

CONTROLLING DIESEL PARTICULATE MATTER IN UNDERGROUND MINES

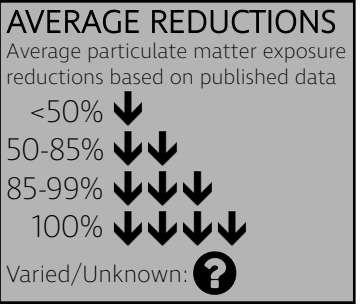


PROACTIVE CONTROLS
Reduce or eliminate diesel particulate emissions before they enter the workplace air

Replacing or repowering old equipment
Newer engines must meet much stricter emissions regulations. Replacing an engine or a piece of equipment with a newer model will significantly decrease emissions. The level of reduction depends on the old and replacement equipment.

Aftertreatment systems
A variety of different aftertreatment systems are available. Emissions reductions depend on the type of filter chosen, as well as the engine and load. Particulate reductions can range from 20-95%.

Preventive maintenance
Maintenance keeps all parts of the engine, as well as any emissions control systems, functioning optimally. Poorly maintained engines can produce significantly more emissions than an engine in good condition.



Proactive controls
More effective ↑

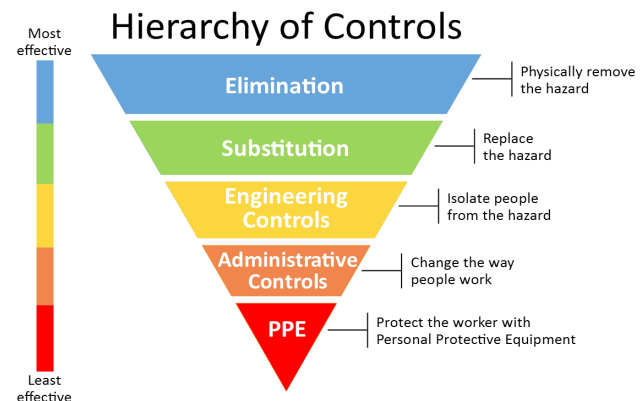
Alternative Energy
Involves replacing diesel equipment with alternatives such as electric.

Rebuilding engines
Manufacturers often offer upgrade kits that can be incorporated into an engine rebuild to improve emissions.

Idling technology
Idling technology works by automatically turning off the engine when the vehicle idles. The emissions reductions will be greater for equipment that spends a high proportion of time idling.

Idling policies
Idling increases both emissions and engine wear. Idling policies limit the amount of time an engine can be idled.

Reactive controls
Less effective ↓



General ventilation
General ventilation dilutes emissions by bringing clean air into the area. The reductions vary depending on the volume of air provided. It also helps reduce ambient air concentration of non-diesel hazards, as well as helping with temperature control.

Operator training
Training can include driving skills, how to recognize maintenance issues, proper use of diesel control technologies, and the health effects of diesel exhaust.

Respirators
PPE should be used as a last resort, and is not a replacement for other controls. The concentration of diesel exhaust in the air should still fall below the regulatory limit. When used, respirators should be fit-tested, and training should be provided to wearers.

Enclosed cabs
When properly functioning, enclosed cabs protect the operator, but do not protect the surrounding workers.

Scheduling and site planning
Control the number of diesel engines operating in an area. Schedule workers during times when fewer diesel engines are working.

Tele-operating
Tele-operation allows the operator to be in a safe location, such as a filtered control room on the surface. Reductions in exposure can be up to 100% if the operator is completely removed from the site. Other workers may still be exposed if they enter the work area, or if emissions circulate to other areas of the mine.

REACTIVE CONTROLS
Remove diesel particulate emissions from the workplace air, or reduce the likelihood that workers will inhale particulate emissions



Towards a cancer-free workplace



CONTROLLING DIESEL PARTICULATE MATTER IN UNDERGROUND MINES

Occupational Cancer Research Centre Report

June 2017

Background

Diesel engine exhaust is a complex mixture of toxic gases and particulates produced from the combustion of diesel fuel (NTP, 2016). The exhaust can contain particulate matter, nitrogen oxides, carbon monoxide, polycyclic aromatic hydrocarbons, sulfur oxides, metals, and many other chemicals (IARC, 2013). The composition of the mixture varies depending on a number of factors including engine type, operating conditions, lubricating oil, additives, emission control systems, maintenance, and fuel composition (NTP, 2016). This report will focus mainly on the particulate matter component of diesel exhaust. Results from animal studies indicate that this component is more relevant to lung cancer outcomes than the gas phase component and the key studies of cancer in humans have focused on diesel engine exhaust particulate, measured as respirable elemental carbon (IARC, 2013).

