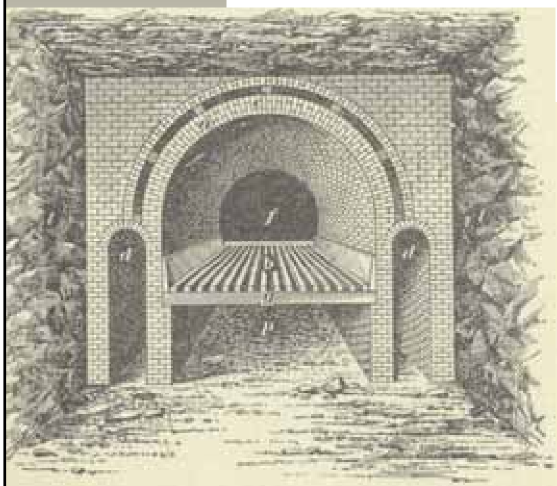
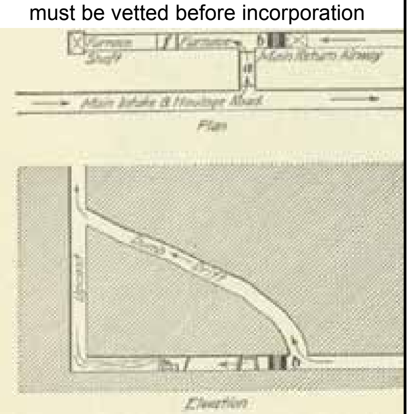
Best Practices Will Change Over Time

- What was "state of the art" in the past will be superseded as new technology is developed.
- But as with any new technology it must be vetted before incorporation





ICS Reference Library, Volume 145, 1907, Fig 15 & 16

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Literature

This is a starting point, not an exhaustive list

Its always good to start with what other people have already done;

- Ventilation Symposium
- Published/Peer Reviewed Papers and Designs
- Well Ventilated Operating Mines (Similar Designs)
- NIOSH
  - *Chekan*
- Mine Design Wiki
  - *Hardcastle and Kocsis*
- Mine Ventilation Australia
  - *Brake*
- Mine Ventilation Services/SRK
  - *Prosser & Wallace*
- HSE Occupational Health in Mines Committee
  - *Gilmour et al.*
- Pittsburgh Safety and Health Technology Center
  - *Schultz*
- Minerals, Metals and Materials Technology Centre
  - *Kurnia and Mujumdar*

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Realize that mitigation strategies for individual hazards will provide a load on the ventilation system

NIOSH - Chekan

Dust Control in Metal/Nonmetal Underground Mining

Crushers and Truck Dumps

- Isolate dust sources from ventilation system
- Airflow to direct dust directly to the exhaust
- Localized Fans installed as close to the dump as possible
- Operators booth should be equipped with filtration systems

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Redundant systems will increase the airflow requirement above what is required for simple overall dilution

Mine Ventilation Australia - *Brake*

- One pass ventilation system with dedicated fresh air supply to each mining area.
- Haulage ramps developed as neutral intake.

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General Comments

- Although with enough design and engineering almost anything can be justified.
- What happens if “engineered” solutions fail?
- How can the ventilation systems be designed to promote success?
- What basic design parameters can be adjusted to provide a basic level of coverage?
- These would be considered “best practices”.

Design Criteria
Equipment Airflow Requirement

Airflow quantity evaluation is a multi-faceted problem, simple justification by a single parameter is not sufficient

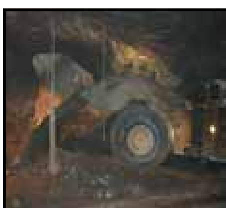
Airflow requirement cannot be based on a single parameter. Multiple parameters need to be met:

- Gas Dilution
- Diesel Particulate
- Heat
- Minimum Velocity

Examples;
0.08 m^3/s per kW for general use in the US
0.06 m^3/s per kW for general use in Ontario or Chile
0.05 m^3/s per kW for general use in Western Australia

Design Criteria - Diesel

- For general ventilation planning a fixed value of cfm/bhp (m^3/s per kW) provides for basic airflow allocations and different engine manufacturers/emissions controls.
- Dilution values for specific equipment based on NIOSH and CANMET testing is also useful as a minimum but may restrict the versatility of the system.



Design Criteria - Diesel

- Lower values can be used based on tested dilution factors but they must be balanced with other parameters (minimum air velocity, and heat).
- Remember that not all equipment in use in the mine will be maintained in an "as new" manner.
- Availability of ultra low sulfur fuel may not be sufficient.

Design Criteria – Air Velocity

Minimum Velocity
- Dust, safety, heat

Maximum Velocity
- Dust, visibility, safety, comfort

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Design Criteria – Air Velocity

Minimum
- Perceptible movement as a minimum for general areas.
- Perceptible movement is generally between 60 ft/min and 80 ft/min. However, for planning purposes we suggest a slightly higher value 100 ft/min.
- Entrainment of dust, 1.5 m/s to 2.5 m/s.

(Vutukuri)

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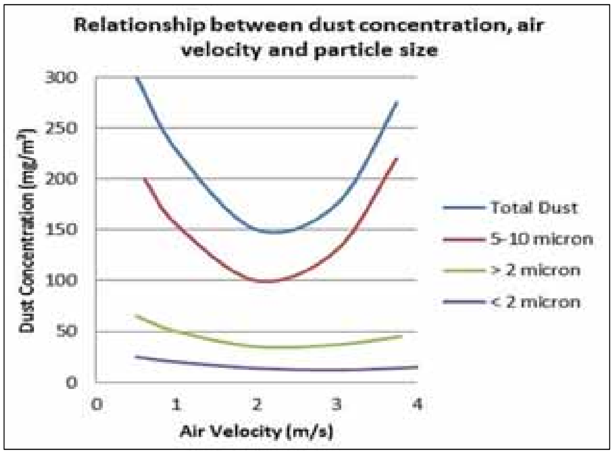
Design Criteria – Air Velocity



(Vutukuri)

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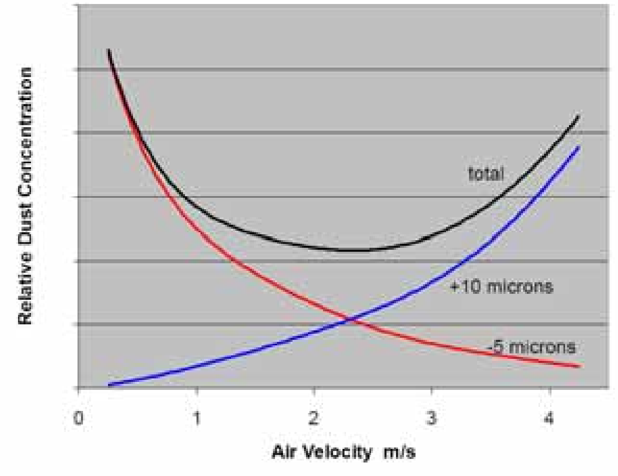
Design Criteria – Air Velocity



After McPherson and Vutukuri

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Design Criteria – Air Velocity

Maximum

- Visibility – dust
- Comfort (not more than 4 m/s)
- Economics (should be evaluated for each region location)
- Safety – Skip/Cage Stability (10 m/s rope guides, 20 m/s for engineered systems with high capital costs)
- Water Blanketing (not between 7 m/s to 12 m/s)

Area	Velocity (m/s)
Working faces	4
Conveyor drifts	5
Main haulage routes	6
Smooth lined main airways	8
Hoisting shafts	10
Ventilation shafts	20

(McPherson)

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Conveyors generally move ore out of the mine, which means that the air source for the conveyor is additive to the overall ventilation load, unless exhaust air is used

Design Criteria – Air Velocity

Conveyors

- Airflow should move in the same direction as the conveyor belt (homotropal).
- Antitropal flow can be achieved but it should be designed to minimize dust (water, moisture content, covered conveyor, dedicated conveyor exhaust).
- As we move away from homotropal flow additional features must be designed into the system.

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Design Criteria - Heat

Just because a mine is not “deep” does not mean heat will not be a factor. Influx of hot/warm water, surface conditions, equipment load, and airflow quantity all contribute to heating issues

- Flow through ventilation system
- Fans should be exhausting, heat loads should be placed near exhaust routes, fresh air routs should be clear of fixed equipment.

Design Criteria - Heat

- The ACGIH (among others) chooses to utilize wet-bulb globe temperature (WBGT) as the basis for establishing TLVs, or other action levels based upon heat stress.
- In addition to the ACGIH, WBGT has been recommended for use as an index of heat stress by NIOSH (NIOSH, 1986) and is also specified in the International Standard (ISO, 1982).
- However useful WBGT is for evaluating conditions in existing mining environments it is not easy to measure. This makes it necessary to rely on more traditional (if less telling) indicators of climate (e.g., wet-bulb temperature, dry-bulb temperature, humidity, effective temperature) (McPherson, 2009).
- Cognitive processing and the ability to perform even routine manual tasks is also impaired by heat stress under some environmental conditions (Hardcastle, 2012).

Design Criteria - Heat

TLV and Action Limit for Heat Stress Exposure (ACGIH, 2007).

Allocation of Work in a Cycle of Work and Recovery	TLV (WBGT values in °C) Light	Moderate	Heavy	Very Heavy	Action Limit (WBGT values in °C) Light	Moderate	Heavy	Very Heavy
75% to 100%	31.0	28.0	N/A	N/A	28.0	25.0	N/A	N/A
50% to 75%	31.0	29.0	27.5	N/A	28.5	26.0	24	N/A
25% to 50%	32.0	30.0	29.0	28.0	29.5	27.0	25.5	24.5
0% to 25%	32.5	31.5	30.5	30	30.0	29.0	28.0	27.0

- Some companies use a reject wet bulb temperature of 26.5°C
- Some companies use a reject wet bulb temperature of 28°C

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Mine Layout - Auxiliary Ventilation Systems

Fundamentally, subsurface ventilation systems are designed to remove the contaminants of dust, gases and heat from the underground environment. This is accomplished by dilution of the contaminant(s) in question, removal from the affected area, or both.

Dilution of dust and gaseous contaminants involves a relatively simple calculation directly proportional to the relative volumes of air and the contaminant.

The removal on contaminants is dependent upon the velocity of the ventilating airstream, along with the fundamental design of the ventilation infrastructure, e.g. the location of intake/return airways, raises, etc.

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Mine Layout - Auxiliary Ventilation Systems

The choice of a blowing (forcing) system of ventilation versus an exhausting system will also have an impact not only on the ventilation system design, but also may impact the tunnel design itself (such as the locations of various connections or fixed facilities, or the need and location(s) of ventilation controls such as doors and regulators.

Each of these types of systems has its own properties and thus its own benefits and drawbacks, they can be more suited to certain types of designs than others.

This process is often iterative; a design is selected, its benefits and consequences examined, and then if necessary an alternative is implemented.

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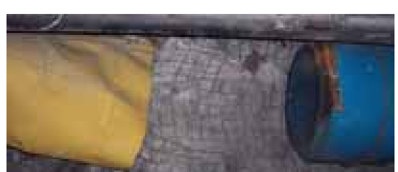
Mine Layout - Auxiliary Ventilation Systems

Long or extended auxiliary ventilation systems often require "booster" fans to be installed.

- The installation of these fans needs to be "engineered".
- Often gaps are left between the discharge of the duct and the next fan. (not a best practice).
- Sometimes the duct will discharge into a closed alcove where the booster will draw air from (not a best practice)
- Upstream duct and booster fan need to be joined.
- Hardline duct, pressure relief dampers, proper fan spacing can all be used.



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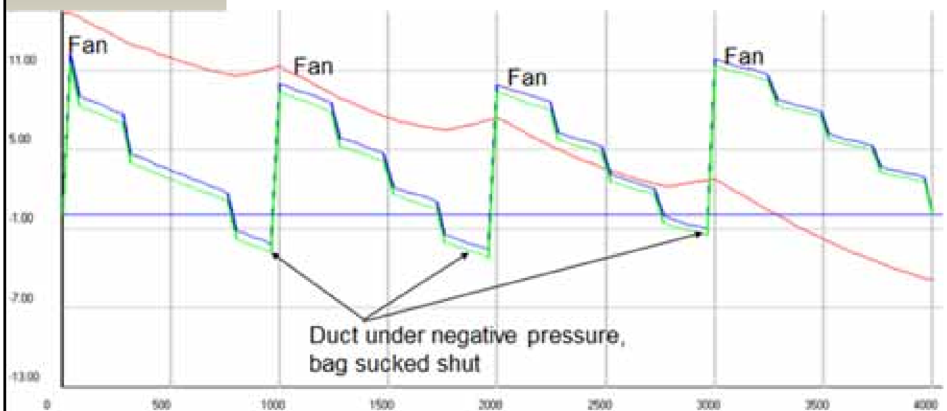
Mine Layout - Auxiliary Ventilation Systems

Planning for Duct Booster Fans



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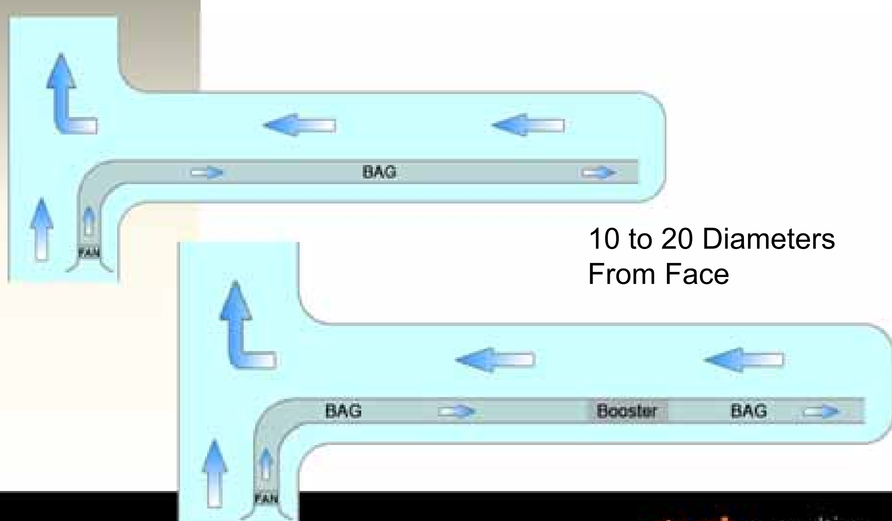
Mine Layout - Auxiliary Ventilation Systems



