Scientific Services
for Transport & Industry
4-RAIL
Services Ltd

Unit 11, Ironbridge Close, Great Central Way
London NW10 0UF

Telephone: 020 8955 1700
Facsimile: 020 8830 1003
Email: enquiries@4-rail.com

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# *SIMULATIONS OF S STOCK TRAIN FAN SYSTEMS TO ASSESS THE EFFECT ON DUST IN BALLAST ON THE METROPOLITAN LINE*

*Prepared for:* *Mr Colin Chettle*
*Project Manager – SSR Upgrade*
*London Underground*
*8th Floor Euston House*
*24 Eversholt Street*
*Euston*
*London*
*NW1 1AD*

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*Prepared by:* *R. Griffiths*
*Technologist*

*Signature:* .......... [redacted]

*Certified by:* *Dr S. P. Hargreaves*
*Senior Consultant*

*Signature:* .......... [redacted]

**VAT Registration No: 691 5975 82**
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**Great Central Way, London NW10 0UF**
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# 1 Introduction

1.1 London Underground are currently in the process of upgrading Metropolitan Line A Stock trains with new S Stock, the first of which is reportedly due for commissioning in March 2010. It had come to the attention of the project manager that the new trains make use of two systems which differed considerably from the A stock. These were the cooling fans for the braking system and the positioning of the exhaust vents of the air conditioning (HVAC) systems on the top of the trains.

1.2 The exhaust cowling from the braking system fans is positioned below the sole bar of the train on each carriage and is directed downwards towards the track. The problem identified with this was that the airflow could potentially raise airborne dust from track ballast, particularly in closed sections of the line and in station areas. It was also thought possible that air exhausts from the HVAC units could disturb dust at higher levels (e.g. on cable runs) within closed sections.

1.3 4-RAIL Services Limited were requested to carry out a program of testing to assess possible dust raising by simulating the airflows of the S stock trains in the track environment. The information gathered would provide a realistic view of the extent of the problem, and identify areas where tunnel cleaning would be required.

1.4 The area of track under consideration for this investigation was the Metropolitan Line (north and southbound roads) between a site slightly north of Baker Street Station and Aldgate Station. These sections comprised both open and closed areas. The work to simulate the train airflow ducts firstly required the identification of test sites on the line; in many instances it was of primary importance to find areas that would represent the ‘worst case scenario’.

1.5 The findings of the preliminary assessments carried out during two track walks undertaken on 3rd and 4th June 2009 are reported in 4RS-RG-090149-R211501. During the surveys, sites were visually assessed and allocated a rating of 0 – 5 (5 being dustier). A small handheld air pump with a nozzle was used to disturb minor amounts of dust during the surveys (Figure 1).

# 2 Aims of the Investigation

2.1 The primary aim of the investigation was to determine the likely effect that the S Stock train braking system exhaust airflow will have on track ballast on the Metropolitan Line. In particular, it was required to provide an assessment of whether the levels of dust in stations and tunnels would be expected to increase from present levels due to introduction of the new trains.

2.2 Of slightly less concern was the S Stock train HVAC exhaust airflows. It was required to provide an assessment of whether this lesser concern was valid by assessing the decrease in air velocity from the exhaust apertures of the HVAC units and relating this to the distances from the apertures to areas within tunnels that may be dusty.

# 3 Methods of Assessment

3.1 The section of track to be covered was reportedly about 6 – 7 km long; it was therefore agreed that it would be impossible to test every position along the line. Preliminary assessments had identified areas of higher concern than others, and in most cases, particular sites were chosen so as to be representative of a section of track.

3.2 The concept decided upon was a custom test rig mounted to a track trolley such that it could be moved between locations during engineering hours. Strict controls were required to ensure that any dust raised did not resettle on station platforms or interfere with train running. This meant that tests would have to be made while stationary. However, due to less wind interference, this was also thought to be representative of a worst case scenario.

3.3 The design of the test rig required an inspection of an S Stock train such that a similar fan exhaust and airspeed could be built into the rig

3.4 To simulate the airspeeds of the HVAC unit, a simple laboratory test was designed to assess the likely airspeeds at various distances from the exhaust apertures.

## 4 Inspection of S Stock Train at Asfordby Depot

4.1 A visit was arranged for the S Stock train testing depot in Asfordby near Leicester on 15th June 2009. The primary aim of the inspection was to determine the positioning, size, shape, orientation and airflow speeds of the braking system exhaust duct, Figure 2. As far as possible it had also been desired to inspect the train HVAC units on the new trains, Figure 3.

4.2 Documentation received from the client had indicated that the average airflow speed and air volume from the braking system fans was about 6.3 m/s and 1.05 $m^3/s$ respectively. For the HVAC unit, the average air speed at the outlets was 5 m/s and the fan flow rate was 1.53 $m^3/s$ per fan. Brake fan airspeeds were verified at the depot using a calibrated vane anemometer at a distance of about 50 mm from the cowling, parallel to the end angle of the cover at various positions as shown in Figures 2, 4 and 5. The following airspeeds were measured:

| Position | Airflow Readings (m/s) | Average Airflow Speed (m/s) |
|---|---|---|
| 1 | 7.33, 6.34, 6.90, 6.75 | 6.83 |
| 2 | 6.45, 6.48, 5.88, 5.77 | 6.16 |
| 3 | 7.80, 7.75, 7.36, 7.87 | 7.69 |
| 4 | 0.98, 0.52 | - |
| 5 | 5.80, 5.44, 7.25, 7.89, 8.32 | 6.94 |

4.3 The cowling was formed of steel sheet with a rectangular aperture at its front edge. A curved baffle plate was positioned on its underside as shown in Figure 4. The back edge of the baffle plate did not extend fully to the main aperture, i.e. there was a rectangular gap present. There was also a small curved plate (vent) mounted in this gap, between the main grid and the baffle plate as shown in Figure 5. During testing, it was found that very little air escaped through the gap between the back of the baffle plate and the main aperture, but there was some flow through the curved vent (this corresponds to position 5 in the table in 4.2).

4.4 Airspeeds were measured at various distances from the cowling, parallel to its angled end edge. The following measurements were made:

| Distance from cowling edge (mm) | Airflow Readings (m/s) | Average Airflow Speed (m/s) |
|---|---|---|
| 100 – 125 | 7.22, 6.59, 6.65, 6.82, 6.24 | 6.70 |
| 200 | 4.84, 4.75, 4.62, 4.34, 4.28 | 4.57 |
| 300 | 3.75, 3.77, 3.60, 3.61, 3.24 | 3.60 |
| 400 | 2.12, 2.50, 2.62, 1.63, 1.55 | 2.08 |
| ~500 (floor) | 2.57, 1.77, 1.48, 1.38, 1.63 | 1.77 |

4.5 Since the train was in a depot, it was situated on rails at about the same level as the surrounding floor. The front edge of the cowling was about 450mm above the ground level and the back edge about 350mm above this level. In general, rail height is about 150mm above ballast level. Therefore, the front edge of the cowling would be about 600 mm above the ballast level in most cases.

The fall in airflow speed with distance from the aperture is shown graphically in Figure 6. The trend suggests that at a distance of 600 mm from the aperture the airflow speed would be likely to fall between 1.50 and 1.75 m/s.

4.6 On the day of the visit the HVAC system could not be operated due to a system fault. For this reason, it was not possible to verify the reported airspeeds from the HVAC exhaust apertures.

## 5 Fan Simulation Test Rig Design and Construction

5.1 To assess the likely airspeed at various distances from one of the HVAC unit exhausts a simple laboratory bench test was set up. A slotted vent of identical size to those used on the S Stock trains was cut from aluminium sheet and attached to a PF400 fan which was adjusted to achieve a flow of about 5.3 m/s (Figure 7). The variation in airspeeds with distance from the vent is shown in Figure 8, where it is evident that at a distance of 1.5m from the vent, the airspeed is essentially zero.

5.2 Initial assessments of the likely potential for dust disturbance showed that the braking system fan was of more concern than the HVAC system fan. The reasons for this were as follows:

- The risk of dust disturbance from the HVAC fans only applies to tunnel/covered sections of track where dust may have settled on high cable runs, control boxes etc. In open sections of track the risk is considered negligible.
- The potential for discomfort to passengers is higher in station areas than in tunnel/covered sections of track, but due to the layout and high ceilings in most station areas on the Metropolitan Line, it is very unlikely that airflows from the HVAC fans would have sufficient force to reach levels where dust may have settled in station areas.
- The average airflow speed at the outlets of the HVAC units was reported to be 5 m/s and laboratory tests showed that at a distance of 1m, the airspeed would be just over 1 m/s.
- Tunnel sections on the Metropolitan Line are generous with space at most locations, i.e. the tunnel walls in most instances are thought to be at least 1m from the position of the outlets.

As a start, it was therefore agreed that a full simulation of the HVAC unit was not required and that laboratory tests as described in section 5.1 would be adequate to assess the impact of these units. Efforts were then focused onto simulating the braking exhaust fans. It was thought that the worst case scenario would be when the train was stationary, with full force of the fans blowing into the ballast, i.e. not affected by the train forward velocity. The preliminary concept for simulations was therefore to set up the test rig at a particular site within an enclosure, run the test, obtain the dust level readings and then move to the next site.

5.3 The braking fan exhaust cowling was constructed using 1mm aluminium sheeting and connected to a steel frame that could be affixed to a track trolley. The cowling size, shape and orientation were arranged to be very similar to the real exhaust cowling on S Stock trains and made use of an identical curved buffer plate to direct airflow.

5.4 A PF400 ventilation fan was connected to the cowling using a flexible plastic manifold. Preliminary calibrations of the equipment showed that to achieve the required airflow speed at the outlet (6 – 7 m/s), a portion of the fan inlet needed to be blocked off. This was considered useful since it would allow testing at the standard airflow rate, and also at a higher airflow rate (about 12 – 13 m/s) as an extra reassurance check.

5.5 A wooden framed enclosure using transparent 1mm thick plastic sheeting (constructed in sections) was to be used to confine any dust raised to the test area. All aspects of the test rig design were aimed towards reliability combined with quick and easy assembly on site, ease of movement, safety during transport, flexibility to allow testing of both cess and 6 foot areas and allowance for the position of a traction current rail. It was feared prior to testing that significant amounts of dust may be raised by these tests, and possibly escape the enclosure; for this reason several other design precautions were employed to minimise this risk.

5.6 Some cable runs, particularly under platform recesses at Liverpool Street and Moorgate Stations were found to be contaminated by considerable amount of loose dust. The enclosure that was built did not include these areas but they were of lesser importance for testing compared with the track ballast, since this dust can be readily observed and relatively easily removed. It had already been established that cable runs would require cleaning.

5.7 A vacuum system was to be attached to the side of the enclosure during testing, such that samples of any dust raised by the fans could be collected for later analysis. Pre-weighed vacuum bags were to be used and changed after each test.

5.8 Dust levels within the enclosure were to be measured by Grimm dust monitoring machines. Two types of Grimm machine were available, one measuring particles/$m^3$, and one measuring particle mass/$m^3$. Since the particle mass Grimm machine was factory calibrated to measure rock dust rather than tunnel dust, it was initially planned to use only the Grimm particle machine. Also, the particle machine was able to sample dust readings every 6 seconds, whereas the particle mass machine could only log data once per minute. It was later decided to use both machines as a backup anyway, and to estimate a correction factor for rock dust vs tunnel dust based on increased iron concentrations in tunnel dust.

5.9 Ballast samples were to be taken at each location for laboratory analysis, and each test was to be video recorded for later examination. An example photograph of the test rig assembly on site is shown in Figure 9. Tests were all carried out with the fan exhaust directed at the track ballast between two sleepers.

5.10 Due to limited time availability during engineering hours and the extent of the track length that was required to be covered, certain specific sites as identified in preliminary inspections were to be tested. These included at least one test at every station, particular areas in tunnel sections (near signals) and an open section for reference.

# 6 Test Locations and Procedure

6.1 Brake fan simulation tests were carried out over four site visits. Locations are detailed in the table below, together with the sample numbers of ballast taken from the sites:

| Session No. | Date | Test No. | Location | Side of track | Ballast Sample No. |
|---|---|---|---|---|---|
| 1 | 02/07/2009 | 1 | Moorgate Station (east end) | Cess | 090149/ 030709/1 |
| | | 2 | Moorgate Station (west end) | Cess | 090149/ 030709/2 |
| | | 3 | Tunnel Moorgate to Barbican Stations | Cess | 090149/ 030709/3 |
| 2 | 08/07/2009 | 4 | Baker Street Station Platform 4 covered terminal | Cess | 090149/ 080709/4 |
| | | 5 | Tunnel 200m north Baker Street | 6 foot | 090149/ 030709/5 |
| | | 6 | Tunnel 200m north Baker Street | Cess | 090149/ 030709/6 |
| | | 7 | Great Portland Street Station (west end) | Cess | 090149/ 030709/7 |
| | | 8 | Great Portland Street Station (east end) | 6 foot | - |
| 3 | 09/07/2009 | 9 | Euston Square Station (west end) | Cess | 090149/ 090709/8 |
| | | 10 | Euston Square Station (east end) | 6 foot | 090149/ 090709/9 |
| | | 11 | Kings Cross Station (east end) | Cess | 090149/ 090709/10 |
| | | 12 | Tunnel Kings Cross to Farringdon Stations | Cess | 090149/ 090709/11 |
| | | 13 | Open area Kings Cross to Farringdon Stations | Cess | - |
| 4 | 14/07/2009 | 14 | Aldgate Station (east end) | Cess | 090149/ 150709/12 |
| | | 15 | Aldgate Station (west end) | 6 foot | 090149/ 150709/13 |
| | | 16 | Tunnel Aldgate to Liverpool Street Stations | Cess | 090149/ 150709/14 |
| | | 17 | Liverpool Street Station (east end) | Cess | 090149/ 150709/15 |
| | | 18 | Liverpool Street Station (west end) | Cess | 090149/ 150709/16 |
| | | 19 | Tunnel Liverpool Street to Moorgate Stations | Cess | 090149/ 150709/17 |

6.2 The test rig fan was switched on for 3 – 4 seconds and then switched off. The principle was that the initial blast of air would raise some dust which would then settle slowly with the fan off to allow the Grimm monitors to sample the air under static conditions. This was the most effective way to obtain representative readings. After a short period of 1 to 2 minutes, the fan was switched back on and allowed to run continuously such that a full visual inspection of the effect of the air on the ballast could be made. Data logging of dust levels would be made continuously.

6.3 In most cases after it had been established that there was no risk of dust escaping the enclosure, the fan was set to full flow rate producing an airspeed of 12 – 13 m/s for about 2 minutes. This is effectively equivalent to double the force of a fan on a real S Stock train. The Grimm monitors remained running from start until test completion.

## 7 Results of Analysis of Vacuum Dust Samples

7.1 Prior to testing, it was very uncertain how much and what type of airborne dust would be generated from the ballast by the incident air. It was therefore necessary to attempt to collect this dust for later laboratory analysis. This proved to be important since the Grimm dust monitoring machine is factory calibrated to measure Arizona Road Dust (ARD) rather than tunnel dust. This is a common standard used by dust monitoring machines and is similar to general outdoor dust in most locations.

7.2 The difference is that tunnel dust usually contains much more iron, i.e. it is denser and therefore heavier than ARD which contains a mixture of minerals (primarily montmorillonite, silica, mica and feldspar) that are normally low in iron. Particle mass measurements from the Grimm machine therefore need to be adjusted using a factor related to the weight ratio of the dust collected to ARD. Previous work has established that this factor can vary from 2 to as high as 6 for some tunnel dusts. SEM scans of the tunnel dust collected would give an indication of the possible range in their iron contents such that a reasonable consistent factor could be estimated. Initially the primary aim was to determine the *change* in dust levels rather than the precise measurement, but accuracy as far as possible was also important.

7.3 During each test a vacuum system was used to remove samples of dust from the enclosure into pre-weighed vacuum bags. Due to the very small amounts of dust collected in most cases, gravimetric analysis was ruled out as a reliable indicator of actual weights collected.

7.4 For six tests, there was sufficient dust collected in order for compositional analysis to be undertaken by Scanning Electron Microscopy (SEM) with Energy Dispersive X-Ray (EDX) analysis. These scans are qualitative methods that give an indicative guide to composition. Prior to scanning, the samples were photographed and examined by optical microscopy.

7.5 Photographs of the inside of two of the vacuum bags are shown in Figures 10 and 11 to illustrate the amounts of dust collected. Under microscopic examination it was confirmed to be black in colour, with very fine angular particles mostly below one micron in size. Larger, gritty particles were also seen but in lower amounts. However in one case for the sample taken during testing in the tunnel between King’s Cross and Farringdon there were a lot of gritty particles (see Figure 12). A significant proportion of the large particles shown are too large for the Grimm machine to detect.

7.6 SEM scans of the six dust samples collected showed that in four cases there was mostly iron in the samples (see example in Figure 13), the other two showed somewhat less iron (Figure 14). The spectra in all cases showed chemical elements typical of tunnel dust. A comparison of the peak heights of iron with silicon and calcium in the SEM scans with those of common outdoor dust suggest that a factor of at least 2 should be used and likely closer to 3. In some cases the indication was that even higher factors should be considered, but for the sake of consistency and because dust samples could not be collected from every test site, it was decided to use a factor of 2.5 as a base minimum when interpreting raw data from the Grimm particle mass machine. The elements detected in the dust from the six samples analysed are shown in the table overleaf.

| Sample No. | Location | Elements Detected | Fe:Si ratios |
|---|---|---|---|
| 090149/200709/20 | Aldgate station east end | Carbon, Oxygen, Aluminium, Silicon, Potassium, Calcium, Iron | Fe~Si |
| 090149/200709/21 | Tunnel Aldgate to Liverpool Street | Carbon, Oxygen, Aluminium, Silicon, Calcium, Iron | Fe~Si |
| 090149/200709/22 | King's Cross station east end | Carbon, Oxygen, Aluminium, Silicon, Potassium, Calcium, Iron | Fe>>Si |
| 090149/200709/23 | Euston Square station east end | Carbon, Oxygen, Aluminium, Silicon, Calcium, Iron | Fe >>Si |
| 090149/200709/24 | Euston Square station west end | Carbon, Oxygen, Aluminium, Silicon, Potassium, Calcium, Iron | Fe>>Si |
| 090149/200709/25 | Tunnel King's Cross to Farringdon | Carbon, Oxygen, Aluminium, Silicon, Sulphur, Potassium, Calcium, Iron | Fe>>Si |

## 8 Grimm Test Results

To assist in interpreting the Grimm machine results, note the following:

- A summary of results is shown in Table 1.
- In some traces, dust levels start higher than background levels due to dust disturbed during setting up the test rig and enclosure and other activity in the area. Background levels are therefore taken to be the lowest readings measured during the test period, although this may not always be representative of true background levels.
- The particle count traces show several curves. Each is specific to a particular size range of particle and each trace therefore represents the number of particles in that size range over the time period of the test.
- The Grimm particle count includes all particles up to 80 µm. The largest particle size range category therefore represents particles in the 20 – 80 µm size range. In the following discussion, reference is also made to **total** particle counts, i.e. the sum of counts in all particle size ranges.
- The particle mass traces show cumulative curves, i.e. PM 15 shows all particles below 15 µm in size, PM 10 shows all particles below 10 µm in size, etc.
- The Grimm particle count machine logs one reading every six seconds, whilst the Grimm particle mass machine logs one reading per minute (resulting in lower trace resolution).
- **In all cases, particle masses reported reflect raw data since there is a degree of uncertainty in the conversion factor to be used. As discussed in the previous section, the particle masses should be multiplied by 2.5 to more accurately reflect actual tunnel dust particle weights.**

### 8.1 First site visit

8.1.1 Two tests were carried out at the east and west ends of Moorgate station both in cess areas and both about 20m from the end of each platform. For these tests only particle count information was available. The graphs shown in Figures 15 and 16 indicate about a five-fold increase in total particles in each case, reaching maximums of about 1.10 million/litre and 1.28 million/litre respectively. The breakdown in numbers of particles in particular size ranges all show a substantial increase. For each test site, at peak levels, 64% and 73% respectively of particles were smaller than 0.65 µm in size.

8.1.2 One test was carried out in the cess area of a tunnel between Moorgate and Barbican stations. Figure 17 shows the particle counts measured. The background level was similar to the levels measured in Moorgate station, but only a small rise in dust levels was generated during the normal airspeed test. A full power test here also showed only a further small rise in dust levels. 96 % of particles detected were below 0.65 µm in size.

### 8.2 Second site visit

8.2.1 For the second site visit, only particle mass readings were taken due to a fault with the particle count machine. The readings from the test in the cess area of Baker Street station platform 4 showed a large increase from background readings, with maximum levels approaching 12mg/m$^3$ for the normal speed test (Figure 18). No full speed test was carried out.

8.2.2 A site about 200m north of Baker Street station was tested in both the 6 foot and cess areas. For the 6 foot area (identified as of interest due to sandy and patchy areas of dust being present) the maximum normal speed test readings were slightly above 1mg/m$^3$, Figure 19. On raising the airspeed, this dust level rose to more than 4mg/m$^3$. For the cess area at the same track position, the maximum normal speed test readings rose to about 0.8 mg/m$^3$, further increasing to above 1mg/m$^3$ during the full airspeed test, Figure 20.

8.2.3 At the west end of Great Portland Street station in the cess, normal airspeeds generated significant amounts of dust, up to a maximum of 18mg/m$^3$, Figure 21. Following this reading, the test was allowed to run for a further five minutes, during which time, the readings steadily dropped to about 1 mg/m$^3$. A subsequent full airspeed test then raised the readings back up, but only to about 2.3 mg/m$^3$.

8.2.4 At the east end of Great Portland Street station in the 6 foot area, there was no marked increase in dust levels generated by a standard airspeed test, though the levels measured were above normal background levels. A full airspeed test then did show a marked increase in dust levels, up to about 2.3 mg/m$^3$, Figure 22.

### 8.3 Third site visit

8.3.1 At Euston Square station for the normal airspeed tests, higher particle mass readings were measured at the west end (cess) than the east end (6 foot). Maximum levels measured were about 0.8mg/m$^3$ and 0.3mg/m$^3$ respectively (Figures 24 and 26). Clear evidence could be seen in both particle count traces of increasing dust levels during the standard test, further raised during the full speed tests (Figures 23 and 25).

