Guidance

G2108 Occupational exposure to respirable dust

Issue no.:	A1			

Contents

1 Purpose

1.1 This guidance provides good practice solutions for the occupational exposure to respirable dust.

1.2 This guidance was produced for the construction of Crossrail.

2 Scope

2.1 This guidance may be used for projects that require management of occupational exposure to respirable dust.

3 Guidance

3.1 The unedited Crossrail good practice guide begins on the next page.

4 Responsibilities

4.1 The Deep Tube Tunnels Engineer is responsible for this guidance.

5 Supporting information

5.1.1 This guidance is one of a set that provide overall guidance on the life cycle requirements for Civil Engineering assets.

5.1.2 The complete set is as follows:

Document no.	Title or URL
G050	Civil Engineering – Common Requirements
G0051	Civil Engineering – Bridge Structures
G0052	Civil Engineering – Gravity Drainage Systems
G0053	Civil Engineering – Building and Station Structures
G0054A	Civil Engineering – Earth Structures
G0054B	Earth Structures – Guide for Slope Stability Analysis
G055	Civil Engineering – Deep Tube Tunnels and Shafts
G0056	Civil Engineering – Pumping Systems
G0057	Civil Engineering – Miscellaneous Assets
G0058	Civil Engineering – Technical Advice Notes
G1299	Guidance on Civil Engineering Asset Strategic and Tactical Risk Models
G1417	Grouting to control seepage in tunnels and structures
G2105	Construction Railway Operations
G2106	Sprayed concrete lining exclusion zone management
G2107	Pressure Systems
G2108	Occupational Exposure to Respirable Dust

5.1.3 The above give guidance and explanation in support of the following standards:

Document no.	Title or URL
S1050	Civil Engineering – Common Requirements
S1051	Civil Engineering – Bridge Structures
S1052	Civil Engineering – Gravity Drainage Systems
S1053	Civil Engineering – Building and Station Structures
S1054	Civil Engineering – Earth Structures
S1055	Civil Engineering – Deep Tube Tunnels and Shafts
S1056	Civil Engineering – Pumping Systems
S1057	Civil Engineering – Miscellaneous Assets
S1060	Civil Engineering – Bridges and Structures inspection standard
S1061	Civil Engineering – Bridges and Structures Assessment
S1062	Temporary Works
S1063	Civil Engineering - Cutting, grinding, drilling, fixing to and supporting from existing structures
S1064	Civil Engineering - Waterproofing
S1800	Cable Runs
S1801	Competence requirements for undertaking Civil Engineering Safety Critical Work

6 Person accountable for the document

Name	Job title
Keith Bowers	Principal Tunnel Engineer

7 Document history

Issue no.	Date	Changes	Author
A1	June 2016	Incorporation of Crossrail best practice guide into LU Standards suite	Mohammed Gajia

8 References

Document no.	Title or URL
	Occupational exposure to respirable dust, respirable crystalline silica and diesel engine exhaust emissions in the London tunnelling environment.

9 Attachments

SUMMARY

Crossrail is a 118-kilometre (73-mile) railway line under construction in England. Work began in 2009 and it is Europe's largest railway and infrastructure construction projects. During tunnelling projects exposures to potentially hazardous agents may occur due to the work being carried out in a confined space. Exposure measurements reported in the peer-reviewed literature suggest that all exposures are higher in underground work compared to outdoor construction workers. Relatively few studies have been conducted specifically looking at occupational exposures in tunnelling, and results from personal exposure measurements are especially lacking.

A series of measurement campaigns were undertaken to investigate exposure to respirable dust (RD), respirable crystalline silica (RCS) and diesel engine exhaust emissions (DEEE) of the workers involved in tunnel construction. Workers monitored included those working on TBMs (tunnel boring machines) and SCL (spray concrete lining) activities. Personal exposure measurements were obtained using cyclone sampling heads, with temporal variability and levels of black carbon (BC) (as a marker for DEEE) and RD being assessed using a MicroAeth AE51 and TSI SidePak fitted with a cyclone, respectively.

During SCL work job titles with the highest mean personal RD exposures were the back-up sprayer (Arithmetic Mean (AM) 2.40 mg/m^3) and sprayer (AM 1.55 mg/m^3). Both undertook the concrete spray activities and were observed to be in the restricted zone during excavation and spray activities. The inspector and pump men experienced the lowest mean RD exposures. All RD concentrations were below the Health and Safety Executive (HSE) Workplace Exposure Limit (WEL) for RD (4 mg/m^3), although there were several instances where 8-hr concentrations were in excess of 1 mg/m^3 (the IOM recommended exposure limit). The highest RCS exposure was observed for the back-up sprayer, with a maximum measured RCS concentration of 0.24 mg/m^3. Concentrations in excess of 0.1 mg/m^3, the 8-hr TWA WEL, for RCS were also reported for an engineer, lead miner and two plant operators. With respect to the SCL static samples, the highest mean (1.28 mg/m^3) and maximum RD concentration (1.4 mg/m^3) were measured within the restricted zone. The maximum RCS concentration of 0.04 mg/m^3 was also observed within the restricted zone.

All the REC concentrations measured with personal samples in the TBM environment were below the 100 μg/m^3 reference limit. All RD measurements collected in the TBM environment were below the WEL, although for the job titles segment lift, grout pump, ring building, rail extension and conveyor extension there were a number of instances where the RD exposures were in excess of 1 mg/m^3 (the IOM recommended exposure limit). The job titles with mean RD concentrations in excess of 1 mg/m^3 were the conveyor extension (AM 1.65 mg/m^3) and rail extension operators (AM 1.10 mg/m^3). The highest observed REC concentration was for a segment lifter (37 μg/m^3) and the conveyor extension and rail

extension operators were reported to have the highest mean REC concentrations (AM 30 and 26 μg/m^3 respectively). For the static samples, the highest mean RD and REC concentrations were observed at the transfer hopper location (RD AM 1.38 mg/m^3 and REC AM 33 μg/m^3) and segment lift area (RD 1.38 and REC 40 μg/m^3 although this was based on only one sample). The maximum RD concentration was also reported in the segment lift area and the TBM bridge area (2.2 mg/m^3) with the maximum REC concentration also being observed at the TBM bridge area (52 μg/m^3).

Temporal direct reading measurements using the MicroAeth revealed the impact of excavation, vehicular and locomotive movements with peaks in BC concentrations usually coinciding with these activities. During the TBM monitoring period the supply air was turned down during surveying activities. The impact of this on BC concentrations was evident in the temporal data and concentrations were reduced when the supply air was returned back to the usual settings. BC concentrations were higher in the SCL environment in comparison to the TBM environment (mean SCL concentrations over measurement period ranged from 17-54 μg/m^3 in SCL environment compared to 3-8 μg/m^3 in TBM environment).

SidePaks were used to log the temporal trends in RD over the monitoring period. Similar trends as for the BC temporal and summary data were observed, with excavation, spray and vehicular activities leading to relatively higher concentrations in the SCL environment. The impact of the locomotive movement and the reduction in supply air was again demonstrated in the TBM SidePak data.

The results in our monitoring campaigns suggest that DEEE exposures are higher in the SCL environments than the TBM environment and it is considered that future monitoring campaigns should focus on assessing DEEE exposures in the SCL environment and necessary measures should be implemented to control exposure. In the SCL environment, exposure to RD and RCS could be significant. Engineering controls such as de-dusters should be appropriately located and used during tunnelling operations. Respiratory protection equipment is provided and refresher operator training should be given on how to use and wear these correctly. It is recommended that face-fit testing be undertaken to ensure that suitable and sufficient RPE is provided to the SCL operators.

Given the levels, further engineering control measures should be taken to reduce the RD exposure throughout the TBM but particularly in the conveyor extension area. The REC concentrations were lower than the SCL environment. However, measures should be taken to reduce exposures further, for example by replacing older, less efficient locomotives (‘yellow’ engines), and avoiding unnecessary running or idling of diesel engines. Efficient ventilation is needed to assist in the removal of RD and DEEE. The supply air to the TBM was turned down on two of the monitoring days and the impact of this on RD and REC was clearly observed. Further investigation is needed to ascertain why this practice takes place so that it can be eliminated or reduced.

CONTENTS

1 INTRODUCTION

Crossrail is a 118-kilometre (73-mile) railway line under construction in England. It is due to begin full operation in 2018, serving London and surrounding areas by providing a new east-to-west route across Greater London. Work began in 2009 and it is Europe's largest railway and infrastructure construction projects. The project's main feature is 42 km (26 miles) of new tunnels. There are five tunneled sections each with an internal diameter of 6.2 m (20 ft), totaling 21 km (13 miles) in length.

The Control of Substances Hazardous to Health (COSHH) Regulations require employers to control substances that are hazardous to health. The objective of the COSHH Regulations is to prevent, or to adequately control, exposure to substances hazardous to health, so as to prevent ill health. During large scale construction projects it is important to monitor exposures of workers to hazardous substances used in, or generated during the work to assess compliance with workplace exposure limits (WELs) set to protect workers' health and reduce exposures as low as is reasonably practicable. This is particularly the case during tunnelling projects where potential exposure to hazardous agents may occur due to work in confined spaces.

Measurements reported in the peer-reviewed literature have shown that exposures are generally higher in underground work compared to outdoor construction workers [Bakke *et al*., 2002]. Although construction is one of the prominent industries on which the occupational hygiene community focuses, it is very diverse and extrapolation from one environment to the next, or even from one construction site to the next, is difficult [Bakke *et al.*, 2002]. Few studies have been conducted specifically looking at occupational exposures in tunnelling, and information from personal exposure measurements are lacking.

Exposures of interest in the tunnelling environment are primarily respirable dust (RD); respirable silica, carbon monoxide, nitrogen dioxide (NO_2) and diesel exhaust [Bakke, 2004]. Substantial exposure to total dust, RD and α-quartz were reported during tunnel construction work in Norway, while exposure to oil mist (from diesel exhaust and oil spraying) was high for shaft drillers [Bakke *et al*., 2001]. Bakke *et al*. [2002] indicated that as much as 15% of total dust measurements, 5% of RD measurements and 21% of quartz measurements exceeded the Norwegian OELs of 10 mg/m^3, 5 mg/m^3 and 0.1 mg/m^3, respectively. Exposure to NO_2 was also measured as well as elemental carbon (EC) as an index of exposure to diesel exhaust [Pronk *et al.*, 2009; Vermeulen *et al.*, 2010]. EC levels of 100-340 µg/m^3 were measured, indicating that even the lowest measured concentrations in these sites were above those considered to have an impact on health [van Tongeren *et al*., 2013]. However, distinct differences in exposure levels and determinants were found for the different jobs conducted in tunnel construction work [Bakke *et al*., 2002]. Important determinants associated with increased exposure were the type of drill rigs used, mechanical scaling, shotcreting, drilling, mucking and repairing of ventilation ducts.

In the Crossrail project each of the five tunneled sections consists of two tunnels excavated at the same time using two Tunnel Boring Machines (TBMs) (Figure 1).

The tunnel linings are constructed from pre-manufactured concrete sections which are transported to the TBMs via locomotives for installation. The project uses eight 7.1m diameter TBMs from Herrenknecht AG (Germany). Two types are used; 'slurry' type for the Thames tunnel, which involves tunneling through chalk and 'Earth Pressure Balance Machines' (EPBM) for tunneling through clay, sand and gravel. At the front of the TBM is a full face cutter head which rotates at around 1 to 3 rpm. As the TBM advances forward the cutter head excavates the ground. The loosened material is removed from the cutter head via a screw conveyor, which moves the material through the back of the TBM and out of the tunnel via a conveyor belt. The concrete segments are transported by tunnel locomotives into the tunnels and loaded onto the TBM. As the TBM advances forward, the precast concrete segments are built into 23 tonne rings to line the tunnels behind the TBM cutter head. Diesel locomotives operate regularly behind the TBM transporting the personnel, materials etc. necessary for the operation. Exposure to DEEE is of concern (with respect to this programme of research) as well as RD and it was agreed that sampling will take place in two TBM environments.

Figure 1: TBM Sophia breaks ground at Plumstead Portal, Jan 2013. Image Copyright of Crossrail Ltd

In addition to the rail tunnels, the project involved the construction of the station platform tunnels, concourses and associated cross passages and escalator tunnels etc. The construction of these parts of the tunnels uses a technique called Spray Concrete Lining (SCL) where concrete is sprayed to provide support to the surrounding soil (Figure 2). This technique involves excavation followed by concrete spraying and is a continuous process. The SCL technique uses concrete formulated close to the site which is pumped down to concrete mixers located within the tunnel.

Figure 2: Sprayed concrete lining works (sprayer on left, engineer on right). Note: operator exclusion zone. Image Copyright of Crossrail Ltd

A measurement campaign was carried out to investigate exposure to diesel engine exhaust emissions (DEEE), respirable crystalline silica (RCS) and RD of the workers involved in the work and compare these exposure levels with the UK WEL or, in the absence of a WEL, with other relevant European reference limits or recommended guidance levels.

2 AIMS AND OBJECTIVES

This research focusses on particulate exposure and more specifically on RD, RCS and DEEE (measured as respirable elemental carbon (REC)).

The specific aims and objectives of the programme of work were as follows:

1. To measure personal exposure to RD, RCS and REC during tunnelling projects carried out by or on behalf of Crossrail in London.
2. To estimate average exposure to RD, RCS and REC for those workers/occupations who are likely to have the highest exposure levels.
3. To explore temporal variability of black carbon (BC) in the various tunnels.
4. To compare average exposure levels to WELs where available or other relevant reference values and recommended guidance levels.

During initial discussion with representatives of Crossrail and their contractors it was agreed that the research would focus on the TBM and SCL environments and that different measurement strategies would be employed. In the SCL environment, the focus of the campaign was on exposure to RD and RCS whereas in the TBM environment the focus was on RD and REC. In addition, temporal variability of RD was also included in the study design. A sampling strategy was developed based on these discussions and agreements.

In addition, measurement data for the hazardous substances of interest to this study were made available to IOM on an anonymous basis by Crossrails' tunnelling contractors' occupational hygiene providers. These measurements were summarised and compared with the results obtained during the IOM measurement campaigns.

3 RELEVENT WORKPLACE EXPOSURE LIMITS AND GUIDANCE LEVELS

WELs are exposure limits set by the Health and Safety Executive (HSE) in Britain to protect the health of workers. WELs are concentrations of hazardous substances in the air, averaged over a specified period of time, referred to as a time weighted average (TWA). Substances that have been assigned a WEL are subject to the requirements of the COSHH Regulations. These Regulations require employers to prevent or control exposure to hazardous substances. Control is defined as adequate only if a) the principles of good control practice are applied, b) any WEL is not exceeded and c) exposure to asthmagens, carcinogens and mutagens are reduced as low as is reasonably practicable.

The absence of a substance from the list of WELs does not indicate that it is safe. For these substances, exposure should be controlled to a level to which nearly all the working population could be exposed, day after day at work, without any adverse effects on health.

Control of exposure to any kind of airborne dust is also required under COSHH, and WELs for respirable dust are set at 4 mg/m^3 (as a TWA over an eight-hour period) (HSE, 2011).

However, the IOM considers that the current British WELs for airborne dust are unsafe and employers should attempt to reduce exposures to help prevent further cases of respiratory disease amongst their workers. We suggest that, until safe limits are put in place, employers should aim to keep exposure to RD below 1 mg/m^3 (IOM, 2011). The value of 1 mg/m^3 for RD has been considered by other organisations to be a more appropriate guideline (BOHS, 2012).

The WEL for RCS is of 0.1 mg/m^3 8-hour TWA (HSE, 2011). The WEL for RCS is not a safe limit and given the serious health risk associated with this, employers are required to reduce exposure below the WEL.

For REC there is currently no existing WEL in the UK. A reference level for DEEE of 100 µg/m^3 was recently used in a European Union project on socioeconomic, health and environmental impact of possible amendments to the EU Carcinogens and Mutagens Directive (*SHEcan*)[1] (IOM, 2012). In Austria, technical guidance concentrations (TRK values) for diesel exhaust particles are given separately for underground mining and for other workplaces. The values are based on technical feasibility and do not consider health effects of diesel exhaust. The 8-hr TWA for underground mining is 300 µg/m^3. In Switzerland, EC in the respirable fraction of diesel exhaust particles is applied as the indicator substance for DEEE exposure and the 8-hr TWA is 100 µg/m^3 (OSHWiki, 2013). For this report, the value of 100 µg/m^3 is used as a reference limit for REC.

The term '8-hour reference period' relates to the procedure whereby the occupational exposures in any 24-hour period are treated as equivalent to a single uniform exposure for 8 hours (the 8-hour TWA) exposure.