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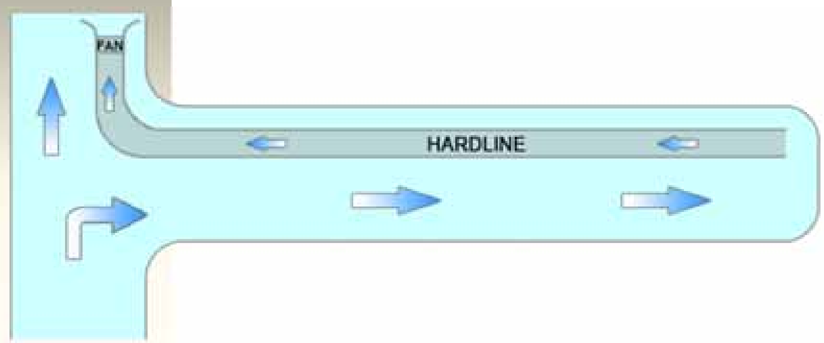
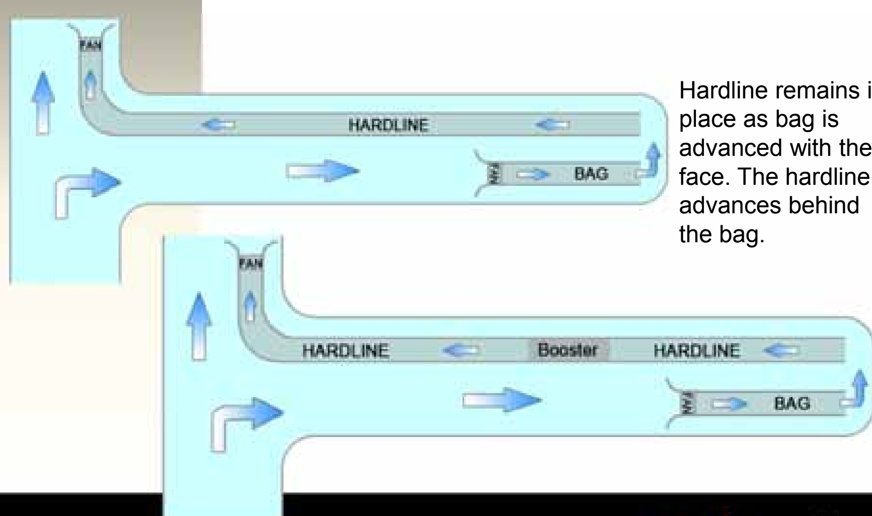
Mine Layout - Auxiliary Ventilation Systems

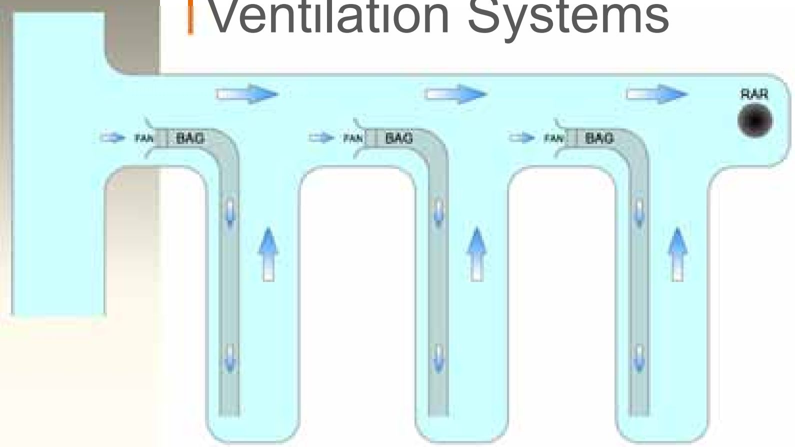


Mine Layout - Auxiliary Ventilation Systems



Hardline remains in place as bag is advanced with the face. The hardline advances behind the bag.

Mine Layout - Auxiliary Ventilation Systems



- Each mining area receives adequate airflow, but the air supplied to the downstream face will receive partially contaminated air.
- Airflow gets progressively more contaminated the further along the level it travels.

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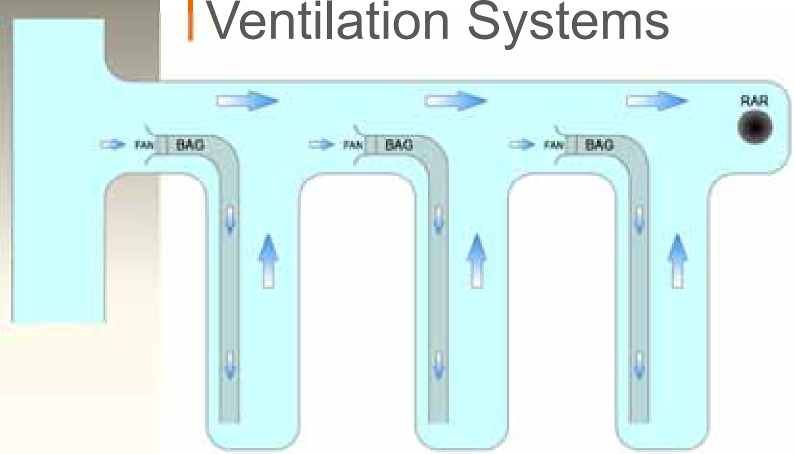
Mine Layout - Auxiliary Ventilation Systems



- Fresh air is supplied directly to the mining areas
- Minimum airflow quantities and velocities need to be examined for the main level access
- Duct integrity needs to be managed closely

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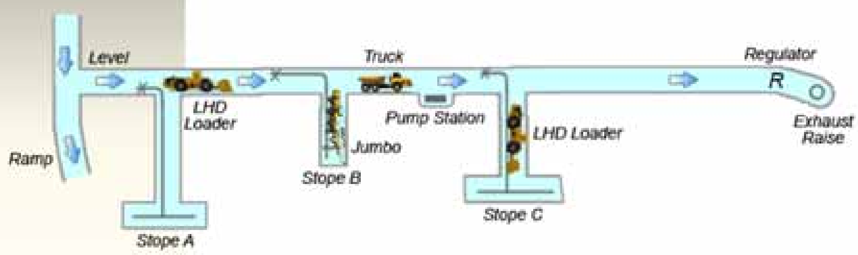
Level - Truck Loading



Loading trucks on the level greatly increase the airflow requirement on the level and diminishes the air quality.

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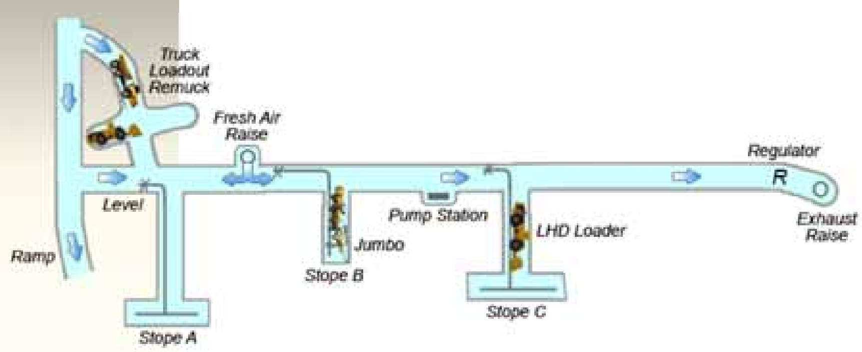
Level - Truck Loading



Loading trucks in the ramp or in a ramp “bypass” keeps the truck airflow requirement off the level.

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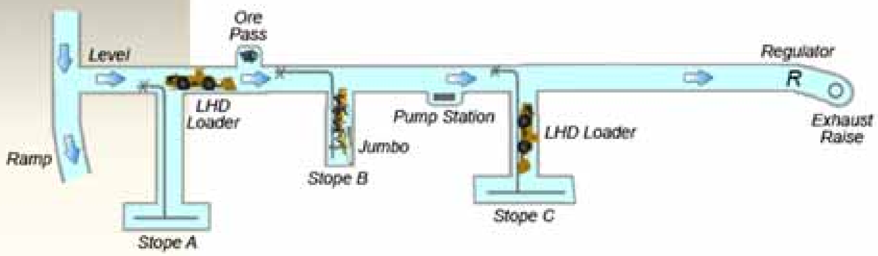
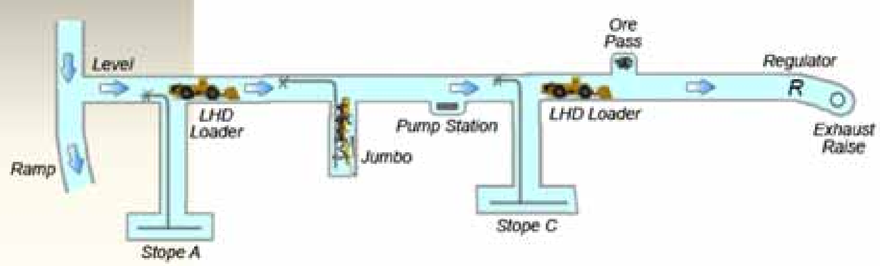
Level - Ore Passes



If an ore pass is located in the airstream feeding the stopes then there will be an increased risk of dust contamination.

Level - Ore Passes



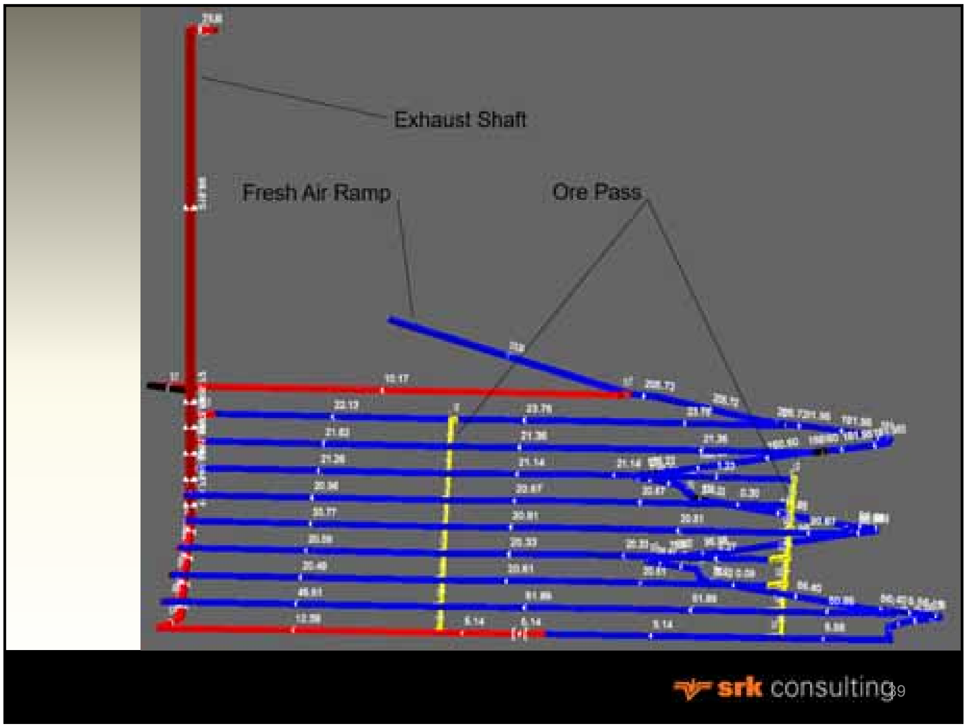
Ore passes should be located such that their impact on the level can be minimized.

Ore Pass Issues

- Ore passes are frequently used in multi-level metal mines.
- Much of the time the ore passes are modeled with either a high resistance or are omitted from the model.
- Is this really the case?
- What happens when an ore pass is opened?

Ore Pass Issues - Continued

- Short circuiting of air from one level to the next.
- Injection of dusty air onto the level.
- Uncontrolled disruption in the ventilation system.
- Improper location of Ore Pass accesses


Exhaust Shaft
Fresh Air Ramp
Ore Pass
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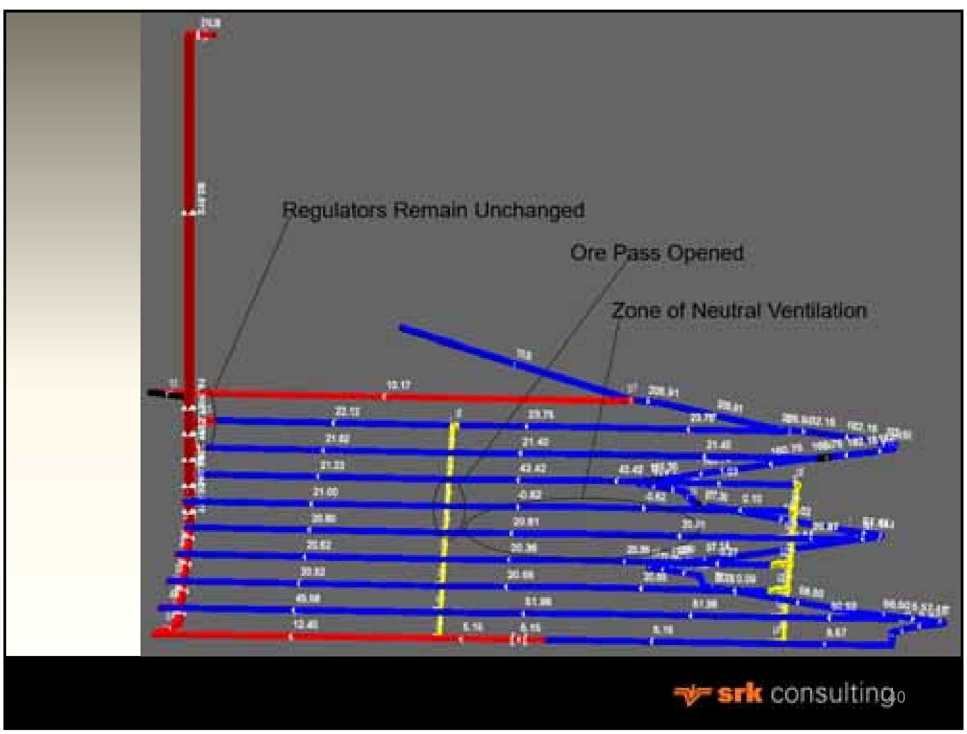
Regulators Remain Unchanged
Ore Pass Opened
Zone of Neutral Ventilation
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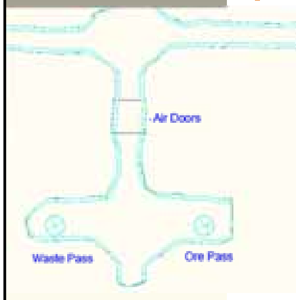
40

Ore Pass Control



Isolated “Alcoves”

LHD Plugs/ Covers

Conveyor Belt Flaps

Automatic Lifters

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Ore Pass Modeling - Strategy

- Ensure the control technique in the model matches the technique to be used in the mine.
- Conduct a sensitivity analysis to determine the effect of the leakage route.