Diesel engine exhaust is classified as a Group 1 *definite human carcinogen* by the International Agency for Research on Cancer. Exposure to diesel engine exhaust causes lung cancer, and there is limited evidence that it may cause bladder cancer (IARC, 2013). Cardiovascular disease is also linked to exposure to particulate matter air pollution, of which diesel emissions are a major contributor (Brook et al, 2010). Exposure to diesel engine exhaust can also cause eye, throat and bronchial irritation, light-headedness, nausea, coughing, phlegm, allergic reactions, or increased severity of allergic responses.

Diesel engines are widely used in mining for many different applications. Approximately 9,100 workers in the Ontario mining industry are estimated to be exposed to diesel engine exhaust (CAREX Canada, 2014). Almost all exposure occurs via inhalation. CAREX Canada estimates that approximately 56% of the mine workers occupationally exposed to diesel engine exhaust in Ontario are exposed at high levels due to the accumulation of emissions underground (CAREX Canada, 2014).

Regulation of diesel particulate has used as a measure either total carbon, which is made up of organic carbon plus elemental carbon, or elemental carbon alone. Currently, elemental carbon is believed to be the best measure of diesel particulate matter, as it makes up the bulk of diesel particulate emissions, and is less susceptible to interference from other particulate sources in the workplace (HEI, 2015). Ontario regulation requires that the time-weighted average exposure of a mine worker to diesel particulate matter must be no more than 0.4 mg/m³ total carbon, or that the elemental carbon multiplied by 1.3 is not more than 0.4 mg/m³ (Occupational Health and Safety Act Reg. 854). However, based on current research this level does not sufficiently protect workers' health. The Occupational Cancer Research Centre recommends reducing emissions to 0.02 mg/m³ measured as elemental carbon.

About the diagram

This diagram showcases the control strategies available for diesel engine exhaust in the Ontario mining sector. It incorporates the Hierarchy of Controls, where control strategies are ranked from most effective (elimination or substitution) to least effective (personal protective equipment). The diagram also distinguishes between proactive controls (which eliminate or reduce diesel emissions *before* they enter workplace air) and reactive controls (which reduce the concentration of diesel emissions *already present* in workplace air, or reduce the likelihood that workers will inhale the emissions). Proactive controls are generally considered to be more effective than reactive controls.

An effective emissions control program utilises multiple controls from across the Hierarchy, and includes emissions monitoring to evaluate the effectiveness of the program.

Monitoring Emissions

While an emissions monitoring program does not actively lower emissions, it is important in order to ensure that diesel controls are working effectively and are sufficient for the amount of diesel exhaust being produced. Tracking emissions can be used to inform diesel control policies, especially when combined with vehicle and personnel tracking (Bugarski et al, 2011).

Diesel engine exhaust is a complex mixture, and there are a number of substances that can be monitored. Particulate matter (measured as total carbon or elemental carbon) is of high concern, while gases found in diesel emissions include carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons, oxygen and sulphur dioxide.

Emissions monitoring includes undiluted emissions measurements and ambient air measurements. Undiluted emissions measurements include both 'tailpipe output' and 'engine out' (upstream of aftertreatment systems) emissions, and can help to identify and distinguish between engine maintenance issues and failures of emission control devices (Bugarski et al, 2011). These measurements can also help to estimate ventilation requirements. Undiluted emissions from diesel engines must contain less than 600 ppm by volume of carbon dioxide, and must be tested at routine intervals and after repairs (Occupational Health and Safety Act Reg. 854). For more information on how to test for gases in undiluted emissions, see [Bugarski et al, 2011](#) Section 2.4 and [Ontario Ministry of Labour, 2014](#).

Ambient air monitoring (personal and area sampling) indicates whether the overall diesel emissions control strategy is effective, sufficient, and functioning properly to ensure workers' health. Ontario Regulation 854 sets the maximum concentration of diesel particulate matter in underground mines at 400 ug/m³, measured as total carbon (Occupational Health and Safety Act Reg. 854). However, based on current research this level does not sufficiently protect workers' health. The Occupational Cancer Research Centre recommends reducing emissions to 20 ug/m³ measured as elemental carbon. Gases produced by diesel engines can be measured in a few different ways, including colorimetric dosimeter tubes and portable real-time continuous gas monitors (Bugarski et al, 2011). Occupational exposure limits for gases and other hazardous substances can be found in Ontario Reg. 833 (Occupational Health and Safety Act Reg. 833). For more information on sampling in underground mines, see [Bugarski et al, 2011](#) Section 4 and [Ontario Ministry of Labour, 2015](#).

