BEST PRACTICE GUIDE
AIR QUALITY

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Index

Introduction

Preface

A fundamental element of the Crossrail project was the construction of a number of tunnels under London; these tunnels were created using tunnel boring machines (TBM's), sprayed concrete lining (SCL) processes and other tunnelling methods, supported by diesel plant operations.

Each of these processes had the potential to expose workers to airborne contaminants that, if not adequately controlled, can lead to significant harm. This Guide has brought together all of these activities to ensure best practice in the identification and control of the health risks during tunnelling activities.

This Best Practice Guide was produced through collaboration between representatives from Crossrail and two main tunnelling contractors – BFK and DSJV and their Occupational Hygiene provider, Park Health. Thanks are due to all those involved in the preparation, review and issue of this Guide.

Purpose

This Best Practice Guide details legal requirements and best practice standards, specific to air quality during construction of a railway in tunnel environments. This guide will help construction organisations optimise occupational health risk management in a manner that ensures efficiency and productivity.

This Best Practice Guide proposes minimum requirements for the protection of health of the railway construction workers; local arrangements should meet (or exceed) these requirements.

This Best Practice Guide is applicable to all personnel involved in ensuring air quality during tunnelling activities.

It should be used alongside:

- BS6164:2011 – Code of practice for health and safety in tunnelling in the construction industry
- Local rules, procedures and processes governing health and safety of the construction railway
- The Construction (Health, Safety and Welfare) Regulations 1996
- Occupational exposure to nitrogen monoxide in a tunnel environment. British Tunnelling Society April 2008
- Crossrail Best Practice Guide - Construction Railways Operations
- Crossrail Best Practice Guide - Sprayed Concrete Lining Exclusion Zone Management

Note: Compliance with this Guide does not ensure compliance with the above.

Overview of Health Hazards

There are three major hazards associated with tunnelling activities which operatives could be exposed to:

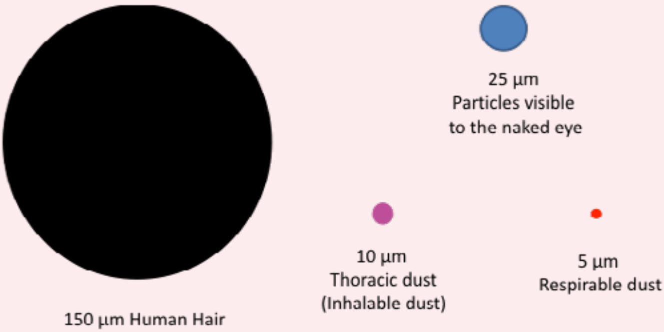
Gases

Toxic and / or asphyxiant

Flammable

Dusts

Comparative size



High air temperatures and humidity

Exposure limits

Levels should be reduced to the lowest level reasonable practicable and in any event below the Workplace Exposure Limit (WEL).

Good practice for the control of substances hazardous to health are laid out in COSHH Regulation 7, (7) and the Approved Code of Practice (ACOP) Guide for COSHH (L5, Sixth Edition 2013). Under the COSHH regulations, the HSE approves limits, as agreed and set by the EU, on the airborne concentrations that workers may be exposed to, generally expressed as the Workplace Exposure Limit (WEL). These limits are usually an average exposure time, weighted over an 8 hour period but with additional short term, higher concentration limits that must not be exceeded.

The following table lists the limits for the principal airborne contaminants met in the Crossrail works:

Contaminant (Source)		8 hour	15 minutes	Source for WEL/ exposure limits
Gases (Diesel plant, welding, cutting and burning)	Nitrogen monoxide (NO)	5 ppm	15 ppm	HSE & (British Tunnelling Society recommend designing NO to 3 ppm)
	Nitrogen dioxide (NO^2)	1 ppm	3 ppm	
	Carbon monoxide (CO)	30 ppm	200 ppm	EH40/2005 2nd Ed 2011
	Carbon dioxide (CO2)	0.5%	1.5%	
	Hydrocarbons (HC)	1 ppm	3ppm	
Dust (Fume) (Diesel plant, SCL, excavation, welding cutting and burning)	Inhalable (approximately ≤10μm)	10 mg/m^3	N/a	
	Respirable (approximately ≤5μm)	4 mg/m^3	N/a	
	PM1 (≤1μm)	0.15 mg/m^3	N/a	
	Respirable crystalline silica (approximately ≤5μm)	0.1mg/m^3	N/a	
	Elemental carbon	0.02mg/m^3		

Notes:

1. Where no WEL is designated by EH40, the requirements of COSHH apply together with the ALARP principle if a substance has been identified as being a carcinogen, mutagen or asthmagen (as described on the HSE web site).

2. Oxygen should be maintained above 19% (EH40 & BS6164).

3. Where shifts longer than 8 hours are worked, the WEL is reduced accordingly. The WEL for shift time (t) hours is given by:

$$WEL_t = \frac{8}{t} WEL$$

4. When determining exposure levels, allowance for background levels must be made. For example, at Camden in London the mean background level of NO is 0.17 ppm with peaks of around 1 ppm.

5. It seems likely that in the near future the EU (Directive 98/24/EC) will adopt a WEL for NO of 2 ppm and for NO^2 0.5 ppm.

6. The size fraction of dusts (and fume) are described in British Standards Institution Workplace atmospheres - Size fraction definitions for measurement of airborne particles BS EN 481 1993 ISBN 0 580 22140 7.

7. Fume from welding cutting and burning may contain metallic elements such as manganese (Mn – WEL 4 mg/m^3, STEL 0.5mg/m^3), nickel (Ni- WEL 0.5 mg/m^3), hexavalent chromium (Cr VI– WEL 0.5 mg/m^3), cobalt (Co – WEL 0.1 mg/m^3), and lead (Pb – WEL 0.15mg/m^3, under review).

8. Fume is the suspension of small solid particles built up through condensation from the gaseous state. (HSG 258)

9. In addition to the above, high air temperatures may be hazardous due to:

   - Loss of concentration leading to mistakes, which can lead to accidents.
   - Heat related illness and sometimes even death.

   In high temperatures, the human body controls its temperature largely by the evaporation of sweat. Consequently, the sensation of warmth is governed by the dry bulb (DB) temperature of the air, the wet bulb (WB) temperature (a measure of humidity) and the air velocity. These parameters may be combined into an index of heat stress.

10. There are no legal limits on the temperatures that people may work in, though the US Threshold Limit Values may be used, which are based on the Wet bulb globe temperature (WBGT) index (used to estimate the effect of temperature, humidity and wind speed on humans). BS6164 recommends that the wet bulb temperature should be less than 27^{0}C, a similar recommendation being given by

HSE in the Work in Compressed Air Regulations. In ‘the prevention of heat illness in mines, the HSE recommends that if the WB temperature rises above 32^{0}C, then substantial extra control measures should be implemented.

11. Radon is a chemically inert gas that occurs naturally in the environment as a result of the radioactive decay of radium, present in trace quantities in many types of rock. Two isotopes, radon-222 (radon) and radon-220 (thoron) may be found in radiologically significant quantities in air. Quantities in open air are low, but concentrations can readily increase by two or three orders of magnitude in enclosed spaces with restricted ventilation rates. The residence time of air in the workplace is important due to the rate of radioactive decay.

    A long residence time may allow equilibrium of decay products to occur.

12. Glauconitic sands may be experienced in the tunnel horizon with significant levels associated with depletion in oxygen in the working environment. The greater risk being in small heading work and cutter head intervention. In all cases of this work, gas monitoring should be carried out prior to entry and a permit to work system followed. However, recent research at Imperial College, undertaken for Thames Water’s Tideway Project, has thrown doubt on the involvement of Glauconitic sands in hypoxia (oxygen depletion).

Other hazards that are not mentioned in this guide but would also need to be assessed, managed and monitored include; noise, vibration and manual handling.

Part A – Hazard Identification

Section A1 – Tunnel boring machines (TBM's)

Tunnel boring machines are used to excavate tunnels and although largely powered by electric motors, may include ancillary diesel engines. Operatives, materials and supplies are also transported to and from the work area by diesel powered locos.

