Establishing Total Airflow Requirements for Underground Metal/Non-metal Mines based on the Diesel Equipment Fleet

By:

J. Daniel Stinnette, PE

A thesis submitted to the Department of Mining Engineering

In conformity with the requirements for

the degree of Master of Applied Science

Queen’s University

Kingston, Ontario, Canada

May, 2013

Copyright © Joseph Daniel Stinnette, 2013
Abstract

Traditionally, ventilation requirements for modern, mechanized underground mines have been based upon the power of the diesel equipment fleet, with a multiplier (determined from empirical data collected and compiled over a long period of time or required by regulations) being applied in order to determine the total airflow volume requirements of entire mines and/or individual sections or working areas. Often, in the absence of unusual geographic, climatic or geologic conditions that warranted special consideration, the airflow required for the dilution of diesel exhaust products would provide sufficient ventilation for the entire mine. However, recent studies regarding the health-effects of diesel exhaust, particularly the relationship between exposure to diesel emissions and cancer in humans, coupled with additional scrutiny on so called greenhouse gas emissions, have resulted changes to the regulations for engine and equipment manufacturers to provide cleaner burning and less polluting equipment; and are currently causing profound uncertainty in the mining industry. This influence is particularly felt in the case of ventilation engineers and those involved in long-term mine planning who have responsibility for designing the ventilation systems of both existing and future mining projects around the world.

This thesis identifies the major parameters affecting airflow requirements for diesel-powered mining equipment and examines how each of them will change in scale and scope in the aftermath of regulatory changes mandating drastic reductions in the type and amount of diesel engine emissions. Culminating from this research, a new
procedure for making total airflow determinations based on the underground diesel equipment fleet is proposed and tested with a practical case-study.

Ultimately, the determination of the amount of airflow required for an underground mining operation or other sub-surface facility can depend on several factors, including the equipment fleet, ambient temperature, rock type, mining method and airway type (or use). Obtaining a universal, repeatable protocol for determining airflow quantities required for underground diesel equipment fleets is in the best interest of the industry as a whole, including ventilation practitioners, mine-planning engineers, mining financiers, executives, equipment manufacturers, and of course, the mine workers themselves, who perhaps have the most at stake of anyone involved in the equation.
Acknowledgements

I would like to thank my wife Christina, not only for her patience and understanding, but for her tireless efforts in caring for our family while I was otherwise occupied with the research and writing of this thesis. I would also like to thank my advisor Euler De Souza for his guidance and editorial insight. Finally, I was greatly assisted throughout this process by many of my colleagues who willingly and patiently shared their wisdom and experience; for their contribution I am much humbled and appreciative.
# Table of Contents

Abstract ........................................................................................................................... ii

Acknowledgements ......................................................................................................... iv

List of Abbreviations ..................................................................................................... xvii

Chapter 1 Introduction ..................................................................................................... 1

Chapter 2 Brief History of Diesel Use in Underground Mines .......................................... 4

Chapter 3 Desultory Health Effects of Diesel Contaminants ........................................... 6

3.1 Gaseous Emissions ................................................................................................... 6

3.1.1 carbon monoxide ............................................................................................. 7

3.1.2 Carbon Dioxide ............................................................................................... 7

3.1.3 Oxides of Nitrogen ......................................................................................... 8

3.2 Particulate Emissions ............................................................................................ 8

3.3 Heat ....................................................................................................................... 11

3.3.1 Heat Stress .................................................................................................... 13

3.3.2 Heat Strain ..................................................................................................... 15

3.4 Mineral Dust(s) ................................................................................................... 17

3.4.1 Classification(s) of Dust ............................................................................... 17

3.4.2 Epidemiology ................................................................................................. 18

Chapter 4 History of Diesel Emissions Regulations (Nonroad) ...................................... 22

4.1 Gaseous Emissions (Mining Industry) ................................................................... 22

4.2 Particulate Emissions (Mining Industry) ............................................................... 23

4.3 U.S. EPA Tier I - IV (Governmental Regulations) .............................................. 25

4.4 Other International Governmental Regulations .................................................... 29
Chapter 6 Advances in Diesel Engine Technology .......................................................... 57

6.1 The Original “Diesel” Engine ................................................................................. 58

6.1.1 Induction Stroke ............................................................................................ 60

6.1.2 Compression Stroke ...................................................................................... 61

6.1.3 Power Stroke ................................................................................................. 62

6.1.4 Exhaust Stroke .............................................................................................. 63

6.2 Turbochargers and Electronic Engine Management ............................................ 65

6.3 US EPA Tier IV / EU Stage IV Engine Technology ............................................. 67

6.3.1 Advanced Engine Design and Adjustment (EEC) .............................................. 68

6.3.2 High Pressure Common Rail Injection (HPCR) .............................................. 70

6.3.3 Charge Air Coolers (CAC) ............................................................................. 71

6.3.4 Variable Geometry Turbochargers (VGT) ...................................................... 72

6.3.5 Exhaust Gas Recirculation (EGR) .................................................................. 72

6.3.6 Diesel Oxidation Catalysts (DOC) .................................................................. 73

6.3.7 Diesel Particulate Filters (DPF) ..................................................................... 74

6.3.8 Selective Catalytic Reduction (SCR) ............................................................. 75

6.3.9 Combinations and Groupings of Tier IV Technology .................................... 76

Chapter 7 Environmental Sampling and Monitoring ................................................ 79

7.1 Gaseous Emissions ............................................................................................ 80

7.1.1 Gas Detector Tubes ...................................................................................... 80

7.1.2 Digital Handheld Gas Detectors .................................................................... 81

7.2 Particulate Emissions ....................................................................................... 81

7.2.1 NIOSH 5040 Method ................................................................................... 81
7.2.2 Real-time ambient sampling ................................................................. 85
7.3 Heat ........................................................................................................... 87
7.4 Mineral Dust ............................................................................................. 88
  7.4.1 Gravimetric Sampling Method ............................................................ 90
  7.4.2 Photometric Sampling Method ............................................................ 91
  7.4.3 Tapered-Element Oscillating Microbalance Method ......................... 92
Chapter 8 Factors Affecting Airflow Requirement(s) for Mines .................. 94
  8.1 Geographic Design Considerations ....................................................... 96
    8.1.1 Sub-freezing Environments (Climate) .................................................. 96
    8.1.2 Hot and/or Humid Climates ............................................................... 99
    8.1.3 Alpine (High Altitude) Environments ................................ ................ 101
    8.1.4 Proximity to Local Population(s) ....................................................... 105
    8.1.5 Regulatory Oversight ......................................................................... 107
  8.2 Geologic Design Considerations ......................................................... 108
    8.2.1 Virgin Rock Temperature / Geothermal Gradient ............................ 109
    8.2.2 Rock Stability and Ground Control .................................................. 110
    8.2.3 Strata-Specific Hazards ..................................................................... 112
  8.3 Strategic Design Criteria ........................................................................ 113
    8.3.1 Equipment Selection ......................................................................... 113
    8.3.2 Mining Method .................................................................................. 115
    8.3.3 Fixed Facilities .................................................................................. 116
    8.3.4 Conceptual Design / Best Practice .................................................... 117
    8.3.5 Auxiliary Ventilation ......................................................................... 120
8.3.6 Ventilation Economics ................................................................. 123
8.3.7 Other......................................................................................... 124

Chapter 9 Economic and Non-Economic Implications of Change .................. 126

9.1 Economic Impacts of Tier IV Engine Regulations .................................. 126
9.1.1 Equipment Cost(s) ..................................................................... 127
9.1.2 Parts and Maintenance Cost(s) .................................................... 128
9.1.3 Technician/Personnel Cost(s) ...................................................... 129
9.1.4 Fuel (ULSD) Cost(s) ................................................................. 129

9.2 Non-Economic Impacts of Tier IV Engine Regulations ......................... 130
9.2.1 Technician and Mechanic Availability ........................................ 130
9.2.2 Required Training and Specialized Skill(s) Development for Operators .. 130
9.2.3 Fuel Selection and Availability ................................................. 131

Chapter 10 Proposed New Model for Estimating Airflow Requirements for Diesel Equipment Fleets .............................................................. 133

10.1 Contaminant Products of Diesel Equipment in Underground Environments .. 135
10.1.1 Gaseous Products of Combustion .............................................. 135
10.1.2 Diesel Particulate Matter .......................................................... 135
10.1.3 Heat ....................................................................................... 136
10.1.4 Mineral Dust .......................................................................... 136

10.2 Existing Model for Calculating Diesel Equipment Airflow Requirements ...... 137
10.2.1 Statutory Compliance ............................................................... 138
10.2.2 Direct Engine Testing (EQI, etc.) .............................................. 140
10.2.3 Empirical Derivation (Experience) ........................................... 142
Chapter 12 Conclusions and Recommendations ......................................................... 202
References .................................................................................................................. 206
Appendix A Selected Design Criteria for Ventilation System Design ....................... 216
Appendix B Sensitivity of Airflow Determination Method for Diesel Heat ............... 221
Appendix C Supporting Information for the Case Study ............................................. 225
List of Tables

Table 1: Timeline of Diesel Use in Underground Mines (Kenzy and Ramani, 1980) ...... 4
Table 2: TLV and Action Limit for Heat Stress Exposure (ACGIH, 2007) ................. 14
Table 3: TLVs for Selected Aerosol Compounds (ACGIH, 2007) ......................... 21
Table 4: US EPA Tier I – III Nonroad Diesel Emission Standards (DieselNet) .......... 27
Table 5: US EPA Tier IV Nonroad Diesel Emission Standards (DieselNet) .......... 28
Table 6: World Diesel Emissions Regulations (Kubota Corporation) ................. 30
Table 7: Sample of MSHA Diesel Engine Approval Information (MSHA, 2012) ....... 42
Table 8: Fan Curve Conversion for Altitude (Density) Changes ......................... 103
Table 9: Selected Ventilation Regulations for Diesel Mining Equipment .............. 139
Table 10: Historic Ventilation Rates for Approved MSHA Engines (Haney, 2012) ... 148
Table 11: Comparison of Methods for Calculating Required LHD Airflow .......... 157
Table 12: Estimated k-factors for Various Drift Dimensions (Cross-Section) ......... 164
Table 13: Resistance Values for Selected Ventilation Controls .......................... 164
Table 14: Total Airflow Requirements for Twin Decline Development .................. 166
Table 15: Total Airflow Requirements for LOM Case (Maximum Demand) .......... 167
Table 16: Mine Weather Station Data ................................................................. 182
Table 17: Estimated Air Heating Requirements for the Access Decline Portal ...... 182
Table 18: Heater Sizing Calculation for the Access Decline Portal ..................... 183
Table 19: Estimated Air Heating Requirements for the Intake Raise .................... 184
Table 20: Heater Sizing Calculation for the Intake Raise .................................. 184
Table 21: Estimated Capital Costs for the Mine Ventilation Equipment ............... 186
Table 22: Estimated Operating Costs for the Primary Fan and Heater Installations. .. 187
Table 23: Total Airflow Requirements for Twin Decline Development....................... 190
Table 24: Total Airflow Requirements for LOM Case (Maximum Demand)............... 190
Table 25: Estimated Air Heating Requirements for the Intake Raise. ......................... 196
Table 26: Heater Sizing Calculation for the Intake Raise. ........................................ 197
Table 27: Estimated Capital Costs for the Mine Ventilation Equipment. ....................... 199
Table 28: Estimated Operating Costs for the Primary Fan and Heater Installations. .. 199
List of Figures

Figure 1: Graphical Representation of Aerosol DPM (Twigg and Phillips, 2009). ............ 9
Figure 2: Heat Production of Diesel Engines by Type/Mode. .................................. 12
Figure 3: Spectrum of Heat Strain in Humans (US Army RIEM, 2003). .................... 15
Figure 4: Tier IV Requirements during the Transitional Period (Deutz) ................... 28
Figure 5: Emissions Reductions Required to Achieve Tier IV Compliance (Deutz) ....... 29
Figure 6: DPM Reduction Techniques ................................................................. 33
Figure 7: Map of World Diesel Sulphur Levels (UNEP, 2012). .............................. 37
Figure 8: The Fundamental Chemical Reactions within a DOC. (Bugarski, et al, 2011) 45
Figure 9: Wall-flow Substrate in a Typical DPF (Diesel Technician Society, 2007) .... 48
Figure 10: Caterpillar R2900 LHD with Environmental Cabin Installed (Caterpillar) ... 51
Figure 11: NIOSH-designed Pressurization and Filtration System (Cecala, 2012) ....... 52
Figure 12: Diesel Engines circa 1922 and 2012 (Kubota Corporation) ..................... 58
Figure 13: The Diesel Cycle (Georgia State University) ....................................... 59
Figure 14: Typical Diesel Engine Cylinder/Piston (Georgia State University) ............. 60
Figure 15: Induction Stroke of a Diesel Engine (Kruse Technology) ....................... 61
Figure 16: Compression Stroke of a Diesel Engine (Kruse Technology) ................. 62
Figure 17: Power Stroke of a Diesel Engine (Kruse Technology) ......................... 63
Figure 18: Exhaust Stroke of a Diesel Engine (Kruse Technology) ....................... 64
Figure 19: Patent Drawing for Alfred Büchi's Turbocharger 1906 (STK, 2012) ........... 65
Figure 20: PM vs. NOx Curve for Diesel Engines (John Deere) ............................. 70
Figure 21: High Pressure Common Rail Injection System (Kubota) ....................... 71
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACGIH</td>
<td>American Conference of Governmental Industrial Hygienists</td>
</tr>
<tr>
<td>ALARA</td>
<td>As Low As Reasonably Achievable</td>
</tr>
<tr>
<td>DPM</td>
<td>Diesel Particulate Matter</td>
</tr>
<tr>
<td>CFR</td>
<td>Code of Federal Regulations (US)</td>
</tr>
<tr>
<td>CO</td>
<td>carbon monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>DPF</td>
<td>Diesel Particulate Filter</td>
</tr>
<tr>
<td>DOC</td>
<td>Diesel Oxidation Catalyst</td>
</tr>
<tr>
<td>EBMP</td>
<td>Emissions-Based Maintenance Program(s)</td>
</tr>
<tr>
<td>EC</td>
<td>Elemental Carbon</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency (US)</td>
</tr>
<tr>
<td>EQI</td>
<td>Exhaust Quality Index (Canada)</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>IARC</td>
<td>International Agency for Research on Cancer</td>
</tr>
<tr>
<td>LHD</td>
<td>Load Haul Dump (i.e., Scooptram, Loader)</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>LSD</td>
<td>Low-Sulfur Fuel</td>
</tr>
<tr>
<td>MSHA</td>
<td>Mine Safety and Health Administration (US)</td>
</tr>
<tr>
<td>MW</td>
<td>Molecular Weight</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Oxides of Nitrogen</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>-------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>NRCan</td>
<td>Natural Resources Canada</td>
</tr>
<tr>
<td>NIOSH</td>
<td>National Institute of Occupational Safety and Health (US)</td>
</tr>
<tr>
<td>OC</td>
<td>Organic Carbon</td>
</tr>
<tr>
<td>PEL</td>
<td>Personal Exposure Limit</td>
</tr>
<tr>
<td>PF</td>
<td>Protection Factor</td>
</tr>
<tr>
<td>PI</td>
<td>Particulate Index (US)</td>
</tr>
<tr>
<td>POC</td>
<td>Products of Combustion</td>
</tr>
<tr>
<td>PPE</td>
<td>Personal Protective Equipment</td>
</tr>
<tr>
<td>RCD</td>
<td>Respirable Combustible Dust</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>STEL</td>
<td>Short-term Exposure Limit</td>
</tr>
<tr>
<td>TC</td>
<td>Total Carbon</td>
</tr>
<tr>
<td>TLV</td>
<td>Threshold Limit Value</td>
</tr>
<tr>
<td>U/LRT</td>
<td>Upper/Lower Respiratory Tract</td>
</tr>
<tr>
<td>ULSD</td>
<td>Ultra Low-Sulfur Fuel</td>
</tr>
<tr>
<td>VRT</td>
<td>Virgin Rock Temperature</td>
</tr>
<tr>
<td>WBGT</td>
<td>Wet Bulb Globe Temperature</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Promulgation of new rules, either directly or indirectly affecting the toxic emissions of diesel engines has, and will, continue to have profound effects on the ventilation quantities necessary for diluting and removing noxious contaminants in underground environments. In much of the world, the emissions of diesel-powered equipment are governed by the U.S. Environmental Protection Agency’s (EPA’s) “tiered” emissions standards (similar regulations exist elsewhere in North America, Europe and Australasia under the aegis of various other regulatory bodies). Current EPA regulations call for all “off-highway” or nonroad diesel-powered vehicles (such as those found in the mining industry) to meet “Tier IV” emissions standards by 2014, with interim standards being enforced in a “phased” approach leading up to that time. By the time the rule is fully implemented in 2014, toxic emissions (including CO, NOₓ and Particulate Emissions) of nonroad diesel engines will be reduced by approximately 90%. Naturally, this has led to much confusion and uncertainty surrounding the calculation of airflow requirements for underground mines and other industrial excavations.

This thesis will trace the history of diesel equipment in use underground, as well as their inevitable regulation by the pertinent governmental authorities (with a focus on U.S. regulations and the Mine Safety & Health Administration in particular, as generally this country has led the world specifically in regulating diesel emissions in underground mines). An examination of the other factors affecting the calculation(s) of total airflow
required for diesel-powered equipment (e.g. dust, heat) is also included. The various health and safety risk factors associated with all potential contaminant products for diesel equipment are presented with recommendations for environmental sampling procedures for determining exposure levels. The parameters affecting ventilation system design are presented, along with a discussion of current methods for making the determination of airflow quantities required for diesel equipment and their deficiencies. Following this, a new protocol for the determination of airflow volume(s) based on the diesel equipment fleet required by planned and existing mining projects is submitted. This new method incorporates consideration of all potential contaminants generated by diesel equipment and will provide significant protection to workers regardless of the equipment chosen. The validity of the proposed method is verified with a case study, that also allows for a direct comparison with existing methods of total airflow determination.

Chapter 2 includes a brief history of diesel engine use in underground mines. Chapter 3 discusses the known health effects of the contaminant products introduced into the underground atmosphere as a result of diesel equipment operation. Diesel engine use and emissions regulations from around the world are presented in Chapter 4. Detailed analyses of the various diesel emissions control technologies are given in Chapter 5. Chapter 6 provides an overview of the history of diesel engine technology and advancement. Analyses of the methods for sampling gaseous and particulate components of diesel engine exhaust in the ambient environment (underground) are discussed in Chapter 7.
Readers who are familiar with these topics may wish to skip directly to the discussion of the factors affecting airflow requirements contained in Chapter 8, which marks the end of the review of literature and the beginning of the demonstration of the newly proposed technique(s) for making total airflow determinations for underground mines based on the diesel equipment fleet.
Chapter 2

Brief History of Diesel Use in Underground Mines

The recent history of underground mining in North America has been intertwined with the diesel engine for almost 80 years. Although the first diesel engine was thought to have been introduced into a U.S. underground metal/non-metal mine in 1939 (see Table 1), their rapid adoption by the industry did not occur until the 1960’s, when they increasingly replaced manual labour and/or pneumatic-powered devices as the “work-horses” of the industry.

Table 1: Timeline of Diesel Use in Underground Mines (Kenzy and Ramani, 1980).

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1882</td>
<td>Diesel Engine Invented</td>
</tr>
<tr>
<td>1886</td>
<td>First Gasoline Locomotive in an Underground Mine (Germany)</td>
</tr>
<tr>
<td>1897</td>
<td>Diesel Engine Reduced to a Practical Size</td>
</tr>
<tr>
<td>1906</td>
<td>First Gasoline Engine in a U.S. Mine</td>
</tr>
<tr>
<td>1915</td>
<td>Most States in the U.S. Outlaw Gasoline Engines Underground</td>
</tr>
<tr>
<td>1927</td>
<td>First Diesel Engine in an Underground Mine (Germany)</td>
</tr>
<tr>
<td>1934</td>
<td>Diesels in Belgian, British, and French Underground Coal Mines</td>
</tr>
<tr>
<td>1939</td>
<td>First Diesel Engine in a U.S. Underground Mine (Pennsylvania)</td>
</tr>
<tr>
<td>1946</td>
<td>First Diesel Engine in a U.S. Underground Coal Mine</td>
</tr>
<tr>
<td>1950</td>
<td>Development of the First Diesel-powered LHD</td>
</tr>
</tbody>
</table>

Several reasons exist for the success of the diesel engine within the context of the mining industry. Generally, these engines provide higher torque at greater efficiencies than their gasoline counterparts, while generating less carbon monoxide. Despite a greater energy density than gasoline, diesel fuel also has a significantly lower vapour
pressure and flash point, making its use in underground mines significantly safer. Operationally, diesel equipment is far more flexible than electrically-powered equipment and does not require a tethered power source or batteries (which require regular charging and charging facilities close-by).

Currently, diesel engines are ubiquitous across all underground mining and tunnelling applications, with a specialized piece of diesel machinery existing for almost every job description involved in the mining cycle, from drilling and bolting active faces, scaling, loading explosives, and performing other support work to loading and hauling ore and waste products within the ore handling system. Today, it is virtually unfathomable to imagine a modern mining scenario without the widespread use of diesel equipment.

Although current trends towards ever-larger equipment might lead some to believe that there will be fewer individual pieces of diesel equipment in the future, high demand for mineral commodities, coupled with ever-increasing mechanization and technological innovations (such as manually and/or automatically remote-controlled equipment) make it unlikely that the underground mining industry’s dependence on diesel engines will abate at any time in the near future. Furthermore, the total overall power of the diesel fleet(s) found in mining applications continues to rise across all mines and mine types.
Chapter 3
Desultory Health Effects of Diesel Contaminants

Diesel-powered mining equipment contributes to four types of contaminant that must be mitigated completely or at least partially by the mine ventilation system. Either directly or indirectly, diesel equipment produces toxic gases, particulates (DPM), heat and dust through their normal operation in mines. Diesel emissions (exhaust) consist of both gaseous and particulate emissions components and each has unique qualities that pose particular threats to humans and require individual mitigation strategies. Heat is a contaminant that varies in its effect on the ambient environment based on other environmental factors, and can range from having a beneficial effect (i.e. reducing air heating requirements in winter) to being the single most important parameter in determining the ventilation system design and infrastructure. Mineral dust created through the operation of diesel equipment also poses a variable threat to human health, which depends heavily on the content of the dust (silica, asbestos, etc.) and on the dust control measures that are implemented.

3.1 Gaseous Emissions

The toxic gaseous emissions from diesel engines consist primarily of carbon monoxide (CO), carbon dioxide (CO₂), oxides of nitrogen (NOₓ) and water vapour (H₂O).
3.1.1 Carbon Monoxide

Carbon monoxide is an odourless, colourless and flammable gas that is produced by incomplete combustion in diesel engines. Its density is just slightly less than that of ambient air. Once entrained in the lungs, it blocks the adsorption of oxygen to red blood cells, thereby indirectly depriving the cell tissues of the body of oxygen. Symptoms of CO poisoning (i.e. headache, dizziness, fatigue, nausea, etc.) mimic those of many other common illnesses, leading people (including those affected by CO poisoning) to misdiagnose their condition. Prolonged exposure can lead to death at concentrations as low as 400 ppm. At concentrations above 1500 ppm, death can occur in one hour or less. Often, victims of CO poisoning will fall asleep, and die without regaining consciousness. CO is explosive in the range of 12.5 to 74% in air.

3.1.2 Carbon Dioxide

Carbon dioxide is also a product of diesel exhaust (besides occurring naturally in the atmosphere). In its gaseous state, CO₂ is odourless and colourless as well as inflammable. Its density is roughly 1.5 times that found in typical ambient air. At higher concentrations, CO₂ can displace oxygen in the ambient environment and cause asphyxiation although it is also known to have other distinct affects upon the body aside from those of oxygen deficiency. CO₂ begins to have toxic effects on the body at concentrations greater than 3%. At this level of concentration, heart and respiratory rates are increased. Between 10 and 20% concentration in air, the symptoms of CO₂ exposure include dizziness, nausea and a loss of consciousness. Rapid death can occur at concentrations greater than 20%.
3.1.3 Oxides of Nitrogen

The oxides of nitrogen (NO\textsubscript{x}) and specifically nitrogen dioxide (NO\textsubscript{2}) are extremely toxic components of diesel emissions. NO\textsubscript{2} can appear a reddish-brown in higher concentrations, and may have a slight scent that has been described as acidic. It is heavier than ambient air. NO\textsubscript{2} reacts in the human respiratory system to produce nitric acid that causes pulmonary edema. NO\textsubscript{2} has been assumed to be toxic in humans in concentrations as little as 1 ppm. At concentrations of 10 ppm, irritation of the upper respiratory tract occurs. Tightness of the chest can rapidly occur at 80 ppm concentrations, while pulmonary edema resulting in death can occur within 30 minutes at concentrations of just 90 ppm.

3.2 Particulate Emissions

Although diesel emissions have long been recognized as a potential threat to the health of miners, one could argue that the acute and chronic effects of long-term diesel particulate exposure are not well understood. In fact, both of these effects are still the subject of much research, study and debate today, and opinions regarding the significance of the threat to humans are still changing as the results of new studies continue to be published. The particulate component of diesel engine exhaust is an area of particular concern to occupational/industrial hygienists for two primary reasons. Firstly, the particles involved are extremely small (less than one microgram \(\mu\text{g}\)) and thus highly respirable, and secondly they frequently adsorb a host of other chemicals that are
potentially harmful (e.g. aromatic hydrocarbons, aldehydes, etc.). These particular attributes make DPM an ideal carrier to deliver particularly harmful substances deep into the lungs where they are more easily transmitted or deposited into the body.

Figure 1 shows a graphical representation of DPM as it exists in the mine atmosphere.

![Graphical Representation of Aerosol DPM](image_url)

**Figure 1: Graphical Representation of Aerosol DPM (Twigg and Phillips, 2009).**

Two landmark studies linking exposure to diesel exhaust and cancer in humans were released in 2012; one by the U.S.-based National Institute for Occupational Safety and Health (NIOSH) and one by the International Agency for Research on Cancer (IARC), a part of the World Health Organization (WHO). Both of these studies are expected to have a profound effect on the way in which diesel emissions are perceived and regulated around the world.

IARC is an inter-disciplinary organization with a focus on identifying root causes of cancer and coordinating cancer research in across a multi-national population. While its
focus is on discerning and classifying potentially carcinogenic substances, it is also involved in educating, coordinating and vetting cancer research around the world. Through its relationship with the WHO, the IARC is also influential in shaping policy and regulations, although that is not specifically part of its mandate.

In June 2012, IARC issued a press release stating that it had reclassified diesel engine exhaust as a human carcinogen (Group 1) based on sufficient evidence. Previously, diesel engine exhaust was classified only as probably carcinogenic to humans (Group 2A). Although this distinction may seem relatively minor, it in fact, marks a massive shift in the world-wide perception of diesel engine exhaust, with the potential to further drive regulations around the world, particularly in developing nations, and other areas that are currently without legislation governing the control of diesel emissions. Generally, organisations such as the U.S. EPA and NIOSH follow the IARC’s recommendations for the classification of carcinogenic and suspected carcinogenic substances.

Currently, the research of both acute and chronic health effects of DPM exposure is also being conducted at private and public institutions around the world. In October of 2011, Dr. Reynard Vincent presented some preliminary findings on the subject as part of the keynote address at the Mining Diesel Emissions Council’s annual meeting in Toronto, Canada. Included amongst the findings from Dr. Vincent’s research was that particulate exposure at the levels typically found in urban and occupational settings causes measurable acute and chronic respiratory and cardiopulmonary effects. Acute effects included increased blood pressure (lasting for up to two days), increased peptide
production and increased heart rate. Chronic effects included brain inflammation and alzheimers-like pathology in those exposed to airborne particulates for extended periods of time. Additionally, reduced neurobehavioral characteristics were noted in exposed children, who were also found to have a lower IQ than non-exposed children among other chronic health effects (Vincent, 2011). The research by Dr. Vincent and his colleagues on the subject of DPM-related health effects including cardiovascular and pulmonary function, allergic responses Upper/Lower Respiratory Tract (U/LRT) irritation is ongoing.

3.3 Heat

Owing to the overall efficiency of internal combustion engines, diesel-powered equipment can be expected to produce roughly three times as much heat (kW) as mechanical work (kW). Of this heat production, approximately one-third is produced as direct radiative losses from the machine, one-third is produced as heat from the exhaust gases, and one-third is produced as shaft output power (less work done against gravity) that is later converted to heat due to frictional power losses (McPherson, 2009). The heat produced by diesel equipment is also different from that produced by other sources in that a significant portion of the heat generated is produced as latent heat. Through water vapour in the exhaust gases, emissions controls¹ and evaporation associated with the cooling system of the equipment and from tunnel walls, anywhere from 3 – 10 litres of water are produced by the equipment for each litre of fuel consumed.

¹ Many Tier IV and equivalent engine packages have added selective catalytic reduction (SCR) controls which involve the direct injection of a water-based urea solution directly to the exhaust system of the engine consumed at a rate of 3 – 5% of total fuel use.
This relationship of heat produced relative to work performed is illustrated in Figure 2.

![Diagram showing heat production of diesel engines by type/mode]

Figure 2: Heat Production of Diesel Engines by Type/Mode.

From the above figure it is obvious that the heat produced by diesel equipment relative to the work performed is significant, and must be accounted for.

Although the terms are sometimes used incorrectly, “heat stress” is generally defined as the combination of environmental heat sources as they impact the ambient
environment, while “heat strain” refers to the health effects in humans caused by the heat stress.

3.3.1 Heat Stress

Just as there are many and diverse sources of environmental heat, the methods for measuring and comparing conditions in underground environments show considerable variation, with some being better suited for application in mining environments than others.

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. For mining environments (i.e., where a radiant heat source is not visible) the wet-bulb globe temperature depends solely on the natural wet-bulb temperature and the globe temperature of the ambient air. The natural wet-bulb temperature is the temperature displayed by a wet-bulb thermometer aspirated by the ventilating air stream (the “natural” air velocity). The globe temperature is the temperature measured inside a non-reflective black hollow sphere. The relationship between wet-bulb globe temperature and natural wet-bulb and globe temperatures is given in Equation 1.

**Equation 1:**  
\[ T_{wbg} = 0.7T_{nw} + 0.3T_g \]

where:  
- \( T_{wbg} \) = wet-bulb globe temperature (°C)  
- \( T_{nw} \) = natural wet-bulb temperature (°C)
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, its function as a predictive tool is not as clear. Currently, no commercially available climatic simulators are able to forecast WBGT, making it necessary to rely on more traditional (if less telling) indicators of climate (e.g., wet-bulb temperature, dry-bulb temperature, humidity) (McPherson, 2009). Nonetheless, ACGIH presents TLVs for WBGT based upon a worker’s acclimatisation (at least 5 of the last 7 days, or 7 – 10 of the last 14 days worked in the conditions and adjusted for clothing and work rate).

Table 2 gives the ACGIH screening criteria for heat stress exposure.

Table 2: TLV and Action Limit for Heat Stress Exposure (ACGIH, 2007).

<table>
<thead>
<tr>
<th>Allocation of Work in a Cycle of Work and Recovery</th>
<th>TLV (WBGT values in °C)</th>
<th>Action Limit (WBGT values in °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light</td>
<td>Moderate</td>
</tr>
<tr>
<td>75% to 100%</td>
<td>31.0</td>
<td>28.0</td>
</tr>
<tr>
<td>50% to 75%</td>
<td>31.0</td>
<td>29.0</td>
</tr>
<tr>
<td>25% to 50%</td>
<td>32.0</td>
<td>30.0</td>
</tr>
<tr>
<td>0% to 25%</td>
<td>32.5</td>
<td>31.5</td>
</tr>
</tbody>
</table>
3.3.2 Heat Strain

Physiological responses and illnesses associated with heat exposure (from any source) vary considerably in their severity, from mild discomfort to death, with progression between the two ends of the spectrum occurring in almost infinitesimal steps. Furthermore, individuals within a given labour force may have naturally occurring (genetic) differences in their heat tolerance, and differing degrees of acclimatization, making vastly disparate reactions from the same environment possible across the workforce.

Figure 3 depicts the range of physiological response to heat stress in humans.

![Figure 3: Spectrum of Heat Strain in Humans (US Army RIEM, 2003).](image-url)
As previously discussed, clothing type and physical exertion (metabolic rate) have a great influence on the body’s ability for thermoregulation. Additionally, the following factors are listed as potentially exacerbating heat strain in humans; dehydration, salt depletion, lack of heat acclimatization, poor physical fitness, excessive body weight, skin disorders, drugs (both legal and illegal), alcohol use, inflammation and fever, gastroenteritis, chronic disease (e.g., diabetes, cardiovascular disease, congestive heart failure), and genetics (e.g., cystic fibrosis, malignant hypothermia) (US Army RIEM, 2003).

Cognitive processing and the ability to perform even routine manual tasks is also impaired by heat stress under some environmental conditions (Hardcastle, 2012). Although the effects of such mental deterioration caused by heat stress have not been empirically demonstrated, this area is currently under study. Although difficult to quantify, the potential implications for worker health and safety (accident prevention), and even productivity are clear.

General mitigation for heat strain consists of an active monitoring program, with effective administrative controls and a clearly defined identification and action plan in cases where heat strain is suspected. The risk of heat strain can be significantly lessened by taking time to determine workers natural response(s) to heat stress and providing them time to acclimatize to their environment. Adequate supplies of water, salt tablets and regular work/rest scheduling can provide additional protection to the workers. If these are insufficient, other means of cooling may be required, ranging from
specifically-designed garments, to air-conditioned equipment cabins or mechanical refrigeration of the ventilating air.

3.4 Mineral Dust(s)

Although not directly emitted from diesel engines, most diesel-powered equipment will produce mineral dust when operated underground. For this reason, mineral dust(s), or “dust” will be addressed as a contaminant product of underground diesel equipment for the purposes of this thesis.

3.4.1 Classification(s) of Dust

Mineral dust(s) found in mining environments are generally classified in one of two ways; first by their component particle size (this group is often abbreviated into two fractions, respirable and non-respirable) and secondly by their mineral composition (e.g. silica, asbestos, coal, etc.).

When classifying dust according to size, it is common to refer to the projected area of a particle in comparison to a similarly-sized spherical particle, or the equivalent geometric diameter. Respirable dust refers to that fraction which is small enough to reach into the lungs, bypassing the body’s natural defence mechanisms (e.g., mucous membranes, cilia, etc.). These particles range from a maximum equivalent diameter of 7 microns down to particles much smaller than a micron. These are considered the most dangerous dust fraction, as their small size means they can remain suspended in air
almost indefinitely, and are easily transmitted and deposited in the lungs. Their small size also allows them to react much more readily with the body’s tissues and chemistry once inside. Since dust particles less than 10 microns equivalent diameter are invisible to the naked eye, respirable dust cannot be seen; however, if visible (i.e., non-respirable) dust is present in an airstream, it should be assumed that respirable dust is also present (McPherson, 2009)

3.4.2 Epidemiology

The negative health effects of various forms of dust can vary significantly from minor discomfort to acute and life-threatening symptoms. McPherson identifies five sub-categories of dust in his 2009 text, based on the specific nature of the hazard they present to human health. The five groups are:

1. Toxic Dust – consisting of dusts that can cause chemical reactions within the body resulting in negative health impacts (e.g., arsenic, lead, cadmium, nickel, selenium, etc.).

2. Carcinogenic Dust – consisting of dusts that result in tumor growth when inhaled into the lungs (e.g., radon daughters\(^2\), asbestos, quartz, DPM, etc.).

3. Fibrogenic Dust – consisting of dusts that scar lung tissue due to a scouring effect (e.g. quartz, asbestos, talc, mica).

\(^2\) Although radon is a gas, it decays into microscopic solid particles that commonly adhere to aerosol particulates in the atmosphere. These particles are known as radon daughters and represent one of the most dangerous forms of dust due to the cell mutations caused by alpha and beta radiation that occurs within the lungs (McPherson, 2009).
4. Explosive Dust – consisting of dusts that present a risk of explosion (e.g. coal, sulphides, other metallic dusts).\textsuperscript{3}

5. Nuisance Dust – consisting of dusts that result in irritation of the eyes, nose, throat, etc., without causing negative long-term health effects (e.g., limestone, gypsum, halites and potash).

Although all five types are possible in modern mining environments, it is most common to encounter mineral dusts that fall into the categories of Fibrogenic and/or Nuisance dusts. There are obviously many exceptions to this, and individual geology/morphology is profoundly influential in determining what types of mineral dusts will be encountered at any given mining operation.

Respirable mineral dust is inhaled into the lungs as part of the normal breathing process, and becomes deposited deep into the lungs where it impacts the body in a number of damaging ways. Fibrogenic dusts cut into lung tissue causing scars to form and build up over time, greatly diminishing lung capacity and function. Other dusts (e.g., coal) simply amalgamate in the lungs to form effective barriers to normal pulmonary function. Carcinogenic dusts cause the formation of tumours that may appear in the lungs and/or spread to other parts of the body.