[1] http://www.occupationalcancer.eu

The 8-hour TWA may be represented mathematically by:

$$(C1T1+C2T2+\ldots CnTn) / 8$$

Where:

> C1 is the occupational exposure and T1 is the associated exposure time in hours in any 24-hour period.

The results from the measurement campaigns are presented as 8-hour TWAs.

4 STUDY OUTLINE

Four 3-day measurement surveys were carried out in tunnel environments.

Personal exposure to RD, RCS and REC was assessed for a duration representative of the operators working shift (no less than 50% of the workers shift, ideally 75% of the shift duration).

Real time monitoring of BC was used to investigate the temporal variability and levels of DEEE. Whilst not included in the original agreed proposal, we also used real time monitoring of particulates to investigate the temporal variability in RD.

The project originally aimed to collect 60 RCS and 60 REC personal samples (all of which would be analysed for RD) over the course of the sampling campaigns (depending on availability of operators for sampling), with direct reading instruments (measuring for BC and RD) being used on each day of sampling. It was however evident that there were insufficient operators available to obtain the required numbers of personal samples and so static sampling was also employed to achieve the required number.

During each day of sampling, relevant contextual information was documented (where possible) describing the observed activities and operators working practices. In addition, relative humidity and temperature were recorded, as were details of the tunnel environment.

5 METHODS

5.1 IDENTIFICATION OF MONITORING SITES

Crossrail representatives identified suitable environments for IOM personnel to visit and conduct the monitoring campaigns. These were selected with due consideration to the typical tunnelling activities scheduled to take place during the timescales of the project.

5.2 SAMPLING STRATEGY

During a preliminary scoping visit by IOM and Crossrail representatives on 16th June 2014 and the discussions that followed, it was decided that two distinct tunnelling activities would be assessed during the campaign – TBMs and SCL.

Diesel locomotives operate regularly behind the TBM transporting the personnel, materials etc. necessary for the operation. Exposure to DEEE is of concern (with respect to this programme of research) as well as RD and it was agreed that sampling will take place in two TBM environments.

Exposure to REC and RD was expressed as being the primary concern during SLC works (with respect to this programme of research) and it was agreed that sampling would take place in two SCL environments.

A summary of the measurement strategies are detailed in Table 1.

Table 1: Measurement strategies to be employed in tunnel environments

Measurement	SCL	TBM
Primary agent of interest	RCS & RD	DEEE & RD
Personal samples	RD & RCS analysis	RD & REC analysis
Direct reading instruments	RD & BC	RD & BC

On each day of sampling it was intended that up to 10 pumped measurements would be collected (either 10 RD/RCS or 10 RD/REC measurements depending on environment). However, the actual number of personal samples was dependent on the availability and willingness of operators to participate, also with due consideration to their work tasks and ensuring their safety would not be compromised through the wearing of the devices.

In the TBM environment the following operators were targeted *a priori* with final selection being decided following discussions with on-site personnel and the lead miner for the 'gang' working on each day of monitoring:

- TBM driver
- Grout pump operator
- Conveyor operator(s)
- Segment builder(s)
- Engineer

In addition, the locomotive driver was also targeted where possible.

In the SCL environments, the following operators were targeted *a priori* with final selection again being decided following discussions with on-site personnel on each day of monitoring:

- Nozzleman (spray operator)
- SCL surveyor
- Pump operator
- Operators involved in excavation activities
- Engineer

Static area sampling was also used to achieve the required sample numbers.

5.3 SAMPLING METHODS

5.3.1 Personal and static pumped air samples

Personal measurements (sampling for a duration representative of the operators full shift) was conducted amongst identified workers and who agreed to participate. Measurements were carried out using Higgins Dewell cyclones connected to a personal pump set at a flow-rate of 2.2 L/min. For measuring RCS the cyclones were loaded with a PVC filter, while for measuring REC heat-treated quartz filers were used. The cyclone sampling head was placed within the breathing zone (within 200mm of the nose and mouth) on the dominant side of the worker, normally on the lapel of the workers overalls. Operators were asked to avoid placing jackets / overalls over the sampling head and in instances were operators were required to wear face visors they were advised to ensure that the sampler was not covered by these.

Measurements were conducted at each tunnelling site for 3 consecutive days. Depending on shift patterns, repeat measurements were collected from some workers on different days.

Static samples were located in areas where operators may reasonably be positioned, concerns about exposure had been raised and/or where previous static monitoring had been undertaken by Crossrail contractors' occupational hygiene providers. The sampling head was located at typical adult breathing zone height.

Air sampling to determine personal exposures of RD, RCS and REC was carried out in accordance with HSE MDHS 14/4 – General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols (HSE, 2014). The flow rate was set using a calibrated flowmeter and checked at the start and finish of the sampling period. In instances where the sample flow rate deviated by 10% or more the sample was classed as void and not analysed.

For quality assurance purposes, field blanks for each sample medium were obtained on each day of the monitoring campaign. These samples were handled in an identical manner to the other samples with the exception that no air was drawn through them.

5.4 DIRECT READING INSTRUMENTS

A MicroAeth AE51 (hereafter referred to as MicroAeth) equipped with a microCyclone was used to measure BC and to investigate the temporal variability and levels of DEEE. The MicroAeth was set to log measurements at a time base of 60 seconds and a flow rate of 50ml/min. The BC concentrations recorded are presented in µg/m^3. Additional measurements were collected using the MicroAeth in the office area and during journey time from the researchers hotel and site to provide an indication of the background BC concentrations in a non-occupational environment.

TSI SidePak AM501 devices (hereafter referred to as SidePak), fitted with a cyclone, were also used to monitor RD in real time. The device logged measurements in mg/m^3 at a flow rate of 1.7 l/min, with a log interval of 1 minute, time constant 1 second. A calibration factor of 1 (factory setting) was used.

5.4.1 Environmental conditions

Relative humidity (RH) (%) and temperature (^{0}C) were logged at one-minute intervals during the measurement campaigns using a Lascar EL-USB-2. In addition, background environmental conditions for each day of sampling were obtained from www.wunderground.com.

5.4.2 PREPARATION OF SAMPLE MEDIA

Heat treated filters were supplied by Scientific Analysis Laboratories (SAL), Manchester, and used for sampling REC. Preparation, numbering and pre-weighing of sampling media to be used on-site was carried out by the IOM laboratory. Weighing of filters for use in the cyclone cassettes was carried out in accordance with IOM internal Instruction Manual 2 'Gravimetric analysis' (IOM, 2008).

5.5 SAMPLE ANALYSIS

The RCS samples were analysed to determine the gravimetric and RCS concentrations by IOMs analytical laboratory in Edinburgh in accordance with IOM Instruction manual IM 2 using modifications of HSE (2014) for RD and HSE (2005) for REC. The REC samples were analysed gravimetrically in the first instance by IOMs laboratory as detailed above. These heat-treated quartz filters were then analysed for REC by SAL, Manchester, using Analytik Jena 5000.

The analytical limit of detection (LOD) for the sample analysis was 0.05 mg for RD, 0.02 mg for RCS and 1.0 µg for REC.

5.6 DATA COLLECTION

A standardised proforma was used by the researchers to record key information from each sampling campaign. The form allowed for details of the sample number, details of the operator, the time on and time off, and the flow rates at the beginning and end of sampling to be recorded. In addition, behavioural observations and other relevant contextual information were recorded.

5.7 MEAUREMENT DATA FROM CONTRACTORS OCCUPATIONAL HYGIENE PROVIDERS

RD, RCS and REC 8-hr TWA measurement results collected during previous TBM and SCL activities were obtained on an anonymous basis from the contractors occupational hygiene providers. Due to the anonymous nature, limited contextual information was provided; however, details of the job title and sample location monitored were made available. IOM were advised that the data provided were collected from a number of different sites over an extended period of time (~Feb 2013–Aug 2014), as works progressed and control measures were implemented and upgraded. RD samples were typically collected using IOM heads loaded with polyurethane foams rather than the cyclone sampling heads employed in the current campaigns. In instances where RD was further analysed for RCS a cyclone sampling head was used.

5.8 DATA ANALYSIS

Measurements obtained using the direct reading instrument were downloaded and imported into MS Excel. On occasions negative values were observed in the MicroAeth data and these were removed for the data analysis. The temporal variability in concentrations was graphically displayed, with descriptive statistics of the measurements over each shift being calculated.

The pumped sampling results were reported as 8-hr TWA. Descriptive statistics were provided by sample type and occupational group / location for each of the measurement campaigns / tunnel environments. This included arithmetic mean (AM), median, standard deviation (SD), geometric mean (GM), geometric standard deviation (GSD), minimum (min) and maximum (max). Data obtained from the contractors occupational hygiene provider were also coded by IOM (where possible) by occupational group / location, with descriptive statistics being provided. For all the pumped sample measurement data, in the event of concentrations being recorded as less than the analytical LOD, a value of half the LOD was assigned for the purposes of the data analysis. The measurement results were compared with the measurements collected by IOM. In addition, the 8-hr TWAs were compared with the relevant WEL and reference levels.

6 RESULTS

6.1 Introduction

A total of four monitoring campaigns were completed, two monitoring in SCL environments and the remaining two during TBM works.

Table 2 summarises the dates when the monitoring campaigns were undertaken and the sites assessed.

Table 2: Details of monitoring campaigns completed

Campaign	Dates (2014)	Environment	Site
1	6-8th Aug	SCL	Fisher Street
2	4-6th Nov	SCL	Farringdon
3	25-27th Nov	TBM	Stepney Green (Drive Y)
4	10-12th Dec	TBM	Stepney Green (Drive Y)

The following sections detail the activities observed and assessed during the monitoring campaigns, descriptive summary statistics for the pumped samples obtained during the measurement campaigns and also from the contractors' occupational hygiene providers. The temporal trends in the direct reading instrument data are displayed, with summary statistics also being presented.

6.2 Environmental conditions

A summary of the environmental conditions within the tunnel environment (recorded using the Lascar data logger) during the monitoring period is provided in Table 3. In addition, details of the general outdoor environment, using measurements recorded at midday at the nearest weather station (www.wunderground.com) are also presented.

Table 3: Tunnel and outdoor environmental conditions

	Tunnel conditions		Outdoor conditions		
Date	**Temp. (^oC)**	**RH (%)**	**Temp. (^oC)**	**RH (%)**	**Wind speed (m/s)**
06/08/14	23	66	22	69	4.6
07/08/14	22	66	24	50	2.6
08/08/14	22	74	21	73	3.1
04/11/14	23	50	11	67	1.0
05/11/14	23	52	10	76	4.6
06/11/14	24	48	12	62	5.1
25/11/14	21	53	7	87	2.6
26/11/14	22	60	9	91	1.0
27/11/14	24	59	10	87	2.6
10/12/14	23	56	8	66	7.7
11/12/14	23	55	8	71	9.3
12/12/14	24	55	9	82	6.2

6.3 SITE OBSERVATIONS, PERSONAL MONITORED AND STATIC SAMPLING LOCATIONS

6.3.1 SCL monitoring campaigns

The first monitoring campaign took place at Fisher Street, Westbound Crossover Tunnel where cross passage 5 (CP5) was being excavated. Engineer reports were made available for each day of monitoring and a summary of the activities undertaken during each measurement period as recorded by the engineers is provided in Appendix 1. It is evident from the reports and also the observations during the sampling campaigns that activities were mostly focussed on excavation works and that concrete spraying activities only took place on the second day of monitoring.

The second SCL monitoring campaign took place at Farringdon. Monitoring was undertaken during SCL activities in both the East and Westbound running tunnels (RTE and RTW). Again, engineers' reports were made available and a summary of these for each of the monitoring days is provided in Appendix 1 (Tables A2 (RTE) and A3 (RTW)). It was evident that more spraying occurred during this monitoring campaign than the first.

Supply air was fed into the tunnel environments. The sprayer and back-up sprayers wore air fed visors during SCL activities due to their proximity to the face being sprayed. It was also observed that the engineer wore an air fed visor during spraying activities. Sprayers and engineers also wore disposable Tyvek overalls over their normal protective clothing. Other personnel in the SCL restricted area were provided and required to wear 3M 8835 P3 disposable respirators when concrete spraying activities were taking place.

In both SCL monitoring campaigns plant machinery operated in the tunnel environment to excavate and remove the London Clay earth, as well as to deliver the concrete mix for spraying. The composition of the Concrete mix P420 during the monitoring campaign (SSD mix design) was reported to be as follows: cement 420 kg/m^3; limestone 629 kg/m^3; sand mixture 1168 kg/m^3 and water 145 kg/m^3. It was reported that both the concrete mix and the London clay being excavated contain low levels of crystalline silica.

Personal samplers were worn by several operators, with their job titles being categorised as follows:

- Sprayer- responsible for operating the concrete spray equipment.
- Back-up sprayer – assists the sprayer.
- Engineer – responsible for surveying and ensuring excavation and spraying adheres to specification/plans.
- Plant operator- operate the various plant equipment that move around the tunnel environment, e.g. excavator, dumper truck.
- Lead miner- manages the SCL team activities.
- Crack injectors – repairing of cracks in concrete through rehabilitation injection.
- Pumpman – responsible for supply of concrete to spray equipment.
- Inspector – oversees the SCL process for the Client (Crossrail).

Of these job titles, the sprayer, back-up sprayer and engineers are likely to experience the highest exposures due to their proximity to the spraying operation and face being excavated. Plant operators are also at risk due to the operation of diesel powered vehicles. Many other operators would typically be located either in or near the restricted area observing activities, waiting for progress to be sufficient to allow their particular work activities to take place. The SCL operators worked an 8-hour shift pattern.

In monitoring campaign 1, the direct reading instruments and a pumped sample were located on a hop-up in the general tunnel environment initially 12 rings (19 m from the SCL restricted zone, and approximately 30 rings (48 m) from the work face (Figure 3) although the distances increased on each day of monitoring as the work advanced. The samplers were located at head height.

Figure 3: Location of static samplers in monitoring campaign 1 (IOM)

In monitoring campaign 2, static samplers were installed within the restricted zone of both RTE and RTW (circled in Figures 4 and 5). In each location a SidePak and pumped cyclone sampler were located, with the MicroAeth also being located in RTE.

Figure 4: Location of static samples (circled) in restricted zone, RTE (IOM)

Figure 5: Location of static samples (circled) in restricted zone, RTW. Location of sprayer and engineer also visible (IOM)

6.3.2 TBM monitoring campaigns

The details of monitoring campaigns 3 and 4 are summarised together as these took place on the same TMB (Drive Y Limmo to Farringdon East on the Eastbound tunnel) within a 3 week period. There are two main processes involved during TBM work – shoving (mining, followed by removal of earth by a conveyor belt system) and building (actual fitting of the ring segments). On average 12 rings are built per shift, with a maximum of 16 rings in full production.

The earth being mined and removed via the conveyor system was observed to have a 'porridge consistency' on several of the monitoring days and slightly more solid on others. Due to the consistency of the earth being excavated, splash back from the conveyor system onto nearby surfaces occurred; this dried very quickly, allowing opportunity for resuspension. The TBM crews therefore adopted general housekeeping / cleaning activities on a regular basis, usually during periods when no mining or ring building was undertaken.

Engineer reports were obtained for each day of monitoring and these are summarised in Appendix 2. This details the number of rings built over the whole shift (not necessarily during the actual monitoring periods), other activities undertaken and any delays encountered. The movement of locomotive engines delivering materials and transporting people to and from the TMB was recorded. In addition, the researchers also recorded details of the number of visits made by the locomotives to the TBM during the actual monitoring periods. These are also detailed in Appendix 2. The locomotives used were model 'Schoma CHL-200G' with a diesel-hydrostatic drive system. The fuel consumption (depending on operating conditions) is 0.25 l/KWh. The locomotives in operation had the optional diesel particulate filter and catalytic exhaust cleaner fitted in the exhaust system. During the discussions with the contractors occupational hygiene provider the researchers were advised that the locomotives in operation were new and had more efficient extraction systems then locomotives which had been used previously.

There were no activities observed on the TBM where the wearing of respiratory protective equipment (RPE) was mandatory. 32.63 m^3/s air is supplied from the surface down to the TBM. TBM crew may reduce the air flow, for example, during tunnel ventilation dust extensions (every 100 m of excavation) and in exceptional situations. During monitoring on the 11th December an authorised surveying task was undertaken which resulted in the supply air being turned down. During this period it was evident that there was a 'haze' in the air and a lack of air movement around the TBM. The researchers were advised that the turning down of the supply air was a regular occurrence during these activities. The supply air was increased back to its normal settings and at around 10.50am the air subjectively felt 'fresher' and the supply air tubing was observed to be re-inflated. On the 9th December the IOM researchers were also advised at around 11am that the supply air earlier that shift had been reduced to 25% and was running up to 40%, after being increased to 50% which was judged too high. On 27th November an unusual event occurred that impacted on the operators usual work practices. A segment had been installed in the wrong position which resulted in remedial work being undertaken to relocate the segment into the correct location.