Control Strategies in Mining

1. Alternative energy

Electric engines do not produce tailpipe emissions (100% reduction) and are therefore one of the best options for reducing diesel engine emissions and protecting workers' health (US Department of Energy, 2016). They also produce less noise and heat than diesel engines. Hybrid diesel-electric vehicles can significantly reduce emissions. A study by CANMET-MMSL demonstrated reductions between 25-40% (Laverdure et al, 2011). An EPA-verified hybrid engine for non-road gantry cranes results in a 74% reduction in particulate emissions compared to a Tier 2 engine, and a 56% fuel economy improvement (US EPA, 2016a).

The cost of new electric equipment is high, but this cost may be offset by both lowered operating costs (fuel and maintenance) as well as lowered ventilation requirements, which can be a significant savings (Varaschin and De Souza, 2015; McCrae, 2016).

2. Replace or Repower old equipment

The emissions reductions for replacing or repowering old equipment with new engines depends on the original equipment, as well as the new engine. Emissions standards for new models of off-road diesel engines have been regulated in Canada since 2006. The Canadian regulations generally follow the US Environmental Protection Agency's tier system, which has emissions standards from Tier 1 up to Tier 4 (the current strictest standards). The emissions reductions when moving from older to newer engines can be significant. Repowering a 1975-1986 (unregulated) scraper with a Tier 1 or Tier 2 engine reduces particulate matter emissions by an estimated 62% or 81%, respectively (Scott et al, 2005). Tier 4 standards for off-road equipment reduce allowed particulate emissions by 50-95% (based on engine type) compared to previous standards (Diesel Technology Forum; US EPA, 2016c; MassDEP, 2008).

It should be noted that field-tested emissions reductions were not available for off-road diesel equipment, but the changing standards give some idea of the significant impact of replacing or repowering old diesel equipment.

Replacing or repowering old equipment involves a significant upfront cost, especially if the entire vehicle is replaced. Repowering is the cheaper option (e.g., \$30,000-\$40,000 for a 2002-2007 model engine repowering kit) (Diesel Technology Forum, 2003). It may be a good option if the vehicle is in good shape. Replacing or repowering the equipment can also have cost benefits in terms of decreased maintenance costs, and increased efficiency.

3. Rebuild engines

When an engine is rebuilt, the engine can be upgraded by incorporating emissions-reducing parts. Manufacturers sometimes provide emissions upgrade kits that can be used during a rebuild for this purpose. Emissions reductions will depend on the engine and the kit. For example, caterpillar produces

an emissions upgrade kit that is verified by the EPA to reduce particulate matter by 15% for specific models (US EPA, 2016a).

Incorporating an emissions reduction kit during a rebuild will increase the cost of the rebuild by several thousand dollars (US EPA, 2007).

4. Aftertreatment systems

Emissions reductions from aftertreatment systems will depend on the aftertreatment system chosen and the equipment they are installed on, among other factors. The choice of which aftertreatment system to use will depend on the engine and specific application, duty cycle, operating conditions, and the emissions reductions required. Examples of aftertreatment systems that decrease diesel particulate matter include:

- Diesel particulate filters (DPF): 80-99% particulate matter reduction (costs: \$5000-\$20,000)
- Flow-through filters (FTF): 50-75% particulate matter reduction (costs: \$3000-\$5000)
- Diesel oxidation catalysts (DOC): 20-50% particulate matter reduction (costs: \$1000-\$2000)

Crankcase emissions also contribute to overall diesel particulate emissions, and are not controlled by tailpipe aftertreatment systems. Uncontrolled crankcase emissions can represent 35% of total particulate emissions for earlier engine models, and higher percentages for newer engines with better tailpipe controls (Jaroszczyk et al, 2006). Crankcase emissions are even higher relative to tailpipe contributions when the engine is idling (Scott et al, 2005). Closed crankcase ventilation systems help control crankcase emissions, and can reduce overall particulate matter emissions by 10-15% (Diesel Technology Forum, 2006).