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Ventilation System Design with Respect to Minimization of DPM

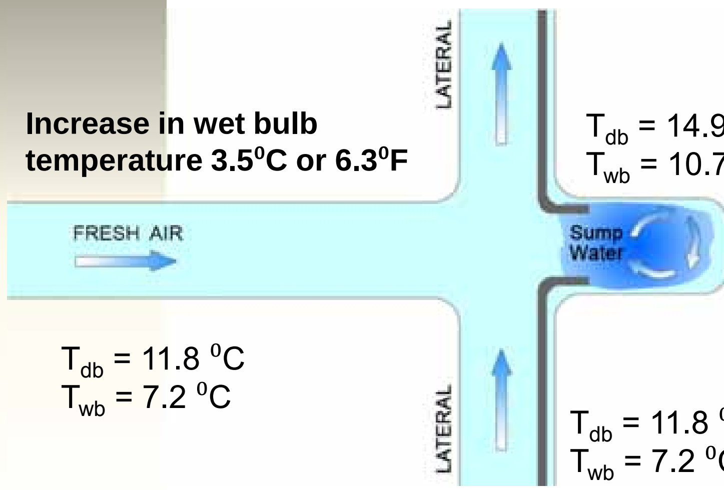
- One pass ventilation circuit minimizes DPM concentrations.
- Full airflow allocation required for dilution – previous 100% (dilution for largest piece of equipment), 75% (second largest), 50% (all other equipment) rule should not be used.

Ventilation Design with Respect to Minimization of Heat Loads

- Differences between electric equipment and diesel equipment.
- Forcing and exhausting duct systems, temperature increases across auxiliary fans.
- Keep auxiliary duct systems to a minimum and keep duct lengths short.
- Keep water away from the air splits.

Consequences of Not Covering Sumps – Real Life Example

Increase in wet bulb temperature 3.5⁰C or 6.3⁰F



T_{db} = 14.9 ^{0}C
T_{wb} = 10.7 ^{0}C

T_{db} = 11.8 ^{0}C
T_{wb} = 7.2 ^{0}C

T_{db} = 11.8 ^{0}C
T_{wb} = 7.2 ^{0}C

Shop, Fuel Bay, and Garage Ventilation

- Establish Minimum Velocities
- Use air changes for airflow evaluation
- Air change rationale
- Discharge or exhaust location
- Isolation doors
- Fire suppression

Shop, Fuel Bay, and Garage Ventilation

- Example Air Change Rates
- Assumptions are built into rates like welding fume hoods, hookups for diesel exhaust extraction at tailpipe.

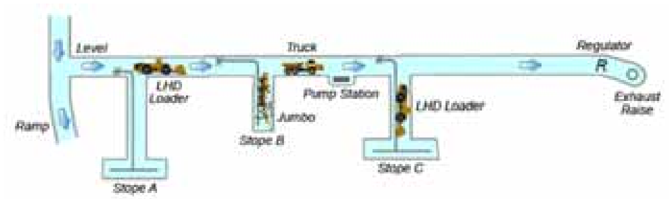
Location	Minutes per Air Change
Training Room	6
Offices	5
Warehouse Areas	7
Electrical Room	6
Service Bay	3
Sanitary Facilities	5
Lunchroom	5

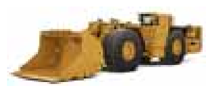
Airflow Calculation Based on Air Change Rates

Location	Area Dimensions (m)			Minutes per Air Change	Volume (m^3)	Airflow (m^3/s)	Number of Areas	Total (m^3/s)
Office	5	5	60	5	1500	5.0	3	**15.0**
Training	5	5	60	6	1500	4.2	2	**8.4**
Warehouse	7	6	80	7	3360	8.0	2	**16.0**
Service Bay	7	6	40	3	1680	9.3	6	**18.6**
Total airflow								**58.0**

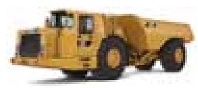
- Contaminants directed to exhaust at point of origin
- Fans can be used to provide localized flow direction
- Fuel Bays and lubricant storage areas should be directly exhausted (isolation or fire doors)

Airflow Calculation - Diesel





CAT R1700 LHD Loader



CAT AD30 Truck

CAT R1700 263 kW x 2 x 0.06 m^3/s/kW = 31.6 m^3/s

CAT AD30 305 kW x 1 x 0.06 m^3/s/kW = 18.3 m^3/s

Total Airflow for Level = <u>50 m^3/s</u>

Airflow Calculation – NIOSH/MSHA

CAT R1700 LHD Loader

CAT AD30 Truck

MSHA Web Site Approved Equipment List

				Dilution	**PI**
7E-B018	CATERPILLAR	3406E ATAAC	400 @ 2100	18500	13000

Truck – Diesel Dilution = 18,500 cfm (8.73 m^3/s), DPM 5x13,000
= 65000 cfm (30.68 m^3/s)

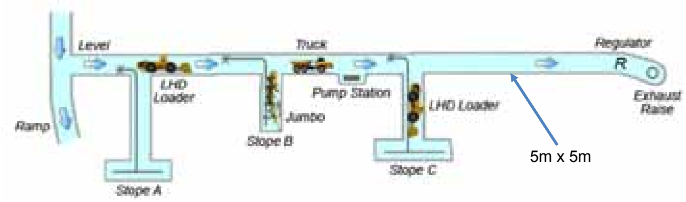
				Dilution	**PI**
7E-B018	CATERPILLAR	3406E ATAAC	360 @ 2100	17000	14000

LHD – Diesel Dilution = 17,000 cfm (8.02 m^3/s), DPM 5x14,000
= 70000 cfm (33.04 m^3/s)

Total Level Airflow (Diesel Dilution)– 8.73+8.02+8.02 = <u>24.77 m^3/s</u>

Total Level Airflow (DPM Dilution to 160)– 30.68+33.04+33.04 = <u>96.76 m^3/s</u>

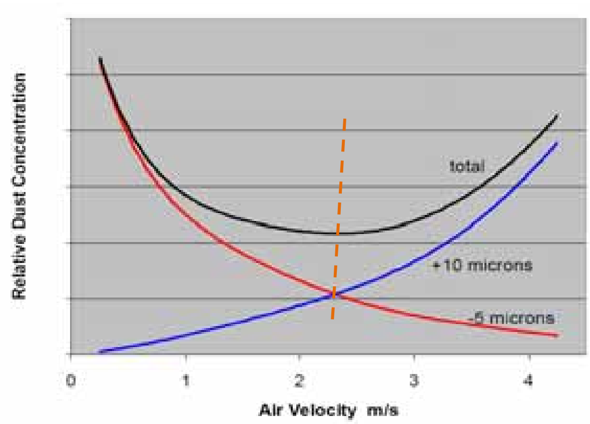
Airflow Calculation – Minimum Velocity



High equipment usage area, Equipment loading, Dust Generation

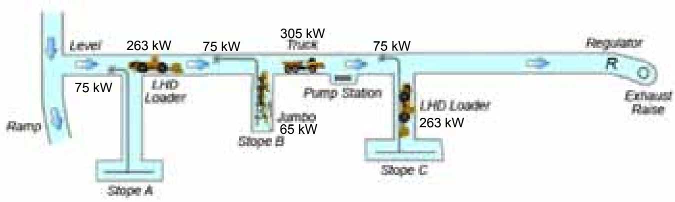
$$\underbrace{2\text{m/s}}_{\text{Minimum Air Velocity, See Dust Figure Above}} \times \overbrace{(5\text{m} \times 5\text{m} \times 95\%)}^{\text{Cross Sectional Area with 95\% Arch Factor}} = 47.5\ \text{m}^3/\text{s}$$

Airflow Calculation – Minimum Velocity



Airflow Calculation - Heat

Heat loads are equipment, power stations, sumps, concrete/fill, and explosives



When considering heat loads, all heat loads (electric and diesel are considered)

Equipment Load For This Example

- 1 305 kW truck
- 2 263 kW LHD
- 1 65 kW Jumbo
- 3 75 kW Auxiliary Fans

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Airflow Calculation - Heat

Equipment need to have a basic motor utilization added (average % of full load)

Equipment Heat Loads

- 1 305 kW truck, Utilization 50%, Diesel
- 1 263 kW LHD, Utilization 75%, Diesel
- 1 263 kW LHD, Utilization 50%, Diesel
- 1 65 kW Jumbo, Utilization 100% Electric
- 3 75 kW Auxiliary Fans, Utilization 75% Electric

Diesel equipment need to have a value of water per liter of fuel added (3.2 liters/liter for this example) (values between 1.1 and 1.5 have been determined in laboratory analysis but can reach as high as 9 in field studies)

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Simulation or Calculation Programs are used for this; CLIMSIM, VentSIM, VUMA, and Others.

Rock Mass Heat Loads

Airflow Calculation - Heat

Level Inlet Conditions 27°C Dry Bulb/23°C Wet Bulb, Barometric Pressure 101.325 kPa

Depth – 1310 meters below collar elevation

Friction Factor – 0.012 kg/m^3

Drift Wetness Factor – 0.15

Virgin Rock Temperature – 27.2°C

Geothermal Step – 30 meters per °C

Conductivity 4.2 W/m°C

Diffusivity 1.5 $m^2/sx10^{-6}$

Fine Tuning Heat Related Items Not Used In This Example (Omitted for Simplicity)

Airflow Calculation - Heat

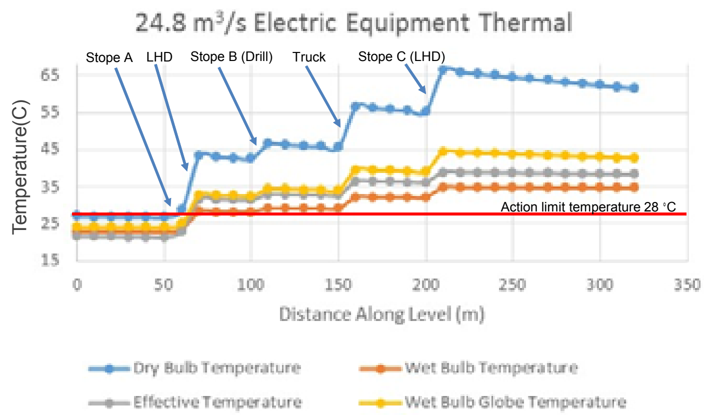
Additional parameters not included in this example;

- Sumps
- Broken Ore/Muck
- Transformer Stations
- Compressed Air (provides slight cooling)
- Use of Explosives

Airflow Calculation – Heat, Diesel Equipment (Airflow from NIOSH/MSHA)

In general, diesel equipment produces 2.3 to 2.6 kW heat per kW work

Assume 1300m Level inlet conditions are 27C dry bulb temperature and 23C wet bulb temperature



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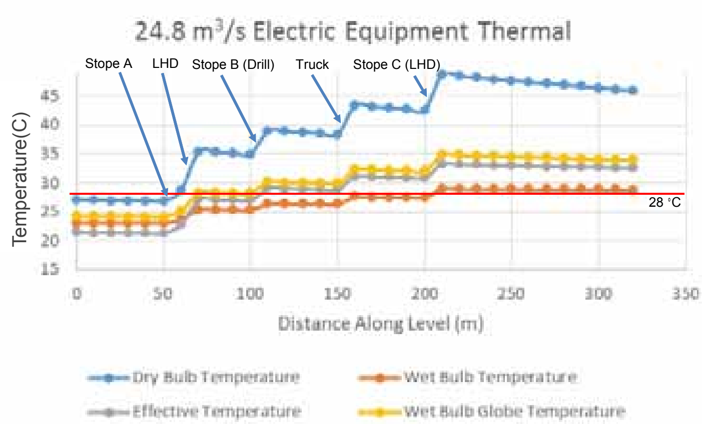
Airflow Calculation – What if All Electrical Equipment is Used? (Airflow from NIOSH/MSHA)

Dry bulb temperature is still very high, wet bulb temperature is just above 28°C

If all of the diesel equipment is replaced with electric equipment then the wet bulb temperature will be depressed by approximately 2 ½ °C



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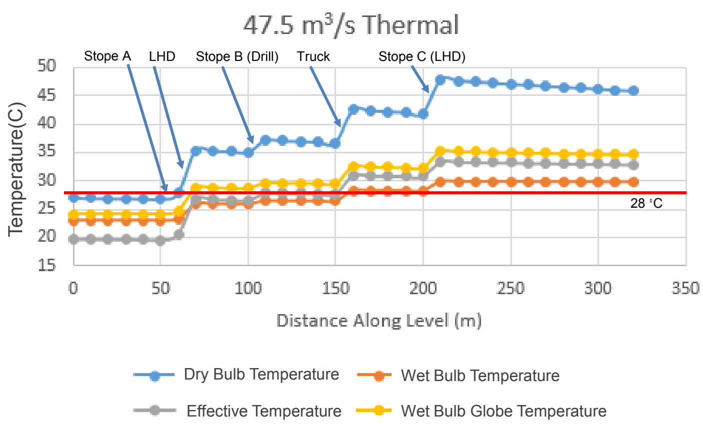
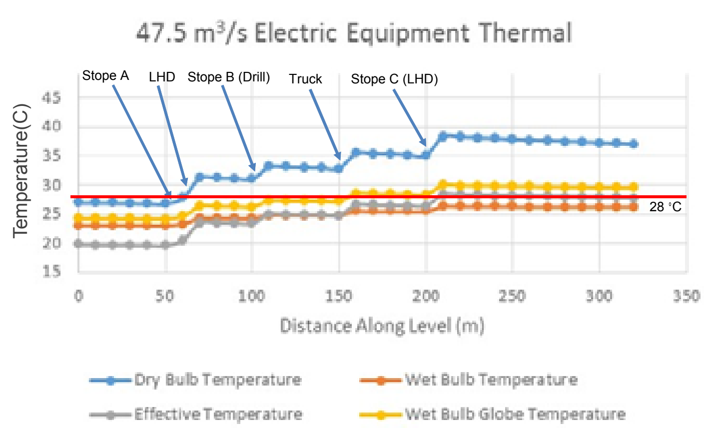
Airflow Calculation –
Heat Diesel Equipment
(Airflow from General Dilution/Velocity)

Assume 1300m Level inlet conditions are 27°C dry bulb temperature and 23°C wet bulb temperature



Airflow Calculation –
What if All Electrical Equipment is Used?
(Airflow from General Dilution/Velocity)

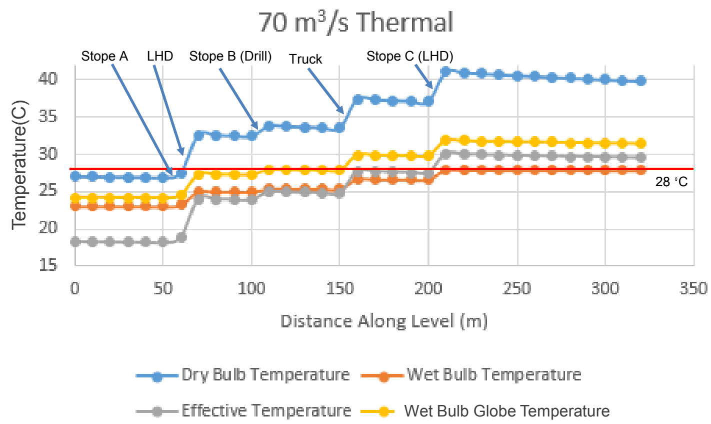
If all of the diesel equipment is replaced with electric equipment then the wet bulb temperature will be slightly below 26.5°C



Airflow Calculation – Heat Diesel Equipment

Assume 1300m Level inlet conditions are 27C dry bulb temperature and 23°C wet bulb temperature

70 m³/s would be required to maintain the wet bulb temperature below 28°C



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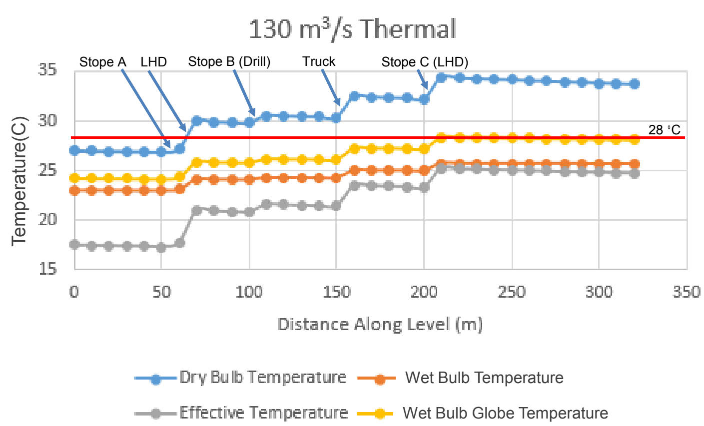
Airflow Calculation – Heat Diesel Equipment

130 m³/s would be required to maintain the wet bulb, wet bulb globe and effective temperature below 28°C



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Airflow Calculation – Heat
What if LHDs are Electric?