The list of chronic dust-related diseases is well documented and studied, particularly within the mining industry, where this has been perceived as a problem as far back as \textsuperscript{3} These dusts predominantly present a safety hazard rather than a health hazard.
1912, when the Union of South Africa introduced laws governing gold mining activities in the Witwatersrand (McPherson, 2009). Currently, pulmonary diseases associated with mineral dusts include pneumoconiosis (including coal dust “black lung”), asbestosis, silicosis and various cancers of the bronchial system. Each of these diseases has been proven to stem from exposures in mines, and each is capable of severe debilitation up to and including death.

The prevention of dust-related diseases within the mining industry can be achieved through the implementation of a variety of engineering and administrative controls designed to minimize the exposure of workers to potentially harmful mineral dusts, coupled with an active program to monitor and identify the health of individual workers through regular medical screening for those at risk (i.e. regular chest x-rays).

Table 3 gives the ACGIH TLVs for some selected aerosol compounds.
Table 3: TLVs for Selected Aerosol Compounds (ACGIH, 2007).

<table>
<thead>
<tr>
<th>Substance (Documentation Date)</th>
<th>TWA</th>
<th>STEL</th>
<th>Notations</th>
<th>MW</th>
<th>TLV Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum oxide</td>
<td>10 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>102.0</td>
<td>LRT irr; pneumoconiosis</td>
</tr>
<tr>
<td>Arsenic (1990)</td>
<td>0.01 mg/m³</td>
<td>-</td>
<td>A1; BEI</td>
<td>74.9</td>
<td>Lung cancer</td>
</tr>
<tr>
<td>Asbestos (1994)</td>
<td>0.1 f/cc</td>
<td>-</td>
<td>A1</td>
<td>N/A</td>
<td>Pneumoconiosis, mesothelioma</td>
</tr>
<tr>
<td>Calcium silicate (1988)</td>
<td>10 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>N/A</td>
<td>URT irr</td>
</tr>
<tr>
<td>Calcium sulphate (2005)</td>
<td>10 mg/m³</td>
<td>-</td>
<td>-</td>
<td>136.1</td>
<td>Nasal symptoms</td>
</tr>
<tr>
<td>Carbon black (1985)</td>
<td>3.5 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Coal anthracite (1995)</td>
<td>0.4 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>-</td>
<td>Lung dam; pulm fibrosis</td>
</tr>
<tr>
<td>Coal bituminous (1995)</td>
<td>0.9 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>-</td>
<td>Lung dam; pulm fibrosis</td>
</tr>
<tr>
<td>Flourides (1979)</td>
<td>2.5 mg/m³</td>
<td>-</td>
<td>A4; BEI</td>
<td>Varies</td>
<td>Bone dam; flourosis</td>
</tr>
<tr>
<td>Graphite (1988)</td>
<td>2 mg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Pneumoconiosis</td>
</tr>
<tr>
<td>Kaolin (1990)</td>
<td>2 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>-</td>
<td>Pneumoconiosis</td>
</tr>
<tr>
<td>Magnesium Oxide (200)</td>
<td>10 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>40.3</td>
<td></td>
</tr>
<tr>
<td>Mica (1962)</td>
<td>3 mg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Pneumoconiosis</td>
</tr>
</tbody>
</table>

**Nuisance dusts**

<table>
<thead>
<tr>
<th>Substance</th>
<th>TWA</th>
<th>STEL</th>
<th>Notations</th>
<th>MW</th>
<th>TLV Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Mist - mineral (1992)</td>
<td>5 mg/m³</td>
<td>10 mg/m³</td>
<td>(-)</td>
<td>-</td>
<td>(Lung)</td>
</tr>
<tr>
<td>Portland Cement (1992)</td>
<td>10 mg/m³</td>
<td>(-)</td>
<td>(-)</td>
<td>-</td>
<td>(Irr; dermatitis)</td>
</tr>
<tr>
<td>Radon Daughters</td>
<td>4 WLM/year</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Silica crystalline α Quartz (2205)</td>
<td>0.025 mg/m³</td>
<td>-</td>
<td>A2</td>
<td>60.1</td>
<td>Pulmonary fibrosis; lung cancer</td>
</tr>
<tr>
<td>Silicon Carbide (1999)</td>
<td>10 mg/m³</td>
<td>-</td>
<td>-</td>
<td>60.1</td>
<td>URT irr</td>
</tr>
<tr>
<td>Talc (1980)</td>
<td>2 mg/m³</td>
<td>-</td>
<td>A4</td>
<td>-</td>
<td>LRT irr</td>
</tr>
<tr>
<td>Zinc Oxide (2001)</td>
<td>2 mg/m³</td>
<td>10 mg/m³</td>
<td>-</td>
<td>81.4</td>
<td>Metal fume fever</td>
</tr>
</tbody>
</table>
Chapter 4

History of Diesel Emissions Regulations (Nonroad)

Under the U.S. Bureau of Mines, emissions testing of diesel engines was performed as early as the 1950s under Schedule 24 (30 CFR part 32). Part 32 was later amended by Part 7 to allow for third-party engine testing (Haney, 2012).

4.1 Gaseous Emissions (Mining Industry)

The gaseous components of diesel emissions have been regulated in metal/non-metal mines in the U.S. since 1973. In 1988, an advisory committee for the Mine Safety & Health Administration (MSHA) recommended a three-part approach to the regulation and control of diesel emissions in underground mines. This was the first time (in the U.S.) that the gaseous and particulate emissions from diesel engines were specifically targeted for regulation. The impetus for this decision was the position of both NIOSH and the International Agency for Research on Cancer (IARC) that labelled diesel emissions as a “probable” carcinogen. TLV values for CO, CO₂, NO and NO₂ were recommended; there was no recommendation proposing a TLV for diesel particulate matter (DPM) at this time, owing largely to the fact that no accurate method for the measurement of DPM existed.

Currently, the MSHA TLVs for the gaseous components of diesel exhaust; CO (25 ppm), CO₂ (5000 ppm), NO (25 ppm), and NO₂ (3 ppm) have been adopted in accordance with the standard(s) set in place by the ACGIH. Most other countries in the
developed world have adopted similar standards for mining, with some going a step further by being more conservative with requirements for individual gases. In Germany, the TLV for NO$_2$ is expected to drop to “less than” 1 ppm (Dahmann, 2010); this despite the fact that most experts agree that there is no accurate means of measuring the NO$_2$ content at those levels.

4.2 Particulate Emissions (Mining Industry)

In order to correct the obvious deficiency in the 1988 regulations (namely that no existing method for measuring particulate diesel emissions existed that would produce results at the level of accuracy needed) a NIOSH team led by Dr. Eileen Birch developed the 5040 Method (NIOSH, 1998). This method involves the determination of organic carbon (OC) and elemental carbon (EC) as a surrogate for DPM through the use of a thermal-optical analyzer. A specially designed and application-specific software aids in the quantification of the EC/OC split as well as the total carbon (TC) present on the filter. By knowing the area of the filter punch, the area of the filter, and the total volume of air pulled through the sampling apparatus, it is possible to determine the DPM (Carbon) content of the ambient air in units of micrograms per cubic meter (μg/m$^3$), which subsequently became the standard for measuring ambient DPM content for mines around the world owing to its precision (1 μg Carbon).

As part of the landmark diesel Particulate Matter “Final Rule” in the U.S., a DPM TLV of 160 μg/m$^3$ TC was implemented in a phased-approach over a period of approximately six years beginning in 2001. The NIOSH 5040 method is prescribed in this rule for
determining compliance with the MSHA standard, along with other provisions covering required sampling by the mines (“as necessary to ensure compliance”) and training of employees exposed to DPM regarding the specific hazards and other requirements.

Prior to the development of the 5040 Method, determinations of DPM or “respirable combustible dust” (RCD Method) were performed gravimetrically, similar to other methods for respirable dusts by simply weighing the filter before and after its placement into a 400 °C oven for two hours. This method has several deficiencies when applied to DPM, however; being susceptible to contamination from other dusts, fumes and oil mist, and generally not being accurate at the level(s) (40 μg) that were eventually determined to be necessary to enforce the PEL for ambient DPM in the U.S. In some other countries, notably Canada (where regulation of mines is implemented at the provincial level), this method was utilized more recently. It is notable that in Ontario, the DPM regulations were tightened in 2011 to a level of TC or 1.3 X EC < 400 μg/m³ TC (Ontario MOL, 2011).

In general, mining regulations around the world seem to be implementing TLVs for DPM at similar levels, and these are determined by similar methods as those employed by MSHA in cases where DPM is regulated by the relevant occupational health and safety authorities. German and Swiss mining law stipulates maximum allowable DPM levels of 100 μg/m³ TC for all underground non-coal mines, and the Australian Institute of Occupational Hygienists (AIOH) has also chosen to recommend that workers there not exceed exposure to DPM at levels greater than 100 μg/m³ EC (AIOH, 2007).
Ironically, perhaps the regulation with the greatest effect on the use of diesel equipment in underground mining practice came not from MSHA, but resulted from the regulation of nonroad diesel-powered vehicles by the U.S. Environmental Protection Agency (EPA). In an effort to improve overall air quality, the U.S. EPA mandated compliance with the so called “Clean Air Rules of 2004”, that were designed to decrease emissions from nonroad diesel engines by more than 90%, being implemented in a phased approach, with the most stringent requirements (Tier IV) becoming effective in 2014. In addition to decreasing emissions based on a variety of engine controls and technological changes, the maximum fuel sulphur content was limited to 15 ppm by the year 2010.

Due to the nature of these regulations and to the fact that they were targeted directly at the engine manufacturers, these changes stand to drastically reduce the emissions from the diesel fleets in underground mines, regardless of other environmental factors that are present. However, as will be examined later in Section 8, it is too early to know how much this will impact the determination of airflow volume required for the safe operation of underground mines as a whole.

In 1994, the US EPA began restricting the emissions of nonroad diesel-powered equipment. “Tier I” of the proposed regulations was phased in for engines greater than 50 brake horsepower (bhp) or 37 kilowatts (kW) starting in 1996. In 1996, a “Statement of Principles” between the EPA, California Air Resources Board (CARB) and the engine
manufacturers Caterpillar, Cummins, Deere, Detroit Diesel, Deutz, Isuzu, Komatsu, Kubota, Mitsubishi, Navistar, New Holland, Wis-Con, and Yanmar regarding nonroad diesel engines was signed (Dieselnet, 2012). EPA Tier II standards for engine emissions were phased in between 2001 and 2006, with further reductions required beginning in years 2006 through 2008 as part of the Tier III standards. Tier IV (including Tier IV interim), the final, and most restrictive regulations of diesel emissions, began in 2008 and will be gradually implemented through 2015. By the time that the Tier IV final standards are fully enforced, the engine-out NOx and PM emitted by compliant diesel engines will be reduced by approximately 90%.

The fuel-sulphur content standards for the EPA regulations began in 2007, with all nonroad diesel fuel being restricted to a maximum of 500 ppm sulphur content. The fuel sulphur content was further reduced by the standard to a maximum of 15 ppm beginning in 2010.

Table 4 shows the US EPA regulations for Tier I through Tier III. Tier IV Standards are given in Table 5. Figure 4 provides an overlapping view of the requirements during the transitional period. A graphical representation of the reduction in emissions required to achieve Tier IV compliance is given on Figure 5.
Table 4: US EPA Tier I – III Nonroad Diesel Emission Standards (DieselNet).

<table>
<thead>
<tr>
<th>Engine Power</th>
<th>Tier</th>
<th>Year</th>
<th>CO</th>
<th>HC</th>
<th>NMHC+NOx</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW &lt; 8 (hp &lt; 11)</td>
<td>Tier 1</td>
<td>2000</td>
<td>8.0</td>
<td>–</td>
<td>10.5</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2005</td>
<td>8.0</td>
<td>–</td>
<td>7.5</td>
<td>–</td>
<td>0.8</td>
</tr>
<tr>
<td>8 ≤ kW &lt; 19 (11 ≤ hp &lt; 25)</td>
<td>Tier 1</td>
<td>2000</td>
<td>6.6</td>
<td>–</td>
<td>9.5</td>
<td>–</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2005</td>
<td>6.6</td>
<td>–</td>
<td>7.5</td>
<td>–</td>
<td>0.8</td>
</tr>
<tr>
<td>19 ≤ kW &lt; 37 (25 ≤ hp &lt; 50)</td>
<td>Tier 1</td>
<td>1999</td>
<td>5.5</td>
<td>–</td>
<td>9.5</td>
<td>–</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2004</td>
<td>5.5</td>
<td>–</td>
<td>7.5</td>
<td>–</td>
<td>0.6</td>
</tr>
<tr>
<td>37 ≤ kW &lt; 75 (50 ≤ hp &lt; 100)</td>
<td>Tier 1</td>
<td>1998</td>
<td>–</td>
<td>–</td>
<td>9.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2004</td>
<td>5.0</td>
<td>7.5</td>
<td>–</td>
<td>–</td>
<td>0.4</td>
</tr>
<tr>
<td>75 ≤ kW &lt; 130 (100 ≤ hp &lt; 175)</td>
<td>Tier 1</td>
<td>1997</td>
<td>–</td>
<td>–</td>
<td>9.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2003</td>
<td>5.0</td>
<td>6.6</td>
<td>–</td>
<td>–</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Tier 3</td>
<td>2007</td>
<td>5.0</td>
<td>4.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>130 ≤ kW &lt; 225 (175 ≤ hp &lt; 300)</td>
<td>Tier 1</td>
<td>1996</td>
<td>11.4</td>
<td>1.3</td>
<td>9.2</td>
<td>0.54</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2003</td>
<td>3.5</td>
<td>6.6</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Tier 3</td>
<td>2006</td>
<td>3.5</td>
<td>4.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>225 ≤ kW &lt; 450 (300 ≤ hp &lt; 600)</td>
<td>Tier 1</td>
<td>1996</td>
<td>11.4</td>
<td>1.3</td>
<td>9.2</td>
<td>0.54</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2001</td>
<td>3.5</td>
<td>6.4</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Tier 3</td>
<td>2006</td>
<td>3.5</td>
<td>4.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>450 ≤ kW &lt; 560 (600 ≤ hp &lt; 750)</td>
<td>Tier 1</td>
<td>1996</td>
<td>11.4</td>
<td>1.3</td>
<td>9.2</td>
<td>0.54</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2002</td>
<td>3.5</td>
<td>6.4</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Tier 3</td>
<td>2006</td>
<td>3.5</td>
<td>4.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>kW ≥ 560 (hp ≥ 750)</td>
<td>Tier 1</td>
<td>2000</td>
<td>11.4</td>
<td>1.3</td>
<td>9.2</td>
<td>0.54</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Tier 2</td>
<td>2006</td>
<td>3.5</td>
<td>6.4</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
</tbody>
</table>

† Not adopted, engines must meet Tier 2 PM standard.
Table 5: US EPA Tier IV Nonroad Diesel Emission Standards (DieselNet).

<table>
<thead>
<tr>
<th>Engine Power</th>
<th>Year</th>
<th>CO</th>
<th>NMHC</th>
<th>NMHC + NOx</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW &lt; 8 (hp &lt; 11)</td>
<td>2008</td>
<td>8.0 (5.0)</td>
<td>–</td>
<td>7.5 (5.6)</td>
<td>–</td>
<td>0.4a (0.3)</td>
</tr>
<tr>
<td>8 ≤ kW &lt; 19 (11 ≤ hp &lt; 25)</td>
<td>2008</td>
<td>6.0 (4.9)</td>
<td>–</td>
<td>7.5 (5.6)</td>
<td>–</td>
<td>0.4 (0.3)</td>
</tr>
<tr>
<td>19 ≤ kW &lt; 37 (25 ≤ hp &lt; 50)</td>
<td>2008</td>
<td>5.5 (4.1)</td>
<td>–</td>
<td>7.5 (5.6)</td>
<td>–</td>
<td>0.3 (0.22)</td>
</tr>
<tr>
<td>37 ≤ kW &lt; 56 (50 ≤ hp &lt; 75)</td>
<td>2013</td>
<td>5.5 (4.1)</td>
<td>–</td>
<td>8.7 (3.5)</td>
<td>–</td>
<td>0.3 (0.22)</td>
</tr>
<tr>
<td>56 ≤ kW &lt; 120 (75 ≤ hp &lt; 175)</td>
<td>2012-2014c</td>
<td>5.0 (3.7)</td>
<td>–</td>
<td>8.7 (3.5)</td>
<td>–</td>
<td>0.3 (0.22)</td>
</tr>
<tr>
<td>120 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)</td>
<td>2011-2014d</td>
<td>3.5 (2.6)</td>
<td>0.19 (0.14)</td>
<td>–</td>
<td>0.40 (0.30)</td>
<td>0.02 (0.015)</td>
</tr>
</tbody>
</table>

In engines of 56–560 kW rated power, the NOx and HC standards are phased-in over a few year period, as indicated in the notes to Table 3. The initial standards (PM compliance) are sometimes referred to as the ‘interim Tier 4’ or ‘Tier 4I’, transitional Tier 4 or ‘Tier 4 A’, while the final standards (NOx/HC compliance) are sometimes referred to as ‘Tier 4 B’.

As an alternative to introducing the required percentage of Tier 4 compliant engines, manufacturers may certify all their engines to an alternative NOx limit in each model year during the phase-in period. These alternative NOx standards are:

- Engines 56–120 kW:
  - Option 1: NOx = 2.2 g/kWh = 1.7 g/bhp-hr (Tier 2 credits used to comply, MY 2012-2013)
  - Option 2: NOx = 3.4 g/kWh = 2.5 g/bhp-hr (no Tier 2 credits claimed, MY 2012-2014)
- Engines 130–560 kW: NOx = 2.0 g/kWh = 1.5 g/bhp-hr (MY 2011-2013)

Engines Above 560 kW: Tier 4 emission standards for engines above 560 kW are listed in Table 4. The 2011 standards are sometimes referred to as ‘transitional Tier 4’, while the 2015 limits represent final Tier 4 standards.

Regulated Emissions: NOx / HC / CO / PM - g/HP-hr

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HP=11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11SHP=25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25HP=50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50HP=75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75HP=100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100HP=175</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>175HP=300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300HP=500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600HP=750</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Tier IV Requirements during the Transitional Period (Deutz).
In addition to the stringent restriction of the most toxic diesel emissions, the EPA also mandates the manner in which the engines will be tested for compliance purposes. For certification/verification of compliance with the Tier IV standards, diesel engines must be measured with the ISO8178 C1, 8-mode steady-state test as well as the Nonroad Transient Cycle test and given a not-to-exceed (NTE) emission limit. The tests are designed to test various duty cycles, and mimic the peaks and troughs of power demand for nonroad vehicle applications.

4.4 Other International Governmental Regulations

In countries governed by the European Union (EU), nonroad diesel engine emissions are controlled by Stage I through Stage IV regulations that are roughly equivalent to
Tiers I – IV of the US EPA standards. Canada has adopted the US EPA standards formally. Other nations that have implemented specific standards applicable to nonroad diesel engine emissions include Japan, Turkey, South Korea, India, China and Brasil. The scope and breadth of these statutes vary greatly, from equal to the US/EU standards to marginal control of engine-out emissions. For mining projects, understanding the locally applicable legal standards for both diesel engine emissions and fuel quality are imperative. Even in some locations without specific laws governing the use of diesel equipment in underground mines, large, international mining companies voluntarily adopt more stringent standards recognized by the international community (i.e. EPA, Tier IV or EU Stage IV). A summation of current (and projected) governmental regulations for diesel engine emissions is shown on Table 6.

Table 6: World Diesel Emissions Regulations (Kubota Corporation).
Chapter 5

Practical Control of Diesel Emissions Underground

The options for the treatment and reduction of diesel emissions have increased dramatically in the past decade. A myriad of control strategies and products are now available to industrial consumers, all of varying scopes, efficiencies, and expense. Noting the high cost of some of the available options, the question often arises as to what controls apply where, and how a combination of options can provide the most efficient use of the allocated resources. Based upon information gathered from the sampling and analysis, various combinations of emissions control measures can be determined and analyzed for any particular application. This “targeted” approach allows mine operators to concentrate their efforts on any areas of greatest need, and address their concerns in the most efficient manner possible. An important part of this process is the realization that there is no one answer for the reduction of DPM exposure.

Furthermore, each DPM control technology or strategy is applied in various scopes, from mine-wide application, to the modification or replacement of individual pieces of equipment. The types and quantities of the controls applied can also have a direct effect on the results achieved by their application; however, it is important to note that in such a dynamic system, specific results are nearly impossible to predict. Each control applied will not only affect the propagation of emissions in the underground environment, but may also affect the usefulness of some other measures employed.
Consider that the high sulphur content of some off-road diesel fuel can completely preclude the use of most particulate filters and exhaust after-treatment devices. Catalyzed diesel particulate filters (DPF’s) have high efficiencies and favorable regeneration characteristics, but can also generate increased NO\textsubscript{x} emissions, which may place an added burden on the ventilation system. Although the individual problems identified in the analysis stage must each be addressed, it is important not to lose sight of the effects of any proposed changes on the whole system.

The effects of DPM are also additive, and the exposure level of individuals increases with the number of upstream sources of DPM. This is an important consideration when choosing DPM reduction technologies/applications, since controls which affect upstream sources and equipment can have a great influence on the exposure of personnel working downstream.

Figure 6 shows various DPM reduction techniques, as well as the scope of their utility in reducing emissions. Items near the bottom of the pyramid have a broader application and effective area than those toward the top of the pyramid, which are generally more targeted and application specific. The top of the pyramid represents operator-specific protection, and should only be used if other methods are ineffective at reducing exposures below the prescribed levels.
The various emissions control options available to mine operators will be discussed in greater detail in the following sub-sections. These include ventilation, fuels and fuel additives, emissions-based maintenance programs, engines, exhaust aftertreatment, environmental cabins, administrative controls and personal protective equipment.

5.1 Ventilation

The dilution of diesel emissions with fresh air is one of the most commonly used and most easily understood methods of control. Whether used to control gaseous or particulate contaminants, the means of calculating the concentration of a particular pollutant is governed by the following equation.

\[
C = \frac{G_f}{Q_f}
\]

where: \( C \) = contaminant concentration (%)
\[ G_f = \text{contaminant flow-rate (m}^3/\text{s}) \]

\[ Q_f = \text{ventilation flow-rate (m}^3/\text{s}) \]

This results in a simple, directly proportional relationship between the quantity of fresh air delivered to any given area (i.e. mine, section, heading, etc.) and the concentration of the contaminant in question. For example, if the total delivered airflow to a mine is doubled, the concentration of CO in the exhaust will be halved. It is this simple to calculate and predictable result that makes dilution such an effective means of controlling diesel emissions. However, the dilution of diesel emissions via the mine’s primary or auxiliary ventilation systems does have its limitations, as the total volume allowed by the mine infrastructure usually has a hard limit (forced by economic or safety and health criteria), above which any increases are only possible with significant economic investments.

5.1.1 Primary Ventilation System(s)

The design, implementation and maintenance of a comprehensive underground ventilation system is a complex and often expensive proposition, and one that is dependent on a wide variety of parameters unique to each individual mine or facility. The primary mine ventilation system is responsible for delivering the total airflow required (based on the relevant operating parameters, i.e. operating diesel equipment, heating, cooling, dust control, etc.) to the mine ventilation circuit with the correct distribution provided by controls such as booster fans, doors, regulators and bulkheads. Since delivery of the required ventilating air is accomplished via the physical mine
infrastructure (declines, raises, etc.), the total quantity is limited by the upper limit(s) or carrying capacity of that infrastructure.

For example, long established upper velocity limits⁴ for dedicated ventilation raises allow a maximum of approximately 20 m/s (McPherson, 2009). While velocities above this limit are certainly possible, they arrive only with a significant increase to the fan(s) operating pressure and corresponding penalties in the form of power and cost. Thus, if dilution via the primary ventilation system is to be utilized as a means of lowering the diesel emissions exposure rates in a mine, it will only be possible insofar as the current ventilation system has capacity for the required increase in flow. If additional infrastructure is required, a careful economic analysis must be conducted in order to justify the cost of the new mine infrastructure, and to ensure that a more cost-effective application of resources does not exist.

5.1.2 Secondary (Auxiliary) Ventilation System(s)

Secondary or auxiliary ventilation systems provide the needed quantity of airflow to working faces in dead-end headings and drifts. While the size of mine infrastructure and other environmental conditions such as dust or heat may place limits on the primary system, auxiliary systems are limited only by the size of fan/duct combination and the distance to the working face; however, they are dependent on the primary system for an adequate quality of available airflow. As long as a sufficient quantity of uncontaminated air is available, auxiliary systems remain an easy to implement and relatively

---

⁴ Some of these “long-established” limits are currently being re-examined due to relatively recent and significant changes to the economics of airway development in mines, specifically the cost of developing vertical airways.
inexpensive means of providing control of diesel emissions. In some instances, however, they may not be capable of providing the required airflow to the source of the contaminants, usually due to some constriction of the duct size due to the localized equipment in operation or the distance of the working face from the source of fresh air, or some combination of the two. In these instances, some other means of controlling the contaminants from the diesel engines directly at the source must be identified and implemented.

5.2 Fuel Source(s) and Additives

The choice of fuel utilized in the diesel equipment can have a significant impact on both the quantity and quality of the emissions produced by the engine. Different fuels and fuel types can have disparate emissions profiles (e.g. particulate size, distribution, gaseous fractions, etc.) and may also impact the scope and applicability of other emissions controls.

5.2.1 Low Sulphur and Ultra-Low Sulphur Diesel

Low Sulphur (500 ppm) diesel fuel (LSD) has been required by the U.S. EPA for nonroad equipment since 2007, and Ultra-Low Sulphur fuel (15 ppm), also known as ULSD, will be universally required by 2014 (US EPA, Diesel Fuel page). The percentage of organic carbon particulates in diesel emissions decreases roughly proportional to the amount of sulphur present in the fuel (Bugarski et al, 2011). Although almost all countries in the developed world have altered their refining process(es) to supply only this type of fuel (Low Sulphur or ULSD), it is important to
note that in some developing nations, a consistent supply of low or ultra-low Sulphur fuel is difficult or impossible to come by. This is important, not just for the proportional increase in particulate emissions associated with the Sulphur content itself, but because the Sulphur content actually precludes the use of many of the more common exhaust after-treatment devices, which become easily plugged by the organic particulates and prematurely plug up and fail, often causing significant damage to the engine and equipment.

Figure 7 depicts the maximum standards for diesel fuel sulphur levels around the world (where such standards exist).

---

*Figure 7: Map of World Diesel Sulphur Levels (UNEP, 2012).*
For ULSD fuel that is transported by pipeline at any point during its life-cycle, additional problems associate with fuel-filter plugging and injector failures have been reported (Forbush, 2011). These problems have been traced to the addition of drag reducers (stearamides) and/or corrosion inhibitors (carboxylate salts) by fuel manufacturers prior to transport. Additional fuel additives are available to reduce or eliminate the negative effects of the stearamides and carboxylate salts, but these must be purchased and added to the fuel separately by the end-user.

5.2.2 Biodiesel

Biodiesel is a generic term for several diesel-fuel substitutes that may include recycled frying oil (yellow grease) or any number of natural or synthetically produced products that can be used in diesel engines. The most effective fuel biodiesel currently available is derived from soy-beans, and provides particulate emissions reductions roughly proportional to the quantity of biodiesel utilized in the consuming engine. Since biodiesel is commonly blended with petroleum-based diesel fuel, they are commonly designated by the percentage of biodiesel in the overall fuel blend, with B-20 representing a fuel containing 20% biodiesel and B-100 equivalent to pure biodiesel. Typical blend ratios found in mining range from B-5 to B-100, based on the mine operator’s specific needs as well as fuel availability. Biodiesel also results in changes to the particulate fraction of the emissions, which may have adverse effects on human health (Bugarski, et al, 2011), but this topic is only now being identified and studied. Furthermore, biodiesel blends greater than B-20 can have significantly detrimental
effects on the seals and gaskets in modern diesel engines, and may void the manufacturer’s warranty. If biodiesel blends greater than B-20 are to be used in mines, care should be taken to minimize the potential negative effects of the fuel on the engines of the equipment fleet. Other operational considerations for the use of biodiesel include the separation of fuel sources for equipment not required (or capable) to run biodiesel blends and special handling of the blended fuel in climates that experience sub-freezing temperatures.

The relative cost(s) of biodiesel fuel options varies greatly between different fuel types based on the fuel type and source. Yellow grease (recycled cooking oil) is generally the cheapest, while soy-based products are often significantly higher in cost than traditional diesel fuel. In many locations, the cost of biodiesel fuel is offset by government-sponsored credits or subsidies designed to promote their use. Since there are currently no mandatory regulations governing the production of biodiesel, quality and consistency of the delivered fuel remain a concern in many parts of the world.

5.2.3 Aftermarket fuel additives (emissions reducers)

A variety of aftermarket fuel additives designed to reduce various components of diesel engine emissions are currently available (although most are not approved for Tier IV engines). The majority of these are variations on base or precious-metal catalytic solutions that are added in small quantities to the fuel either in bulk or at the equipment. The effectiveness of these types of fuel additives is not established, and in any case, highly variable from product to product. For the purpose(s) of this author, urea-type
injection systems that are part of Tier IV engine systems are not included in this sub-segment of products as they are considered part of the larger engine system designed to meet the more stringent emissions requirements of the North American and European regulatory bodies.

5.3 Emissions-based Maintenance Program(s)

Emissions-based maintenance programs (EBMP) have proven to be one of the most effective means of managing (and lowering) diesel emissions in mines. Preventative maintenance (PM) programs performed on heavy equipment should be expanded to include DPM control. Although almost all mines have some type of preventative maintenance program in effect, programs that are specifically tailored to measuring and tracking diesel emissions can provide significant reduction in engine-out emissions and often have ancillary benefits that can go some way towards defraying the cost of their implementation. In some cases, programs of this nature have been capable of removing up to 50% of DPM emissions and 60% of CO emissions (Forbush, 2001). In addition to reducing the engine-out emissions, these programs often result in reductions to fuel consumption, vehicle down-time and replacement parts (McGinn, 2000).

Specific pieces of underground equipment within a mine may be functioning poorly and demand immediate attention. Identifying problem vehicles is an important method for eliminating isolated and unpredictable high exposures experienced once mine-wide
reductions in emission levels are made. This is another benefit of programs that measure and track the emissions of an equipment fleet over time.

5.4 Engine Type/Specification

The type of powerplant selected for an underground vehicle can have a dramatic effect on the emissions profile put out by that vehicle. With multiple different engine types, manufacturers and technologies available on the market, the range of emissions emitted are just as varied. Even within a single company, engines with comparable power rating but of different vintage, series or designation can have vastly different emissions profiles.

5.4.1 Diesel Engines

The differences between the various certified engines, from pre-tier to Tier I through Tier IV have been well documented. As engine technology improved, generally the trend was for emissions to decrease, although this has not always been the case. One well documented aberration was the reduction in DPM in the Tier II engines that often emitted less DPM than their Tier III counterparts (that were optimized for NOx reductions). Although all Tier IV engine systems (Tier IV certification applies to the engine paired with a specific set of controls, aftertreatment, etc.) are anticipated to achieve drastic reductions in both gaseous and particulate emissions, it is likely that lower “Tier” engines will be present in mines for much of the foreseeable future.
Many resources from engine testing authorities exist to assist mine operators in understanding both the absolute emissions profiles of the engine choices on the market, as well as the differences between competing powerplant options. Two of the most commonly accepted authorities on this subject are Natural Resources Canada and MSHA, which both publish lists of diesel engines approved for use in underground mines along with detailed emissions profile information.

Table 7 shows an example of the information supplied by MSHA on its approved diesel engines page. Along with a recommended ventilation rate, detailed emissions data is provided including the particulate index (PI) and the grams per horsepower-hour of particulate emissions produced. The PI of a given engine is the volume of airflow required to dilute the particulate emissions to 1.0 mg/m$^3$. In Canada, an Air Quality Index (AQI) is used in the engine certification process to determine the required volume of ventilation to dilute the exhaust constituents to safe levels and to select the cleanest (least polluting) engines possible for a given application.

Table 7: Sample of MSHA Diesel Engine Approval Information (MSHA, 2012).

<table>
<thead>
<tr>
<th>Approval Number</th>
<th>Engine Manufacturer</th>
<th>Model</th>
<th>HP @ RPM at 1000ft AMSL</th>
<th>Ventilation Rate CFM</th>
<th>Particulate Index CFM</th>
<th>DPM grams/hr weighted</th>
<th>grams/hr weighted Filter Eff. for 5.0 grams/hr</th>
<th>Filter Eff. for 2.5 grams/hr</th>
<th>Date Issued</th>
<th>EPA Compliant per 72.502-1</th>
<th>BP Max Limit, in.H2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>07-ENA040007-1</td>
<td>DEUTZ</td>
<td>BF4M 1013EC</td>
<td>158 @ 2300</td>
<td>7000</td>
<td>4000</td>
<td>6.2</td>
<td>0.07</td>
<td>19</td>
<td>60</td>
<td>Y</td>
<td>30</td>
</tr>
<tr>
<td>07-ENA040007-1</td>
<td>DEUTZ</td>
<td>BF4M 1013FC</td>
<td>157 @ 230</td>
<td>6500</td>
<td>3000</td>
<td>4.88</td>
<td>0.06</td>
<td>0</td>
<td>40</td>
<td>Y</td>
<td>30</td>
</tr>
<tr>
<td>07-ENA040007-1</td>
<td>DEUTZ</td>
<td>BF4M 1013FC</td>
<td>173 @ 2300</td>
<td>7000</td>
<td>4000</td>
<td>6.2</td>
<td>0.07</td>
<td>19</td>
<td>60</td>
<td>Y</td>
<td>30</td>
</tr>
</tbody>
</table>

Several interesting conclusions may be drawn from this data. Note that each configuration results from the same engine manufacturer and model number. While comparing the first two entries, one can see that although both show approximately the
same horsepower rating, the second configuration has a much lower recommended ventilation rate, PI and DPM grams/hr produced. When comparing the first and third entries in the table, the rated horsepower has increased approximately 9.5%, while the ventilation rate, PI and DPM grams/hr has remained constant.

5.4.2 Alternative powerplants
The most common alternative to diesel-powered equipment in underground mining applications is electric-powered equipment, which has been commonly used in both, tethered and battery-operated forms for decades. Although some people believe that electrically powered equipment require no ventilation since they technically produce no emissions, this is not the case. Electric equipment produces heat, an important contaminant in underground environments that is controlled by ventilation, and is often the source of mineral dust that is produced from the normal activities of the equipment as it operates. Although these factors must be considered when determining the airflow required for electric-powered equipment, the amount of airflow needed to mitigate the heat and dust generated is not able to be calculated by a simple numeric multiplier (Willick, 2010)

Although they have not yet gained widespread use in underground mines, there are several additional alternative powerplant options for various mining equipment that are currently undergoing tests to determine their safety, durability and applicability in underground mining environments. These alternative power technologies include diesel-electric hybrids, fuel cells and liquefied natural gas (LNG). Studies conducted by
NIOSH show that diesel electric hybrids are capable of reducing emissions by 40 – 60%, as well as cutting overall fuel consumption by 20 – 40% while fuel cells would offer an alternative with zero emissions (Matikainen et al, 2010, Hodgins, 2010). Although not currently ready for widespread application, these technologies all represent promising alternatives to diesel-powered equipment that may become viable options at some point in the future.

By doing some research through easily available channels, it is possible to obtain engine packages for almost all existing or newly ordered equipment that will minimize the emissions produced for a given application or power range. This important step in lowering the emissions exposure levels in the underground is significant, and should not be overlooked.

5.5 Exhaust Aftertreatment

This section will describe the various types of exhaust aftertreatment available to consumers and their relative merits/effectiveness.

5.5.1 Diesel Oxidation Catalysts

Diesel Oxidation Catalytic Converters or DOCs work by oxidizing CO and hydrocarbons in untreated diesel exhaust to CO$_2$ and water vapour. Through the use of the catalyst, the oxidation temperature is reduced, allowing the process to occur during lower than normal exhaust temperatures. Although the oxidation process can reduce DPM by removing some of the adsorbed hydrocarbons, the elemental carbon fraction of the
transmitted DPM is not reduced or otherwise affected by the DOC. This process is shown on Figure 8.

![Fundamental Chemical Reactions within a DOC](image)

**Figure 8: The Fundamental Chemical Reactions within a DOC. (Bugarski, et al, 2011)**

The oxidation of exhaust components can also have negative effects, as it is possible for the process to convert NO to NO\textsubscript{2}, and sulphates from the SO\textsubscript{2} present in untreated diesel exhaust. The production of NO\textsubscript{2} is of particular concern, considering its low TLV (5ppm) and high toxicity to the human body. It is also possible for the DOC to increase both the particulate mass and the number of particles in diesel exhaust depending on the fuel sulphur levels and exhaust temperature combinations.