There are a number of aftertreatment systems aimed at reducing emissions of nitrogen oxides. These include:

- Exhaust gas recirculation (EGR): 50-90% NO_x reduction (cost: \$13,000-\$15,000)
- Selective catalytic reduction (SCR): 50-90% NO_x reduction (cost: \$10,000-\$50,000)
- Lean NO_x catalysts (LNC): 20-30% NO_x reduction

Both the US Environmental Protection Agency and the California Environmental Protection Agency offer lists of verified diesel emission control strategies:

- <https://www.epa.gov/verified-diesel-tech/verified-technologies-list-clean-diesel>
- <https://www.arb.ca.gov/diesel/verdev/vt/cvt.htm>

References:

- DPF: US EPA, 2007; Diesel Technology Forum, 2003; MassDEP, 2008; Diesel Technology Forum, 2006; Bugarski et al, 2009; Bugarski et al, 2006b; Bugarski et al, 2006a; Stachulak et al, 2006; Mischler & Colinet, 2009; Scott et al, 2005; US EPA, 2016; Bugarski et al, 2011
- FTF: MassDEP, 2008; Scott et al, 2005; Bugarski et al, 2011

- DOC: US EPA, 2007; Diesel Technology Forum, 2003; MassDEP, 2008; Diesel Technology Forum, 2006; Bugarski et al, 2009; Bugarski et al, 2006b; Mischler & Colinet, 2009; Scott et al, 2005; Bugarski et al, 2011
- EGR: Diesel Technology Forum, 2003; Diesel Technology Forum, 2006
- SCR: Diesel Technology Forum, 2003; Diesel Technology Forum, 2006; Scott et al, 2005; US EPA, 2016; Bugarski et al, 2011
- LNC: Diesel Technology Forum, 2003; Diesel Technology Forum, 2006; Scott et al, 2005; Bugarski et al, 2011
- Costs: US EPA, 2007; Diesel Technology Forum, 2003; MassDEP, 2008

5. Anti-Idling Technology

Anti-idling technology generally works by shutting off the engine after it has been idling for a set amount of time. Some off-road equipment comes already installed with features that will automatically shut off the engine after a few minutes of idling, although this may not be available for mining equipment (US EPA, 2007). Other technologies that reduce idling include those that provide services that would otherwise require the engine to be on, such as heat, air conditioning, or electricity (US EPA, 2016b). For example, auxiliary power units (APUs) provide power to the cab without running the engine, and are a good application if equipment is idled in order to maintain cab comfort (US EPA, 2007).

One study found that for an uncontrolled 89 hp engine, operating at a load factor of 0.21, one hour of idling produces 13g of particulate matter, 155g of NO_x, and 65g each of CO and CO₂ (US EPA, 2007).

Costs for anti-idling technology for off-road equipment varies, but can range from \$500-\$9,000 (US EPA, 2007). Reducing idling can result in fuel cost savings, longer engine life, and reduced maintenance costs. To estimate potential savings from reduced idling, visit <http://www.ucair.org/wp-content/uploads/2013/05/Idling-for-Heavy-Duty-Vehicles.pdf>.

6. General Ventilation

General ventilation is the flow of air into and out of a working area. Forced ventilation uses fans to move air through the space at a set rate. The reduction in concentration of diesel emissions in the mine atmosphere due to general ventilation depends on the volume of clean air directed to the working area. Increasing airflow can be achieved by using higher horsepower fans or adding more fans in parallel, and adding new ventilation shafts or airways. Increased airflow can also be achieved by improving the efficiency of the ventilation, by using stoppings to block air to nonessential areas (and proper maintenance of the stoppings), or through the placement of auxiliary fans to direct air toward working areas (Bugarski et al, 2011). Ontario regulation requires mechanical ventilation in underground mines to provide air flow of at least 0.06 m³/s per kilowatt of power of the diesel equipment operating in the mine (Occupational Health and Safety Act Reg. 854).

A benefit of general ventilation is that as well as helping to dilute diesel emissions, it can also help reduce the concentration of other hazardous substances, such as crystalline silica or radon, which can be

found in the air in underground mines. General ventilation can also help to regulate the temperature underground.

Ventilation costs are often the biggest source of power costs for underground mines.