The most likely hazards during tunnel boring activities are:

Dust

Quartz (SiO2) exposure can cause lung cancer and other serious lung conditions and may be present in the strata, foamed concrete and concrete rings

Chromium VI exposure can cause significant health issues affecting the respiratory tract and skin and may be present in concrete.

Ferrous Sulphate exposure can cause serious lung conditions and may be present in cement and foamed concrete.

Strata Gas

Flammable gas (methane, hydrogen sulphide) can be emitted naturally from the strata or from other sources such as peat, river silts, landfills, sewage and other contaminated ground, including from spillages of petroleum spirit.

Methane can occur naturally in soils at very low concentrations, as can carbon dioxide, although concentrations of the latter of up to 20% are not uncommon. In addition, the gas flow may be dependent on factors such as atmospheric pressure and/or its rate of change, as well as rainfall.

Toxic gases, such as carbon dioxide, may be emitted from the strata or released from abandoned mine workings, made ground or landfill sites. Small volumes of ammonia, detectable by odour, have been reported to be emitted in TBM drives when boring through concrete during the use of ground conditioning fluid.

Oxygen deficient air can form wherever it is confined in the presence of chemical or biological processes that require oxygen.

Exhaust gases and fumes

The HSE state that, diesel engine exhaust emissions (commonly known as 'diesel fumes') are a mixture of gases, vapours, liquid aerosols and other substances , made up of particles (particulate matter). They contain products of combustion, including:

- Black carbon (soot)
- Nitrogen
- Water
- Carbon monoxide
- Aldehydes
- Nitrogen monoxide – in sunlight rapidly decomposes to give nitrogen dioxide; in tunnels this does not occur as quickly
- Nitrogen dioxide
- Sulphur dioxide
- Polycyclic aromatic hydrocarbons

The carbon particle or soot content varies from 60% to 80% depending on the fuel used and the type of engine. Most of the contaminants are adsorbed onto the soot.

Heat

Energy from machines, that is not used during 'useful' thermodynamic work (breaking and lifting material), will appear as heat. Diesel power is considerably less efficient than electric power. As a rough guide, 100kW of machine power in airflow of 10m3/s would increase the dry bulb (DB) by 3^{0}C and the wet bulb (WB) by 4.5^{0}C.

The temperature of strata rises with increasing depth (in the UK around 2.5^{0}C/100m but depends on geology and tectonic history).

Some heat may be stored in the machinery and surroundings, with the remainder transferred to the ventilating air either directly or by the evaporation of water.

Section A2 - Sprayed concrete lining (SCL)

Following excavation, tunnels are lined using sprayed concrete and other secondary linings. Spraying equipment is generally electrically powered during spraying, but by diesel engines during movement. Concrete may be delivered by diesel remixers and operatives, materials and supplies may also be transported by diesel powered locos or vehicles.

The most likely hazards are:

Dust

Wet-mix sprayed concrete lining may contain:

- Cement - ~20% quartz (SiO^2)
- Microsilica 100% quartz (SiO^2), (≤1µm)
- Aggregates - up to 95% quartz (SiO^2)

- Admixtures
- Liquid alkali-free set accelerators
- Fibres

After-treatment (waterproofing and fireproofing)

With SCL, the total inhalable dust had been found to be the principle hazard, with in the order of 1000mg/m^3 being reported. However, respirable and quartz concentrations are generally been below the appropriate Workplace Exposure Limit - WEL (10 mg/m^3, 4 mg/m^3 and 0.1 mg/m^3 respectively) when using adequate ventilation.

Preparatory work for installation of the secondary lining can create significant levels of dust and require an element of cleaning by sweeping or using air lances to prepare the surfaces, both of which are known to be leading causes of raising dust into the atmosphere.

Heat

Concrete setting is an exothermic reaction, warming the immediate environment.

Contaminants

The airborne contaminants are:

- CO, CO^2, methane and reduced O^2 levels – due to little natural ventilation
- NO, NO^2 – due to plant movement and ancillary works

Section A3 – Diesel plant

Diesel engine exhaust emissions (DEEE) are the main hazard in the use of diesel plant and are made up of a complex mixture for gases, fumes and particulate matter.

The most likely constituents that may be experienced are as follows;

- carbon monoxide
- carbon dioxide
- nitrogen oxides
- sulphur oxides
- hydrocarbons (polycyclic aromatic hydrocarbons, alcohols, aldehydes, ketones)
- soot including elemental or black carbon – this is deemed to be the carcinogenic constituent of DEEE

Despite the large number of hazardous compounds that can be present in DEEE, the key compounds that individuals may be exposed to, that may have an adverse health effect would likely be nitrogen oxides and soot (elemental carbon).

Complaints by operatives about DEEE exposure are typically associated with exposure to nitrogen oxides and their effect on the body. Nitrogen Monoxide (NO) is a toxic, odourless gas and converts to nitrogen dioxide (NO^2) by reacting with oxygen (O^2) in the atmosphere in the presence of sunlight. Nitrogen Dioxide is a toxic gas with an acutely irritating taste. Even at very low levels, below legal limits, it causes irritation to the mucous membranes, namely the nose, eyes and throat. This can be felt initially in the eyes, before leading to coughing and breathlessness. However, in the absence of sunlight the half-life of the NO conversion to NO^2 is typically one week. Therefore in a ventilation tunnel environment the rate of reaction is insufficient to significantly change the results of the concentrations of NO and NO^2.

In 2012 the International Agency for Research on Cancer (IARC) reclassified DEEE as a Group 1 carcinogen. The current understanding is that this carcinogenic property is due to the elemental carbon in the soot of DEEE. This acts like a sponge and transports various hydrocarbons, such as polycyclic aromatic hydrocarbons, and other chemicals into the lungs.

Section A4 – Welding and burning

Fumes

Hot works such as welding and burning on the TBM will give rise to metal fumes. Where welding or burning is of mild steel, there is a potential to produce iron oxide fume. Exposure to metal fumes such as these can lead to pneumonia, occupational asthma, reduced lung function and lung irritation.

Welding fume typically contains manganese, nickel and chromium with up to 80g/kg produced per mass of electrode consumed. As well as fume contaminants from the surface, coatings including oil and grease are also released.

Where the metal work has been coated then the hazards may be significantly increased. Galvanised steel produces zinc fume, which can cause zinc fume fever – a serious lung disease which can take several days to develop.

Welding or burning of stainless steel leads to exposure to nickel and hexavalent chromium (CsVI). These are both asthmagens and potent carcinogens and exposure must be carefully controlled.

Sometimes the metal will be coated with a paint which cannot be removed by normal means prior to burning. If this is the case then consideration must be given to the pigments and chemicals inside this paint. A common example would be anti-corrosion paints, which contain zinc phosphate pigments. This paint may result in similar effects to that experienced when burning galvanised steel. Other coatings may produce cyanide and a detailed risk assessment is required to identify the likely hazards and control measures put into place.

Section A5 – Other tunnelling works (including cutting)

Other works include:

- Removal of concrete segments at tunnel enlargements:

  Creates dust which may contain crystalline silica

- Scabbling of concrete track slabs:

  Creates dust which may contain crystalline silica

- Hand mining:

  Risk of local pollution from powered hand tools and high heat stress due to confined space and difficulty in applying ventilation.

Part B – Controls

Section B1 – Elimination

General

Although elimination of any hazard should be the first priority, as it completely removes the potential harm the hazard presents, exposure to dusts cannot be fully eliminated due to the nature of mining activities. The focus should therefore be on reducing the risk of exposure to as low as reasonably practicable (ALARP). Similarly, it is currently not possible to eliminate all diesel machines from tunnelling or hazardous airborne gases. The focus again must be to reduce their presence within the tunnel and implement engineering controls – see below.

Access to the worksite should be restricted, with the establishment of zones; an exclusion zone where access during the spraying and curing process and excavating are prohibited and a restriction zone where access is restricted to authorised personnel only. The rear edge of the restricted zone should be moved far enough from the face that airborne contaminant concentrations are insignificant.

TBM'S

Where appropriate:

- Install precast concrete segments.
- Cast lining in situ
- Use ready mix concrete rather than mix on site.
- Minimise the requirement to mill by careful control of spraying

Diesel plant

Consideration should always be given to prevent the use of any equipment that produces hazardous emissions in the underground environment. Obviously the demands of other drivers, such as safety and production, will govern what is practicable. Where plant is required and cannot be replaced, rather than eliminate the plant altogether consider eliminating using the plant in high risk areas.