Personal samplers were worn by several operators, with their job titles being categorised as follows.

- Segment lifters – move delivered segments into loading bay for movement into ring building area. Also insert dowels. This is located at upper middle area of TBM.
- Lead miner – responsible for the management and supervision of the TBM crew. Will move throughout TBM but observed to be mostly at the front.
- Engineer – responsible for surveying and ensuring advance and ring building adheres to specification/plans. Typically located in ring building area or engineers office on TBM.
- Group pump operator- responsible for ensuring the grout is pumped during ring building activities. They are located at a control panel near the back end of the TBM, close to one of the main locomotive stops.
- TBM driver – responsible for driving TBM. Located in office (with door mostly closed) at the front of TBM under conveyor.
- Ring Builder – work in the ring building area at the front of the TBM, ensuring that the segment pieces of installed correctly. When not ring building they are usually still located in the front area of the TBM.
- Locomotive driver- drives the locomotives between Stepney Green and the TBM. On occasion, it was observed that the locomotive driver would assist with some rail extension activities.
- Rail extender – works at the back of the TBM and periodically extends the rails as the TBM moves forward so to allow locomotive movement to and from the TBM.
- Conveyor extender – works on the upper level of the TBM and responsible for extending the conveyor belt that transports the excavated earth.

Of these group titles, the group pump operator was considered to have the highest DEEE exposure due to his working position being close to where the locomotive stops to unload the segments and other materials. The locomotive driver may potentially also experience relatively high DEEE exposures. The conveyor extender is considered to potentially experience the highest RD exposures due to his proximity to the conveyor belt removing the excavated earth. It was reported that this was a dusty operation and measures had been taken to increase ventilation in this area by modifying the duct system running along the upper level.

Rest breaks are taken in a small canteen area located on the upper level of the TBM. The TBM operators work a 12 hour shift pattern, of which around 11 hours are spent located on the TBM.

Static pumped samples were located at the transfer hopper and conveyor extension areas on the upper level. On the lower level, samples were located at the group pump operator station, the TBM bridge area, the pipe/walkway extension and segment lift. These areas were identified as areas with potentially high RD and DEEE levels based on previous monitoring results that had been undertaken by the contractor's occupational hygiene providers and on-site observations. In addition, a number of samplers were located in areas near where operators were working and for whom it was not possible to collect personal samples on that particular day. The MicroAeth was positioned at the group pump operator station as this was the area identified as experiencing the highest DEEE exposure. A SidePak was also located here, with a second SidePak being located in the conveyor extension area. Figures 6-7 illustrate some of the static monitoring locations.

Figure 6: Static samplers at group pump operator station. Figure shows locomotive and grout pump operator (seated). Researcher recording locomotive movements.

Figure 7: Static samplers located at conveyor extension area

6.4 PUMPED SAMPLES

6.4.1 Measurements collected during monitoring campaigns

Table 4 provides the descriptive statistics for the personal samples collected during the two SCL monitoring campaigns summarised by the job titles monitored. Table 5 provides the descriptive statistics for the TBM personal samples, again for the two monitoring campaigns combined.

For the personal samples collected in the SCL environment (Table 4), all the RD concentrations were above the analytical LOD. There were no instances where the 8-hr personal exposures were in excess of 4 mg/m^3. There were several instances where 8-hr personal exposures were in excess of 1 mg/m^3 and all job titles, except for the pump man and inspector, had maximum concentrations in excess of 1 mg/m^3. The job titles that experienced the highest mean exposures were the back-up sprayer (AM 2.40 mg/m^3) and sprayer (AM 1.55 mg/m^3) who both undertook the concrete spray activities and were observed to be in the restricted zone during excavation activities. The maximum concentration of 3.2 mg/m^3 was also for a spray operator. The inspector and pump men experienced the lowest mean RD exposures. The back-up sprayer also experienced the highest mean RCS concentrations of the job titles assessed, as well as the highest RCS concentration of 0.24 mg/m^3, both of which exceed the 8-hr TWA WEL of 0.1 mg/m^3 for RCS. Although 26 of the 49 (53%) concentrations were less than the LOD for RCS, a total of five RCS measurements were found to be either at or exceeding the WEL. In addition to the back-up sprayer these were an engineer, lead miner and 2 plant operators.

For the personal samples collected in the TBM environment, all the RD and REC concentrations were above the analytical LOD (Table 5). None of the concentrations were in excess of the REC reference limit of 100 µg/m^3. None of the RD concentrations were in excess of the RD WEL of 4 mg/m^3, however, there were a number of instances where the RD exposures were in excess of 1 mg/m^3. These included the job titles segment lift, grout pump, ring building, rail extension and conveyor extension. The job titles reporting where the mean RD concentrations were in excess of 1 mg/m^3 were the conveyor extension (AM 1.65 mg/m^3) and rail extension operators (AM 1.10 mg/m^3). The highest reported REC concentration reported was for a segment lifter (37 µg/m^3) and the conveyor extension and rail extension operators were reported to have the highest mean REC concentrations (AM 30 and 26 µg/m^3 respectively).

Table 6 provides the descriptive statistics for the static samples collected during the two monitoring campaigns for the SCL environments, summarised by location monitored. Table 7 provides the descriptive statistics for static samples located in the TBM environment, again for the two monitoring campaigns combined, summarised by location.

The SCL static measurements were grouped according to whether they were located within or outwith the SCL restricted zone or at the secondary lining work (Table 6). All the RD concentrations were above the analytical LOD. The area which experienced the highest mean (1.28 mg/m^3) and maximum concentration (1.4 mg/m^3) was within the restricted zone. 60% of the RCS measurements were less than the LOD and the maximum concentration of 0.04 mg/m^3 was also observed within the restricted zone.

The TBM measurements were also grouped accordingly to location (Table 7). All the RD and REC concentrations were above the analytical LOD. The highest mean RD and REC concentrations were observed at the transfer hopper location (RD AM 1.38 mg/m^3 and REC AM 33 $\mu g/m^3$) and segment lift area (RD 1.38 and REC 40 $\mu g/m^3$ although this was based on only one sample). The maximum RD concentration was also reported in the segment lift area and the TBM bridge area (2.2 mg/m^3) with the maximum REC concentration also being observed at the TBM bridge area (52 $\mu g/m^3$).

Table 4: Personal RD and RCS results by job title, SCL environment

Job title	N	RD dust (mg/m^3)							RCS (mg/m^3)							
		AM	Median	SD	GM	GSD	Min	Max	n<LOD	AM	Median	SD	GM	GSD	Min	Max
Sprayer	11	1.55	1.30	1.07	1.20	2.16	0.40	***3.20***	6	0.03	0.02	0.02	0.02	1.97	0.01	0.09
Engineer	9	0.97	1.00	0.55	0.80	1.99	0.30	1.70	5	0.04	0.03	0.05	0.03	2.15	0.02	0.16
Plant operator	12	1.06	0.95	0.60	0.91	1.80	0.40	2.30	5	0.06	0.05	0.06	0.05	2.44	0.02	0.20
Back-up sprayer	2	***2.40***	***2.40***	0.71	***2.35***	1.35	1.90	2.90	0	***0.13***	***0.13***	0.16	***0.07***	5.80	0.02	***0.24***
Lead miner	7	1.14	0.80	0.85	0.92	2.02	0.40	2.70	3	0.04	0.03	0.03	0.03	2.19	0.02	0.10
Crack injectors	3	0.87	0.80	0.21	0.85	1.26	0.70	1.10	3	0.02	0.02	0.00	0.02	1.00	0.02	0.02
Pumpman	4	0.50	0.50	0.12	0.49	1.26	0.40	0.60	3	0.05	0.05	0.04	0.04	2.44	0.02	0.09
Inspector	1	0.30	0.30		0.30		0.30	0.30	1	0.02	0.02		0.02		0.02	0.02

* values in bold and italics denote highest AM, median, GM and maximum values

Table 5: Personal RD and REC results by job title, TBM environment

Job title	N	RD (mg/m^3)							REC ($\mu g/m^3$)						
		AM	Median	SD	GM	GSD	Min	Max	AM	Median	SD	GM	GSD	Min	Max
Segment lift	8	0.42	0.34	0.41	0.30	2.41	0.07	1.38	17	14	8	16	1.47	11	***37***
Lead miner	1	0.14	0.14		0.14		0.14	0.14	12	12		12		12	12
Engineer	6	0.60	0.55	0.32	0.52	1.79	0.28	0.96	20	17	7	19	1.42	14	32
Grout pump	5	0.72	0.69	0.31	0.66	1.58	0.41	1.10	19	19	6	18	1.37	12	26
TBM driver	5	0.52	0.41	0.26	0.48	1.59	0.28	0.96	17	17	5	17	1.36	11	26
Ring building	3	0.78	0.83	0.35	0.72	1.66	0.41	1.10	20	21	8	19	1.50	12	28
Loco driver	2	0.89	0.89	0.10	0.89	1.12	0.83	0.96	21	21	4	20	1.21	18	23
Rail extension	2	1.10	1.10	0.19	1.09	1.19	0.96	1.24	26	26	6	26	1.25	22	30
Conveyor extension	2	***1.65***	***1.65***	0.19	***1.64***	1.13	1.51	***1.79***	***30***	***30***	3	***29***	1.10	28	32
Pipe/walkway extension	2	0.76	0.76	0.29	0.73	1.49	0.55	0.96	18	18	2	18	1.12	17	19

* values in bold and italics denote highest AM, median, GM and maximum values

Table 6: Static RD and RCS results by location, SCL environment

Location	RD (mg/m^3)								RCS (mg/m^3)							
	N	AM	Median	SD	GM	GSD	Min	Max	n<LOD	AM	Median	SD	GM	GSD	Min	Max
Inside restricted zone	4	***1.28***	***1.30***	0.13	***1.27***	1.11	1.10	***1.40***	2	***0.03***	***0.03***	0.01	0.02	1.76	0.02	***0.04***
Secondary lining	1	0.80	0.80		0.80		0.80	0.80	0	***0.03***	***0.03***		***0.03***		0.03	0.03
Outside restricted zone	4	0.40	0.40	0.08	0.39	1.23	0.30	0.50	4	0.02	0.02	0.00	0.02	1.00	0.02	0.02

* values in bold and italics denote highest AM, median, GM and maximum values

Table 7: Static RD and REC results by location, TBM environment

Location	RD (mg/m^3)								REC (µg/m^3)							
	N	AM	Median	SD	GM	GSD	Min	Max	N	AM	Median	SD	GM	GSD	Min	Max
Transfer hopper	6	**1.38**	1.17	0.51	1.3	1.43	0.83	**2.2**	6	33	33	6	33	1.21	25	41
Grout pump	5	0.63	0.55	0.46	0.48	2.47	0.14	1.24	5	19	19	6	18	1.36	14	29
TBM bridge area	7	0.81	0.41	0.72	0.61	2.13	0.28	***2.2***	7	25	21	14	22	1.70	12	***52***
Conveyor extension	6	0.89	0.89	0.14	0.88	1.18	0.69	1.1	6	23	23	4	23	1.17	19	29
Pipe/walkway extension	2	0.34	0.34	0.1	0.34	1.33	0.28	0.41	2	14	14	0	14	1.00	14	14
Segment lift	1	***1.38***	***1.38***		***1.38***		1.38	1.38	1	***40***	***40***		***40***		40	40

* values in bold and italics denote highest AM, median, GM and maximum values

6.4.2 Measurements collected from contractors occupational hygienists

Tables 8 and 9 provides a summary of the personal sample results made available by the contractors occupational hygiene provider for measurements collected during previous SCL and TBM monitoring activities. Tables 10 and 11 provides a summary of the static sample results made available for measurements collected during previous SCL and TBM monitoring activities respectively. These data were collected from multiple sites, over an extended time period as works progressed and control measures were implemented and upgraded. Using the information provided by the contractors the data were allocated to job titles and areas where possible by the project team so to be consistent with the terminology used in this report and so some errors in allocation may have occurred. In some instances it was not possible to allocate static sampling areas to the terminology previously used and so the static sampling areas noted by the contractors are presented in these instances.

For the personal samples collected in the SCL environment (Table 8), three of the RD concentrations were below the analytical LOD (7%) whereas 5 of the RCS (42%) were below the LOD. The maximum concentration of 15.5 mg/m^3 was obtained from an engineer. No unusual activities were reported during this sampling period; however this measurement was collected at a time prior to the installation of the de-dusters (which are used to reduce the dust content in the air). Seven job titles reported maximum concentrations in excess of 1 mg/m^3, these being sprayer, engineer, plant operator, lead miner, pump man and operative and there were measurements also in excess of the 8-hr TWA WEL of 4 mg/m^3. Three RCS concentrations exceeded the 8-hr TWA WEL of 0.1 mg/m^3, these all being collected from plant operators. The plant operator also had the highest mean RCS exposures (AM 0.2 mg/m^3). No other information was available to put the results into context.

For the personal samples collected in the TBM environment, one of the RD concentrations was below the analytical LOD whereas none of the REC was below the LOD. The highest RD concentration was reported for a back-up miner (2.19 mg/m^3), with the locomotive driver reporting a RD concentration of 0.99 mg/m^3. One REC concentration (grout pump operator) was at the reference value of 100 µg/m^3 (Table 9). Very few REC measurement results were available and again, no further information was available in put the measurement results into context.

For the SCL static measurements, the highest RD measurement result was 5.06 mg/m^3 collected inside the restricted zone, with the highest mean for a static location being at the edge of the restricted zone (AM 1.4; GM 1.31 mg/m^3). In Table 10 it is evident that there were a number of occasions were concentrations were in excess of both the 8-hr TWA WEL of 4 mg/m^3 and also the 1 mg/m^3 (the IOM recommended guidance level). The number of RCS measurement results provided was limited. The highest concentration of 0.15 mg/m^3 was for a sample located inside the restricted zone.

For the TBM static measurements provided the maximum RD concentration was observed at the transfer hopper location (3.39 mg/m^3) and the mean was close to 1 mg/m^3. The maximum REC concentrations were reported to be at the grout pump station and conveyor extension (30 µg/m^3).