7. Tele-operation

Tele-operating is distant control of the equipment by an operator who is out of the equipment's line-of-site. Tele-operation allows the operator to be in a safe location, such as in a filtered control room on the surface, an environmentally-controlled cab located away from the active face, or even in an operating centre away from the mine site (Fisher & Schnittger, 2012; Bugarski et al, 2012). This protects the operator from diesel engine emissions, as well as other hazards such as noise, dust, whole body vibration, injuries, and ergonomic discomforts (Paraszczak et al, 2015). Exposure reduction depends on where the operator is located, but can be up to 100% for the operator. However, there is no exposure reduction for nearby workers.

There are some potential production benefits to tele-operation as well. Travel time for miners during shift changes may decrease as the operator control room may be more accessible than the area where the equipment is operating (Paraszczak et al, 2015). As well, the equipment can be operated during blast clearance times, before blasting fumes have dissipated, as the operator will not be exposed (Fisher & Schnittger, 2012; Paraszczak et al, 2015). However, minor equipment failures may lead to longer shut down times, as the operator is not on site to make small maintenance adjustments (Paraszczak et al, 2015). Specialized equipment and technologies are needed in order to implement tele-operation, and these devices may also require maintenance by skilled personnel (Fisher & Schnittger, 2012).

8. Enclosed cabs

Enclosed cabs help to reduce diesel exhaust exposure to the vehicle operator. Properly functioning enclosed cabs can reduce diesel particulate and dust exposure by 90% or more (Bugarski et al, 2011). However, if cabs are not optimized, they can be less than 40% efficient in removing dust and diesel particulate matter (Bugarski et al, 2011). Factors that affect the proper functioning of cabs include use of recirculation filters, intake filter efficiency, cab integrity, open windows, etc. Having a heating and air conditioning unit within the cab, as well as prohibiting smoking in cabs can help to reduce open windows and increase cab effectiveness. Cabs can be retrofitted on to some older equipment, or included in newly purchased equipment. Space restrictions within the mine may be an issue when implementing enclosed cabs. Another consideration is that enclosed cabs do not reduce exposure to miners working nearby.

9. Preventive maintenance

Diesel emissions can increase significantly due to wear or breakdown of the engine components or aftertreatment systems. The impact on emissions will vary depending on the type of engine and the state of wear. One report for the Diesel Emissions Evaluation Program (DEEP) found that in test

situations, depending on the engine design technology and condition, maintenance decreased particulate matter emissions by up to 55% (McGinn). Another study found that a basic tune-up of 'gross smoke emitting' vehicles reduced particulate matter emissions by 40% on average (Diesel Technology Forum, 2003). An EPA study of a 2000-year model on-road heavy diesel engine found particulate matter emissions increases for specific maintenance issues: clogged air filters caused a 40-50% increase; excess oil consumption resulted in over 100% increase; higher lube oil consumption caused up to 85% increase, minor ejector problems caused 35-75% increase; and nozzle hole wear in the fuel injectors resulted in up to 85% increase (US EPA, 2007). It should be noted that these emissions increases were not measured for non-road equipment, but give some idea of the benefits of proper maintenance for large diesel engines. Preventive maintenance programs should involve equipment inventory, usage tracking, knowledge of maintenance requirements for each engine, and routine performance checks. This tracking can be done manually or through specialized maintenance program software. Training operators to be able to identify signs of poor maintenance can also help avoid major engine failures.

A basic tuneup can cost in the range of \$500-\$2000 (Diesel Technology Forum, 2003). However, performing regular maintenance can save money by avoiding larger problems and engine malfunctions. Proper maintenance can also reduce fuel and oil consumption. Manual tracking of maintenance needs involves fairly low administrative costs. Software to track maintenance needs can be expensive (on the order of \$100,000 to set up) (US EPA, 2007), but may be more practical for larger companies.

10. Idling policies

Idling policies set specific limits on the amount of time a vehicle can be left at idle. An idling policy should define warm-up and cool-down periods for diesel equipment, based on manufacturer's recommendations (US EPA, 2007). Generally, newer equipment requires almost no warm-up and cool-down time, so idling to avoid shutdown is unnecessary. Idling also puts wear on the engine and decreases engine life, increases fuel costs, and produces emissions. For example, an uncontrolled backhoe loader with an 89 horsepower engine operating under a load factor of 0.21 produces approximately 13 g of particulate matter in one hour of idling (US EPA, 2007).

Many operators may not be aware of the other costs of idling. Educating operators about idling policies and why idling should be avoided is therefore an important component of idle-reduction policies (US EPA, 2007).