The use of diesel generators underground should be avoided, where possible, by careful planning and using mains power wherever available.

Welding and burning

Wherever possible, consideration must be given to eliminating the need for welding or burning. Alternative means of achieving the same goal must always be considered, be that mechanical cutting or fixing and pre-fabrication off site. These alternatives may introduce other occupational health hazards, so it is important to choose a method that works with the specific environment and existing control regime.

Other tunnelling works

Segment removal

Removing segments to side passages for breaking and using crushers with integral dust suppression systems is much more effective than breaking segments in the main tunnel and suppressing dust with hand sprays.

Scabbling

Processes such as scabbling may use large diesel plant which shields the operators from the main airflow, whilst directly exposing them to exhaust emissions. Where possible, operators should be on the upwind side of the plant or local devices to increase air speeds must be used.

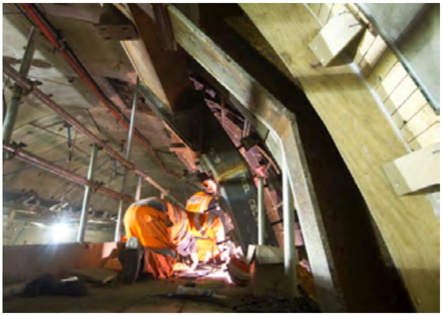
It is preferable to use the type of machine with an on-board dust collector.

Hand Mining

Hand mining is more strenuous than mechanised mining and often involves working in confined spaces. Where heat is a problem, workers will experience a greater heat stress and be at concomitant greater risk of accidents. Small powered hand tools are often used and care must be taken to ensure there is sufficient ventilation to control any diesel or other emissions

Hand mining in large opening

Where space is limited, it is often difficult to ensure that the area is fully ventilated as duct size has to be minimised, therefore, restricting the flow. Inadequate ventilation can lead to dead spots allowing any contamination to collect.



Working in limited space

Forced ventilation is generally preferable in these situations as it provides a higher velocity than with exhaust, scouring the area to dilute any contamination and reducing the heat stress index of the environment. Therefore, the use of hand mining should be minimised and replaced by mechanised mining, where possible.

Section B2 – Substitution

Diesel plant

For the underground environment, the only viable substitution for diesel powered plant would be electric (mains or battery but not generator) or hybrid power (diesel and electric).

Such machines, already available include:

- Locos
- Excavators
- Spray machines

Use of petrol powered plant must be avoided as it greatly increases the risk of Carbon Monoxide and can be potentially lethal.

Substitution of DEEE should be concentrated on:

- Cleaner burning, low sulphur fuels
- Use of hybrid/diesel engine equipment suitable for the job
- Consider smaller engine equipment – large engines that run a lower end of their power range will, over time, become less efficient and increase the levels of emissions released.

Welding and burning

The best way of controlling the potential exposure to fumes, is to consider the location where the operation is being performed. The risk of exposure to fume is significantly reduced when welding and burning is performed in the fresh air environment rather than underground. Whilst the worker performing the hot work requires the same controls measures as those required underground, there is reduced risk of exposing other people in the tunnel.

Other tunnelling works

Engineering controls include:

- Crushers and scabbling machines with integral dust collectors
- Local ventilation to direct air to operators and scour the small working areas typical of hand mining

Dust controls:

- Eliminate use of broom and replace with vacuums.

Section B3 – Engineering

Diesel plant

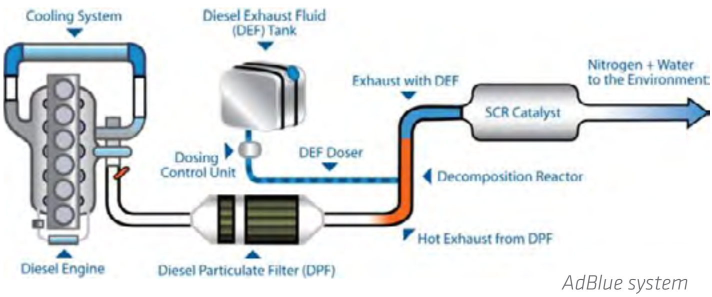
Engineering control of DEEE is an effective means by which any potential exposure can be mitigated. Engineering controls can be on the plant itself, or in the tunnel environment. The controls that should be considered for use on the plant include:

- All plant should be fitted with Diesel Particulate Filters (DPF's)
- Where possible, plant should be fitted with Diesel Exhaust Fluid (DEF) systems (also known as AdBlue)
- The positioning of the exhaust stack is an important consideration, particularly in tunnels. Exhausts of locos should always be away from the walkway. This is most relevant when the loco is in Tunnel Boring Machines (TBM).

Diesel Particulate Filter

Machines should be fitted with a suitable diesel particulate filter which removes particulate mater from diesel exhaust by physical filtration. The most common type is a ceramic (cordierite or silicon carbide) honeycomb monolith. The filtration efficiency of diesel particulate filters is >99% for solid matter. Since diesel particulate matter (DPM) has a non-solid portion, the total efficiency for DPM is lower than this and is reported to be at >90%.

These systems require regular maintenance to ensure that they are working efficiently. Some engines will self-clean these filters by blowing them clear. This is a process that must be managed so it is only performed in safe places, where exposure is limited.



AdBlue system

Selective Catalytic Reduction

In order to achieve the lowest levels of NO emissions, it is likely that the engines will be using Selective Catalytic Reduction (SCR) in order to meet the appropriate latest EU standard. SCR requires the use of a reagent, called AdBlue, which is injected from a dedicated tank into the exhaust pipe, in front of the SCR catalyst. As it is heated in the exhaust, the AdBlue changes into ammonia (NH^3) and carbon dioxide (CO^2). When the nitrogen oxide (NOx) gases from the exhaust pipe react inside the catalyst with the ammonia, the NOx molecules in the exhaust are converted into harmless nitrogen and water, which is released to the atmosphere as steam. The process is shown above.

These systems require regular maintenance to ensure that they are working efficiently, and the AdBlue solution must be regularly topped up.

Welding and burning

Welding and burning underground should never take place without two forms of engineering controls in place. These are:

- The provision of fresh air. This is to eliminate the health impact of hot work gases any asphyxiant effect that may occur by fumes and gases displacing oxygen
- Local Extraction Ventilation (LEV). This captures the harmful fumes and gases produced by the hot work, filters out the contaminants and vents the cleaned air back into the workplace

These two forms of ventilation work in tandem with each other to minimise exposures to these fumes. Where a filtration unit cannot be used, fans and semi rigid ducting can be used to capture and remove fumes from a worker. Give serious consideration to where these fumes are moved to, as it may be that you are simply moving the problem to another location.

Cutting and burning works should employ a small dust filter (3 m^3/s) classified as L, M (Class L must not allow more than 1% of extracted dust to pass out of the filter to a "maximum allowable concentration" greater than 1 mg/m^3). Class M must not allow more than 0.1% of extracted dust to pass out of the filter to a "maximum allowable concentration (greater than 0.1 mg/m^3)

Section B4 – Ventilation

Ventilation systems need to account for the advancement of the works i.e. repositioning as the work advances and the introduction of temporary bulkheads.

TBM Ventilation

The ventilation requirements depend on:

- The number of machines,
- The rated power of the machines,
- The work rate of the machines,
- The emissions from the machines (given by EU Directive 97/68/EC),
- If it can be shown that sufficient ventilation is available to dilute the NO component, then all other components of the emissions will be below their respective WEL's,
- The intake pollution (in Central London this averages around 0.2 ppm NO)

As a guide, 100 kW of power operating for 10 hours in Central London requires 20 m^3/s of air to ensure that the NO concentration is below 3 ppm.

Background levels of particulate matter measured by the London Air Quality Network would also need to be included in the calculation.
http://www.londonair.org.uk/

Note: During Crossrail construction, air was blown into the machine from the surface by a two stage axial fan through 1.6m flexible ventilation ducting to the rear of the tunnel boring machine. The choice of the two stage fan provided flexibility in subsequent station construction as it allowed the stages to be split and a single fan to be used at one location. Local ventilation on the machine was provided by an extraction system that vented outbye of the incoming fresh air.