8.3.2 High particle count levels were measured during the tests at Kings Cross station, particularly in the 0.3 – 0.4 µm particle size range. The total count approached 2.4 million/litre which was the highest particle count reading obtained at any site during the surveys (Figure 27). The particle mass readings were not as noticeably high reaching only about 0.8 mg/m$^3$, Figure 28. This is consistent with most of the particles being in a low size category. Higher airspeeds raised the particle count readings back to similar levels as the normal speed test, but considerably increased the particle mass readings to over 2.5 mg/m$^3$, which appeared to continue rising as the test was terminated.

8.3.3 In the cess area of a tunnel between King's Cross and Farringdon stations, normal airspeeds generated only small increases in dust levels, up to about 0.7 mg/m$^3$, though background dust in this tunnel was higher than elsewhere so the effect was less noticeable, Figure 30. At higher airspeeds, the maximum dust levels were close to 1.1 mg/m$^3$. Particle counts showed slow but steady increases during the initial stages of each airspeed test level, Figure 29.

8.3.4 A test was carried out in an open (uncovered) area between King's Cross and Farringdon stations to assess the effect of the elements on dust in track ballast. Two distinct humps in the particle count traces indicate the normal and higher airspeed tests, Figure 31. The stages of testing from particle mass data trace is less clear cut (Figure 32), but the video evidence defined the timing of the switch to full airspeed. It appeared that the maximum reading of 0.45 mg/m$^3$ was achieved during the full speed test. This was amongst the lowest readings obtained during the surveys.

### 8.4 Fourth Site Visit

8.4.1 The first test at Aldgate station was carried out in the cess at the east end of Platform 2 where a large increase in both particle counts and particle mass was recorded with normal airspeeds generating more than 7 mg/m$^3$ (up from background levels of about 0.05 mg/m$^3$). Particle count data showed the largest fraction of particles to be in the 0.4 – 0.5 µm size range. No noticeable peak was generated by the full airspeed test for the particle count trace and only a small peak was seen for the higher airspeed test in the particle count trace (Figures 33 and 34).

8.4.2 The second test at Aldgate station was carried out in the 6 foot area between Platforms 2 and 3. Here only a marginal increase in particle counts and particle mass was seen for the normal airspeed test (particle mass peaked at around 0.1 mg/m$^3$). For the higher airspeed test, particle mass increased noticeably but only up to 0.27mg/m$^3$. An increase was also noted in particle counts, here most particles were in the 0.3 – 0.4 µm size range (Figures 35 and 36).

8.4.3 In the cess of the tunnel between Aldgate and Liverpool Street, normal airspeed tests showed some effect on dust in the track ballast (hump in the trace in Figure 37) and a considerable increase in particle mass up to about 6 mg/m$^3$ (Figure 38). Higher airspeed tests did not show a clear increase in airborne particle counts or mass readings.

8.4.4 Two tests were carried out in cess areas at Liverpool Street station, one each at the east and west ends of the platform. In both cases, the normal airspeed tests induced significant increases in airborne dust levels though in both cases these peaked at around 0.6 mg/m$^3$ (up from background levels of about 0.1 mg/m$^3$. The full airspeed tests did not show marked increases in the dust levels generated (Figures 39 – 42).

8.4.5 The last test on the fourth site visit was in the tunnel between Liverpool Street and Moorgate stations. The initial normal airspeed test induced a large increase in particle counts, particularly in the 0.3 – 0.4 µm size range. However maximum particle mass measurements only rose to about 0.2 mg/m$^3$. At higher airspeeds little increase was seen in the airborne dust levels (Figures 43 and 44).

## 9 General Comments and Observations

9.1 Taking all parameters into account, the test rig was considered to provide a close simulation to the real S Stock brake fan exhausts. The only area of concern was that the real train exhaust cowling incorporated an extra directional vent, but this was small and angled in such a way that its line distance to the track ballast was close to 1m.

9.2 The higher speed tests were carried out as a check to cover any unforeseen issues, effectively doubling the expected exhaust airspeed. In most cases disturbance of ballast litter was seen during normal speed tests, and considerable disturbance was seen during higher speed tests. In general, ballast litter such as leaves and other debris was observed to move along the horizontal in all directions (particularly sideways) away from the exhaust cowling.

9.3 The time allowed for each test did vary. Some sites were thought to be more of a risk than others, and with the limited time available during engineering hours, it was more important to thoroughly check the riskier sites by spending more time on them than to attempt to keep to consistent times for all sites.

9.4 For all tests, there was no visible indication of dust being raised by the airflows. For most tests, there was a spike in the dust level after the normal airspeed tests which then dropped off somewhat. During the subsequent full airspeed tests in some cases there was a second, larger spike in the dust levels, but in others there was only a slight increase or none at all.

9.5 During initial inspections at Asfordby Depot and calibrations of the test rig, it was found that the airspeed at track ballast level would be less than 2 m/s. After visually assessing the effect of the airflow on the ballast, it was thought that very little of the airflow would be able to penetrate deeper than about two ballast stone layers with sufficient force to raise dust from below the surface, i.e. dust raised would likely be mainly from the top two layers of ballast.

## 10 Ballast Sample Analysis

10.1 Ballast samples were taken at seventeen of the nineteen test sites surveyed for later laboratory analysis. Dust from all seventeen samples were examined for the presence of asbestos and also qualitatively scanned by EDX for elemental composition. Twelve ballast samples were analysed for various other common contaminants. Prior to analysis, the samples were visually examined and several were examined by optical microscopy.

10.2 The samples varied widely in composition and colour, indicating wide differences in age and time undisturbed. Figure 45 shows a ballast sample taken from the test site in the cess at the west end of Great Portland Street station. Note that the ballast stones are darker on one side than the other; this is indicative of the top and bottom surfaces. The top surface, if undisturbed, collects more dust and dirt and will generally darken with time.

10.3 A photograph of ballast collected from Liverpool Street station is shown in Figure 46. Here there is a lot of sandy loose material, but this is not visible looking at the ballast on site, and is largely below the top two layers of stones in the ballast. There was also a lot of fluff type material in the Liverpool Street station samples. In some samples ballast stones were covered with sandy material, others appeared to be very old and greasy, adding to their darker colour.

10.4 Dust from all seventeen ballast samples was examined by Scanning Electron Microscopy and qualitative chemical compositions were obtained using Energy Dispersive X-ray Spectroscopy. Spectra from two representative samples are shown in Figures 47 and 48. In all cases, the elements detected were typical of tunnel dust, the high iron peaks indicating iron oxides and ferrous wear debris from wheels and rails, the calcium and sulphur are likely from gypsum and other cementitious building materials, silicon from silica sands and aluminium from general clays. Traces of potassium, chlorine, titanium and sodium were also seen in varying amounts across the sample range. Zinc and a trace of copper were also detected in the sample from Aldgate station cess (090149/150709/12).

10.5 All seventeen samples dust samples from the ballast were analysed for the presence of asbestos, none was detected. Twelve of the samples were selected for further analysis, the results of these tests are reported in 4RS-CSI-090149-R211504 with full discussion regarding interpretation and implications. Some samples were found to contain levels of metals that could class them as hazardous according to the Kelly, Dutch or DEFRA CLEA guidelines The recommendations regarding treatment and handling of the ballast apply equally to the dust in the ballast. The levels of contaminants that indicated greatest potential risk were found in the following samples:

| 4-RAIL Services Sample No. | Location | Contamination |
|---|---|---|
| 090149/080709/5 | Tunnel 200m north of Baker Street (6 foot) | Boron, Nickel, Sulphate, PAH, TPH and pH |
| 090149/090709/8 | Euston Square Station (West End) | TPH and pH |
| 090149/150709/12 | Aldgate Station Platform 2 (cess) | Boron, Cadmium, Copper, Lead, Nickel, Zinc, Phenols, TPH & pH |
| 090149/150709/15 | Liverpool Street Station (East End) | Cadmium, TPH and pH |

Note: Total Petroleum Hydrocarbons (TPH) is a measure of the oils and greases present in the ballast. Polyaromatic Hydrocarbons (PAH) are a sub group of TPH and include certain compounds that can be carcinogenic.

## 11 Relation of Simulation Effects to Real S Stock Trains

11.1 In order to relate the results obtained from the testing to likely effects of the new S Stock trains, a number of estimates and assumptions are required to be made. Firstly, it must be noted that dust concentrations obtained during the test surveys are elevated due to the concentrating effects of the enclosure used. However, the process of blowing the fan for a short time, followed by a lull period that would allow an equilibrium to be reached inside the enclosure allowed a very reasonable dust concentration to be logged *within the enclosure*.

11.2 Disturbed dust especially in the sub micron size range does not settle readily and may spread very far from its source. From a single one-event source that is not confined and assuming unlimited ‘spreadability’, the dust concentration in the air will be high near the source and rapidly drop off with distance from the source approximately proportional to the inverse of distance cubed. In a confined space, that same source would result in an equilibrium being reached within a certain time inside that space.

11.3 S Stock trains have eight cars, each with one brake fan mounted below platform level (exhausts are orientated alternately such that there are four on each side of a train). Dust generated by their disturbance would for the most part be initially confined to areas under the train and platform recess. However, on train departure, air turbulence would result in this dusty air being free to mix with cleaner air and spread throughout the platforms.

11.4 For the scenario of a train standing in a platform for a significant length of time, e.g. 10 minutes with fans running, it would be expected that general air currents would be able to increase the dust concentration in platform areas. Some dust would constantly be resettling, but without an external method of removal of dusty air, it would be likely to remain in the platform area. The amount of dust generated by the fans from a stationary train would become less with time but with the arrival and departure of trains throughout a day, it is thought that an equilibrium level would soon be reached within the platform area.

11.5 A basic calculation of dust levels within 4 meters of the platform, 4 meters high and as long as the train (about 130 meters for eight cars) can be made from the results of the test surveys (assuming dust is retained within this volume). This air volume alongside the train is 2080 $m^3$ (the volume of the space within the enclosure used during the testing was 1.63 $m^3$). For a case where a dust weight concentration of 10mg/$m^3$ was recorded in the test enclosure, and assuming this is an average level that would be generated at any point along the track, then the following gives an approximation to likely dust concentrations within the volume described alongside the platform :

| | |
|---|---|
| 'True' dust conc. in enclosure | = 10 mg/$m^3$ x 2.5 (Grimm correction factor) |
| | = 25mg/$m^3$ |
| 'True' dust conc. in full volume | = 25/2080 |
| | = 0.013 mg/$m^3$ (equilibrium) |
| For four fans run once : | = 0.013 x 4 |
| | = 0.05 mg/$m^3$ |

11.6 Equilibrium dust concentrations in stations will depend very much on the volume of enclosed space near the platforms. For example, although quite high levels of particle masses were seen during the tests at Aldgate Station Platform 2 cess and Baker Street station Platform 4 cess, the volume through which this dust could spread in these cases is large. On the other hand, this mitigating effect could be lessened somewhat in a case where two or conceivably three trains were all in the station at the same time.

11.7 Although a stationary train would be the worst case condition with respect to effect on a particular position, higher station dust levels could be generated by a slowly moving train, i.e. coming to a stop or starting to move off. In this case, the fans could be directed at most of the sections of track ballast, and air speed at track ballast level for slow train speeds would not be markedly different from that of a stationary train. This would mean that the whole section of track could be exposed to at least one fan for some duration, i.e. the number of sources of dust could potentially be increased to 100 or more. It is therefore possible that the calculated dust concentration in the volume described during initial runs of the trains could be of the order of 1.3 mg/$m^3$ or higher, and more continuously generated along the whole length of the train. It should also be remembered that the Grimm correction factor used here is 2.5, whereas for some tunnel dust types this factor could be as high as 6.

11.8 At some stations the cable runs under the platform recesses were very dusty. Although the fans are not directed at the cable runs, airflow turbulence under the recess could disturb some of this dust, and add to any dust from the track ballast. This cable run dust was very easily disturbed.

11.9 Dust generated in the cess area would be temporarily confined under the platform recess, but movement of the train would create turbulence that would bring the dust up between the train and the platform. Once the train departed this dust under the recess would spread out. Dust generated in the 6 foot area of the track would be less confined and could spread across to the opposite platform.

11.10 Note that the total dust concentrations in stations would be the sum of current levels and the additional dust generated by the new trains, i.e. the levels found reflect the possible increases rather than absolute levels. Over time it is possible that (with constant airflows) dust levels in track ballast would be cleared from areas under the exhaust fans to settle elsewhere, e.g. the four foot or under the traction current rails.

## 12 Discussion

12.1 Tests have confirmed that the exit air velocity from the S Stock train brake fans is between 6 and 7 m/s, the average reading obtained was 6.8m/s compared to the reported 6.3m/s. Further tests showed that the air velocity striking track ballast from the S Stock trains will be about 1.5 m/s for a stationary train. The exit airspeed steadily decreases with distance from the exit.

12.2 The air velocity from the vents of the HVAC unit on the S stock train could not be verified, but tests using the reported airspeeds and a similar vent showed that at a distance of 1.5m from the vent the airspeed is essentially zero. It should be noted that the tests were carried out for one vent, whereas the S Stock train has four vents; the significance of this is that the larger volume of air being forced from the four vents would be less affected by stationary surrounding air. Nevertheless, it is considered to be very unlikely that these airflows would be capable of disturbing significant amounts of dust on cable runs and increasing covered section dust levels to a level that might pose a danger to passengers or staff.

12.3 Tests carried out on dust in track ballast during the preliminary surveys (reported in 4RS-RG-090149-R211501) suggested that significant visible dust might be expected to be raised from large air exhausts blowing onto the ballast. However the initial tests were carried out with a highly directional nozzle at close range, and although the pump was small, a flow rate of 6.5 m/s was measured at a distance of about 50 mm from the nozzle. During the main tests a much larger volume of air was being pumped, but this was also spread over a larger area and at a larger distance of 600 mm. Since the expected airspeed at ballast level would not be above 2 m/s, it is therefore concluded that this airspeed is insufficient to shift larger *visible* particles.

12.4 Among the criteria for dust being visible is not only particle size, but also particle concentration and the distance through which that dust concentration is viewed. Relatively speaking, the 1.63m$^3$ enclosure used during the testing is small. This was thought to explain why no ‘visible dust’ was seen.

Air movements as well as dust particle sizes, concentration and colour are all parameters that affect the visibility of dust. Previous dust monitoring work carried out by 4-Rail Services Limited operatives at Hampstead Underground Station (and several others) has indicated that under suitable circumstances over the distance of a platform, respirable dust at a concentration of 1mg/m$^3$ can cause a hazy effect to be visible. Note that levels of 0.5 – 1.0 mg/m$^3$ are not uncommon in some London Underground stations during normal traffic hours.

12.5 Very little dust was collected in the vacuum bags during brake fan simulations – insufficient to carry out a reliable gravimetric analysis. However, important compositional information was gained for six of the tests, which could be used to estimate a correction factor for the Grimm dust monitors. In all cases, the samples were composed of elements typical of tunnel dust. Strong peaks of silicon, calcium and (in particular) iron were seen in the dust spectra in most cases.

12.6 A summary of the Grimm dust monitor results is shown in Table 1. In the table maximums are reported as all particles of size 20 µm and lower for the particle measurement, and 15 µm and lower for the particle mass measurement. Note again that the readings reflect raw data and a correction factor which was estimated to be about 2.5 as a minimum should be applied. It must be remembered that for some types of tunnel dust, this factor can be as high as 6.

12.7 The full power (12 – 13 m/s) airspeed testing carried out showed some conflicting results. In some cases, after the normal (6.3 m/s) speed test the dust levels peaked and then started to drop off. On application of the full airspeed there was a further bigger spike in the dust level traces followed by another drop off. However, in other cases the full power test showed only a smaller spike than the normal speed test and sometimes no clear spike at all.

There are a number of possible reasons for this. One is that different conditions of adherence of dust to track ballast could result in most of the available dust being blown off during the normal test in some cases. Drier, finer, loose or friable dust may be all blown off at once while wetter, greasier dust particles would require faster airflows to be moved. In some cases even these faster airflows may not be sufficient to shift more ingrained dust. Other factors would be the amount of dust present, the size distribution of dust particulates and the extent that air can penetrate gaps in the ballast (related to the condition of the ballast)

12.8 The points noted in 12.7 above provide some evidence that dust may disperse from the ballast directly under the fans after continuous running of S Stock trains. Dust raised will tend to resettle, but after numerous runs it might tend to settle elsewhere due to changes in aerodynamics of the tunnel/station and train system. This can not be confirmed without running an S Stock train on the line.

12.9 As a general rule, more dust was raised in the cess areas than in the 6 foot areas, particularly within stations. This was also suggested after the initial site surveys, and is probably due to the natural way that air currents and turbulence move dust around within the track area. Dusty air is moved to both the cess and 6 foot during arrival and passing of trains, but the confining effect of the platform recess wall would tend to concentrate dust in the cess area. It was also noticed that for the tests in the 6 foot, exhaust air from the brake fan was directed at the traction current rail (which runs in the 6 foot within stations). This had the effect of partially deflecting/blocking the airflow from reaching the ballast.

12.10 The testing showed that the airflows generated by the S Stock train brake fans are insufficient to cause immediate noticeable airborne dust, and there is good confidence that the tested sites as a whole were representative of all possible site conditions. In most cases particles in the size range 0 – 0.65 µm made up the majority of dust raised. This must be balanced against the view that in terms of particle mass per unit volume, larger particles in size ranges up to 10 µm make up for most of the weight of the dust measured.

12.11 According to the ISO/CEN respirable dust convention (published in the UK as part of BS CEN 481:1993), any particle with an aerodynamic diameter of less than 10 µm is termed 'respirable', i.e. capable of penetrating deep into the lungs. Particles larger than 10 µm but smaller than 25 µm are termed the thoracic fraction, i.e. they may enter the chest/lung area, but tend not to collect deep in the lungs. Particles of all sizes and larger than 25 µm (typically up to 100 µm are termed 'inhalable'. According to the HSE EH40/2005 Workplace Exposure Limits, the mass concentrations of inhalable and respirable dust particles should not exceed 10 mg/m$^3$ and 4mg/m$^3$ respectively averaged over an 8 hour work shift.

12.12 The indications are that only in the worst combination of possible circumstances would the levels of inhalable and respirable dust rise to levels near the workplace exposure limits defined in the HSE guidelines. To get an idea of the maximum possible increase in dust levels, the same calculation performed in section 11.5 can be made using the highest dust level recorded (18 mg/m$^3$ at Great Portland Street), a Grimm correction factor of 5 and a platform volume of 2080 m$^3$. In the case of a train moving slowly, this gives a total airborne dust concentration of 4.3 mg/m$^3$ which is considered to be an extreme case and very unlikely to ever occur. However, there is fairly compelling evidence that dust levels at Baker Street, Great Portland Street, Euston Square, King's Cross and Aldgate stations could rise to 'nuisance' levels of 1 – 2 mg/m$^3$, where a slight hazy effect might be seen or which might cause quicker than usual build-up of dust on surfaces.

The HSE limits apply to an 8 hour exposure period, i.e. in the event that levels at the limit or even somewhat higher occurred, they would be unlikely to pose a health risk to train passengers, though contractors or station staff exposed for longer periods on a regular basis could be at risk.

12.13 Dust levels generated at Liverpool Street station were lower than at the stations mentioned in 12.12, but the ballast here appeared more greasy on the surface. The effect of this would be to lessen the amount of dust that could become airborne due to its 'stickiness'. However, dust was certainly generated and combined with the low ceilings and small volume (compared to some other stations) and no open air sections nearby, it is probable that nuisance dust would be generated within the station under ideal conditions.

Station sizes and air currents vary widely and there are too many variables involved to incorporate every possible effect. The results therefore do not purport to predict precise dust levels, but generally indicate that dust will be raised to levels above current ones and there is therefore a potential risk.

12.14 For tunnel or covered areas of track, there is no risk of visible dust being raised, even when trains are stopped at signals. Respirable dust levels in localised areas of tunnels could be similar to those in station areas, but the time of potential exposure to these levels would be short, and is not considered to be a risk to passengers or train staff.

12.15 The results of SEM and EDX analysis of the dust collected in the vacuum bags and from the ballast samples taken show chemical elements typical of tunnel dust. In most cases the majority of the samples were found to be composed of ferrous debris and iron oxides. Other materials identified were general sands, clays and cementitious building material.

Levels of sulphur (which in conjunction with calcium is usually indicative of gypsum) in the ballast sample dust were higher than in the vacuum bag dust. This is because the ballast samples would have included material taken from at least four to five ballast layer stones deep, where remaining gypsum and other building material dust has probably remained after previous works. No asbestos was detected in samples from the ballast.

# 13 Conclusions

13.1 The amount of airborne dust generated during the initial surveys of the Metropolitan Line track led to an over-estimate of the level of visible dust likely to be raised during the main testing phase.

13.2 The reported airspeed from the S Stock train brake fan exhaust was found to be fairly accurate. Airspeed at a distance of 600 mm from the exhaust (ballast level) was found to be less than 2 m/s.

13.3 Airspeeds from the HVAC unit could not be verified, but simulation of the exhaust vent using the reported airspeeds showed that little dust disturbance could be expected at a distance of 1.5 m away.

13.4 Due to the low ballast level and HVAC airspeeds, the new S Stock trains are very unlikely to generate clouds of visible dust or sand during running along the Metropolitan Line track in either stations or tunnels.

13.5 Exact levels of dust will only be known when the new trains are run on the Metropolitan Line track. However, the tests carried out have indicated a range of expected dust levels and have shown that changes in station dust levels are likely to occur after the introduction of S Stock trains.

13.6 The testing procedure carried out has shown that most dust disturbed from the ballast in all cases is likely to be in the 0 – 0.65 µm size range. SEM scans showed high iron composition in the dust. A Grimm correction factor of at least 2.5 should be applied to particle masses.

13.7 For the particular site positions tested, the largest increases in airborne particle *masses* were at Baker Street, Great Portland Street, Euston Square and Aldgate stations. High particle *numbers* were also seen at Kings Cross station.

13.8 The worst case scenario is thought to be the case of a slow moving train entering or leaving a station where the moving brake fans are directed at most of the length of the track. In a station with a smaller enclosed volume there is potential for airborne respirable dust levels in the range of 1 - 2mg/m$^3$ to be generated. Stations with low enclosed volumes are at King's Cross, Great Portland Street, Euston Square and Liverpool Street

13.9 Under certain conditions, 'nuisance' dust levels of 1 – 2 mg/m$^3$ could result in a slight 'haze' being visible when viewed along a platform long.