Instituting an idling policy has a low administrative cost, for operator training and tracking of idling.

11. Operator Training

Operator training to improve driving skills can reduce emissions by reducing fuel consumption, engine wear and maintenance needs, and time required to complete a task.

Other types of training can include awareness campaigns on the health hazards of diesel engine exhaust, proper respirator use, how to spot maintenance issues, costs of idling, effective use of enclosed cabs, and use and maintenance of emissions control technologies.

12. Scheduling and site planning

The goal of scheduling and site planning is to limit the number of vehicles producing diesel exhaust in a given area, or limit the number of miners who will be exposed to the exhaust. Examples include routing traffic away from miners' work areas, routing haul trucks in return air (especially when ascending ramps while loaded), and limiting the number of engines in a given area based on the ventilation volume available (Mischler & Colinet, 2009).

As an example, the number of diesel vehicles operating in an area can be limited by setting up a system of tags, where vehicle operators must take a tag before entering a section. If no tags are available, the vehicle may not enter until another vehicle leaves. Passages can also be set up to be one-way only, in order to reduce vehicle traffic through the area (Bugarski et al, 2011).

Where possible, miners who aren't using diesel equipment could be scheduled to work during times when less diesel equipment is operating in the area. This decreases the number of miners potentially exposed, especially if diesel equipment operators can be protected by enclosed cabs (Bugarski et al, 2011). However, it is important to note that job rotation is not a viable control, as it increases the number of miners exposed to diesel engine emissions (Bugarski et al, 2011).

13. Respirators

Respirators can help reduce the wearer's exposure to diesel particulate and other hazardous substances, but should not take the place of other control measures. Underground mines in Ontario are required to provide mechanical ventilation if diesel equipment is operating, and the flow of air must reduce the concentration of diesel emissions below prescribed levels (Occupational Health and Safety Act Reg. 854). Respirators cannot be used to achieve this reduction in concentration – they can only be used to further reduce worker exposure. Respirators should therefore only be used as one component of an overall prevention and control program.

There are many different types of respirators. Air-purifying respirators filter contaminants from the air, while supplied air respirators provide fresh air from an uncontaminated source, such as a compressed air cylinder. Supplied air respirators typically give a higher protection than air-purifying respirators, and they also provide protection against concurrent exposures, but may be more cumbersome or restrict mobility, and are more expensive (IHSA, 2013).

Air-purifying respirators are further divided into powered (where a blower passes air through the filter) and non-powered (where air is drawn through the filter by the wearer's breath). Powered air-purifying respirators (PAPRs) generally give a higher level of protection than non-powered air-purifying respirators. The filters used in air-purifying respirators can be specific to a hazard or type of hazard, or may cover multiple exposures, and therefore need to be carefully selected for the environment (IHSA, 2013). Particulate filters may be described by their filter efficiency (from 95-99.97%) and oil resistance (N = not resistant to oil; R = somewhat resistant to oil; P = oil-resistant). If air-purifying respirators are used for diesel particulate matter, oil-resistance is recommended (Janssen & Bidwell, 2006).

Respirators have assigned protection factors (APFs) which represent the level of respiratory protection for a specific type of hazard that the respirator is expected to provide in the workplace when properly

functioning, fitted, and used by trained wearers. Higher APFs represent a greater potential to filter out specific hazardous substances. Multiplying the APF by the occupational exposure limit for the hazard gives the maximum air contaminant level that the respirator is expected to provide protection against, under ideal circumstances. The US National Institute for Occupational Safety and Health (NIOSH) has assigned average APFs for different respirator types that range from 10 (for half-facepiece non-powered air purifying respirators), to 1000 (full facepiece PAPRs), to 10,000 (self-contained breathing apparatus, SCBA). The US National Institute for Occupational Safety and Health (NIOSH) provides a list of certified respirators which can be found here: <https://wwwn.cdc.gov/niosh-cel/> (NIOSH, 2017).

However, actual respirator effectiveness under real workplace conditions can vary. Achieving adequate protection relies on choosing the correct type of respirator and filter media; appropriate maintenance, cleaning and storage; effective changeout schedules for any filters, canisters, or cartridges; proper fit testing; wearer training; and proper use by individual employees (Sargent & Gallo, 2003; Mayer & Korhonen, 1999). Respirators can impact visibility, comfort, and ease of breathing, and may be worn incorrectly in order to minimise these effects (Howie, 2005). Factors specific to the workplace, such as composition, concentration, and size distribution of the particulate may also affect respirator performance (Gao et al, 2015; Eninger et al, 2008; Reponen et al, 2011).