Workshop ventilation on the TBM requires careful consideration, as a number of dead air spots can occur on the machine where the flow of air is displaced by the size of cabinets and other plant. Furthermore, the problem of heat load when driving through foam concrete needs to be given sufficient consideration to ensure the comfort of operatives.

View of ducting system at rear of TBM

1.6 m Layflat ventilation duct to TBM

In order to improve ventilation to dead areas of the TBM, local systems to increase air flow and/or velocity may need to be employed. Ad-hoc systems involving local piercing of the TBM ventilation ducting so that air could circulate around the workspace have been used historically, but are not recommended as this method risks recirculating air through the TBM.

Ad-hoc air distribution system

Typical venture air mover

Venturi air movers can be employed, fed from the compressed air main in the tunnel and capable of inducing airflows without the risk of recirculation.

Ducting secured to protect it from damage by passing vehicles.

Following the creation of the tunnels using the TBM's, passing places for plant are often created; however, the restriction in the tunnel area may result in damage to ducting. To counter this, attempts should be made to secure the ducting away from harm, without restricting airflow.

SCL Ventilation

Ventilation systems described below to be used in order of preference:

- Through ventilation.
- Exhaust ventilation.
- Forced exhaust overlap ventilation

Ventilation is used to dilute gases, dust and heat. While ventilation should provide all the necessary control of gases and heat, it is unlikely to be sufficient to control dust, particularly in SCL works, unless the airflow carries the dust away from the workforce.

The design of a ventilation system will be based on the anticipated hazards. Once installed, confirmation that the system is adequate must be obtained.

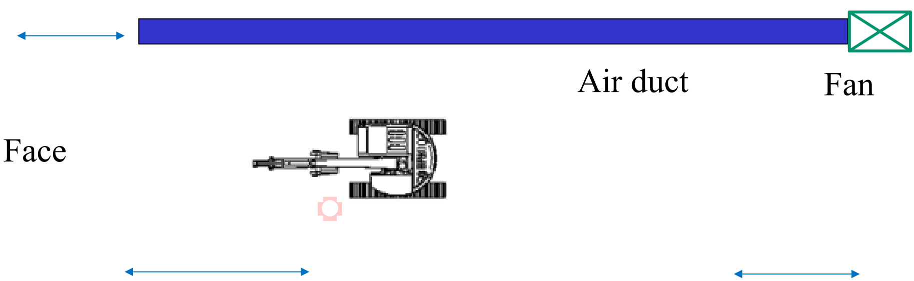
Ventilation can be provided by using fans connected to ducting to either force or exhaust air from the surface (or as close to the surface as is possible).

Ducted airflows require the largest diameter of ducting to be efficient. The resistance of a duct increases inversely with the fifth power of the diameter.

Ventilation systems must be installed correctly. In ducted systems, there should be no tight bends close to the fan. However, since it is often not possible to install fans aligned with a tunnel, a pragmatic approach should be taken ensuring that the fans are able to provide the required airflow with the duct layout.

Equipment should not be installed close to ventilation systems causing them to be restricted. Ducts must be maintained and, if damaged, replaced or repaired using suitable materials as soon as possible. Care should be taken to avoid contaminating inlet air.

Fan at tunnel entrance with steel ducting



Through ventilation

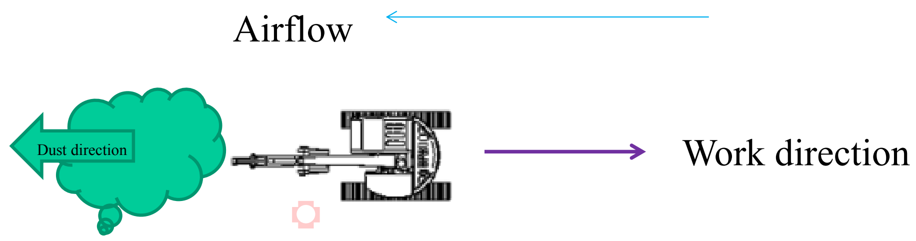
Through ventilation offers the best control for dust, as the problem is moved elsewhere away from the work area. However, this is only likely to be used in remote areas where dust produced will not affect others in the tunnel.

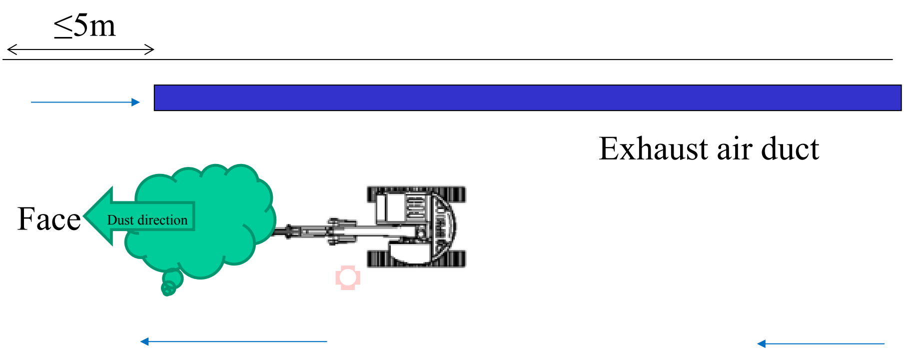
Exhaust ventilation

Exhaust ventilation is best for dust control in a tunnel with a dead end, or where a bulkhead can be put up - providing there is sufficient airflow to achieve a velocity of 0.5 m/s1. If the fan is outbye, the duct must be rigid or semi-rigid, designed to withstand the fan pressure. Alternatively, the fan can be at the face and layflat ducting may be used. A de-duster may be needed to prevent dust from causing problems elsewhere. If at the surface, room must be found for the de-dusters.

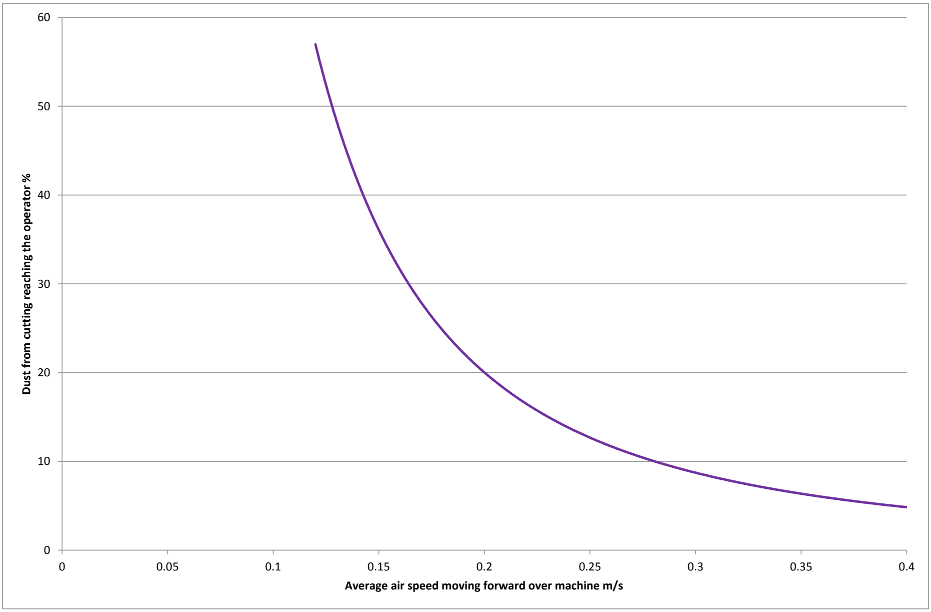
The Crossrail project involved the driving of pilot tunnels and the following shows a typical ventilation layout using an overlap system for the sequence pilot tunnel excavation and enlargement.