Most DOCs utilize one of two filter substrates, cordierite (a ceramic monolith) or metallic-honeycomb. Both substrates have relative merits and drawbacks. The ceramic
monolith substrates have a low-thermal mass, and provide good adherence for the catalyst wash-coat. Metallic substrates are characterized by a high surface area and lower-temperature initiation of CO conversion.

For most DOCs, the effectiveness of the DOC depends largely on the catalyst used; and the variation between catalysts from manufacturer to manufacturer is great. Common catalysts include base metals, precious metals and other specialty materials such as Mn-Mullite (Sm, Gd) Mn₂O₅. Mullite-type catalysts have been shown to perform more efficiently than platinum-based catalysts, while producing less NO₂ and at a lower cost (Wang, et al, 2012) but despite this, their widespread adoption by the mining industry has not occurred, and the majority of the DOCs in use today utilize base or precious-metal catalysts.

In light of the variations in performance seen from DOCs due to the critical nature that the catalyst plays in their performance (these catalysts are proprietary, and their effectiveness varies greatly) care needs to be taken when specifying their use in mining applications, particularly in instances where NO₂ production will be of concern. However, DOCs have proven to be effective at reducing DPM in mines, particularly when coupled with DPFs of all types.

5.5.2 Diesel Particulate Filters

Diesel Particulate Filters (DPFs) encompass a wide range of technologies, substances, types and methods of cleaning or regeneration. While it is not possible to present a
comprehensive review of all the types, manufacturers and options here, this section will give an overview of the many types of DPFs available, their relative merits and drawbacks, and an examination of their range(s) of effectiveness in typical mining applications. DPFs have received near-universal acceptance by the mining industry for use in reducing DPM in underground mines due to a range of operational characteristics that include filtration efficiency, applicability/availability and operational durability (robustness). Modern DPFs are so effective at removing DPM in part because the filtered material adds significantly to the filtration efficiency, resulting in significantly better performance in used filters when compared with new or freshly regenerated units. However, in order for them to be effective, the proper sizing and selection of individual units for specific pieces of equipment is important, as is the careful monitoring of exhaust backpressure and temperature.

Ceramic monolith DPFs, including those with Silicon Carbide (SiC) and Cordierite (Mg₂Al₄Si₅O₁₈) have proven to be 85-87% efficient at removing DPM by mass (MSHA). These DPFs can be either passively or actively regenerated. The Cordierite and SiC DPFs have several differences related to their unique properties, which make their proper selection extremely dependent on local applications, equipment, and operational conditions.

Figure 9 depicts a typical wall-flow ceramic filter substrate.
Sintered metal DPF systems utilize a series of metal plates coated with sintered steel as a filter substrate for removing DPM from the equipment’s exhaust stream. These filters are rated at 80 – 99% efficient at removing DPM by MSHA.

Passively regenerating filters continuously renew themselves by “burning-off” the collected DPM under controlled conditions. Generally, this occurs when there is sufficient combination of exhaust gas temperature and DPM present. Actively regenerating DPFs require that the filter element be removed and “cooked” inside a specially designed oven. Some manufacturers offer on-board, active regeneration, accomplished via in-line electric burners (especially popular for sintered metal filters) or in some cases, the injection of raw diesel fuel directly to the exhaust upstream of the filter.
In some cases, uncontrolled regeneration can occur, resulting in thermal runaway, destruction of the filter, and often a vehicle fire. Uncontrolled regeneration can be prevented by following manufacturers guidelines regarding operation, maintenance, replacement and operating parameters (i.e. backpressure).

5.5.3 Disposable-Type Filters
Disposable Diesel Exhaust Filters have seen widespread adoption, particularly in underground coal mines in the US, due to the preclusion of standard DPFs or DOCs. Owing to regulations limiting the exhaust temperature of inby diesel equipment, the exhaust systems of the vehicle fleets in these mines are equipped with heat exchangers or water jackets that reduce the temperature of the exhaust gases below 150 degrees Celsius, allowing the use of inexpensive paper filters to be used for removing the particulate components of diesel exhaust. Although these types of systems have been shown to be 97% effective at removing particulate emissions when used in conjunction with DOCs, their use has not been widely adopted outside of the underground coal industry, likely due to their high initial cost and the space required for the installation of the complex system of exhaust tubing, heat exchangers (or water jackets) filter housing, etc. (Schnakenburg and Bugarsky, 2002).

5.5.4 Selective Catalytic Reduction
Selective Catalytic Reduction (SCR) systems inject a urea mixture into the exhaust system of the equipment as a means of reducing the NOx production at the tailpipe. The Urea mixture is hydrolyzed to ammonia in the exhaust stream. Recent studies at
an underground salt mine in Canada have proven that SCR systems can produce reductions in NOx emissions of 60 – 65%, with DPM reductions of approximately 25% on vehicles of up to 725 hp (Rubeli and Cassidy, 2010). Although systems of this type are expected to be common once the introduction of EPA Tier IV compliant equipment is introduced, this technology has demonstrated that it can be effectively implemented in retrofit applications, and is reasonably cost-effective and sustainable in mining applications. Additional information regarding SCR systems installed as part of Tier IV compliant engine packages can be found in Section 7.3.

5.6 Environmental Cabins

When correctly designed and maintained, environmental cabins on diesel equipment provided an excellent means of reducing the exposure of vehicle operators (inside the cabin). In order to the cab to work effectively, it must provide clean filtered air to the operator and be completely sealed, including at the windows and doors. Testing performed by NIOSH verified the performance of these cabs at between 43 and 90% efficient at removing DPM (Noll and Grau, 2008). These results were confirmed via side-by-side comparisons between NIOSH 5040 samples and real-time DPM monitors. Filter efficiencies at the low end of the range were shown to be the result of breaches of the cabin due to opening windows or doors. Better education and administrative policies relating to operator behaviour can help ensure that the negative effects of intentionally opening cabin doors and windows can help, but regular inspections and
proper maintenance are also necessary to ensure that the controls are working properly.

Figure 10 shows a modern LHD with a typical environmental cabin installed.

Figure 10: Caterpillar R2900 LHD with Environmental Cabin Installed (Caterpillar).

Later work by a NIOSH-led team identified several parameters affecting the efficiency of equipment cabins in filtering dust, and designed a new type of enclosure that would provide filtered, pressurized air to the equipment operator. While unpressurized cabins generally exhibit a protection factor (PF) between 3 and 10 (protection factor equals the dust concentration outside the cab divided by the concentration inside the cab), the PF measured for the new type of pressurized cabin reached as high as 100 (Cecala, et al, 2012). Despite the capability to produce PFs as high as 1000 in a laboratory setting, the
practical values of PF remained at 10 – 20 for most real-world applications. The primary reason for this is the unavoidable breaches in the system that occur whenever the operator opens the cabin door, and dust is blown in, or brought in on the operators, clothing, boots, etc. Despite this, the new design featuring pressurized and filtered cabin air results in significant reductions in particulate exposure levels. Although the benchmark testing was performed by analyzing mineral dust exposure, similar results can be expected with respect to reducing DPM.

Figure 11 gives a diagram of the NIOSH-designed cabin filtration and pressurization system.

Figure 11: NIOSH-designed Pressurization and Filtration System (Cecala, 2012).
5.7 Administrative Controls

A wide variety of administrative controls are currently being used by mine managers and superintendents in an effort to reduce diesel emissions in their mines. While many such procedures and practices have been proven effective in lowering diesel emissions, some administrative controls are specifically banned; specifically, MSHA regulations forbid the use of job rotation (substituting workers performing work resulting in high exposures with others during the course of a shift) as this is considered to increase the number of miners exposed to diesel emissions (71 Federal Register 28924, 2006). Although the types of administrative controls vary widely in their application and adoption throughout the mining industry, three of the most common administrative controls for reducing diesel emissions exposure are discussed here; limiting equipment idle time, limiting the number of equipment in use in a given split of ventilation and remote control/automation of equipment.

5.7.1 Limiting Engine Idle Time

Limiting the amount of time that diesel-powered equipment is allowed to spend idling is one of the most commonly used and effective means of reducing diesel emissions at the source. The widespread adoption of this measure is likely due to a few key factors; it can be implemented immediately, it requires no special equipment or training, and it can result in considerable cost savings (a typical piece of underground mining equipment uses approximately one gallon of fuel per hour of time spent idling). Modern diesel engines do NOT suffer any negative consequences from being shut down when
not in use, provided that their cooling system(s) are working properly (many advanced, turbo-charged engines require the engine to be run for a period of time following heavy use).

5.7.2 Limiting the Number of Equipment Allowed in a Heading or Drift

Limiting the number, type and total power of equipment present in a single split of air is another useful method for ensuring that sufficient ventilation to dilute the exhaust products of the equipment is provided for any given area. If both the airflow in a section and the ventilation rates of the mine’s equipment fleet are known, then the total amount of equipment allowed can be easily calculated by adding up the ventilation rates until the total airflow present is met (if the addition of a piece of equipment would require more airflow than is present, this vehicle is held outside the area or re-routed until another leaves the area). This process represents a simple means of ensuring that the amount of airflow required never exceeds what is available. In practice this can be accomplished by having a “Tag Board” at the entrance to active areas, ramps and headings where each vehicles identifier is placed when they enter and removed when they leave. In some cases, this task is accomplished automatically through remotely located dispatchers who receive information regarding the location of the mine’s equipment fleet either through radio calls from their operators or by radio transmitters that automatically transmit a vehicle’s position.
5.7.3 Remote Control and Automation

Another commonly adopted method of reducing the exposure of workers is removing the worker(s) from the hazard. In regards to diesel emissions, this is commonly achieved by using remotely controlled vehicles to accomplish tasks such as mucking, drilling, and applying shotcrete. By removing the operator from the vehicle, it is possible to have them located in an area with superior ventilation, sometimes even outside the mine. This practice often has additional benefits in that other hazards (e.g. falling rock, dust, etc.) are also avoided. Other jobs with the potential for high exposure can be automated; for example, by feeding drill-steel into the drill automatically, the need for the operator to leave the enclosed and filtered cab is eliminated.

5.8 Personal Protective Equipment (Respirators)

Respirators consist of wearable devices that filter the ambient air prior to its entering the lungs of the wearer. Respirators come in many forms, ranging from simple “paper” filter masks, to complex devices that fully cover the head and include battery-powered pumps and high-efficiency cartridge filters. While they can be extremely effective (up to 99.97% dust removal efficiency), respirators should only be used if all other means of reducing diesel emissions have proven unsuccessful (Bugarski, et al, 2011). This is in part due to the ease in which their effectiveness can be compromised. Improper fit or use of a respirator can cause its actual effectiveness to plummet. Common causes of respirator degradation are: wearing the wrong size of respirator, wearing the wrong type of respirator, having excessive facial hair, not wearing the respirator when required, or removing the respirator in order to communicate with others. If respirator use is
required, they should be administered only as part of a comprehensive program that includes training in hazard recognition, fit and use of the respirators, an established fit-testing system and a regular maintenance and/or replacement policy.
In 1892 a young Rudolf Diesel patented his idea for a high-pressure, compression ignition engine based upon the Carnot cycle. By 1897, he had built a working prototype of his invention, which would become known as the “Diesel Engine”. From its humble beginnings in late-nineteenth century, the diesel engine is undoubtedly one of the most influential inventions in the history of man. It is arguable that no other single contribution has had such a profound effect on the industrialization of the world, and thus such an influence in shaping modern society. In fact, it would be virtually impossible to envision the modern mining industry without it. Yet the modern Tier IV engines that power today’s mining equipment bear little resemblance to the simple, unadorned apparatus patented by Diesel and adapted during the early twentieth century. Understanding how and why the engine has evolved over the last 120 years will be integral to understanding the current iteration of this ubiquitous mining powerplant.

A diesel engine circa 1922 next to a 2012, Tier IV compliant variant are shown on Figure 12.
6.1 The Original “Diesel” Engine

Rudolf Diesel’s original internal combustion engine is based on the Carnot cycle, with ignition resulting from auto-compression of the air drawn into the combustion chamber (into which the fuel is injected). Although the Carnot cycle represents the maximum possible theoretical efficiency for any heat engine, the Diesel cycle is nonetheless considered to be the most efficient type of internal combustion process, particularly when compared to the Otto cycle (governing spark-ignition internal combustion engines), and is thus particularly suited for industrial applications where application specific equipment can be designed around a continuous and efficient power source.

The Diesel cycle consists of four basic elements or activities; induction, compression, expansion, and exhaust occurring within a cylinder, which is controlled by a
reciprocating piston in order to convert the output power into rotating a rotating shaft. The compression and expansion of the gas(es) contained in the cylinder occur adiabatically.

Figure 13 shows a graphical representation of the Diesel cycle (pV diagram). Figure 14 depicts a typical diesel engine cylinder/piston.

Figure 13: The Diesel Cycle (Georgia State University).
6.1.1 Induction Stroke

The induction stroke begins with the piston at (theoretical) Top Dead Centre (TDC) in the stroke, with the intake valve open to allow fresh air to enter the cylinder as the piston retreats. The induction stroke is shown on Figure 15.
6.1.2 Compression Stroke

During the compression stroke the piston travels from (theoretical) Bottom Dead Centre (BDC) to TDC, compressing the air adiabatically. At TDC (approximately) the fuel is injected by a high pressure injector\(^5\); with the temperature of the compressed charge air immediately resulting in ignition. The compression stroke is shown on Figure 16.

---

\(^5\) The use of a high pressure injector nozzle was key to the patent of Diesels original engine design, as another so called “compression-spark” heat engine had been submitted several years prior by Herbert Akroyd Stuart.
Figure 16: Compression Stroke of a Diesel Engine (Kruse Technology).

# 6.1.3 Power Stroke

Ignition of the fuel/air mixture causes the mixture to rapidly expand adiabatically as the piston travels from TDC to BDC. The power stroke is shown on Figure 17.
6.1.4 Exhaust Stroke

The exhaust stroke begins with the piston at BDC. As the piston travels up towards TDC the exhaust valve opens, allowing the products of combustion to exit the cylinder. Upon completion of the exhaust stroke, the four-step process (induction through exhaust) is repeated. The exhaust stroke is shown on Figure 18.
The relative simplicity of the design, construction and operation of Diesel's invention, was in no part responsible for their widespread adoption and use throughout the world. Over the first century of its existence, the basic form and function of the engine that bears his name continued to see improvements made in its design, generally centred around how to make incremental improvements to the existing components or simply make them larger and more powerful. Some of these improvements included the turbo-charger (used to pre-compress the air prior to entering the cylinder(s) in 1906 and the invention of the common rail injection system by Clessie Cummins in 1946 (Cummins, 1998). These, among other modifications to the original design gradually gained acceptance over time; however, the next significant leap forward in diesel engine
technology came after the oil embargo of the early seventies, when the high price and critically low availability of fuel stocks drove the demand for even more efficient, powerful diesel engines.

6.2 Turbochargers and Electronic Engine Management

The first patent granted to protect a “turbocharger” for use to pre-compress the intake air for a diesel engine was filed in 1905 by Swiss engineer Dr. Alfred Büchi (STK, 2012). Dr. Büchi received patent No. 204630 from the German government for a “combustion machine consisting of a compressor (turbine-type), a piston engine, and a turbine in sequential arrangement. Dr. Büchi’s turbocharger was the first ever device to utilize the exhaust of the diesel engine to spin a turbine that in turn drove a compressor and forced additional charge air into the cylinder during the induction stroke.

Figure 19 depicts one of the original patent drawings submitted by the designer.

Figure 19: Patent Drawing for Alfred Büchi’s Turbocharger 1906 (STK, 2012).
The exhaust air from the diesel engine turns the turbine that acts to precompress the air which is then cooled prior to entering the cylinder, resulting in increased charge air densities, higher fuel dosing and greater power output. Although his design was initially dismissed as being impractical and uneconomic (STK, 2012), Dr. Büchi had in reality provided the first and most significant improvement to Diesel’s original design and changed the future of the diesel engine forever.

Beginning with the oil crisis in 1973, the use of turbochargers to boost efficiency and performance of diesel-powered vehicles became more and more widespread. In 1978, Mercedes Benz began producing a turbo-charged diesel in its popular 300 series sedan for the passenger car market, followed quickly in 1981 by a similar offering from Volkswagen (STK, 2012). Some of the benefits provided by the use of turbochargers on diesel engines include:

- Increased performance (output) from the same size (displacement) engine.
- Smaller, lighter engines available for the same power output.
- Increased torque output at lower engine rpms.
- Decreased engine noise.
- Decreased fuel consumption.
- Fewer and less toxic emissions.

Closely following the widespread adoption of turbochargers by the commercial/industrial diesel engine market, the traditional methods of controlling the timing of the various
engine operations and processes were unable to keep up with the demand for ever
more efficient and powerful engines. In 1986, Bosch invented an electronic engine
control (EEC) module for diesel-powered passenger cars, followed in 1989 by a unit for
commercial vehicles. This electronic engine management system allowed for vastly
greater control of the engine functions, including increased efficiency, and various
engine speed control options (Bosch, 2006).

Now that commercial and industrial diesel engines were commonly equipped with both
turbochargers and electronic engine management systems, the stage was set for the
most drastic technological changes to diesel engine design in history. As part of a
global effort to reduce greenhouse gas emissions, the EU and US EPA instituted
regulations that dramatically reduced the allowable emissions of both the gaseous and
particulate fractions of diesel exhaust below what was experienced, or even achievable
with the technology at the time of their enactment. In order to meet the new, stringent
requirements, drastic changes to almost every feature of Rudolf’s iconic engine design
would be necessary.

6.3 US EPA Tier IV / EU Stage IV Engine Technology

The drastic reductions in particulate and gaseous emissions mandated by the US and
EU regulations would not be possible without significant changes to almost every
involved system and function of the diesel engine as it existed prior to their
implementation. For the first time in history, the diesel engine would be totally re-made,
with every component re-engineered, and in some cases, entirely new systems or controls added. Furthermore, these changes would be universally applied across all manufacturers without regard to perceived need, efficacy, cost effectiveness or consumer demand.

Although the legislation only prescribed the final emissions allowed and left the choice of how to arrive there up to the individual manufacturers, the nature of the changes required resulted in common solutions being employed, or at least investigated by almost all of the companies that produce nonroad diesel engines out of necessity. The types and names of controls sometimes vary although their functions have been generally adopted by the industry. In any case, the descriptions and abbreviations are the authors' (unless otherwise noted) and individual components of various engines may be known by alternative names and or descriptions. The function(s) of the various components, however, are applied almost universally where present in Tier IV/Stage IV compliant engines.

6.3.1 Advanced Engine Design and Adjustment (EEC)

For most if not all manufacturers, the road to Tier IV compliance began with a re-evaluation of their existing engines, with individual components and processes analyzed individually and collectively in order to optimize efficiency and performance with regard to the emissions profile.
One area of the engine in particular that received a great deal of attention was the optimum design for piston heads. Advanced CAD and fluid modelling of the combustion process with varying piston head designs led to empirical improvements in piston development for the new engines by eliminating areas of uneven temperature or incomplete combustion in the cylinder.

The EEC modules for the engines were also optimized to achieve the most advantageous engine timing profile for the required emissions profile. In diesel engines, the production of particulate emissions and NO$_x$ are roughly proportional through an inverse relationship; as PM increases, NO$_x$ decreases and vice-versa. Advancing or retarding the engine timing allows the variation of the ratio of PM/ NO$_x$ in the exhaust.

Figure 20 shows the inverse relationship between PM and NO$_x$. The position of an individual engine on the curve can be altered by adjusting engine timing electronically.
# 6.3.2 High Pressure Common Rail Injection (HPCR)

Through the use of a separate, high-pressure fuel pump, HPCR systems generate a high (1.4 to 2.0 kilobar or 20,000 to 30,000 psi) fuel pressure in a common accumulator that is shared by each injector (cylinder). Fuel is delivered to the cylinders through electronically controlled solenoid valves that provide millisecond accuracy to the ignition process. This gives the engine a great deal of flexibility in the amount and timing of the fuel injection process across all ranges of engine rpm, particularly improving torque response at lower rpms.

Figure 21 depicts the general arrangement of a high pressure common rail injection system for a modern diesel engine.
6.3.3 Charge Air Coolers (CAC)

Charge air coolers serve two purposes in the integrated emissions control systems of modern diesel engines by cooling the compressed inlet air prior to entering the cylinders; the cooler air is denser than warm air allowing more fuel to be burned in the combustion process and thereby increasing the efficiency of the engine, and the lower combustion temperature(s) results in less NO\textsubscript{x} produced. Tier IV compliant diesel engines may or may not contain CACs, as there are other means of increasing the density and decreasing the temperature of cylinder intake air.

Figure 22 depicts a schematic of a prototypical diesel engine with pre-cooling of the cylinder inlet air applied.
6.3.4 Variable Geometry Turbochargers (VGT)

Variable geometry turbochargers allow the adjustment of the inlet air density according to the changing demands of the equipment, with the end result being to supply a consistent inlet condition for the engine. This consistency increases efficiency and allows the engine output to be maximized for any given size (displacement).

6.3.5 Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation (EGR) functions by returning a portion of the air expelled from the cylinder(s) during the exhaust stroke back into the cylinder(s) intake. EGR systems may be externally cooled via heat exchangers prior to being returned to the combustion chamber. By substituting some of the oxygen entering the cylinder with CO₂ from the...
recirculated exhaust, surplus oxygen in the combustion process is reduced and along with peak combustion temperatures, resulting is less NOx generated overall.

Figure 23 shows the addition of a VGT and cooled EGR.

![Figure 23: Prototypical Diesel Engine with VGT and EGR Added (John Deere).](image)

6.3.6 Diesel Oxidation Catalysts (DOC)

For all Tier IV/Stage IV compliant engines, the engine aftertreatment package is individually serialized and certified along with the engine. For most packages that utilize a DPF to control particulate emissions, an upstream DOC is included in line with the exhaust. DOCs utilize catalytically-coated filter substrates to oxidize CO in the engine exhaust to CO2. Additional information regarding DOCs was presented in Section 5.5.1.
6.3.7 Diesel Particulate Filters (DPF)

Owing to their high filter efficiencies (up to 99%) DPFs are frequently used as part of approved Tier IV/Stage IV engine packages to remove particulate emissions from the exhaust stream of the engine. Whether the filter substrate is wall-flow or flow-through, cordierite or ceramic, these filters are an integral part to many manufacturer’s compliant engine systems. Section 5.5.2 contains additional information regarding DPFs.

A schematic of a diesel engine with the inclusion of DOC and DPF to the exhaust circuit is shown on Figure 24.

Figure 24: Prototypical Diesel Engine Including DOC and DPF (John Deere).
# 6.3.8 Selective Catalytic Reduction (SCR)

The significant reductions in NO\textsubscript{x} that can be realized with SCR systems (up to 65%) make them almost ubiquitous installations in Tier IV/Stage IV compliant engine systems. SCR systems consist of a small pump that injects a urea mixture (approximately 65 – 70% water) from an attached urea tank (mandated by the EPA to be no less than 5% by volume the size of the fuel tank) into the SCR unit located in line with the engine exhaust. Inside the SCR unit, the exhaust is hydrolyzed into ammonia and water vapour before being released into the ambient environment.

The general layout and chemical processes involved in a typical SCR aftertreatment installation are shown on Figure 25. Figure 26 depicts the prototypical diesel engine with SCR attached.

![Figure 25: Explanation of a Typical SCR System (Volvo Penta).](image)
6.3.9 Combinations and Groupings of Tier IV Technology

Bearing in mind the inverse relationship between DPM and NO\textsubscript{x}, coupled with the magnitude of the reductions required in each contaminant to achieve Tier IV/Stage IV standards, it stands to reason that any compliant engine package will include multiple control technologies. Coupled with the variations possible through the advanced EEC modules the possible combinations and permutations are almost endless.
Figure 27 shows the NOx vs. PM emission rate curve with the relevant application of control options included.

Figure 27: PM vs. NOx Curve Showing Emission Control Options (John Deere).

If an SCR system is utilized as part of the compliant engine package, a further consideration to “Total Liquid Consumption” (fuel plus DEF use) must be given.

Figure 28 shows the relationship between total fluid consumption and engine-out NOx emissions as a result of varying in-cylinder PM control (using advanced EEC).
In light of this reality, some manufacturers have elected to produce compliant engines with EECs set to minimize PM production and compensate with larger SCR packages, while other companies have elected to adjust the EEC to minimize total fluid consumption and remove the PM emissions through the use of a DOC/DPF combination. Both options have distinct advantages and disadvantages: minimizing total fluid consumption results in the most efficient engines with minimal fuel cost; eliminating DOC/DPF aftertreatment simplifies the engine package, reduces capital cost and minimizes the space required for the installation. Ultimately, with so many variations possible, it is not surprising that no two solutions are exactly the same.
Chapter 7

Environmental Sampling and Monitoring

Adequate sampling should form the basis for any comprehensive analyses of diesel emissions exposure in an underground environment. This is how the mine operator is able to assess the level of compliance with applicable laws and check the status of the overall system of control activities from maintenance activities to the success of various engineering and administrative actions that may be implemented. The conditions and exposure levels vary greatly from mine to mine, and between separate locations within the same mine. As a result, it becomes highly important to evaluate emissions levels at each individual mine, and in as many areas and for as many processes as possible to ensure that no potential sources of exposure are overlooked.

Once an exposure rate has been calculated, a database of sampling information can be compiled, consisting of pertinent information recorded for each individual sample. This information includes the pump calibration information and the sampling notes, as well as the final exposure level. By grouping all of this information together, it is possible to evaluate the exposure data in a meaningful context, and the data can be sorted into a series of groups based on various parameters associated with exposure levels. The exposure levels can be analyzed in terms of ventilation rates and velocities, operators, activity type, equipment type, and location in order to spot trends, and identify specific problems within the system both on a macro and a micro scale.
7.1 Gaseous Emissions

Gaseous components of diesel exhaust are generally measured with manually aspirated “stain tubes” or with any number of digital gas sensors that are commercially available from a wide range of manufacturers.

7.1.1 Gas Detector Tubes

Manually operated gas detection tubes are perhaps the simplest (and least accurate) means of determining gas concentrations in real-time. The tubes can be used for each of the principal components found in diesel emissions, and provide an economical option for obtaining ambient readings of gas concentrations in ppm-hours. To obtain TWA values for exposure levels, the direct reading from the stain tube is divided by the length of sampling time, giving the TWA for the measured gas in ppm. No calibration, laboratory analyses or further interpretation of results is required, all at a cost of a few dollars per sample.

Figure 29 shows a typical gas detection tube with explanation of markings (courtesy of Environmental Equipment and Supply).

Figure 29: Typical Gas Detector Tube Showing Readout.
Electro-chemical gas detectors are the most common type of re-usable, handheld gas detectors. These units are compact, affordable and robust enough to survive for many years in the underground mining environment with typical use and maintenance. Electro-chemical gas detectors work by generating an electric charge when the specific gas type is present. This electrical charge can be measured, which corresponds to a digital readout on the screen of the device. These types of detectors range in price from several hundreds to several thousands of dollars, and must be periodically recalibrated in order to function. However, if properly calibrated and maintained, these highly accurate and portable sensors provide great options for measuring the gaseous components of diesel emissions underground.

### 7.2 Particulate Emissions

For particulate emissions (DPM) ambient air sample collection replicates the process of human inhalation exposure most closely, and therefore gives results that are easier to correlate than do tailpipe emissions tests or other methods of DPM sampling.

#### 7.2.1 NIOSH 5040 Method

The most accurate means of determining the quantity of DPM in an ambient air sample is the NIOSH 5040 method. This method involves the use of a specialized, wearable pump designed to deliver a constant flow (volume rate) with an accurate timing device. The pump is connected to a “sample train” which includes an MSHA approved Jeweled-
Impactor cassette (with quartz-fiber filter), cyclone, and holder assembly. Since the purpose of the on-site sampling is to provide a “snap-shot” of the DPM levels throughout the mine under representative conditions, it is necessary to record all of the pertinent parameters which potentially have an effect on either DPM emissions or the sampling results. Such critical factors include the pump calibration and timing process, the direction and quantity of the ventilation, the condition of local ventilation structures/controls, the type and number(s) of equipment in the sample area (as well as the engine type and manufacturer), visible clues such as smoke or haze, and other notes stemming from direct observation of the sampling process. The importance of accurately reporting such information cannot be overstated; information gathered during on-site sampling is an integral part of the sampling process.

The NIOSH 5040 Method allows the determination of organic carbon (OC) and elemental carbon (EC) as a surrogate for DPM by a thermal optical analyzer. First, DPM is collected on a specially manufactured quartz fiber filter using standard air sampling equipment. A portion of the filter with a known area is then removed and placed in a quartz “oven”. The organic and elemental carbon in the sample are measured using a two-stage thermal-optical analysis technique. In the first stage, organic and carbonate carbon are evolved in a helium atmosphere, where the temperature is gradually stepped up to 850° C. The evolved carbon is oxidized catalytically to carbon dioxide (CO₂), and eventually reduced to methane (CH₄) in a nickel-firebrick methanator. A flame ionization detector quantifies the CH₄. Stage Two involves the introduction of an oxygen-helium mixture into the atmosphere of the oven,
and another gradual temperature increase, this time to 900° C. As this occurs, pyrolytic carbon is oxidized and filter transmittance increases. The initial increase in laser transmittance is associated with pyrolytic carbon. Once the transmittance of the filter reaches its initial value, all Carbon volatized after that is considered elemental carbon. A specially designed and application-specific software aids in the quantification of the EC.

As with any laboratory analyses that will undergo statistical analyses or be evaluated for its causative effects, a strict protocol for quality assurance of the laboratory results must be identified and followed. Before any analysis is conducted, the accuracy of the thermal-optical analyzer is tested with a series of calibration standards. This is done by depositing known volumes of calibration solution with known carbon content onto pre-cleaned quartz filters. The filters are then analyzed in the instrument, and the measured carbon content of each sample correlated with the calculated theoretical content. So called “instrument blanks” are run at a rate of approximately one blank for every five samples. This is when a pre-cleaned filter is analyzed to purposefully obtain a “zero-point” for carbon levels and verify the instrument results. Additionally, duplicate samples are analyzed at the rate of approximately one in every ten samples and evaluated for consistency. Additional protocols may be required to establish “chain of ownership” and ensure that contamination is avoided.

The results from the laboratory analysis are given in units of micrograms (µg) of Total Carbon (TC) present on the filter. TC is defined as the sum of OC and EC. The results
from the thermal-optical analyzer are presented in units of micrograms of OC, EC, and TC per square centimeter of filter (µg/cm²). In cases of carbonate interference, the carbonate fraction of OC is removed by integration with the aid of specialized software. The TC present on the filter is calculated by multiplying the TC given from the analysis (µg/cm²) by the filter deposit area (cm²), resulting in TC on the filter (µg).

The original design of the Jeweled-Impactor cassettes (JIC) manufactured by SKC, Inc. for the sampling of ambient DPM concentrations was such that the filter deposit area varied significantly from cassette to cassette. However, a recent modification to the cassette design has resulted in a much more uniform deposit area. It is important to note that while the laboratory results are reported in units of µg of TC present on the filter, the ambient concentration is based on the exposure of the filter in units of µg/m³. This requires additional calculations that correlate the pump flow-rate and sample run time with the results of the thermal-optical analyzer. Once the results of the laboratory analysis are obtained, the exposure levels associated with each sample must be calculated. This requires the correlation of the pump calibration data and the corresponding TC level from the laboratory analysis. The exposure level of the sample is given by the following equation:

\[ E = \frac{TC(Q_p)t}{1000} \]
where: $E = \text{DPM exposure (µg/m}^3\text{)}$

$TC = \text{total carbon (µg)}$

$Q_p = \text{pump flow-rate (l/min)}$

$t = \text{pump run-time (min)}$

The DPM exposure, when calculated in this manner, is considered to be the most accurate determination available, and is specified by many regulations for purposes of compliance determination.

### 7.2.2 Real-time ambient sampling

Following the initial DPM regulations enacted in the U.S. by MSHA, several companies developed belt-wearable pumps that allow the estimation of equivalent DPM exposure in real-time. These units generally utilize some form of photo-acoustic method or condensation counter for measuring respirable combustible dust entering the unit and display a corresponding DPM exposure level in terms of µg/m$^3$ 8-hr shift equivalent. Until recently, these real-time DPM monitors suffered serious drawbacks, namely a significant and inescapable susceptibility to interference from common mine atmospheric constituents such as mineral dust and oil mists.

In response to this deficiency, the Respiratory Hazards and Control Branch at NIOSH developed a new method for measuring EC in real-time and using it as the basis for a determination of equivalent DPM exposure. This process also involves the use of laser transmittance (similar to the NIOSH 5040 Method) but without the need for thermal
evolution. This new method draws in ambient air from the underground environment through a particle size selector that filters out anything greater than 1 micron. The submicron particles (EC has been demonstrated to be completely submicron) are collected on a replaceable filter, while a laser passes through the filter and records changes in transmittance. The determination of real-time DPM [equivalent] concentrations is then performed through an algorithm correlated from data obtained by NIOSH using the 5040 method.

Figure 30 shows a wearable, real-time DPM monitor with example readout (courtesy of FLIR).

Figure 30: Wearable, Real-time DPM Monitor Manufactured by FLIR.
7.3 Heat

Sampling for heat stress in the underground environment should be carried out in a repeatable manner as often as necessary to prevent exposure(s) to dangerous conditions (according to the accepted criteria of each individual location/company/etc.). The sampling should encompass all areas of the mine where it is possible for employees to experience heat strain, and should also be biased towards those areas where the risk of heat strain is most likely.

Measurements can be taken either through hard-wired instruments that make constant, real-time measurements and display or transmit them, or with hand-held instruments that may be easily transported and taken into any part of the mine. Generally, some combination of the two types of measurements are utilized, with a system of “weather stations” installed at key locations underground transmitting real-time data back to a central monitoring system while hand-held units provide measurements in active production and development headings based on need.

The choice of what parameters to measure (e.g. WBGT, Wet-bulb temperature, etc.) may be based on the individual location and the relevant parameters that form the action limit(s), whether internal or regulatory. If heat stress/heat strain for a particular location is regulated via WBGT, then this is the parameter that should be measured. If measurements are being taken for the purpose of correlating a climatic model, then the variables of wet/dry-bulb temperature and relative humidity will likely be necessary.
A variety of climate-measuring devices for both permanent and portable installations are currently available commercially. Figure 31 illustrates a typical portable device for measuring WBGT.

![Figure 31: Portable WBGT-measurement tool (General, 2011).](image)

### 7.4 Mineral Dust

The accurate determination of dust concentrations in any underground mining environment is both difficult and imperative in order to effectively quantify and control exposures of harmful levels to the workforce. This task is made considerably more difficult, by the varied nature with which dust is generated throughout the mine, and the many locations that both the dust source (e.g., equipment) and the worker may travel in any given shift. Furthermore, different types of sampling may be performed, based on whether or not the information will be used to determine compliance with a specific
regulation, or if it is merely to gauge the effectiveness of a control measure or identify a particular source of mineral dust.

Some dust sampling equipment and/or locations may be set by regulations, while personal samples are by definition, worn on the body of the person being sampled.

Particle size selection for respirable dust samples is generally accomplished using a Dorr-Oliver type cyclone assembly, in conjunction with a pump flow-rate that is adjusted to give the desired cut point (e.g., 4 μm, 5 μm, etc.).

Figure 32 shows a cyclone assembly used for obtaining respirable dust samples using the standard gravimetric-type method.
7.4.1 Gravimetric Sampling Method

Gravimetric sampling is still the most commonly used method for determining ambient dust concentration levels in mines (NIOSH, 2010). The method of sample collection is similar to that described in Sub-section 7.2.1 for DPM. By using a continuous volume air sampling pump set to a flow rate of approximately 1.7 liters per minute in conjunction with a standard Dorr-Oliver type cyclone, the appropriate cut rate is achieved. The respirable dust fraction is deposited onto a filter, which is then weighed on a precision
microbalance. The dust concentration can then be calculated via the sample weight (mg) and the total sample volume (m$^3$). If a determination of silica content in the dust sample is required, then a further step is required. Analysis of samples using x-ray diffraction (XRD) techniques will provide the percent silica present in any given sample.

A typical gravimetric dust sampling train is shown on Figure 33.

Figure 33: Typical Gravimetric Dust Sampling Train (NIOSH, 2010).

# 7.4.2 Photometric Sampling Method

It is also possible to measure real-time dust concentrations through the use of photometric (light-scattering) devices. When a beam of light passes through a dust stream, the resultant deviation can be used to determine the dust content present. Although these devices can suffer from interference associated with water or oil mists, they have one great advantage over traditional gravimetric sampling pumps; namely,
the ability to produce real-time information on the dust concentration(s) in addition to full-shift measurements.

Figure 34 shows a schematic of a photometric dust sampling device.