Poorly fitted respirators significantly increase worker exposure compared to properly fitted respirators (Zhuang et al, 2003; Gao et al, 2016; Coffey et al, 2004; Reponen et al, 2011). Therefore, fit testing should be performed at least annually, as well as whenever a new type of mask is used. Every type of mask will not fit every person. User seal checks should also be performed each time a respirator is used (Or et al, 2012; Zhuang et al, 2003).

Even for well-fitting respirators, most particle penetration occurs from leakage via the face seal (Sargent & Gallo, 2003; Cho et al, 2010), and passing a fit test does not necessarily guarantee the wearer's protection (Kim et al, 2015). Leakage around the respirator face seal can be exacerbated by facial hair; changes in weight; face shape or changes in face shape (e.g. due to dental work); movement of facial muscles; working posture; sweat or dust on the face; heavy breathing; and interference from other protective equipment such as hardhats (Sargent & Gallo, 2003; Kim et al, 2015; Mayer & Korhonen, 1999; Howie, 2005; Cho et al, 2010). Some of these factors, such as facial sweating and difficult working postures, may not be avoidable for underground miners.

When respirators are used in the workplace, a respirator program should be in place that includes all aspects of respirator use, including selection, maintenance, storage, cleaning, training, fitting, and supervision (MSHA, 2006).

Other Control Strategies

These control strategies may not be applicable to mining, as in the case of local exhaust ventilation, or are not fully understood in terms of the possible health impacts (e.g. biodiesel).

1. Local Exhaust Ventilation (LEV)

Local exhaust ventilation (LEV) is an engineering control that captures emissions close to the source, before they enter the general atmosphere, and exhausts them to a safe area away from workers (Health & Safety Authority, 2014). Examples of LEV technology for diesel equipment include tailpipe exhaust extraction systems and stack exhaust hoses (Safe Work Australia, 2015). These systems work well on stationary equipment where diesel emissions can be discharged to outside. The effectiveness of LEV depends on many factors, including how it is designed and set up, the airflow, maintenance, and adherence to proper use (Health & Safety Authority, 2014). While LEV systems are likely not applicable underground, they may be of use if diesel engines are used in enclosed surface applications.

2. Alternative Fuels

Diesel fuel composition is regulated in Canada. For off-road engines, ultra-low sulphur diesel fuel (ULSD) containing less than 15 ppm sulphur has been required since 2012 (CAREX Canada, 2016). ULSD allows the use of many aftertreatment systems that cannot be used with higher-sulphur fuels (US EPA, 2007).

Apart from ULSD, a few alternative fuels have been tested for diesel equipment. The most common of these are biodiesel blends. Biodiesel blends of up to 20% can usually be used in most equipment with minimal modifications (Bugarski et al, 2011). However, biodiesel fuels can degrade more rapidly, may include impurities or varying quality, may not be compatible with all types of seals and gaskets, and have a higher gel point and so may not be practical in cold weather (Bugarski et al, 2011).

Generally, the use of biodiesel results in reductions in particulate matter mass, carbon monoxide, and hydrocarbons, but an increase in nitrogen oxides (Bugarski et al, 2011). The amount of particulate matter emitted when biodiesel is used is dependent on the engine, operating conditions, and blend (Bugarski et al, 2010). The US EPA has verified a 0-47% reduction in particulate matter emissions for biodiesel blends of 1-100%, for on-highway use (US EPA, 2016a). A study in an experimental mine setting found that biodiesel blends of 20-50% reduced elemental carbon by 33-66%, depending on the blend and type of biodiesel, but increased nitrogen dioxide (Bugarski et al, 2006b). Tests by NIOSH found that the mass concentration of diesel particulate matter decreased by approximately 50% when 100% biodiesel was used (Mischler & Colinet, 2009).

However, there are some concerns that biodiesel emissions may have increased toxicity compared to regular diesel emissions (Bugarski et al, 2011). Biodiesel may increase the fraction of particle-bound volatile organics and the number concentration of aerosols, especially under light-load conditions (Bugarski et al, 2010). Overall, there is little known about how the changes in physical and chemical properties when using biodiesel may affect health (Bugarski et al, 2010).

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