Equipment Heat Loads

Equipment need to have a basic motor utilization added (average % of full load)

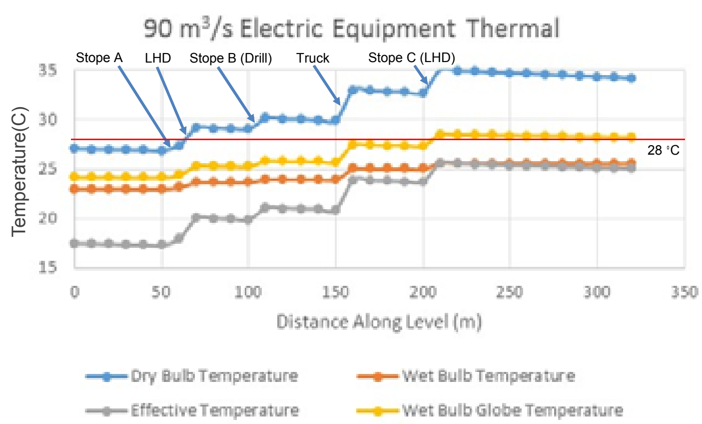
- 1 305 kW truck, Utilization 50%, Diesel
- 1 263 kW LHD, Utilization 75%, Electric
- 1 263 kW LHD, Utilization 50%, Electric
- 1 65 kW Jumbo, Utilization 100% Electric
- 3 75 kW Auxiliary Fans, Utilization 75% Electric

Diesel equipment need to have a value of water per liter of fuel added (3.2 liters/liter for this example) (values between 1.1 and 1.5 have been determined in laboratory analysis but can reach as high as 9 in field studies)

Airflow Calculation – Heat
Electric LHDs

In general electric equipment produces 2.3 to 2.6 times less heat than diesel equipment

90 m³/s with electric LHDs provides an equivalent thermal condition to 130 m³/s with diesel equipment



Airflow Calculation – Heat
What if all Equipment is Electric?

Equipment Heat Loads

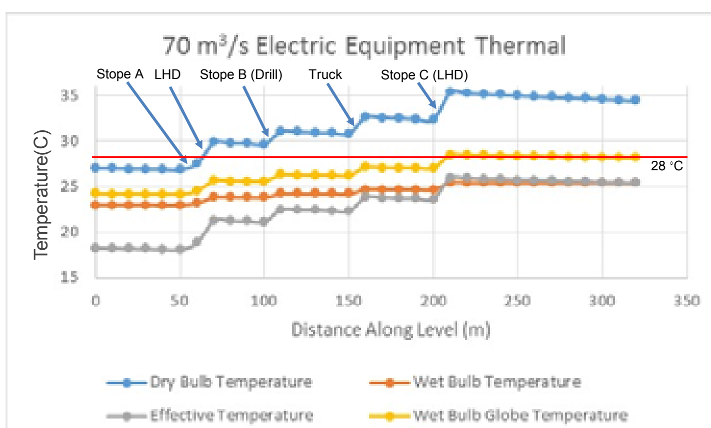
Equipment need to have a basic motor utilization added (average % of full load)

- 1 305 kW truck, Utilization 50%, Electric
- 1 263 kW LHD, Utilization 75%, Electric
- 1 263 kW LHD, Utilization 50%, Electric
- 1 65 kW Jumbo, Utilization 100% Electric
- 3 75 kW Auxiliary Fans, Utilization 75% Electric

Airflow Calculation – Heat
Electric LHDs and Truck

In general electric equipment produces 2.3 to 2.6 times less heat than diesel equipment

70 m³/s with electric LHDs and Truck provides an equivalent thermal condition to 130 m³/s with diesel equipment



Comparison of Values (Mining Area)

Each general mining area would require this type of airflow evaluation. This is not the overall airflow requirement for the mine, but the supplied airflow requirement

Method	Airflow (m^3/s)
Generalized Dilution Factor (0.06 m^3/s per kW)	50
MSHA (NIOSH) Dilution (Diesel)	25
MSHA (NIOSH) Dilution (Particulate)	97
Minimum Velocity (for Dust Control)	48
Max Wet Bulb Temperature (28°C)	70
Wet Bulb Globe Temperature (28°C)	130
Wet Bulb Globe Temperature (Electric LHDs) (28°C)	90
Wet Bulb Globe Temperature (Electric LHDs and Truck) (28°C)	70

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Relationship Between Mining Area Values and Total Mine Airflow

The mining area airflow requirement does not directly translate to the overall mine airflow requirement.

- Leakage rates must be accounted for.
- Leakage rates may vary from 25% to 90% depending upon many site specific factors:
    1. Number of Bulkheads
    2. Type of Construction for Bulkheads
    3. Age of Infrastructure
    4. Doors
    5. Intake/Exhaust Connections
    6. Fan Placement
    7. Ventilation of Dedicated Areas (Ramps, etc.)

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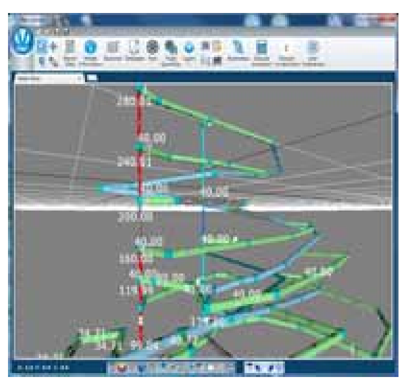
Relationship Between Mining Area Values and Total Mine Airflow

How is the total mine airflow determined?

- Applying generic system efficiency values – least accurate
- Developing a ventilation model based on empirically derived values (friction factors, resistance estimates) – moderately successful
- Developing a ventilation model based on site measured data and measured infrastructure values – greatest success
- More information on this will be discussed this afternoon

Relationship Between Mining Area Values and Total Mine Airflow

- Ventilation Modeling Software is Used to Establish These Models:
  - VnetPC,
  - VentSIM,
  - VUMA, etc.



Ventilation Design Process

Thank you for your attention

Feel free to ask questions here or contact me later at:

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Ventilation Design Case Studies
MDEC Workshop October 4, 2016

CAllen, Vale Ontario Operations
JStachulak, MIRARCO

Agenda

1. Context
2. Case Study Scenarios
3. Design Criteria
    1. Air Volume
    2. Vent Plan
    3. Environment
    4. Economics
    5. Risk
4. Ventilation Design
5. Heat Load Modeling
6. Comparison of Results
7. Benefits
8. Summary
9. References

Context

Design Approach

- In mechanized mines, ventilation design is mainly based on dilution of diesel exhaust contaminants.
  - This volume is generally adequate to cover all other factors that are part of ventilation design (ie 0.06 m^3/s per kW)
- When considering alternative power sources for mobile equipment (ie battery), the design basis must consider other factors such as dust, gas, heat and air velocity.
- Designing to minimum regulations does not guarantee an acceptable design, but a design must be sure to meet any regulations.
- Start the design process with robust and good practice principles
  - A weak starting process can only degrade and create restrictions
  - Work to a “fit-for-purpose” design

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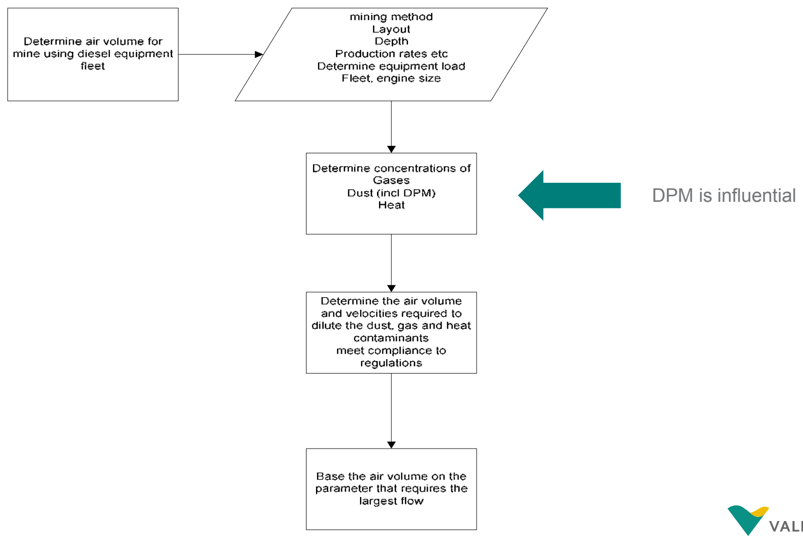
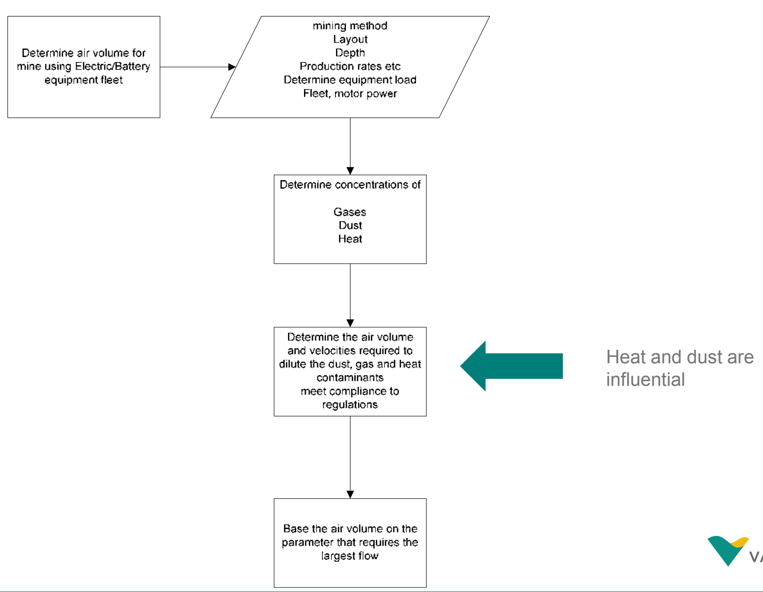
Air Volume - Diesel Engine



Air Volume - Electric Powered

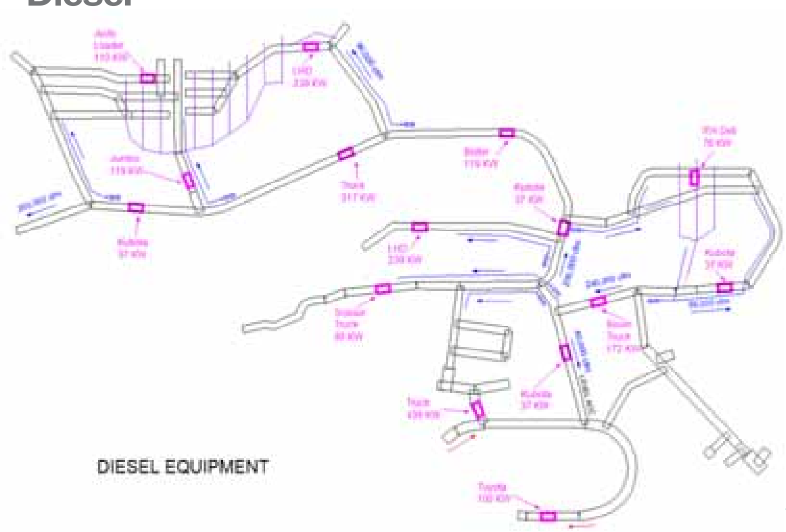


2 Case Study Scenarios

Scenario Assumptions

- Deep mine example
- Calculate the air volume per production level
- Parameters (mining method, depth, intake air temperature, target stope and reject temperatures) are kept constant except the type of mobile power source and the air volume to maintain the same temperature between scenarios

Level Layout for equipment placement Diesel



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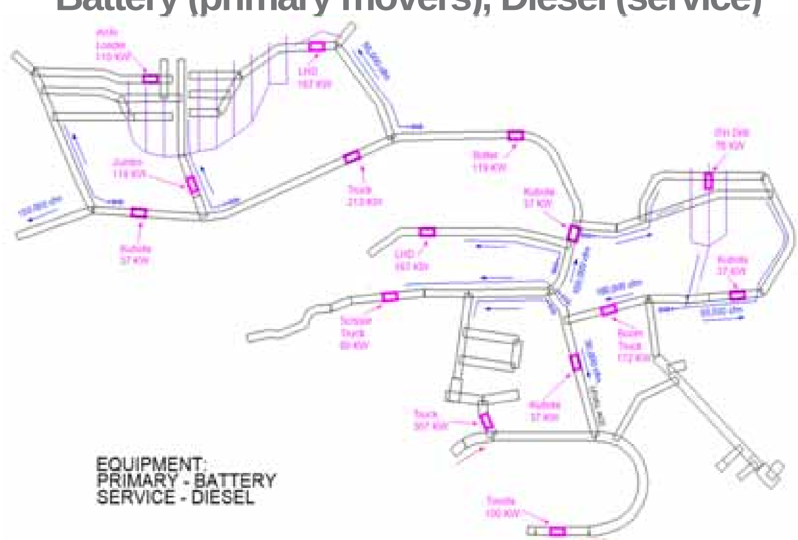
Level Layout for equipment placement Battery (primary movers), Diesel (service)