Through ventilation

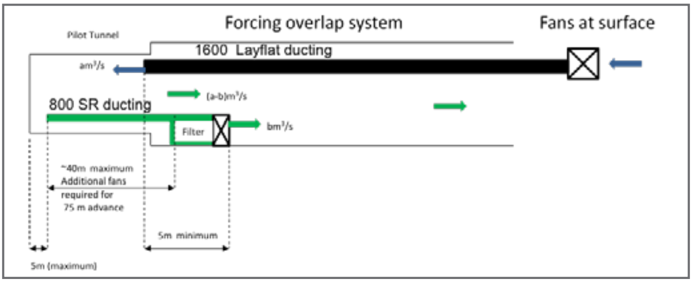




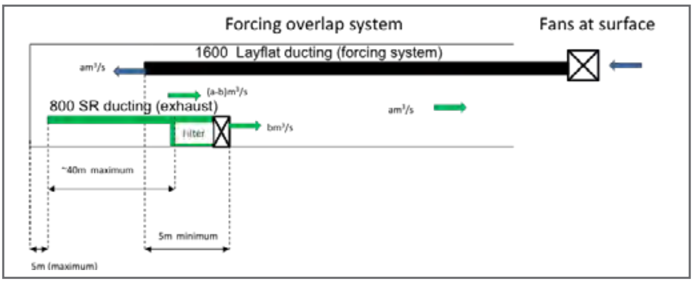
Exhaust ventilation



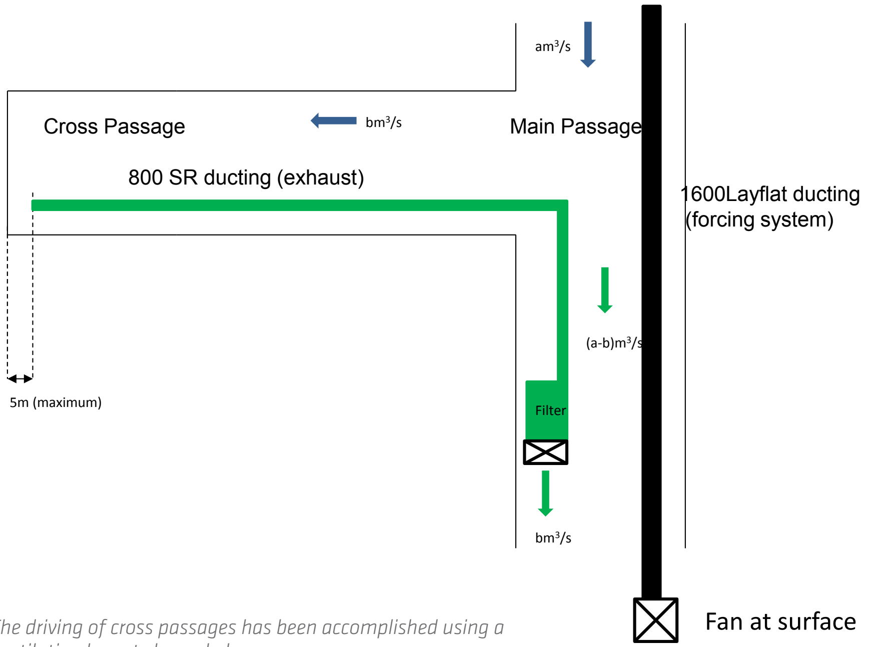
National Coal Board data showing dust back-up against air velocity.



Pilot Tunnel



Enlargement



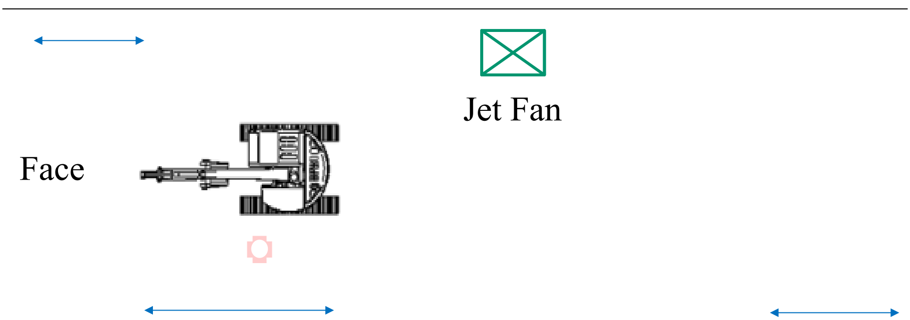
The driving of cross passages has been accomplished using a ventilation layout shown below.

Forced ventilation

In open ended tunnels and those with multiple shafts, jet fans may be used.

Jet fans are more efficient than ducted systems particularly when assisted by a natural ventilation flow, however, the direction of natural flows may change over a 24 hour period.

Jet fans may be used to increase airflows in tunnels where a ventilation circuit exists. Such fans create airflows greater than the air passing through the fan. However, they do not add air in blind tunnels but can increase local air velocities and air mixing.



Jet Fan mounted on tunnel wall

Diesel plant - Ventilation

Engineering controls must also be centred on the provision of fresh air and the recirculation of air. The number of workers, the amount of plant and the condition of plant must all be taken into account when evaluating the requirements of the ventilation system.

Consideration must be given to the stagnation of air in sites, particularly as work progresses and previously open areas are closed off. Typically DEEE emissions are hot and therefore rise to the roof space. This can be a particular problem should there be work at height at the time. However, since DEEE contains a mixture of gases denser than air (at normal temperatures) it may sink to ground level once cooled. Therefore an even distribution of air must be maintained throughout the work site.

The ventilation required will depend on:

- The number of machines and plant equipment
- The rated power of the machines
- The work rate of the machines.
- The emissions from the machines (given by EU Directive 97/68/EC)
- The evidence of sufficient ventilation available to dilute the NO component and that all other components of the emissions will be below their respective WELs'.
- The intake pollution (in Central London this averages around 0.2 ppm NO)

As a guide, 100 kW of power operating for 10 hours in Central London requires 20 m^3/s of air to ensure that the NO concentration is below 3 ppm.

Section B4 – Dust control

Sprays

Sprays should be used to minimise dust from:

- Excavation
- Milling
- Roadway dust

Suppression by high pressure water sprays used in cannons and mist cannons is claimed by manufactures to be typically around 80% effective. However, independent research has shown that the maximum efficiency achievable is 40% and fine droplets need to be close to the dust source and water/airflow ratio should be 0.1%, (i.e. water flow in l/s equals airflow in m^3/s); these conditions are generally not achieved in these devices.

Water cannon (spray just visible as a haze)

Atomised spray ring

Sprays directed at the tip of machine tool consistently apply water at the point where dust is made.

Spray system for pecker

Hand held sprays produced from a hosepipe are less effective and efficiency is dependent on the attention paid by the operator.

Use of hand held spray

Roadway dust (trackout)

Dust deposited by traffic in the tunnels is remobilised or re-suspended by the movement of following traffic. To control this source, roadways should be regularly damped down and swept.

Mechanical brush sweepers are effective at removing coarse materials and pollutants. They are less effective removing fine materials.

High-efficiency street sweepers and associated operations (vacuum and scrubbers) may increase the proportion of total solids removal from 30 – 70+%.

Damping down has the potential to reduce airborne PM10 (particulate matter up to 10 micrometers) concentrations by up to 30%.

TBM's

Conveyor dust

Dust from conveyors can be a problem where:

- Material is dry
- Transfer points are unshielded and/ or exposed to high air velocities
- Conveyors are poorly aligned and/or maintained

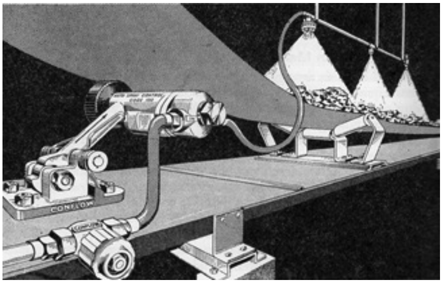
Solutions are:

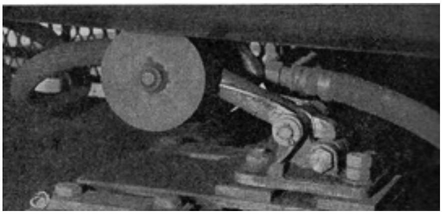
- Keep the material moist using automatic sprays (shown right

Prevent dust from being carried back on the return side using a system of scrappers (shown below)

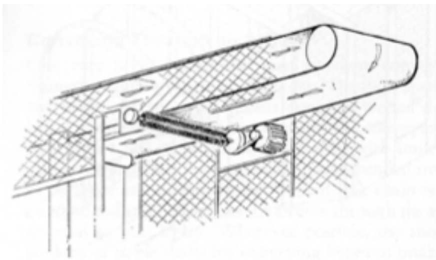
Dust scrappers

- Ensure transfer points are covered.
- Ensure conveyors are aligned correctly

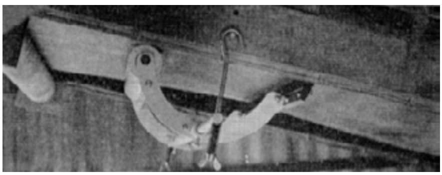




Automatic spray control valve on a belt conveyor



Motorised



Spring loaded

SCL Dust Control

De-dusters

There are two principle types of de-dusters used in tunnelling, both of which range in capacity from ~4 m^3/s to ~50 m^3/s:

Wet de-duster

Dust laden air is discharged by a venturi type air nozzle or fan and mixed with a curtain of small droplets, which wet the dust particles. At the discharge, air, water and dust particles are separated by centrifugal action, wet particles being pushed against the wall and the air discharged outside.