![Figure 34: Photometric Dust Sampler (McPherson, 2009).](image)

### 7.4.3 Tapered-Element Oscillating Microbalance Method

Culminating in 2006, NIOSH developed a real-time personal dust monitor (PDM) based on a tapered-element oscillating microbalance (TEOM) that gives a real-time gravimetric-based measurement of dust concentrations. The TEOM consists of a tube with a filter on one end that oscillates at a known frequency. As dust builds up on the filter, the period of oscillation changes, allowing the determination of dust concentrations. The output data can be read on a digital screen attached to the device, or downloaded to a computer for further evaluation and record keeping.

An exploded view of the NIOSH PDM is shown on Figure 35.
Figure 35: Exploded View of the PDM using TEOM technology (McPherson, 2009).
In his seminal text on the subject of ventilation, Malcolm McPherson describes ventilation as “the lifeblood of a mine...” and goes on to describe one of the paradoxes central to the job of ventilation engineers; namely that the more improved their system of ventilation, the more production that can result, which in turn increases the dust, heat and gases produced by the mining cycle, thus increasing the need for additional or improved ventilation (McPherson, 2009).

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. The transfer of heat from in-mine sources to ventilation streams, although significantly more complex in nature, is nonetheless able to be relatively accurately estimated and calculated. However, McPherson notes that “the estimation of airflow requirements is the most empirical of all aspects of modern mine ventilation planning...” and that “Attempts to extrapolate empirically-derived data to
circumstances beyond those similar in nature to those in which they were evolved may lead to serious errors” (McPherson, 2009).

Experience in ventilation planning has shown, that of all contaminant sources within modern underground mines, diesel equipment have generally taken primacy in ventilation quantity determinations; meaning that an airflow determination based on the power of the diesel fleet will be sufficient to dilute/remove all contaminants from all other sources. This rule has generally been true in ventilation planning exercises except in cases of extreme heat or cold due to environmental or geological conditions based upon the physical location of the mine. However, with the drastic reductions in diesel emissions mandated by regulatory bodies (EPA Tier IV, EURO Stage IV) it remains to be seen whether or not this will remain to be the case once the use of these engines and equipment become widespread in underground mines.

In any case, it will be helpful in revisiting here some of the other factors that must be accounted for when making a determination of the total airflow required for a planned underground mine or facility. The parameters listed in this section are general owing to current variations and lack of universally accepted criteria within the mining community. Instead, the following sub-sections are intended to present the reader with a list of important considerations in the design of a comprehensive underground ventilation system. Specific numbers or standards may be found in Appendix A.
8.1 Geographic Design Considerations

Geographic Design Criteria include parameters that are governed by the geographic location of the mine or deposit, including temperature extremes that are governed by climate (as opposed to those caused by strata), the proximity of population centres and the relevant regulatory bodies that govern the mining industry.

# 8.1.1 Sub-freezing Environments (Climate)

The combination of low ambient temperatures coupled with the range of typical airflow velocities found underground can lead to several potentially dangerous conditions for the workforce, including hypothermia and frostbite in sub-freezing climates. While individual reactions to cold temperatures vary, and some degree of cold-weather acclimatization by workers has been observed, ambient wintertime temperatures in many parts of the world are severe enough to cause injury or, in extreme cases, death. Conditions such as frostbite (freezing of the flesh) and hypothermia (cooling of the body’s core temperature) are risks that must be addressed by the ventilation plan for any proposed project experiencing such conditions. All workers subjected to sub-freezing temperatures should be made aware of the various health risks associated with their work, and be properly educated in how to protect against cold-related injury. Topics such as proper dress, working in pairs, warming breaks and cold-weather diet should be included, in addition to recognizing the signs of cold-stress and proper treatment/first aid procedures.
Raised air velocities in sub-freezing temperatures significantly increase the rate of cooling experienced by workers exposed to such conditions. Equivalent Wind Chill Temperature (Wind Chill) is defined as the ambient temperature in an airstream moving at 1.8 m/s giving the same rate of cooling as the actual temperature and wind speed.

Figure 36 shows equivalent Wind Chill temperature data developed by the U.S. Army Research Institute for Environmental Medicine.

Figure 36: Equivalent Wind Chill Temperature – US Army RIEM.
Figure 37 gives the relative dangers of air temperatures for varying airflow velocities, adapted from the American Conference of Governmental Industrial Hygienists (ACGIH) TLVs and BEIs.

![Wind Chill Dangers Graph](image)

Figure 37: Wind Chill Dangers (ACGIH TLVs and BEIs, 1999).

In climates where the naturally-occurring temperature of the air is below 0 °C, air heating is often necessary to prevent the failure of ground-control measures, the buildup of ice in underground entries, damage to equipment and danger to the workforce from...
cold-related injuries. Ice buildup in mine entries can impact the safe operation of the mine by causing potential safety hazards (from slipping personnel/vehicles and from possible rock failure due to freeze/thaw cycles). In addition, cold temperatures can have a negative effect on exposed personnel who are more likely to suffer from lapses in safety or productivity than those working in more temperate environments.

Once the need for mine air heating has been established, several options are available to maximize the suitability, reliability and cost-effectiveness of any proposed system. Air heating can be accomplished through many varied methods, including waste-heat recovery from other local facilities or warm exhaust air, direct heating utilizing a variety of fuel sources, indirect heating, ice production (latent heat) and geothermal heating.

8.1.2 Hot and/or Humid Climates

Hot, humid climates can cause a variety of physiological problems for a mine’s workforce up to and including death if not adequately addressed through a variety of available mitigation factors. Identifying and controlling climatic conditions that can lead to adverse effects is essential when designing a proposed ventilation system.

The spectrum of heat illnesses ranges from cramping, and mental/physical fatigue to renal failure and heat stroke in extreme cases. If acclimatized, given adequate water, clothing and sufficient rest, workers are able to tolerate any naturally occurring climatic heat stress (US Army RIEM, 2003); however, mining operations often contain combinations of factors that will render the body’s natural heat response insufficient for
protecting against heat stress. These factors can include the amount of clothing and PPE needed, the combination of physical exertion level/shift length and the limited availability of potable water supplies.

Miners exposed to hot, humid conditions underground should be trained in identifying the signs and symptoms of heat stress. Adequate water should be provided, along with appropriate clothing and work/rest schedules. Maximum (Stop Work) Wet Bulb (WB) or Wet Bulb Globe (WBG) Temperatures should be established for any mining operation where the risk for heat illness has been identified. If necessary, the ambient temperatures can be reduced by applying air cooling (refrigeration).

Cooling of the miner’s work environment can occur within mines at a variety of levels (scope and locations) from an enclosed vehicle cabin to spot coolers located in strategic locations underground. In some cases, refrigeration is provided at the surface with a massive “bulk” air cooling installation. Air cooling on this scale represents a massive capital and operating expense which in some cases can exceed the cost of the ventilation system excluding the cooling. As such, air refrigeration design should be optimized with an engineering study whenever necessary to identify the most efficient means of meeting the thermal design criteria for the project. Specialized software designed to assist ventilation planners and engineers can be helpful in predicting the ambient underground conditions and the effects of any mitigation strategies in the event that some air cooling is necessary.
8.1.3 Alpine (High Altitude) Environments

Mining operations located at high altitudes (above 2000 m) come with many unique challenges for the ventilation engineer/planner, which include in no particular order; a greater amplitude in diurnal and seasonal temperature fluctuations, reduced oxygen content in the ambient air, altered fan performance, and different diesel engine performance characteristics.

Most manufacturers fan curves are given at standard density (1.21 kg/m$^3$) and are useful only for those inlet conditions. In order to accurately predict the fan operating point(s) at varying air densities the universal fan laws$^6$ can be used to predict the performance of a fan at corresponding altitudes.

The theoretical fan total pressure developed by any given fan can be derived from the rotational and tangential velocities of the impeller. This relationship is expressed in Equation 4 also known as “Euler’s Equation”.

**Equation 4 (Euler’s Equation):** $p_T = \rho u_2 C_{u2}$

where: 
- $p_T$ = fan total pressure (Pa)
- $\rho$ = fan air density (kg/m$^3$)
- $u_2$ = peripheral speed of the blade tip (m/s)
- $C_{u2}$ = tangential fluid velocity (m/s)

$^6$ The “Fan Laws” are a particular version of a more general series of similarity laws that apply to all classes of turbomachinery. They are presented in various ways in various texts but universally express the relationships between performance variables for any two fans that have similar flow conditions (Fan Engineering, 1999).
From Euler’s Equation it can plainly be seen that the fan pressure developed is directly proportional to the inlet air density (for a constant volume), which forms the basis for determining the operating characteristic curve at any density other than standard according to Equation 5:

\[
\frac{p_{ft1}}{p_{ft2}} = \frac{\rho_1}{\rho_2}
\]

where:
- \(p_{fta}\) = fan total pressure at point 1 (Pa)
- \(p_{ftb}\) = fan total pressure at point 2 (Pa)
- \(\rho\) = fan air density at point 1 (kg/m\(^3\))
- \(\rho\) = fan air density at point 2 (kg/m\(^3\))

In practical application, this form of the equation is used to project “standard” density fan characteristic curves to whatever air density is expected at the inlet. For a case where mining occurs at approximately 3,000 metres ASL (at an estimated air density of 0.82 kg/m\(^3\)) this conversion process for a typical auxiliary ventilation fan is shown in Table 8 and represented graphically in Figure 38. Figure 39 shows the original fan curve with the original operating point plotted in red and the adjusted operating point shown in yellow (for actual density at altitude).

If the ventilation modelling and planning is performed with assumptions relevant to the correct altitude and air density (which also affects resistance calculations) and the fan curve is not properly adjusted to account for the changes in performance associated
with this appropriate air density, then it is possible to select and specify a fan that will not meet the operating requirements of the mine ventilation system.

Table 8: Fan Curve Conversion for Altitude (Density) Changes.

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Standard Density* Pressure Drop (kPa)</th>
<th>Quantity (kcfm)</th>
<th>Mine Density** Pressure Drop (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.9</td>
<td>23.70</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>2.7</td>
<td>29.15</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>32.70</td>
<td>1.7</td>
</tr>
<tr>
<td>4</td>
<td>2.2</td>
<td>35.31</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>2.0</td>
<td>37.20</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>1.7</td>
<td>39.10</td>
<td>1.2</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>40.76</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>1.2</td>
<td>42.18</td>
<td>0.9</td>
</tr>
<tr>
<td>9</td>
<td>1.0</td>
<td>43.60</td>
<td>0.7</td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>45.02</td>
<td>0.5</td>
</tr>
<tr>
<td>11</td>
<td>0.5</td>
<td>46.21</td>
<td>0.3</td>
</tr>
</tbody>
</table>

* 1.201 kg/m³  
** 0.82 kg/m³  

![Figure 38: Fan Curve Conversion for Altitude (Density) Changes.](chart.png)
Figure 39: Shift in Fan Operating Point at Altitude Adjusted for Air Density.

At high altitudes where ambient air density and oxygen content are reduced the performance of diesel engines also suffers if not properly adjusted to meet the appropriate inlet conditions, often resulting in increased emissions and eventually, damage. Most diesel engine manufacturers provide engine derate curves for high altitude operations for each of the engine models or series.

Figure 40 gives an example of one such derate curve. Note the provision of a general rule for derating engine power at approximately 3% per 300m in elevation above sea
level where the equipment will be operating. This recommendation is commonly applicable across all modern diesel equipment utilized by the mining industry (but should only be used when engine-specific data is not available).

Figure 40: Engine Derate Curves for Cummins QSK23-G3 NR1 (Cummins, 2003).

8.1.4 Proximity to Local Population(s)

The proximity to local population (non-mining related) can have several impacts on the proposed ventilation system, many having to do with local regulations or ordinances that will be covered in the next section (8.1.5). One impact that is not necessarily dictated by regulations (although it may be) is nonetheless a critical consideration of ventilation systems in close proximity to population centres or even individual and isolated dwellings. Noise pollution, particularly the incessant, low-frequency type that is commonly associated with fan installations has the potential to cause disruption and annoyance in the lives of those living within earshot. In some cases, negative health effects have been observed, even in cases where audible noise falls quite low on the
spectrum of what is perceptible. In general, little information about the negative health-effects of low-frequency noise and vibration is available (Findeis and Peters, 2004), although the relationship between audible noise pollution and conflict among nearby residents can be clearly illustrated in a number of cases.

If residential dwellings exist in the proximity of a mining project, then consideration to the ambient noise levels produced by the mine ventilation system should be given even above that required by the relevant regulatory bodies. Main fan installations may be located underground if possible, and if surface fan installations are necessary, then all available steps should be taken in order to minimize the creation and propagation of the resultant noise. Practically, this can be achieved through the use of silencers and other sound-deadening installations (e.g. spray-foam) and utilizing any fan discharge ducting to direct the air away from nearby homes.

Figure 41 shows the available reductions in noise level(s) at a distance of approximately 3 metres from a typical mining fan with various combinations of available silencers. Note that the decibel (dB) scale is logarithmic, meaning that a 15 dB reduction in decibel levels represents noise intensity approximately 30 times less.
8.1.5 Regulatory Oversight

The final and perhaps most critical effect that a mining project’s geographic location will have on its ventilation system design will be the assignation of a regulatory body (or bodies) that have jurisdiction over the operation of said system. Mining laws and
regulations vary greatly throughout the world from country to country and sometimes within regional states or provinces that comprise a single sovereign nation.

Often, the differences in these regulations extend not only to what is governed by law, but in many cases, the extent of the regulations and specific allowable levels of various airborne contaminants. For example; as we have previously seen, some regulatory bodies limit the ambient levels of diesel emissions within a mine based on allowable PELs or TLVs for various components of their particulate and gaseous emissions, while other countries specify the amount of air that must be provided for the equipment based on the rated engine power and still others will dictate only the airflow velocities in underground tunnels.

Ventilation-related regulations around the world range from allowable contaminant levels, to primary fan locations, to the frequency during with which checks of the ambient environment must be performed. An investigation of the applicable laws and regulations is a critical step in designing any ventilation system for an existing or proposed mine.

8.2 Geologic Design Considerations

Vagaries of geology also have a significant role to play in the ventilation system design process. Rock mass temperatures, morphology, and component mineralization can all impart particular health-hazards to the underground environment that need to be
mitigated by the ventilation system. In many mines, a significant portion of the heat load is the result of inflow from the rock strata and must be controlled by either ventilation alone or a combination of ventilation and mechanical refrigeration.

8.2.1 Virgin Rock Temperature / Geothermal Gradient
Determining the virgin rock temperature (VRT) or natural temperature of the in-situ strata prior to any outside influence can be critical to the design of the underground ventilation system. The VRT depends on a variety of factors including the thermal conductivity (k) of the rock mass, as well as the thickness of the earth’s crust at that location. Other factors that affect the VRT include fracturing and water presence. The Geothermal Gradient (°C/100m) and its inverse, Geothermal Step (m/°C) are also important parameters when performing heat-flow and sub-surface climatic simulations that will affect the ventilation system design.

In existing mines, the measurement of VRT with thermocouple probes at freshly-blasted mining faces is quite simply accomplished. Testing has shown that borehole temperatures peak at approximately one shift after blasting occurs, with the rock mass beginning to cool after this point (Duckworth, 1999).

In order to determine Geothermal Gradient/Step, concurrent readings on at least two levels with known elevations must be performed. The slope of the line then provides the Geothermal Gradient, which can be used for extrapolating the VRT at greater depth. This determination is more difficult in planned mines, as both VRT and Geothermal
Gradient can vary widely even among relatively similar (close) geographic areas. The common inclusion of temperature logging in down-hole exploration drills has aided this process greatly, although it should be noted that there is a significant offset in the area of rock immediately below the surface which does not conform to the properties of VRT and Geothermal Gradient at depth.

The strata heat-load must be identified and accounted for in any comprehensive ventilation plan, and if the heat-flow into the underground workings is expected to significantly contribute to the temperature of the underground workings, then an accurate assessment of the climatic conditions must be performed. Owing to the relatively high cost of mechanical refrigeration, an accurate determination of the cooling required will allow greater efficiency in the design and avoid the need for too much additional capacity being included in the overall ventilation system design to protect against the unknown.

8.2.2 Rock Stability and Ground Control
Where ambient conditions vary from above to below the freezing point, especially in areas containing water sources, ground control and stabilization issues can arise due to freeze/thaw cycles. Thus the desire to protect the workforce from damaging fluctuations in temperature needs to be balanced with the need to protect the integrity of the underground workings. This damage can occur as a result of freeze/thaw cycles in hardrock mines, as well as from gradual heating resulting from normal operations in areas of permafrost.
Repetitive freeze/thaw cycles, particularly downstream of intake portals/collars can have severely impact the integrity of drift and shaft walls in underground hardrock mines whether lined or unlined. The exact effects will result from a combination of climate (temperature fluctuations, precipitation, etc.) and geology (rock type, RMI, permeability, etc.) and can vary greatly from operation to operation. Often, air heating is required at operations with only mild sub-freezing climates owing to the need to protect the integrity of the mine’s main intakes and accesses and facilities (i.e. water and compressed air lines) rather than for the safety and comfort of the workforce. If the ventilation design fails to provide sufficient air heating capacity to prevent successive freeze/thaw cycles from occurring, the resulting damage to mine infrastructure can result in significant disruptions to the mine operations.

Although not as common, there are several areas of the world where mining occurs within zones of permafrost. This presents a similar hazard to the stability of the ground, although one with a uniquely different solution. In this case, care must be taken to ensure that the temperature rise from normal mining activities does not rise enough to allow the thawing of the permafrost ground, when it would become unstable. In the summer of 1983, partial melting of the permafrost at the Polaris Mine led to an unplanned mine closure and the installation of refrigeration units for the mine intake (Cominco, Ltd., 1984). This type of situation presents a unique challenge to the ventilation engineer who must consider also how to protect the underground workforce from sub-freezing temperature/airflow velocity combinations that can result in
dangerous conditions (See Sub-section 8.1.1), and may require the installation of refrigeration units, and/or drift insulation such as proprietary shotcretes or sprayed-on polyurethane foams.

8.2.3 Strata-Specific Hazards

Strata-specific hazards affecting the ventilation system design include the presence of minerals such as silica and asbestos, or the presence of gases like radon or hydrogen sulphide (H₂S). Although these hazards are generally identified by drilling during the initial exploration/conceptual design phase, their consideration in the ventilation system design is no less important.

For particulate hazards associated with the rock strata such as dust, silica dust or asbestos, airflow velocity becomes an important consideration in the ventilation system. Additional thought must be given to how active areas are ventilated, with series ventilation of active headings to be avoided at all cost. Dust scrubbers operating independently from the primary ventilation system can be employed as necessary, and homotropical ventilation should be utilized in all haulage routes, regardless of the method of transport (diesel equipment or conveyors).

For gaseous contaminants such as H₂S control is accomplished primarily by dilution (See Equation 1) and a calculation of how much air required for the mitigation of the hazard can be determined once the inflow rates of the gaseous hazard are known (or estimated).
If radiation or radioactive contaminants are expected, whether particulate or gaseous in nature, avoidance of the hazard becomes paramount. Devising a ventilation scheme whereby ventilating air is passed immediately into the exhaust after travelling over a potential source of contamination is required (this is commonly referred to as “single-pass” ventilation). Manipulation of differential pressure within the mining circuit should be performed to ensure that leakage always occurs from intake to exhaust.

It should be noted that when the contaminants of Silica dust and Radon are combined, their resultant effects on human health are compounded; the presence of dust in the lungs significantly increases the danger of inhaled radioactive substances remaining in the body (IAEA, 1961).

8.3 Strategic Design Criteria

Strategic Design Criteria include all of those design considerations that result from the choice(s) of mine design and operation, i.e. mining method, equipment selection, fixed facilities located underground, etc. Ultimately, it is these “choices” that perhaps have the greatest impact on the ultimate design of the primary ventilation system.

8.3.1 Equipment Selection

The selection of an equipment fleet for a planned underground mining project, or even the addition of new equipment to an existing mine is the source of many of the basic
requirements for that mine’s ventilation system. Some of these parameters might be obvious, like the amount of airflow required for the dilution of the particulate and gaseous emissions of the diesel equipment. Others, such as the dimensions of the underground entries and the need to cool the added heat load may not be so apparent.

Selection of the underground equipment fleet is often based solely upon the production/loading capacity required by the economic feasibility of the project. Although meeting those criteria is important, the repercussions for the ventilation system can be profound, particularly if that equipment fleet is not optimized with regard to ventilation. As has been previously discussed (Sub-section 5.4.1) the airflow required for different engines of the same power can vary greatly. Along with the gaseous and particulate engine emissions, the ventilation system must also remove dust and heat from the mine. Although they are generally considered less practical owing to restrictions on use and lower availability, electrically-powered equipment produces only about one-third of the heat that a comparable diesel-powered vehicle does. In cases where ventilation capacity is limited, electric vehicles should be considered.

Other equipment selection decisions that greatly affect the ventilation system design include the choice of haulage method (conveyor versus rubber-tyred haulage). Conveyor drives represent significant heat sources, and conveyor belts, particularly transfer points can be sources of hazardous dust if not properly ventilated, while LHDs and haul trucks emit heat, dust and toxic emissions continually throughout their route(s) underground. Each type of equipment comes with its own unique ventilation needs and
requires a different approach to hazard mitigation. It is not uncommon, of course, to have both types of haulage equipment underground in the same mine.

Current trends among underground mines also indicate that both the total power of installed equipment and the power of individual pieces of equipment are both rising. Not only do larger engines require additional airflow for the dilution of their contaminant emissions (dust, heat, POC), but they also frequently require entries with larger cross-sectional areas. Larger drifts can also boost airflow requirements in order to maintain minimum velocity criteria. As minimum cross-sectional areas approach or even exceed 35 m², the airflow required to meet minimum velocity criteria can actually exceed that required to mitigate the hazardous by-products of the vehicles themselves.

8.3.2 Mining Method
Although the morphology and size of an economic mineral deposit are important factors in selecting a mining method, almost all resources have at least a few alternatives when it comes to a method for extracting the ore. Just as there is great variation amongst minerals, deposit types and methods of extraction, the variations in the size and scope of the supporting ventilation systems is equally immense. As might be expected, airflow requirements for a small, narrow-vein (slusher) stoping gold mine in California’s Sierra Nevada Range are quite different from a 100,000-ton per day block-cave copper mine in Mongolia or Indonesia.
Although there may be similarities between them, no two mines are exactly alike, and neither should be their ventilation systems. The mine design should be carefully considered prior to developing a ventilation system plan, and the unique requirements of each method addressed. Will there by a conveyor hauling ore to a shaft bottom or will a fleet of diesel haul trucks travel up and down a ramp system? How will the project be developed? How many surface connections are planned/possible? What are the points of critical ventilation demand throughout the life of the project? What is the planned blasting schedule? These (and more) are all questions that should be answered during the ventilation system design process.

A further principle that should guide all phases of ventilation design is the concept that all known risks to the health and safety of the workforce should be kept “as low as reasonably achievable”. This so called ALARA principle often guides ventilation engineers to design and implement ventilation systems that go significantly beyond what is actually required by law in the quest of producing the safest environment possible for the workforce.

8.3.3 Fixed Facilities
When located underground fixed facilities such as shops, crushers, lunchrooms, fuel bays, electrical/motor rooms, etc., can contribute significantly to the total airflow requirement of a mine. For many of these locations, ventilating air should be immediately removed from the ventilation circuit and passed into the return air courses, further complicating the ventilation design.
Some of the requirements for a mine’s fixed facilities may be governed by regulations, such as a requirement for ventilating shops or fuel bays directly to return or a standard for the number of air changes that must occur in a particular area. Others are governed by industry standards or the experience(s) of the ventilation engineer designing the system.

8.3.4 Conceptual Design / Best Practice

The choice of a forcing (push) system of ventilation versus an exhausting (pull) system or a push-pull system will also have an impact not only on the ventilation system design, but also may impact the mine design itself (such as the locations of various drift connections or fixed facilities, or the need and location(s) of ventilation controls such as doors and regulators. As 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 mines and mine designs than others. Like other parts of the ventilation system design, this process is often iterative; first a design is selected, its benefits and consequences examined, and then if necessary an alternative is implemented.

As previously mentioned, the practice of ventilation engineering is one filled with paradoxes. One of these stems from the underlying nature of ventilation within the scope of mining activities as a practice wholly dedicated to the health and safety of the workforce. As such, it is often not perceived to contribute directly to mining production.

---

7 While studies linking a safe and secure workforce to high productivity and those linking high accident rates with high production costs abound, this perception is nonetheless still very much widespread within the industry.
(and revenue) and is constantly scrutinized for the cost and effort taken in its application. This frequently results in the design of a ventilation system consisting of a series of compromises between the added security or reduced risk of the design component and its real (capital plus operating) cost. As with any large-scale project, compromises are a helpful and necessary component of the design process; however, some ventilation system design features are so critical from a health and safety perspective that they should not be eliminated from any sound ventilation system design.

Whenever possible, the series ventilation of active areas within the mine environment should be avoided. Series ventilation or the reuse of ventilating air contributes to significantly increased risk(s) for any exposed workers downstream of the initial point of contamination. Although series ventilation may sometimes be necessary, particularly during development and in the case of auxiliary ventilation systems, special precautions should be taken if it is to be incorporated into the mine ventilation plan. Where series ventilation is unavoidable, the following four controls should always be implemented:

“First, a second means of egress with its own independent secure supply of fresh air, preferably pressurised above and adjacent ‘dirty’ intakes, so leakage is out of the second means of egress and not into it. This second egress should have no risky combustion sources in it."
Secondly, robust, secure fresh air bases or refuge chambers should be sized and located so that they are sufficiently close to all working places.

Thirdly, self-contained self-rescuers sized to match the rest of the egress strategy should be carried by all persons underground at all times. Egress procedures should be written and miners trained for escape through smoke, as operating a series ventilation system will inevitably result in some miners being required to escape through smoke.

Lastly, early combustion warning and personnel notification systems, including the judicious use of real-time carbon monoxide monitors in intake and exhaust circuits and systems such as the PED should be implemented.” (Brake, 2006)

Although these recommendations alone may not be sufficient protection to the workforce should a system of series ventilation be employed, they can be considered for form a minimum of protection that must be considered in such cases.

Another potentially hazardous (although not uncommon) ventilation design involves the use of the haulage ramp as the primary intake source for a mine. Increasingly, metal/non-metal underground mines with substantial diesel equipment fleets are eschewing the development of two or more ventilation raises for primary ventilation systems in favour of a single ramp providing fresh-air to the mine that is then exhausted through another ramp or a single exhaust raise. Systems of this type place the single greatest fire source (both in terms of probability and fuel supply) directly in the mine’s
fresh air source! Although frequently expedient (allowing rapid development) and relatively cheap (eliminating one or more dedicated ventilation raises), ventilation systems of this type should be avoided owing to the significant increase in risks associated with an underground fire in the main haulage ramp.

Although they represent infrequent events, underground fires have historically been the source of more than 90% of metal/non metal mining disasters (defined as having five or more fatalities) over the past 150 years (CDC/NIOSH, undated).

8.3.5 Auxiliary Ventilation

Although auxiliary ventilation is by definition generally not considered part of the primary ventilation system, it is absolutely essential to any properly-functioning ventilation system. Regardless of the suitability of the primary ventilation system, and the efficacy of the design and installation of its component parts, auxiliary ventilation will always be relied upon at the developing faces of the mine. In these cases, great care should be taken to calculate the airflow required for ALL phases of the development process (e.g. drilling, loading/blasting, mucking) and properly sizing both the fan and duct components of the system. Although proper installation techniques can be expected during the planning phase, reasonable assumptions should be made regarding leakage.

The choice of blowing or exhausting systems should be made based upon the specific needs of the project/area and whether the principal contaminant is dust, gas or heat. Blowing systems are particularly useful in mixing gaseous contaminants (methane, for
example) and for delivering cool air directly to the faces in the case of hot headings. Forcing systems are also capable of using flexible ducting (often referred to as “blowing bag”), which is cheaper and easier to install than the rigid ducting required for exhausting-type systems. The primary disadvantage of blowing systems is that any contaminants (i.e., dust) introduced at the face are then carried back over any workers located throughout the entire length of the heading. Exhausting systems are usually employed to remove dust from the active heading. Under this scenario, fresh air is pulled to the heading through the drift prior to entering being pulled into the duct at the face. Exhausting systems have the added advantage that they can be used in conjunction with a dust filtration unit or scrubber that cleans the air prior to releasing it back into the primary ventilation circuit (McPherson, 2009).

Figure 42 shows the general arrangement of a forcing and an exhausting auxiliary ventilation system configuration with the proper duct overlap in the supply drift.
Figure 42: Forcing and Exhausting Auxiliary Ventilation Systems (McPherson, 2009).

Whether they are forcing or exhausting, auxiliary systems should always be installed such that the duct runs from within 10 m of the working face to approximately 10 m past the intersection where the fresh air stream is located (in order to prevent recirculation). The amount of air passed through the auxiliary ventilation system should not be more than approximately 50% of the quantity of air in the drift that comprises the primary circuit (De Souza, et al, 2011).
The question of economic feasibility is one of the central components of any mine design. This is particularly true with regard to the ventilation system, which is often seen as a cost-item that does not, at least directly, contribute to the profitability of the mine in the way that an extra loader, or haul truck, or heading does. As a result, the ventilation engineer may find him or herself justifying increases in capital or operating cost to a sceptical management. This is often the case in projects that are cost-driven, whereby all costs are carefully counted and weighed against the expected (resultant) profitability. In some (albeit rare) cases, mining projects are schedule driven. In these instances, the extraction process is so profitable as to outweigh almost all considerations of cost (i.e., almost any cost expenditure can be justified in order to meet the production schedule of the project). For a schedule-driven project, the ventilation system design is driven by the need to support the mining activities according to the proposed production schedule. The difference between cost-driven and schedule-driven projects is important from a design perspective, and must be considered when generating a ventilation system design for any proposed project or expansion that requires additional ventilation.

When considering economic costs or cost savings vis-à-vis the ventilation system design, comparisons should always be made with a consistent unit basis. This means that a consistent currency should be selected (commonly U.S. dollars) along with a set point in time (usually the Present). It is common for mining ventures to be funded in a different currency than what is used where the mine is physically located (sometimes
from a mix of companies and currencies) and establishing a consistent basis for cost evaluations should be one of the design criteria for any project. The importance of evaluating economic alternatives on the basis of Net Present Value (NPV) is particularly important in light of the long project life experienced by many mining operations. Over the life of mine, variations in the worth of both currency and commodity prices can have a profound impact on the feasibility of a particular project or ventilation design.

8.3.7 Other

The list of strategic design parameters includes a wide and varied list; as such it is almost impossible to list them all. However, this author has noticed that one design consideration in particular has gone unnoticed for some time and is now becoming significant with regard to ventilation system performance. For several regulated contaminants (foremost among them being DPM exposure in locations where this is currently legislated), the PEL is listed as a shift-weighted average (SWA). For shift lengths that exceed 8-hours in length, the measured full-shift exposure is then multiplied by the length of the shift in minutes divided by 480. It is not uncommon for miners today to work ten or even twelve-hour shifts, and in these cases, not only their total full-shift exposure must be significantly less than that worked by their 8-hour working counterparts, but their rate of exposure must also be proportionally less. In such situations, the ventilation rates specified in the ventilation design may need to be also proportionally higher in order to meet the legislated SWA PEL.
The choice of a blowing (forcing) system of ventilation versus an exhausting system or a push-pull system will also have an impact not only on the ventilation system design, but also may impact the mine design itself (such as the locations of various drift connections or fixed facilities, or the need and location(s) of ventilation controls such as doors and regulators. As 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 mines and mine designs than others. Like other parts of the ventilation system design, this process is often iterative; a design is selected, its benefits and consequences examined, and then if necessary an alternative is implemented.
Chapter 9

Economic and Non-Economic Implications of Change

The transition within the mining industry to Tier IV engines and equipment will come with far reaching impacts both of a monetary and operational nature. This section will examine both economic (such as the increased cost of Tier IV engines and parts, additional technicians, mechanics, etc.) and non-economic (such as the availability of technical expertise, requisite fuels, parts, etc.) factors resulting from the new engine standards.

9.1 Economic Impacts of Tier IV Engine Regulations

Predicting long-term economic data is a complex and time consuming practice, often involving teams of highly-trained individuals and specialized algorithms performed on computer arrays. While predictions of this type will not be possible (or even attempted) here, some of the economic factors that will influence the underground mining industry as a result of the EPA Tier IV and equivalent regulations will be discussed and examined in a conceptual context. Where empirical data exists to support the assumptions made it will be presented; when no such correlation is possible, anecdotal evidence will be provided as available. While the exact cost of implementing the Tier IV regulations will not be known for several years, what is known is that there will be an increase in the capital and operating cost associated with regulatory compliance.
9.1.1 Equipment Cost(s)

Amongst all of the uncertainty surrounding the introduction of Tier IV and equivalent-compliant engines to the industry there is one underlying constant: the engines, ergo the equipment will cost more. The reasons for this are many and varied. First and foremost, the added controls required to make the engines Tier IV compliant are complex and expensive. There is a real, “dollar” cost associated with the optimized-design pistons, EGR valves and aftertreatment controls that must be included. Then there are the changes to the engines and equipment that are not directly associated with emissions control, but must be made in order to accommodate those additions (i.e. engine cowlings and covers, parts that must be miniaturized in order to make room for the emissions controls, hoses, tubing, wiring, etc.). Finally, each manufacturer of Tier IV-compliant engines has only achieved that status through the investment of millions of dollars of research and investment funds, which must be recouped through sales.

As vehicles and equipment with Tier IV engines have not yet been brought to market, any speculation as to their actual cost is fraught with uncertainty. According to the official estimate by the EPA, the cost of the added Tier IV emissions controls was only expected to increase the cost of the engine by 1 – 3% (Dieselnet, 2012). However, based upon estimates from various industry and manufacturer sources the actual increase in the purchase price of Tier IV compliant equipment will fall in the range of 50 – 90%. In one example, the price of a Tier III Atlas Copco Genset was scheduled to

---

8 The author’s information stems largely from first-hand conversations with representatives from Atlas-Copco, Caterpillar, Cummins, John Deere, Kubota, mtu and Volvo representatives both at MineExpo and the Mining Diesel Emissions Council Conference in the 3rd Quarter of 2012.
increase from approximately US$100,000 to US$190,000 when outfitted with a Tier IV-compliant engine.

Only after the introduction of Tier IV engines is implemented will the true cost of this change be known, and it is likely that prices will fluctuate for a period of time before a stable cost, or cost increase, can be tabulated. Nonetheless, it is obvious at this time that the estimated 1 – 3% cost increase postulated by the EPA is grossly optimistic (inadequate) for planning or budgeting purposes.

9.1.2 Parts and Maintenance Cost(s)
Regardless of the purchase price, new Tier IV equipment will also likely have significantly higher maintenance costs associated with them than even their respective, Tier III counterparts. This is partially due to the increased number and complexity of the emissions control systems themselves (necessitating more, and more expensive parts), and partially due to the increase and tasks that will need to be performed as part of any preventative maintenance activities.

Although questions about overall reliability and/or susceptibility to damage will likely not be answered before some time has passed, manufacturers have admitted that the new Tier IV engines will be more difficult to maintain, and more sensitive to dust and heat in the intake air supply. In a manual aimed at answering the questions of existing and potential customers, Caterpillar explains that it fully expects the cost of Tier IV engine ownership to rise (Caterpillar, Inc., 2011).
9.1.3 Technician/Personnel Cost(s)
Another hidden cost of the Tier IV engine implementation will be the training and hiring of new maintenance personnel. Once Tier IV equipped vehicles are present in the fleet, their preventative maintenance and any necessary repairs must be performed by a qualified person. Either the manufacturer must be retained to perform this service, new qualified staff hired, or existing staff will need to be retrained. This will all occur during a period in which qualified diesel mechanics are already in short supply. In this author’s opinion, budgeting for a single, additional maintenance staff person (or equivalent) to coordinate and perform the maintenance of the Tier IV equipment fleet should be the minimum that mine operators should plan for when considering the increased cost of the Tier IV regulations.

9.1.4 Fuel (ULSD) Cost(s)
According to the EPA, the increase in the price of fuel associated with the switch to the now mandated ULSD is expected to be approximately 7 cents per gallon (Dieselnet, 2012). This slight jump in fuel cost is expected to be partially offset by the anticipated increase in fuel efficiency for the Tier IV engines (estimated at 5%). Again, it is not possible to accurately predict the price of diesel fuel with any degree of accuracy, but an overall fuel cost increase on the order of 1 – 2% can be expected.
9.2 Non-Economic Impacts of Tier IV Engine Regulations

In addition to the economic cost of Tier IV compliance, there are many potential practical and operational stumbling blocks that will need to be overcome in order to effectively integrate a Tier IV equipment fleet into an underground mining operation.