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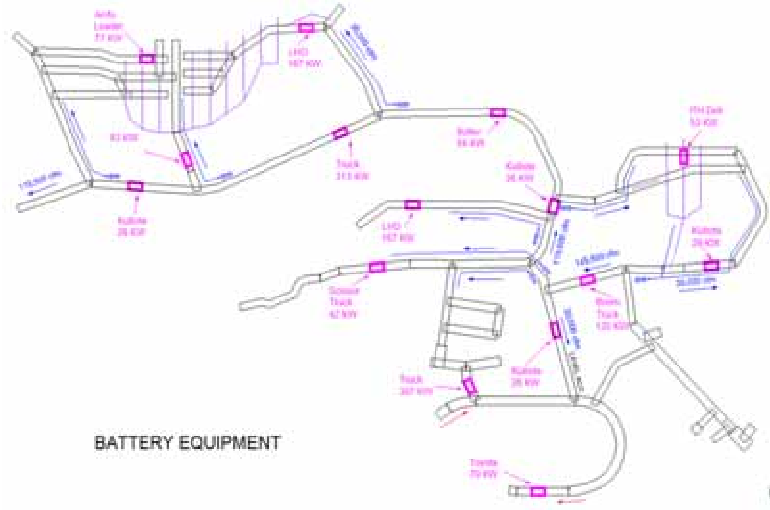
Level Layout for equipment placement Battery (primary and secondary)



Diesel Equipment List

Diesel Equipment Load

Diesel Equipment								
Activity	**Equipment**	**# of Equipment**	**HP**	**Total HP**	**Factor**	**100cfm/bhp**	**Utilization**	**CFM required**
					1.2			
Level - Production	8 yrd scoop	2	325	650	780	78000	100%	78000
	Personnel Carrier	1	134	134	160.8	16080	40%	6432
	ITH	1	102	102	122.4	12240	40%	4896
	Anfo loader	1	147	147	176.4	17640	40%	7056
	Kubota	1	50	50	60	6000	40%	2400
	30 T truck	1	409	409	490.8	49080	100%	49080
	Bolter	1	160	160	192	19200	40%	7680
								155544
	Volume Aux Recirc	30 % factor					30%	46663
Production		7		**1652**	**1790**			**202207**
Development	8 yrd scoop	1	325	325	390	39000	100%	39000
	30 T truck	1	409	409	490.8	49080	100%	49080
	Bolter	1	160	160	192	19200	40%	7680
	Personnel Carrier	1	134	134	160.8	16080	40%	6432
								102192
		25 % factor					25%	25548
Development		4		**1028**	**1234**			**127740**
Totals	**Production**	6		9912	10742			1115083
	Development	3		3084	3701			383220
	Development Ramp	1		1028	1234			127740
				14024	**15677**			**1626043**
SUBTOTAL MOBILE EQUIPMENT				**14024**	15677			***1626043***
	Infrastructure (Garages, conveyors)	1						100000
	SUBTOTAL INFRASTRUCTURE							***100000***
	BASE SUBTOTAL							***1726043***
	Fel 3 Design Primary Leakage Factor 15 %						0.15	258906
	TOTAL FRESH AIR VOLUME							**1984950**

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Battery Equipment List

Battery Equipment Load

Battery Equipment					
Activity	**Equipment**	**# of Equipment**	**HP**	**Total HP**	**Factor**
					1.2
Level - Production	8 yd scoop	2	227	454	544.8
	Personnel Carrier	1	94	94	112.8
	ITH	1	71	71	85.2
	Anfo loader	1	103	103	123.6
	Kubota	1	35	35	42
	30 T truck	1	286	286	343.2
	Bolter	1	112	112	134.4
	Volume Aux Recirc	15 % factor			
Production		7		**1155**	**1252**
Development	8 yd scoop	1	227	227	272.4
	30 T truck	1	286	286	343.2
	Bolter	1	112	112	134.4
	Personnel Carrier	1	94	94	112.8
		25 % factor			
Development		4		**719**	**863**
Totals	**Production**	6		6930	7510
	Development	3		2157	2588
	Development Ramp	1		719	863
				9806	**10961**
SUBTOTAL MOBILE EQUIPMENT				**9806**	10961
	Infrastructure (Garages, conveyors)	1			
	Fel 3 Design Primary Leakage Factor 15 %				
	TOTAL FRESH AIR VOLUME				

3

Design Criteria

Air Volume

- Apply legislated m^3/s per kw (cfm/bhp) for the diesel fleet.
- Air volumes throughout the mine must meet TLV regulations (ie Ontario must meet Reg 833) for diesel and electric fleet
- Determine the air volume required by building a 1st principles equipment allocation to suit the mining activity.
- Assign mobile vehicles (trucks, LHDs, graders) a usage factor in the diesel or electric volume calculations, then add:
  - any allowances for leakage, equipment fleet changes, study level of confidence
  - airflow for each known main infrastructure sufficient to manage working temperatures based on expected activity in the facility.
- If it is determined that cooling is required, complete a study to determine if increased air volume can reduce or eliminate the refrigeration requirement.
- The air volumes are based on a development and production plan and schedule with indication of mobile fleet requirements per production zone

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Ventilation Plan

- Create a conceptual production airflow distribution plan
  - o Identify the location, size & type of vent raises for each option
  - o Develop a list of controls, with locations, required in the design
  - o List the main surface and booster fans required and their full production operating points
  - o Develop preliminary circuit flows for each phase of development & production
  - o Include a description of the ventilation infrastructure
  - o List primary fan operating points, fan type, approximate HP of all main fans, mine air heater load and cooling load, if applicable
- Follow Vale Ventilation Design Criteria (ie. airlock recommendations, velocity criteria, etc)
- Temperatures must be controlled to remain within limits established in the Thermal Management Program

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Ventilation Plan

- To reduce risk, potential ventilation critical issues and system limitations need to be identified early in the design
- It is good practice, if possible, to supply escape way systems with fresh air
- Garages should be located close to return air systems to allow exhaust to go immediately to a return air system
- One pass ventilation is desired for primary ventilation systems, particular to diesel powered fleets, to avoid re-circulating contaminants
- Include and describe the Ventilation Control System selected to incorporate in the design
- In creating a ventilation design, consider how people would move to refuge stations and what the rescue-ability would be to reach these employees (ie ramp ventilation, fresh air delivery methodology)
- If heat is a concern, determine how much air is required to dilute heat to acceptable levels and/or what cooling load is required of a mechanical refrigeration system (or alternative)

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Environment

- Temperatures must be controlled to remain within safe limits established in site's heat management program
  - Target Reject temperature must not be exceeded
  - Workplace temperatures should remain below thermal work limits. If extreme workplace temperatures are expected, the design must be assessed for impact to production due to work/rest criteria.
  - Use climatic data from local (10 yr) average for heating and cooling calculations
  - Determine the conductivity, diffusivity, and geothermal gradient specific to the site to be used in heat load studies
  - Confirm location of refrigeration plant and air coolers [surface or underground]
  - Designs should incorporate a minimum velocity in the workplace of 0.5 m/s (100 ft/min); case dependent
- Determine potential dust sources
- Surface noise levels must be within regulated and internal limits
  - Determine Main Fan locations, configuration, size, etc (surface/underground)
  - Complete noise modeling
- The practice of controlled re-circulation of air should be avoided for diesel equipment, and an analysis must be completed for the application in an electric mine.

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Economics

- Complete an economic analysis using capex and opex to evaluate and recommend appropriate main airway sizing
  - o Apply the current discount factors to economic calculations
  - o Apply the power rate recommended by the Energy Dept
  - o Use development rates approved by the specific site location
- Optimize the ventilation system critical path based on the economic analysis
- Size the primary airways to achieve the lowest NPV

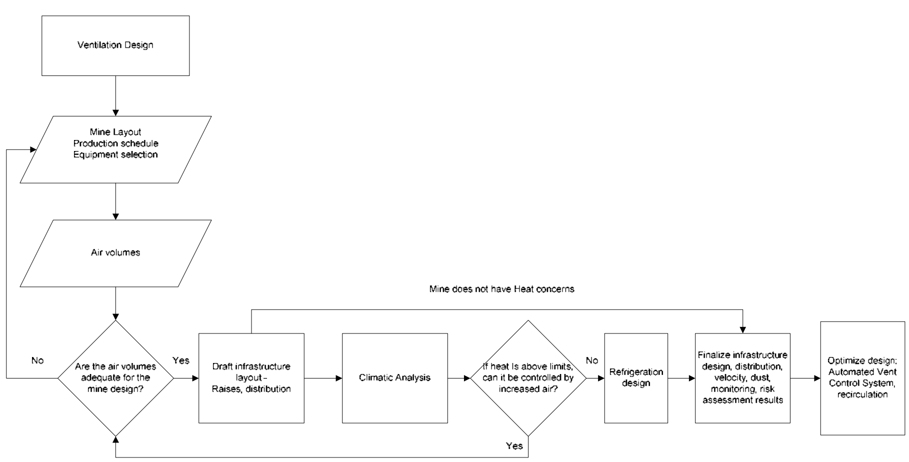
Hazards

- A risk assessment highlights any potential hazards, limitations and critical issues inherent within the design. It should include:
  - o rescue-ability, secure power sources to refuge stations, potential for exhaust, intake contamination, high temperatures, operability constraints, high fire potential, workplace contaminants, etc
  - o Utilize the Bowtie Method for high risk items to ensure controls to reduce the risk are incorporated into the design
- If the ventilation design deviates from the design criteria, a risk assessment must be conducted

4

Ventilation Design

Ventilation Design



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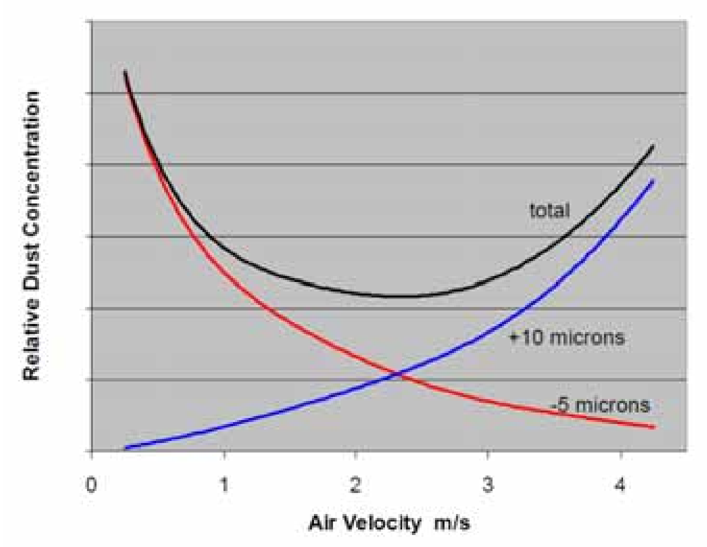
Velocity



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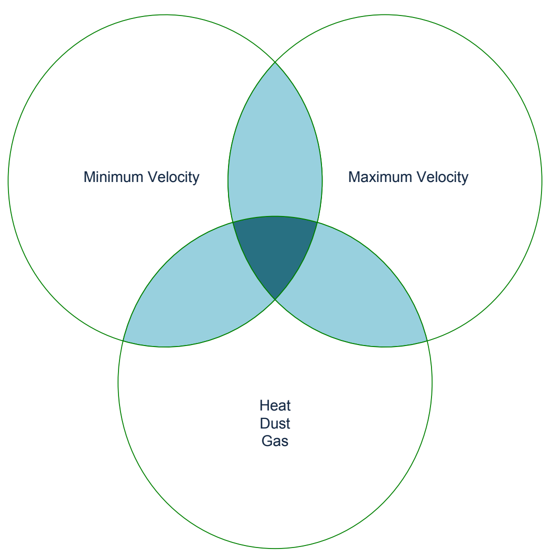
Air Velocity



- Air velocity must be considered once the air volume requirements have been met for the other parameters
- The velocity balance is necessary for safety
  - Max velocity for Submicron size to dilute
  - Min velocity to not create dust and discomfort

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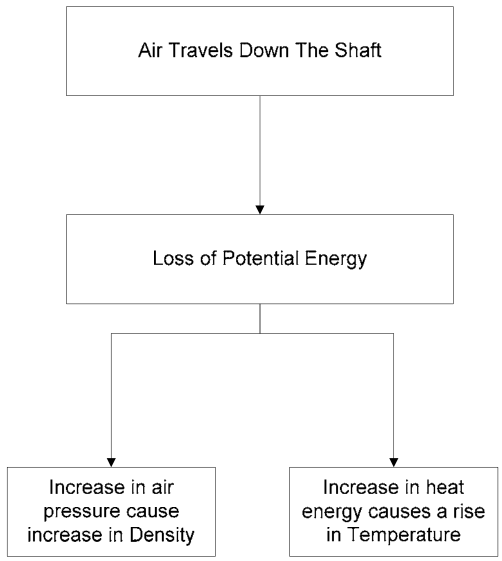
5 Heat Load Modeling

Sources of Heat

- Wall Rock
- Broken Rock
- Electrical Load from fixed equipment, fans, pumps
- Mobile equipment - Diesel and Electric Load,
- Autocompression (not an external heat source)
- Metabolism
- Curing, sandfill and concrete
- Oxidation

Auto compression



Heat from Diesel

- Heat from diesel is in the form of sensible and latent when added together is the total heat
- Total Heat can be determined from several methods:
  - The fuel consumption rate where heat is calculated from the burning of the fuel over a period of time, or
  - The efficiency of the diesel engine - a diesel engine working at its rated capacity requires an input power approximately 3 times that of its output power; which ends up as heat.
- Rules of thumb are applied based on the equipment duty and size
  - Load factor - Vehicles going upgrade use more power than vehicles operating on the level vs vehicles going downgrade.
  - Volume of water generation per volume of fuel
- The rise in enthalpy (total heat) from the engine drives the ventilation rate to meet a target temperature

Heat from Battery

- Heat from electric equipment is in the form of sensible heat
- The electric motor is efficient, therefore the power consumption is equal to the heat generated plus a small inefficiency.
- Rules of thumb are applied based on the equipment duty and size
  - Load factor - Vehicles going upgrade use more power than vehicles operating on the level vs vehicles going downgrade
- The rise in heat from the engine drives the ventilation rate to meet a target temperature