Some de-dusters are equipped with a washed filter screen. The water circuit is generally closed circuit. Some types require an external fan.

The wet de-dusters are smaller in size than the equivalent dry de-duster but may have lower capture efficiency (95% cf 99.9%).

Wet de-dusters suffer from a build-up of cement in the water recirculation system as well as on the integral fan. Good maintenance is essential.

Wet de-duster at surface

Dry de-duster

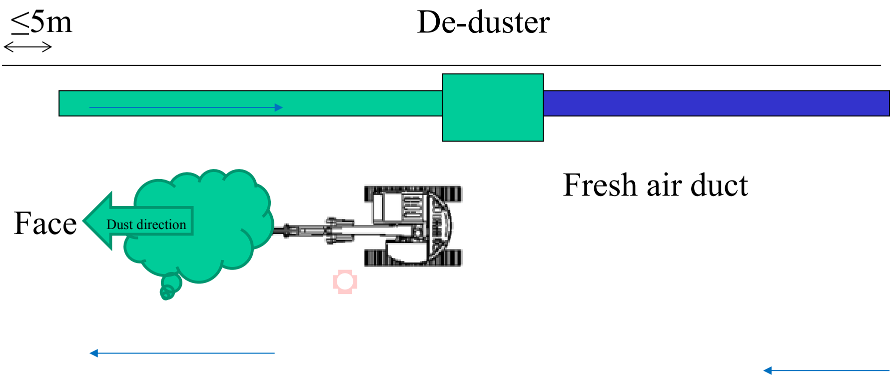
Dust laden air is drawn into the filter body via a ductwork system. At the inlet of the de-duster, a grid is used to eliminate larger particles, as well as to distribute the air for optimal passage through a bank of filter elements. Dust deposited on the surface of the filter elements is cleaned by a pulse of compressed air operating around every 25s. The dust shaken from the filters falls into a hopper, from where a worm screw transports the dust through an airtight valve.

The dust is collected in an external container and can be safely removed, although careless transportation may result in dust being returned to the ventilation.

All types require an external fan.

Dry de-duster underground

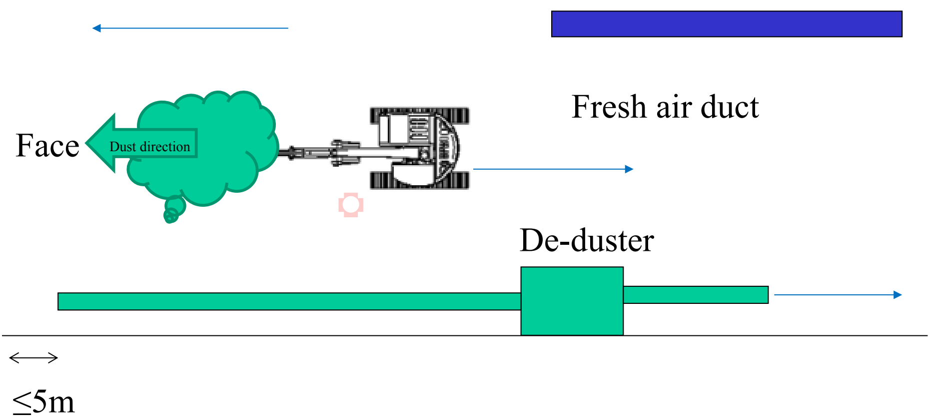
De-dusters can be used with a simple exhaust ventilation system, the de-duster being underground or at the surface.



De-duster with simple exhaust ventilation

Alternatively, de-dusters may be used with a forcing exhaust overlap ventilation system, the two ducts being on opposite sides of the roadway. Fresh air is forced to the face and dust laden air collected by the exhaust system as shown below. To avoid recirculation, the discharge of the forcing system must be at least 5m inbye of the discharge from the exhaust. The forcing system provides fresh air to the workforce and the exhaust pulls air through the dust producing region. The forcing system delivers about twice as much air as exhausting systems.

A simple form of dry de-duster consisting of a Bondina filter panel at a fan discharge can be used with some effect. The panel requires charging regularly to maintain efficiency and to reduce the risk of reducing airflow through the fan compromising the control of contaminants elsewhere.



Forced exhaust overlap ventilation

De-dusters on earth pressure balance machines in the UK are a new concept and in order to provide advice to the appropriate level of de-dusting the machine supplier should provide evidence of what has been installed


Bondina filter panel

on previous machines to determine selection – see below.

The choice will be based on the dimensions of the unit and the space available in the tunnel. The wet systems require regular cleaning of the water tank, nevertheless, a build-up of sprayed concrete on the internal impeller can cause failures.

The biggest difficulty with the use of de-dusters is the relatively small capacity, necessitated by the demands of tunnel space compared to the large tunnel cross section. Although using exhaust ventilation enables the de-duster to be sited at the surface, the conflicting demand on the available space within the confines of many construction sites can make the use of large units unfeasible. A minimum air velocity of 0.5 m/s is required to prevent dust moving back against the airflow towards the operator.

Diesel plant de-dusters

Providing the diesel plant is fitted with the appropriate filters, no de-dusters are required for the control of the diesel emissions. Clearly, this is not the case for the dust created by the machines activity which may be from excavation, breaking or transport of concrete.

Projekt	Name / Location	Typ	Ø [m]	A [m²]	Enstauber-leistung [m³/min]	Factor m³/min/ m²
S-705	Crossrail C300 London	EPB	7,08	39,4	400	10,2
			7,08	39,4	800	20,3
S-547	NKWT, Germany	EPB	10,11	80,3	500	6,2
S-512/514	Brisbane, Australia	EPB	12,45	121,7	1050	8,6
S-400	Joshimath, India	Double Shield Hardrock TBM	6,48	33,0	300	9,1
S-467	New York, USA	Double Shield Hardrock TBM	6,83	36,6	400	10,9
S-487	West Drainage Tunnel	Double Shield Hardrock TBM	7,21	40,8	400	9,8
S-201/202	Guadarrama	Double Shield Hardrock TBM	9,51	71,0	600	8,4
S-373	Cabreara	Double Shield Hardrock TBM	9,69	73,7	800	10,8
S-612/614	Prag, Czechia	Double Shield Hardrock TBM	9,99	78,4	800	10,2
S-303	Wienerwald, Austria	Single Shield TBM	10,35	84,1	800	9,5
S-256	Islisberg, Switzerland	Single Shield TBM	11,80	109,4	800	7,3

Empirical Valkues HK: 10-12 m³/min per m² Tunnel Face Area at Hard Rock TBMs / open Grippers

Section B5 – Selection of locos

All non-road mobile machinery shall:

- use fuels with a sulphur content equivalent to ultra low sulphur diesel fuel meeting the specification within EN590:2004:
- comply with the current or immediately previous EU Directive Staged Emission Standards; and
- vehicles which are not EU stage III (b) or IV, and the power output is over 37kW, should be fitted with an after-treatment device(s) as stated on the approved list managed by the Energy Saving Trust. Ongoing conformity to a performance standard to be defined and ensured through a programme of on-site checks which should be recorded and reviewed.