13.10 The health risk to passengers is thought to be minimal since dust levels are very unlikely to exceed HSE guidelines (4 mg/m$^3$ respirable over 8 hours). However, there is a slight risk to station staff and contractors that would be exposed for a longer period.

13.11 Dust levels estimated in this investigation should be added to current levels to obtain an indication of dust levels in a station during running of S Stock trains. It remains unclear whether increases in dust levels would tend to lower again over time.

13.12 More dust was generated during tests carried out in the cess than in 6 foot areas since the cess collects more dust and is not partially protected from airflows by the position of a traction current rail (in stations).

13.13 It was visually assessed that the brake fan airflow would not easily disturb dust lying lower than about two ballast stone layers deep. However, dust on cable runs under the platform recess in stations would significantly add to dust generated from the ballast.

13.14 Tests in covered sections away from stations have shown that airborne dust will be generated in these areas, but the risk to passengers and staff is low due to the likely short exposure times.

13.15 Open areas of track pose very little airborne dust risk, since there is less dust on/in the ballast and what dust there is would not be confined, i.e. it would be relatively easily dispersed. This also applies to Barbican Station, and parts of Farringdon and Baker Street Stations.

13.16 The samples collected in the vacuum bags were found to be composed of elements typical of tunnel dust, mainly iron oxide/ferrous debris, silica (quartz), clays and cementitious building materials.

13.17 No asbestos was detected in any of the dust or ballast samples taken. Several ballast samples however contained levels of contaminants that would (for the purposes of disposal) class them as Hazardous (see 4RS-CSI-090149-R211504).

## 14 Recommendations

14.1 Cable runs within station areas and possibly in tunnel sections up to 50 meters away from stations should be cleared of all visible dust.

14.2 Platform recesses in covered stations should be cleared of visible loose sandy material or suitably covered with new ballast.

14.3 Initially, it should not be necessary to clean dust from track ballast in covered sections. This may be reassessed after introduction of S Stock trains on the line.

14.4 The possibility of removing dust from track ballast in the cess and 6 foot areas of covered stations should be further investigated. Sites with highest potential risk are King’s Cross, Great Portland Street and Euston Square Stations.

14.5 A suggestion to remove dust in ballast would be to develop a machine (or modify an existing one) using a similar concept to the test rig built for this investigation, i.e. blow air into an enclosure to get dust airborne and then vacuum that air through a filter to remove the dust.

14.6 At a later stage, cleaning track ballast in the cess and 6 foot areas at Baker Street, Farringdon, Moorgate, Liverpool Street and Aldgate Stations should be considered. Dust levels at Barbican station are not thought to present a risk.

14.7 Current dust levels at all stations should be measured during traffic hours for later comparison to levels that could be measured after ballast cleaning and after introduction of the new trains.

14.8 The recommendations in report 4RS-CSI-090149-R211504 should be referenced when dealing with track ballast and dust collected at certain locations (particularly Aldgate, Euston Square and Liverpool Street Stations).

## Table 1: Summary of Grimm Dust Monitor Results

| Test No. | Location | Total Particles >20µm (million/litre) | | | Particle Mass >15µm (µg/m³)* | | |
|---|---|---|---|---|---|---|---|
| | | Low | High (normal power) | High (full power) | Low | High (normal power) | High (full power) |
| 1 | Moorgate Station (East End) | 0.19 | 1.11 | N/A | - | - | - |
| 2 | Moorgate Station (West End) | 0.25 | 1.28 | 0.42 | - | - | - |
| 3 | Tunnel between Moorgate and Barbican | 0.27 | 0.35 | 0.42 | - | - | - |
| 4 | Baker Street Station Platform 4 (cess) | - | - | - | 202 | 11908 | N/A |
| 5 | Tunnel 200m north of Baker Street (6 foot) | - | - | - | 193 | 1125 | 4317 |
| 6 | Tunnel 200m north of Baker Street (cess) | - | - | - | 197 | 789 | 1057 |
| 7 | Great Portland Street Station (West End) | - | - | - | 341 | 18373 | 2586 |
| 8 | Great Portland Street Station (East End) | - | - | - | 291 | NCP | 2343 |
| 9 | Euston Square Station (West End) | 0.58 | 0.82 | 1.09 | 274 | 815 | 1819 |
| 10 | Euston Square Station (East End) | 0.25 | 0.38 | 0.54 | 82 | 276 | 1417 |
| 11 | Kings Cross Station (East End) | 0.83 | 2.43 | 2.33 | 170 | 877 | >2500 |
| 12 | Tunnel between Kings Cross and Farringdon Stn | 0.05 | 0.08 | 0.12 | 631 | 713 | 1093 |
| 13 | Open area between Kings Cross and Farringdon Stn | 0.02 | 0.05 | 0.07 | 49 | NCP (~380) | 464 |
| 14 | Aldgate Station Platform 2 (cess) | 0.02 | 0.87 | NCP | 43 | 7443 | 2119 |
| 15 | Aldgate Station Platform 2 (6 foot) | 0.02 | 0.03 | 0.04 | 24 | 104 | 275 |
| 16 | Tunnel between Aldgate and Liverpool Street Stn | 0.02 | 0.05 | 0.03 | 83 | 6212 | NCP |
| 17 | Liverpool Street Station (East End) | 0.02 | 0.08 | NCP | 181 | 579 | NCP |
| 18 | Liverpool Street Station (West End) | 0.03 | 0.16 | NCP | 106 | 636 | NCP |
| 19 | Tunnel between Liverpool Street and Moorgate Stn | 0.02 | 0.13 | 0.03 | 35 | 196 | NCP |

* : Note that the particle mass readings must be multiplied by a correction factor. An estimate of 2.5 is made for this factor based on tunnel dust composition.
N/A : No test carried out
NCR : No clear peak in trace