Table 8: Personal RD and RCS results by job title, SCL environment from contractors' occupational hygiene providers

	RD (mg/m^3)								RCS (mg/m^3)							
Job title	**N**	**M**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**	**N**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**
Inspector	1	0.42	0.42		0.42		0.42	0.42								
Sprayer	17	1.56	1.06	1.41	1.00	2.93	0.10	5.10	4	0.05	0.06	0.03	0.04	2.61	0.01	0.08
Engineer	13	***4.23***	***1.40***	5.12	***2.29***	3.05	0.64	***15.50***	1	0.04	0.04		0.04		0.04	0.04
Plant operator	8	0.92	0.80	0.58	0.71	2.48	0.10	1.94	3	***0.20***	***0.25***	0.16	0.01	6.00	0.10	***0.33***
Lead miner	2	1.55	1.55	0.78	1.44	1.70	0.99	2.10	1	0.01	0.01		0.01		0.01	0.01
Pumpman	4	1.57	1.29	0.70	1.47	1.49	1.10	2.60	2	0.01	0.01	0.00	0.01		0.01	0.01
Fitter	1	0.73	0.73		0.73		0.73	0.73								
Grouting	1	0.31	0.31		0.31		0.31	0.31								
Operative	2	0.89	0.89	0.28	0.87	1.38	0.69	1.09	1	0.18	0.18		***0.18***	0.18	0.18	0.18
Pit boss	1	0.76	0.76		0.76		0.76	0.76								
Surveyor	2	2.24	2.24	3.03	0.66	14.48	0.10	4.38								
Fixer	1	1.13	1.13		1.13		1.13	1.13								

* values in bold and italics denote highest AM, median, GM and maximum values

Table 9: Personal RD and REC results by job title, TBM environment from contractors' occupational hygiene providers

	RD (mg/m3)								REC (µg/m3)							
Job title	**N**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**	**N**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**
Locomotive driver	4	0.71	0.69	0.24	0.68	1.41	0.46	0.99	2	24	24	12	22	1.67	15	32
TBM driver	2	0.36	0.36	0.42	0.20	5.45	0.06	0.66								
Grout pump	2	0.11	0.11	0.00	0.11	1.00	0.11	0.11	1	***110***	***110***		***110***		***110***	***110***
Conveyor extension	2	0.39	0.39	0.37	0.28	3.30	0.12	0.65								
Back-up miner	1	***2.19***	***2.19***		***2.19***		2.19	***2.19***								
CRL inspector	1	0.05	0.05		0.05		0.05	0.05								

* values in bold and italics denote highest AM, median, GM and maximum values

Table 10: Static RD and RCS results by location, SCL environment from contractors' occupational hygiene providers

Location	RD (mg/m³)								RCS (mg/m³)							
	N	AM	Median	SD	GM	GSD	Min	Max	n<LOD	AM	Median	SD	GM	GSD	Min	Max
Outside restricted zone	28	0.69	0.67	0.43	0.50	2.58	0.10	1.77								
Inside restricted zone	40	1.18	0.95	1.07	0.76	2.93	0.08	***5.06***	4	***0.10***	***0.11***	0.06	***0.07***	3.38	0.01	***0.15***
Grouting	1	0.10	0.10		0.10		0.10	0.10								
Edge restricted zone	17	1.40	1.40	0.46	1.31	1.51	0.38	2.24	1	0.01	0.01		0.01		0.01	0.01
Deduster	4	0.99	0.83	0.88	0.62	3.69	0.10	2.21								
Steel reinforcement	2	0.28	0.28	0.08	0.27	1.33	0.22	0.33								
Shaft	6	0.46	0.45	0.31	0.36	2.33	0.10	0.89								
Junction/cross passage	20	0.86	0.79	0.83	0.57	2.78	0.10	3.86	1	0.00	0.00		0.00		0.00	0.00
Muncher	6	0.65	0.44	0.73	0.36	3.34	0.10	2.01	1	0.01	0.01		0.01		0.01	0.01
Alimack	1	0.15	0.15		0.15		0.15	0.15								
Walkway general tunnel	3	0.59	0.57	0.50	0.40	3.45	0.10	1.10								
Muck away	3	0.43	0.42	0.34	0.32	2.85	0.10	0.77								
Secondary lining	1	***1.88***	***1.88***		***1.88***		1.88	1.88								
Safe zone	7	0.37	0.35	0.23	0.32	1.90	0.10	0.83								
Yard box	6	0.77	0.79	0.52	0.59	2.36	0.17	1.46								

* values in bold and italics denote highest AM, median, GM and maximum values

Table 11: Static RD and REC results by location, TMB environment obtained from contractors occupational hygiene providers

	RD (mg/m³)								REC (µg/m³)							
Location	**N**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**	**N**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**
TBM bridge area	4	0.25	0.26	0.08	0.24	1.41	0.15	0.34	1	2	2	0	2	0	2	2
Grout pump	4	0.29	0.30	0.19	0.22	2.55	0.06	0.51	2	20	20	7	19	1.44	15	25
Loco driver	1	0.74	0.74		0.74		0.74	0.74	1	13	13	0	13	0	13	13
Refuge	5	0.38	0.48	0.19	0.30	2.50	0.06	0.52	3	15	17	6	14	1.64	8	20
Conveyor extension	11	0.52	0.72	0.37	0.33	3.38	0.05	***0.98***	2	25	25	11	24	1.60	17	33
Segment lift	4	0.20	0.22	0.10	0.17	2.13	0.06	0.30	2	6	6	8	3	6.39	1	12
Loco stop	2	0.25	0.25	0.08	0.24	1.41	0.19	0.31	2	11	11	6	10	1.75	7	15
Loco stop (upper level)	2	0.16	0.16	0.14	0.12	3.00	0.06	0.26								
Transfer hopper	6	***0.98***	0.55	1.23	0.51	3.78	0.07	3.39								
Booster hopper	1	0.89	***0.89***		***0.89***		0.89	0.89								

* values in bold and italics denote highest AM, median, GM and maximum values

6.5 BLACK CARBON DIRECT READING INSTRUMENT

Table 12 provides summary statistic for the BC concentrations recorded using the MicroAeth on each day of sampling in the SCL environment, with Figures 8-13 showing the temporal trends in BC concentrations. The recorded BC concentrations were, on average, greater during monitoring campaign 1, which is most likely due to the location of the samplers. During this time the direct reading instrument was located on a hop-up where diesel operated vehicles frequently passed by. In the second monitoring campaign the device was located in the SCL restricted zone which had less vehicular movement. The maximum one minute average BC concentration recorded was 206.47 µg/m^3 on 08/08/14.

Table 12: BC concentrations (µg/m^3) with SCL works

Date	AM	Median	SD	GM	GSD	Min	Max
06/08/14	29.19	26.15	11.15	27.30	1.43	15.51	65.47
07/08/14	39.83	36.55	17.05	37.17	1.43	15.86	137.10
08/08/14	57.24	53.90	22.46	53.79	1.41	23.88	206.47
04/11/14	31.08	19.83	27.49	22.34	2.24	5.21	148.51
05/11/14	20.15	17.09	11.36	17.82	1.62	5.07	84.49
06/11/14	22.49	18.99	12.19	19.82	1.64	7.00	72.35

As the activities in the tunnel areas could not be observed continuously during the monitoring campaigns, the engineers' reports (Appendix 1) were reviewed to help identify activities that may be contributing to the peak concentrations visible in Figures 8-13.

In Figure 8 the BC remain fairly low and relatively constant compared to other days of this monitoring campaign. During this shift it was apparent that mostly excavation activities were taking place with the removed earth being retained further up the tunnel. There was limited vehicular movement near the sampling position in comparison to the other two days of monitoring campaign 1. It is considered that the peaks evident in Figures 9 and 10 were as a result of vehicles removing the excavated earth.

The peaks in Figure 11-13 coincide with the excavation and spraying activities reported by the engineer. These activities involving the use of diesel operated equipment such as excavators, cement mixers, etc.

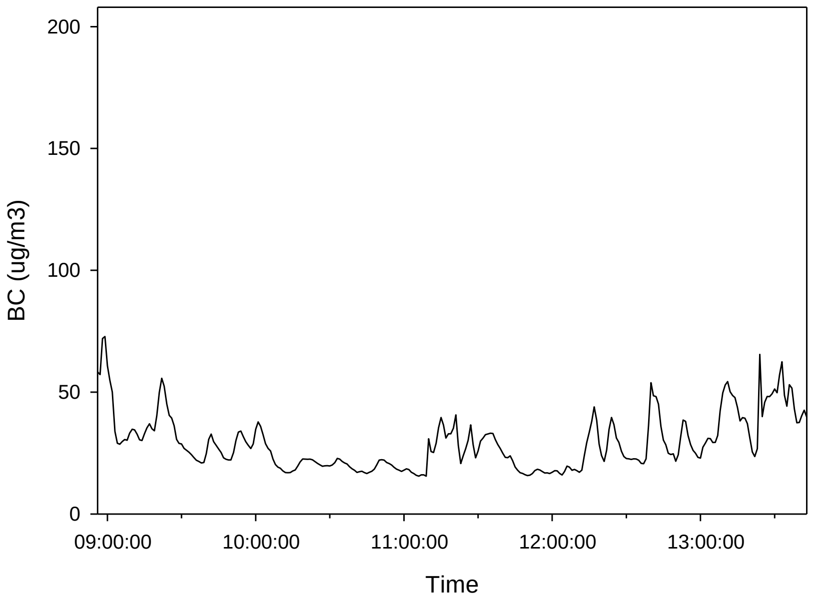


Figure 8: Temporal BC concentrations, hop-up outside SCL restricted zone, 06/08/14

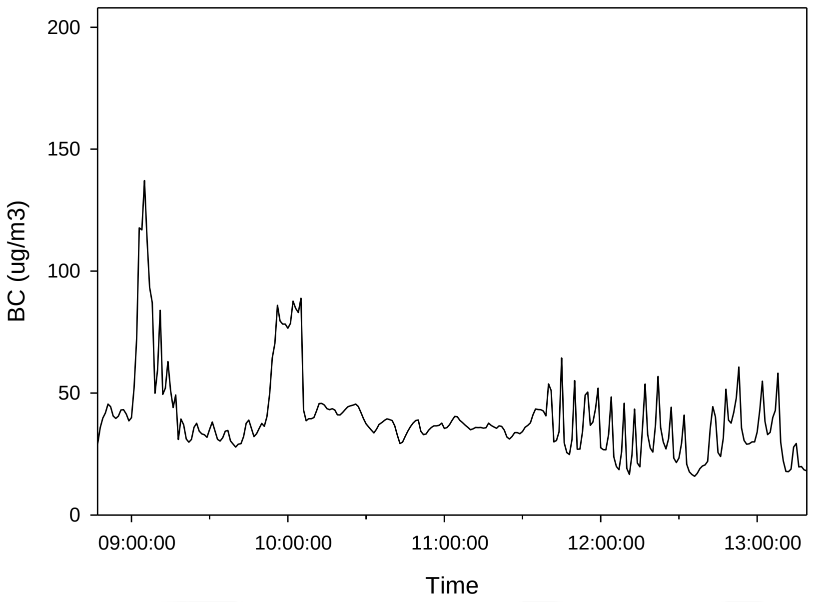


Figure 9: Temporal BC concentrations, hop-up outside SCL restricted zone, 07/08/14.

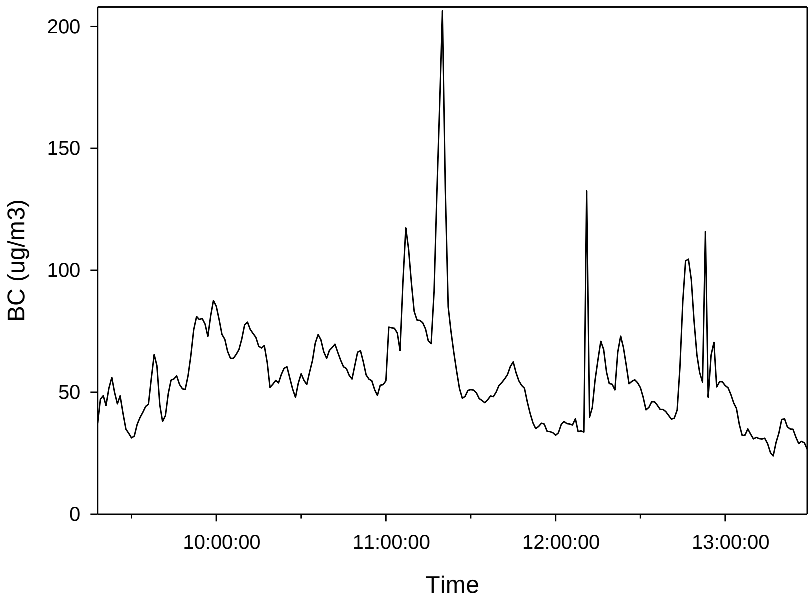


Figure 10: Temporal BC concentrations, hop-up outside SCL restricted zone, 08/08/14.

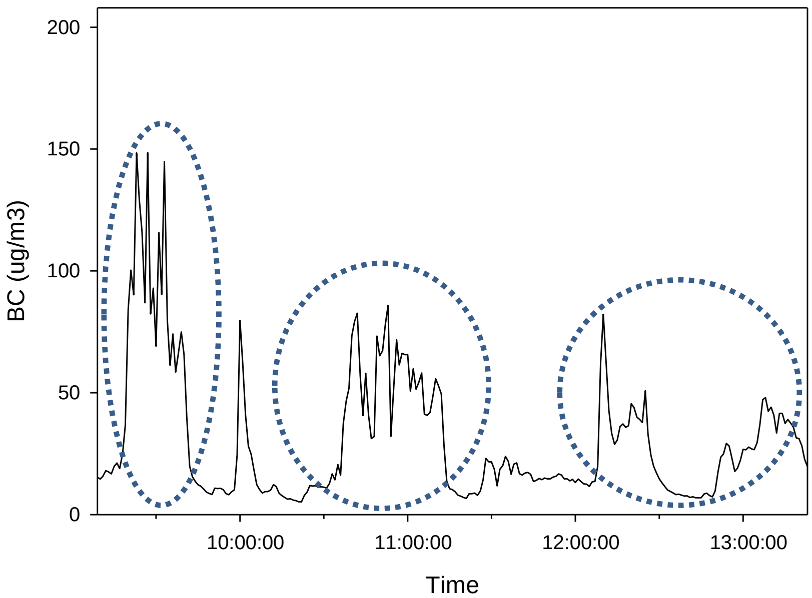


Figure 11: Temporal BC concentrations recorded inside SCL restricted zone, 04/11/14. Note: Circle denote (from left to right) 1st and 2nd peaks excavation activities, 3rd spraying activities

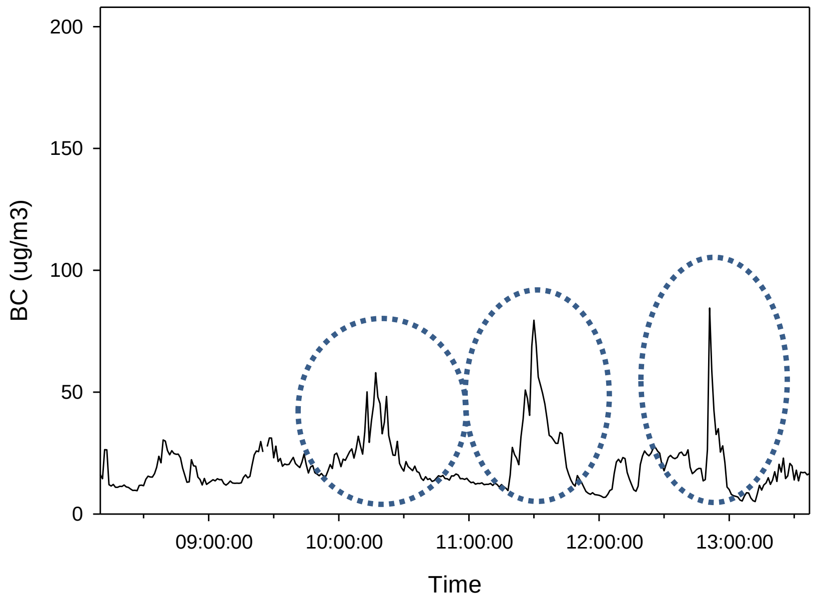


Figure 12: Temporal BC concentrations recorded inside SCL restricted zone, 05/11/14. Note: Circles denote (from left to right) 1st peak - excavation activities, 2nd and 3rd peaks linked to spraying activities

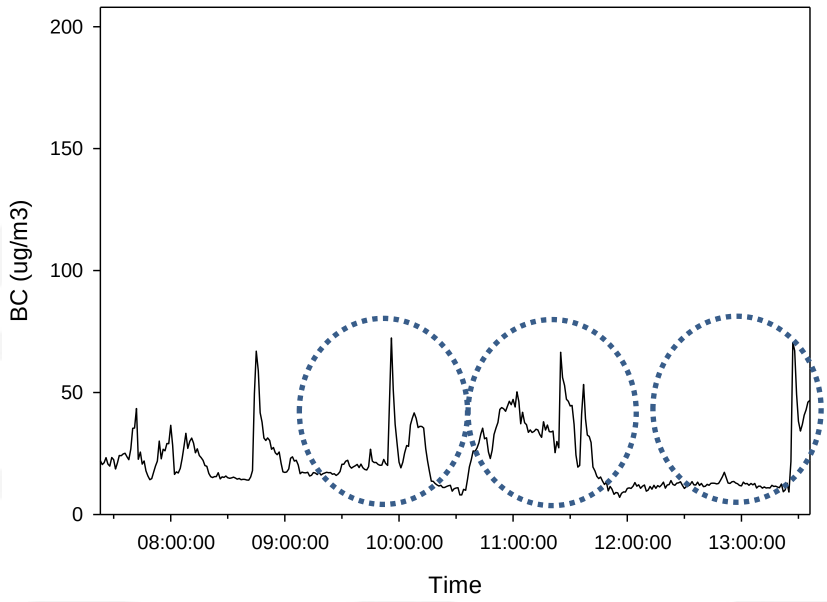


Figure 13: Temporal BC concentrations recorded inside SCL restricted zone, 06/11/14. Note: Circles denote peaks linked to initial and primary spray activities.

To put the BC concentrations obtained in the SCL environment into some context, the MicroAeth was used to monitor background measurements of BC in non-tunnel environments, both outdoors and indoors, on several occasions during the SCL monitoring campaigns (Table 13).

It is clear that the BC concentrations in the non-tunnel environments are a factor of 10 lower than the environments where SCL activities are being undertaken. The data also suggest that the BC concentrations are increased in the outdoor environment where cars and other vehicles are operating. However, they are not so high as in the tunnel environments and hence the concentrations reported in Table 12 are predominately due to sources from within the tunnel, rather than from supply air being brought into the tunnel environment.