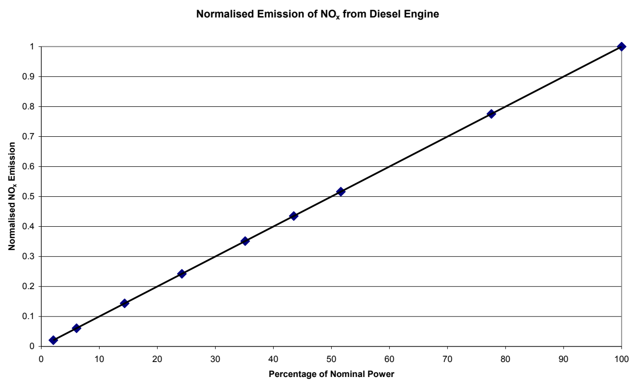
The soot/particulate filters are the key to the control of diesel fume in the tunnel. Part of the regular maintenance of tunnel locos should include regular back pressure testing of filters with the criteria being set for the removal, cleaning and regeneration.

Machine Selection

Machines should be selected on the basis that their emissions conform to the latest EU regulations, which in the UK are given in 'The nonroad mobile machinery (emissions of gaseous and particulate pollutants) Regulations 1999 1053'. The table below is an example of the emissions that must be achieved for vehicles introduced after the end of 2014

Machines should not be oversized as larger machines that run at low power are less efficient than smaller machines running closer to full power as shown below.

Stage IV Standards for Non road Engines						
Cat.	Net Power	Date	CO	HC	NO_x	PM
	kW		g/kWh			
Q	130 ≤ P ≤ 560	2014.01	3.5	0.19	0.4	0.025
R	56 ≤ P < 130	2014.10	5.0	0.19	0.4	0.025



Section B6 – Administrative measure

Restricted access

During tunnelling, exclusion zones (no people) are used to protect against falling debris and restricted zones (authorised access only) are used to minimise exposure to the dust.

During spraying, exclusion zones (no people) are used to protect against falls of SCL and restricted zones (authorised access only) are used to minimise exposure to the dust. The figure below shows the type of restricted zone, although the absence of work at the time the picture was taken accounts for the large number of people within the zone.

View of restricted area (no work underway)

Diesel plant

Control over DEEE is best achieved using engineering controls; however these should be managed using administrative measures.

Because the effectiveness of DPFs and catalytic convertors are dependent on engine temperature, provision must be made to enable engines to warm up before use. A documented startup procedure should be followed, particularly for plant that hasn't been used for a period of time. Wherever possible this should not be performed underground.

Where a fleet of plant is available for use, this should all be evenly used or regularly run to ensure all engines are running efficiently.

There should be restricted access near diesel plant and operatives should avoid standing in the exhaust stream, as the exhaust carries the highest concentration of contaminants. Keep cabs protected by keeping windows up and regularly check the efficiency of the in-cabin air filters and replace if required.

Ensure site emergency equipment and welfare arrangements are not placed near diesel plant operations.

Welding and cutting

Hot works should be performed in areas of restricted access. This should be clearly marked with the PPE requirements at entry points. Because hot works release gases and fumes into the workplace, it is easy to be exposed to these without realising

Section B7 – Personal protective equipment

The use of personal protective equipment is generally regarded as a last resort, but where ventilation and dust suppression cannot eliminate the hazards it should be used as a control measure. The primary PPE is respiratory protective equipment (RPE) the type of which will be determined by occupational hygiene monitoring. The RPE includes respirators and dust masks. The following table details the type of respirator available together with the protection provided.

Whichever type is used, if the mask does not make a tight seal all the way around the face the operatives may breathe in contaminated air that leaks from the edges of the face seal. Most respiratory protection comes in a variety of styles and sizes and fit people differently because people's faces do not have uniform shapes. Training should be provided on how to correctly put the mask on and how to wear it correctly. This information should be provided by the supplier of the respirator.

Importantly, tight fitting respiratory protection requires fit testing to ensure an adequate fit to the face and cannot

British Standard	Type of Respiratory Protective Equipment (RPE)	Hazards which the Respiratory Protective Equipment will Protect Against.	Class or Filter	Assigned Protection Factor
BS EN 149	Particle filter which covers the nose, mouth and chin	Only protects against dust particles NOT against gases or vapours	FFP1 FFP2 FFP3	4 10 20
BS EN 140	Half mask cover the nose, mouth and chin. It is usually made of rubber or silicon and has replaceable filters.	The mask can be fitted with a series of replaceable filters to protect against dust hazards and gas hazards	P1 P2 P3 Gas Gas+P3	4 10 20 10 10
BS EN 136	Full mask covering all the face. It is usually made of rubber or silicon and has replaceable filters	The mask can be fitted with a series of replaceable filters to protect against dust hazards and gas hazards	P2 P3 Gas Gas +P3	10 40 20 20
EN 12941	This is a positive pressure full face hood/helmet	This mask/helmet can be used to protect against dust particles and certain gases/vapour hazards	TH 1 TH 2 TH 3	10 20 40

be used with facial hair. Where dust is present or likely to contain silica it is the recommended to use at least class P2 or P3 protection respectively. P3 protection should be used in the restricted zone and during cleaning activities for SCL works.

For those working within the restricted zone during spraying, full face hoods are used, as shown in the figure on Page 10.

For those elsewhere and during excavation, disposable masks similar to that shown below are the most common form used. Such masks are designed for use over a single shift and may be fitted with a valve. The benefits of the valve type are claimed to be:

- Reduces exhalation effort
- Cooler to wear
- Stays comfortable for longer
- Less likely to mist up eyewear

Disposable tight fit mask without valve

Diesel engine exhaust emissions

Because of the varied chemicals that make up DEEE, it is very difficult to find RPE that would provide sufficient protection. Soot/Elemental Carbon can be controlled using a standard Particulate (P) type mask; however for the complex other gases this should be a combined filter (ABEKP) type. This type of PPE should only be used in an emergency, and not as a means of enabling the continuation of work in a contaminated atmosphere.

As with all respiratory protection, users of this RPE must be face fit tested for the specific type of mask they are provided (make, model and filter specific).

Welding

Where ventilation is insufficient by itself, respiratory protection is an integral form of control. Where work is being performed on galvanised or stainless steel, these should be considered a mandatory control measure, in conjunction with LEV.

Because the majority of the ill health effects associated with welding are related to the metal fume itself, the respiratory protection should be a particulate (P3) filter. The minimum standard would be a disposable mask, but for high risk activities consideration should be given to using a positive pressure air fed hood, with a belt mounted pump.

Where there is a confined space, this may require the use of supplied air respiratory protection. This connects to an airline which feeds air from an external source.

Part C – Monitoring

The monitoring of the control regime is an integral part of the process, as it is the means by which employers can ensure adverse effect on the worker's health are being determined

Section C1 – Air quality

General

Wherever workers are required to use respiratory protection, air quality monitoring must be performed to evaluate the concentrations they are exposed to. This will ensure that the ventilation is working effectively, and that the masks are of a suitable type and filter grade.

Monitoring must include personal pumped sampling. This involves the fitting of a worker with pumps, which draw known volumes of air through specific filters. This allows for laboratory analysis and accurate concentrations to be ascertained.

Air quality monitoring takes several forms. Regular monitoring to be performed in set locations using data logging equipment. These must check for Nitrogen Monoxide as part of the suite of gases tested for.

These can be your first port of call to identify whether any change has occurred, however be aware of compatibility issues. Most sensors can be affected by other gases, such as hydrogen, so ensure that this is being managed.

This form of static sampling cannot effectively test for particulate in the air – nor can it evaluate the level of elemental carbon in the air.

The most accurate form of testing is by using pumped sampling techniques. These draw known volumes of air through specific filters, which allow for laboratory analysis and accurate concentrations to be ascertained.

These concentrations must be compared to tables of Occupational Exposure Limits (such as the EH40) to evaluate the level and compliance with the COSHH regulations. These tables are not often comprehensive, for example nitrogen dioxide is not listed on the EH40. In these circumstances other British standards should be used, such as BS6164.

Gases

The following gases are generally monitored at various fixed points using electronic sensors which communicate with a central point, generally the tally hut:

- Methane (CH4)
- Carbon Monoxide (CO)
- Carbon Dioxide (CO^2)
- Nitrous Oxide (NO)
- Nitrogen Dioxide (NO^2)
- Hydrogen Sulphide (H^2S)
- Sulphur Dioxide (SO^2)
- Oxygen (O^2), enrichment and depletion

In addition, air temperature (DB) and air velocity may also be monitored.