**Figure 1. Dust disturbed in 6 foot area in tunnel 200m north of Baker Street**

**Figure 2. External view of S Stock brake fan exhaust cowling**

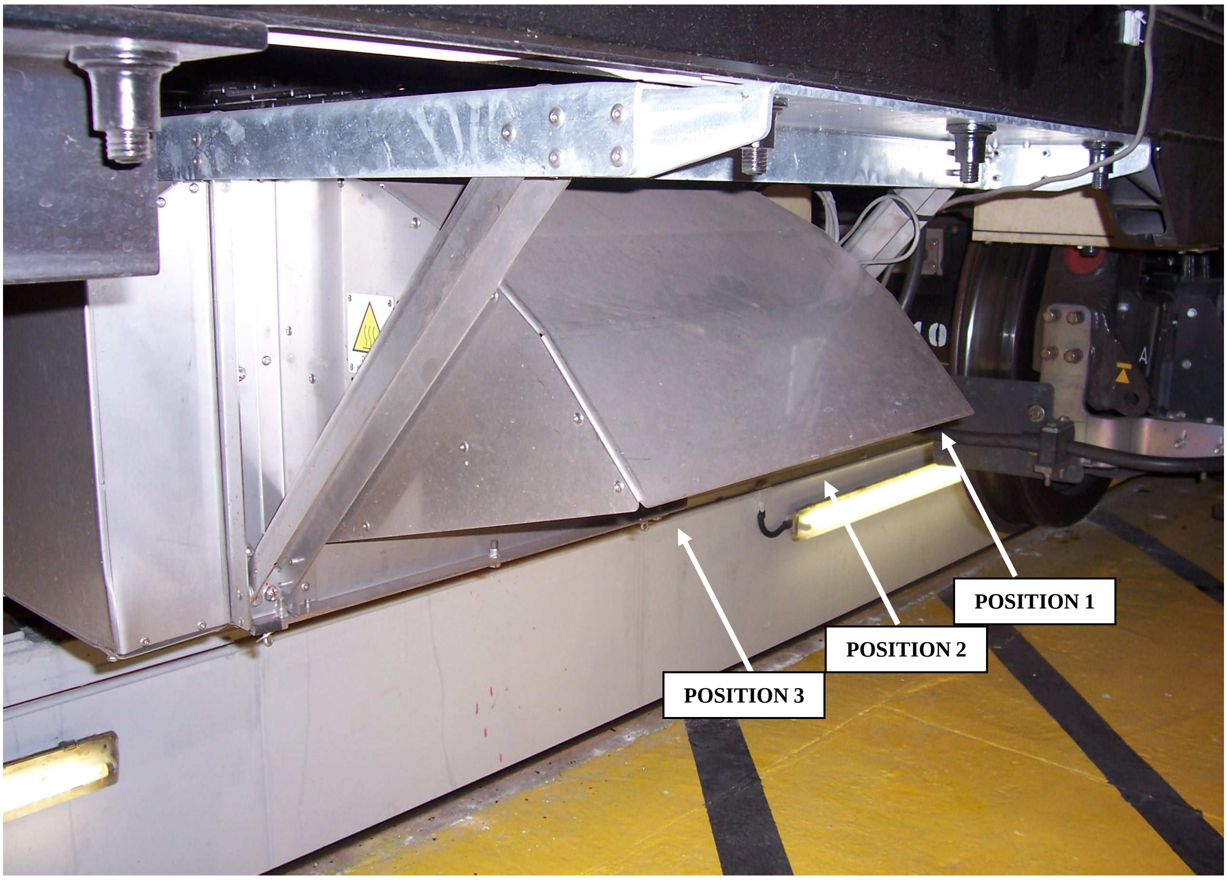

**Figure 3. Top view of air inlets and exhausts of S Stock train HVAC unit**

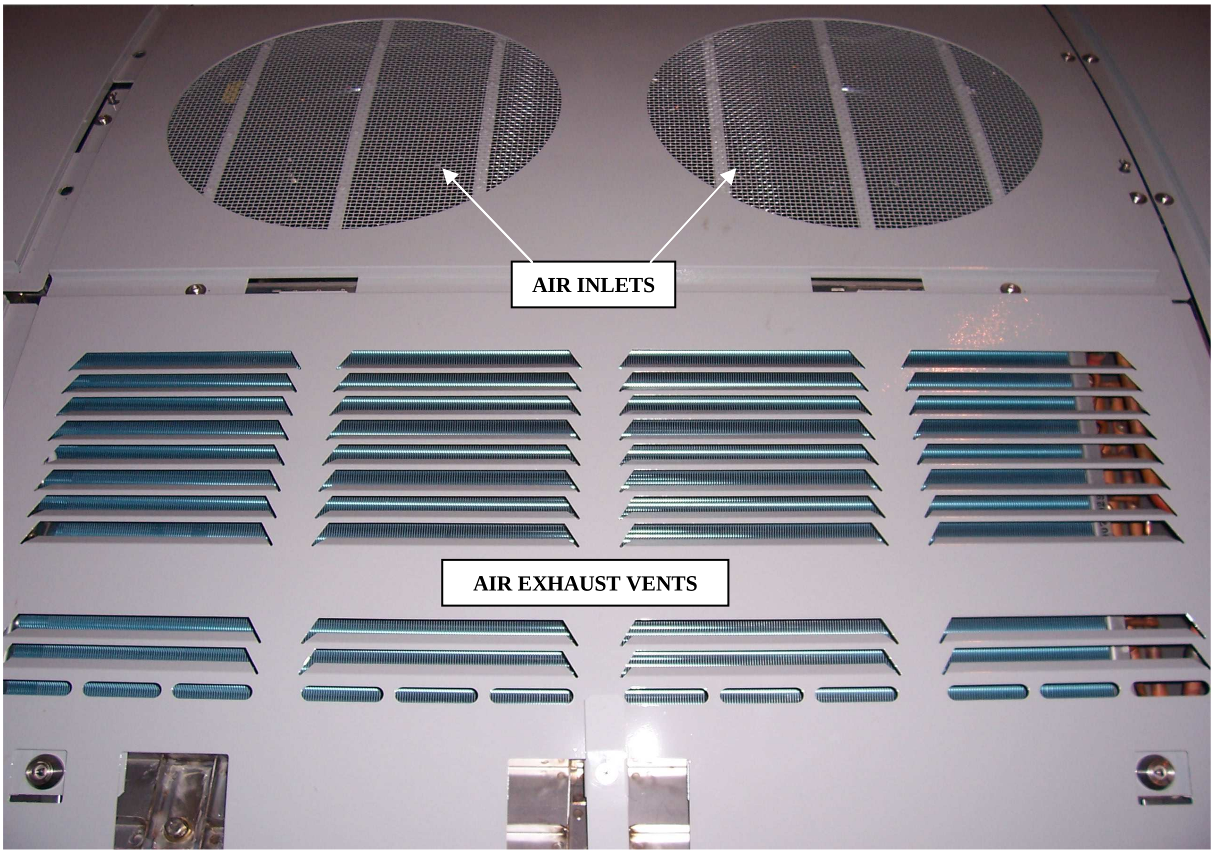


**Figure 4. View from underside of S Stock brake fan exhaust showing baffle plate**

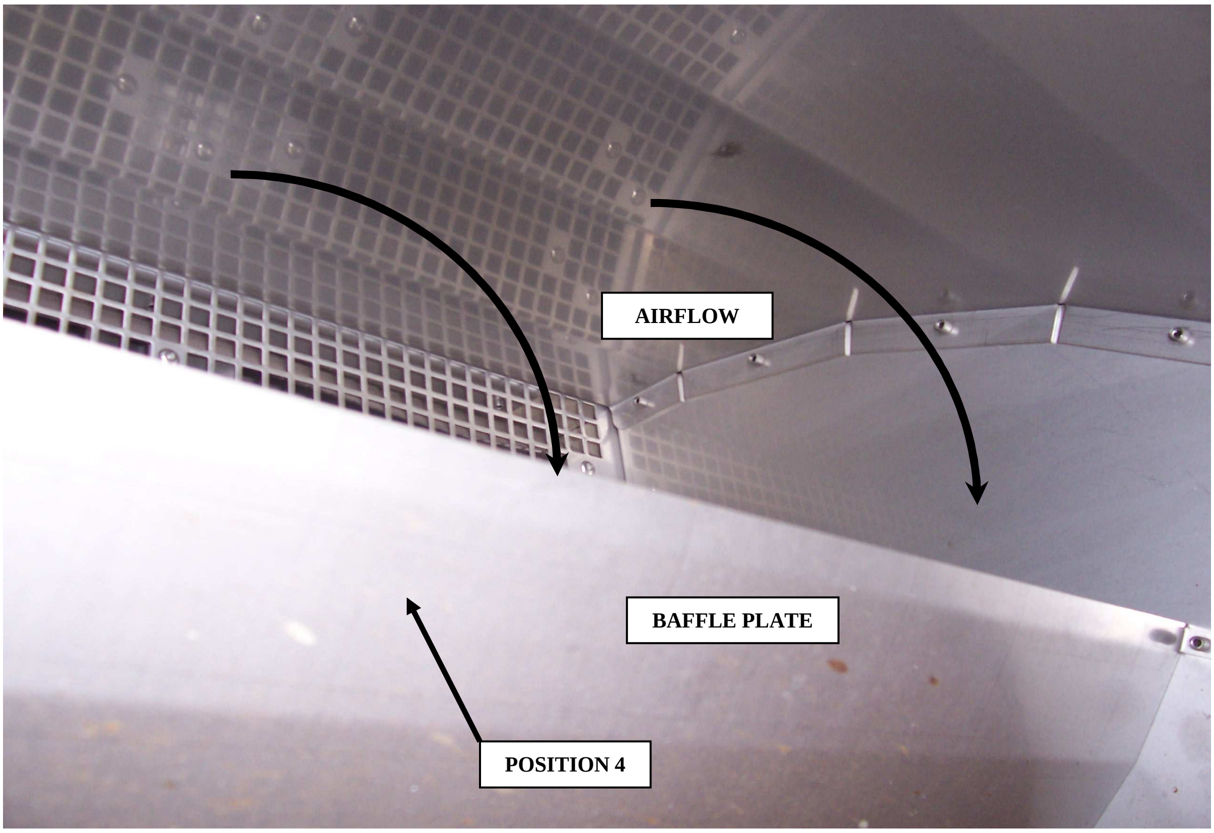

**Figure 5. Underside view of small directional vent behind main exhaust of brake fan**


**Figure 6. Air speed variation with distance from S Stock brake fan exhaust**

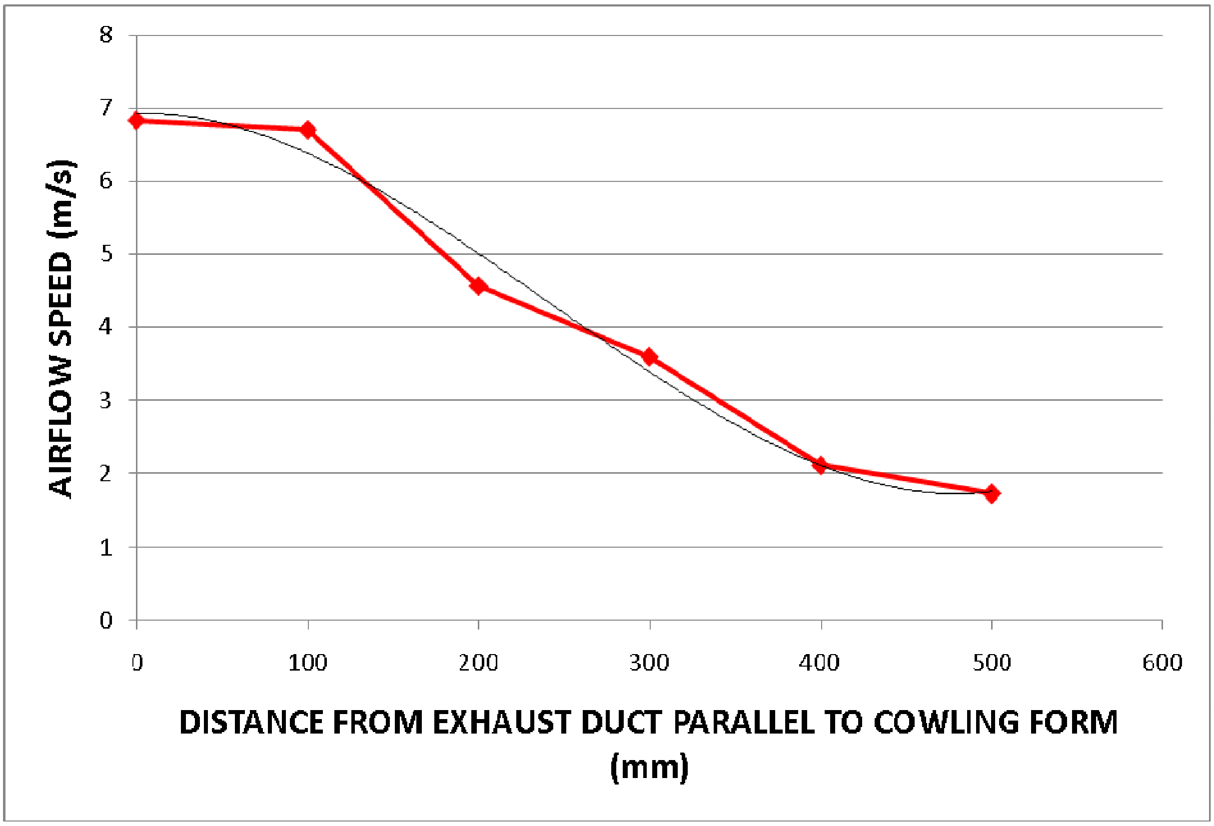

**Figure 7. Test equipment used to assess airspeeds from HVAC unit exhausts**

**Figure 8. Air speed variation with distance from simulated HVAC fan exhaust**

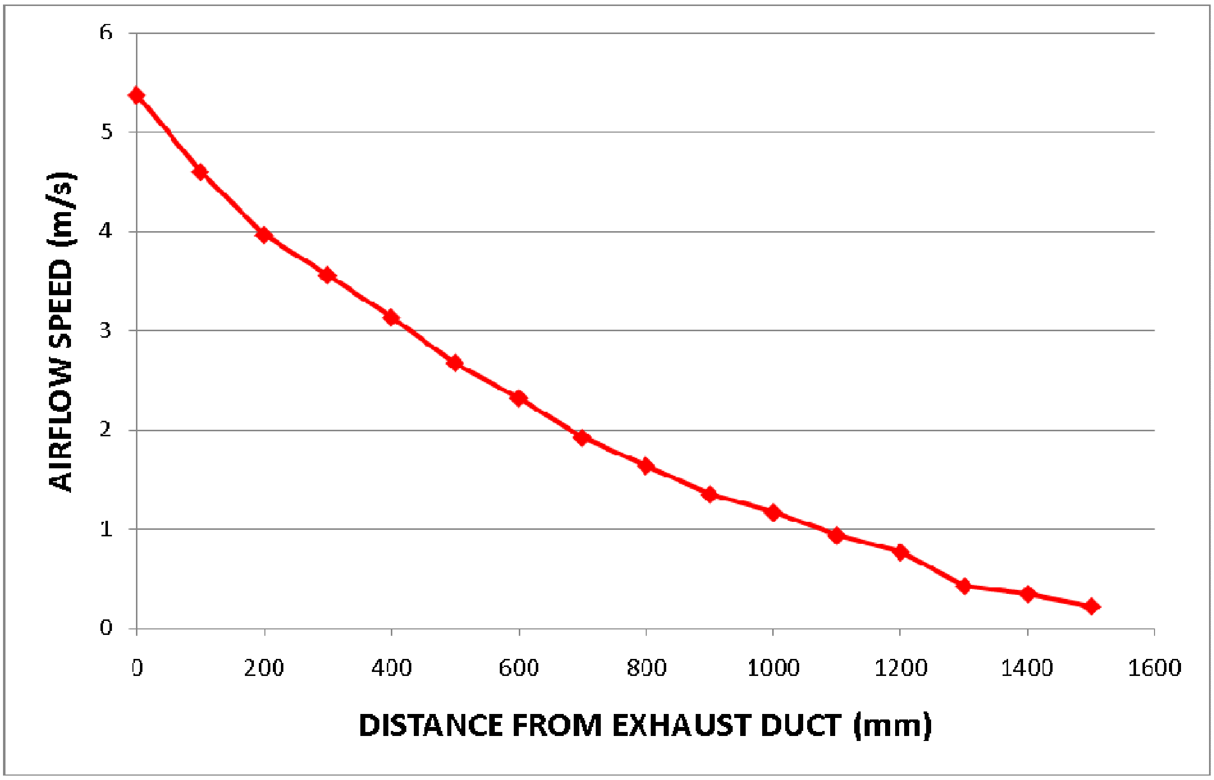

**Figure 9. Test equipment and enclosure on site in tunnel section**

**Figure 10. Close view of dust collected in vacuum bag from test at Euston Square Station (east end)**

**Figure 11. Dust collected in vacuum bag from test at King's Cross Station**

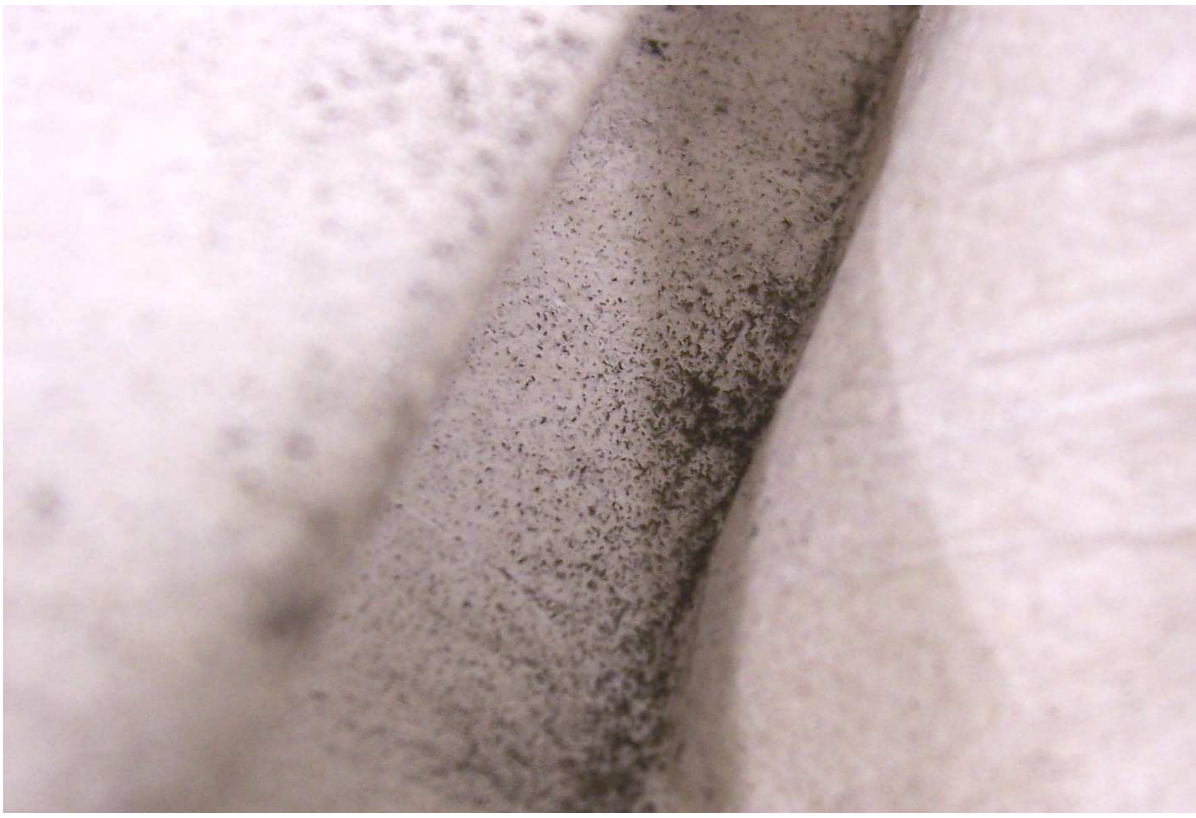

**Figure 12. Dust containing gritty particles collected from test in tunnel between King's Cross and Farringdon Stations**