Table 13: BC concentrations (μg/m^3) in non-tunnel environments during SCL monitoring campaigns

Date	Description	AM	SD	GM	GSD	Min	Max
08/08/14	Site office	3.81	0.30	3.80	1.08	3.25	4.50
04/11/14	Walking -site to hotel	9.18	5.25	6.22	3.40	0.19	22.05
05/11/14	Walking -site to hotel	10.30	5.19	9.19	1.64	4.29	23.18
05/11/14	Hotel room	2.20	0.82	2.10	1.35	1.60	4.26
06/11/14	Walking -hotel to site	5.31	3.20	4.32	2.03	0.59	13.58

Table 14 provides summary statistics for the BC concentrations recorded at the grout pumps station (lower level) on each of the monitoring days. The maximum one minute concentrations recorded during the TBM monitoring campaigns was 41 μg/m^3.

Table 14: BC concentrations (μg/m^3) on TBM over sampling period, sampling position at grout pump operator location

Date	AM	Median	SD	GM	GSD	Min	Max
25/11/14	4.95	4.58	2.90	4.44	1.54	2.35	17.78
26/11/14	6.48	6.07	2.16	6.22	1.31	2.84	25.77
27/11/14	6.22	6.06	3.43	5.59	1.58	0.86	36.42
10/12/14	5.07	3.52	3.94	4.05	1.89	0.95	25.31
11/12/14*	8.35	4.83	6.76	6.10	2.27	0.12	40.78
12/12/14	2.93	2.87	1.30	2.59	1.74	0.09	9.89

* Device was found to be switched off and was then restarted. No measurements collected for around 30 minute period

Figures 14 to 19 show the temporal BC concentrations over the monitoring periods. Included in these figures is information on when locomotives entered the TBM (shown by a green vertical line) and when they left the TBM (shown by a red vertical line). During the periods that the locomotive was present in the TMB the engines would be intermittently switched on and off as the locomotive moved to various locations to drop materials off.

In most of the monitoring periods peaks in BC concentrations were evident once the locomotive entered the TBM (as illustrated by Figures 15 and 16) and these usually coincided with when the locomotive positioned itself at the grout pump operator station. It was observed that the driver did switch the locomotive engines off when not moving therefore idling of the engine was minimised.

As highlighted in Section 6.3.2, on the 10th December the project team were advised (at around 11am) that the supply air had been reduced to 25% earlier in the shift and that it had then been increased back to 40%. It is evident from Figure 17 that a gradual increase in BC concentrations over this time period which then reduce around the time the supply air was then increased. A similar pattern is evident in Figure 18. On this day it was evident that there was a 'haze' in the air and a lack of air movement around the TBM and it was identified that the supply air had been turned down. At around 10.50am the air subjectively felt 'fresher' and the supply air tubing was observed to be re-inflated. In Figure 18 it is again evident that there is a gradual increase in BC concentrations during this time period, with the concentrations then declining when the supply air was back running to its usual level. The MicroAeth was found to be switched off during a routine check shortly after this time period and was then restarted.

These Figures highlight the need to ensure that any event requiring the supply air to be reduced should be minimised and that if it is reduced, it is increased back to normal as soon as possible.

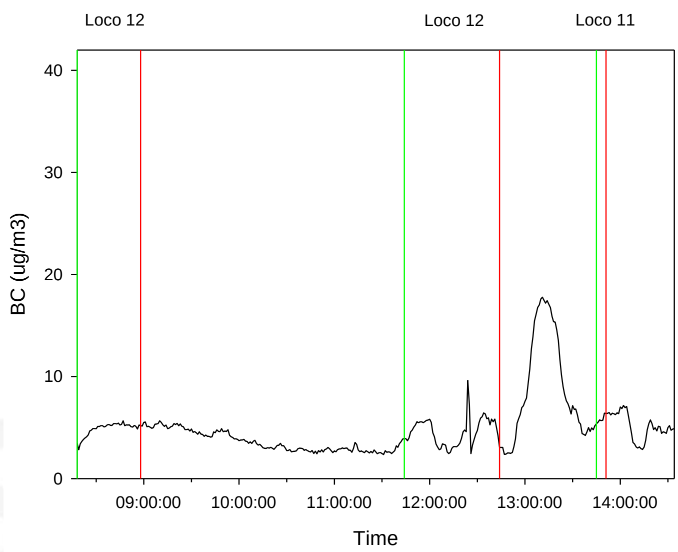


Figure 14: Temporal BC concentrations grout pump station, 25/11/14

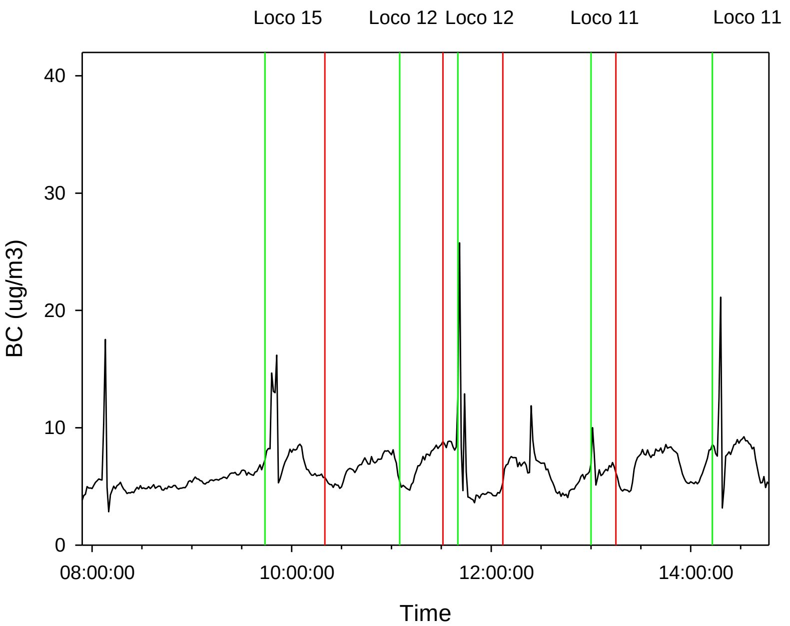


Figure 15: Temporal BC concentrations, grout pump station, 26/11/14

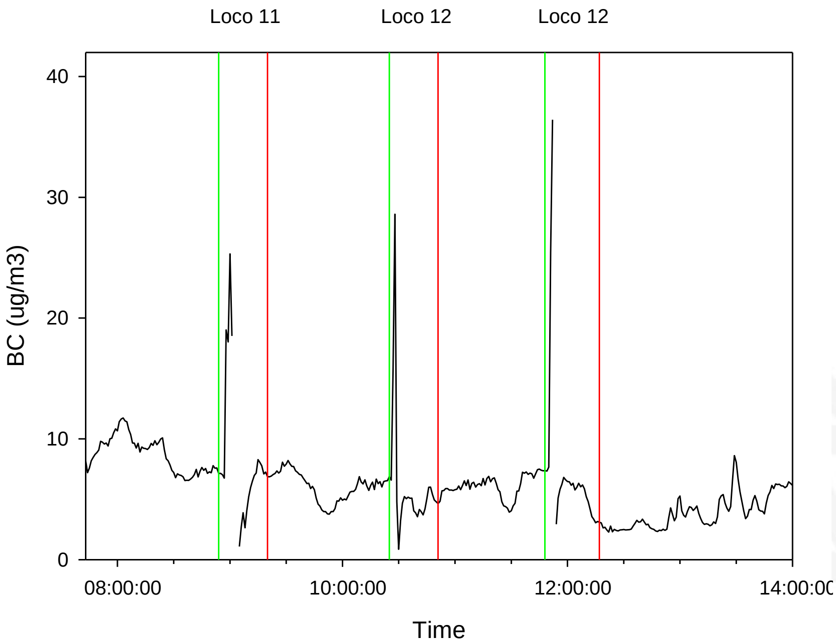


Figure 16: Temporal BC concentrations, grout pump station, 27/11/14

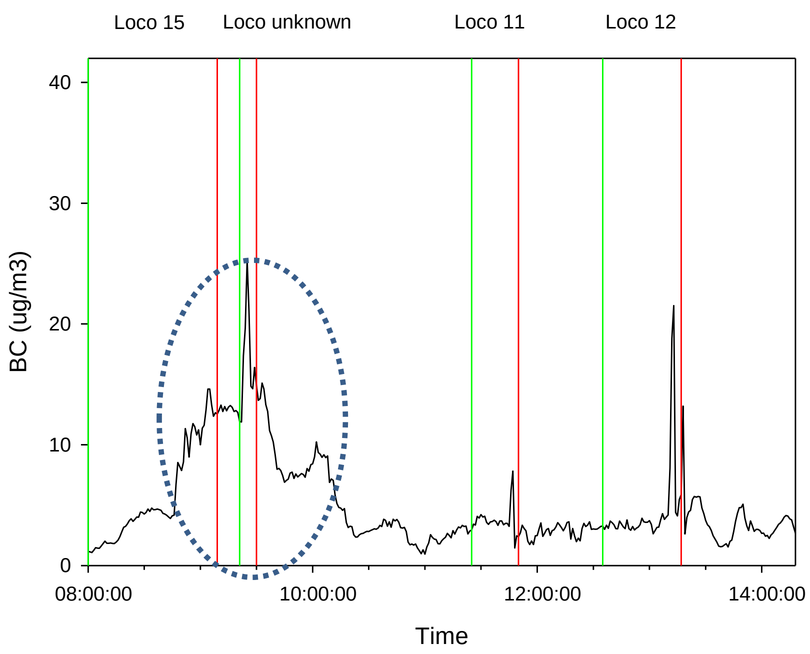


Figure 17: Temporal BC concentrations, grout pump station, 10/12/14
Note: Circle denotes period when supply air was turned down and then increased

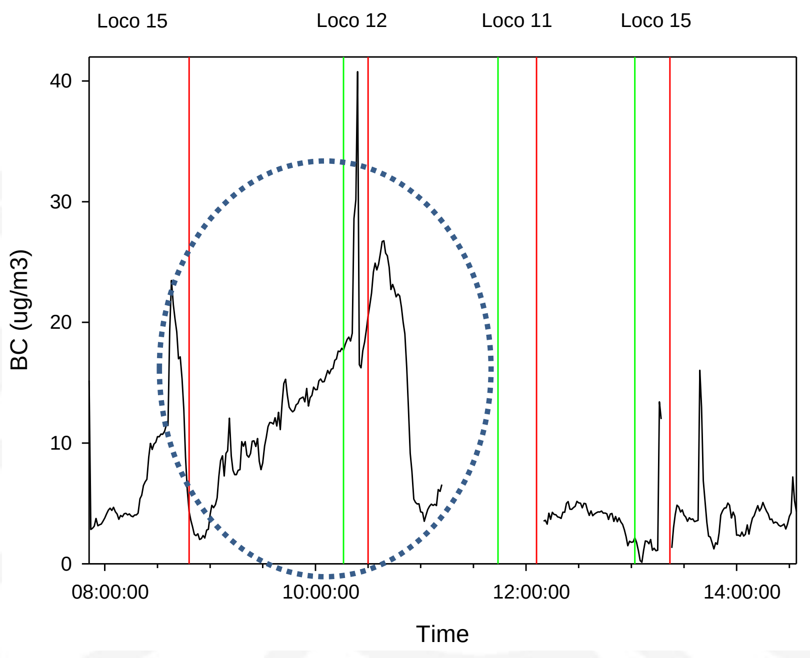


Figure 18: Temporal BC concentrations, grout pump station, 11/12/14
Note: Circle denotes period when supply air was turned down and then increased

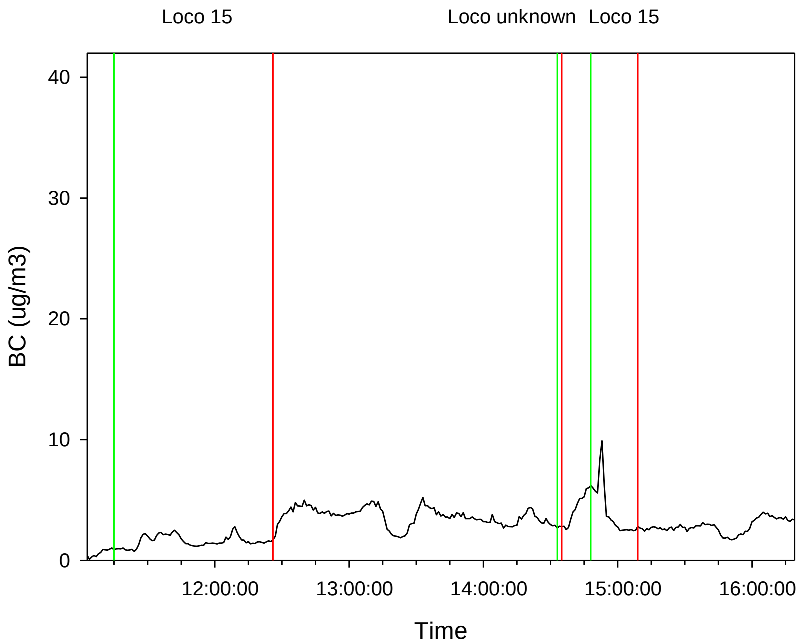


Figure 19: Temporal BC concentrations, grout pump station, 12/12/14

Again, to put the BC concentrations into some context, the MicroAeth was used to collect background measurements of BC in non-tunnel environments, both outdoors and indoors, on several occasions during the TBM monitoring campaigns (Table 15). The hotel was located around 3 miles from the site and travel to and from the site required a short walk and a journey on the Dockland Light Railway.

Table 15: BC concentrations (μg/m^3) in non-tunnel environments during TBM monitoring campaigns

Date	Description	AM	SD	GM	GSD	Min	Max
25/11/14	Hotel to site	4.40	1.35	4.18	1.40	1.59	7.69
25/11/14	Site to hotel	2.81	1.97	2.21	1.99	0.47	6.99
25/11/14	Hotel room	1.23	0.33	1.19	1.28	0.83	2.06
26/11/14	Hotel room & hotel to site	2.37	1.67	1.69	2.46	0.18	6.75
26/11/14	From site to hotel	8.28	4.30	7.12	1.81	1.89	22.14
26/11/14	Hotel room	2.50	0.53	2.45	1.21	1.40	5.43
27/11/14	Hotel to site	3.40	2.07	2.88	1.85	0.25	13.69
10/12/14	Hotel to site	1.62	1.74	1.03	2.72	0.11	7.16
11/12/14	Hotel to site	0.69	0.93	0.24	5.92	0.00	3.60
12/12/14	Hotel to site	0.69	0.88	0.26	5.33	0.00	3.72

The BC concentrations in tunnel environments were slightly elevated compared to those experienced during travel to and from the site (TBM AM range 2.93-8.35 μg/m^3 compared to 0.69-8.28 μg/m^3 travel to / from site). The low BC concentrations experienced whilst travelling to the site on 10-12th December may be attributable to the wet weather at these times.

6.6 RESPIRABLE DUST DIRECT READING INSTRUMENT

SidePaks were used to log the temporal trends in RD over the monitoring period. These devices were not calibrated for the airborne dust in the tunnels. Therefore, the measurement results cannot be compared with any exposure limit but are useful in terms of investigating temporal trends in RD concentrations and the relative differences in tunnelling environments and monitoring days.

Table 16 provides summary statistic for the RD concentrations recorded by the SidePak on each day of sampling in the SCL environment during monitoring campaign 1. Figures 20a-c show RD logged by the two SidePaks side by side in the tunnel environment during the first sampling campaign (y-axis on log scale), with good agreement between the two devices being noted.

Higher mean RD concentrations were reported on the last day of monitoring during this campaign and this is also evident in Figure 20c. It is considered that the higher peaks shown in this figure result from vehicles removing excavated earth.

Table 17 provides the summary statistics for the RD concentrations recorded by the SidePak on each day of sampling in the SCL environment during monitoring campaign 2. In comparison to Table 16, the mean concentrations are higher in the second monitoring campaign which is perhaps not surprising given that the devices were located inside the SCL restricted area. Higher mean RD concentrations were reported on the last day of monitoring during this campaign and which is probably due to the longer spraying activities that took place in both the RTE and RTW on this day in comparison with the previous days.

Figures 21a-c show RD concentrations logged by SidePaks in the RTE SCL restricted zone for each day of sampling during monitoring campaign 2. The engineers reports in Appendix 1 were reviewed to identify activities undertaken which coincided with the elevated concentrations and these were typically spray activities.

Figures 22a show the RD logged by SidePaks in the secondary lining work area on 4th November 2014 and Figures 22 b and c show the concentrations recorded in the RTW SCL exclusion zone on the 5th and 6th November respectively during Monitoring Campaign 2. Again, in Figures 22b and c, the engineers' reports suggest that the elevated concentrations are linked to spray activities.