9.2.1 Technician and Mechanic Availability
Currently in North America, there exists a shortage of qualified diesel mechanics that is not likely to be alleviated by the time Tier IV engines are required and implemented. Even if one assumes that the engine manufacturers will supply any needed maintenance training to the mine operators as requested, there is still likely to be a dearth of personnel with the requisite skills for Tier IV engine maintenance and repair. Those mechanics with adequate training will also be under considerable pressure from the much larger and already established on-highway market. Providing sufficient maintenance personnel for the new Tier IV equipment will likely be a major challenge for underground mine operators, at least in the near-term future.

9.2.2 Required Training and Specialized Skill(s) Development for Operators
Although Tier IV equipped vehicles generally operate in the same manner as their pre and sub-tier counterparts, the new equipment does have an array of new dashboard lights, warning features and operations that will need to be understood by their operators in order to ensure their safe and reliable operation. For example, information regarding the soot load of the DPF and regeneration status is now displayed in the
cabin of Tier IV compliant Caterpillar equipment, along with the ability for operators to either force or prevent a regeneration cycle from occurring (Caterpillar, Inc., 2012). Failure to understand this new information and respond appropriately could lead to damaged equipment and/or unsafe conditions. In light of this, it is reasonable to expect that at least a significant portion of the underground workforce will need to be (re)trained in the operation of the underground equipment, and it would be naive to think that this can occur without any disruption to the normal activities of the mine.

9.2.3 Fuel Selection and Availability

All Tier IV equipment is designed to operate with only ULSD (defined as having 15 ppm sulphur or less) and CJ-4 Low-ash oil. Using fuel or oil not meeting these specifications will cause a loss of performance and damage to the equipment. While meeting these specifications should not be a problem in most of North America and Europe (with some notable exceptions, including Mexico, France, and Russia), there are still many areas of the world where this fuel is simply not available (see Figure 7).

In any market where a guaranteed ULSD supply is not available, Tier IV equipment should not be considered or installed. While this is not likely to greatly affect the smaller, locally-owned and operated mining companies, this could pose a problem for large multinational mining corporations that have sole-supplier agreements and standardized equipment fleets and maintenance policies across their operations.
Although not required by law, Tier IV equipment is certified by most manufacturers to run on Biodiesel blends up to B20 without suffering any negative effects and while retaining the full protection of the original warranty provided that the sulphur content of the blend does not exceed 15 ppm. This will place some operators in a unique dilemma, as many have elected to switch their fuel supply to B100 in order to comply with the mining regulations governing PEL for DPM exposure. Of course, no mine is required to use the Tier IV equipment, so continuing to utilize their existing fleet with B100 is an option in the short term, though eventually those mines will be required to use ULSD in any new (Tier IV) equipment. Having two separate and incompatible underground fuel supplies is certainly not an ideal or sustainable solution for any mine operator, but neither is a wholesale replacement of the entire equipment fleet, especially for the operators who adopted Biodiesel as a very effective solution to their DPM exposure compliance⁹.

---

⁹ This will be particularly vexing for many mine operators who chose to convert to high-percentage biodiesel blends specifically because they did not have the capital to replace or repower an aging diesel fleet with newer, cleaner equipment and have based their ventilation, maintenance and mine operation protocols based on this strategy. Ultimately, due to their incompatibility with Tier IV equipment, this method for controlling DPM emissions is not sustainable in the long-term.
Chapter 10

Proposed New Model for Estimating Airflow Requirements for Diesel Equipment Fleets

As alluded to in Chapter 8, the determination of airflow quantity is both a difficult and essential step in the mine design process. There are many factors that influence the selection of mining equipment (e.g. host rock strength, mining method, production rates, location, depth, etc.) and wide variations in emissions characteristics even amongst vehicles of similar size and power. Navigating these uncertainties and arriving at a reasonable estimate of total airflow, while difficult, remains one of the most important aspects of underground mine design.

Perhaps not surprisingly given the number of parameters affecting the total airflow required for a piece of diesel equipment, there is currently little consensus as to how the determination for total airflow is performed, and the process can vary considerably from mine to mine, country to country and even province to province. Whatever the criteria used, this is a process that is critical to the success of the mine (particularly in the case of new mine design) and should be performed while carefully considering how the equipment fleet required will be influenced by all of the parameters outlined in Chapter 9. Only once the selection of the necessary equipment is made can the process of determining the total amount of airflow required be completed.
Figure 43 shows a graphical representation of the relationship between the initial design parameters with the selection of equipment fleets and ultimately, ventilation rates. This process correctly incorporates the separate calculation of airflow rates ($Q$) for each of the four contaminant products (i.e., gases, particulates, heat and dust) with the total ventilation amount (or rate) required equivalent to whichever is greatest.

Figure 43: Relationship between Design Parameters and Ventilation Rates.
10.1 Contaminant Products of Diesel Equipment in Underground Environments

In addition to the noxious gaseous and particulate components of the exhaust, there are two other contaminants generated by diesel equipment that must be mitigated by the ventilation system. All diesel engines create heat, and in most mining environments, their activities also generate mineral (rock) dust. All of these pollutants represent a danger to the underground workforce, and must be mitigated at least partially by the ventilation system. The deleterious health effects of the contaminants associated with diesel engine use in underground environments are well chronicled in Section 4.0; this section is intended merely as a review of what the pollutants are, and why their consideration is important in considering total airflow requirements.

10.1.1 Gaseous Products of Combustion

The gaseous POC from diesel engines include CO, CO$_2$, and NO$_x$. Although diesel engines also produce water vapour, this is not considered a gaseous contaminant, and its influence on the ambient underground environment will be further addressed in the sub-section addressing “Heat”. The dilution of gaseous POC is achieved by a sufficient quantity of fresh air, with the velocity of airflow also playing a part in removing contaminants from the source where workers are likely to be exposed.

10.1.2 Diesel Particulate Matter

The production of DPM varies considerably among sizes, types, manufacturers and even series of diesel engines. Being sub-micron in size, DPM behaves as an aerosol,
and its control is similar to that of any other gaseous contaminant; dilution and removal by the ventilation system. Due to its status as a human carcinogen, the regulation of DPM exposure levels has experienced a state of flux over the last decade, and further changes to statutes is expected in mining regions around the world.

10.1.3 Heat
The heat added to the ambient environment due to the operation of diesel equipment is the result of many factors including the fuel consumption, efficiency and water generation of a particular vehicle and the inlet air temperature and density. In certain environments, heat stress poses a significant health risk to workers, and in some cases, modern diesel equipment (which can be damaged by elevated air temperatures at the inlet). Sufficient quantity of fresh air acts as a heat sink, removing heat from the equipment and transporting away from the source(s).

10.1.4 Mineral Dust
Dust is perhaps the most difficult of the contaminant products of diesel equipment to quantify and mitigate. Although diesel engines do not directly produce mineral dust, it is difficult to imagine an underground environment in which the operation of diesel equipment does not directly result in the generation or propagation of mineral dust. The mitigation of dust generated by operating diesel equipment is most commonly accounted for in traditional airflow calculations through the application of minimum airflow velocities where diesel equipment will be operating (notwithstanding the application of water/water sprays or other dust control installations).
10.2 Existing Model for Calculating Diesel Equipment Airflow Requirements

The most generally accepted model for determining the total airflow required for a diesel equipment fleet involves utilizing an accepted multiplier (given in the project design criteria) of the equipment power and with percentage reductions made for the utilization and/or availability of individual pieces of equipment. Both the values themselves (0.045 – 1.00 m³/s per kW) and the methods for arriving at those values (empirical derivation, statutory compliance, EQI, ALARA, etc.) demonstrate considerable variability. In addition, whatever criteria are eventually selected must be further balanced within the economic framework of the mine\(^\text{10}\).

What is common among the different methods of determining the proper rate of ventilation is that whatever the method used for arriving at the multiplier, once this number has been identified, it is generally accepted that it will be sufficient to cover all four contaminant products. Generally, separate calculations for each contaminant are not performed, and when they are, such as in the case of heat load generated by the diesel fleet, this is more often a result of concerns with other phenomena (i.e. strata heat) rather than a particular desire to quantify the ventilation required for the equipment fleet.

\(^{10}\) Although direct cost (either capital or operating) should never be used to justify a deficient design or condition with regard to the health and safety of the workforce, the economics of a project must nevertheless be considered during the design process, and responsible compromises may need to be made between operations (production) and ventilation capacity, particularly in the case of existing mines.
In the past, the gaseous and/or particulate emission rates of the diesel-powered equipment were of sufficient quantity that ventilation sufficient to dilute and remove these contaminants could reasonably be expected to provide sufficient airflow for cooling of the air stream and the removal of any dust generated (including whatever other dust management controls were implemented). However, this could potentially lead to great inefficiencies whereby the amount of airflow provided was significantly more than what was required, particularly with more recent, low-emission engines. At the scale of many large mining complexes, these inefficiencies can potentially result in substantial penalties in terms of the capital and operating cost of the ventilation system. More often, the total airflow requirement for underground mines has been undersized (insufficient flow) especially in cases where the impacts of heat and dust were not considered during the design phase and ventilation rates were derived solely from bench tests by regulatory agencies.

10.2.1 Statutory Compliance

In many parts of the world, ventilation rates are mandated by the relevant regulatory bodies for mining. The origin(s) of the multiplier used, although generally considered to have its roots in a scientific analysis of the various contaminants, is often muddied by time, and the exact justification(s) for the specified numeric multiplier and the influence of other considerations (i.e. economic impact) are not known. This uncertainty is further compounded by the variations found in the required airflow for diesel equipment.
Table 9 gives a selection of statutory ventilation requirements for prominent mining countries.

**Table 9: Selected Ventilation Regulations for Diesel Mining Equipment.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Statutory Ventilation Rate(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>0.06 m³/s per kW minimum.</td>
</tr>
<tr>
<td>Canada</td>
<td>Varies by province from 0.045 - 0.092 m³/s per kW minimum - most commonly 0.06 m³/s per kW.</td>
</tr>
<tr>
<td>Chile</td>
<td>2.83 m³/min per effective brake horsepower minimum (0.063 m³/s per kW equivalent).</td>
</tr>
<tr>
<td>China</td>
<td>0.067 m³/s per kW.</td>
</tr>
<tr>
<td>South Africa</td>
<td>0.063 m³/s per kW minimum (based on &quot;best practice&quot;).</td>
</tr>
<tr>
<td>USA</td>
<td>Based on MSHA certificate - ventilation required to dilute contaminants to specified levels at the tailpipe.</td>
</tr>
</tbody>
</table>

Upon examining the above Table, one might ask the question, is the performance of diesel equipment significantly different in Australia than it is in the United States? What about the differences in emissions produced from a diesel engine in Chile’s Copiapó region (elevation 1,000 masl) compared to the performance of the same engine in an Andean mine (elevation 5,000+ masl)? Do the toxic emissions, gaseous or particulate affect those in B.C. (25 ppm CO PEL) differently than those in the Yukon (50 ppm CO PEL)?

Clearly there are significant, fundamental problems with this method of determining total airflow based on fixed rates of ventilation, yet this is by far the most commonly used
method for performing these calculations today and is even written directly into the mining regulations in many important mining regions of the world. Furthermore, the fact that heat and/or dust is not specifically acknowledged as a diesel contaminant as part of the regulations (covered by the word "minimum" in the regulations) can lead to underestimating the amount of airflow required even in cases where newer/cleaner equipment is utilized.

10.2.2 Direct Engine Testing (EQI, etc.)

In Canada and the United States the regulatory bodies responsible for defining and enforcing mining legislation have developed extensive laboratory testing protocols to measure diesel engine emissions and determine the amount of ventilation required to dilute potentially harmful gaseous and particulate POC at the tailpipe based on each individual engine’s performance.

NRCan, the governmental agency responsible for measuring diesel engines approved for use in Canadian underground mines calculates the Exhaust Quality Index (EQI) for approved diesel engines according to the following formula:

\[
\text{Equation 6 (EQI): } EQI = \frac{CO}{50} + \frac{NO}{25} + \frac{DPM}{2} + 1.5 \left[ \frac{SO_2}{3} + \frac{DPM}{2} \right] + 1.2 \left[ \frac{NO_2}{3} + \frac{DPM}{2} \right]
\]

where: DPM (mg/m³) and gas concentrations (ppm) are measured in raw exhaust gases.
The engine is run through a fully repeatable 18-mode operational test. Sufficient airflow is provided in order to reduce the EQI to a value of “3” for the purpose of establishing the engine’s approved ventilation rate, with the final ventilation rate equivalent to the greatest amount of ventilation required at any point during the test.

In the United States, MSHA certifies a “nameplate” ventilation rate for specific pieces of equipment based on an 8-mode operating test. The amount of air required to dilute gaseous components of the engine exhaust (CO to 50 ppm, CO₂ to 5000 ppm, NO to 25 ppm and NO₂ to 5 ppm) at each mode is calculated, with the approved ventilation rate equal to the highest of the 8-mode test value. MSHA also calculates a “Particulate Index” (PI) for each approved engine, based on a weighted average of the 8-mode tests. The PI for an approved engine is equivalent to the amount of air required to dilute the particulate emissions of an engine to 1 mg/m³ (note that this value is significantly higher than the 0.16 mg/m³ MSHA SWA PEL for DPM). It should also be noted that the MSHA PI ventilation rate is for informational purposes only and NOT enforceable by the agencies inspectorate (Dieselnet, 2012).

The method utilized by NRCan and MSHA for determining diesel engine airflow requirements applies specific and repeatable criteria to establish ventilation rates for the gaseous and particulate emissions of diesel engines, and is generally a more accurate means of determining the total airflow requirements for an individual engine (fleet airflow requirements may be calculated by a simple summation of the total airflow requirements for each piece of equipment in the fleet assuming that sufficient maintenance is
performed over the life of the engine). Although this accuracy is often helpful in comparing similar pieces of equipment, this method is still deficient in accounting for the heat and dust generated by diesel equipment. Usually, the values generated from the engine testing are less than those generated from the direct multiplier and their application in making fleet airflow determinations can lead to estimates of total required airflows that are even less than those made using the regulatory multiplier in practice (keeping in mind that it is not common practice to account for the heat generated from diesel equipment except in cases where strata heat and VRT are known concerns).

10.2.3 Empirical Derivation (Experience)
The empirical method of determining the ventilation rate for underground diesel equipment is perhaps the most accurate, yet hardest to implement method of determining diesel fleet airflows. This is largely because of the number of data points required to establish meaningful values capable of predicting the contaminant production from the combination of complex mining parameters that affect the required flow rates.

In light of the practical requirements for establishing sufficient numbers that are empirically derived, then implemented, vetted and altered as necessary in a somewhat iterative process, it is generally only well-established ventilation consulting firms and the largest of mining corporations that have the ability to determine reasonable ventilation rates based solely on empirical data.
As ventilation rates based on empirical evidence (compliance or non-compliance with local regulations and often verified) account for all contaminants produced by diesel engines (and yet must still provide a reasonable factor of safety), those values based on vehicle power tend to be higher than those specified by the various regulatory bodies. For determining required airflow based on a diesel vehicle’s power, Mine Ventilation Services, Incorporated\textsuperscript{11} engineers recommend using a value of 0.080 m\textsuperscript{3}/s per kW. The Canadian ventilation consulting firm AirFinders, Incorporated uses a value of approximately 0.063 m\textsuperscript{3}/s per kW\textsuperscript{12}. After implementation of the MSHA Final Rule for DPM Exposure in 2008, the Senior Ventilation Engineer at Freeport McMoRan’s Henderson Mine began using a value of 0.095 m\textsuperscript{3}/s per kW for determining all future ventilation requirements based on the operating diesel equipment fleet (Loring and Shea, 2010).

Figure 44 shows a comparison of ventilation rates for varying mine types based on a survey of mines conducted in 2001. A significant distinction is clearly visible based on the different mining methods, although it should be noticed that this information was voluntarily provided, and is in no way indicative of industry “best practice” or even regulatory compliance.

\textsuperscript{11} The author is employed as a Principal Engineer with MVS, Inc. The ventilation rate referenced was developed empirically as a result of almost 30 years of data collected regarding mine ventilation systems around the world. \textsuperscript{12} This number is used when determining the airflow required for specific equipment utilized in specific areas/situations.
Although less common, total airflow determinations for underground mines are also sometimes made based on production (tonnage) rates. These types of airflow calculations are even more general than the application of ventilation rates based on the diesel vehicle fleet power, and are not adjusted to account for differences in fixed facilities such as underground shops, sumps, lunchrooms, etc.

For comparison, Figure 45 gives an example of ventilation rates based on total mine production (mass of airflow utilized per mass of ore produced).
As might be expected, the amount of air required as a proportionality of mass flow to mass ore shows a distinct inverse trend. While this may be a useful metric for a comparison between mines of similar sizes and operating methodologies, this method of making total airflow determinations for planned mines or mining complexes is NOT recommended due to the great variations in equipment fleets, distribution, local conditions and fixed facilities impacting both mine and ventilation system design.

10.2.4 ALARA

The ALARA principle or industry “best practice” is also sometimes used to determine the amount of ventilation required for underground diesel equipment. Sometimes (although rarely) this concept is mentioned specifically in mining legislation, as is the
case in South Africa (Gangal, 2012). While certainly admirable in theory, in application the concept of “best practice” is not well defined, and subjective by nature. As such, concepts such as ALARA, “best practice” and any other similar programs should only be used to augment whatever engineering method has been chosen to determine total airflow requirements for mines. While this may in some cases result in increases to the total quantity of airflow required for a particular mine or section of a mine based on specific contaminants, this approach should be commended and implemented where practicable.

10.3 Proposed Model for Calculating Tier IV Equipment Airflow Requirements

In light of the drastic reductions in the amount of gaseous POC and DPM achieved in Tier IV and equivalent certified engines, the process for determining the total airflow required for these engines has become significantly more complex, with a need to evaluate each contaminant type and the airflow required to control their potentially harmful effects individually; a necessity in order to fully and accurately mitigate all of the hazards associated with diesel equipment.

Although dust is often a design consideration during ventilation system planning exercises, particularly in cases where silica is present, it is rarely directly associated with the equipment fleet. And despite the fact that much attention has been shown to reducing the amount of gaseous and particulate emissions emitted by modern diesel engines, almost no thought has been given to reducing the amount of heat generated
by this equipment (this is a factor of fuel consumed, so ultimately, reductions may not even be possible at similar power levels). This is further compounded by the trend for ever increasing power in underground equipment and results in heat being one of the most difficult to control contaminants in the underground mining environment (Brake and Nixon, 2008).

It is this disconnect between what is currently considered and what should be considered when determining total airflow requirements for an underground mine based on its predicted equipment fleet that necessitates the adoption of a new paradigm by industry practitioners and which forms the impetus for this research. In the future, any determination of total airflow based on the equipment fleet must consider the toxic exhaust gases, DPM, waste heat and dust in order to be complete.

10.3.1 Gaseous POC and DPM

Prior to the separate consideration of heat and dust, it was necessary to apply a ventilation rate that would account for these considerations even when reductions had been made to the gaseous and particulate contaminant emissions of approved diesel engines over the last decade. This is likely the principal reason why there has not been a prior recalculation of ventilation rates (when applied globally as part of a total airflow determination for a mine diesel fleet) even though nameplate ventilation rates for approved engines have been dropping substantially over the past several years.
As the methodology for determining ventilation rates for “approved” engines by NRCan and MSHA has been previously discussed, it will not be repeated here. Robert Haney (President of Haney Environmental Consulting, LLC) has compiled a recent summary of ventilation rates based on engine type (non-Tier to Tiers I – IV).

A summary of Dr. Haney’s findings is presented in Table 10. Note that PI for MSHA approved engines is based on the dilution of DPM to the arbitrary value of 1.0 mg/m³ and that approximately five times more airflow is required to meet the U.S. statutory requirements for DPM exposure in metal/non-metal mines (Non-Coal).

Table 10: Historic Ventilation Rates for Approved MSHA Engines (Haney, 2012).

<table>
<thead>
<tr>
<th>EPA Tier</th>
<th>Number of Engines Tested</th>
<th>Gaseous Vent Rate, m³/s/kW (cfm/hp)</th>
<th>PI, m³/s/kW (cfm/hp)</th>
<th>5 × PI, m³/s/kW (cfm/hp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non EPA Compliant Less than 73 kW (99 hp)</td>
<td>21</td>
<td>0.050 ± 0.057 (79 ± 90)</td>
<td>0.119 ± 0.088 (188 ± 139)</td>
<td>0.595 ± 0.438 (942 ± 693)</td>
</tr>
<tr>
<td>Non EPA Compliant Gr. or Eq. to 73 kW (99 hp)</td>
<td>41</td>
<td>0.038 ± 0.0076 (60 ± 12)</td>
<td>0.059 ± 0.024 (94 ± 38)</td>
<td>0.297 ± 0.119 (468 ± 188)</td>
</tr>
<tr>
<td>Tier 1/2 Less than 73 kW (99 hp)</td>
<td>73</td>
<td>0.030 ± 0.0095 (60 ± 15)*</td>
<td>0.041 ± 0.015 (65 ± 24)</td>
<td>0.206 ± 0.076 (324 ± 120)</td>
</tr>
<tr>
<td>Tier 1/2 Gr. or Eq. to 73 kW (99 hp)</td>
<td>141</td>
<td>0.035 ± 0.0076 (55 ± 12)*</td>
<td>0.012 ± 0.0095 (31 ± 15)</td>
<td>0.098 ± 0.047 (156 ± 74)</td>
</tr>
<tr>
<td>Tier 3 Less than 73 kW (99 hp)</td>
<td>27</td>
<td>0.032 ± 0.0044 (50 ± 7)**</td>
<td>0.028 ± 0.015 (44 ± 23)</td>
<td>0.139 ± 0.071 (219 ± 113)</td>
</tr>
<tr>
<td>Tier 3 Gr. or Eq. to 73 kW (99 hp)</td>
<td>47</td>
<td>0.025 ± 0.0032 (39 ± 5)**</td>
<td>0.025 ± 0.0089 (39 ± 14)</td>
<td>0.123 ± 0.046 (194 ± 72)</td>
</tr>
<tr>
<td>Tier 4</td>
<td>2</td>
<td>0.025 ± 0.0032 (39 ± 5)**</td>
<td>0.002 (3.2)***</td>
<td>0.010 (16.0)***</td>
</tr>
</tbody>
</table>

*Based on NO  **Based on CO₂  ***Based on a PI of 0.01 gm/hp-hr.
One of the most striking findings of this study is the great discrepancy between historically used ventilation rates (the most common of which being 0.063 m$^3$/s per kW) and those that would actually be required to meet modern standards for DPM in the non-Tier rated engines of the past. Also of note is the great reduction in measured ventilation rates required for Tier IV engines (although only two were available for study). As more engines are tested, these parameters should be updated to provide the most recent values available.

Approved ventilation rates should be available in the future for all Tier IV engines, and nameplate values from NRCan and MSHA can be used for existing equipment fleets and older engines provided that the airflow required based on the contaminants of heat and dust are also calculated. For more general calculations, and in cases where the exact equipment may not be known (i.e. conceptual or prefeasibility designs), a value of 0.025 m$^3$/s per kW (0.022 – 0.028) may be used for determining the airflow required for diluting gaseous contaminants and 0.010 m$^3$/s per kW (0.009 – 0.011) for DPM. Once the adoption of Tier IV engines becomes more widespread, these numbers can be verified empirically, and altered to better reflect the actual conditions experienced underground if necessary.

10.3.2 Heat

The determination of the total airflow required for cooling Tier IV diesel equipment is not significantly different than the determination of cooling airflow required for other diesel equipment; however, it has become an even more critical step in the ventilation
planning process owing to the drastic reductions in airflow required for the dilution of exhaust gases and DPM which now render the heat generated by equipment significantly more impactful to the design calculations. As was previously mentioned in the introduction to this Section, heat has traditionally been an unregarded product of diesel equipment use underground, commonly leading to situations where the ventilation system is undersized for the equipment fleet and resulting in increased risk to the workforce and/or diminished production capacity.

Unlike many contaminants mitigated by the ventilation system, it is not necessary to determine the maximum heat production of the equipment, and in planning exercises the average rate of heat production is generally calculated and used in determining the proper ventilation rate(s) required.

Calculating the heat production from a diesel-powered machine can be practically accomplished through the following process.

First, the Total Heat is determined based on the fuel consumption rate:

\[ Q_T = \frac{f_c \times C_{diesel}}{3600} \]

where: \( Q_T \) = total heat (kW)

\( f_c \) = fuel consumption (litres/hr)

\( C_{diesel} \) = heat content of diesel (kJ/litre)
Next, the Latent Heat is calculated:

**Equation 8:** \[ Q_l = \frac{V_{H2O} \times l_{H2O}}{3600} \]

where: \( Q_l \) = latent heat (kW)

\( V_{H2O} \) = volume of water production (litres/hr)

\( l_{H2O} \) = latent heat of vaporisation of water (kJ/kg)

The Sensible Heat generated is simply the difference between the Total Heat and the Latent Heat:

**Equation 9:** \[ Q_s = Q_T - Q_l \]

where: \( Q_s \) = sensible heat (kW)

\( Q_T \) = total heat (kW)

\( Q_l \) = latent heat (kW)

The associated temperature rise in the ambient air across the machine is a function of the flow rate of air:

**Equation 10:** \[ \Delta T = \frac{q}{\dot{m}_{air} \times C_p} \]

where: \( \Delta T \) = Temperature Change (K)

\( q \) = heat (kW)

\( \dot{m}_{air} \) = mass flow rate of air (kg/s)
Often this equation is changed slightly to solve for the ventilation rate necessary to limit the temperature increase across the machine to a certain point, or to ensure that conditions do not reach the design criteria for stop-work temperature. Note that the mass flow rate of air should be converted to a volume flow rate using the air density in order that a proper comparison to the other ventilation rates can be made:

**Equation 11:**

\[ VR = \frac{v_{\text{air}}}{P_{\text{machine}}} \]

where:

- \( VR \) = ventilation rate (m\(^3\)/s per kW)
- \( v_{\text{air}} \) = volume flow rate of air (m\(^3\)/s)
- \( P_{\text{machine}} \) = machine power (kW)

Now it is possible to both calculate the heat added to the mine environment and establish criteria for evaluation and comparison based on the other contaminant products of the diesel equipment fleet.

A sensitivity analysis of the preceding method for determining the amount of airflow required to mitigate the heat generated from a piece of diesel equipment based on the parameters of fuel consumption, water production, allowable temperature rise and air density is provided in Appendix B.
10.3.3 Mineral Dust

Again, the dust created by diesel-powered equipment does not vary significantly from that generated by older equipment, the examination of how much airflow is required to remove the hazard has become more important based on the reduction(s) of the airflow required based on other contaminant products (i.e. gases, DPM). As long as mechanical equipment is utilized to break, load and transport material in underground mines, dust will be generated at the sites where the mineral is disturbed, and it will be equally important to eliminate, minimize or remove this hazard from the ambient underground environment as long as there are people present in these areas.

Although many forms of dust control in underground environments exist, including the extremely effective use of water sprays and dust filtration units, ventilation remains the most commonly used means of diluting and removing mineral dust from the underground environment. Respirable (sub-micron) dust settles from the airstream at an almost negligible rate, and should be controlled via dilution in a manner similar to other gaseous contaminants. In the case of larger particles it is primarily the airflow velocity that dictates the distance and time the dust particles will be entrained in the air stream\(^\text{13}\) (McPherson, 2009). If the airflow velocity is too great, then additional dust particles can be picked up by the ventilating air.

Figure 46 illustrates the relationship between dust concentration and air stream velocity.

\(^\text{13}\) The time taken for dust particles to settle is also heavily dependent on their shape and mass.
Figure 46: Dust Concentrations at Various Air Velocities (McPherson, 2009).

From Figure 46 it can be seen that airborne dust concentrations are minimized at and airflow velocity of approximately 2.2 m/s. However; the curve becomes relatively flat at approximately 1 m/s, which should be considered the minimum airflow velocity in areas where diesel equipment is in operation.

A further benefit of an airflow velocity of at least 1 m/s in development and production locations such as loading points and muck bays is that it also contributes to a significant airflow penetration distance into areas that are not part of the primary ventilation circuit.
In studies conducted by C. A. Rawlins and H.R. Phillips (2005) for a blind heading (LHD Load Point) a “figure of eight” pattern of flow for dust dispersion was measured against various airflow velocities in the connecting drift. In this case, penetration distance into the blind headings of 3 m X 3 m and 4 m X 4m cross-section was maximized between 1.3 and 1.4 m/s; with a significant benefit achieved at 1 m/s.

This information is provided graphically in Figure 47.

![Figure 47: Air Penetration Depth vs. Airflow Velocity (Rawlins and Phillips, 2005).](image)

Selecting appropriate airflow velocities for design criteria can also prevent the stratification of exhaust gases and respirable dust within mine entries where diesel equipment is operating. Homotropical ventilation should also be considered along
haulage routes to further minimize the generation and propagation of harmful mineral dust underground.

Ultimately, since dust control in modern underground mining environments usually incorporates a combination of active and passive installations including but not limited to the ventilation system, using the minimum velocity requirement alone for dust control may lead to overestimating the ventilation requirement. Also, the minimum requirement associated with one drift based on airflow velocity may not be sufficient when there are multiple vehicles operating in that drift. Therefore, minimum velocity should only be used as the governing criteria in areas where no other dust control measures are in place and only one piece of diesel equipment is expected to be in operation.

### 10.4 Comparison of Methods for Determining Airflow Requirement(s)

Now that the predominant methods for determining the airflow required for diesel equipment fleets have been outlined, a brief comparison of the methods (old and new) will be performed utilizing a test case featuring an actual piece of mining equipment. The total airflow required for this LHD will be determined utilizing the existing methods of Direct Engine Testing and Empirical Derivation, as well as individually for the contaminants of Gaseous POC, DPM, Heat and Dust. The results will then be presented for the purpose of evaluation and comparison.
The LHD selected for this comparison is the commercially available Sandvik\textsuperscript{14} LH517 powered by a Volvo TAD1361VE 285 kW Tier IVi engine. This LHD has a rated capacity of 17,200 kg in its 7 cubic meter bucket and is approved for use in underground mines by NRCan under CSA M424.2-90 (non-gassy mines). Minimum drift dimensions of approximately 5 m wide by 6.5 m high are required for this Loader to achieve full mobility.

The results of the total required airflow determination for the test LHD using the various methods of calculation are shown in Table 11.

<table>
<thead>
<tr>
<th>Method of Determining Airflow</th>
<th>Total Airflow (m\textsuperscript{3}/s)</th>
<th>Ventilation Rate (m\textsuperscript{3}/s per kW)</th>
<th>% of Greatest (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Engine Testing*</td>
<td>5.9</td>
<td>0.021</td>
<td>18</td>
</tr>
<tr>
<td>Empirical Derivation</td>
<td>18.0</td>
<td>0.063</td>
<td>55</td>
</tr>
<tr>
<td>Proposed Method Gaseous POC</td>
<td>8.0</td>
<td>0.028</td>
<td>25</td>
</tr>
<tr>
<td>Proposed Method DPM</td>
<td>3.1</td>
<td>0.011</td>
<td>10</td>
</tr>
<tr>
<td>Proposed Method Heat</td>
<td>21.4</td>
<td>0.075</td>
<td>66</td>
</tr>
<tr>
<td>Proposed Method Dust</td>
<td>32.5</td>
<td>N/A</td>
<td>100</td>
</tr>
</tbody>
</table>

\*NRCan, 2011.

This example clearly illustrates not only the differences between the methods of calculation, but in this case, the profound changes in the total airflow determination caused by the addition of heat and dust as design criteria. While it may be possible to

\textsuperscript{14} This machine (and engine) were chosen at random due to the availability of the pertinent engine data. This does not constitute any endorsement of these products and companies, or statement regarding their suitability or use in underground environments.
justify a reduction in the airflow required for dust control provided that other design features (e.g. water sprays) are added to the area in question, the mitigation of heat (the next highest airflow requirement) remains a concern and could even be exacerbated by the addition of water to the local environment (raising the humidity and ultimately the wet-bulb temperature). Despite the significant reductions made in the gaseous POC and DPM emissions of the Tier IVi engine, the overall airflow required has not significantly changed, and may even be increased in cases where the critical design parameters of heat and dust were not previous considered. Clearly, a 90% reduction in required airflow that many anticipated based upon a similar decrease in the amount of gaseous and particulate contaminants at the tailpipe is not justified.
Chapter 11
Practical Application of Proposed Model (Case Study)

For the purpose of further explaining the proposed new protocol for making total airflow determinations based on the diesel equipment fleet, the method will be applied to an actual mining scenario including actual mine design and fleet data that have been anonymized. Naturally, this information will focus on the diesel equipment fleet and distribution throughout the mine life, but additional and relevant mine design information will be included where applicable in the interest of clarity and realism.

To further aid the comparison with conventional methods of total airflow calculation(s), the original data from the ventilation design study will first be included and presented so that a better analysis of the differences can be obtained.

11.1 Introduction to Case Study – Mine Design and Parameters

The mine chosen as the test case for the new airflow protocol is a small base-metal mine that is located in the mountains of British Columbia, henceforth referred to as “The Mine”. The Mine will utilize the block-caving method of mining with a maximum production of approximately 6,000 tonnes per day (tpd). Haulage from the extraction panels to the central crusher will occur via the production LHDs themselves; there is no haulage level and no haul trucks are required once development is complete. The Mine has four surface connections; two raises that connect to the top of the mountain
containing the orebody and two declines containing the principal access travelway and a conveyor, respectively. There is a full-service underground shop located immediately proximate to the extraction level.

Figure 48 gives an isometric view of the main mining area. A plan view of The Mine including the two declines is shown on Figure 49.

![Isometric View of the Main Mining Area](image)

**Figure 48: Isometric View of the Main Mining Area.**
Figure 49: Plan view of "The Mine".
The airflow requirements for the mine were calculated based on the total equipment expected to be operating, with separate calculations performed for the extraction and undercut levels. The airflow requirements for each vehicle were based on the vehicle power in kilowatts (kW). The overall airflow requirements for each section were calculated by summing the individual equipment airflow requirements. It was assumed that all vehicles will be turned off when not in use for extended periods. In addition to the vehicle requirements, the ventilation system must account for leakage and other design factors where appropriate. Flexibility must exist within the ventilation system for the relocation of active areas within the mine or for possible future changes to the proposed mine plan(s) and tonnage rate(s).

In order to simplify the presentation of the ventilation system design process, several stages of mine development that were included in the original study have been removed for clarity (the process of determining the airflow demand for a mine for each year in development and production, while important, is repetitive and offers nothing new to the discussion). The mine was first modelled at what was considered its “maximum” capacity based upon the production schedule and fleet requirements. Earlier points in the Mine’s development were then configured to preserve topology within the ventilation system design over time, culminating in a ventilation design for the first year of mine development. Two points in time will be presented in the case study for comparison between the conventional and proposed new methods of diesel fleet airflow determination: the LOM/Maximum Demand scenario which forms the basis for the final ventilation system design, and the initial development calculation(s) that give an idea of
development airflow requirements, including their impact on infrastructure (auxiliary ventilation duct and fan sizing, drift dimensions, etc.).

11.1.1 Design Criteria and Concepts

The design criteria and concepts for this project were originally chosen based on the principles outlined in Chapter 9. Owing to site environmental and geological conditions, air heating will be required at the intake raise in order to protect the structural integrity of the installation and at the intake portal to keep the mine services (air, water lines and access route) from freezing. Summer temperatures are relatively mild, and there will be no need for refrigeration or cooling at any point.

The mine will utilize the principle of parallel ventilation whenever possible to ensure that the re-use of air underground is minimized. The underground shop and crusher will be ventilated directly to exhaust, and water sprays will be utilized for dust suppression at the drawpoints, central crusher and along the conveyor as necessary. Furthermore, the access decline, conveyor and underground shop ventilation is accomplished with a ventilation split kept completely separate from the production air for added safety.

Airflow velocities in drifts designed for heavy vehicle traffic were kept below 4 m/s, while the conveyor drifts were maintained at less than 2 m/s. A minimum velocity of 1 m/s was provided to all active production panels. The ventilation sub-levels (dedicated drifts for providing/removing airflow) were limited to a maximum velocity of 10 m/s while the airflow velocity in the primary ventilation raises was capped at 20 m/s.
All primary fan installations will be equipped with variable frequency drives for flexibility, better control and optimal efficiency.

The various drift dimensions and associated Atkinson resistance factors (k-factors) utilized in developing the ventilation models are given in Table 12.

Table 12: Estimated k-factors for Various Drift Dimensions (Cross-Section).

<table>
<thead>
<tr>
<th>Airway Description</th>
<th>Dimensions (m x m)</th>
<th>Area (m²)</th>
<th>Perimeter (m)</th>
<th>Friction Factor (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation Drift</td>
<td>6.0 X 6.0/5.0</td>
<td>36.0</td>
<td>24.0</td>
<td>0.0095</td>
</tr>
<tr>
<td>Access Decline</td>
<td>5.0 X 5.0</td>
<td>25.0</td>
<td>20.0</td>
<td>0.0110</td>
</tr>
<tr>
<td>Extraction Level</td>
<td>5.0 X 4.5</td>
<td>22.5</td>
<td>19.0</td>
<td>0.0120</td>
</tr>
<tr>
<td>Conveyor Decline</td>
<td>4.5 X 4.5</td>
<td>20.3</td>
<td>18.0</td>
<td>0.0150</td>
</tr>
<tr>
<td>Raise – Bored</td>
<td>5.0 φ</td>
<td>19.6</td>
<td>15.7</td>
<td>0.0055</td>
</tr>
</tbody>
</table>

Note: Empirical values based on data collected at similar operations at 1.0 – 1.2 kg/m³ air density.