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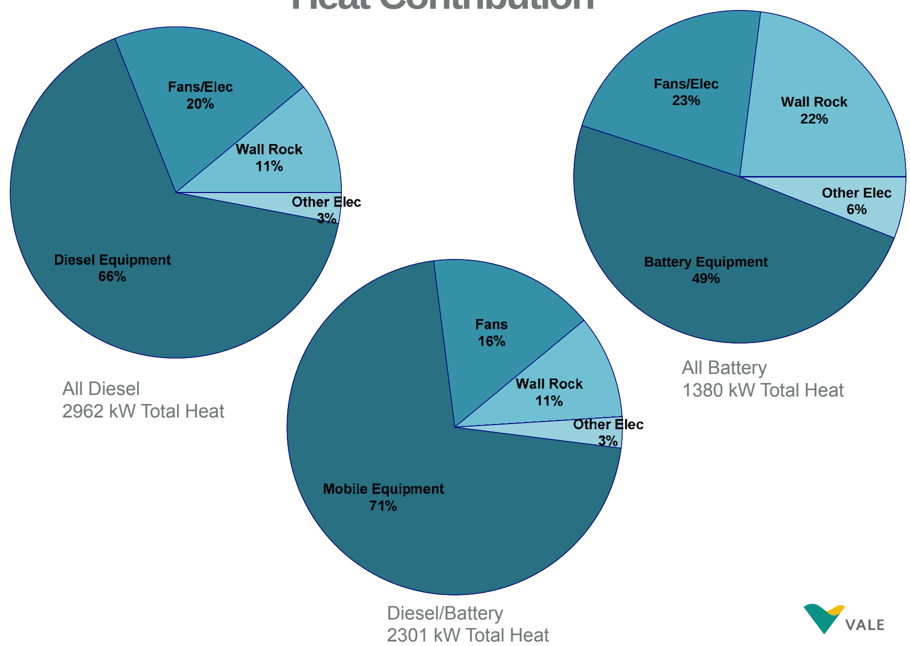
6 Comparison of Results

Heat Contribution



Heat Generation Comparison

Equipment Type	Wall Rock	Fans	Mobile Equipment	Other Electric Heat Source	Total Heat
All Electric	297 kW 22%	312 kW 23%	682 kW 49%	89 kW 6%	1380 kW 100%
All Diesel	320 kW 11%	602 kW 20%	1951 kW 66%	89 kW 3%	2962 kW 100%
Electric Primary Diesel Secondary	333 kW 11%	568kW 16%	1311 kW 71%	89 kW 3%	2301 kW 100%

Velocity

Equipment	Location	Volume (cfm)	Velocity (ft/min)
Diesel	Main Drift	200,000	735
	Stope Access	90,000	330
Battery	Main Drift	116,000	426
	Stope Access	35,000	128
Diesel/Electric	Main Drift	180,000	662
	Stope Access	55,000	202

Drift dimensions are 16ft x 17ft (272 ft^2)
Minimum velocity – 100 ft/min (0.5 m/s)
Optimum velocity – 200 ft/min (1.0 m/s)

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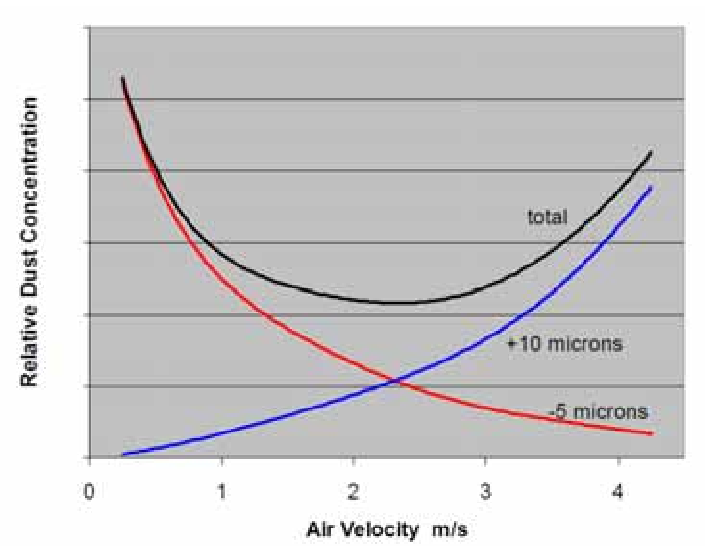
Dust Concentration vs Velocity



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7

Benefits

Infrastructure Reduction

Equipment	Air Volume (cfm)	Volume Reduction	Raise Bore Diameter (feet)	Size Reduction
Diesel	200,000	200,000→180,000 10%	11	11 → 10.5 5%
Diesel/Battery	180,000	180,000→116,000 35.5%	10.5	10.5 →8.7 17%
Battery	116,000	200,000→116,000 42%	8.7	11 → 8.7 21%

Raise size reduction per Level

Equipment	Air Volume (cfm)	Volume Reduction	Raise Bore Diameter (feet)	Size Reduction
Diesel	830,000	830,000→690,000 17%	19	19 → 17.5 8%
Battery	690,000	690,000→570,000 17.4%	17.5	17.5 →16.5 4%
Diesel/Battery	570,000	830,000→570,000 31%	16.5	19 → 16.5 13%

Raise size reduction per Area

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Energy – Fans

Equipment	Air Volume (cfm)	Volume Reduction	Fan Power (HP)	Power Reduction (6 fans/level)
Diesel	90,000	90,000→55,000 39%	180	1080 → 480 55.5%
Battery/Diesel	55,000	55,000→35,000 36%	80	480 →240 50%
Battery	35,000	90,000→35,000 61%	40	1080 → 240 78%

Power reduction for 6 **auxiliary** fans on one level

Equipment	Air Volume (cfm)	Volume Reduction	Fan Power (HP)	Power Reduction
Diesel	830,000	830,000→690,000 17%	2616	2616 → 2283 13%
Battery/Diesel	690,000	690,000→570,000 17.4%	2283	2283 →1719 25%
Battery	570,000	830,000→570,000 31%	1719	2616 → 1719 34%

Power reduction for **Primary** fans

Energy – Fan Operating Cost

Equipment	Air Volume (cfm)	Fan Power 6 fans/level (HP)	Power Cost Per year
Diesel	90,000	1080	$529,000
Battery/Diesel	55,000	480	$235,000
Battery	35,000	240	$118,000

Power cost for **auxiliary** fans on one level

Equipment	Air Volume (cfm)	Fan Power (HP)	Power Cost Per year
Diesel	830,000	2616	$1,282,200
Battery/Diesel	690,000	2283	$1,118,900
Battery	570,000	1719	$842,500

Power cost for **Primary** fans

The power savings from Diesel to Battery/Diesel = $1,045,300/yr
The power savings from Diesel to Battery = $1,672,700/yr

Energy – Heating and Cooling

Equipment	Air Volume (cfm)	Volume Reduction	Natural Gas (ft^3)	Natural Gas Reduction
Diesel	830,000	830,000→690,000 17%	57,558,948	57.6M ft^3 → 47.8M ft^3 17%
Battery/Diesel	690,000	690,000→570,000 17.4%	47,850,210	47.8M ft^3 → 39.5M ft^3 17.4%
Battery	570,000	830,000→570,000 31%	39,528,434	57.6M ft^3 → 39.5M ft^3 31%

Reduction of **Natural Gas**

Equipment	Air Volume (cfm)	Volume Reduction	Cooling (MW)	Cooling Reduction
Diesel	830,000	830,000→690,000 17%	13	13 MW → 10.8 MW 17%
Battery/Diesel	690,000	690,000→570,000 17.4%	10.8	10.8 MW → 8.9 MW 17.6%
Battery	570,000	830,000→570,000 31%	8.9	13 MW → 8.9 MW 31.5%

Reduction of **Refrigeration**

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8 Summary

Summary

- The primary role of an underground ventilation system is to provide airflow to dilute and remove contaminants created in the mining process to safe levels where people are required to work or travel.
- Mine ventilation design can be complicated so a structured approach is required to ensure a robust and fit-for-purpose system.
- The electric or battery mine will require a more comprehensive design that considers the impact of velocity, heat and dust levels from air volume reductions that are possible as a result of zero emission engines.
- There are benefits to the mine design from replacing diesel engines with electric or battery powered equipment. These benefits consist of capital cost reductions from smaller raises and fans, and operating cost reductions from reducing power and natural gas demand.

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NATURAL RESOURCES CANADA - INVENTIVE BY NATURE

Energy management strategies in auxiliary mine ventilation systems

Michelle Levesque

Senior Engineer in Mine/Mill Energy Efficiency and Underground Mine Environment, CanmetMINING

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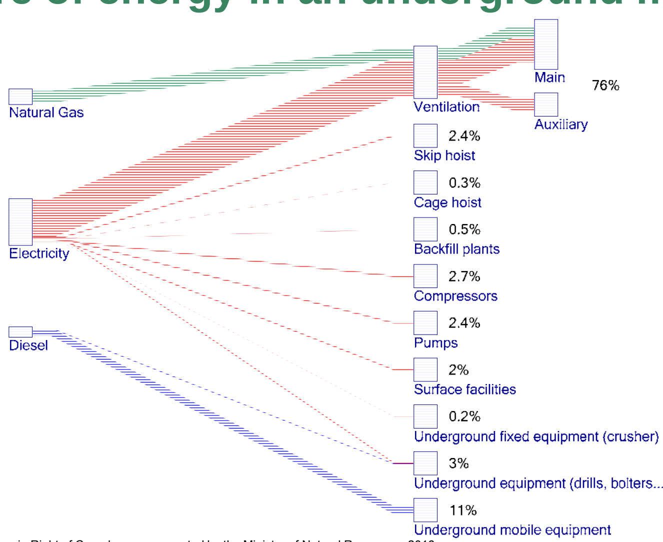
Ventilation system consumes the largest share of energy in an underground mine



(Levesque, 2015)

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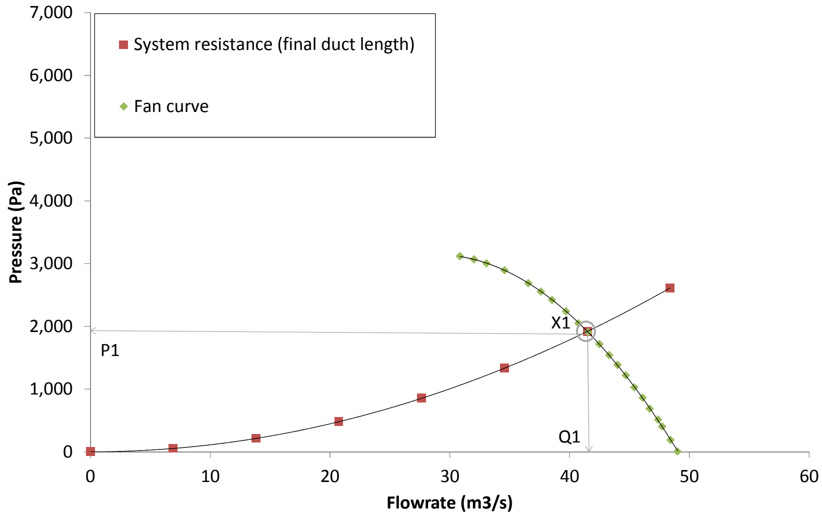
The fan operating point is at the intercept of the fan and resistance curves



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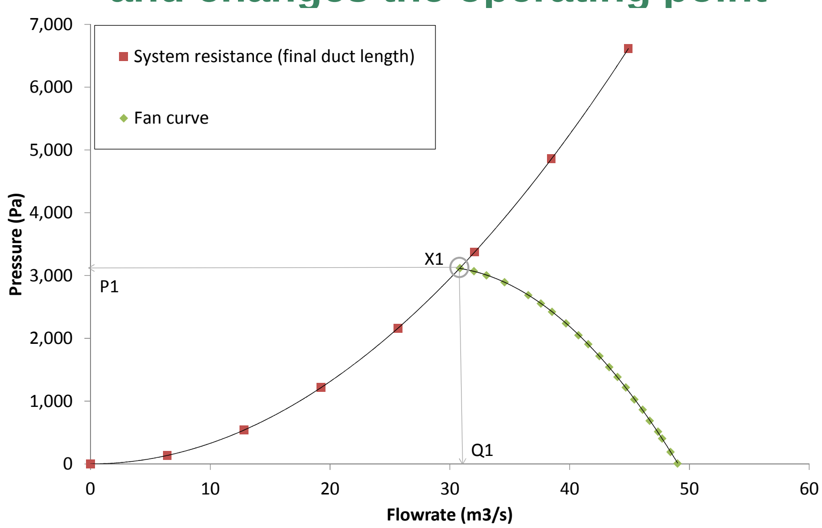
As the duct extends the resistance increases and changes the operating point



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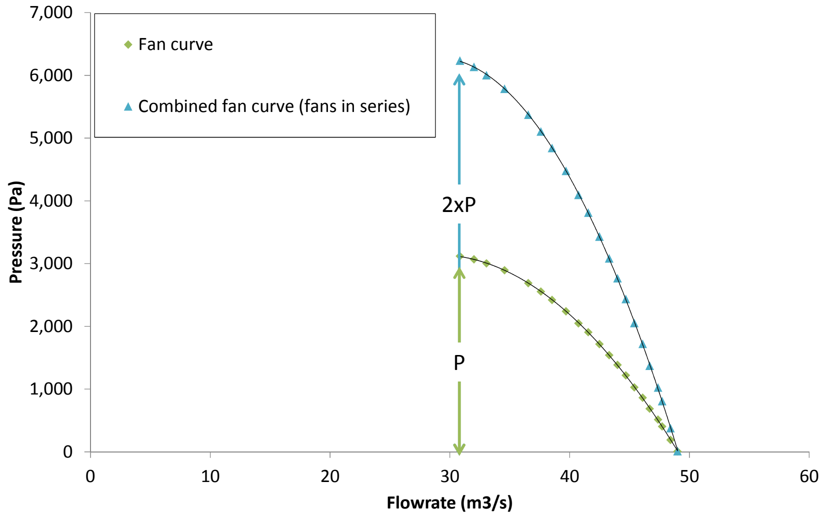
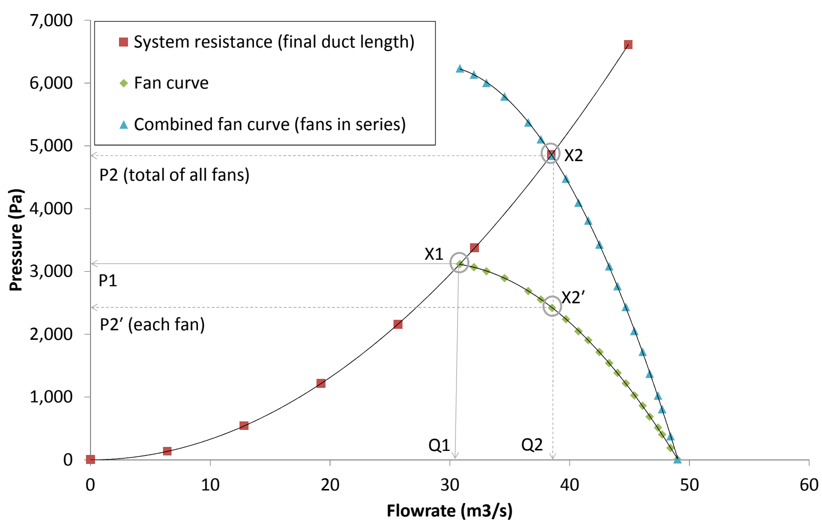
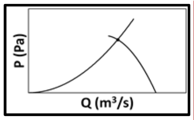
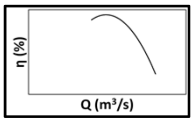
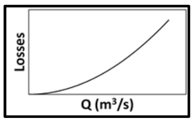
For 2 fans installed in series the pressure is doubled but the flowrate is the same