Table 16: RD concentrations (mg/m^3) recorded using co-located SidePaks on 'hop-up' outside SCL restricted zone

	SidePak 10511052							SidePak 10511053						
Date	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**
06/08/14	0.24	0.23	0.07	0.23	1.28	0.14	0.66	0.21	0.20	0.06	0.20	1.28	0.11	0.56
07/08/14	0.26	0.23	0.10	0.24	1.40	0.11	0.71	0.23	0.21	0.08	0.21	1.40	0.10	0.53
08/08/14	0.49	0.34	0.47	0.39	1.74	0.18	3.08	0.46	0.31	0.49	0.36	1.78	0.17	3.02

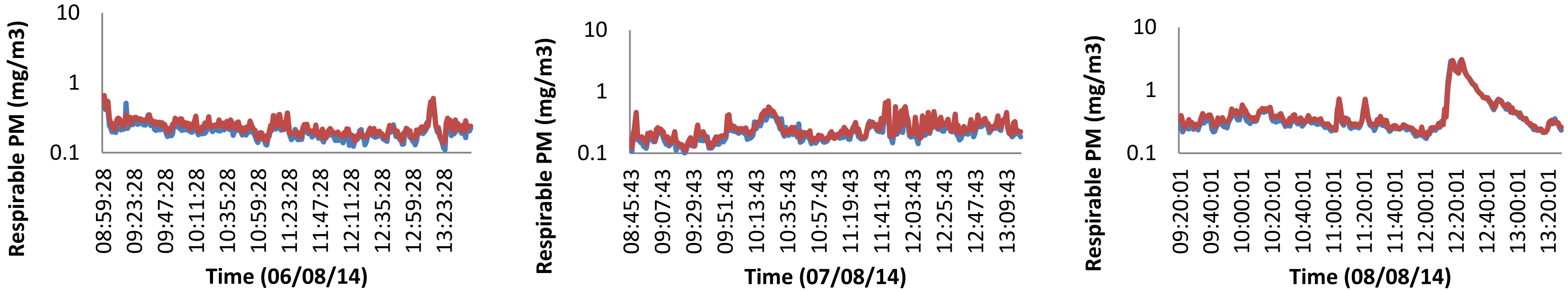


Figure 20 a-c: Temporal trends in RD concentrations (mg/m^3) during monitoring campaign 1
Note: Blue line is SidePak 1051103 and red line is SidePak 10511052.

Table 17: RD concentrations (mg/m^3) recorded using SidePaks located inside the SCL restricted zones

	Running Tunnel East (mg/m^3)							Secondary Lining (4/11/14) and Running Tunnel West (5/11/14 and 6/11/14) (mg/m^3)						
Date	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**	**AM**	**Median**	**SD**	**GM**	**GSD**	**Min**	**Max**
04/11/14	0.71	0.26	0.98	0.35	3.04	0.05	4.39	0.60	0.46	0.36	0.51	1.79	0.16	1.57
05/11/14	0.77	0.44	0.82	0.49	2.44	0.13	4.62	0.60	0.12	1.08	0.19	3.79	0.03	4.40
06/11/14	2.08	0.83	2.69	1.08	2.98	0.15	10.88	0.74	0.14	1.18	0.26	3.82	0.06	5.14

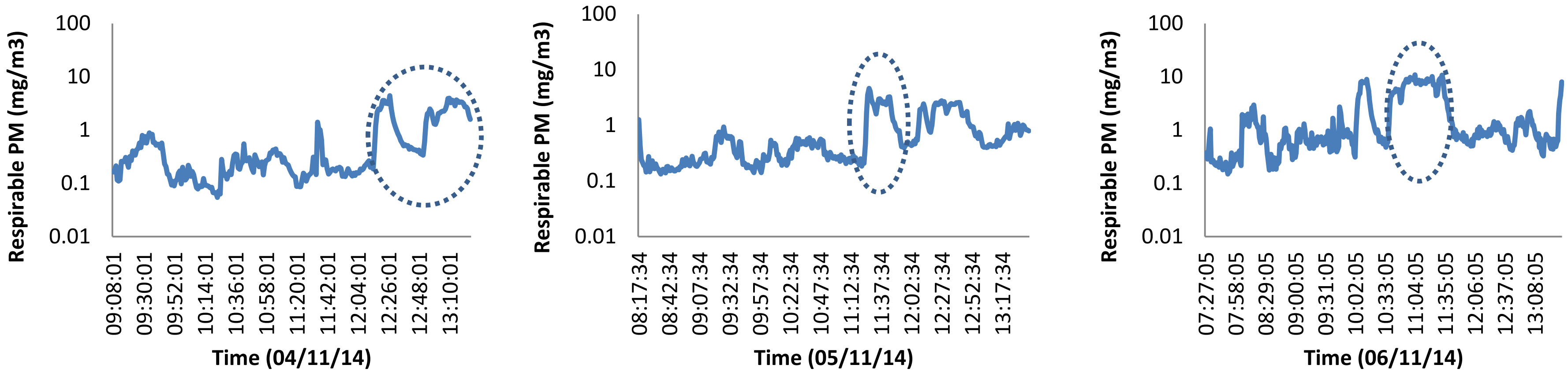


Figure 21a-c: Temporal trends in RD concentrations (mg/m^3) during monitoring campaign 2, RTE
Note: Circled areas show approximate spray times

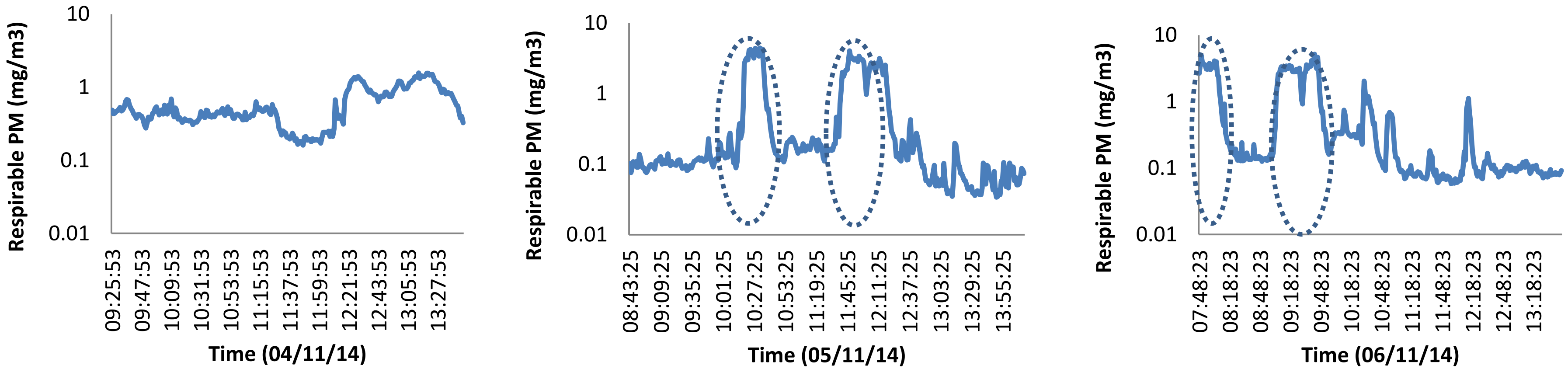


Figure 22a-c: Temporal trends in RD concentrations (mg/m^3) during monitoring campaign 2, RTW
Note: Circled areas show approximate spray times

Table 18 provides summary statistic for the RD concentrations recorded by the SidePak on each day of sampling at the group pump operator station, with Figures 23-28 showing the temporal trends concentrations at this location over each of the monitoring periods. The movement of locomotives in and out of the TBM is also displayed in these figures.

Table 18: Temporal RD concentrations (mg/m^3) on TBM over sampling period at grout pump operator station

Date	AM	Median	SD	GM	GSD	Min	Max
25/11/14	0.12	0.08	0.08	0.10	1.91	0.03	0.60
26/11/14	0.20	0.20	0.09	0.18	1.65	0.07	0.44
27/11/14	0.29	0.21	0.29	0.20	2.14	0.06	1.27
10/12/14	0.41	0.25	0.35	0.30	2.15	0.05	1.41
11/12/14	0.57	0.34	0.48	0.39	2.53	0.05	1.96
12/12/14	0.15	0.15	0.08	0.11	2.32	0.01	0.36

The highest mean and maximum concentrations were reported on the 10th and 11th December. As previously identified, the supply air was turned down for a period of time on both days and is likely to be responsible for the elevated concentrations.

In Figures 26 and 27 it is clear that RD concentrations followed a similar trend as was reported for the BC temporal trends, this being a gradual increase in concentrations during the period of time the supply air was lowered, with the concentrations then decreasing when it was ramped back up to normal.