The resistances of ventilation controls such as doors, bulkheads and curtains are provided in Table 13.

Table 13: Resistance Values for Selected Ventilation Controls.

<table>
<thead>
<tr>
<th>Description</th>
<th>Resistance* (Ns²/m⁸)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door</td>
<td>12.5</td>
</tr>
<tr>
<td>Bulkhead (Shotcrete)</td>
<td>250.0</td>
</tr>
<tr>
<td>Brattice Bulkhead</td>
<td>3.0</td>
</tr>
<tr>
<td>Slatted Curtain</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Note: At an average air density of 1.2 kg/m³.
Additional design parameters and information regarding the basis for the ventilation system design, including the fan curves and site environmental data can be found in Appendix C.

11.1.2 Ventilation Modelling and Software Package

In order to assist in determining projected fan operating points, flow distribution, regulator and door locations and leakage amounts, ventilation models were created to represent the two points in time chosen for this study. The models generated were constructed from a combination of resistance parameters that are outlined in the Design Criteria coupled with physical drift parameters provided by the client. Where necessary, shock losses were accounted for by applying an appropriate shock-loss factor to the branch in the ventilation model(s). The VnetPC Pro+ software package was utilized for all of the modeling exercises involving the primary ventilation system for The Mine while any necessary simulations of the auxiliary ventilation system(s) was performed utilizing DuctSIM.

The VnetPC program is a self-contained software package designed to assist mine engineers in the planning of mine ventilation layouts. Using data obtained from ventilation surveys or determined from known airway dimensions and characteristics, existing ventilation networks can be simulated in such a manner that airflow rates, frictional pressure drops, and fan operating points approximate those of the actual system. The program has been developed based upon the assumption of incompressible flow and follows Kirchhoff’s Laws as well as utilizing an accelerated form
of the Hardy Cross iterative technique to converge to a solution. DuctSIM is a simplified ventilation simulator that allows the user to model an auxiliary (fan and duct) installation that accounts for shock losses and leakage. Both packages are currently commercially available.

11.2 Case Study – Part I: Conventional Method of Airflow Determination

Based on the projected mine equipment, total airflow requirements for various stages of the mine development were calculated based on 0.063 m$^3$/s per kW and the utilization numbers provided by the client. In this case, 0.063 m$^3$/s per kW was chosen as the method of determining the total airflow for the diesel equipment fleet based on the statutory requirement in B.C.

Table 14 shows the total airflow required during development of the twin declines. This flow will be provided by the fan installation located at the Conveyor Decline Portal.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Utilization (%)</th>
<th>Power (kW)</th>
<th>Quantity</th>
<th>Airflow (m$^3$/s)</th>
<th>Total (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHD</td>
<td>100%</td>
<td>291</td>
<td>2</td>
<td>17.5</td>
<td>35</td>
</tr>
<tr>
<td>Haul Truck</td>
<td>95%</td>
<td>410</td>
<td>2</td>
<td>23.4</td>
<td>47</td>
</tr>
<tr>
<td>Light Duty Vehicle</td>
<td>100%</td>
<td>111</td>
<td>2</td>
<td>6.7</td>
<td>13</td>
</tr>
<tr>
<td>Jumbo/Bolter</td>
<td>50%</td>
<td>111</td>
<td>2</td>
<td>3.3</td>
<td>6.66</td>
</tr>
</tbody>
</table>

Table 14: Total Airflow Requirements for Twin Decline Development.
Table 15 gives the total airflow requirements for the mine once a “steady-state” has been reached in the mine’s production and equipment fleet.

Table 15: Total Airflow Requirements for LOM Case (Maximum Demand).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Utilization (%)</th>
<th>Power (kW)</th>
<th>Quantity</th>
<th>Airflow (m³/s)</th>
<th>Total (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHD</td>
<td>100%</td>
<td>291</td>
<td>14</td>
<td>17.5</td>
<td>244</td>
</tr>
<tr>
<td>Haul Truck</td>
<td>95%</td>
<td>410</td>
<td>2</td>
<td>23.4</td>
<td>47</td>
</tr>
<tr>
<td>Light Duty Vehicle</td>
<td>65%</td>
<td>111</td>
<td>5</td>
<td>4.3</td>
<td>22</td>
</tr>
<tr>
<td>Jumbo</td>
<td>15%</td>
<td>111</td>
<td>6</td>
<td>1.0</td>
<td>6</td>
</tr>
<tr>
<td>Shotcrete Truck</td>
<td>75%</td>
<td>200</td>
<td>3</td>
<td>9.0</td>
<td>27</td>
</tr>
<tr>
<td>Road Grader</td>
<td>25%</td>
<td>265</td>
<td>1</td>
<td>4.0</td>
<td>15</td>
</tr>
<tr>
<td>Shop</td>
<td>100%</td>
<td>N/A</td>
<td>1</td>
<td>40.0</td>
<td>40</td>
</tr>
<tr>
<td>Conveyor</td>
<td>100%</td>
<td>N/A</td>
<td>1</td>
<td>25.0</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sum:</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>426</strong></td>
<td></td>
</tr>
</tbody>
</table>

During peak production, any eleven of the extraction panels will be active at any given time, requiring approximately 193 m³/s. Furthermore, sufficient airflow is necessary in the Rim Drift to allow a single LHD to move between panels, requiring an additional 35 m³/s on that level. Approximately 50 m³/s is needed for the Undercut Level. The underground shop is ventilated with 40 m³/s and the conveyor drift with a further 25 m³/s. Other areas of the mine are not controlled for airflow.

11.2.1 Maximum Demand Model – Part I

At this point, the development activities of the Mine cease, and the mine experiences a quasi-steady-state period of maximum production (eleven active production panels) until the ramp-down of production at the end of mine life. By beginning the design of the ventilation system with this point of “maximum demand”, it is possible to size the
ventilation infrastructure adequately, and to establish the endpoint of the mine ventilation system’s evolution. By working towards this known configuration, the system is able to evolve from the start of development, ensuring that all intermediate points are achievable.

The ventilation system design for the Mine includes two primary ventilation circuits that are kept completely separated from each other. The decline circuit draws intake air down the Access Decline, which splits at the bottom of the ramp; approximately 40 m$^3$/s provides ventilation for the shop and is exhausted through a short raise down to the Exhaust Sub-level, a further 25 m$^3$/s ventilates the sump area and travels up the Conveyor Decline prior to being exhausted at the portal. The fan installation for this circuit is located in a specially-constructed bulkhead located at the portal of the Conveyor Decline.

The primary, or production ventilation circuit intakes air through a dedicated, 5-m raise located adjacent to the ramp at the start of the Intake Sub-level. A primary fan installation is located at the raise bottom, which forces air down the Intake Sub-level below the mining horizon to the northern side of the extraction panels. A series of 2-m diameter raises connect from the ventilation sub-level up to each extraction panel and periodically along the Undercut Level. Each of the production raises will be controlled via a valve-type regulator located on the Extraction Level and a drop-board regulator on the Undercut Level. Extraction panels will also have a door
located at the northernmost end of the panel that will control airflow into/through the North Rim Drift.

For active panels, the intake raise regulator is opened until the desired airflow is achieved (this can be determined based on the airflow quantity sensor that will be installed in the panel). If a panel is “closed”, meaning that the production LHD is moving to another panel, the loader operator can close the intake regulator before leaving the area.

Figure 50 shows a detail of the Extraction Level including the proposed regulators and doors.

![Diagram of Extraction Panel Detail Showing Regulators and Doors](https://via.placeholder.com/150)

**Figure 50: Extraction Panel Detail Showing Regulators and Doors.**
Each of the eleven active panels on the Extraction Level are provided with a minimum of 22 m$^3$/s, with the outermost panels also ventilated at the same rate in order to allow for transportation of equipment from one side of the mine to the other without disturbing production. Once leaving the panels on the southern side of the level, air is collected in the parallel haulage drifts and funneled towards the central crusher. Exhaust raises connected to the southernmost (outer) haulage drift transport air down to the Exhaust Sub-level, where it is then carried out of the mine through the primary exhaust fan installation and the dedicated 5-m diameter exhaust raise.

The central crusher is ventilated with a dedicated exhaust raise controlled via a regulator at a volume of 40 m$^3$/s.

Figure 51 shows the predicted airflow distribution on the Extraction Level during the LOM case. Note that the location of the active panels can change rapidly with the adjustment of the in-panel regulators.
11.2.2 Twin Decline Development Model – Part I

The first development model represents the maximum extent of the twin declines, and represents the longest circuit in the mine prior to the establishment of the ventilation sub-levels and the two primary fan installations. The parallel fan installation at the Conveyor Decline Portal allows the auxiliary fans and ducts utilized during the development period to remain a consistent size, power, diameter and length,
respectively. The Conveyor Decline was chosen as the location for the fan installation because it was assumed that there would be much fewer personnel in the Conveyor Decline above the last open cross-cut (all haulage was assumed to occur in the Access Decline in accordance with the mine development plan) and that this design would allow for minimal realized velocities for the crushed material once the conveyor system is installed and utilized.

Air enters the mine through the Access Decline portal, and travels down the slope to the most recently developed cross-cut (furthest from the portal) where it passes through into the Conveyor Decline and is exhausted out of the mine through the Conveyor Decline fans. The auxiliary fans required will be placed in the bottom of the Access Decline approximately 10 m above the last open cross-cut, with a single fan and 1.4-m diameter flexible duct installed in each decline running from the fan to the face. Bulkheads will be constructed in the cross-cuts upon completion of the next, necessitating the relocation of the auxiliary fans and duct. In this manner, the auxiliary ventilation will be “leapfrogged” through the development period, minimizing the associated costs and delivering a consistent quantity of airflow to the working faces.

Figure 52 depicts the general arrangement of the ventilation system design for the development of the twin declines of the Mine.
Ventilation modeling of auxiliary ventilation fan and duct combinations were performed using DuctSIM software. For the ventilation of the Mine development, 1.4-m diameter flexible (blowing bag) duct was paired with 50 kW, 1.4-m diameter fans. This combination meets the demands of the decline development as well as other development requirements of the mine once the bottom of the decline is reached. The recommended combination of fan and duct is capable of providing 20 m³/s to active faces up to 660 m away at operating pressures that range from 1.5 – 2 kPa. The airflow quantity of 20 m³/s was chosen for these exercises because it represents the amount of airflow required for a single LHD. For headings where additional equipment (i.e. Haul Truck) is required, two fan/duct systems can be installed in parallel. For longer development headings, additional fans may be added in series in order to extend the length of the duct required. Standardizing the infrastructure for auxiliary ventilation at the mine has many operational benefits regarding cost, installation, maintenance and planning.

Figure 52: Schematic of the Development Ventilation System Design for the Mine.
Figure 53 shows a cross-section of the auxiliary ventilation system installed in the Access Decline. Figure 54 and Figure 55 depict graphical representations of the auxiliary system performance at lengths of 180 m (Decline Development) and 660 m (mine development), respectively.

Figure 53: Cross-section of Access Decline with Auxiliary Ventilation System.
Figure 54: Graphical DuctSIM Results for Decline Development (180 m).

Figure 55: Graphical DuctSIM Results for Mine Development (660 m).
11.2.3 Primary Fan Installations – Part I

The ventilation system design requires three primary fan installations. Each of these fan installations (located at the Conveyor Decline Portal, Intake Raise and Exhaust Raise) will include VFD controls and other fan and ventilation monitoring equipment. For further operational flexibility, each primary fan installation will consist of two identical fans installed in parallel. This type of installation increases flexibility in the ventilation system by allowing the operation of a single fan when production, maintenance or operational demands require it, or in the event of an unplanned fan outage (NOTE: in the case of the primary intake and exhaust fan installations, a change in the operation of one fan will require adjustment of the opposite installation in order for the system to remain balanced). Additional fan data obtained from the manufacturer may be found in Appendix B.

The Conveyor Decline portal fan installation is located at the top of the Conveyor Decline. This location will eventually require that a conveyor regulator be cut in the fan bulkhead, with the two parallel fans installed below the conveyor belt. The two fans installed at this location will be the first to be installed at the mine, and will be an integral part of the ventilation system for the development of the twin declines, before later providing all of the airflow required for the Declines once the production ventilation circuit is completed and the primary intake and exhaust fans are installed and operated.
During the development of the twin declines, the parallel fan installation will evacuate approximately 139 m$^3$/s from the conveyor decline at a maximum pressure of approximately 1.6 kPa.

Once the primary ventilation circuit of the mine is established (including the intake and exhaust raise fan installations) one of the Conveyor Decline Fans will be turned off. Under these conditions, the remaining fan will exhaust 38 m$^3$/s at approximately 0.25 kPa. The fan that is operational can be periodically switched with the fan that is off in order to preserve both fans and ensure that either can be utilized in the event of a planned or unplanned fan shut-down.

Figure 56 shows a view of the proposed Conveyor Decline fan bulkhead. Figure 57 depicts the Conveyor Decline fan location in plan view.
Figure 56: Conveyor Decline Fan Bulkhead with Regulator.

Figure 57: Conveyor Decline Portal Fan Installation (Plan View).
Parallel fans located at the bottom of the intake raise provide approximately 370 m$^3$/s of fresh air to the mine at 2.6 kPa. The fans should be located a minimum of 40 m downstream of the raise bottom. A suitable cavern should be excavated for this site, including sufficient room to fit the two fans side-by-side, with enough overhead clearance to install a crane capable of lifting the fans in-place.

Locating these fans underground will facilitate access for inspection and maintenance purposes, particularly during winter months, when snow and cold temperatures can make access to the top of the raises difficult. In addition, the location downstream of the air heaters will ensure that the fans are protected from ice build-up and freezing temperatures that would be present on the surface. In light of these advantages, special permission will be sought from the B.C. Mining and Minerals Division in order to locate these fans underground.

Figure 58 shows the location of the primary intake fan installation in the plan view.

Figure 58: Primary Intake Fan Installation (Plan View).
Figure 59 shows a cross-sectional view of the intake fan installation.

![Figure 59: Primary Intake Fan Installation (Cross-section).]

The primary exhaust fan installation is the “twin” of the intake fan installation. Located opposite the intake in the exhaust sub-level, the two parallel fans propel approximately 400 m$^3$/s of air up the 5-m diameter exhaust raise and out of the mine. The estimated operating pressure of the exhaust fans is 2.2 kPa.

The underground location of the primary exhaust fans facilitates access to the fan site for inspection and maintenance services, and also minimizes noise concerns at the surface.

Figure 60 shows a plan view of the primary exhaust fan installation. Figure 61 depicts the installation in cross-section.
11.2.4 Air Heating – Part I

The heating calculations for the Mine were based upon the site environmental data and the project design criteria of +2 °C delivered intake air temperature. The calculations were performed assuming direct-fired propane heaters.

The site environmental data utilized as the basis for these calculations were taken from existing mine weather stations. These data are shown in Table 16.
The calculations in support of determining the air heating requirements for the Access Decline portal heater are provided in Table 17. The heat required is based on the expected temperature rise necessary to heat the ambient air to +2 °C prior to its introduction underground. The required volumes of propane were calculated based on assumptions of energy content of the propane, an overall efficiency of the heater units of 99% and a fuel cost of approximately 0.50 US$/liter.

Although the average amount of heat required is generally much less, the period of greatest demand should be used to determine the size (capacity) of the heater installation for any given location. For the purposes of this study, the average minimum...
monthly temperature was used to size the heaters. In cases where the ambient intake air temperature falls significantly below this value, additional measures such as reducing airflow, salting roadways, reducing equipment/personnel or stopping work may be required.

Table 18 shows the calculations for the purpose(s) of sizing the air heater installation for the Access Decline.

### Table 18: Heater Sizing Calculation for the Access Decline Portal.

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow:</td>
<td>420.0 m³/s</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.05 kg/m³</td>
</tr>
<tr>
<td>Air Density at -T°C</td>
<td>1.10 kg/m³</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>20 °C Change</td>
</tr>
<tr>
<td>Mass Flow of Air (mₐ):</td>
<td>462.0 kg/s</td>
</tr>
<tr>
<td>Heat Required (qₐ=mₐCₚΔT)</td>
<td>9.29 MW (=MJ/s)</td>
</tr>
<tr>
<td>Calorific value of Propane:</td>
<td>25.3 MJ/l</td>
</tr>
<tr>
<td>Propane flow rate:</td>
<td>0.3670 l/s</td>
</tr>
<tr>
<td>Hourly flow rate:</td>
<td>1321.4 l/hr</td>
</tr>
</tbody>
</table>

The calculations in support of determining the air heating requirements for the Intake Raise heater are provided in Table 19.
Table 19: Estimated Air Heating Requirements for the Intake Raise.

<table>
<thead>
<tr>
<th></th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow (m₃/s)</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
<td>420.0</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Air Density at -T°C</td>
<td>1.10</td>
<td>1.11</td>
<td>1.10</td>
<td>1.07</td>
<td>1.05</td>
<td>1.03</td>
<td>1.01</td>
<td>1.02</td>
<td>1.04</td>
<td>1.07</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>11.6</td>
<td>12.3</td>
<td>11.5</td>
<td>4.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.5</td>
<td>8.8</td>
<td>13.8 °C</td>
<td>Change</td>
</tr>
<tr>
<td>Mass Flow of Air (mₐ):</td>
<td>463.3</td>
<td>464.5</td>
<td>463.3</td>
<td>451.1</td>
<td>441.8</td>
<td>432.2</td>
<td>425.0</td>
<td>428.8</td>
<td>436.4</td>
<td>451.1</td>
<td>458.6</td>
<td>467.5 kg/s</td>
</tr>
<tr>
<td>Heat Required (qₐ=mₐCpₐΔT)</td>
<td>5.40</td>
<td>5.74</td>
<td>5.35</td>
<td>1.99</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>2.04</td>
<td>4.06</td>
<td>6.48 MW (=MJ/s)</td>
</tr>
<tr>
<td>Calorific value of Propane:</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3 MJ/l</td>
</tr>
<tr>
<td>Propane flow rate:</td>
<td>0.2135</td>
<td>0.2270</td>
<td>0.2116</td>
<td>0.0788</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0806</td>
<td>0.1603</td>
<td>0.2563 l/s</td>
</tr>
<tr>
<td>Hourly flow rate:</td>
<td>768.5</td>
<td>817.1</td>
<td>761.9</td>
<td>283.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>290.3</td>
<td>577.2</td>
<td>922.5</td>
<td>l/hr</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>$285,873</td>
<td>$274,534</td>
<td>$283,409</td>
<td>$102,178</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$107,983</td>
<td>$207,781</td>
<td>$343,174</td>
<td>$/mo</td>
</tr>
<tr>
<td>Assumed Max Burn</td>
<td>$1,604,933</td>
<td>$/year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 20 shows the calculations for the purpose(s) of sizing the air heater installation for the intake Raise.

Table 20: Heater Sizing Calculation for the Intake Raise.

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow:</td>
<td>420.0</td>
<td>m³/s</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.05</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Air Density at -T°C</td>
<td>1.10</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>20 °C</td>
<td>Change (from -18.0 to +2)</td>
</tr>
<tr>
<td>Mass Flow of Air (mₐ):</td>
<td>462.0</td>
<td>kg/s</td>
</tr>
<tr>
<td>Heat Required (qₐ=mₐCpₐΔT)</td>
<td>9.29</td>
<td>MW (=MJ/s)</td>
</tr>
<tr>
<td>Calorific value of Propane:</td>
<td>25.3</td>
<td>MJ/l</td>
</tr>
<tr>
<td>Propane flow rate:</td>
<td>0.3670</td>
<td>l/s</td>
</tr>
<tr>
<td>Hourly flow rate:</td>
<td>1321.4</td>
<td>l/hr</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>0.50</td>
<td>$/liquid litre</td>
</tr>
<tr>
<td>Assumed Max Burn</td>
<td>30 days</td>
<td></td>
</tr>
<tr>
<td>Cost per year:</td>
<td>$1,604,933</td>
<td>$/year</td>
</tr>
</tbody>
</table>
11.2.5 Summary of Estimated Capital and Operating Costs – Part I

Once the development models were complete, the ventilation infrastructure (primary fan installations, equipment doors, bulkheads, etc.) required for each scenario were identified in order to present estimates of capital and operating cost (where applicable) for all required ventilation controls. These estimates do NOT include auxiliary ventilation components (e.g. ductings, wyes, or fans) as these components are generally modular and vary widely in their application within the mine life-cycle.

Airlock (double) equipment doors will be required at each of the primary fan installations, including the first cross-cut in-by the Conveyor Access portal fan. Airlocks are also required to isolate the underground shop and on both of the Extraction Level access ramps on the North Rim Drift. Single doors are required at the north end of each active panel on the Extraction Level. Mine weather stations will be located at each fan location and outside of the Access Decline portal. Bundled air quality sensors are recommended for each fan installation as well as in each panel of the Extraction Level and as often as necessary along the Conveyor Decline. Airflow Quantity sensors should be installed in each production panel as well as at each fan installation and in the Access Decline.

The fan cost(s) provided here are for parallel fan installations with Variable Frequency Drives (VFDs).
Raise cost estimates for the project were obtained from a major mining contractor and are included here for informational purposes only.

Other capital cost estimates provided were based upon the most up-to-date cost data available at the time of the work, and do NOT include any installation costs, applicable taxes, fees, or importation duties.

Table 21 gives the estimated capital cost(s) for the recommended ventilation equipment in support of the ventilation design.

**Table 21: Estimated Capital Costs for the Mine Ventilation Equipment.**

<table>
<thead>
<tr>
<th>Fan Installations:</th>
<th>Quantity (m³/s)</th>
<th>Pressure (kPa)</th>
<th>Air Power @ 75% Eff. (kW)</th>
<th>VFD Required?</th>
<th>Heat Required?</th>
<th>Heater Size (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>200</td>
<td>3</td>
<td>800</td>
<td>Yes</td>
<td>Yes</td>
<td>10.0</td>
</tr>
<tr>
<td>Exhaust Raise</td>
<td>200</td>
<td>3</td>
<td>800</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
</tr>
<tr>
<td>Decline</td>
<td>68</td>
<td>1.5</td>
<td>136</td>
<td>Yes</td>
<td>Yes</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fan Installations:</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>VFD Cost ($US)</th>
<th>Monitoring ($US)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>2</td>
<td>$ 520,600</td>
<td>$ 218,750</td>
<td>$ 25,600</td>
<td>$ 1,529,900</td>
<td>$ 1,529,900</td>
</tr>
<tr>
<td>Exhaust Raise</td>
<td>2</td>
<td>$ 520,600</td>
<td>$ 218,750</td>
<td>$ 25,600</td>
<td>$ 1,529,900</td>
<td>$ 3,059,800</td>
</tr>
<tr>
<td>Conveyor Decline</td>
<td>2</td>
<td>$ 68,000</td>
<td>$ 25,000</td>
<td>$ 25,600</td>
<td>$ 237,200</td>
<td>$ 3,297,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilation Raises</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>Method of Excavation</th>
<th>Length (m)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>1</td>
<td>$ 8,200</td>
<td>Raise-Bore</td>
<td>720</td>
<td>$ 5,904,000</td>
<td>$ 5,904,000</td>
</tr>
<tr>
<td>Haulage Decline</td>
<td>1</td>
<td>$ 8,200</td>
<td>Raise-Bore</td>
<td>720</td>
<td>$ 5,904,000</td>
<td>$ 11,808,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heater Installations</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>Installation Cost ($US)</th>
<th>Monitoring ($US)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>1</td>
<td>$ 1,053,700</td>
<td>$ 400,000</td>
<td>-</td>
<td>$ 1,453,700</td>
<td>$ 1,453,700</td>
</tr>
<tr>
<td>Haulage Decline</td>
<td>1</td>
<td>$ 445,800</td>
<td>$ 250,000</td>
<td>-</td>
<td>$ 695,800</td>
<td>$ 2,149,500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment Installations:</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airlock Doors/Fire Doors</td>
<td>34</td>
<td>$ 25,000</td>
<td>$ 850,000</td>
<td>$ 850,000</td>
</tr>
<tr>
<td>Panel Regulators</td>
<td>20</td>
<td>$ 2,500</td>
<td>$ 50,000</td>
<td>$ 90,000</td>
</tr>
<tr>
<td>Airflow Quantity Sensors</td>
<td>25</td>
<td>$ 3,000</td>
<td>$ 75,000</td>
<td>$ 975,000</td>
</tr>
<tr>
<td>Airflow Quality Sensors</td>
<td>34</td>
<td>$ 5,000</td>
<td>$ 170,000</td>
<td>$ 1,145,000</td>
</tr>
<tr>
<td>Mine Weather Stations</td>
<td>4</td>
<td>$ 2,000</td>
<td>$ 8,000</td>
<td>$ 1,153,000</td>
</tr>
</tbody>
</table>

NOTE: All prices shown are for estimating purposes only.
Estimated operating costs were based on a power cost of US$ $0.04 / kWhr at a total efficiency (fan, motor and linkage) of 75% and continuous operation at actual mine density. The cost of power used for estimating purposes was based upon current power costs for existing mine facilities at the approximate mine location (B.C.).

Table 22 shows the estimated annual operating costs for the primary fan and heater installations at the Mine.

**Table 22: Estimated Operating Costs for the Primary Fan and Heater Installations.**

<table>
<thead>
<tr>
<th>Fan Installations</th>
<th>Quantity (m³/s)</th>
<th>Pressure (kPa)</th>
<th>Efficiency (%)</th>
<th>Power (kW)</th>
<th>Annual Cost ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>365</td>
<td>2.7</td>
<td>75%</td>
<td>1314</td>
<td>$460,426</td>
<td>$460,426</td>
</tr>
<tr>
<td>Exhaust Raise</td>
<td>400</td>
<td>2.6</td>
<td>75%</td>
<td>1387</td>
<td>$485,888</td>
<td>$946,314</td>
</tr>
<tr>
<td>Conveyor Decline</td>
<td>35</td>
<td>0.25</td>
<td>75%</td>
<td>12</td>
<td>$4,088</td>
<td>$950,402</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heater Installations</th>
<th>Quantity (m³/s)</th>
<th>Density (kg/m³)</th>
<th>Max Heat (MW)</th>
<th>Propane Cost ($US/litre)</th>
<th>Annual Cost ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>420</td>
<td>1.05</td>
<td>9.3</td>
<td>0.05</td>
<td>$1,605,000</td>
<td>$1,605,000</td>
</tr>
<tr>
<td>Haulage Decline</td>
<td>75</td>
<td>1.10</td>
<td>1.3</td>
<td>0.05</td>
<td>$286,600</td>
<td>$1,891,600</td>
</tr>
</tbody>
</table>

**NOTE:** All prices shown are for estimating purposes only.

Owing to the design of the ventilation system, these operating costs are expected to be fairly uniform over the life of the Mine, beginning when the primary ventilation fans are installed and operational.

**11.3 Case Study – Part II: Proposed New Method of Airflow Determination**

For the purpose(s) of demonstrating the differences between the two methods, the total airflow required to support the equipment fleet was calculated a second time based on
the new methodology proposed in this thesis. In this case, separate airflow calculations were performed for the gaseous emissions, DPM, heat and dust created by the equipment (assuming that all new equipment will be Tier IV).

Because several active and passive dust control measures were specified for this mine, the mitigation of dust generated by the diesel equipment only needs to be considered in drifts where only a single piece of equipment is operating and there are no other dust control measures specified. Despite this, the minimum velocity specified will be maintained in accordance with the original project criteria.

In order to validate the assumptions regarding the impact of the heat generated by the diesel equipment fleet on the ambient conditions underground and the capacity of the ventilation to remove that heat, a calculation of expected VRT is necessary. From a collection of down-hole temperature logs in core-hole drills, the average VRT for the area of mining was calculated to be approximately 12.1 °C.

These data are shown on Figure 62.
In order to prevent ambient temperatures underground from exceeding 32 °C (dry-bulb), the maximum temperature rise across the equipment was limited to 20 °C when determining the minimum airflow (volume) requirement for the diesel equipment fleet (at the minimum anticipated in-situ air density of 1.10 kg/m$^3$).

Table 23 shows the total airflow required during development of the twin declines. This flow will be provided by the fan installation located at the Conveyor Decline Portal.
Table 23: Total Airflow Requirements for TwinDecline Development.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Utilization (%)</th>
<th>Power (kW)</th>
<th>Quantity</th>
<th>Gas Q (m³/s)</th>
<th>DPM Q (m³/s)</th>
<th>Heat Q (m³/s)</th>
<th>Dust Q* (m³/s)</th>
<th>Total** (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHD</td>
<td>100%</td>
<td>291</td>
<td>2</td>
<td>8.1</td>
<td>3.2</td>
<td>23.9</td>
<td>22.5</td>
<td>48</td>
</tr>
<tr>
<td>Haul Truck</td>
<td>100%</td>
<td>410</td>
<td>2</td>
<td>11.5</td>
<td>4.5</td>
<td>33.6</td>
<td>25.0</td>
<td>67</td>
</tr>
<tr>
<td>Light Duty Vehicle</td>
<td>100%</td>
<td>111</td>
<td>2</td>
<td>3.1</td>
<td>1.2</td>
<td>9.1</td>
<td>25.0</td>
<td>18</td>
</tr>
<tr>
<td>Jumbo/Bolter</td>
<td>100%</td>
<td>111</td>
<td>2</td>
<td>3.1</td>
<td>1.2</td>
<td>9.1</td>
<td>25.0</td>
<td>18</td>
</tr>
<tr>
<td><strong>Sum:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>151</td>
</tr>
</tbody>
</table>

Table 24 gives the total airflow requirements for the mine once a “steady-state” has been reached in the mine’s production and equipment fleet.

Table 24: Total Airflow Requirements for LOM Case (Maximum Demand).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Utilization (%)</th>
<th>Power (kW)</th>
<th>Quantity</th>
<th>Gas Q (m³/s)</th>
<th>DPM Q (m³/s)</th>
<th>Heat Q (m³/s)</th>
<th>Dust Q* (m³/s)</th>
<th>Total** (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHD</td>
<td>100%</td>
<td>291</td>
<td>14</td>
<td>8.1</td>
<td>3.2</td>
<td>23.9</td>
<td>22.5</td>
<td>335</td>
</tr>
<tr>
<td>Haul Truck</td>
<td>95%</td>
<td>410</td>
<td>2</td>
<td>10.9</td>
<td>4.3</td>
<td>33.6</td>
<td>25.0</td>
<td>64</td>
</tr>
<tr>
<td>Light Duty Vehicle</td>
<td>65%</td>
<td>111</td>
<td>5</td>
<td>2.0</td>
<td>0.8</td>
<td>9.1</td>
<td>25.0</td>
<td>30</td>
</tr>
<tr>
<td>Jumbo</td>
<td>15%</td>
<td>111</td>
<td>6</td>
<td>0.5</td>
<td>0.2</td>
<td>9.1</td>
<td>25.0</td>
<td>8</td>
</tr>
<tr>
<td>Shotcrete Truck</td>
<td>75%</td>
<td>200</td>
<td>3</td>
<td>4.2</td>
<td>1.7</td>
<td>16.4</td>
<td>25.0</td>
<td>37</td>
</tr>
<tr>
<td>Road Grader</td>
<td>25%</td>
<td>265</td>
<td>1</td>
<td>1.9</td>
<td>0.7</td>
<td>21.7</td>
<td>25.0</td>
<td>5</td>
</tr>
<tr>
<td>Shop</td>
<td>100%</td>
<td>N/A</td>
<td>1</td>
<td>40.0</td>
<td>40.0</td>
<td>40.0</td>
<td>40.0</td>
<td>40</td>
</tr>
<tr>
<td>Conveyor</td>
<td>100%</td>
<td>N/A</td>
<td>1</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td>25</td>
</tr>
<tr>
<td><strong>Sum:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>544</td>
</tr>
</tbody>
</table>

*Based on the cross-sectional area of the drift where the equipment will most often be used.
**Based on the airflow required to mitigate the heat of the equipment.

During this scenario, the eleven active extraction panels will require approximately 263 m³/s. An additional 48 m³/s is supplied to the Rim Drift on that level. Approximately 66 m³/s is provided for the Undercut Level. The airflow requirements for the
underground shop and conveyor drift are unchanged, 40 m³/s and 25 m³/s, respectively. Other areas of the mine are not controlled for airflow.

11.3.1 Maximum Demand Model – Part II

When re-modelling the maximum demand model for the case study, all of the basic design parameters were kept the same whenever possible; infrastructure and other installations were changed only when required to meet the design criteria (e.g. when maximum velocity limits were exceeded). Unless it is explicitly stated, the design concepts and implementation can be assumed to be the same as in Part I of this Case Study.

In the LOM case, the total airflow required in support of the mining activities increased from 425 to 544 m³/s, or approximately 28%. The largest and most immediate change relating to the increase of airflow required in this case is the increase in size required for the primary ventilation raises in order to meet the maximum allowable velocity limit (20 m/s); this was only possible by increasing the diameter of the intake and exhaust raises to 6-m diameter each.

Each of the eleven active panels on the Extraction Level were provided with a higher airflow of 24 m³/s, with the outermost panels also ventilated at the same rate. This did not otherwise require changes in the panel size(s) or the diameters of the panel raises.

Figure 63 shows the predicted airflow distribution on the Extraction Level during the LOM case.
The central crusher, shop and conveyor ventilation rates were unchanged from Part I of this study.

11.3.2 Twin Decline Development Model – Part II

During the development of the twin declines, an increase in the amount of airflow both in the circuit (40 m$^3$/s or 36%) and to the two faces (6.5 m$^3$/s or 37%) was required, to
151 m$^3$/s and 24 m$^3$/s, respectively. This requires a slight increase in the size of the duct to 1.5-m diameter in order to keep the fan pressure below 2.0 kPa over the longest runs of duct (660m).

Figure 64 shows a cross-section of the auxiliary ventilation system installed in the Access Decline.

Figure 64: Cross-section of Access Decline with Auxiliary Ventilation System.
Figure 65 and Figure 66 depict graphical representations of the auxiliary system performance at lengths of 180 m (Decline Development) and 660 m (mine development), respectively.

Figure 65: Graphical DuctSIM Results for Decline Development (180 m).

Figure 66: Graphical DuctSIM Results for Mine Development (660 m).
11.3.3 Primary Fan Installations – Part II

Each of the fan installations (located at the Conveyor Decline Portal, Intake Raise and Exhaust Raise) will include VFD controls and other fan and ventilation monitoring equipment as previously specified. Note that although each of the fan operating points has changed, the same fan will be capable of providing the new operating point in each case.

Development and location of the Conveyor Decline fan installation remains the same as before. During the development of the twin declines, the parallel fan installation will evacuate approximately 151 m$^3$/s from the conveyor decline at a maximum pressure of approximately 1.9 kPa.

Once the primary ventilation circuit of the mine is established (including the intake and exhaust raise fan installations) one of the Conveyor Decline Fans will be turned off. Under these conditions, the remaining fan will exhaust 38 m$^3$/s at approximately 0.25 kPa (this operating point is unchanged from the previous scenario).

Parallel fans located at the bottom of the intake raise provide approximately 445 m$^3$/s of fresh air to the mine at 2.5 kPa through the enlarged 6-m raise.

The primary exhaust fan installation is the “twin” of the intake fan installation. These two parallel fans exhaust approximately 475 m$^3$/s of air up the 6-m diameter exhaust raise and out of the mine. The estimated operating pressure of the exhaust fans is 2.0 kPa.
11.3.4 Air Heating – Part II

Along with the changes to the primary ventilation raises and fan installations, the increase in the required air heating capacity represents a major change to the original ventilation design. The larger capacity air heaters required at the intake raise are both more expensive to purchase and to operate.

The revised calculations in support of determining the air heating requirements for the Intake Raise heater are provided in Table 25.