When a second fan is added to the system the flowrate increases

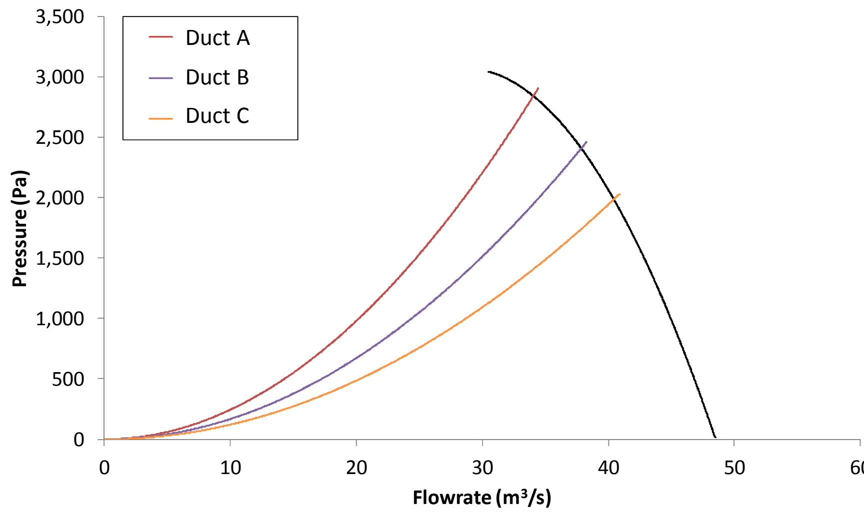


The interactions between the variables in a ventilation system are complex

Fan	fan pressurizes air in duct (gives air flow work that is consumed F_{12})	matching fan to system reduces operating costs	changing fan speed leads to new operating point and new P&Q
	Duct	different duct materials have different capital and operational costs	all other things equal, lower k leads to higher Q
capital constraint on control and efficiency	capital constraint on effectiveness and quality	Money	sub-optimal installations with capital constraints
		Power=RQ^3	Flowrate

(Levesque, 2015)

All else equal, a duct with a lower friction factor will deliver more air



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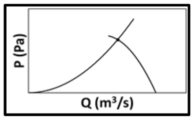
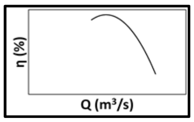
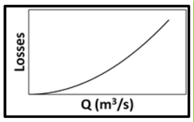
The complexity emerges by tracing the interactions around the matrix

Fan	fan pressurizes air in duct (gives air flow work that is consumed F_{12})	matching fan to system reduces operating costs	changing fan speed leads to new operating point and new P&Q
	Duct	different duct materials have different capital and operational costs	all other things equal, lower k leads to higher Q
capital constraint on control and efficiency	capital constraint on effectiveness and quality	Money	sub-optimal installations with capital constraints
		Power=RQ^3	Flowrate

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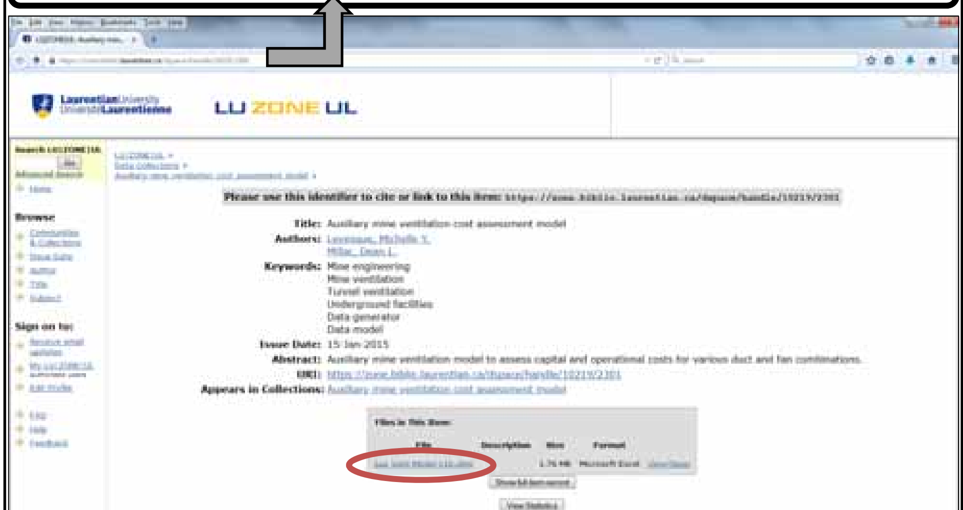

(Levesque and Millar, 2015a)

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Which duct type should the mine use to minimize cost for this situation?

Fan model	4800-VAX-2700
Fan operation	Fixed speed
Fan speed (rpm)	1800
Duct diameter (m)	1.2
Advance rate (m/day)	4
Final duct length (m)	1200
Project life (years)	1

134

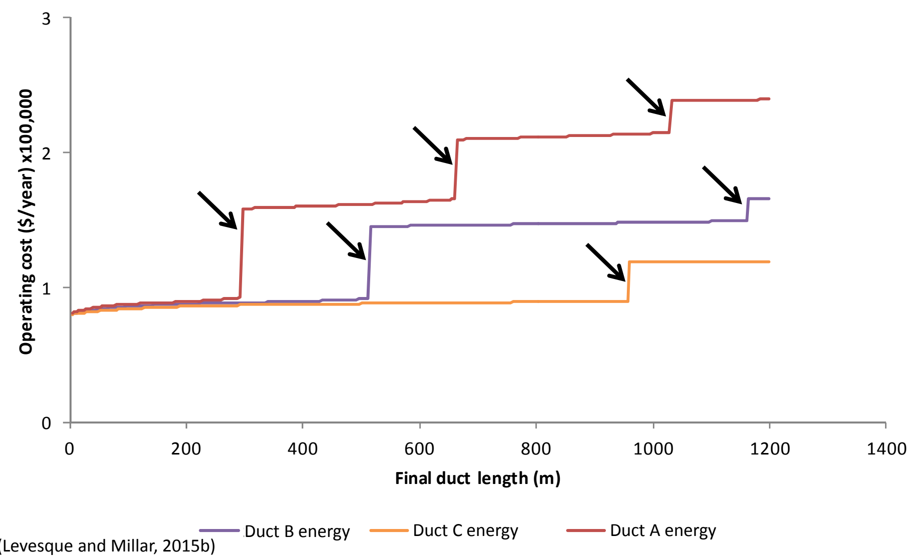
Although the system with Duct A used more energy it was the cheapest option

	Energy cost ($/year)	Total cost ($/year)
Duct A	239,444	353,949
Duct B	166,020	410,536
Duct C	118,958	569,381

… but what about other duct lengths and longer term projects?

135

Duct C uses less energy (fixed speed fan, 1 year installation)



(Levesque and Millar, 2015b)

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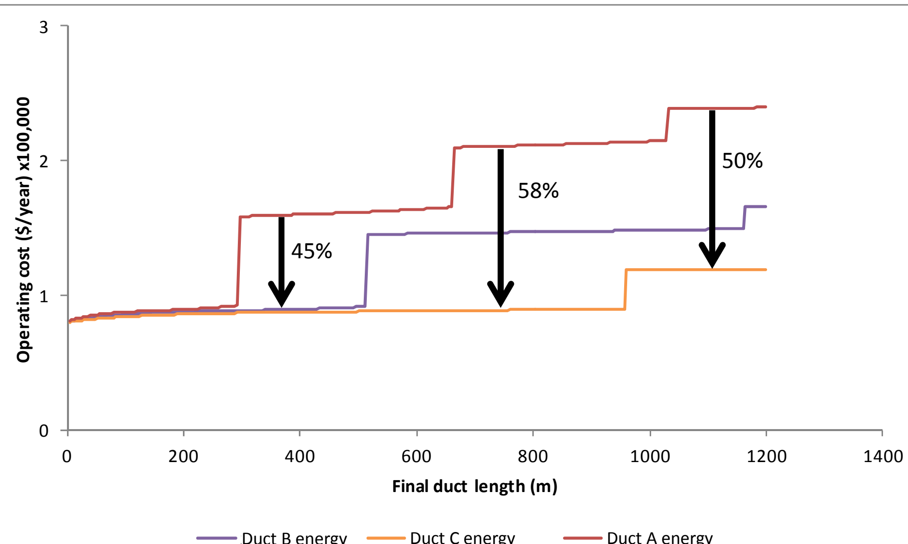
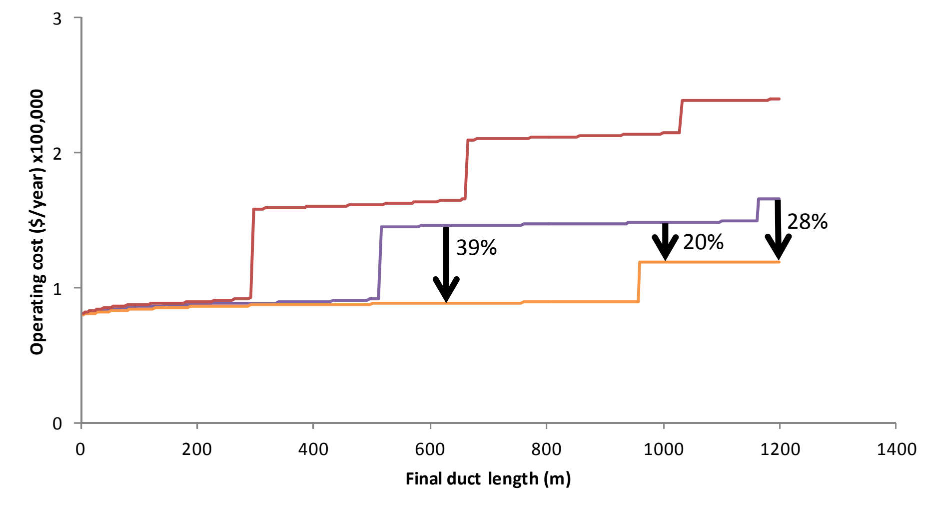
Duct C can save up to 58% energy compared to the Duct A system



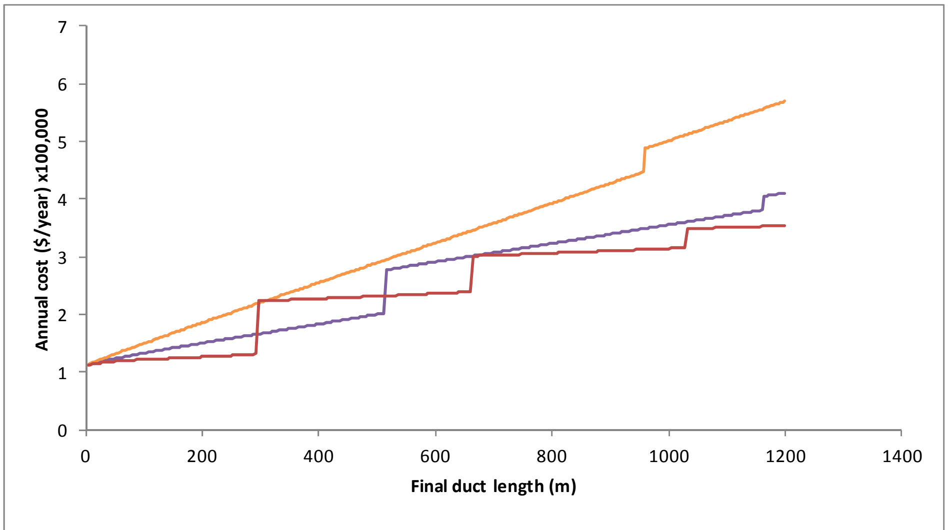
(Levesque and Millar, 2015b)

Duct C can save up to 39% energy compared to the Duct B system



(Levesque and Millar, 2015b)

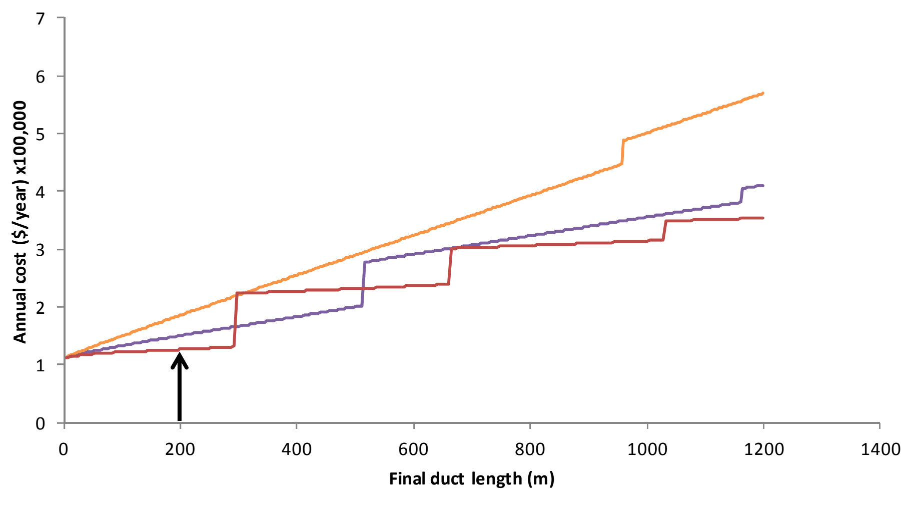
When the capital costs are included the system using Duct C was the most expensive



(Levesque and Millar, 2015b)

139

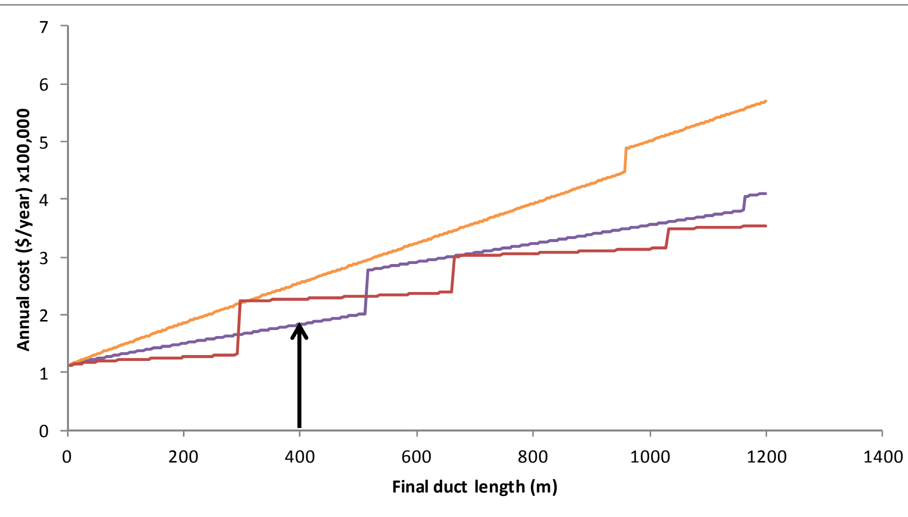
Duct A option is the cheapest for a 200m length