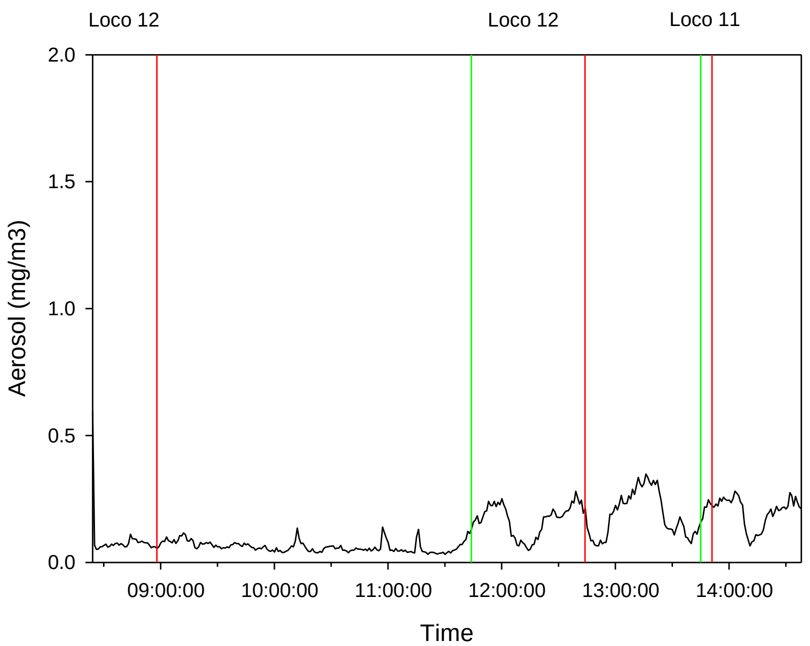


Figure 23: Temporal RD concentrations, grout pump station, 25/11/14

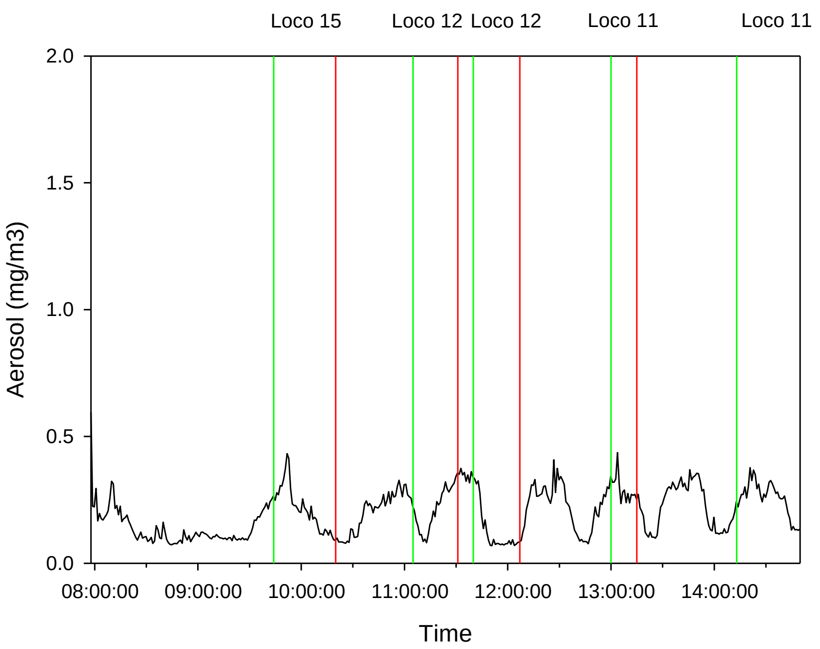


Figure 24: Temporal RD concentrations, grout pump station, 26/11/14

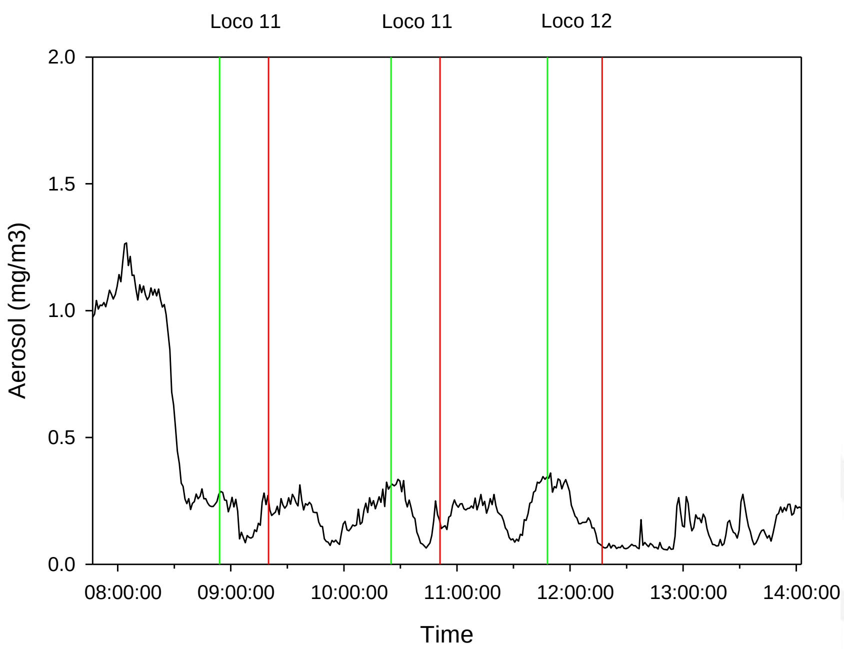


Figure 25: Temporal RD concentrations, grout pump station, 27/11/14

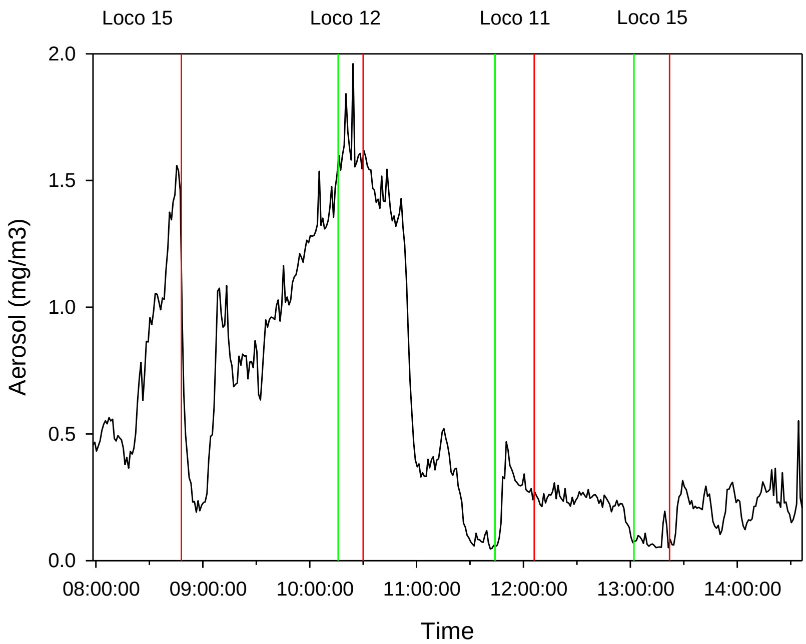


Figure 26: Temporal RD concentrations, grout pump station, 10/12/14

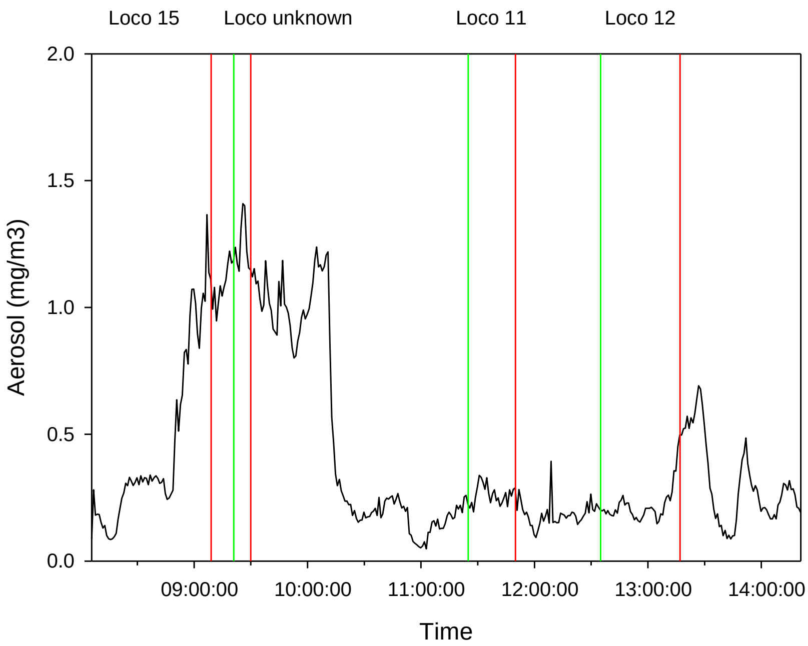


Figure 27: Temporal RD concentrations, grout pump station, 11/12/14

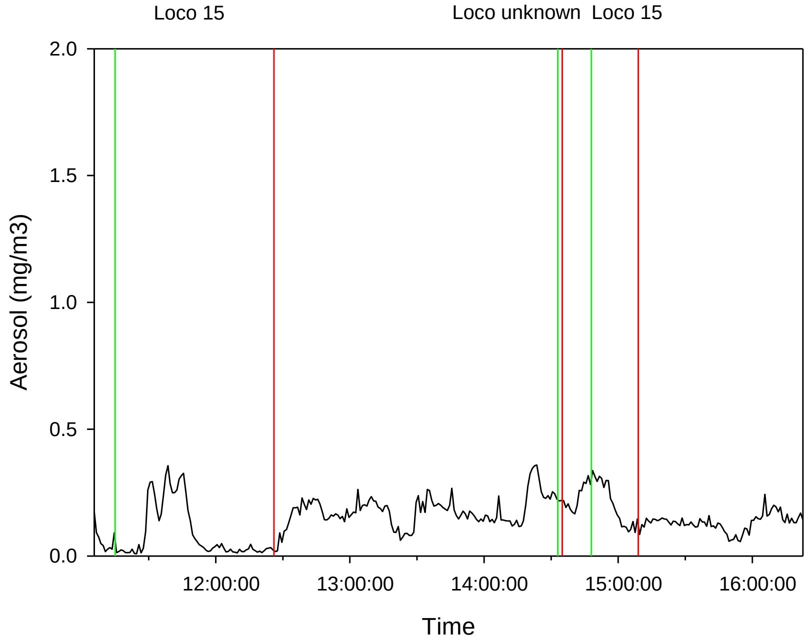


Figure 28: Temporal RD concentrations, grout pump station, 12/12/14

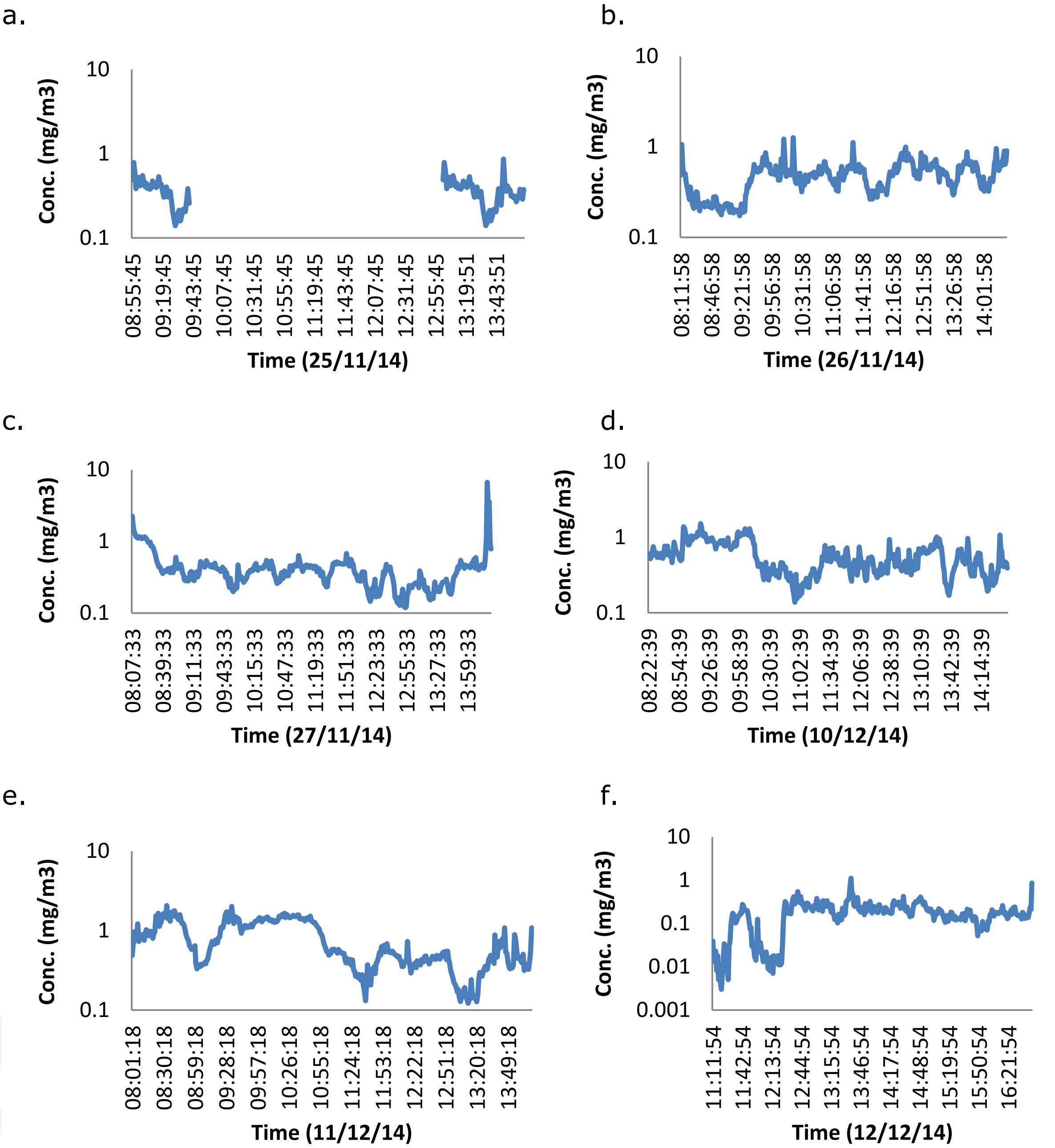
Table 19 provides summary statistics for the RD concentrations recorded by the SidePak on each day of sampling at the conveyor extension area, with Figures 29a-e showing the temporal trends concentrations at this location over each of the monitoring periods. On the first day of sampling the SidePak sustained damage which resulted in limited measurements being collected that day (Figure 29a).

Table 19: Real-time RD concentrations (mg/m^3) on TBM over sampling period, located statically at conveyor extension (upper level of TBM)

Date	AM	Median	SD	GM	GSD	Min	Max
25/11/14*	0.37	0.38	0.13	0.34	1.47	0.14	0.87
26/11/14	0.48	0.49	0.19	0.45	1.51	0.17	1.27
27/11/14	0.45	0.39	0.46	0.38	1.66	0.12	6.63
10/12/14	0.56	0.51	0.27	0.51	1.61	0.14	1.51
11/12/14	0.78	0.58	0.47	0.63	1.97	0.12	2.07
12/12/14	0.18	0.18	0.12	0.13	2.79	0.00	1.10

* SidePak was knocked and sustained damaged during this monitoring period and so duration of sampling was reduced

Again, the highest mean and maximum concentrations were reported on the 10th and 11th December. As previously identified, the supply air was turned down for a period of time on both days and is likely to be responsible for the elevated concentrations.



Figures 29 a-e: Temporal RD concentrations at conveyor extension area on each day of monitoring (y-axis on log scale). Figure 29a shows period SidePak was not in operation.

7 DISCUSSION

This study aimed to measure personal exposure to RD, RCS and REC during tunnelling activities at the Crossrail project, to estimate the average exposure of these to those workers / occupations who were likely to have the highest exposure levels, and to compare the average exposure levels to relevant WELs or reference values. In addition, temporal variability in BC and RD concentrations was also assessed.

The main dust related diseases affecting workers in the construction industry are lung cancer, silicosis, chronic obstructive pulmonary disease and asthma. Prolonged inhalation exposure to diesel fumes could lead to coughing, chestiness and breathlessness. IARC has recently classified diesel exhaust fumes as a human carcinogen (IARC, 2013). The IOM considers that the current British WELs for RD is unsafe and employers should attempt to reduce exposures to help prevent further cases of respiratory disease amongst their workers. The IOM adopts the approach of advising employers that it would be prudent to reduce exposures as far below the RD WEL as is reasonably practicable and that employers should aim to keep exposure to RD below 1 mg/m^3. The WEL for RCS is 0.1 mg/m^3 8-hour TWA. This is not a safe limit and, given the serious health risk associated with this, employers are required to reduce exposure below the WEL. For REC there is currently no existing WEL in the UK and a reference level of 0.1 mg/m^3 for DEEE was recently used in the SHECan project. Employers should take the necessary steps to prevent or adequately control exposure to DEEE.

During initial discussions with representatives of Crossrail and their contractors it was agreed that the research would focus on the TBM and SCL environments and that different measurement strategies would be employed. In the SCL environment, the focus of the campaign was the measurement of RD and RCS whereas in the TBM environment the focus was RD and REC, primarily based on contractors and their occupational hygienists' advice and their first hand observations of the work practices. The overall results in our monitoring campaigns suggest that BC exposures are higher during SCL than TBM activities and it is therefore recommended that future monitoring campaigns should focus on assessing DEEE exposures in the SCL environment.

Personal and static measurements of RD, RCS and REC were collected during the monitoring campaigns alongside information of the activities being undertaken where possible. It was not possible to continually observe all the activities taking place or for all operators to wear the personal sampling equipment. It was also evident that activities did not always progress as intended so the measurements collected during the monitoring campaigns reported here may not be representative of usual TBM or SCL activities. During the campaigns it was apparent that the operators involved and the wider 'gangs' were very interested in learning more about the exposure to RD, RCS and REC they were experiencing during their work. It is important that the results and implications of occupational hygiene monitoring campaigns continue to be communicated back to operators in a timely and appropriate manner.

For the personal samples collected in the SCL environment, all RD concentrations were well below the HSE WEL (4 mg/m^3), although there were several instances where 8-hr concentrations were in excess of 1 mg/m^3 (the IOM recommended exposure limit). All job titles, except for the pump man and inspector, had maximum concentrations in excess of 1 mg/m^3. The job titles that experienced the highest mean exposures were the back-up sprayer and sprayer who both undertook the concrete spray activities and were observed to be in the restricted zone during excavation activities. For RCS there were several instances where the 8-hr TWA WEL of 0.1 mg/m^3 was exceeded and these included the back-up sprayer, engineer, lead miner and 2 plant operators.

It was recognised that spray operators and engineers are likely to experience higher exposures than other operators and they were required to wear powered visors during spray activities. They were also observed to do so. Other operators working within the restricted zone were required to wear disposal 3M 8835 P3 respirators although these were not face fit tested. Where RPE is used, it must be able to provide adequate protection for individual wearers and be suitable for the wearer, task and environment. Face fit testing would allow the identification of suitable and adequate RPE for workers operating in this area. Operators should also receive refresher training on the need to wear RPE in this environment and supervised accordingly (HSE, 2013). However RPE is the last resort with respect to controlling exposure. Engineering controls, for example, de-dusters should be appropriately located and used during tunnelling operations. These should also be maintained to ensure that they operate correctly. Refresher training on the need to use control measures in the correct manner should be provided.

In the TBM environment, all the REC concentrations were below 100 µg/m^3. All of the personal and static RD concentrations were well below the HSE WEL (4 mg/m^3) however there were a number of instances where the RD exposures were in excess of 1 mg/m^3 (the IOM recommended guidance level). These included the job titles segment lift, grout pump, ring building, rail extension and conveyor extension. The job titles reporting where the mean RD concentrations were in excess of 1 mg/m^3 were the conveyor extension and rail extension operators. The highest reported REC concentration was for a segment lifter while the rail extension and conveyor extension operators had the highest mean REC exposure. Anecdotally, the conveyor extension operator was expected to have the highest RD exposure and attempts had reportedly been made to improve ventilation in this area. Further engineering control measures should be taken to reduce the RD exposure throughout the TBM but particularly in the conveyor extension area.

The REC concentrations on the TBM were less than 100 100 µg/m^3 however measures should still be taken to further reduce exposures. Locomotive engines operating during the monitoring campaigns were newer 'white' models which were reported to have more efficient extraction systems. The project team were advised that older, less efficient locomotives ('yellow' engines) were still in operation in the tunnels and so it is possible that higher concentrations may be experienced in tunnels where the older TBMs are used. A significant reduction of potential exposure to DEEE may be achieved by removing the older 'yellow' locomotive engines from circulation and replacing these also with the newer models. Unnecessary running or idling of diesel engines should always be avoided, especially indoors and refresher training should be provided to the locomotive drivers on a regular basis. Efficient ventilation is needed to assist in the removal of RD and DEEE. The supply air to the TBM was turned down during two monitoring periods when surveying activities took place. The impact that this had on exposure levels to RD and BC in the TBM was visualised in the direct reading instrument data. Further investigation is needed to ascertain why this practice takes place so that it can be eliminated or reduced.

Bakke *et al.* (2001) reported the highest RD GM exposures for shotcreters, shaft drillers and TBM workers, ranging from 2-3 mg/m^3. The GMs presented following our monitoring campaigns are lower than these, with the exception of the SCL back-up miner (GM=2.35 mg/m^3) which is based on two measurement results.

Direct reading instruments are useful tools to identify the influence the impact of different activities on exposures and also to help identify any unusual occurrences. The MicroAeth and SidePak were used to log the temporal trends in BC and RD during the monitoring campaigns. Following review of the temporal trends and the reports on the activities that took place during the monitoring activities the devices did prove useful at identifying the impact that excavation and spray activities had on exposures in the SCL environment, as well as the reduction of supply air in the TBM.

Cai *et al.* (2014) noted that when using the MicroAeth AE51 as a personal monitor, abrupt changes in temperature and/or relative humidity could cause false temporary excursions in the BC readings. Similar issues were evident in some of the background measurements collected in non-tunnel environments, particular when moving within a short time period from an indoor to outdoor environment (and vice versa). In instances were negative values were recorded these were removed from the dataset for the analysis. Given that the temperature and relative humidity within the actual tunnel environments was fairly constant, the MicroAeth concentrations were unaffected during the collection of measurements in the tunnels.

The results indicated that in both environments, higher BC concentrations than background (non-tunnel environments) occurred. However, the BC concentrations recorded in the SCL environment were significantly higher than those experienced in the TBM environment. Excavation and spray activities were noted to increase exposure due to the use of diesel powered engines during these times. It is therefore recommended that future monitoring campaigns should focus on assessing DEEE exposures in the SCL environment and that appropriate measures are implemented to control exposures as necessary. For example, appropriate and sufficient ventilation within the tunnel, tailpipe exhaust extraction systems, switching off engines when not required etc. (HSE, 2012).

No previous published studies reporting use of the MicroAeth in tunneling environments could be identified so no direct comparisons of the current measurements could be made. Many studies are however available which report BC concentrations in various micro-environments. For example, Dons *et al.* (2012) report a study which used the MicroAeth to measure personal BC exposure in various micro-environments including transport. Personal exposure was influenced by mode of transport with mean BC concentrations of 2.39 µg/m^3 during travel by train; 5.07 µg/m^3 when travelling on light rail/metro; 5.58 and 6.58 µg /m^3 when travelling on in a car and bus respectively. Don *et al.* (2013) reports average BC concentrations on highways of 10.7 µg/m^3, which were significantly higher than concentrations on rural roads (6.1 µg/m^3) but comparable to concentrations on urban roads (9.6 µg/m^3). These are comparable to the concentrations reported during the TBM monitoring campaigns; however the concentrations reported during the SCL campaigns were higher.

No previous published studies reporting the use of the SidePak in tunneling environments could be identified so no direct comparisons can be made. The devices used the factory standard calibration of 1, which is where the equipment is calibrated to Arizona Road Dust. As this dust may be different in density, shape and size from the airborne dust in the tunnels, the results from the SidePaks should not be compared with the WEL or other reference levels. However, the results do provide useful data to investigating temporal trends in respirable particulate concentrations and the relative differences in tunnelling environments and monitoring days.