**Figure 13. X-ray spectrum of dust collected at Euston Square Station (west end)**

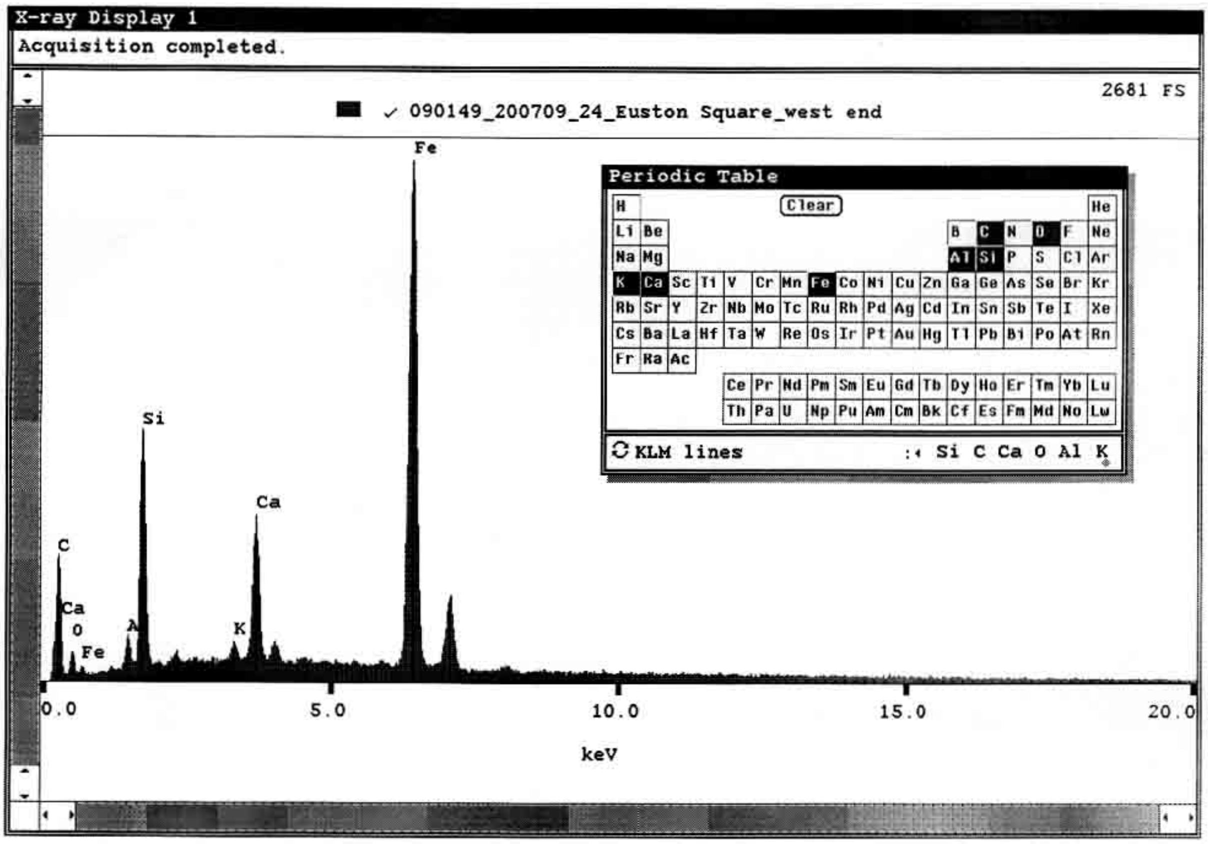


**Figure 14. X-ray spectrum of dust collected at Aldgate Station (east end)**

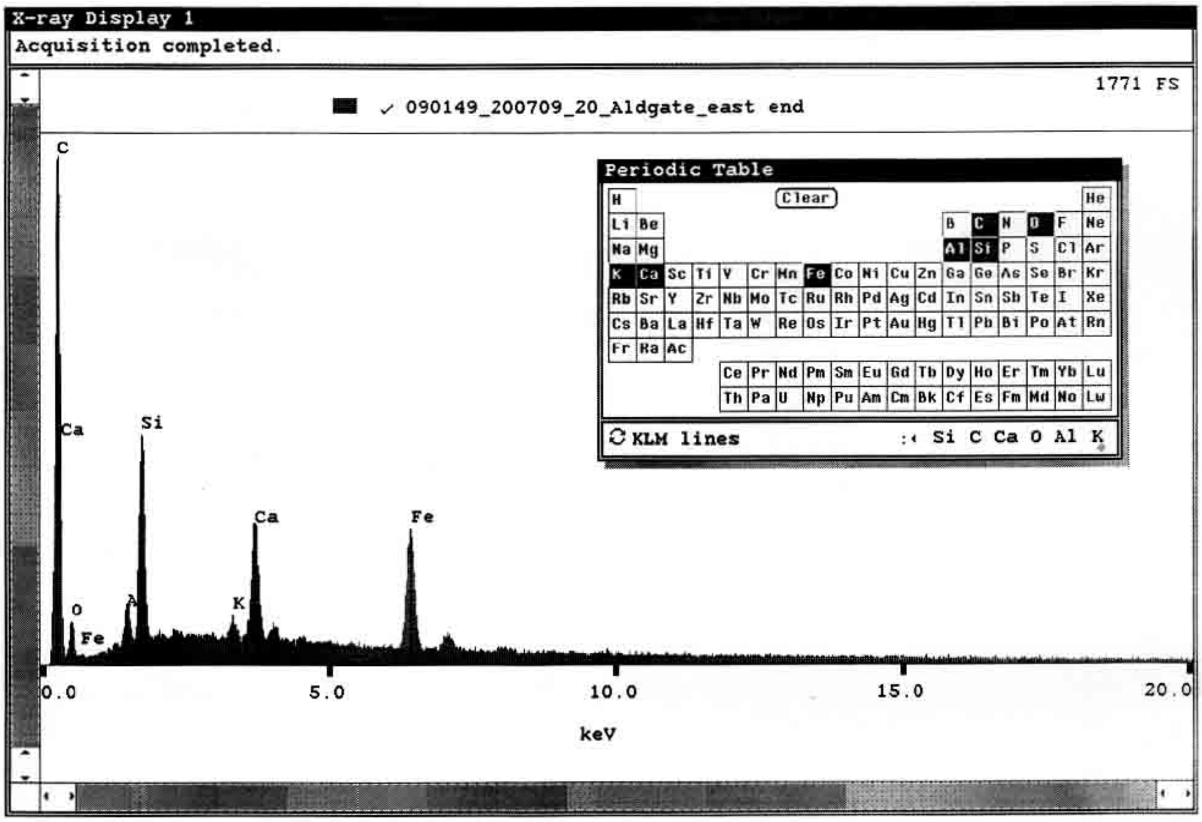

**Figure 15. Particle count data for test in cess at east end of Moorgate Station**

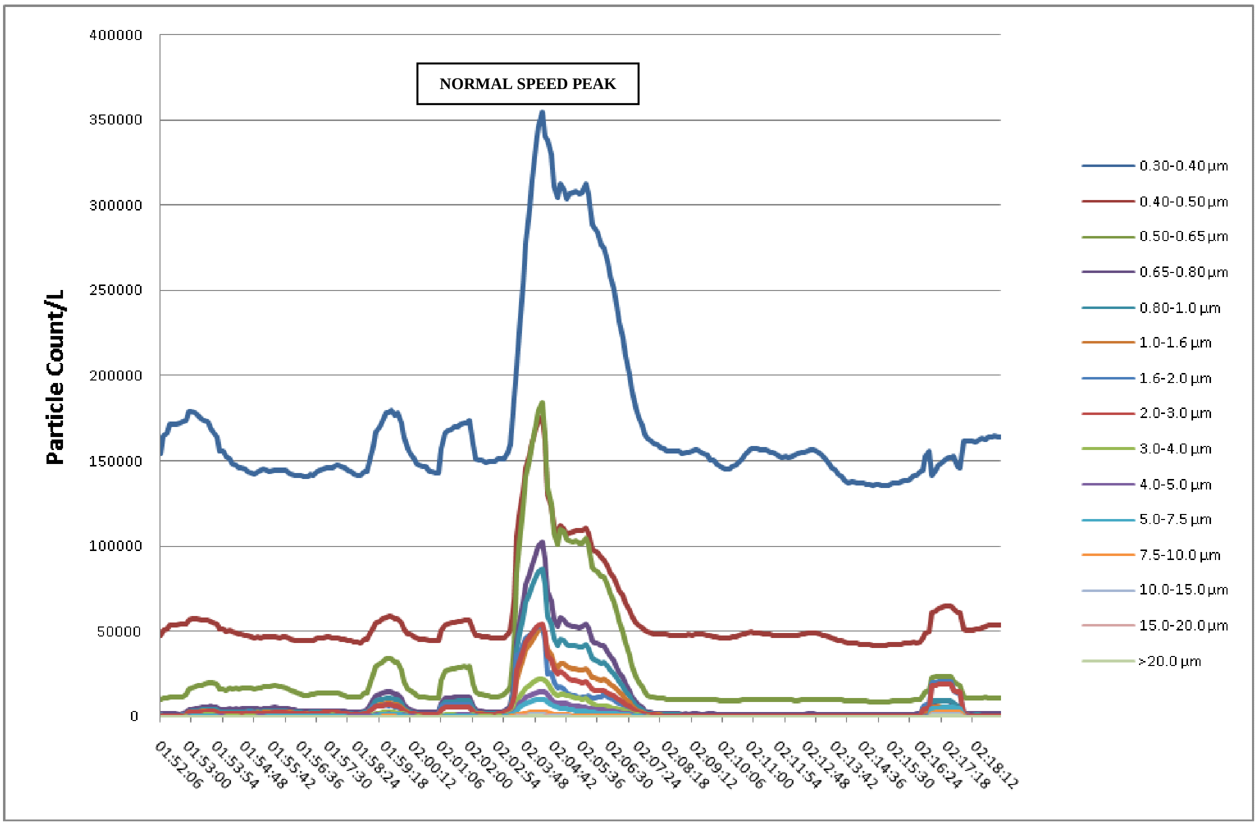


**Figure 16. Particle count data for test in cess at west end of Moorgate Station**

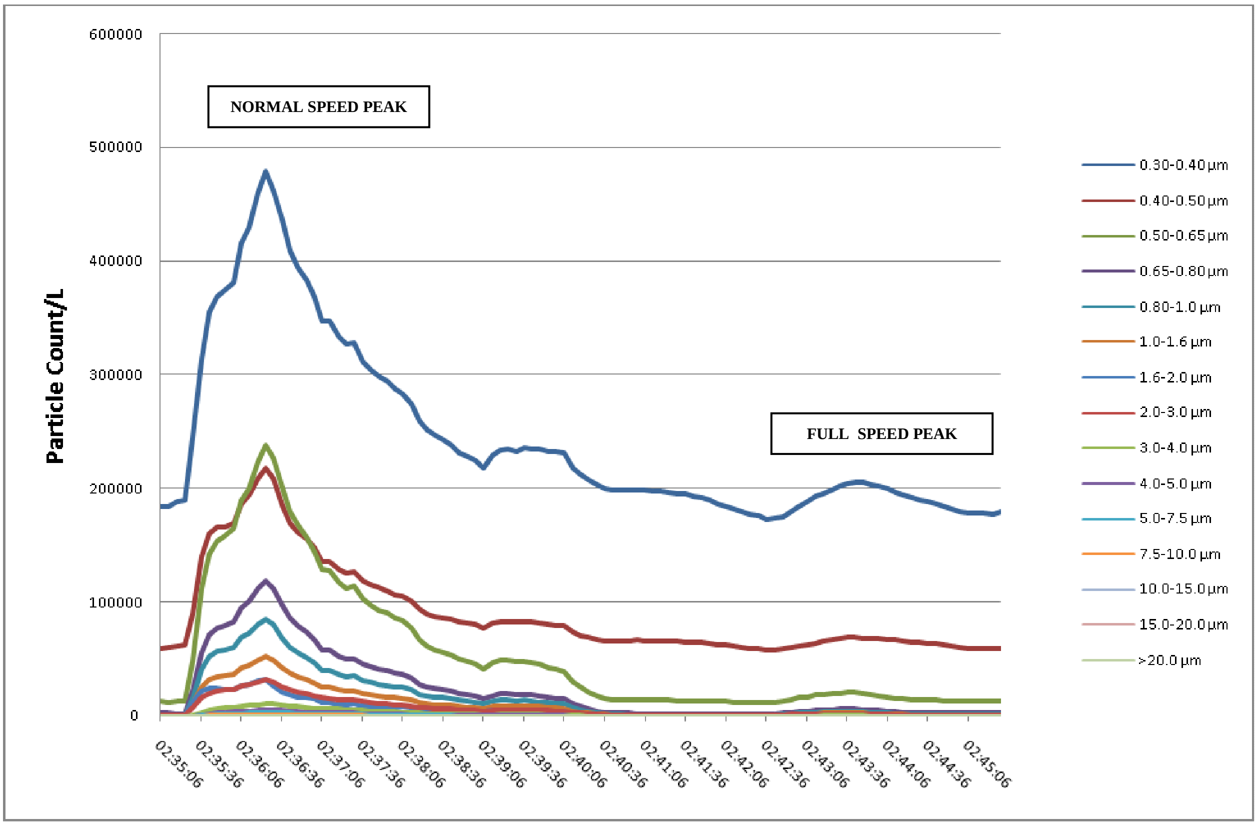

**Figure 17. Particle count data for test in cess in tunnel between Moorgate and Barbican Stations**

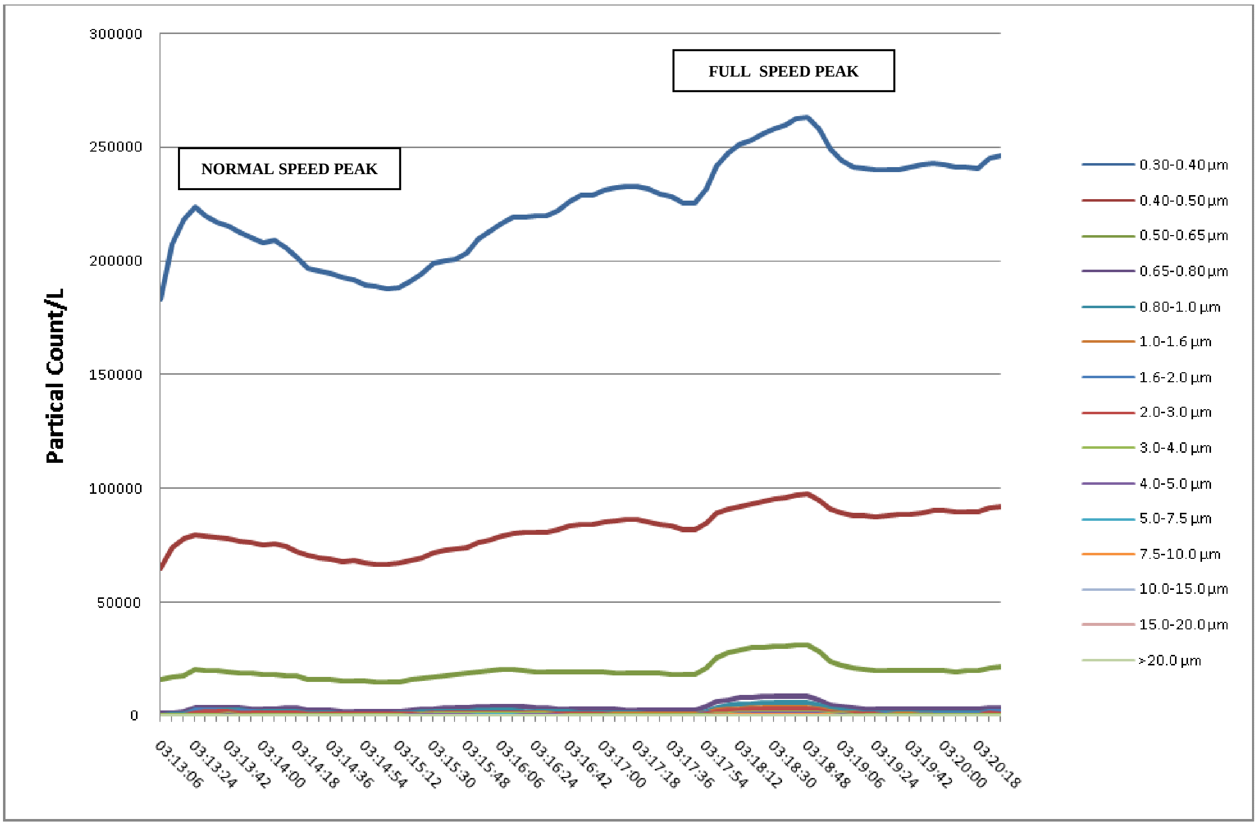


**Figure 18. Particle mass data for test in cess at Baker Street Station platform 4**

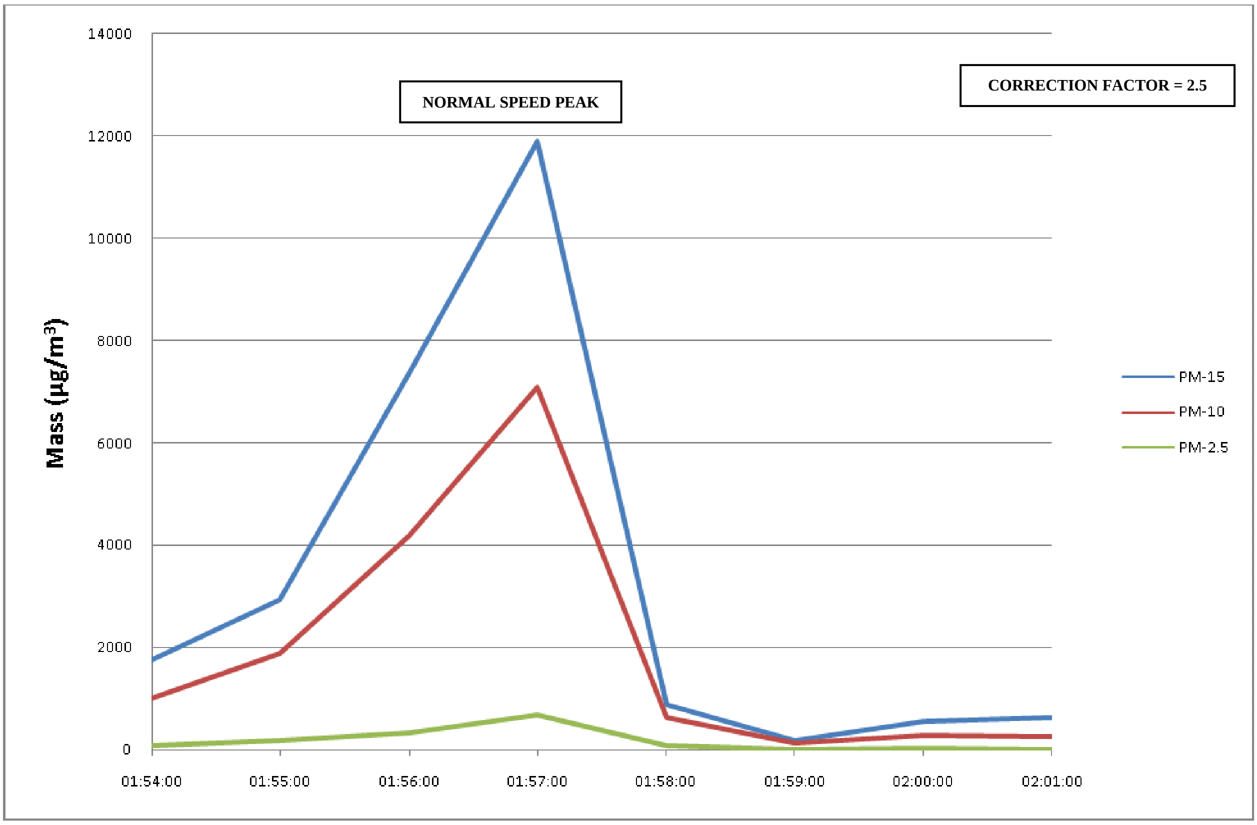

**Figure 19. Particle mass data for test in 6 foot in tunnel 200m north of Baker Street Station**

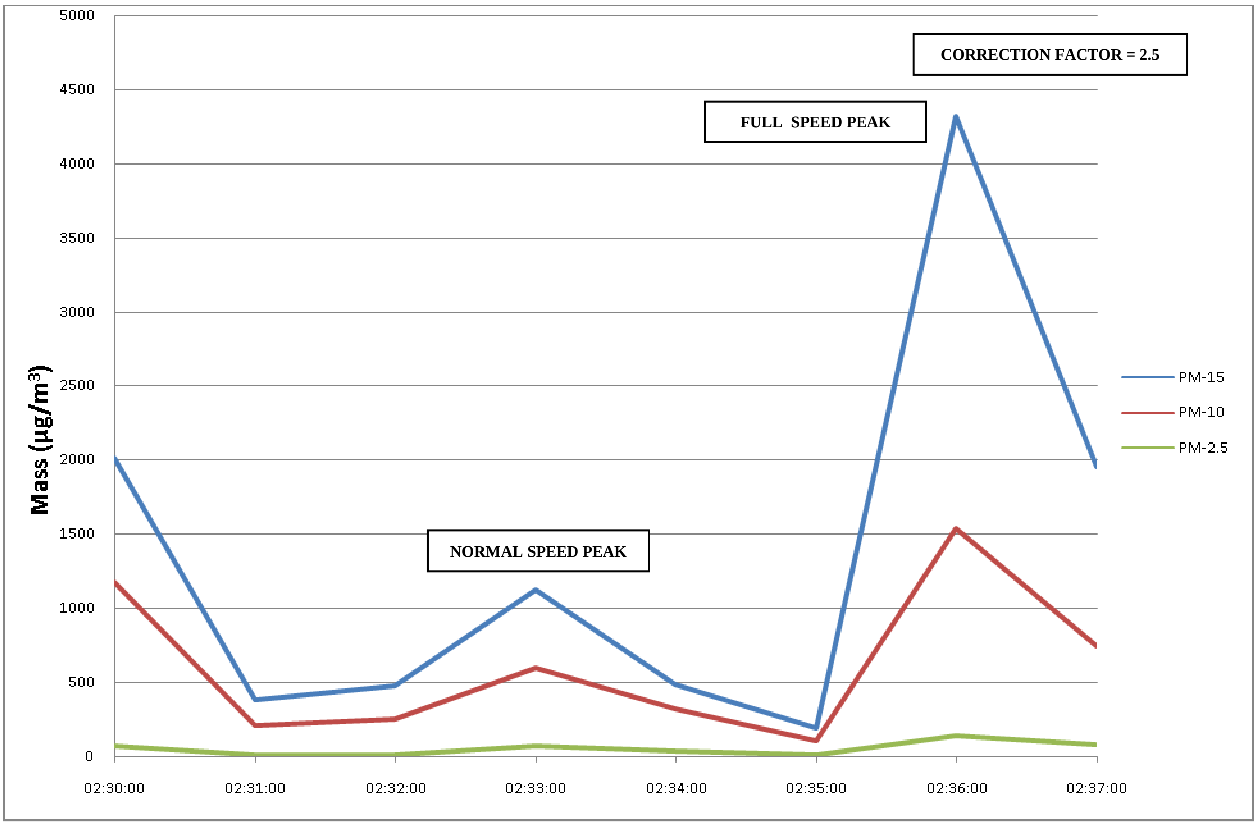


**Figure 20. Particle mass data for test in cess in tunnel 200m north of Baker Street Station**

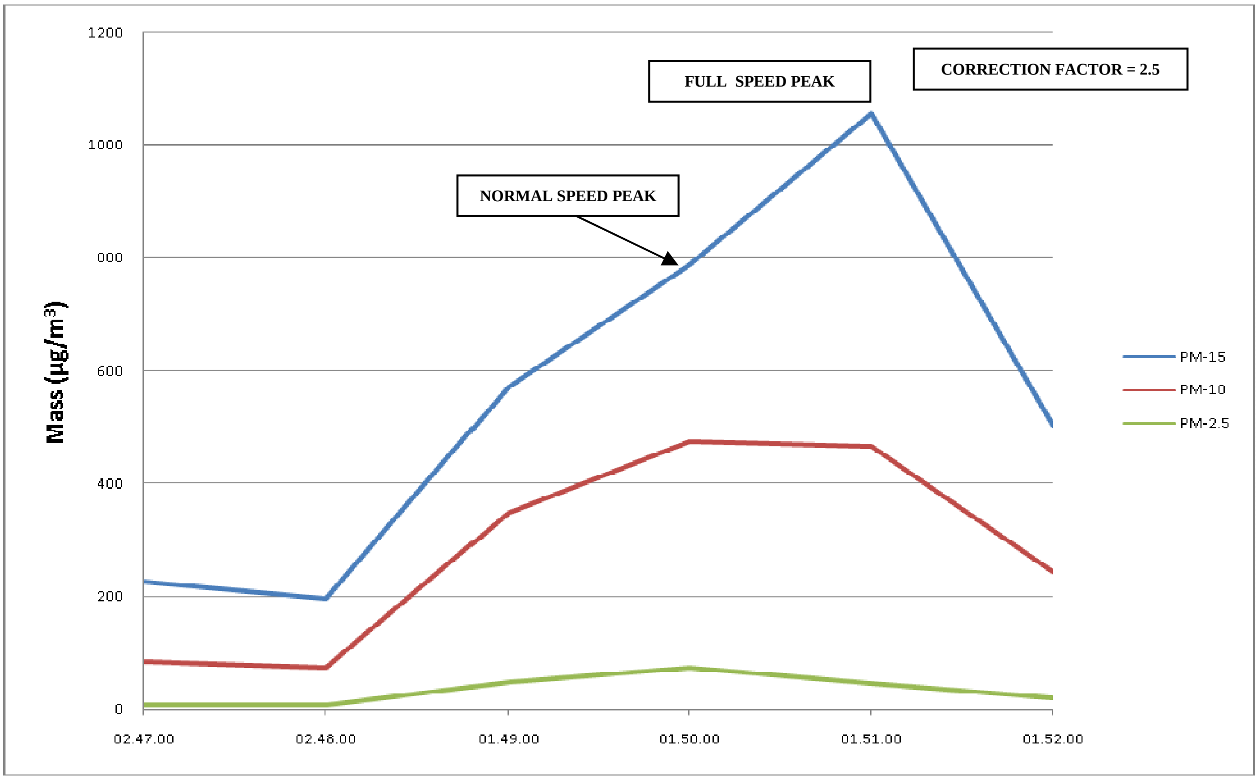

**Figure 21. Particle mass data for test in cess at west end of platform at Great Portland Street Station**

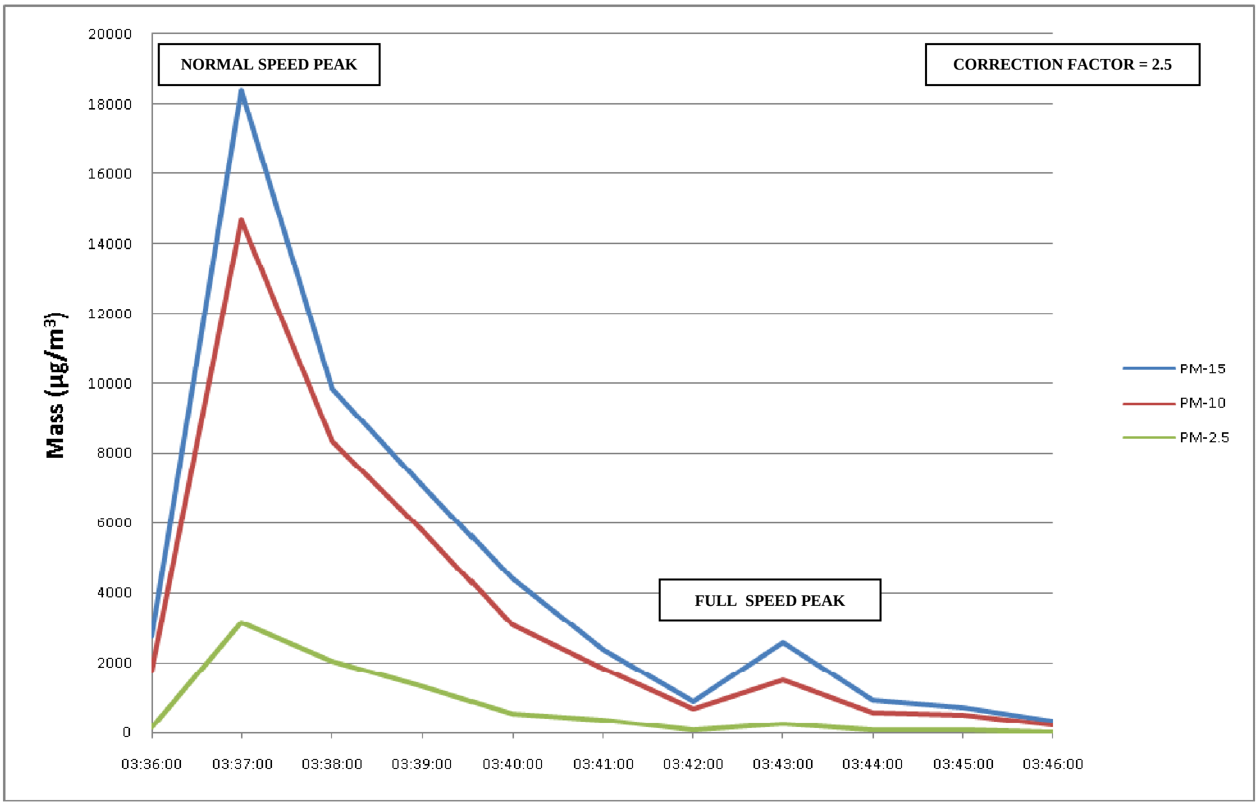