(Levesque and Millar, 2015b)

140

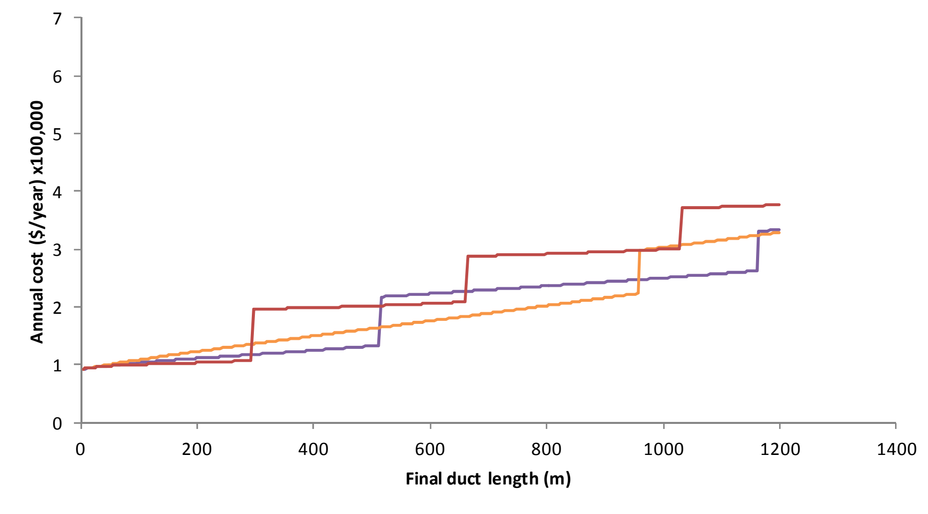
Duct B is the cheapest option when the Duct A system requires a second fan



(Levesque and Millar, 2015b)

141

Duct C can be an economic option if the project life is extended to 3 years



(Levesque and Millar, 2015b)

142

How can we optimize the economics of the system by controlling flowrate?

$$Q_2 = Q_1\left(\frac{n_2}{n_1}\right)$$

$$P_2 = P_1\left(\frac{n_2}{n_1}\right)^2$$

Using the fan laws we can draw fan curves for any speed

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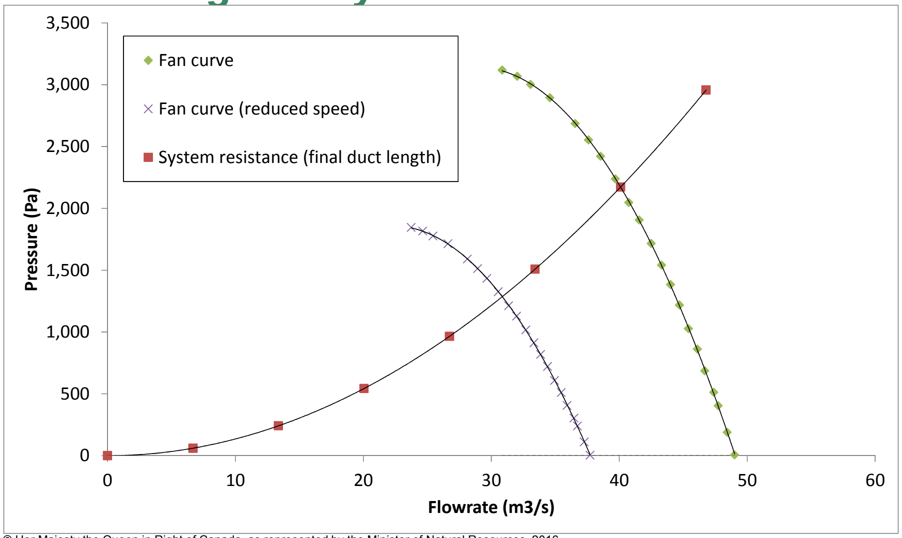
A lower fan speed reduces the flowrate for a given system resistance



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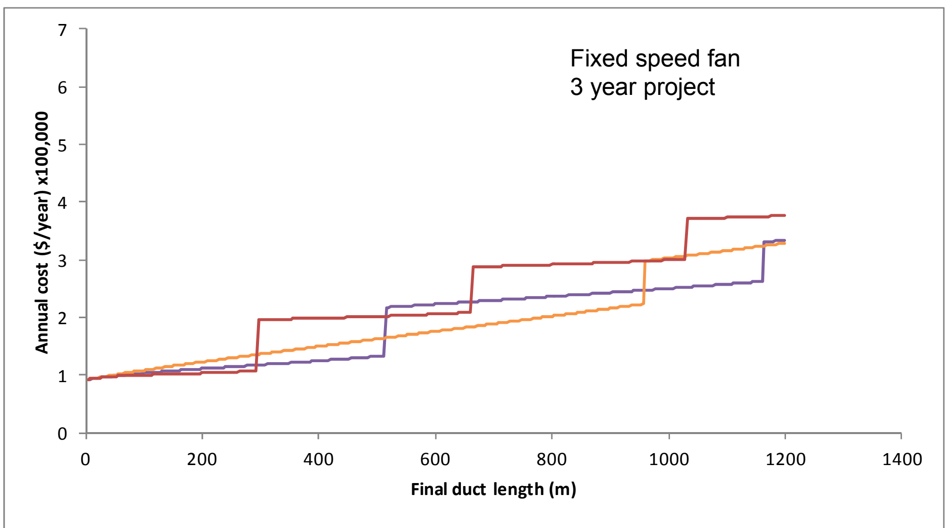
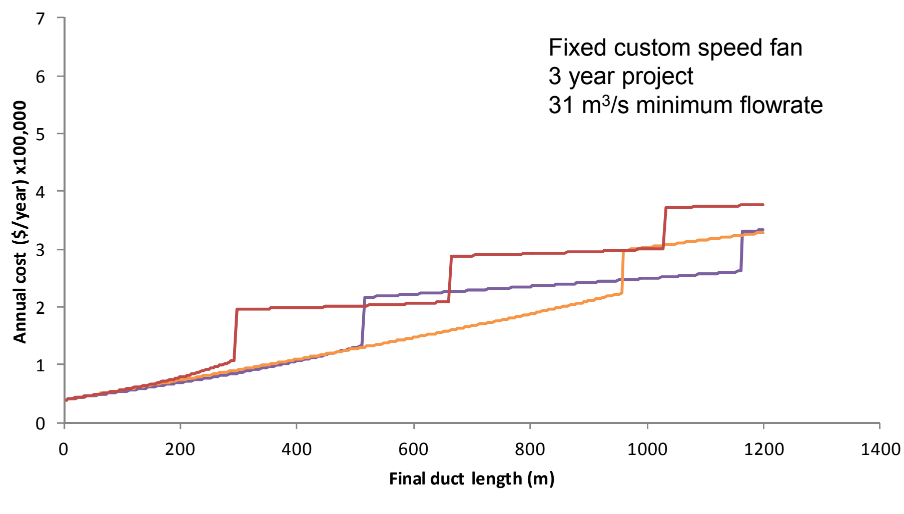
Going back to the case study…



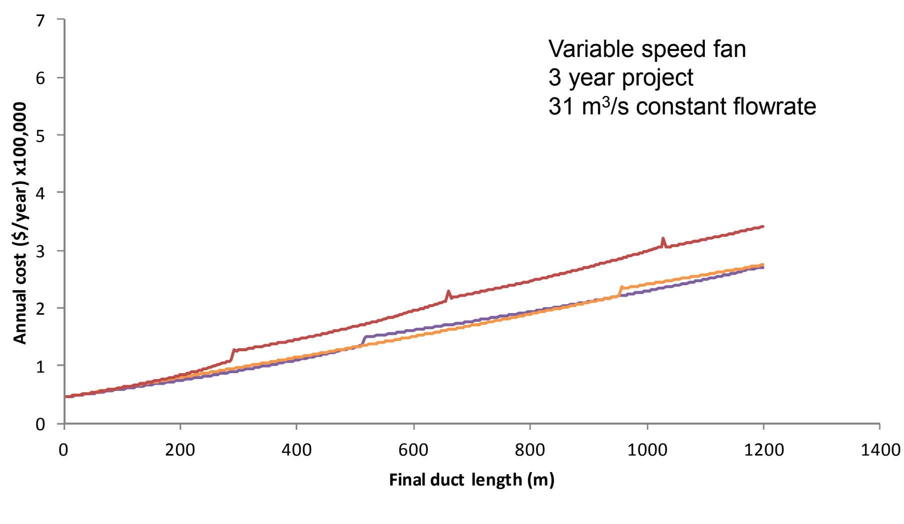
(Levesque and Millar, 2015b)

Speed adjustment improves economics of single fan systems



(Levesque and Millar, 2015b)

Speed control improves economics and smooths discontinuities from multiple fans



(Levesque and Millar, 2015b)

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Operating costs can be minimized by:

- Using lower friction ducts
- Controlling flowrate

… but to optimize the system we also need to consider the fan

148

It's important to consider the system as a whole to minimize costs – fan and duct

	Energy cost ($/year)		Total cost ($/year)	
	Base case	Optimal fan	Base case	Optimal fan
Duct A	239,444	239,444	353,949	353,949
Duct B	166,020	146,158	410,536	403,604
Duct C	118,958	101,925	569,381	560,474

- Fixed speed scenarios at 1800 rpm
- Minimum flowrate: 31 m^3/s
- Duct length: 1200 m
- Project life: 1 year

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If we only needed 25 m^3/s it would be better to purchase a different fan

	Energy cost ($/year)		Total cost ($/year)	
	Base case*	**Optimal fan**	**Base case**	**Optimal fan**
Duct A	239,444	153,513	353,949	251,768
Duct B	166,020	106,512	410,536	340,369
Duct C	118,958	54,552	569,381	493,967

- Fixed speed scenarios at 1800 rpm
- Minimum flowrate: 25 m^3/s
- Duct length: 1200 m
- Project life: 1 year

* The minimum flowrate delivered in this case was 31 m^3/s because the original design did not properly consider the system as a whole

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We can reduce the costs by choosing the right fan and controlling the flowrate

	Energy cost ($/year)		Total cost ($/year)	
Fixed speed (base case)*	239,444		353,949	
Fixed speed (opt. fan)	153,513	(36%)	251,768	(29%)
Fixed custom speed (opt. fan)	137,765	(42%)	236,020	(33%)
Variable speed (opt. fan)	99,889	(58%)	211,026	(40%)

- Fixed speed scenarios at 1800 rpm
- Minimum flowrate: 25 m^3/s
- Duct length: 1200 m
- Project life: 1 year

* The minimum flowrate delivered in this case was 31 m^3/s because the original design did not properly consider the system as a whole

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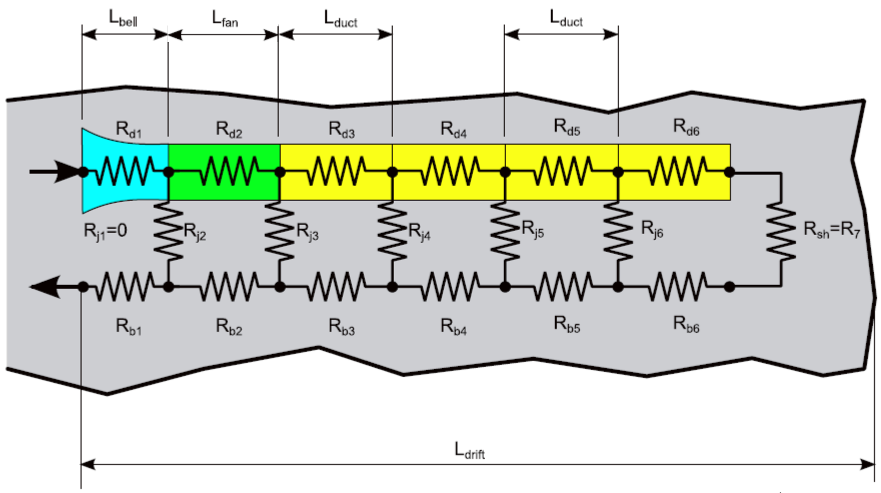
The reality is that there is leakage between the segments in a ventilation system



(Levesque, 2015)

152

Joint resistance dictates the amount of air that leaks between duct segments

- High resistance = Low leakage
- Low resistance = High leakage

With more leakage less air gets to the end of the duct but the power doesn't change much

leakage	2%	5%	10%	25%
Q fan (m^3/s)	26	26	26	28
Q face (m^3/s)	25	24	24	21
Power (kW)	52	52	52	51
Electricity cost ($/year)	36,550	36,430	36,258	35,849

- Fixed speed fan, all scenarios at same speed
- Minimum flowrate: varies
- Duct length: 200 m
- Project life: 1 year

Increasing power to meet air demand in leaky systems can be costly

leakage	2%	5%	10%	25%
Q fan (m^3/s)	26	26	28	33
Q face (m^3/s)	25	25	25	25
Power (kW)	52	55	61	90
Electricity cost ($/year)	36,550	38,743	42,974	63,271
% savings (fixing leaks)		6%	15%	42%

- Fixed speed fan, all scenarios at different speed
- Minimum flowrate: 25 m^3/s
- Duct length: 200 m
- Project life: 1 year

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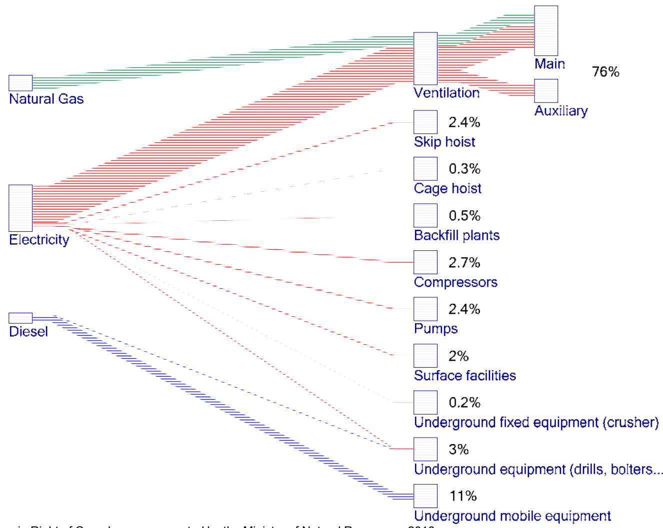
Energy consumed by ventilation system could be reduced



(Levesque, 2015)

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Energy management can result in substantial energy savings

Strategy	% Energy savings	
	Auxiliary	Total
Use low friction ducting	20 to 58	4 to 11
Match the fan to the duct	36	7
Control flowrate	42 to 58	8 to 11
Reduce leakage	6 to 42	1 to 8

Savings may differ or may not be applicable to all mines - cases must be assessed individually

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References

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