Electronic gas sensors may be cross-sensitive to other gases, temperature or air pressure and should be considered in the monitoring of air quality. Examples include the apparent detection of H^2S in the presence of CO and vice versa. Monitoring equipment can be affected by changes in atmospheric pressure and require regular calibration.

Fixed point monitors should be located where they are exposed to mean levels in the tunnel section. Where air velocity is measured, the reading may require calibration against the average velocity in the cross section.

Underground gas measuring station

The central point monitor should be configured to calculate the time weighted exposure level for each gas at each measuring station and issue alarms accordingly, facilitating evacuation if required.

Central monitoring station (Tally Hut).

Where appropriate, hand held gas monitors, such as those shown right can be used. These instruments usually have four sensors - oxygen, flammable and two toxic sensors, such as CO and H^2S.

Dust

Dust monitoring of each shift readings should be taken with hand held monitors to provide an instantaneous value of total inhalable dust. Levels above 50% of the WEL should be investigated.

Additional personal gravimetric sampling should be undertaken, the results of which should be used to determine if dust masks should be worn downstream of excavation and SCL works.

A Casella CEL-712 Microdust Pro hand held dust monitor or similar device should be used to give instantaneous indicative dust concentration readings. However, the instrument requires calibration against a standard gravimetric measurement.

Dust monitoring surveys should be carried out in accordance with HS(G)173 Monitoring Strategies for Toxic Substances, used for personal and positional sampling. Samples of total inhalable and respirable dust are collected onto pre-weighed filters by drawing a known volume of air through sampling heads, using air monitoring pumps. Personal air monitors should be placed in the breathing zone of each operative. Positional samplers should be placed in areas of high or frequent occupation.

A dust monitoring procedure should be developed and should include monthly dust monitoring, carried out by an occupational hygienist, with a report produced which includes recommendations for improvement for each survey. A dust monitoring inspection should also be carried out on a weekly basis as a minimum, by an engineer, using direct reading (real time) instruments and reported to the occupational hygienist.

In addition to the collection of exposure samples, activities and temporal conditions which might influence the result should be noted

Elemental carbon

Evaluating exposures to elemental carbon can be more difficult, as the recent classification has not yet pushed for limits to be established. Crossrail used two limits for elemental carbon;

Minimum standard – levels below 0.1mg/m^3 (8hr TWA) based on the German MAK limits

Best Practice standard – levels below 0.02mg/m^3 (8hr TWA), based on the US TLVs

Section C2 – Ventilation

Testing of the ventilation systems should be done on a regular basis. This is performed using a hand held anemometer (to provide directional air flow readings) or a hot wire probe (to provide accurate readings in any direction).

These readings should be logged and compared to the required airflows as calculated by the ventilation engineers.

Section C3 - Health

Health Monitoring

As tunnelling works have a potential to create a number of health hazards. In addition to a basic health assessment at induction, health surveillance for lung function, skin diseases, and audiometry should be routinely undertaken on at risk groups.

Health surveillance is a means by which a worker's health is checked to see whether their health has deteriorated as a result of their work.

The type of health surveillance should be as stipulated in COSHH and other relevant legislation. Following an assessment of the risks Crossrail introduced a health surveillance programme which included lung function testing every two months for those likely to be exposed to the highest dust levels.

As a minimum it is recommended that the health surveillance programme includes workers from the list below. Organised through the occupational health service provider:

The line manager should be informed of the results of health surveillance and where the lung function test shows impairment the person should be referred by occupational health to their GP or respiratory specialist. The incident should be investigated with a re-assessment of the risk and additional controls put into place where indicated.

TBM ROLES	SCL ROLES	
Segment lifter	Pit Boss	Crane Op
Lead miner	Lead Miner	SCL Apprentice
Engineer	Miner	Ground worker
Grout pump operator	Miner Sprayer	Tally Man
TBM driver	Back up Sprayer	Fitter
Ring builder	Underground op/driller	Electrician
Locomotive driver	Slinger	Engineer
Rail extender	Pump Op	Foreman
Conveyor extender	Plant Op	Yardman
Pipe walkway extender		

Part D - Training

Section D1 - General

Where there is a potential for exposure to airborne contaminants, it is important to make the workforce aware of the risks and the measures in place to control this.

As silica and DEEE are carcinogens and dust, gases and fumes have a potential to cause significant ill health, it is important to keep the workforce regularly informed on the results of testing that has been performed, and any changes that may be required of them or the control regime.

Section D2 - Importance of ventilation

The effective control of airborne contaminant is dependent on maintaining the ventilation as per the design. In particular:

The ventilation should be designed to accommodate the anticipated contaminant load and have a minimum airflow assigned. Regular checks on the performance of the system should be made using a pilot tube to measure the air velocity in the ducts. Alternatively, flows in the tunnel section can be measured with an anemometer making a traverse across the roadway section. Given the height of some tunnels, this is difficult to perform.

Ducting should be adequately maintained and any defects rectified as soon as possible so that air flow is returned to optimal operating levels. Procedures should be put into place to remove staff until safe air quality has been restored.

Collapsed ducting

Damaged ducting

It is paramount that air flow and ducting are maintained and bulkhead doors are kept closed in cross passages as designed to direct the air. Attention to training the workforce in these aspects is required. Fans should not be adjusted or switched off other than by authorised personnel.

Checks on fans are also needed to ensure that they are running vibration free, and that there is no evidence of debris building up. Evidence of the latter is shown below.

Where there is a requirement on the workforce to act, such as turning on ventilation or adjusting machine

Build-up of debris on fan inlet

settings, then the workforce must be trained on how and when to do this. The risk assessment should be reviewed if there is a requirement to switch off ventilation for a regular or prolonged period and additional control measures put into place.

Section D 3 Maintenance and use of de-dusters

Where high dust loads are likely, wet de-dusters should:

- Have the water tank cleaned each shift
- Be washed through weekly.

Dry de-dusters should be inspected to ensure that there is no build-up of dust around the discharge valve.

Part G - Glossary of terms

ALARP	As low as reasonably practicable
COSHH	Control of substances hazardous to health
Dust	Dust is tiny, dry particles in the air
HSE	Health & Safety Executive
Fume	Suspension of small solid particles built up by the condensation from the molecular state
Inbye	Going away
Outbye	Going towards
ppm	Parts per million
R48	Danger of serious damage to health by prolonged exposure
R20	Harmful by inhalation
WEL	Workplace Exposure Limit

Part H - References

COSHH Regulations 2002 (amended): Approved code of practice and guidance.

EH40 Workplace exposure limits 2005 (2nd edition 2011).

European Regulation (EC) No 1272/2008. Classification, labelling and packaging of substances and mixtures came into force on 20 January 2009 in all EU Member States, including the UK. It is known by its abbreviated form, 'the CLP Regulation' or just plain 'CLP'.

HSE. COSHH approach in construction: silica. Tunnelling and shaft sinking: Control approach R; Respiratory protective equipment (RPE). *CN8 2006*

HSE. Construction information sheet 36 Revision 1: Silica

HSE Crystalline Silica in respirable dust. *MDHS 101 2005*

HSE General methods for sampling and gravimetric analysis of respirable and inhalable dust *MDHS 14/3 2000*

HSE. Portland Cement Dust Hazard assessment document *EH75/7. 2005*.

HSE. HSG187 Control of diesel engine exhaust emissions in the workplace. 2012.

HSE. Prevention of heat illness in mines. 2006

Non-Road Mobile Machinery (Emission of Gaseous and Particulate Pollutants) Regulations 1999 *(Statutory Instrument No. 1999/1053)*

Causes of confined space hypoxia during underground construction in the Lambeth Group beneath London, Thames Water 2013

Airborne Dust Capture and Induced Airflow of Various Spray Nozzle Designs. Douglas Pollock and John Organiscak NIOSH, Respiratory Hazards Control Branch, Pittsburgh, Pennsylvania, USA 2007.

European emission standards http://ec.europa.eu/environment/air/transport/road.htm

Crossrail

Target Zero

A STATE OF MIND