**Figure 22. Particle mass data for test in 6 foot area at east end of platform at Great Portland Street Station**

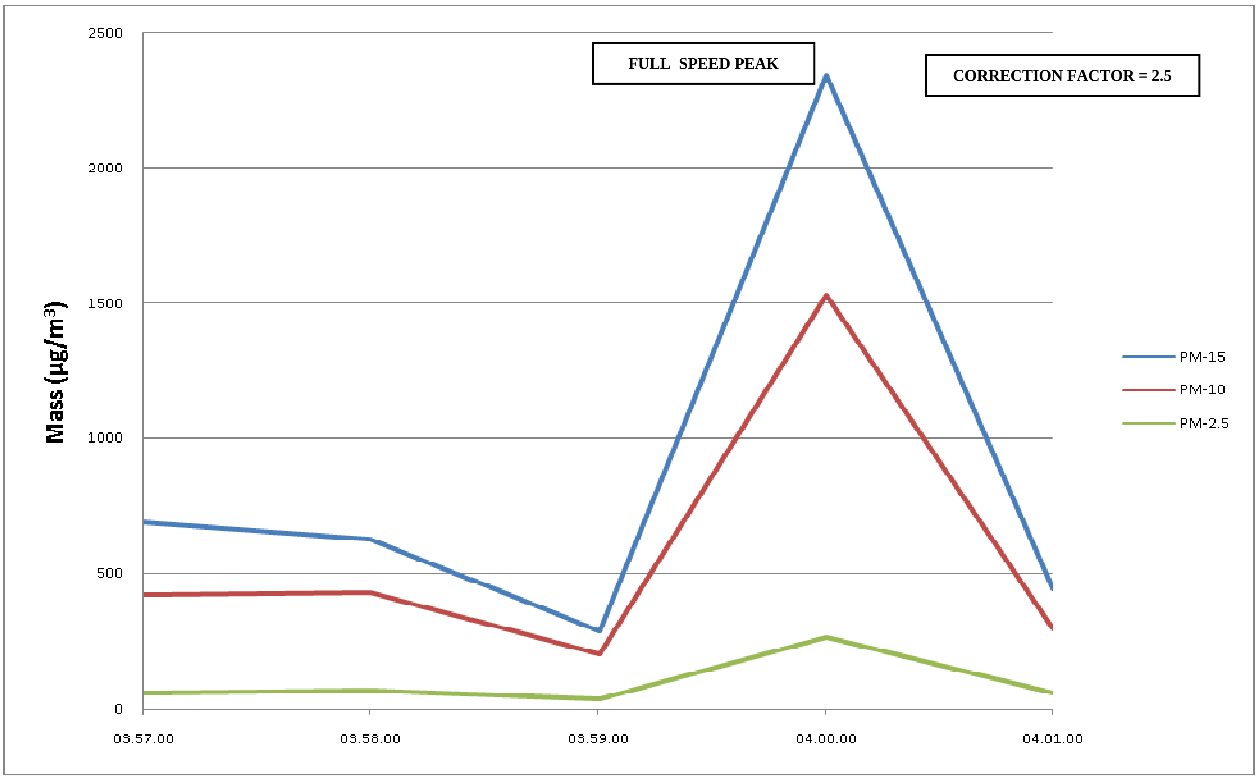

**Figure 23. Particle count data for test in cess area at west end of Euston Square Station**

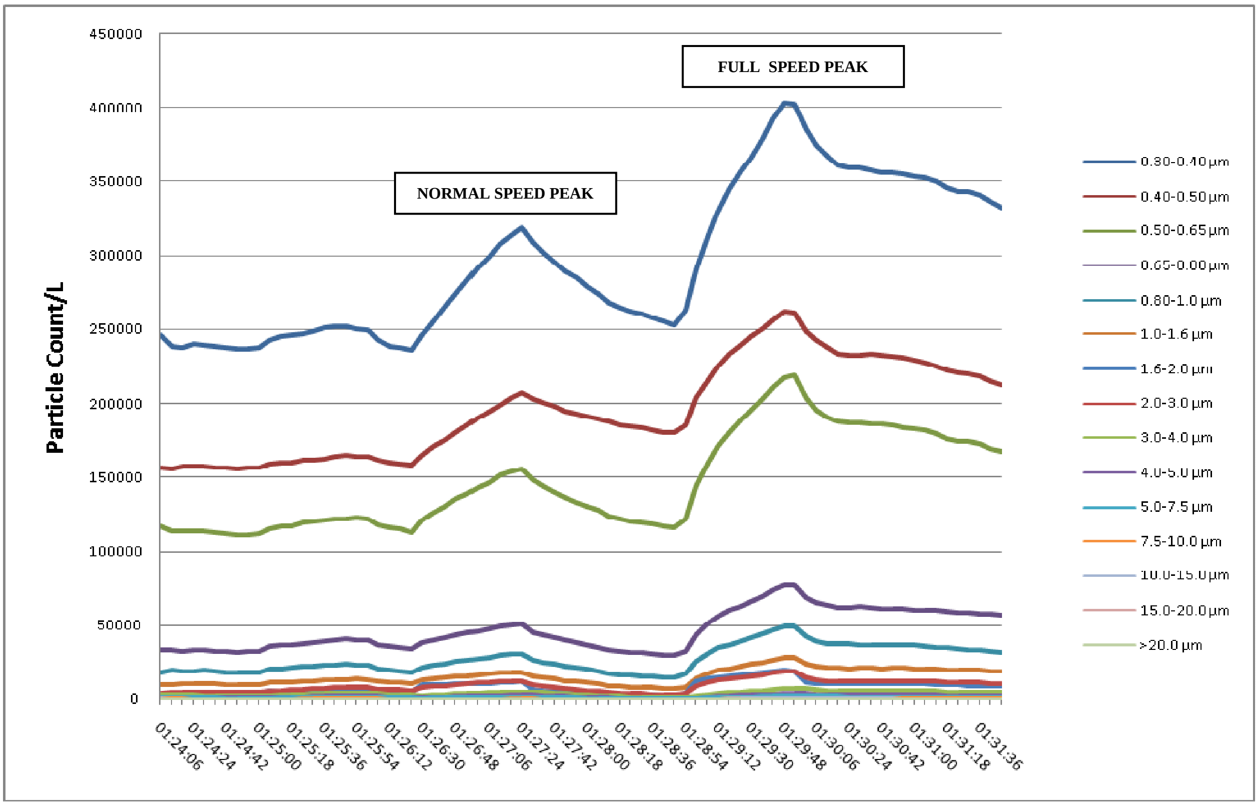


**Figure 24. Particle mass data for test in cess at west end of platform at Euston Square Station**

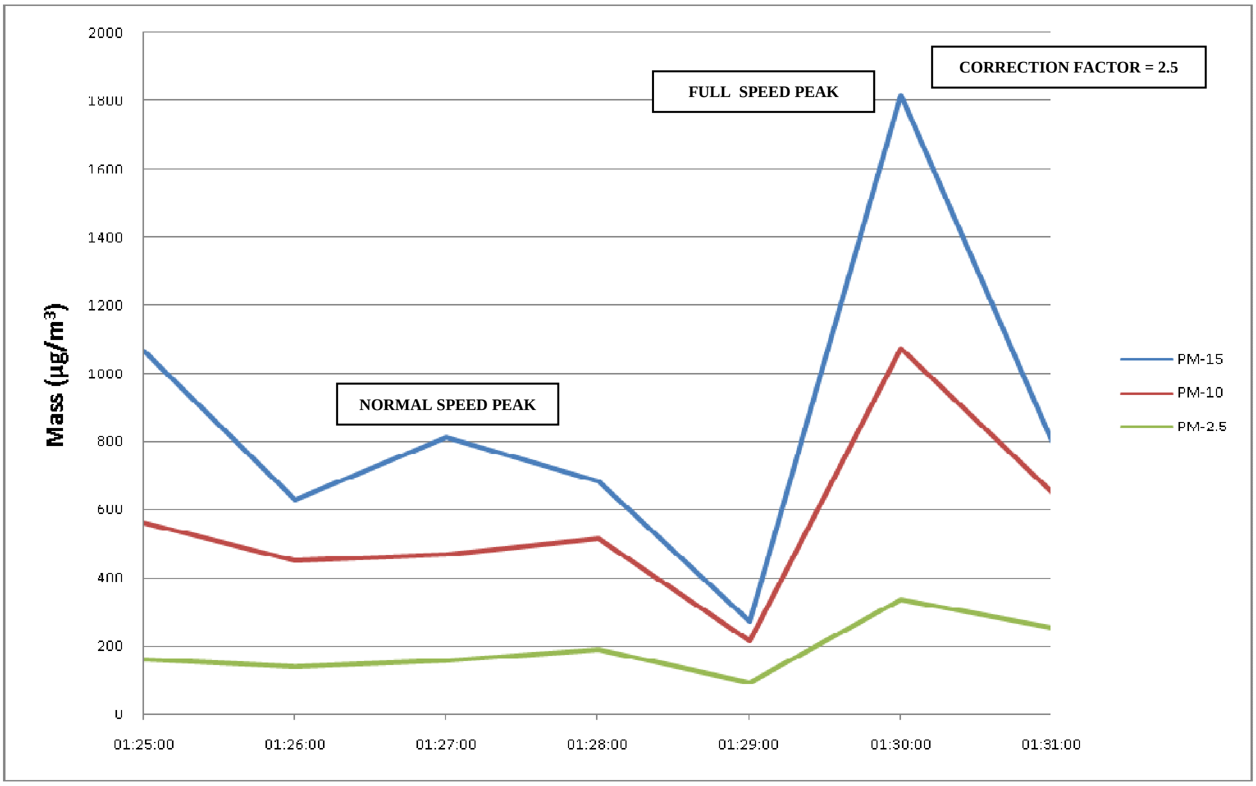

**Figure 25. Particle count data for test in 6 foot at east end of Euston Square Station**

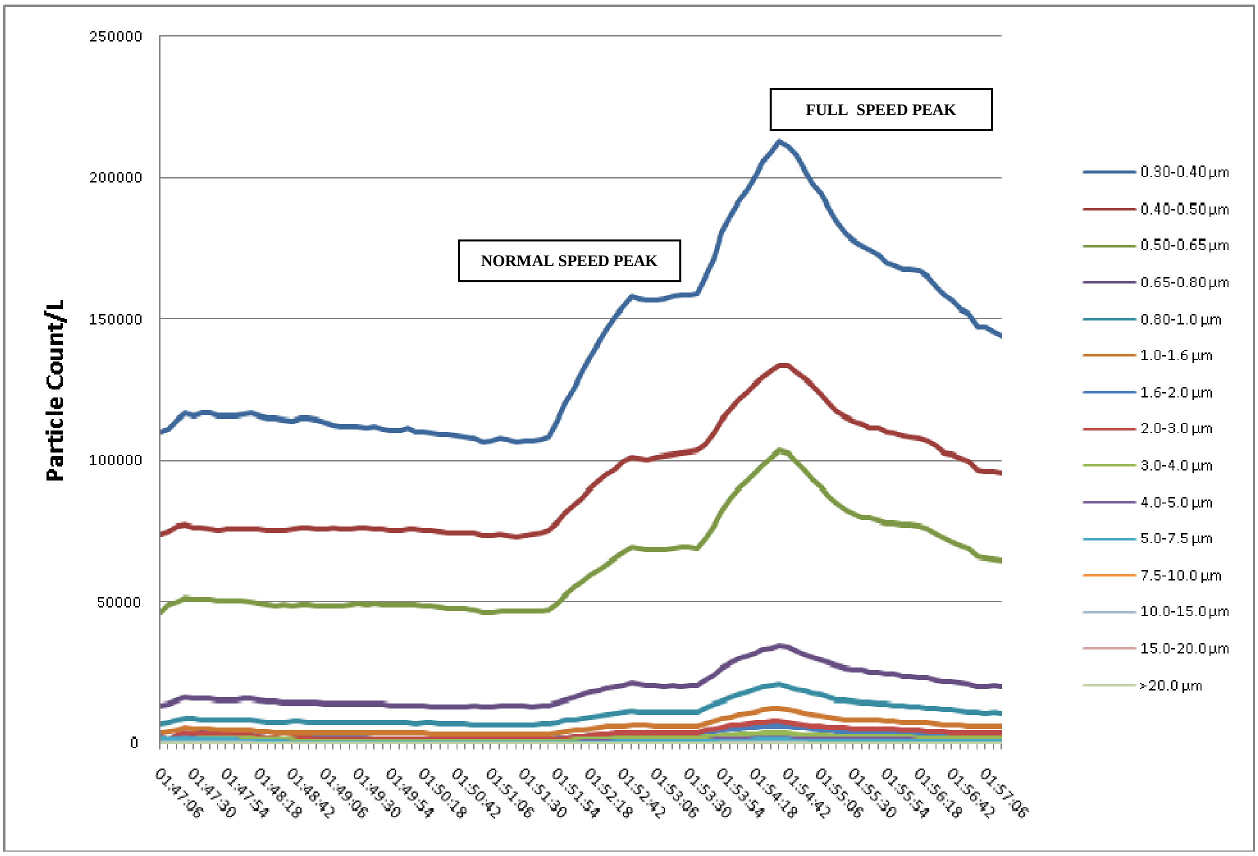


**Figure 26. Particle mass data for test in 6 foot at east end of Euston Square Station**

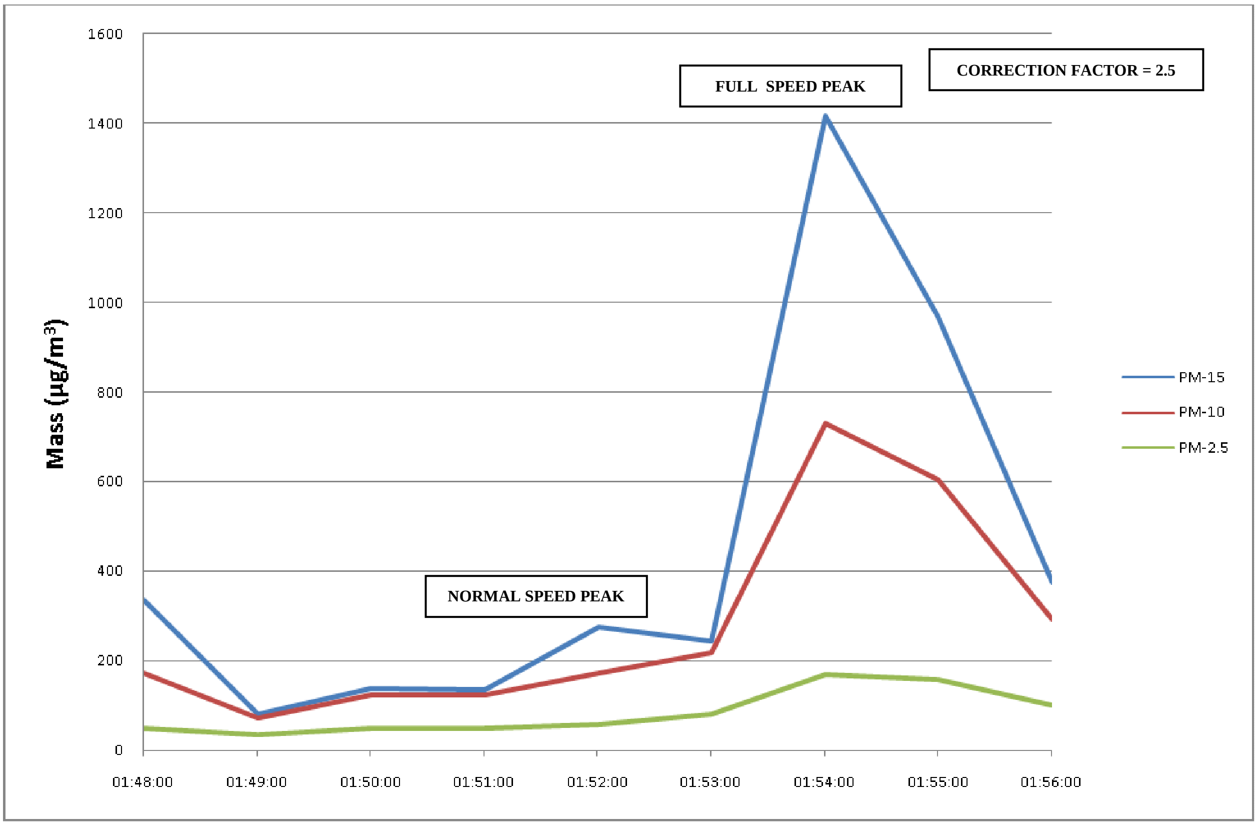

**Figure 27. Particle count data for test in cess area at east end of platform at King's Cross Station**

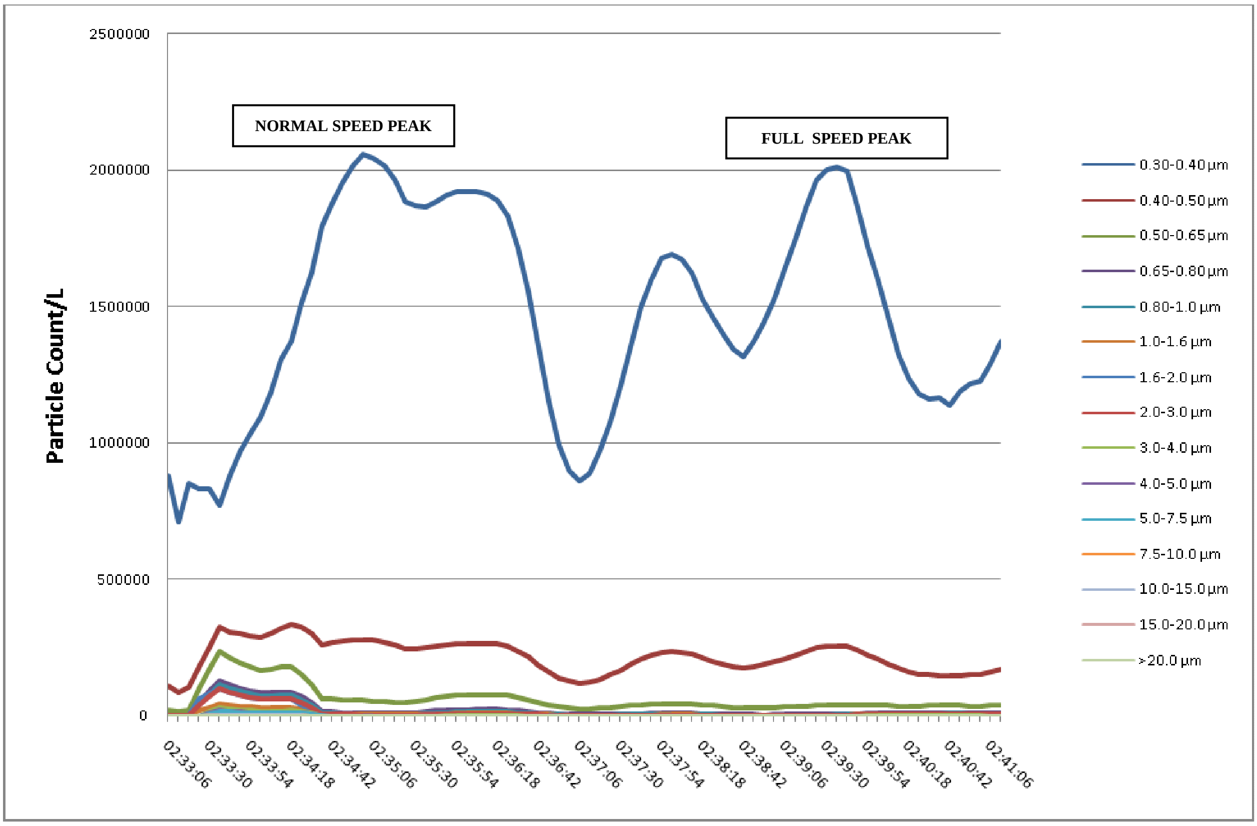


**Figure 28. Particle mass data for test in cess area at east end of platform at King's Cross Station**

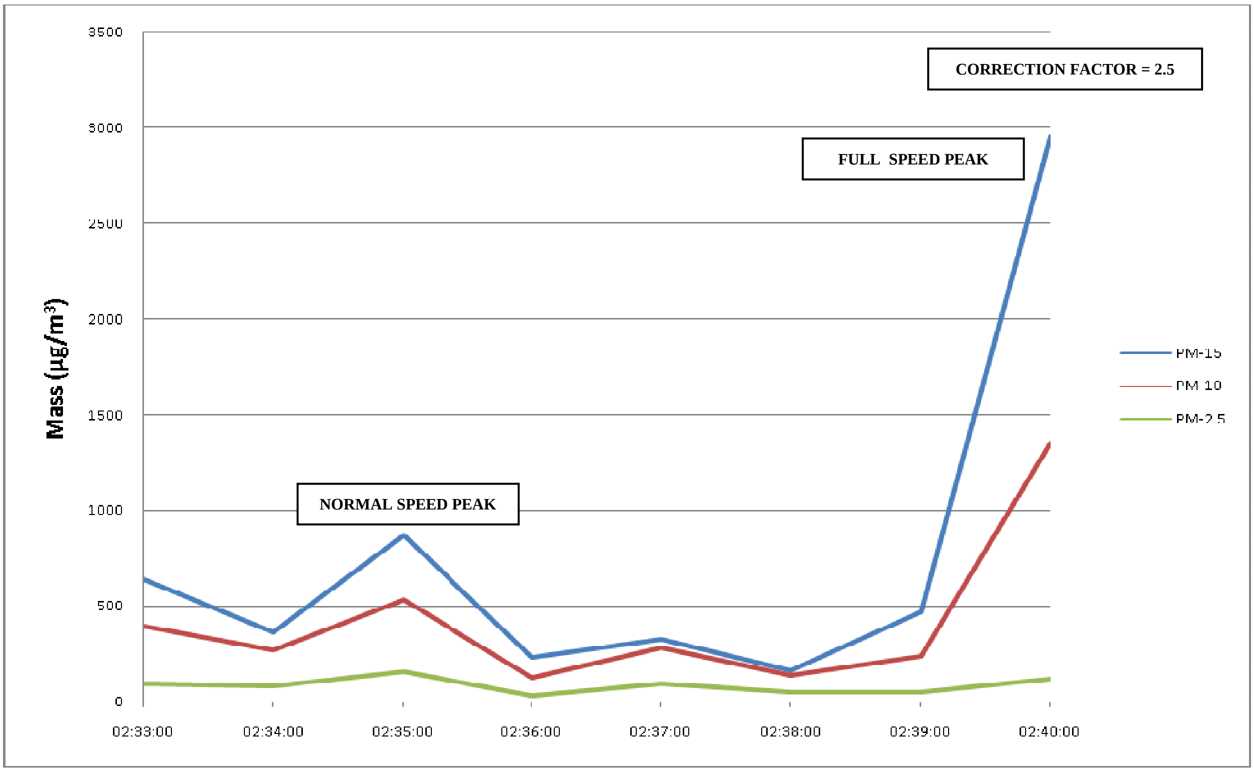

**Figure 29. Particle count data for test in cess area in tunnel between King's Cross and Farringdon Stations**

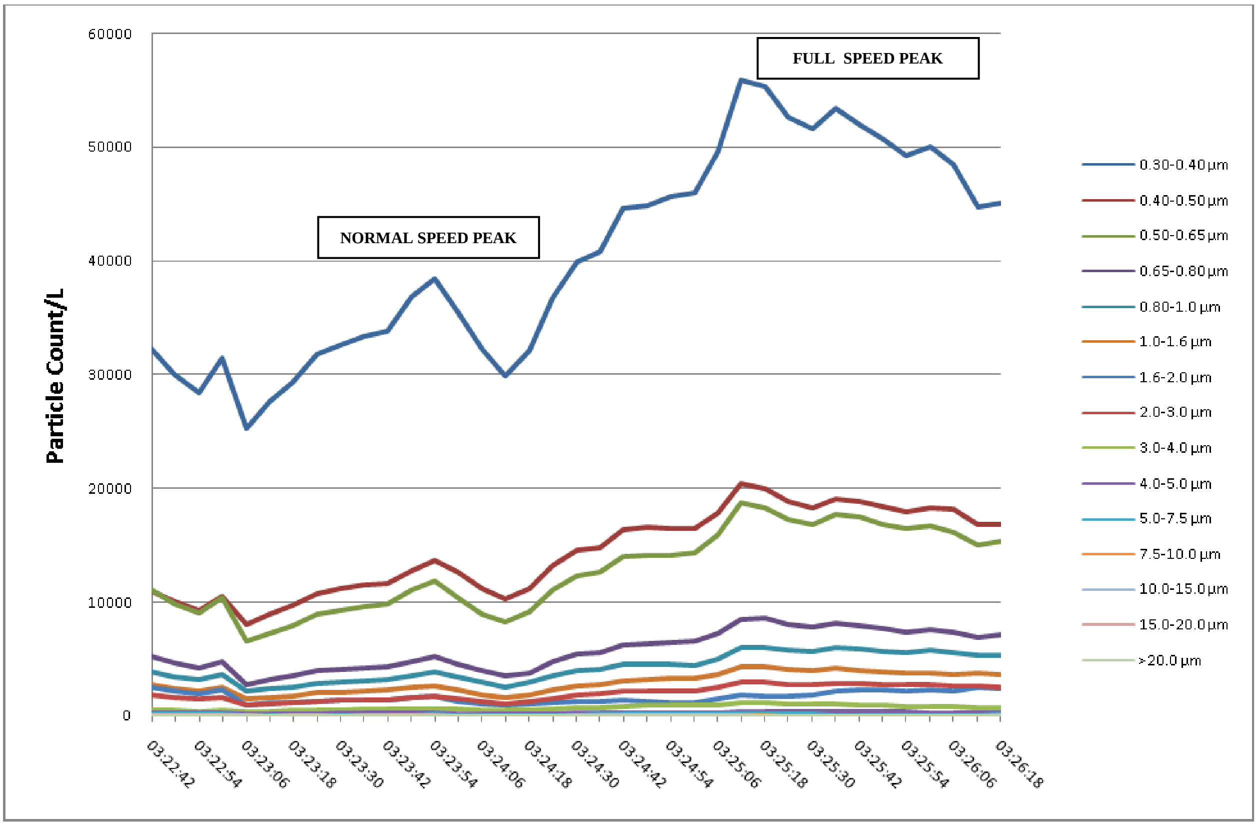


**Figure 30. Particle mass data for test in cess area in tunnel between King's Cross and Farringdon Stations**

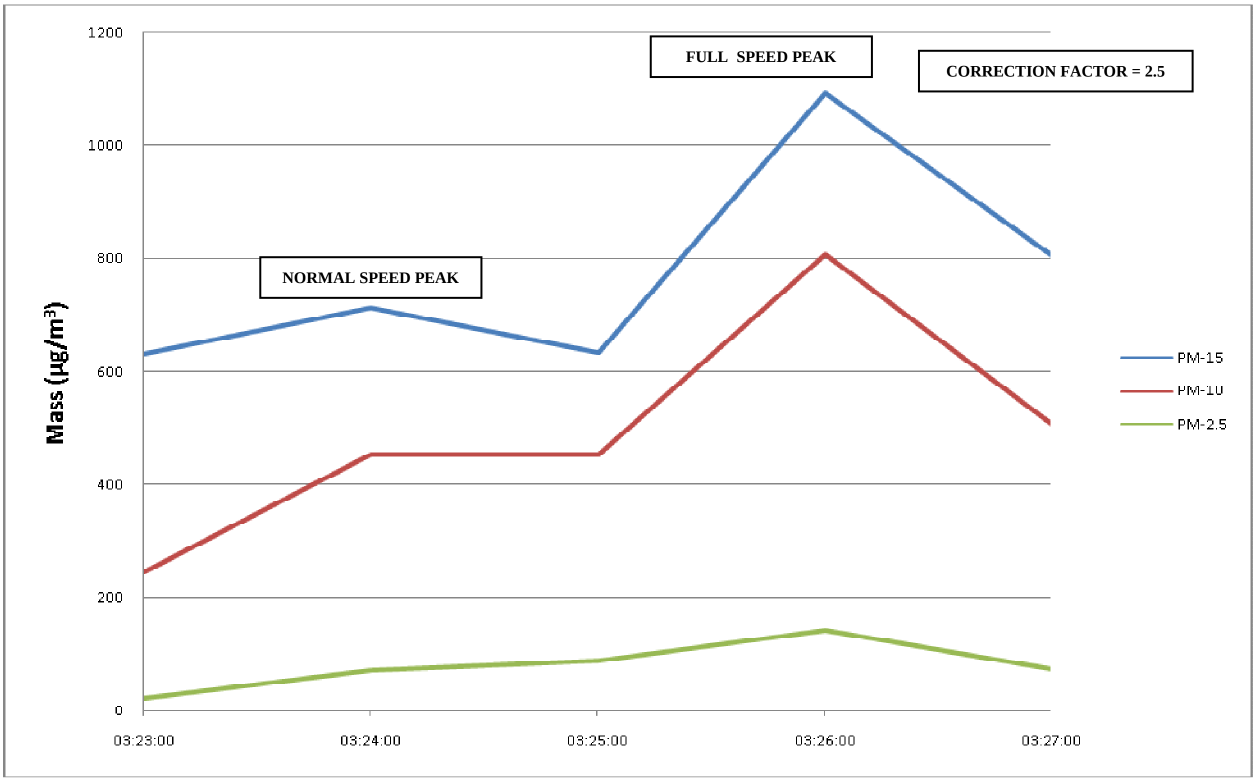