Similar trends as reported for the BC were observed for the RD results from the SidePaks, with excavation, spray and vehicular activities leading to relatively higher concentrations in the SCL environment. The impact of the locomotive movement and the reduction in supply air was again demonstrated in the TBM data and the recommendations as highlighted earlier in this section as again applicable.

Occupational hygiene measurement data for the hazardous substances of interest to this study were made available on an anonymous basis to IOM by the contractors' occupational hygiene providers. Given the confidential nature of the information, some relevant contextual information to help inform the results was unavailable. The measurement results providers were collected from several sites, over an extended time period during which improvements in control methods had been made. In addition different sampling methodology had been used to collect the samples - cyclones were used in the current sampling campaign whereas RD and RCS/EC had been determined previously using an IOM foam sampler. Studies have been undertaken which compare different methods of sampling the respirable fraction. Kenny *et al.* (2001) in a study at different industrial settings (including silica dust) did not found statistically significant differences in the concentration of RD measured by a variety of cyclones and the IOM dual-fraction sampler. In contrast, a study by de Vocht *et al.* (2008) in the brick manufacturing industry found a ratio between the cyclone/IOM of 1.9, and R^2=0.77 for sampling of silica dust. The correlation decreased as the concentration of clay particles increased. The authors concluded that the performance of the IOM foam sampler depends on the relative concentration of clay particulates in the dust matrix. Linnainmaa *et al.* (2008) reported that the IOM foam sampler for RD under-estimated the respirable fraction with high dust loads.

Construction projects of the nature and scale of Crossrail offer a valuable opportunity to collect and store large volumes of occupational hygiene data to allow for a more robust statistical analysis to be undertaken. It is advised that all large scale construction projects should consider the implementation of a controlled sample and contextual information collection protocol. This should include the development of a purpose built central data storage system to allow the collected information to be stored in a controlled and systematic manner. It may be possible that such a scheme may be expanded further across the construction industry.

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ABBREVIATIONS AND GLOSSARY

AM	Arithmetic mean. This is the average of a set of numbers.
BC	Black carbon. This is the most strongly light-absorbing component of particulate matter (PM), and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass.
COSHH	Control of Substances Hazardous to Health. The Control of Substances Hazardous to Health Regulations 2002, as amended is a United Kingdom Statutory Instrument that states general requirements on employers to protect employees and other persons from the hazards of substances used at work by risk assessment, control of exposure, health surveillance and incident planning. There are also duties on employees' to take care of their own exposure to hazardous substances.
CP	Cross Passage. A cross passage is a tunnel cut between two other tunnels for safety or service reasons.
DEEE	Diesel engine exhaust emissions. These are products of diesel combustion and contain a complex mixture of gases, vapours, liquid aerosols and particulate substances.
EC	Elemental carbon. This is emitted during the combustion of fossil fuels as small, sooty particles often with other chemicals attached to their surface.
EPBM	Earth Pressure Balance Machines. A mechanised tunneling method in which spoil is admitted into the tunnel boring machine (TBM) via a screw conveyor arrangement which allows the pressure at the face of the TBM to remain balanced without the use of slurry.
HSE	Health and Safety Executive. The HSE is the national independent watchdog for work-related health, safety and illness. It acts in the public interest to reduce work-related death and serious injury across Great Britain's workplaces. HSE is an executive non-departmental public body, sponsored by the Department for Work and Pensions.
GM	Geometric mean. In mathematics, the GM is a type of average, which indicates the central tendency or typical value of a set of numbers by using the product of their values (as opposed to the AM which uses their sum).
GSD	Geometric standard deviation. The GSD describes how spread out are a set of numbers whose preferred average is the GM. Note that unlike the usual *SD*, the *GSD* is a multiplicative factor, and thus is dimensionless, rather than having the same dimension as the input values.
IOM	Institute of Occupational Medicine. One of the leading providers of workplace health research and consultancy services. Our expertise extends across a very wide range of scientific disciplines.
l/min	litres per minute. Unit of measurement, the transfer of a volume of substance per unit of time.
LOD	Limit of detection. In analytical chemistry, the LOD, is the lowest quantity of a substance that can be distinguished

	from the absence of that substance (a blank value) within a stated confidence limit.
m/s	metres per second. The distance travelled in metres by the time in seconds.
Max	Maximum. The greatest quantity.
MDHS	Methods for the Determination of Hazardous Substances. A series published by HSE Books that describes procedures for measurement of personal exposure to contaminants in air.
mg/m^3	milligrams per cubic metre. Measurement unit of the amount of chemical vapour, fumes or dust in the air.
MicroAeth	MicroAeth AE51. Real-time black carbon aerosol monitor.
Min	Minimum. The smallest quantity.
ml/min	millilitres per minute. Unit of measurement, the transfer of a volume of substance per unit of time.
PPE	Personal protective equipment. PPE is equipment that will protect the user against health or safety risks at work. It can include items such as safety helmets and hard hats, gloves, eye protection, high-visibility clothing, safety footwear and safety harnesses.
RCS	Respirable crystalline silica. RCS is the respirable dust fraction of crystalline silica which enters the body by inhalation.
RD	Respirable dust. The RD fraction corresponds to the proportion of an airborne particle, which penetrates to the pulmonary alveolar region of the lungs.
REC	Respirable elemental carbon. REC corresponds to the respirable fraction of EC which enters the body by inhalation.
RH	Relative humidity. The amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature.
RPE	Respiratory protective equipment. RPE is a particular type of PPE designed to protect the wearer from breathing in harmful substances or from oxygen-deficient atmospheres when other controls are either not possible or insufficient on their own.
Rpm	revolutions per minute. This is a measure of the frequency of rotation, specifically the number of rotations around a fixed axis in one minute. It is used as a measure of rotational speed of a mechanical component.
RTE	Running Tunnel East
RTW	Running Tunnel West
SAL	Scientific Analysis Laboratories. Company name.
SCL	Spray concrete lining. Technique which involves rapidly spraying the excavated ground with concrete to stabilise it and form the permanent tunnel lining.
SD	Standard deviation. The SD is a measure that is used to quantify the amount of variation or dispersion of a set of data values.
SidePak	TSI SidePak AM510. A real time aerosol monitor.
TBM	Tunnel Boring Machine. A machine used to excavate tunnels

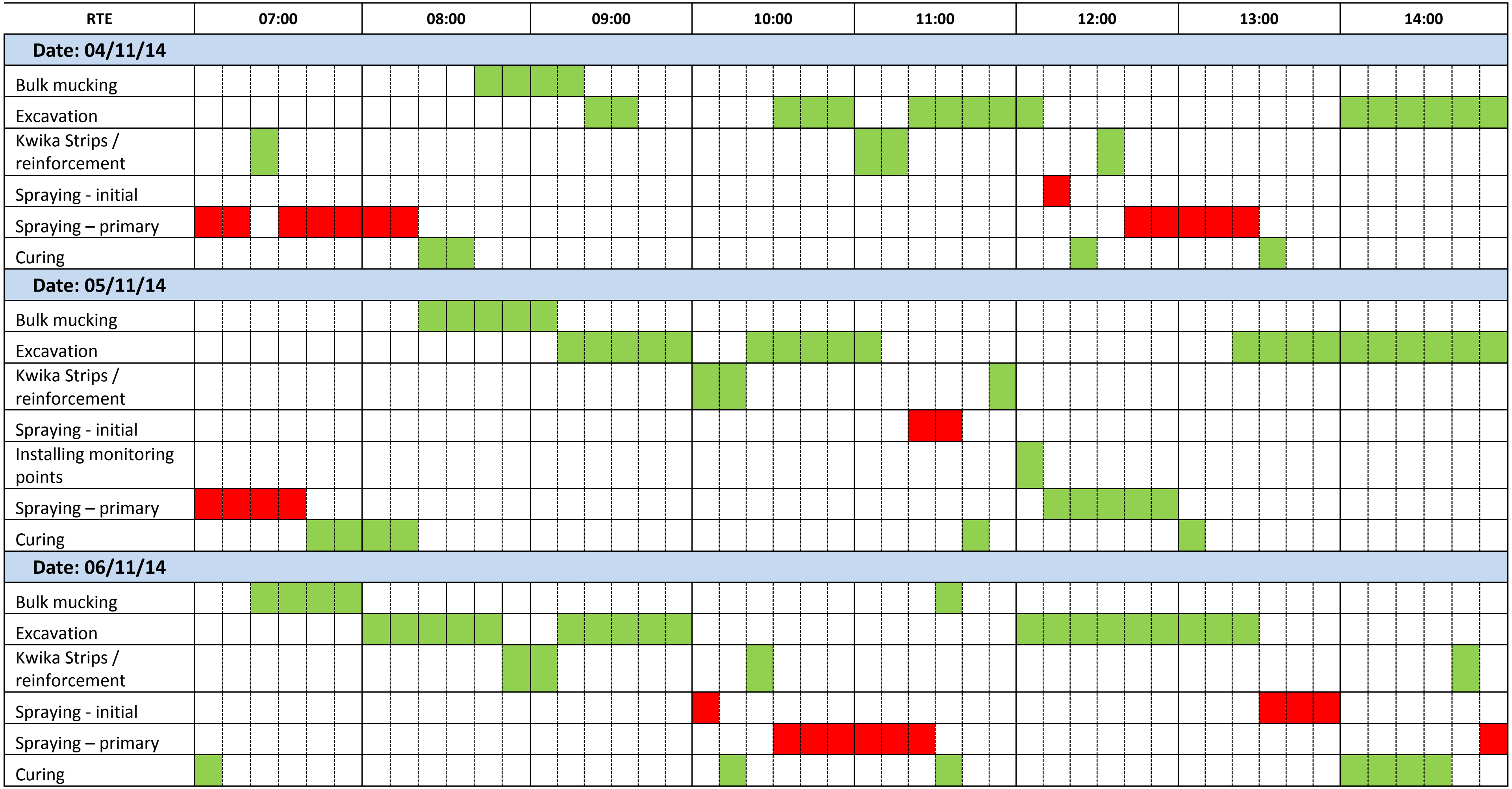
	with a circular cross section through a variety of soil and rock strata.
TWA	Time weighted average. A time weighted average (TWA) is the average exposure over the given time period.
WEL	Workplace Exposure Limit. Exposure limits set by the Health and Safety Executive (HSE) in Britain to protect the health of workers.
$\mu g/m^3$	micrograms per cubic metre. Measurement unit of the amount of chemical vapour, fumes or dust in the air.

APPENDIX 1: SUMMARY OF ENGINEERS REPORT FOR SCL MONITORING CAMPAIGNS

Table A1: Summary of engineers report on activities that took place during SCL works in Monitoring Campaign 1

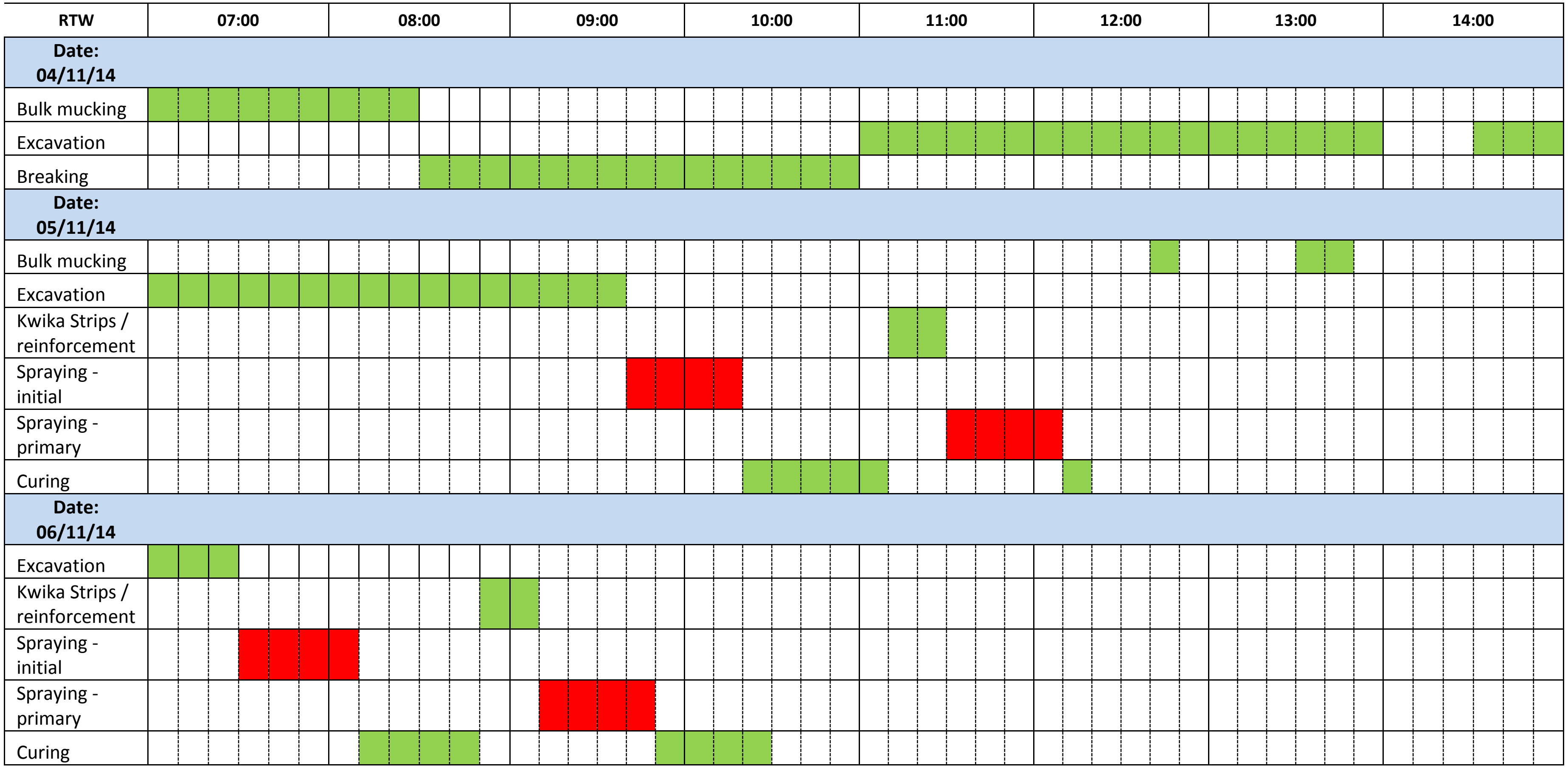
	07:00	08:00	09:00	10:00	11:00	12:00	13:00
Date: 06/08/14							
Break							
Excavating ADV 2							
Muck placing in Eastbound							
Concreting walkway							
Moving plant CP5							
Setting up plant to spray initial							
Date: 07/08/14							
Break							
Spraying initial ADV 4							
Cleaning rebound and joint							
Spraying primary ADV 4							
Waiting for 0.5MPa advance 4 to start ADV 5							
Excavating ADV 5							
Date: 08/08/14							
Break							
6 Cores taken from panel 4							
Excavating ADV 8							
Setting up to Spray							
Moving De-duster base							

Table A2: Summary of engineers report on activities that took place during SCL works in Monitoring Campaign 2, RTE



Note: Red colour shows periods of spray activities

Table A3: Summary of engineers report on activities that took place during SCL works in Monitoring Campaign 2, RTW



Note: Red colour shows periods of spray activities

APPENDIX 2: SUMMARY OF ENGINEERS REPORTS FOR TBM MONITORING CAMPAIGNS AND LOCOMOTIVE MOVEMEMENTS

Table A2.1: Summary of engineers report on activities that took place on TBM during Monitoring Campaigns 3 and 4

Date	Rings built	Comments
25/11/14	10	Belt failure (tension loss), sump pump in ring build areas failed.
26/11/14	11	Tunnel belt stopped at booster and sump pump in ring build areas failed. Cleaning grout from ring build area
27/11/14	8	Segment placed incorrectly and had to be removed and re-built into correct position
10/12/14	8	Changing damaged rollers
11/12/14	9	Surveyors changing laser, waiting from grout
12/12/14	4	Safety 'stand down' (4 hr) so no activity during this time. Waiting on belt at pit bottom to be manned. Advance affected by low penetration, high thrust, cleaning grout lines, extending TBM supply services and general cleaning

Table A2.2: Details of number of locomotive movements, recorded by site during shift and by researchers during actual monitoring periods

	Recorded by site			Recorded by researchers		
Date	11	12	15	11	12	15
25/11/14	7	15	1	1	2	0
26/11/14	8	9	8	2	2	1
27/11/14	8	8	6	1	2	0
10/12/14*	4	4	2	1	1	1
11/12/14	2	3	3	1	1	2
12/12/14*	5	6	5	0	0	2

* Also an additional 'unknown' locomotive movement at TBM recorded by researchers