**Table 25: Estimated Air Heating Requirements for the Intake Raise.**

<table>
<thead>
<tr>
<th>Airflow:</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
<td>485.0</td>
</tr>
<tr>
<td>Air Density</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>Air Density at -T°C</td>
<td>1.10</td>
<td>1.11</td>
<td>1.10</td>
<td>1.07</td>
<td>1.05</td>
<td>1.03</td>
<td>1.01</td>
<td>1.02</td>
<td>1.04</td>
<td>1.07</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>11.6</td>
<td>12.3</td>
<td>11.5</td>
<td>4.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.5</td>
<td>8.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Mass Flow of Air (m_a):</td>
<td>535.0</td>
<td>536.4</td>
<td>535.0</td>
<td>520.9</td>
<td>510.2</td>
<td>499.1</td>
<td>490.8</td>
<td>495.2</td>
<td>503.9</td>
<td>520.9</td>
<td>529.6</td>
<td>539.8</td>
</tr>
<tr>
<td>Heat Required (q_a=m_aC_p(ΔT))</td>
<td>6.24</td>
<td>6.63</td>
<td>6.18</td>
<td>2.30</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.36</td>
<td>4.68</td>
<td>7.49</td>
</tr>
<tr>
<td>Calorific value of Propane:</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
<td>25.3</td>
</tr>
<tr>
<td>Propane flow rate:</td>
<td>0.2465</td>
<td>0.2621</td>
<td>0.2444</td>
<td>0.0910</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0931</td>
<td>0.1851</td>
<td>0.2959</td>
</tr>
<tr>
<td>Hourly flow rate:</td>
<td>887.4</td>
<td>943.5</td>
<td>879.8</td>
<td>327.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>335.2</td>
<td>666.5</td>
<td>1065.3</td>
</tr>
</tbody>
</table>
| $330,116 $317,022 $327,270 $117,991 | $0   | $0       | $0   | $0   | $0 $0 $0 $0 $0 $0 $0 $0 $124,695 $239,937 $396,284 | $/mo | Cost per year: $1,853,315 $/year

Table 26 shows the calculations for the purpose(s) of sizing the air heater installation for the intake Raise.
11.3.5 Summary of Estimated Capital and Operating Costs – Part II

Since the same fans are capable of meeting the revised operating points, it was not necessary to obtain a revised capital cost estimate for those installations. In the case of the air heater(s) associated with the primary intake raise, the cost of the unit was increased proportionally based upon a ratio of the total installed heating capacity in Megawatts. The installation cost was not changed. The recommended number and locations of other ventilation controls did not vary between the two scenarios except as explicitly stated above.

The fan cost(s) provided here are for parallel fan installations with Variable Frequency Drives (VFDs).
Raise cost estimates for the project were obtained from a major mining contractor and are included here for informational purposes only.

All other capital cost estimates provided were based upon the most up-to-date cost data available at the time of the work, and do not include any installation costs, applicable taxes, fees, or importation duties.

Table 27 gives the estimated capital cost(s) for the recommended ventilation equipment in support of the ventilation design for Part II.

Estimated operating costs were based on a power cost of US$ 0.04 / kWhr at a total efficiency (fan, motor and linkage) of 75% and continuous operation at actual mine density. The cost of power used for estimating purposes was based upon current power costs for existing mine facilities in the approximate mine location (B.C.).

Table 28 shows the estimated annual operating costs for the primary fan and heater installations at the Mine.
### Table 27: Estimated Capital Costs for the Mine Ventilation Equipment.

<table>
<thead>
<tr>
<th>Fan Installations:</th>
<th>Quantity (m³/s)</th>
<th>Pressure (kPa)</th>
<th>Air Power @ 75% Eff. (kW)</th>
<th>VFD Required? (Yes/No)</th>
<th>Heat Required? (Yes/No)</th>
<th>Heater Size (Max) (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>200</td>
<td>3</td>
<td>800</td>
<td>Yes</td>
<td>Yes</td>
<td>10.0</td>
</tr>
<tr>
<td>Exhaust Raise</td>
<td>200</td>
<td>3</td>
<td>800</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
</tr>
<tr>
<td>Decline</td>
<td>68</td>
<td>1.5</td>
<td>136</td>
<td>Yes</td>
<td>Yes</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fan Installations:</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>VFD Cost ($US)</th>
<th>Monitoring ($US)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>2</td>
<td>520,600</td>
<td>218,750</td>
<td>25,600</td>
<td>1,529,900</td>
<td>1,529,900</td>
</tr>
<tr>
<td>Exhaust Raise</td>
<td>2</td>
<td>520,600</td>
<td>218,750</td>
<td>25,600</td>
<td>1,529,900</td>
<td>3,059,800</td>
</tr>
<tr>
<td>Conveyor Decline</td>
<td>2</td>
<td>68,000</td>
<td>25,000</td>
<td>25,600</td>
<td>3,059,800</td>
<td>3,297,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilation Raises</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>Method of Excavation</th>
<th>Length (m)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>1</td>
<td>12,500</td>
<td>Raise-Bore</td>
<td>720</td>
<td>9,000,000</td>
<td>9,000,000</td>
</tr>
<tr>
<td>Haulage Decline</td>
<td>1</td>
<td>12,500</td>
<td>Raise-Bore</td>
<td>720</td>
<td>9,000,000</td>
<td>18,000,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heater Installations:</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>Installation Cost ($US)</th>
<th>Monitoring ($US)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>1</td>
<td>1,212,321</td>
<td>400,000</td>
<td>-</td>
<td>1,612,321</td>
<td>1,612,321</td>
</tr>
<tr>
<td>Haulage Decline</td>
<td>1</td>
<td>445,800</td>
<td>250,000</td>
<td>-</td>
<td>695,800</td>
<td>2,308,121</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment Installations:</th>
<th>Quantity (No.)</th>
<th>Unit Cost ($US)</th>
<th>Sub-Total ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airlock Doors/Fire Doors</td>
<td>34</td>
<td>25,000</td>
<td>850,000</td>
<td>850,000</td>
</tr>
<tr>
<td>Panel Regulators</td>
<td>20</td>
<td>2,500</td>
<td>50,000</td>
<td>900,000</td>
</tr>
<tr>
<td>Airflow Quantity Sensors</td>
<td>25</td>
<td>3,000</td>
<td>75,000</td>
<td>975,000</td>
</tr>
<tr>
<td>Airflow Quality Sensors</td>
<td>34</td>
<td>5,000</td>
<td>170,000</td>
<td>1,145,000</td>
</tr>
<tr>
<td>Mine Weather Stations</td>
<td>4</td>
<td>2,000</td>
<td>8,000</td>
<td>1,153,000</td>
</tr>
</tbody>
</table>

### Table 28: Estimated Operating Costs for the Primary Fan and Heater Installations.

<table>
<thead>
<tr>
<th>Fan Installations:</th>
<th>Quantity (m³/s)</th>
<th>Pressure (kPa)</th>
<th>Efficiency (%)</th>
<th>Power (kW)</th>
<th>Annual Cost ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>445</td>
<td>2.5</td>
<td>75%</td>
<td>1494</td>
<td>523,861</td>
<td>523,861</td>
</tr>
<tr>
<td>Exhaust Raise</td>
<td>475</td>
<td>2.0</td>
<td>75%</td>
<td>1286</td>
<td>450,806</td>
<td>974,667</td>
</tr>
<tr>
<td>Conveyor Decline</td>
<td>40</td>
<td>0.25</td>
<td>75%</td>
<td>13</td>
<td>4,675</td>
<td>979,342</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heater Installations:</th>
<th>Quantity (m³/s)</th>
<th>Density (kg/m³)</th>
<th>Max Heat (MW)</th>
<th>Propane Cost ($US/litre)</th>
<th>Annual Cost ($US)</th>
<th>Total ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake Raise</td>
<td>485</td>
<td>1.05</td>
<td>9.3</td>
<td>0.05</td>
<td>1,853,315</td>
<td>1,853,315</td>
</tr>
<tr>
<td>Haulage Decline</td>
<td>75</td>
<td>1.10</td>
<td>1.3</td>
<td>0.05</td>
<td>286,600</td>
<td>2,139,915</td>
</tr>
</tbody>
</table>

NOTE: All prices shown are for estimating purposes only.
As was the case in Part I, these operating costs are expected to be fairly uniform over the life of the Mine, beginning when the primary ventilation fans are installed and operational.

11.4 Summary of the Impact of the New Protocol on the Ventilation System

The implementation of the new protocol for making total airflow determinations for the diesel equipment fleet as proposed in this thesis resulted in several profound impacts on the ventilation system design in the case study that will be summarized here for clarity- no new information is presented in this section.

Based upon the recommended protocol for determining the total airflow required for the mine based upon the diesel equipment fleet (that airflow required for the conveyor, crusher, and shop ventilation, etc. remained unchanged), the total airflow required for the mine increased by approximately 28% from 425 to 545 m³/s.

This resulted in an increase in the total capital cost of the ventilation system from 18.4 million USD to 24.8 million USD or 35%.

Total operating cost for the mine during steady-state production increased 10% from an expected 2.8 million USD to 3.1 million USD annually with the increase almost entirely resulting in the increased air heating capacity.
Other impacts included the slight increase in the size of the auxiliary duct diameter from 1.4-m to 1.5-m (resulting in decreased equipment clearance and a likely increase in both leakage (operating) and maintenance costs associated with the auxiliary ventilation systems.

Although there was an increase in the amount of air required for the LHDs in the production panels this did not result in significantly higher airflows on the Extraction Level owing to the fact that these areas were previous limited by airflow velocity criteria (which at 1 m/s on the 5 m by 4.5 m drifts already required additional airflow over what was required for the equipment based solely on engine power).

Additionally, it should be noted that since the equipment chosen for this case study was already Tier IVi, and that since a relatively high ventilation multiplier (0.063 m³/s per kW) was used to determine the original flows, the resulting change between scenarios is not nearly as dramatic as it could have been (e.g. if nameplate ventilation rates for Tier III equipment had been compared). This was done very much on purpose, however; and highlights a real, like for like comparison between the methods of calculation in a realistic scenario, and not simply recognition of the changes that stem from the reduction in engine emissions themselves.
Chapter 12

Conclusions and Recommendations

Not surprisingly, given the significant reductions in the emissions (gaseous and particulate) of diesel-powered mining equipment, it seems highly unlikely that total flow calculations for future mine and mine expansions will continue to be calculated based simply on engine power. Whereas in the past, total airflow requirements were almost always based on some multiplier of total diesel engine power barring the existence of particular issues associated with heat or dust, usually accounted for by maintaining airflow velocities within certain minimum / maximum ranges for specific areas of the mine.

As with any proposed change, it will be necessary to justify the added time and expense associated both with the calculations and with the implementation of ventilation systems that use the protocol suggested in this thesis for making total airflow determinations for diesel equipment fleets. However, through this thesis, a solid, scientific basis is formed and a case is made for why heat and dust from diesel equipment should be considered and included in making calculations of this nature. And if it makes underground mines safer for their workers, is any greater justification needed, or even possible?

Despite the uncertainty associated with the changes to diesel equipment emissions resulting from the EPA Tier IV and equivalent regulations, and their potential impacts on ventilation system for underground mines, it is important to note, that mine airflow
requirements are unlikely to decrease by 90% as a result of the 90% reduction in emissions associated with Tier IV diesel engines. What is more likely is that other parameters will take precedence, and that in the future, airflow calculations will become slightly more complex and based on a combination of factors that will be unique to each mine. It will take some time for the use of Tier IV diesel-powered engines to change the methods by which we calculate total airflow requirements, and longer still for a consistent new methodology to emerge, if it does at all.

Certainly this significant change to such an important component of underground mine design represents a great challenge to those involved in the planning and design of mine ventilation systems, but as has often been said “great challenges represent great opportunities”. It is my belief that with this great challenge there lies a great opportunity to make a significant change to the way in which the impacts of diesel equipment fleets on mine ventilation systems are viewed and measured, and to improve the ambient environments and overall health and safety of underground mine workers around the world.

By revisiting the methodology for making total airflow determinations for diesel equipment in mines and accounting for all of the associated contaminant products of that equipment, it will be possible to create a healthier environment for the underground workforce. Even with drastic reductions in the gaseous and particulate emissions realized by Tier IV engines, the heat generated by those engines (particularly on the larger side of the spectrum) mandate a ventilation rate that is not significantly lower than
what is commonly used today (generally developed empirically over years of study and measurement). Based on the heat production of diesel engines, the sensitivity analysis showed ventilation rates that varied from approximately 0.06 m$^3$/s per kW to 0.094 m$^3$/s per kW over the range of input parameters likely to be encountered in most mining scenarios with a rate of 0.075 m$^3$/s per kW for “average” conditions (note that this does not include environmental sources of heat such as VRT and geothermal heating).

These newly calculated rates may be considered to reinforce long-used factors that have been developed prior to the drastic reductions in emissions resulting from the EPA Tier IV/EU Stage IV engine regulations, or to further the belief held by some, that it is in fact diesel heat that is the determining or limiting factor in determining required airflow rates for underground diesel equipment. Whatever the case may have been in the past (certainly, DPM and some noxious gases were cause for concern in pre-Tier engines), it is likely that heat is now the determining factor in calculating airflow requirements for Tier IV / Stage IV diesel engines except in cases of cold-climate mines and/or where other dust control methods (i.e., water) are not effectively utilized (or not possible).

As is the case with any research-based publication, the decision must be made at some point to stop the collection of new data so that the information may be compiled, analyzed and presented. Naturally, this necessity may mean that certain areas or concepts that are germane to the topic(s) of study are only briefly touched upon or left out altogether, particularly where the subject matter touches the fore of a new or emerging field. This thesis was no exception. In particular, there are three areas that
will potentially have great impact on the fundamental and underlying assumptions regarding diesel emissions that guided the conclusions put forth in this thesis, yet were not able to be included. Firstly, since Tier IV engines were not available for testing at the time of publication, certain assumptions have been made regarding their expected emissions based on limited Tier IVi data coupled with the levels allowable by the regulations. As Tier IV engines become commercially available and introduced into underground mines, their actual gaseous and particulate emissions should be catalogued so that empirical data can be formed and updated. Secondly, there is emerging evidence that the addition of DPFs to diesel engines can alter the particle size distribution of the emissions, ultimately increasing the fraction of the smallest and most harmful particles. If proven, this could represent a significant risk to the health of those exposed to these particles, and this risk should be recognized and mitigated. Finally, in February of 2013, a Superior Court in Quebec upheld the decision of its Lower Court that a mineworker’s death from lung cancer was a direct result of his exposure to diesel exhaust (Foley, 2013). This ruling has the potential to radically change the way in which diesel emissions are viewed and treated by legislators, mine operators, mine engineers and equipment manufacturers around the world.
References

ACGIH, “2007 TLVs and BEIs”, American Conference of Governmental Industrial Hygienists, 2007, 238 pp


Georgia State University, “The Diesel Engine”, http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/diesel.html.


Wang, W., et al, “Mixed-Phase Oxide catalyst based on Mn-Mullite (Sm, Gd)Mn2O5 for NO oxidation in Diesel Exhaust” Science, 2012.

Appendix A Selected Design Criteria for Ventilation System Design

The following appendix includes common ventilation design criteria presented as a range of values that are commonly used to define the parameters of ventilation system design. Due to the varied nature of mining projects, some individual sites may have values that fall outside of these ranges. These data are presented for informational purposes and are intended as a guide for engineering best practice. Unless otherwise noted, the recommended values were utilized in developing the case study.

Airflow Quantity

The following Table gives recommended parameters for determining airflow quantities in underground mines along with commonly accepted ranges.

<table>
<thead>
<tr>
<th>Location/Description</th>
<th>Quantity (m³/s)</th>
<th>Range (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Airflow per Worker</td>
<td>0.05</td>
<td>0.04 – 0.06</td>
</tr>
<tr>
<td>Diesel Equipment</td>
<td>0.063/rated kW</td>
<td>0.06 – 1.2</td>
</tr>
<tr>
<td>Crusher</td>
<td>40</td>
<td>25 - 60</td>
</tr>
<tr>
<td>Diesel Equipment Shop</td>
<td>40</td>
<td>25 - 60</td>
</tr>
<tr>
<td>Lube/Fuel Bay</td>
<td>15</td>
<td>5 - 25</td>
</tr>
<tr>
<td>Fabrication Shop</td>
<td>20</td>
<td>5 - 25</td>
</tr>
<tr>
<td>Storage Area</td>
<td>15</td>
<td>5 - 25</td>
</tr>
<tr>
<td>Explosive Magazine</td>
<td>5</td>
<td>0 - 10</td>
</tr>
</tbody>
</table>

Airflow Velocity
The following Table gives recommended maximum and minimum airflow velocities based on airway type.

<table>
<thead>
<tr>
<th>Airway</th>
<th>Air Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Conveyor drifts</td>
<td></td>
</tr>
<tr>
<td>- Homotropal Flow</td>
<td>0.8</td>
</tr>
<tr>
<td>- Antitropal Flow</td>
<td>0.8</td>
</tr>
<tr>
<td>Truck haulage drifts</td>
<td>0.8</td>
</tr>
<tr>
<td>Primary ventilation drifts</td>
<td>0.8</td>
</tr>
<tr>
<td>Large diameter shafts and raises</td>
<td>0.8</td>
</tr>
<tr>
<td>Typical ALIMAK raise</td>
<td>0.8</td>
</tr>
<tr>
<td>Drop ventilation raise</td>
<td>0.8</td>
</tr>
<tr>
<td>Minimum drift velocity (no equipment)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Note:** Optimum velocities represent system targets for design purposes.

**Noxious Gases/Aerosols**

The exposure limits for selected gases commonly found in underground mines are given in the following Table. Time-weighted average (TWA) limits represent exposure concentrations that should not be exceeded for up to a 10-hour workday over a maximum of 40 hours in a work week. A short-term exposure limit (STEL) value is a 15-minute maximum that should not be exceeded during any given workday.
Gas | TLV (ppm)
---|---
Asbestos | 
Amosite | 0.5 fibers/cc
Chrysotile | 1.0 fibers/cc
Crocidolite | 0.2 fibers/cc
Unknown | 0.2 fibers/cc
Carbon Dioxide | 5000
Carbon Monoxide | 25
Hydrogen Sulfide | 10
Nitric Oxide | 25
Nitrogen Dioxide | 3

Particulates

The health risks for dust are heavily dependent upon the size and composition of the particles, which is reflected in the associated TLVs.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>TLV (mg/m³)</th>
<th>Range (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respirable Dust</td>
<td>5</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Total Dust</td>
<td>10</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Silica Dust</td>
<td>0.1</td>
<td>0.1 – 0.5</td>
</tr>
<tr>
<td>Diesel Particulate Matter (DPM)</td>
<td>0.16</td>
<td>0.1 – 0.4</td>
</tr>
</tbody>
</table>
Underground Temperatures / Climate

Safe underground temperature ranges can vary significantly based on a variety of factors specific to the project (e.g., acclimatisation of the workforce, job performed, etc.)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Air Temperature (°C wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Air heating required to protect infrastructure</td>
<td>4</td>
</tr>
<tr>
<td>Air heating not required for infrastructure</td>
<td>-5</td>
</tr>
<tr>
<td>Working Areas</td>
<td>0</td>
</tr>
</tbody>
</table>

Economics

Economic parameters are necessary for determining the cost of individual scenarios and/or comparing differences between various options. Values are highly dependent on the nature of individual projects, but at a minimum, the following parameters should be identified.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan/Motor Efficiency</td>
<td>75 %</td>
</tr>
<tr>
<td>Life of Mine/Airway</td>
<td>15 years</td>
</tr>
<tr>
<td>Internal Rate of Return (IRR)</td>
<td>10.0 %</td>
</tr>
<tr>
<td>Average Electrical Power Cost</td>
<td>0.05 $/kWh</td>
</tr>
</tbody>
</table>
Resistance

Resistance characteristics for any given mine can vary considerably based on mine/airway type, condition, air density and other factors. Measured parameters are always preferred, but in their absence, empirically determined resistance factors are helpful for determining airway resistance. The following Table gives a comparison on resistance factors for different airway types from different sources over time (Prosser and Wallace, 1999).

<table>
<thead>
<tr>
<th>Airway Type</th>
<th>Mean MVS Measured Data</th>
<th>Suggested MVS Value</th>
<th>McPherson (1993)</th>
<th>Hartman et. al. (1997)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Airway – Clean Airway (coal or soft rock with rock bolts limited mesh)</td>
<td>0.0075 (41)</td>
<td>0.0075 (41)</td>
<td>0.009 (49)</td>
<td>0.0080 (43)</td>
</tr>
<tr>
<td>Rectangular Airway – Some Irregularities (coal or soft rock with rock bolts limited mesh)</td>
<td>0.0087 (47)</td>
<td>0.0087 (47)</td>
<td>0.009 (49)</td>
<td>0.0091 (49)</td>
</tr>
<tr>
<td>Metal Mine Drift (arched and bolted with limited mesh)</td>
<td>0.0088 (47)</td>
<td>0.010 (60)</td>
<td>0.0120 (65)</td>
<td>0.0269 (145)</td>
</tr>
<tr>
<td>Metal Mine Ramp (arched and bolted with limited mesh)</td>
<td>0.0116 (62)</td>
<td>0.013 (71)</td>
<td>-r/a-</td>
<td>0.0297 (160)</td>
</tr>
<tr>
<td>Metal Mine Beltway (large area, rock bolted with mesh)</td>
<td>0.0140 (75)</td>
<td>0.015 (80)</td>
<td>-r/a-</td>
<td>-r/a-</td>
</tr>
<tr>
<td>Bored Circular Raise (contains entry/exit loss)</td>
<td>0.0047 (25)</td>
<td>0.0650 (27)</td>
<td>0.004 (22)</td>
<td>0.0028 (15)</td>
</tr>
<tr>
<td>Rectangular Alimak Raise (un-timbered with rock bolt and mesh)</td>
<td>0.0126 (61)</td>
<td>0.0129 (70)</td>
<td>0.014 (75)</td>
<td>-r/a-</td>
</tr>
<tr>
<td>TBM Drift (rock bolts with mesh)</td>
<td>0.0044 (24)</td>
<td>0.0050 (26)</td>
<td>0.0055 (30)</td>
<td>0.0037 (20)</td>
</tr>
</tbody>
</table>

Note: Atkinson’s Friction Factor in kg/m² (lb/ft² · ft × 10¹⁰). Bold indicates large discrepancy with MVS measured values.
Appendix B Sensitivity of Airflow Determination Method for Diesel Heat

The following appendix contains a brief examination of the sensitivity of the proposed method of determining the airflow required to mitigate the heat of a piece of diesel equipment based on the parameters of fuel consumption, water production, allowable temperature rise and charge (inlet) air density.

In each case, the assumed values for the parameter in question were varied by plus or minus 20%. The base case is also presented for comparison.

Base Case

Assumptions:
- engine power: 300 kW
- fuel consumption: 0.3 litres/kWhr
- combustion efficiency: 95%
- calorific value of diesel fuel: 34000 kJ/litre
- water produced per litre of fuel: 5 litres
- latent heat of the evaporation of water: 2450 kJ/kg
- specific heat of dry air: 1.005 kJ/kgK
- temperature rise across machine: 20 deg. C
- air density: 1.2 kg/m³

Calculations:
- fuel consumed: 90 litres/hr
- Total Heat Produced: 850 kW
- Latent Heat Produced: 306 kW
- Sensible Heat Produced: 544 kW

Heat Produced per kilowatt of mechanical output: 2.83

Mass Flow Rate of Air Required: 27.1 kg/s
Volume Flow Rate of Air Required: 22.5 m³/s
Ventilation Rate Required: 0.075 m³/s per kW
Fuel Consumption

**Assumptions:**
- **engine power:** 300 kW
- **fuel consumption:** 0.24 litres/kWhr
- **combustion efficiency:** 95%
- **calorific value of diesel fuel:** 34000 kJ/litre
- **water produced per litre of fuel:** 5 litres
- **latent heat of the evaporation of water:** 2450 kJ/kg
- **specific heat of dry air:** 1.005 kJ/kgK
- **temperature rise across machine:** 20 deg. C
- **air density:** 1.2 kg/m³

**Calculations:**
- **fuel consumed:** 72 litres/hr
- **Total Heat Produced:** 680 kW
- **Latent Heat Produced:** 245 kW
- **Sensible Heat Produced:** 435 kW
- **Heat Produced per kilowatt of mechanical output:** 2.27
- **Mass Flow Rate of Air Required:** 21.6 kg/s
- **Volume Flow Rate of Air Required:** 18.0 m³/s
- **Ventilation Rate Required:** 0.060 m³/s per kW

Water Production

**Assumptions:**
- **engine power:** 300 kW
- **fuel consumption:** 0.36 litres/kWhr
- **combustion efficiency:** 95%
- **calorific value of diesel fuel:** 34000 kJ/litre
- **water produced per litre of fuel:** 5 litres
- **latent heat of the evaporation of water:** 2450 kJ/kg
- **specific heat of dry air:** 1.005 kJ/kgK
- **temperature rise across machine:** 20 deg. C
- **air density:** 1.2 kg/m³

**Calculations:**
- **fuel consumed:** 108 litres/hr
- **Total Heat Produced:** 1020 kW
- **Latent Heat Produced:** 368 kW
- **Sensible Heat Produced:** 653 kW
- **Heat Produced per kilowatt of mechanical output:** 3.40
- **Mass Flow Rate of Air Required:** 32.5 kg/s
- **Volume Flow Rate of Air Required:** 27.1 m³/s
- **Ventilation Rate Required:** 0.090 m³/s per kW
Temperature Differential

Assumptions:
- engine power: 300 kW
effectivity: 95%
calorific value of diesel fuel: 34000 kJ/litre
water produced per litre of fuel: 5 litres
latent heat of the evaporation of water: 2450 kJ/kg
specific heat of dry air: 1.005 kJ/kgK
temperature rise across machine: 16 deg. C
air density: 1.2 kg/m³

Calculations:
- fuel consumed: 90 litres/hr
- Total Heat Produced: 850 kW
- Latent Heat Produced: 306 kW
- Sensible Heat Produced: 544 kW

Heat Produced per kilowatt of mechanical output: 2.83

Mass Flow Rate of Air Required: 33.8 kg/s
Volume Flow Rate of Air Required: 28.2 m³/s
Ventilation Rate Required: 0.094 m³/s per kW

Air Density

Assumptions:
- engine power: 300 kW
effectivity: 95%
calorific value of diesel fuel: 34000 kJ/litre
water produced per litre of fuel: 5 litres
latent heat of the evaporation of water: 2450 kJ/kg
specific heat of dry air: 1.005 kJ/kgK
temperature rise across machine: 20 deg. C
air density: 0.96 kg/m³

Calculations:
- fuel consumed: 90 litres/hr
- Total Heat Produced: 850 kW
- Latent Heat Produced: 306 kW
- Sensible Heat Produced: 544 kW

Heat Produced per kilowatt of mechanical output: 2.83

Mass Flow Rate of Air Required: 27.1 kg/s
Volume Flow Rate of Air Required: 28.2 m³/s
Ventilation Rate Required: 0.094 m³/s per kW
The following chart provides a graphical representation of the variation in ventilation rate (m³/s per kW) caused by a +/- 20% variation in the four selected parameters.
Appendix C Supporting Information for the Case Study

The following appendix includes information necessary for the design of the ventilation system in the case study, including air heaters and fan curves.

Fans

**MVS**

**Underground Booster Fans - Single**

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fan Package</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic 12300 AMF 7300 Arr. #3 Mine Fan</td>
<td>$395,000</td>
<td>1</td>
<td>$395,000</td>
</tr>
<tr>
<td>Includes: Inlet bell, inlet screen, discharge expansion joint</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan supports, motor base, floating shaft type coupling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2500 HP - 860 RPM 3/60/4160 Volt VFD capable motor</td>
<td>$237,000</td>
<td>1</td>
<td>$237,000</td>
</tr>
<tr>
<td>Complete with winding and bearing RTD's and space heaters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manually operated fan brake with limit switch</td>
<td>$12,500</td>
<td>1</td>
<td>$12,500</td>
</tr>
<tr>
<td>Counterweight operated backdraft damper</td>
<td>$42,000</td>
<td>1</td>
<td>$42,000</td>
</tr>
<tr>
<td>SP-6 and International Paint system epoxy paint included</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on all fabricated steel components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra sonic flow monitor mounted in discharge cone</td>
<td>$10,600</td>
<td>1</td>
<td>$10,600</td>
</tr>
<tr>
<td>Static pressure sensor with 4-20 mA output signal</td>
<td>$2,500</td>
<td>1</td>
<td>$2,500</td>
</tr>
<tr>
<td>- for differential pressure across bulkhead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan / motor vibration monitor kit with 4 probes B/N 1500/65</td>
<td>$12,500</td>
<td>1</td>
<td>$12,500</td>
</tr>
</tbody>
</table>

**Total (Equipment)**                                                            $712,100

**Spare**

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set fan blades</td>
<td>$27,500</td>
<td>1</td>
<td>$27,500</td>
</tr>
<tr>
<td>Commission Estimated at $12,500.00 / Lot</td>
<td>$12,500</td>
<td>1</td>
<td>$12,500</td>
</tr>
<tr>
<td>To be billed at actual time and material costs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Terms: F.O.B. Winnipeg
25% on approval of drawings and release for fabrication
65% on shipment or readiness to ship
10% on commissioning - or 60 days from shipment - whichever occurs first
# MVS

## Underground Booster Fans - Parallel

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic 11200 AMF 7300 Arr. #3 Mine Fan</td>
<td>$350,000</td>
<td>2</td>
<td>$700,000</td>
</tr>
<tr>
<td>Includes: Inlet bell, inlet screen, discharge expansion joint</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan supports, motor base, floating shaft type coupling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1250 HP - 880 RPM 3/60/4160 Volt VFD capable motor</td>
<td>$123,000</td>
<td>2</td>
<td>$246,000</td>
</tr>
<tr>
<td>Complete with winding and bearing RTD's and space heaters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manually operated fan brake with limit switch</td>
<td>$12,500</td>
<td>2</td>
<td>$25,000</td>
</tr>
<tr>
<td>Counterweight operated backdraft damper</td>
<td>$36,000</td>
<td>2</td>
<td>$72,000</td>
</tr>
<tr>
<td>SP-6 and International Paint system epoxy paint included</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on all fabricated steel components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra sonic flow monitor mounted in discharge cone</td>
<td>$10,600</td>
<td>2</td>
<td>$21,200</td>
</tr>
<tr>
<td>Static pressure sensor with 4-20 mA output signal</td>
<td>$2,500</td>
<td>1</td>
<td>$2,500</td>
</tr>
<tr>
<td>- for differential pressure across bulkhead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan / motor vibration monitor kit with 4 probes B/N 1900/65</td>
<td>$12,500</td>
<td>2</td>
<td>$25,000</td>
</tr>
</tbody>
</table>

**Total (Equipment)**

$1,091,700

### Spares

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set fan blades</td>
<td>$27,500</td>
<td>1</td>
<td>$27,500</td>
</tr>
</tbody>
</table>

### Commissioning Estimated at $12,500.00 / Lot

To be billed at actual time and material costs

**Terms- F.O.B. Winnipeg**

25% on approval of drawings and release for fabrication
65% on shipment or rediness to ship
10% on commissioning - or 60 days from shipment - whichever occurs first
## MVS

### Underground Booster Fan -

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fan Package</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic 9250 AMF 5500 Arr. #4 Mine Fan</td>
<td>$ 250,000</td>
<td>1</td>
<td>$ 250,000</td>
</tr>
<tr>
<td>Includes: Inlet bell, inlet screen, fan supports, 400 HP - 880 RPM 3/60/600 Volt VFD capable motor. Complete with winding and bearing RTD’s and space heaters.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manually operated fan brake with limit switch</td>
<td>$ 7,500</td>
<td>1</td>
<td>$ 7,500</td>
</tr>
<tr>
<td>Counterweight operated backdraft damper</td>
<td>$ 32,000</td>
<td>1</td>
<td>$ 32,000</td>
</tr>
<tr>
<td>SP-6 and International Paint system epoxy paint included on all fabricated steel components.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra sonic flow monitor mounted in discharge cone</td>
<td>$ 10,600</td>
<td>1</td>
<td>$ 10,600</td>
</tr>
<tr>
<td>Static pressure sensor with 4-20 mA output signal - for differential pressure across bulkhead</td>
<td>$ 2,500</td>
<td>1</td>
<td>$ 2,500</td>
</tr>
<tr>
<td>Fan / motor vibration monitor kit with 4 probes B/N 1900/65</td>
<td>$ 12,500</td>
<td>1</td>
<td>$ 12,500</td>
</tr>
<tr>
<td><strong>Total (Equipment)</strong></td>
<td></td>
<td></td>
<td>$ 315,100</td>
</tr>
</tbody>
</table>

### Spares

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set fan blades</td>
<td>$ 27,500</td>
<td>1</td>
<td>$ 27,500</td>
</tr>
<tr>
<td>Commissioning Estimated at $12,500.00 / Lot</td>
<td>$ 12,500</td>
<td>1</td>
<td>$ 12,500</td>
</tr>
<tr>
<td>To be billed at actual time and material costs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Terms: F.O.B. Winnipeg
- 25% on approval of drawings and release for fabrication
- 65% on shipment or readiness to ship
- 10% on commissioning - or 60 days from shipment - whichever occurs first
Fan Performance Curve 12300-AMF-7300 Full Blade

- Diameter: 123.00 in
- Altitude: 4,500 ft asl
- Density: 0.063 lb/ft³
- Speed: 880.0 Rpm
- Temperature: 76.0 degF
- Diffuser Diameter: 162.00 in
- Diffuser Length: 318.00 in
- Ref: Budget
Alphair Ventilating Systems, Inc.
1221 Sherwin Road, Winnipeg, MB, R3H 0V1
Tel (204) 694-0606 Fax (204) 694-0624
MYS (Budget)

**Selection Data Sheet**

**Model:** 12300-AMF-7300 Full Blade JetStream Adjustable Pitch Vane Axial Fan

**Fan Diameter:** 123

### Performance Information (Elevation 4,560 ft. asl)

<table>
<thead>
<tr>
<th>Volume cfm</th>
<th>FTP inWg</th>
<th>FSP inWg</th>
<th>Temp degF</th>
<th>Density</th>
<th>Power HP</th>
<th>Efft %</th>
<th>RPM</th>
<th>BisAng Deg</th>
<th>Vfan lpm</th>
<th>Voone lpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>850,006.0</td>
<td>13.85</td>
<td>12.00</td>
<td>70.8</td>
<td>3.083</td>
<td>2,276.0</td>
<td>85.6</td>
<td>880.0</td>
<td>36.4</td>
<td>10,301.09</td>
<td>5,938.30</td>
</tr>
</tbody>
</table>

### Selection Options Information

- **Speed and Pitch:**
  - [ ] Constant Speed
  - [ ] Variable Speed
  - [ ] Fixed Pitch
  - [ ] Adjustable Pitch
- **Selection Basis:**
  - [ ] Actual Volume
  - [ ] Standard Speed
  - [ ] Mass Flow
  - [ ] Fan SP
  - [ ] Fan TP
- **Outlet Control:**
  - [ ] Open
  - [ ] Ducted
- **Potable Air:**
  - [ ] Yes
  - [ ] No
- **Duct Connection:**
  - [ ] Yes
  - [ ] No
- **Drive:**
  - [ ] Belt
  - [ ] Direct
- **Gas Type:**
  - [ ] Clean Air
  - [ ] Special
- **Freq:**
  - [ ] 50Hz
  - [ ] 60Hz

### Diffuser Information

- **Round Inlet to Round Outlet:**
  - [ ] Fixed Angles
  - [ ] Fixed Dimensions
  - [ ] Standard Geometry
  - [ ] Targeted Velocity
- **Round Inlet to Square Outlet:**
  - [ ] Fixed Angles
  - [ ] Fixed Dimensions
  - [ ] Standard Geometry
  - [ ] Targeted Velocity
- **Target Velocity:** 0.00 fpm
- **B3 Width:** 0.00 in
- **B3 Height:** 0.00 in
- **CC Length:** 310.00 in
- **Diameter:** 182.00 in
- **ECR:** 5,938.29 lpm

### Accessories and Losses Information

<table>
<thead>
<tr>
<th>Accessory Description</th>
<th>Flow Area ft²</th>
<th>Volume cfm</th>
<th>Factor x VP</th>
<th>VP inWg</th>
<th>Loss inWg</th>
</tr>
</thead>
</table>

### Base Sound Data

- **Installation:**
  - AMCA B: Open/Ducted inlet / Ducted/Open Outlet

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lw</td>
<td>127</td>
<td>118</td>
<td>120</td>
<td>121</td>
<td>119</td>
</tr>
<tr>
<td>Lp</td>
<td>124</td>
<td>115</td>
<td>117</td>
<td>116</td>
<td>111</td>
</tr>
<tr>
<td>LpA</td>
<td>99</td>
<td>139</td>
<td>100</td>
<td>102</td>
<td>119</td>
</tr>
</tbody>
</table>

- **Motor:**
  - Option 1: 3 Phase 60 Hz 0.0 HP 0.0 RPM Electric Motor
  - Frame: RTF

### Other Possible JetStream Selections

<table>
<thead>
<tr>
<th>Model</th>
<th>Speed RPM</th>
<th>Power HP</th>
<th>Efft %</th>
<th>Vfan lpm</th>
<th>Voone lpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>12300-AMF-7300 Full Blade</td>
<td>860.0</td>
<td>2,276.0</td>
<td>85.8</td>
<td>15,047.70</td>
<td>5,938.20</td>
</tr>
</tbody>
</table>