**Figure 31. Particle count data for test in cess area of open section between King's Cross and Farringdon Stations**

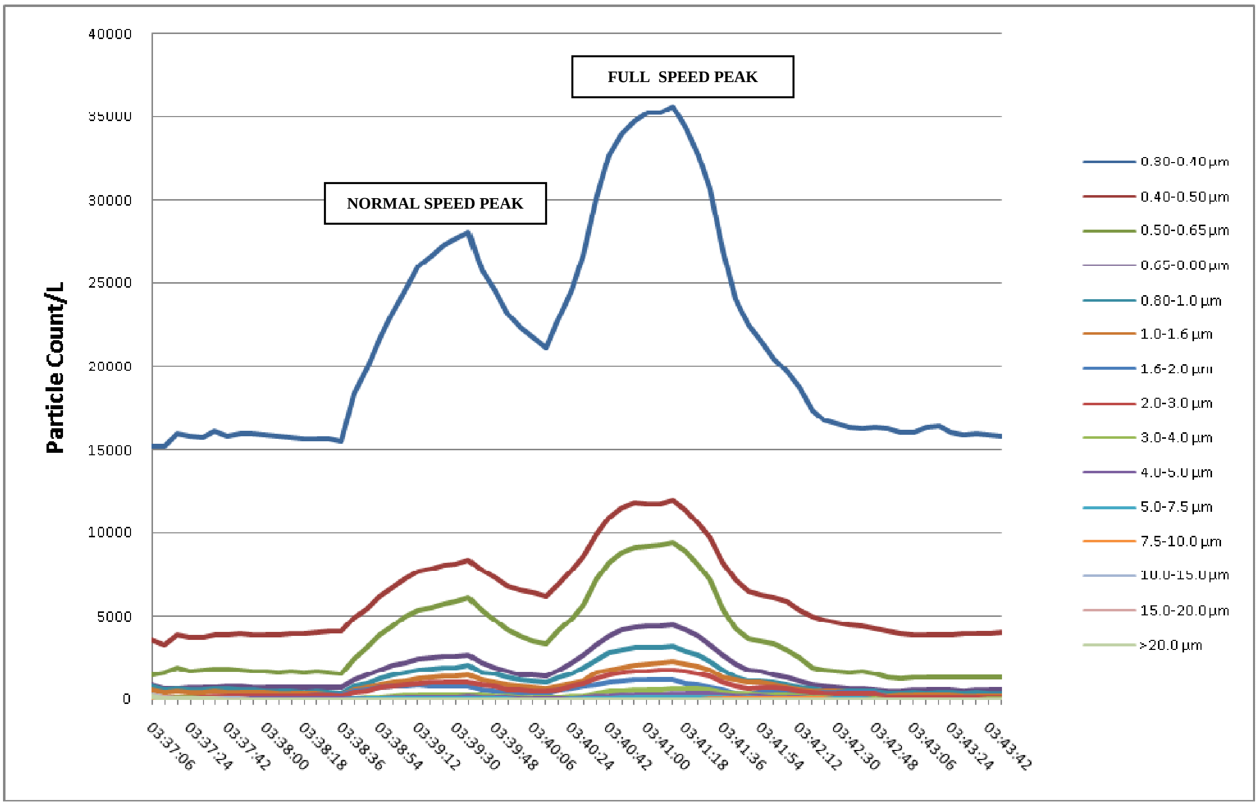


**Figure 32. Particle mass data for test in cess area of open section between King's Cross and Farringdon Stations**

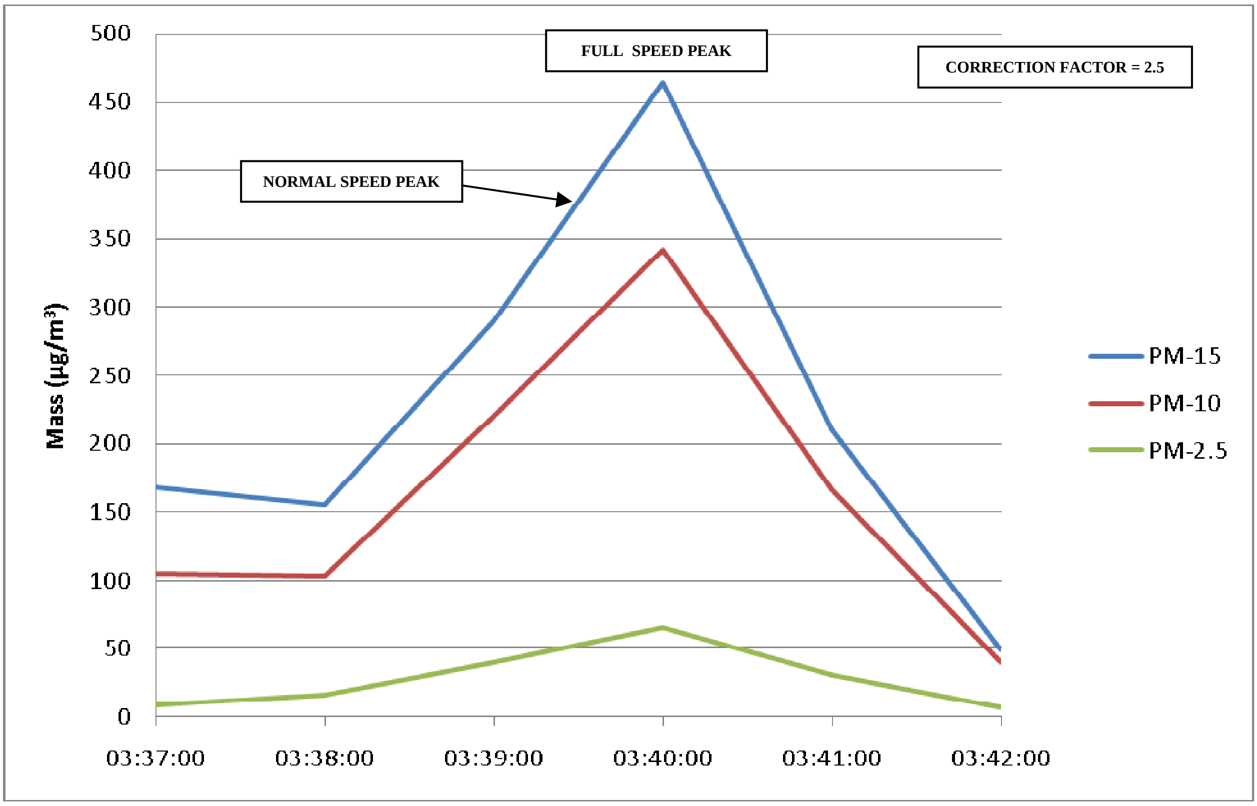

**Figure 33. Particle count data for test in cess area at east end of platform at Aldgate Station**

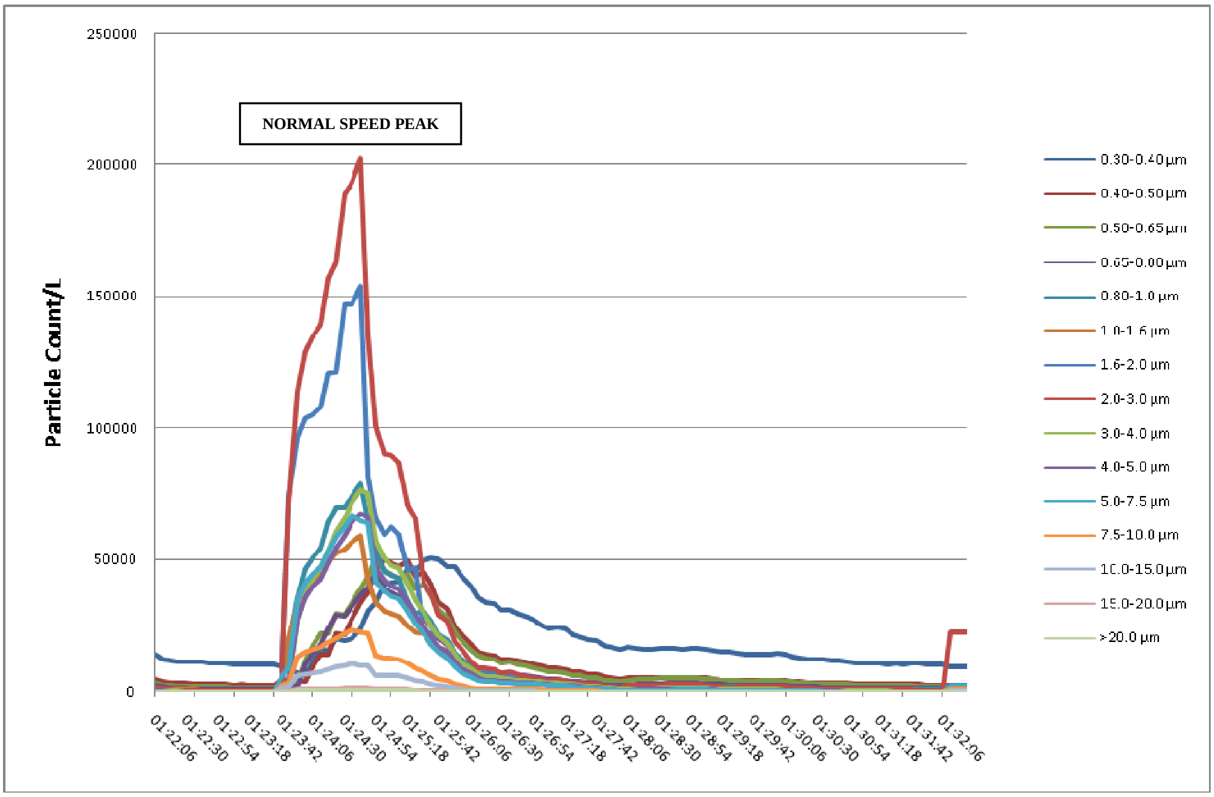


**Figure 34. Particle mass data for test in cess at east end of platform at Aldgate Station**

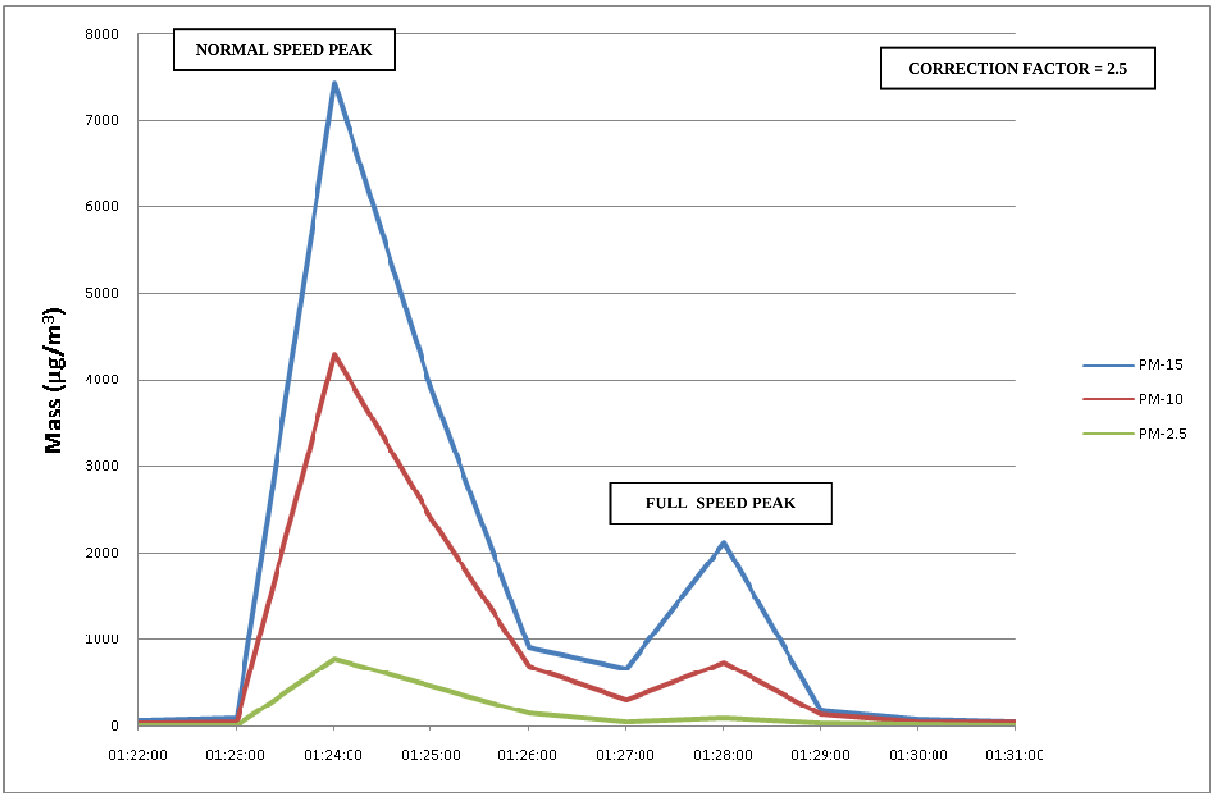

**Figure 35. Particle count data for test in 6 foot at west end of platform at Aldgate Station**

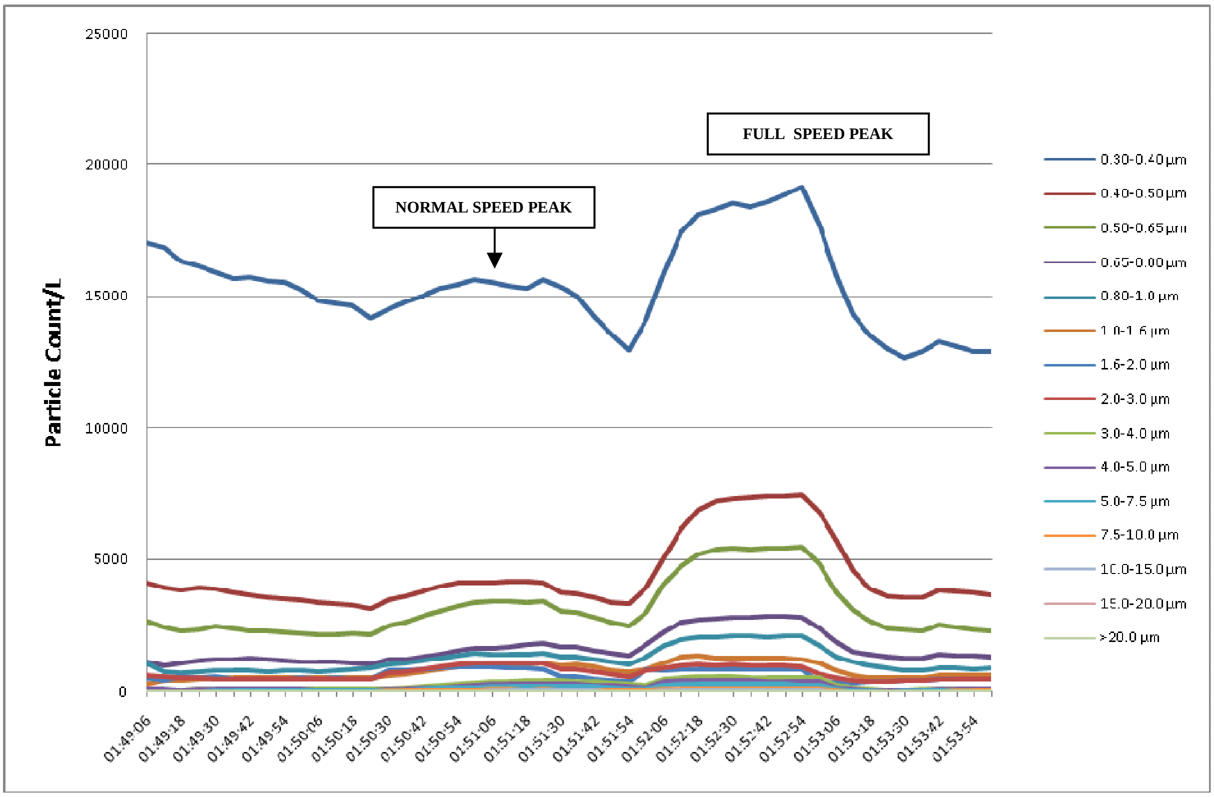


**Figure 36. Particle mass data for test in 6 foot at west end of platform at Aldgate Station**

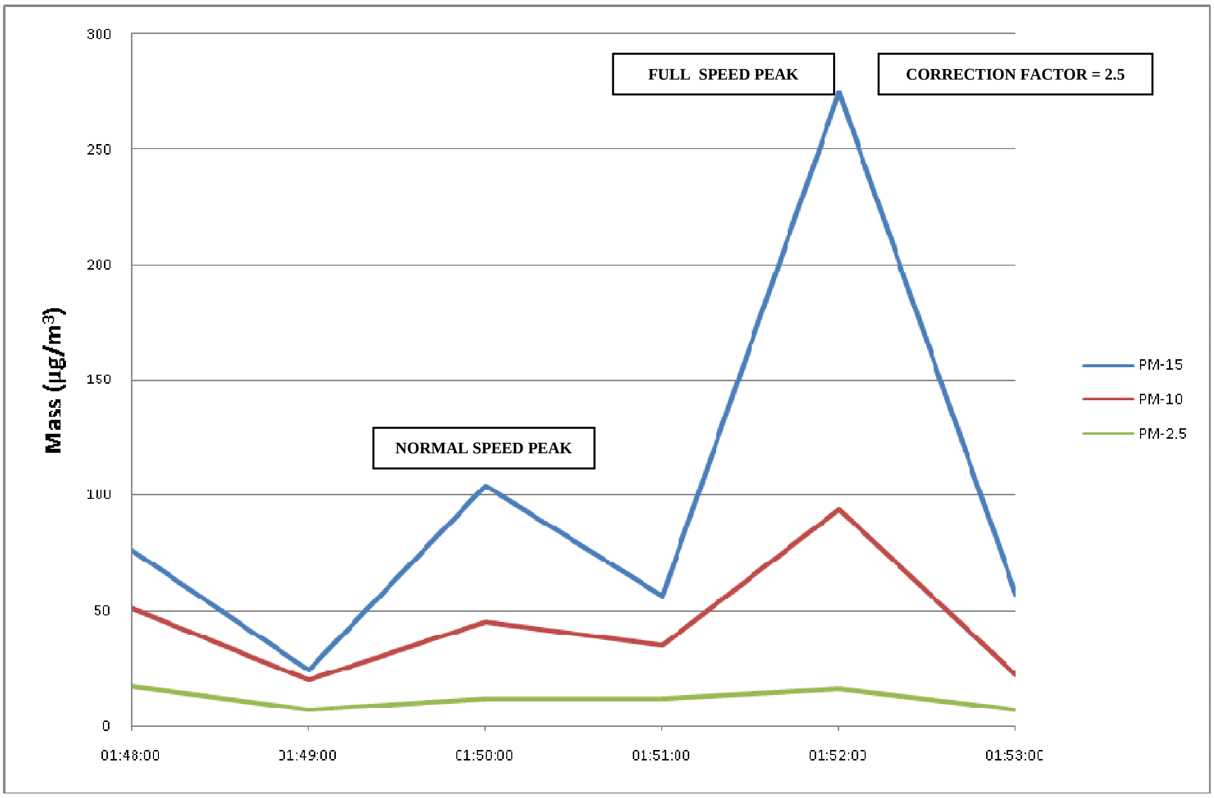

**Figure 37. Particle count data for test in cess area in tunnel between Aldgate and Liverpool Street Stations**

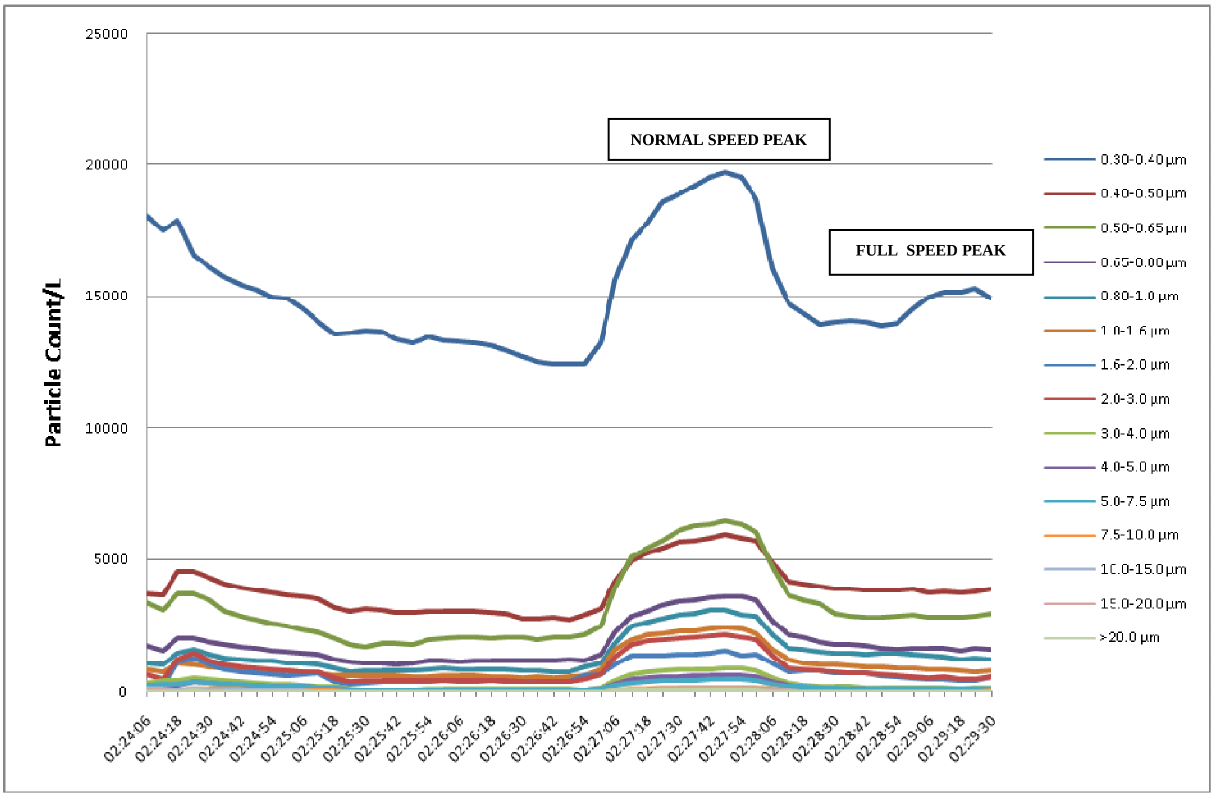


**Figure 38. Particle mass data for test in cess area in tunnel between Aldgate and Liverpool Street Stations**

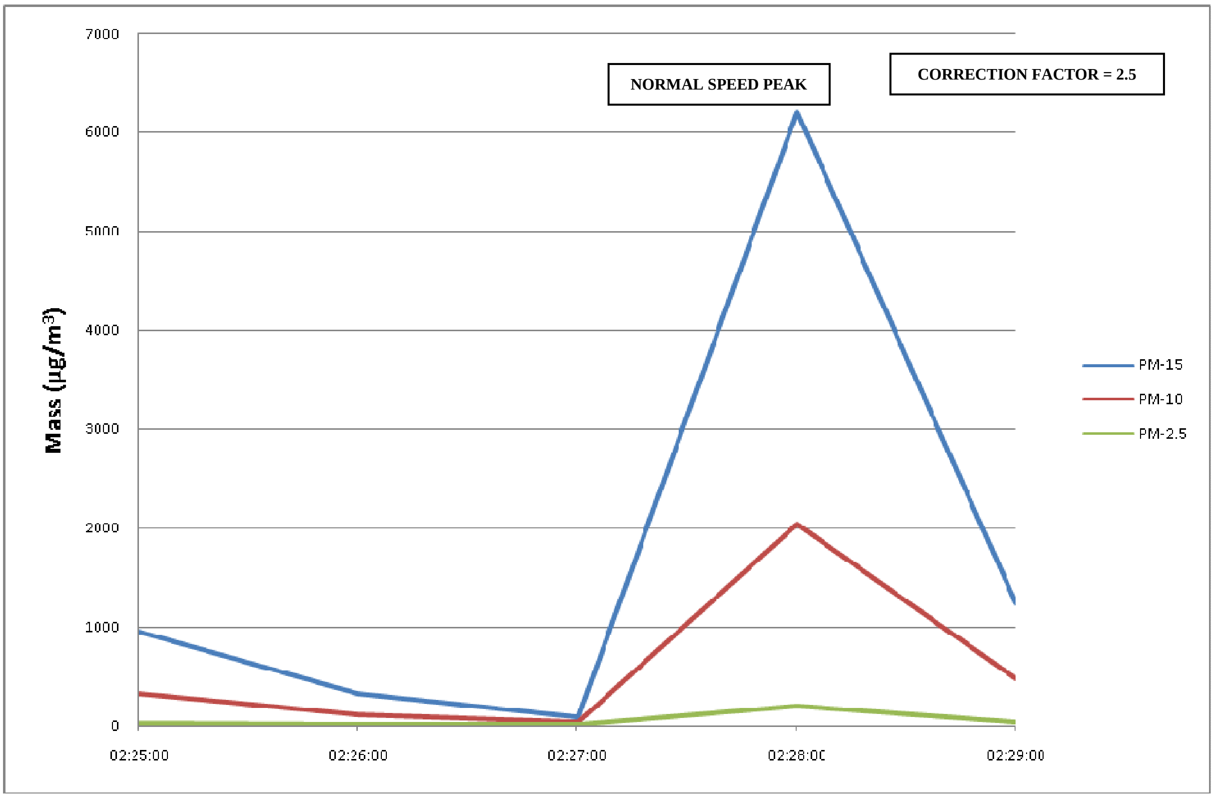

**Figure 39. Particle count data for test in cess area at east end of platform at Liverpool Street Station**

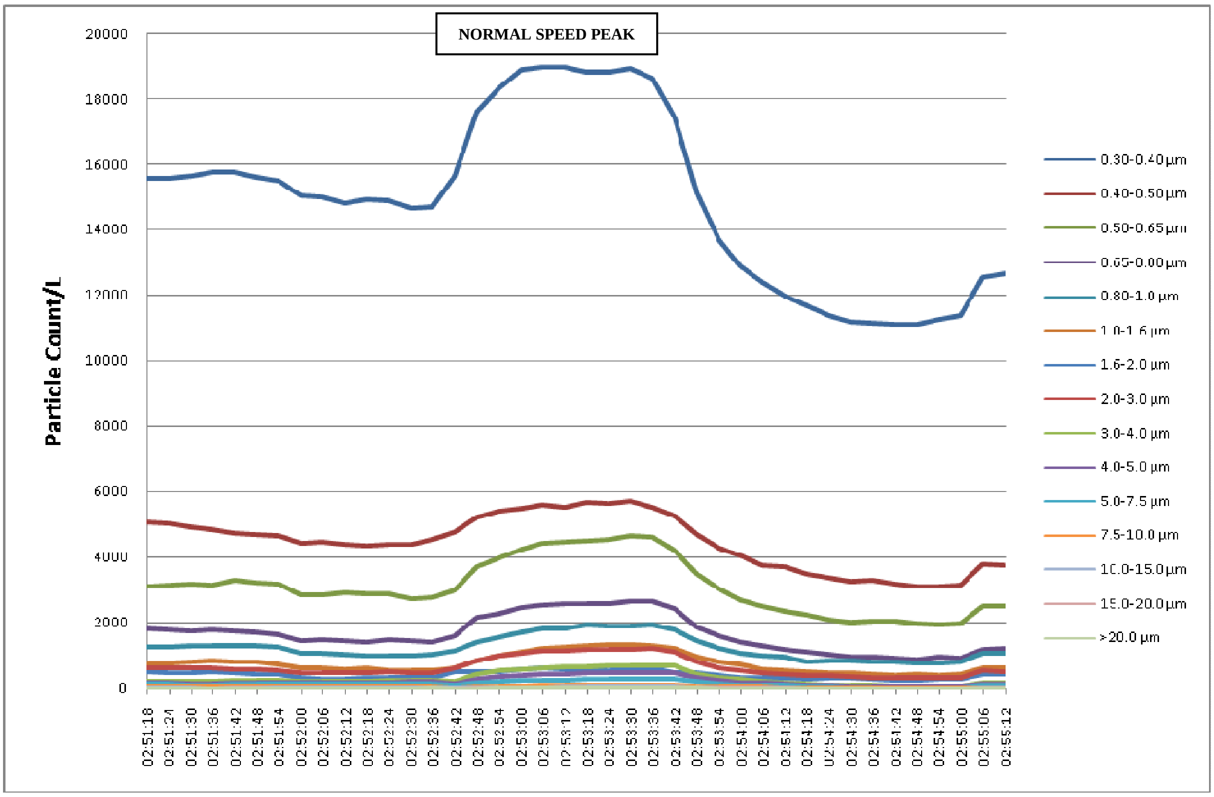


**Figure 40. Particle mass data for test in cess area at east end of platform at Liverpool Street Station**

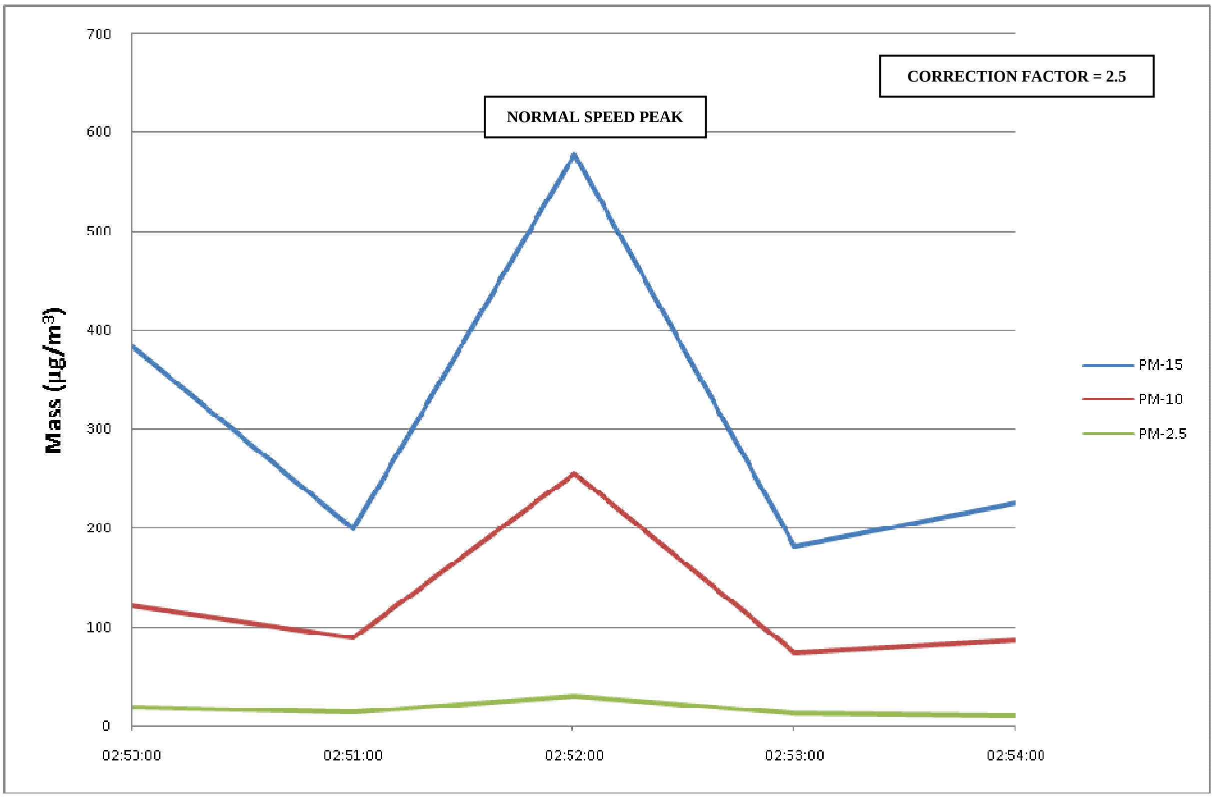

**Figure 41. Particle count data for test in cess area at west end of platform at Liverpool Street Station**

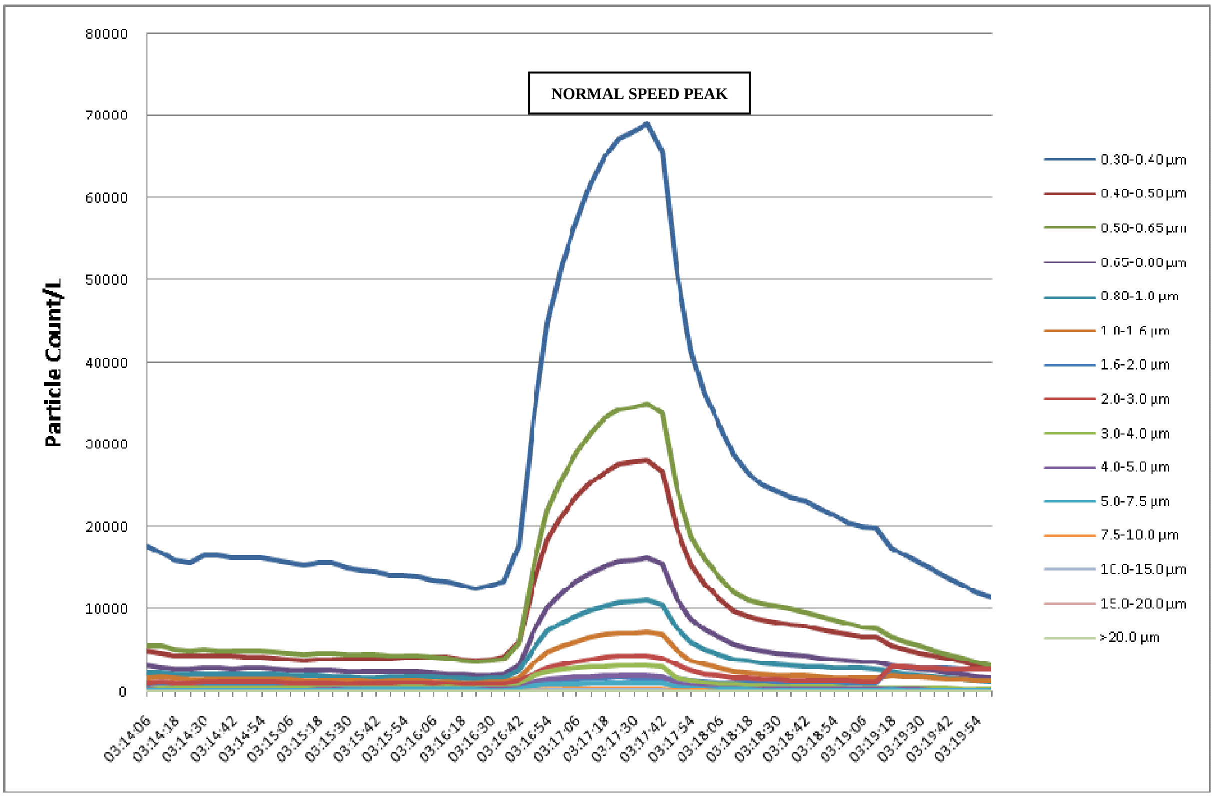


**Figure 42. Particle mass data for test in cess area at west end of platform at Liverpool Street Station**

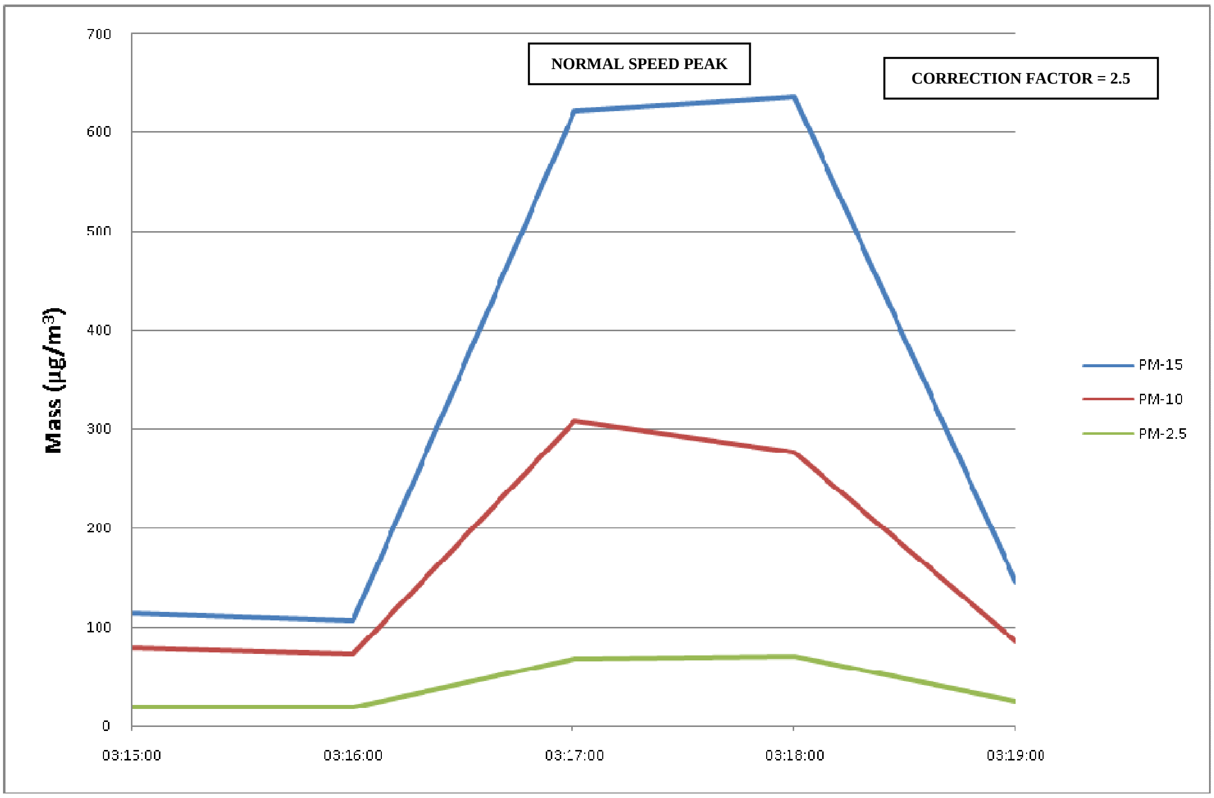

**Figure 43. Particle count data for test in cess area in tunnel between Liverpool Street and Moorgate Stations**

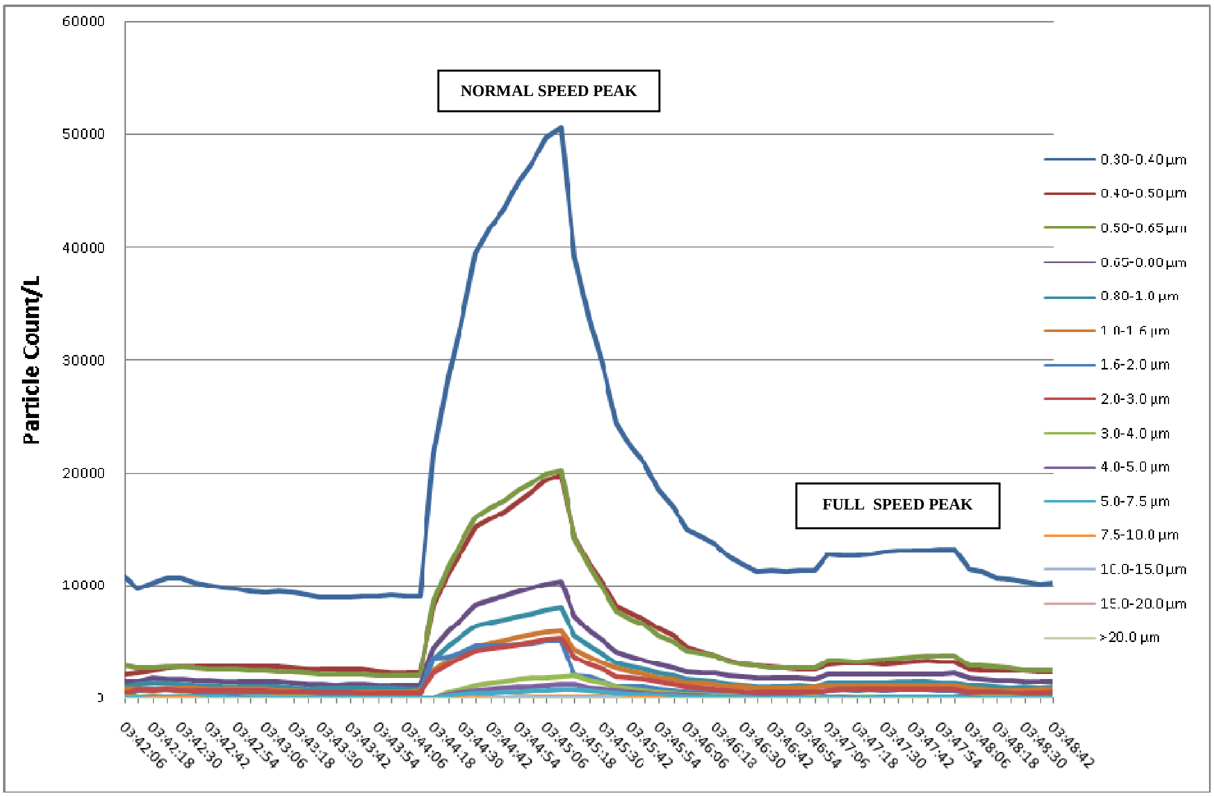


**Figure 44. Particle mass data for test in cess area in tunnel between Liverpool Street and Moorgate Stations**

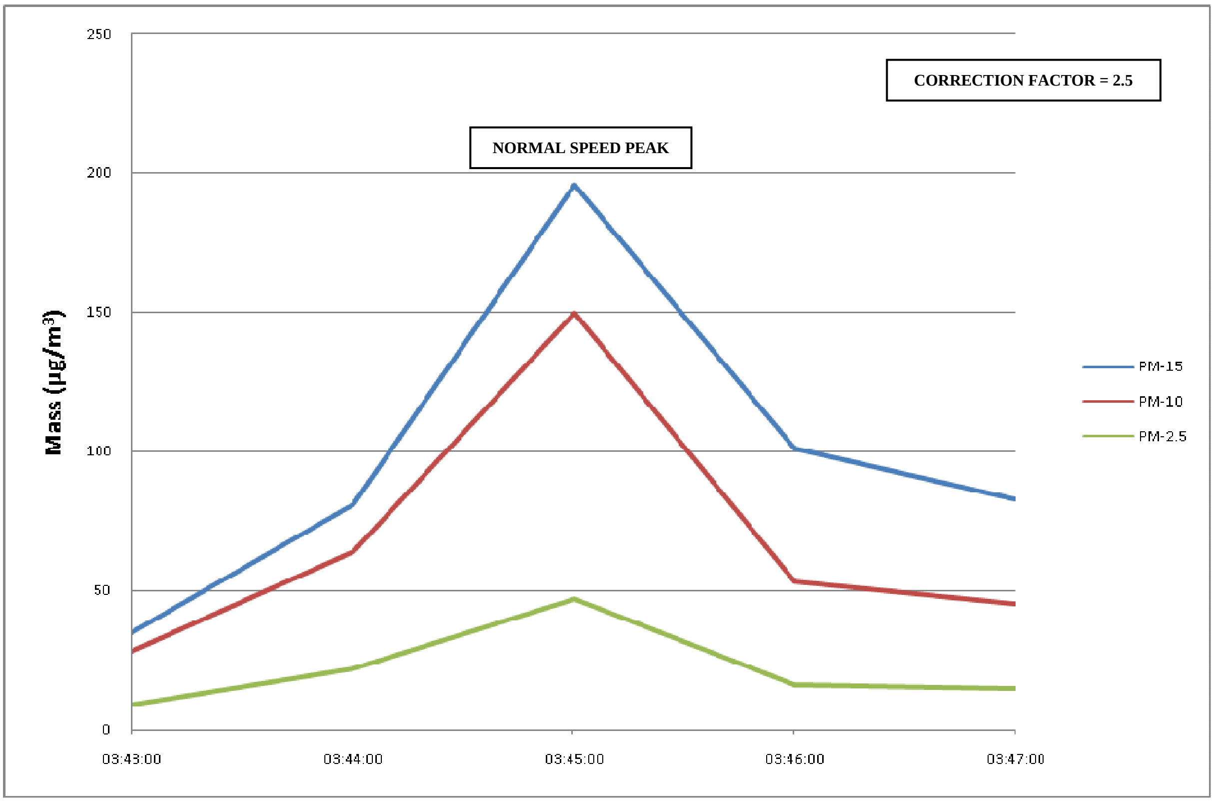

**Figure 45. View of ballast sample taken from Great Portland Street Station ( west end)**

**Figure 46. View of ballast sample taken from Liverpool Street Station (west end)**

**Figure 47.** **X-ray spectrum of dust from ballast collected in tunnel between Moorgate and Barbican Stations**

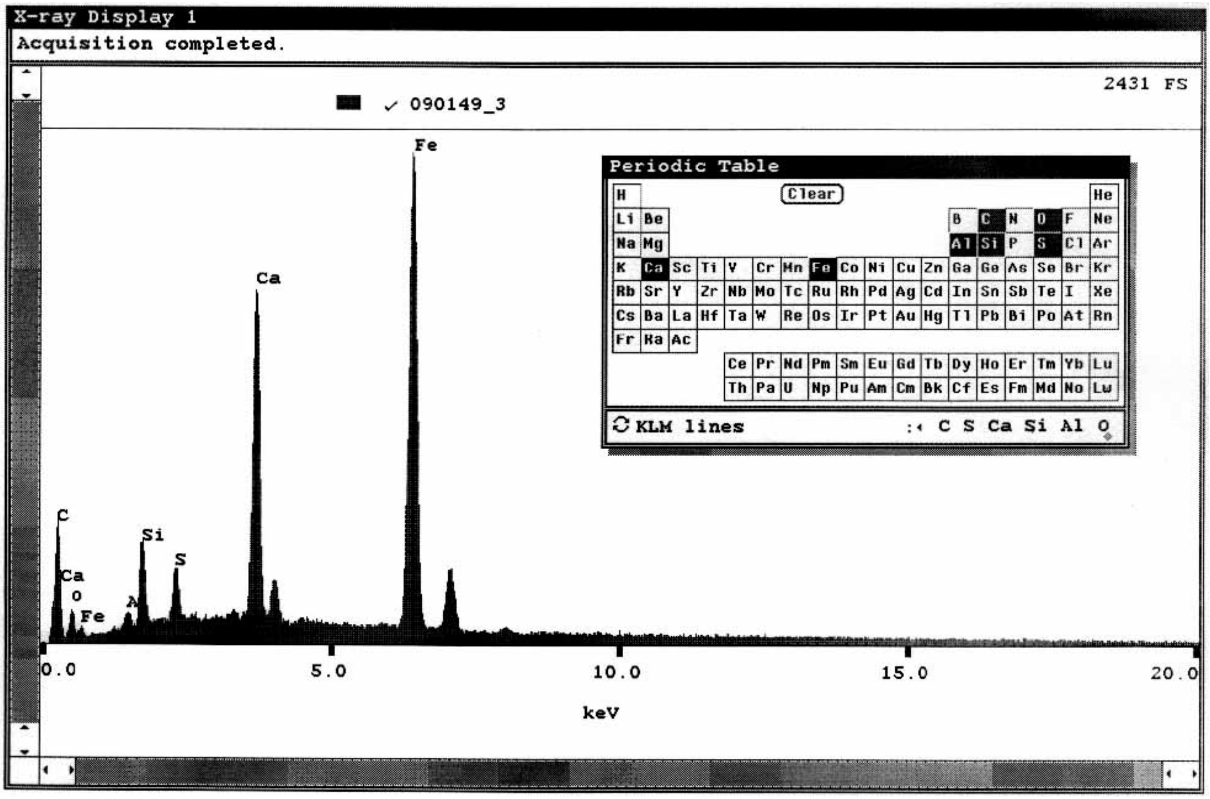


**Figure 48.** **X-ray spectrum of dust from ballast collected in cess area at Aldgate Station**