Over ALL Lp = 117 dBA at 3 feet or 1 meter from fan
dBA at 3.26 feet or 1.00 meter from fan
Fan Performance Curve

11200-AMF-7300 Full Blade

Diameter: 112.00 in
Altitude: 4,560 ft asl
Density: 0.083 lb/ft³

Speed: 880.0 Rpm
Temperature: 70.0 degf

Diffuser Diameter: 148.00 in
Diffuser Length: 294.00 in
Ref: Budget-Parallel
Model: 11200-AMF-7300 Full Blade JetStream Adjustable Pitch Vane Axial Fan

Fan Diameter: 112

### Performance Information

<table>
<thead>
<tr>
<th>Volume</th>
<th>FTP</th>
<th>FSP</th>
<th>Temp</th>
<th>Density</th>
<th>Power</th>
<th>Eff</th>
<th>RPM</th>
<th>Bias Ang</th>
<th>V10r</th>
<th>Vcone</th>
</tr>
</thead>
<tbody>
<tr>
<td>cfm</td>
<td>inWg</td>
<td>inWg</td>
<td>deg</td>
<td>avm</td>
<td>hp</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>423,000</td>
<td>12.00</td>
<td>12.00</td>
<td>70.4</td>
<td>1,036.9</td>
<td>84.1</td>
<td>839.0</td>
<td>36.0</td>
<td>6,211.90</td>
<td>3,557.40</td>
<td></td>
</tr>
</tbody>
</table>

### Selection Options Information

- Speed and Pitch: [ ] Constant Speed [ ] Variable Speed [ ] Fixed Pitch [x] Adjustable Pitch
- Inlet Control: [ ] Open [x] Ducted
- Outlet Control: [ ] Open [x] Ducted
- Discharge Cone: [ ] Yes [ ] No
- Arrangement: (12A) - Direct Drive, Open In, Duct Out, Ducted

### Diffuser Information

- Round inlet to Square Outlet: [x] Fixed Angles [ ] Fixed Dimensions [ ] Standard Geometry [x] Targeted Velocity
- Target Velocity: 6,000 ft/min
- B3 Width: 6.00 in
- AA Height: 6.00 in
- CC Length: 204.00 in
- Diameter: 148.00 in
- ROV: 3,557.44 ft/min

### Accessories and Losses Information

<table>
<thead>
<tr>
<th>Accessory Description</th>
<th>Flow Area</th>
<th>Volume</th>
<th>Factor</th>
<th>VP</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft&lt;sup&gt;2&lt;/sup&gt;</td>
<td>cfm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Sound Data</td>
<td></td>
<td></td>
<td>Position: 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation: AMCA B: Open/Ducted inlet / Ducted/Open Outlet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) (2) (3) (4) (5) (6) (7) (8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lw</td>
<td>124</td>
<td>115</td>
<td>117</td>
<td>116</td>
<td>110</td>
</tr>
<tr>
<td>Lp</td>
<td>117</td>
<td>118</td>
<td>112</td>
<td>113</td>
<td>108</td>
</tr>
<tr>
<td>LpA</td>
<td>92</td>
<td>93</td>
<td>102</td>
<td>100</td>
<td>109</td>
</tr>
<tr>
<td>Cover All Lp</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dB(A) at 3 feet or 1 meter from fan</td>
<td>dB(A) at 3.28 feet or 1.00 meter from fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Motor Data

- Motor Option 1: 3 Phase 60 Hz 0.0 HP G.0 RPM Electric Motor Frame: RFP

### Other Possible JetStream Selections

<table>
<thead>
<tr>
<th>Modal</th>
<th>Speed RPM</th>
<th>Power HP</th>
<th>Eff %</th>
<th>Vfan fpm</th>
<th>Vcone fpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>11200-AMF-7300 Full Blades</td>
<td>880.0</td>
<td>1.026</td>
<td>64.2</td>
<td>10,841.77</td>
<td>3,897.44</td>
</tr>
</tbody>
</table>
Fan Performance Curve

9250-AMF-5500 Full Blade

Rev. 980127-01

Diameter: 92.50 in  
Altitude: 4,560 ft asl  
Density: 0.063 lb/ft³

980.0 Rpm  
Temperature: 70.0 degF  
Diffuser Diameter: 123.00 in

Diffuser Length: 246.00 in  
Ref: Budget
Model: 9250-AMF-5500 Full BladeJetStream Adjustable Pitch Vane Axial Fan

Fan Diameter: 92

**Performance Information**

<table>
<thead>
<tr>
<th>Volume cfm</th>
<th>FTP inWg</th>
<th>PSP inWg</th>
<th>Temp degF</th>
<th>Density lb/ft³</th>
<th>Power HP</th>
<th>Eff %</th>
<th>RPM</th>
<th>BlaAng deg</th>
<th>Vfan fpm</th>
<th>Vcone fpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>285,500.0</td>
<td>6.63</td>
<td>6.09</td>
<td>70.0</td>
<td>0.563</td>
<td>353.9</td>
<td>87.6</td>
<td>680.0</td>
<td>30.1</td>
<td>6,128.50</td>
<td>3,466.00</td>
</tr>
</tbody>
</table>

**Selection Options Information**

- Speed and Pitch: [ ] Constant Speed [ ] Variable Speed [ ] Fixed Pitch [ ] Adjustable Pitch
- Inlet Control: [ ] Open [ ] Ducted
- Outlet Control: [ ] Open [x] Ducted
- Discharge Cone: [x] Yes [ ] No
- Arrangement: (-124) - Direct Drive, Open In, Duct Out, Diffuser
- Drive: [ ] Belt [x] Direct
- Gas Type: [ ] Clean Air [ ] Special
- Freq: [ ] 50Hz [ ] 60Hz

**Diffuser Information**

- Round Inlet to Round Outlet: [ ] Fixed Angles [ ] Fixed Dimensions [x] Standard Geometry
- Round Inlet to Square Outlet: [ ] Fixed Angles [ ] Fixed Dimensions [ ] Standard Geometry [ ] Targeted Velocity
- Target Velocity: 0.00 fpm
- EB Width: 0.00 in
- CC Length: 246.00 in
- Diameter: 123.00 in
- EDV: 3,465.99 in

**Accessories and Losses Information**

<table>
<thead>
<tr>
<th>Accessory Description</th>
<th>Flow Area ft²</th>
<th>Volume cfm</th>
<th>Factor xVP</th>
<th>VP inWg</th>
<th>Loss inWg</th>
</tr>
</thead>
</table>

**Base Sound Data**

<table>
<thead>
<tr>
<th>Position: 1</th>
</tr>
</thead>
</table>

| Lw | 110 | 107 | 109 | 110 | 105 | 103 | 99 |
|---------------------|
| Lp | 100 | 100 | 102 | 104 | 102 | 106 | 98 | 94 |
| LpA | 64 | 85 | 94 | 101 | 101 | 101 | 99 | 93 |

Lp at 102 dBA at 3 feet or 1 meter from fan

**Motor Data**

- Motor Option 1: 3 Phase 60 Hz 0.0 HP 0.0 RPM Electric Motor Frame: RTF

**Other Possible JetStream Selections**

<table>
<thead>
<tr>
<th>Model</th>
<th>Speed RPM</th>
<th>Power HP</th>
<th>Eff %</th>
<th>Vfan fpm</th>
<th>Vcone fpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>10150-AMF-5500 Full Blade</td>
<td>710.0</td>
<td>328.1</td>
<td>90.6</td>
<td>7,884.77</td>
<td>2,659.01</td>
</tr>
<tr>
<td>11200-AMF-5600 Full Blade</td>
<td>690.0</td>
<td>321.8</td>
<td>99.7</td>
<td>6,470.16</td>
<td>2,393.95</td>
</tr>
<tr>
<td>5250-AMF-5500 Full Blade</td>
<td>880.0</td>
<td>353.9</td>
<td>57.0</td>
<td>9,460.15</td>
<td>3,465.99</td>
</tr>
<tr>
<td>10150-AMF-5500 Full Blade</td>
<td>880.0</td>
<td>342.0</td>
<td>86.9</td>
<td>6,720.76</td>
<td>2,856.01</td>
</tr>
<tr>
<td>11200-AMF-5600 Full Blade</td>
<td>710.0</td>
<td>332.2</td>
<td>90.9</td>
<td>6,470.16</td>
<td>2,393.95</td>
</tr>
<tr>
<td>5250-AMF-5500 Full Blade</td>
<td>880.0</td>
<td>357.0</td>
<td>86.8</td>
<td>8,658.34</td>
<td>3,465.99</td>
</tr>
<tr>
<td>10150-AMF-5500 Half Blade</td>
<td>690.0</td>
<td>345.7</td>
<td>86.0</td>
<td>7,265.61</td>
<td>2,856.01</td>
</tr>
<tr>
<td>10150-AMF-5500 Full Blade</td>
<td>710.0</td>
<td>347.0</td>
<td>55.6</td>
<td>7,265.51</td>
<td>2,856.01</td>
</tr>
</tbody>
</table>
**Underground Booster Fan - parallel**

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Unit Cost</th>
<th>Qty.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fan Package</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic 8400 VAX 3150 Arr. #4 Mine Fan</td>
<td>$ 68,000</td>
<td>2</td>
<td>$136,000</td>
</tr>
<tr>
<td>Includes: Inlet bell, inlet screen, fan supports,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 HP - 1180 RPM 3/60/600 Volt VFD capable motor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete with winding and bearing RTD’s and space heaters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counterweight operated backdraft damper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP-6 and International Paint system epoxy paint included</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on all fabricated steel components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra sonic flow monitor mounted in discharge cone</td>
<td>$ 10,600</td>
<td>2</td>
<td>$ 21,200</td>
</tr>
<tr>
<td>Static pressure sensor with 4-20 mA output signal</td>
<td>$ 2,500</td>
<td>1</td>
<td>$  2,500</td>
</tr>
<tr>
<td>- for differential pressure across bulkhead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan / motor vibration monitor kit with 4 probes B/N 1900/65</td>
<td>$ 12,500</td>
<td>1</td>
<td>$ 12,500</td>
</tr>
<tr>
<td><strong>Total (Equipment)</strong></td>
<td></td>
<td></td>
<td>$ 172,200</td>
</tr>
<tr>
<td><strong>Spares</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set fan blades</td>
<td>$ 27,500</td>
<td>1</td>
<td>$ 27,500</td>
</tr>
<tr>
<td>Commissioning Estimated at $12,500.00 / Lot</td>
<td>$ 12,500</td>
<td>1</td>
<td>$ 12,500</td>
</tr>
<tr>
<td>To be billed at actual time and material costs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Terms: F.O.B. Winnipeg
- 25% on approval of drawings and release for fabrication
- 65% on shipment or rediness to ship
- 10% on commissioning - or 60 days from shipment - whichever occurs first
Fan Performance Curve 8400-VAX-3150 Full Blade

- Diameter: 84.00 in
- Speed: 1180.0 Rpm
- Altitude: 4,550 ft asl
- Temperature: 79.0 deg F
- Density: 0.063 lb/ft^3
- Diffuser Diameter: 110.00 in
- Diffuser Length: 77.00 in
- Ref: 236
Alphair Ventilating Systems, Inc.
1221 Sherwin Road, Winnipeg, MB, R3H 0V1
Tel (204) 694-6666 Fax (204) 694-6204

Selection Data Sheet

Model: 8400-VAX-3150 Full Blade Single Stage JetStream Adjustable Pitch Vane Axial Fan
Fan Diameter: 84

Performance Information (Elevation 4,560 ft asl)

<table>
<thead>
<tr>
<th>Volume</th>
<th>FTP</th>
<th>FSP</th>
<th>Temp</th>
<th>Density</th>
<th>Power</th>
<th>Eff</th>
<th>RPM</th>
<th>BlaAng</th>
<th>Vfan</th>
<th>Vcone</th>
</tr>
</thead>
<tbody>
<tr>
<td>cfm</td>
<td>inWg</td>
<td>inWg</td>
<td>degF</td>
<td>lb/m³</td>
<td>HP</td>
<td>%</td>
<td></td>
<td>Deg</td>
<td>tpm</td>
<td>tpm</td>
</tr>
<tr>
<td>143,000</td>
<td>6.24</td>
<td>5.00</td>
<td>70.0</td>
<td>0.003</td>
<td>184.5</td>
<td>78.5</td>
<td>1100</td>
<td>9.7</td>
<td>3,715.80</td>
<td>2,196.30</td>
</tr>
</tbody>
</table>

Selection Options Information

Speed and Pitch: □ Constant Speed □ Variable Speed □ Fixed Pitch □ Adjustable Pitch
Selection Basis: □ Actual Volume □ Standard Speed □ Mass Flow □ Fan SP □ Fan TP
Inlet Control: □ Open □ Ducted
Outlet Control: □ Open □ Ducted
Discharge Cone: □ Yes □ No
Arrangement (12VA): Direct Drive, Open In, Duct Out, Difusser
Drive: □ Belt □ Direct
Gas Type: □ Clean Air □ Special Freq: □ 60Hz □ 50Hz

Diffuser Information

Round Inlet to Round Outlet: □ Fixed Angles □ Fixed Dimensions □ Standard Geometry □ Targeted Velocity
Round Inlet to Square Outlet: □ Fixed Angles □ Fixed Dimensions □ Standard Geometry □ Targeted Velocity
Target Velocity: 0.00 fpm BB Width: 0.00 in CC Length: 77.00 in Diameter: 110.00 in EOV: 2,166.82 fpm

Accessories and Losses Information

Accessory Description Flow Area Volume Factor x VP VP Loss
² cm³ inWg

Base Sound Data

Installation: AMCA B: Open/Ducted inlet / Ducted/Open Outlet

| Lw | 107 | 104 | 112 | 107 | 106 | 102 | 100 |
| Lp | 100 | 97  | 100 | 101 | 98  | 96  | 94  |
| LP | 75  | 82  | 97  | 98  | 98  | 98  | 90  |

Overall Lp 90 dBA at 3 feet or 1 meter from fan dB(A) at 3.28 feet or 1.00 meter from fan

Motor Data

Motor Option 1: 3 Phase 60 Hz 200.0 HP 1200.0 RPM Electric Motor Frame: 447

Other Possible JetStream Selections

<table>
<thead>
<tr>
<th>Model</th>
<th>Speed RPM</th>
<th>Power HP</th>
<th>Eff %</th>
<th>Vfan tpm</th>
<th>Vcone tpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8400-VAX-3150 Full Blade</td>
<td>1100.0</td>
<td>164.5</td>
<td>79.5</td>
<td>4,322.81</td>
<td>2,166.82</td>
</tr>
<tr>
<td>7200-VAX-3150 Full Blade</td>
<td>1189.0</td>
<td>201.2</td>
<td>76.0</td>
<td>6,254.79</td>
<td>2,644.83</td>
</tr>
<tr>
<td>5400-VAX-3150 Full Blade</td>
<td>1789.0</td>
<td>297.1</td>
<td>64.5</td>
<td>13,028.87</td>
<td>5,040.07</td>
</tr>
</tbody>
</table>

237
Air Heating

ACI CANEFCO
(Div. of Advanced Combustion Inc.)
438 BASALTIC ROAD, CONCORD, ONTARIO, CANADA, L4K 5A2
TEL: (905) 417-4771, FAX: (905) 417-4772; E-MAIL: info@aci-ca.com

MVS
4945 E. Yale Ave., Suite 103
Fresno, CA 93727
USA

Attention: Dan Stinette

Reference: PORTAL AND RAISE HEATER INQUIRY

1.0 EXECUTIVE SUMMARY

The following budget proposal includes the design and supply of two custom ACI-CANEFCO M.I.D Mine Air Heaters. In general, M.I.D mine air heaters are manufactured for long life, ease of installation and ease of maintenance. The design philosophy behind the robust construction of the M.I.D Mine Air Heater incorporates over forty years of mine air heater fabrication experience. Specifically, these heaters are manufactured from a heavy structural steel frame with 6”+ thick walls with thermal/acoustic insulation and heavy gauge G90 liner with noise absorption properties, oversized fan intake plenum for optimum airflow and uniform heat distribution, low intake and main structure velocities for reduced pressure loss, power consumption and moisture entrainment, walk-in service enclosure c/w lighting, heat and ventilation, modular construction c/w self-supporting structure c/w lifting points for relocation, pre-painted, steel architectural cladding, high pressure sodium lighting (entrances, plenum, burner section), exit lights (interior and exterior), insulated oversized steel doors c/w locking hardware and state-of-the-art control components.

We are pleased to provide our lot price for the above inquiry complete with the following inclusions:

Fresh Air Raise Heater

- One Complete ACI Mine Heater capable of heating 460 m3/s (40°F rise) in M.I.D series construction for durability and noise abatement requirements.
- One Integral Control Room c/w Gas Valve Trains, Combustion Safety Control System, Three Burners c/w Integral Combustion Air Blowers
- System engineering

LOT BUDGET PRICE........................................................................................................$1,053,725.00
(ACI installation budget of same........$400,000.00)

Portal Heater

- One Complete ACI Mine Heater capable of heating 135 m3/s (40°F rise)* in M.I.D series construction for durability and noise abatement requirements c/w Alphair 7200 VAX 2700 fan and accessories
- One Integral Control Room c/wGas Valve Trains, Combustion Safety Control System, Two Burners c/w Integral Combustion Air Blowers
- System engineering

LOT BUDGET PRICE........................................................................................................$445,814.00
(ACI installation budget of same........$250,000.00)

* See detailed description below regarding temperature rise for portal heater
DRAWINGS FOR APPROVAL: 2-4 weeks after order

ESTIMATED PRODUCTION TIME: 14-18 weeks.

PAYMENT TERMS: 20% with drawings
30% upon receipt of major components at ACI works
50% net 45 days upon shipment

WARRANTY:
ACI will warrant supplied equipment for 12 months from the date of commissioning or 18 months from date of shipment, whichever occurs first. Replacement parts will be issued FOB Concord. Unless otherwise advised, warranty period is increased to 24 months from date of commissioning with ACI-CANEFCO installation.

FREIGHT: FOB our plant, Concord, ON

QUOTATION VALIDITY: 60 Days

LIABILITY:
ACI is not responsible for any consequential damages of any kind, whatsoever caused and not limited to loss of production, profits and contracts.

2.0 HEATER SPECIFICATIONS

Raise Heater
Temperature Differential: 40 F
Airflow: 460 m³/s
Burner Capacity: 45 MM BTUH
Fuel: Propane @ 10Psi
Process Air Pressure Loss through Heater: Approximately 0.25” w.c plus silencer if added

Portal Heater
Temperature Differential: 40 F (note that this is mixed air temperature based on a 80 F temperature differential through the heater with an airflow of 143,000 cfm)
Airflow: 460 m³/s (256,000 cfm)
Burner Capacity: 25,600,000 MM BTUH
Fuel: Propane @ 10Psi
Process Air Pressure Loss through Heater: N/A as heater will be supplied with Integral Alphair fan
3.0 SCOPE OF SUPPLY AND EQUIPMENT DESCRIPTION

The ACI heaters will be manufactured to ACI-CANEFCO M.I.D standards (Modular Integrated Design). Each will be designed for ease of installation and commissioning. The main section of the mine heater will be pre-fabricated in modules, pre-wired, pre-piped and then disassembled for shipment. The raise plenum, (raise heater only) will be sent in structurally reinforced, pre-assembled, pre-insulated, panels with pre-mounted structural members for integrity upon installation. Note: Both heaters inclusive of plenum (raise heater) will be pre-assembled in our facility and then dismantled for shipment.

In general, each heater assembly will be inclusive of:

- Custom M.I.D structure manufactured of welded structural steel framing, thermal/insulation (walls, floor, ceiling). galvanized G90 inner sheet steel, 18 ga. G90 galvanized outer skin and pre-painted outer architectural cladding
- Custom M.I.D Heater Control Room integrally pre-mounted to burner room
- Propane Gas Burners c/w integral combustion air fans for high turndown capability
- Propane Gas Safety Traps (mounted in control room)
- Combustion Control Panel (mounted in control room) c/w flame safeguards, digital temperature controls (plc and communications can be offered as an extra) high temperature limit controller.
- Each Heater is designed to heat 100% of the required airflow and create a 40F temperature differential.

3.1 RAISE HEATER

The Raise Heater is designed to heat 100% of the 450 m3/s airflow requirements to the desired 40F temperature differential (based on average worst case). In general, the complete raise heater will consist of one pre-assembled burner room section c/w control room, raise plenum and one intake section. The burner room will be pre-wired and pre-piped to the control room. The burner room section will be complete with inlet and outlet mating flanges to the fan plenum and intake silencer (if required). The burner and control room sections will be pre-built in one section. The vent raise plenum will be shipped in approximately twelve structurally integrated panels for site re-erection.

The overall Heater, burner section, control room and raise plenum will measure approximately 56'1" x 66'w x 24'1" (see attached drawing).

3.1.1 BURNER ROOM

Burner room will be pre-attached to the burner control room (see section 3.1.3 below) and will measure approximately 50'1" x 12'w x 24'1" h. In general, the burner room will consist of four modules and will have two levels when assembled c/w access ladder between the two floors. The rooms will be pre-piped and wired to flanged pipe connections and an electrical junction box at the end wall.

The modules will be built to industrial standards using heavy steel plate, structural tubing, steel channel and angle. Materials of construction will mainly be as follows:

Main Frame: 4 x 3 x 0.1875 HSS structural steel
Flooring: 3/16" Checker plate, Wall and Ceiling Construction (inside – outside): galvanized 18 gauge perforated steel sheet, 4" ROXUL 3.5 lb/ft3 thermal/insulation, 18 gauge galvanized steel sheet, 24 gauge pre-painted architectural cladding. All hidden structural steel will be finished with primer. All exposed structural steel will be primed and epoxy painted.
The burner section will be designed to maintain appropriate air velocity for proper mixing and low air pressure loss.

Moveable air profile plates surrounding the burners will be provided to ensure optimum air velocity if required.

The burners will be mounted horizontally in lieu of vertically for ease of maintenance (as it is difficult to reach upper flame detectors and burner casings in vertical configurations) and for the prevention of moisture/ice build up in the bottom of vertically mounted burners.

The burner modules will be provided with one electrical receptacle and sealed high pressure sodium lighting fixtures on a walk switch.

All access doors will be double wall, insulated, steel with hardware

The inlet and outlet will be flanged for ease of installation to inlet section and Fan plenum (see section 3.1.4 below).

All fasteners will be Structural Grade

HID fixtures c/w metal halide bulbs will be provided throughout.

### 3.1.2 INLET SECTION

The inlet sections will consist of pre-fabricated weather hoods that will be complete with mounting flanges, support legs, galvanized bird screen and framing for ease of installation to inlet silencer section. The weather hood mounting flanges will be designed to easily mate with the silencer.

The bird screen wire gauge and opening size will be such as to prevent snow, frost and ice build up.

### 3.1.3 HEATER CONTROL ROOM MODULE

The heater control room module will be pre-attached to the burner module and will be pre-built, pre-wired, pre-piped and tested.

The heater control room will measure approximately 16' x 12' x 12' tall. It will be constructed from HSS framing c/w checker plate flooring, pre-painted outer cladding and roofing (all as per section 3.1.1 above), pre-painted inner steel sheet with 4" x 3.5 lb/ft³ thermal insulation in the walls, floor and ceiling.

The control room will be complete with burner observation window, thermostatically controlled electric heater sufficiently sized to maintain 18°C inside temperature as well as room thermostat and single speed fan, upper and lower room venting as specified, interior and exterior lighting, 120 VAC receptacle.

In addition the control room will be complete with the following:

- 1 x 60 A, 600 VAC fused disconnect
- 600 VAC Power distribution panel c/w breakers
- 120 VAC power distribution and lighting panel c/w multi breakers
Four combination starters (one per burner) each c/w one NEMA Size 1 contactor, dual overloads and electrical isolation will be supplied and mounted.

One 15 kVA 600/120 (CANADA), 480/120 (USA) transformer

Two insulated, steel access doors (36" w x 64" h) will be provided (one complete with 12" x 12" viewing window) – one for access between control room and burner room; one for access from outside to control room

All appropriate interior and exterior lighting and receptacles will be provided.

3.1.4 RAISE PLENUM MODULE

The Raise plenum section will measure approximately 36' l x 36' w x 24' tall – NOTE: actual to be confirmed once raise diameter is confirmed (see attached conceptual drawing)

The Raise plenum will be shipped in approximately twelve structurally integrated panels

The Raise plenum will be constructed from heavy structural steel that generally consists of the following:

- C8 x 4.7 Channel framing
- C8 x 18.75 Channel framing
- C10 x 15.3 Channel framing
- 8 x 4 x 0.25 HSS framing
- W10 x 22 I Beam framing

Flat bar and angle bracing

The wall sections will be pre-constructed with 18 ga galvanized perforated steel sheet (inner), 4" thick 3.5 to thermal/noise insulation, 18 ga galvanized outer sheet with 24 gauge pre-painted outer cladding.

The end wall panel sections will be pre-built and flanged to accommodate the burner room connections.

All HID fixtures c/w metal halide bulbs will be provided and installed

A safety railing, painted yellow will be supplied as well as a full screen in front of raise collar.

3.1.5 BURNERS

The heater will have four, 14 ft long APX burners, each c/w three 3 HP, 600/3/60 VAC (CANADA), 460/3/60 VAC (USA) combustion air blowers, extruded aluminum castings, stainless steel air wings, cast iron end plates, flame rod sensor on both ends, and pilot adjust cocks. Each burner is rated at 14 MMBTUH with a 40:1 turndown ratio and low emissions to meet minimum CO and NO2 requirements for mine heating (less than 5 ppm CO and less than 0.5 ppm NO2 throughout operating range).

The burners will be pre-mounted, piped and wired to the adjoining control room and / or to junction boxes / flanged gas connections prior to shipment.
3.1.6 GAS VALVE TRAINS

Four independent, propane valve trains will be provided and pre-mounted/wired/piped in the control room. The valve trains will be built to CSA B149.3 standards (CANADA), NFPA 86 (USA) and will be mounted in the heater control room module (item 3.1.3 above). The control room will contain the following components:

MAIN VALVE TRAINS

One 4” flanged, main inlet valve
Fifteen pressure gauges with isolation cocks
Four 2” NPT lockable isolation valves
Four 2” NPT main gas regulators
Four 2” flanged, combination shut-off valves
Four low gas pressure switches
Four high gas pressure switches
Four 2”, modulating gas control valves
Four 2” test filler valves

PILOT GAS VALVE TRAINS

Four 3/4” NPT pilot gas regulators
Four 3/4” NPT lockable manual shut off valves
Four 3/4” NPT pilot solenoid valves
Four pilot gas adjust cocks (part of burner assembly)
Four 3/4” CGA approved gas flex hoses (one per burner)

3.1.7 COMBUSTION CONTROL PANEL

One, 120/1/60 control panel will be provided and mounted in the heater control room. The panel will be wired, tested and ESA labeled c/w the following unless otherwise advised:

One NEMA 12, Enclosure
Isolation disconnect
Four Honeywell RM7800 series Flame Safeguard Relays
Annunciation lights, associated switches and push buttons
General purpose control and timer relays
20% spare terminals will be provided for other devices

(A controlling / remote monitoring PLC c/w HMI can be provided as a extra if requested)

3.1.8 CO MONITORING

A CO monitoring system will be supplied inclusive of the following:

Draeger Polytron CO Monitor
Docking Station
CO Sensor
3.1.9 ANCILLARY DEVICES

The heater will be complete with the following ancillary devices:

- Three temperature RTD's (shipped loose for field mounting – 2 x 18”, 1 x 12’). (One ambient RTD for slagging of burners, one high limit RTD, one averaging RTD for heater discharge)
- Four Combustion air pressure switches (one per burner)
- One Main air differential pressure switches (mounted in burner module)
- Four ignition transformers (pre-mounted in burner module)

3.2 PORTAL HEATER

The Portal Heater is designed to heat 100% of the 135 m3/s (280,000 cfm) airflow requirements to the desired 40°F temperature differential (based on average worst case). Note that this is achieved by designing the heater and its integral main fan to pass 50% of the total 135 m3/s airflow through itself and heat this air to an 80°F differential. This airflow will mix with the balance of the airflow coming into the portal in order to achieve the desired resultant temperature differential of 40°F.

In general, the complete portal heater will consist of one pre-assembled burner room section c/w control room, fan plenum, intake section and integral main fan. The burner room will be pre-wired and pre-piped to the control room. The burner room section will be complete with inlet and outlet mating flanges to the fan plenum and intake silencer (if required).

The overall heater, burner section, control room and raise plenum will measure approximately 28’l x 32’w x 12’h (see attached drawing – fan length to be added).

3.2.1 BURNER ROOM

Burner room module will be pre-attached to the burner control room (see section 3.1.3 below) and will measure approximately 16’l x 12’w x 12’h. In general, the module will be pre-piped and wired to flanged pipe connections and an electrical junction box at the end wall.

The module will be built to industrial standards using heavy steel plate, structural tubing, steel channel and angle. Materials of construction will mainly be as follows:

- Main Frame: 4 x 3 x 0.1875 HSS structural steel
- Flooring: 3/16” Checker plate. Wall and Ceiling Construction (inside – outside): galvanized 18 gauge perforated steel sheet, 4” ROXUL 3.5 iv/ft² thermal noise insulation, 18 gauge galvanized steel sheet, 24 gauge pre-painted architectural cladding. All hidden structural steel will be finished with primer. All exposed structural steel will be primed and epoxy painted.

The burner section will be designed to maintain appropriate air velocity for proper mixing and low air pressure loss.
Moveable air profile plates surrounding the burners will be provided to ensure optimum air velocity if required.

The burners will be mounted horizontally in lieu of vertically for ease of maintenance (as it is difficult to reach upper flame detectors and burner castings in vertical configurations) and for the prevention of moisture / ice build up in the bottom of vertically mounted burners.

The burner module will be provided with one electrical receptacle and sealed high pressure sodium lighting fixtures on a wall switch.

All access doors will be double wall, insulated, steel with hardware.

The inlet and outlet will be flanged for ease of installation to inlet section and Fan plenum (see section 3.2.4 below).

All fasteners will be Structural Grade.

HID fixtures c/w metal halide bulbs will be provided throughout.

3.2.2 INLET SECTION

The inlet sections will consist of pre-fabricated weather hoods that will be complete with mounting flanges, support legs, galvanized bird screen and framing for ease of installation to inlet silencer section. The weather hood mounting flanges will be designed to easily mate with the silencer.

The bird screen wire gauge and opening size will be such as to prevent snow, frost and ice build up.

3.2.3 HEATER CONTROL ROOM MODULE

The heater control room module will be pre-attached to the burner module and will be pre-built, pre-wired, pre-piped and tested.

The heater control room will measure approximately 16’ l x 12’ w x 12’ tall. It will be constructed from HSS framing c/w checker plate flooring, pre-painted outer cladding and roofing (all as per section 3.1.1 above), pre-painted inner steel sheet with 4” 3.5 lb/ft3 thermal insulation in the walls, floor and ceiling.

The control room will be complete with burner observation window, thermostatically controlled electric heater sufficiently sized to maintain 18 °C inside temperature as well as room thermostat and single speed fan, upper and lower room venting as specified, interior and exterior lighting, 120 VAC receptacle.

In addition the control room will be complete with the following:

1 x 60 A, 600 VAC fused disconnect
600 VAC Power distribution panel c/w breakers
120 VAC power distribution and lighting panel c/w multi breakers
Rockwell Powerflex, 600 VAC variable frequency drive (for mine fan)
Bently Nevada vibration monitoring panel c/w accelerometers (for mine fan)
Ultrasonic airflow monitor (for mine fan)
Static pressure sensor (for mine fan)
Two combination starters (one per burner) each c/w one NEMA Size 1 contactor, dual overloads and electrical isolation will be supplied and mounted.

One 15 kVA 600/120 (CANADA) 480/120 (USA) VAC transformer

Two insulated, steel access doors (36” w x 84” h) will be provided (one complete with 12” x 12” viewing window) – one for access between control room and burner room, one for access from outside to control room.

All appropriate interior and exterior lighting and receptacles will be provided.

3.2.4 FAN PLENUM MODULE

The Fan plenum section will measure approximately 12’ 1” x 16’ w x 12’ tall.

The Fan plenum will be shipped in one section c/w structural floor for ease of installation and placement.

The Fan plenum will be constructed from heavy structural steel that will generally consist of 4” thick, insulated walls c/w pre-painted cladding. Burner room connection nine fan connection flanges.

All HID fixtures c/w metal halide bulbs will be provided and installed.

3.2.5 BURNERS

The heater will have two, 8 ft long APX burners, each c/w three 1 ½ HP, 600/3/60 VAC (CANADA), 460/3/60 VAC (USA) combustion air blowers, extruded aluminum castings, stainless steel air wings, cast iron end plates, flame rod sensor on both ends, and pilot adjust cocks. Each burner is rated at 8.0 MMBTUH with a 40:1 turndown ratio and low emissions to meet minimum CO and NO2 requirements for min heating (less than 5 ppm CO and less than 0.5 ppm NO2 throughout operating range).

The burners will be pre-mounted, piped and wired to the adjoining control room and / or to junction boxes / flanged gas connections prior to shipment.

3.2.6 GAS VALVE TRAINS

Two independent, propane valve trains will be provided and pre-mounted/wired/piped in the control room. The valve trains will be built to CSA B149.3 standards (CANADA), NFPA 86 (USA) and will be mounted in the heater control room module (item 3.2.3 above). The control room will contain the following components:

MAIN VALVE TRAINS

One 3" flanged, main inlet valve
Nine Pressure gauges with isolation cocks
Two 1 ½” NPT lockable isolation valves
Two 1 ½” NPT main gas regulators
Two 1 ½” flanged, combination shut-off valves
Two low gas pressure switches
Two high gas pressure switches
Two 1 ½” modulating gas control valves
Two 1 ½" test firing valves

PILOT GAS VALVE TRAINS

Four 3/4" NPT pilot gas regulators
Four 3/4" NPT lockable manual shut off valves
Four 3/4" NPT pilot solenoid valves
Four pilot gas adjust cocks (part of burner assembly)
Four 3/4" CGA approved gas flex hoses (one per burner)

3.2.7 MAIN CONTROL PANEL

One, 575/3/60 (CANADA) 460/3/60 (USA) main control panel will be provided and mounted in the heater control room. The panel will be wired, tested and ESA labeled c/w the following unless otherwise advised:

One NEMA 12, Enclosure
Isolation disconnect
600/120 (460/120) VAC step-down transformer
Four Honeywell RM7800 series Flame Safeguard Relays
Annunciation lights, associated switches and push buttons
General purpose control and timer relays
20% spare terminals will be provided for other devices

(A controlling / remote monitoring PLC c/w HMI can be provided as an extra if requested)

3.2.8 CO MONITORING

A CO monitoring system will be supplied inclusive of the following:

- Draeger Polytron CO Monitor
- Docking Station
- CO Sensor
- Remote Duct Adapter
- Remote Duct Sensor

3.2.9 ANCILLARY DEVICES

The heater will be complete with the following ancillary devices:

Three temperature RTD’s (shipped loose for field mounting – 2 x 18", 1 x 12")
(One amient RTD for staging of burners, one high limit RTD, one averaging RTD for heater discharge)
Two Combustion air pressure switches (one per burner)
One Main air differential pressure switches (mounted in burner module)
Two ignition transformers (pre-mounted in burner module)
3.2.10  MINE FAN

One complete, Alphair 7200 VAX 2700 Arr. #4 fan, internally direct driven with adjustable pitch at rest, vane axial fan will also be supplied as an integral component to the heater. This will force 50% of the portal airflow through the heater and will accommodate pressure losses associated with the heater.

The fan will be complete with inlet bell and screen, support legs, discharge cone and 125 HP – 1200 RPM 3/60/575 V high efficiency motor (CANADA), (460/3/60 USA)

4.0  COMMISSIONING

Our experienced technicians can be provided for on site commissioning and training for all devices inclusive of burners, controls as an extra to our proposal. Commissioning will be charged on a time and material basis as per pricing schedule attached.

NOTE: Standard time refers to 10-hour work day, Monday – Friday.

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>OVERTIME</th>
<th>SATURDAY</th>
<th>SUNDAY and HOLIDAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$200/hr</td>
<td>$300/hr</td>
<td>$300/hr</td>
<td>$300/hr (Sunday), $300/hr (Holidays)</td>
</tr>
</tbody>
</table>

MILEAGE CHARGE: $0.55/km

TRAVEL EXPENSES: COST + 10%

5.0  PROPANE STORAGE AND DISTRIBUTION

ACI-CANEFCO can design and supply a complete propane storage and distribution facility complete with tanks, vaporizers, pumps, interconnecting piping, loading station, fencing. This will empower HBMS to negotiate their own propane fuel supply costs with various suppliers for substantially reduced running costs.

Cost Extra ........................................................................................................... Available on Request

I trust that this meets your expectations and we encourage you to call if you have any questions or concerns.

Sincerely,

Peter J. Terkovics, P.Eng
Vice President - Sales

ACI-CANEFCO INC.