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Nanoparticles from Printer Emissions in Workplace Environments

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Acknowledgement
This project and report are the result of a partnership between Workplace Health and Safety Queensland (WHSQ), the Queensland University of Technology (QUT), and Safe Work Australia, specifically regarding nanoparticles from printers, and more broadly as part of the development and validation of methods to characterise particles at workplaces in general as a component of the National Nanotechnology Work, Health and Safety Program. Funding for the project was provided by the Commonwealth Department of Innovation, Industry, Science and Research under the National Nanotechnology Strategy.

This report was prepared by the International Laboratory for Air Quality and Health (ILAQH), Queensland University of Technology, Brisbane, Australia. The work was undertaken by Professor Lidia Morawska (Project Leader), Mr Peter McGarry[1] (Principal Researcher), Dr Congrong He, Dr Rohan Jayaratne, Mr Matthew Falk and Ms Lina Wang.

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List of Abbreviations

CPC	Condensation Particle Counter
DustTrak	DustTrak Aerosol Monitor
HVAC	Heating and ventilation air-conditioning
µm	Micrometre
nm	Nanometre
OPC	Optical Particle Counter
PM	Particulate Matter
PNC	Particle Number Concentration
P-Trak	Model 8525 P-Trak Ultrafine Particle Counter
TWA	Time-Weighted Average

Glossary

Where terms from this glossary are used in the body of this report, italic font has been used to signify this.

Excursion guidance criteria – triggers for implementation of exposure controls used in conjunction with either the *local background particle concentration* benchmark or the *particle reference value* benchmark. Exposure controls must be implemented if:

- If exposure levels exceed three times the *particle reference value* for more than a total of 30 minutes during a work day; and/or
- If exposure exceeds five times the *particle reference value*.

Local background particle exposure – local office area eight-hour time-weighted average particle number concentration minus the eight-hour average particle number concentration from printing events. This value is specific to each office environment. The median of all values calculated for this report has been used as the basis for the recommended *particle reference value*.

Nanoparticle – A particle with a nominal diameter smaller than about 100 nm. See also ultrafine particle.

Particle number concentration (PNC) – the concentration of all particles within a defined size range.

$PM_{2.5}$ - Mass concentration of particles with an aerodynamic diameter smaller than 2.5 µm.

Particle reference value – the PNC value used as a benchmark for deciding when control, of human exposure to particle number concentration emission arising from the operation of laser printers, is required. For this report the value of 4.0×10^3 particles cm^{-3} as a single particle reference value for all office environments is highlighted. This value represents the median value of the eight-hour time-weighted average local background particle exposure as calculated for the office locations described in this report. This is not an occupational exposure limit (OEL) or National Exposure Standard (NES), but is intended as a pragmatic guidance level.

Peak particle exposure – the highest PNC recorded for a printing event, as measured in approximate breathing zone of a seated office worker.

Printer particle exposure (eight-hour TWA) – particle number concentration resulting from printer operation multiplied by associated exposure time and divided by eight hours. See explanation of time-weighted average below.

Submicrometre particles – particles smaller than 1 micrometre in diameter.

Supermicrometre particles – particles larger than 1 micrometre in diameter.

Time-weighted average - These are calculations apportioning a measured exposure to the interval of time during which the exposure occurred. A worker may have an elevated exposure during one interval and a lower exposure in the next time interval. The TWA is calculated using the following relationship: TWA = $\sum C_i t_i / \sum t_i$, where C_i is the concentration during the *i*th sampling interval, and t_i is the associated exposure time. By weighting the exposure concentration, C_i, for the *i*th sampling period, t_i, it is possible to determine a worker's estimated TWA exposure to a chemical or agent. The TWA concentration can then be compared to a workplace exposure standard or guidance level. Common averaging times (denominator) include 8-hours, and 15 minutes [1].

Ultrafine particle – A particle sized about 100 nm in diameter or less. See also nanoparticle.

1. Executive Summary

The focus of this work was to investigate exposure of office workers to nanoparticles emitted from laser printers, as well as temporal and spatial variations of nanoparticles within office environments, and to provide guidance on methods to minimise exposure to such emissions.

In 2007 a paper was published in the scientific literature alerting the community to the emission of particles during the operation of laser printers within office locations. This paper generated significant interest both within Australia and worldwide and resulted in a flood of concern being expressed within the media, and directed to Australian State, Territory, and Federal workplace health and safety regulatory bodies. As this paper corresponded to the commencement of the National Nanotechnology Work Health and Safety Program which amongst other things identified a need to validate techniques and methods for characterising airborne nanoparticles arising from the emerging nanotechnology industry, it was considered prudent to investigate both exposure to nanoparticles from laser printer operation and methods for characterising airborne nanoparticles in general.

Scope and limitations of this study

The scope of this study was limited to investigating the characteristics and behaviour of particles arising from the operation of laser printers in office locations and did not include the toxicological evaluation of the aerosol. Therefore no direct conclusion was made regarding the health effects of exposure to these particles.

However, following the completion of this study a separate review of the health risk associated with laser printer emissions concluded the health risk associated with the levels of emissions measured in the original study to be low, although this does not exclude the possibility of health effects for highly sensitive people [2] or those people exposed to higher levels (i.e. higher particle concentration and duration of exposure) of printer emissions to that characterised in the initial study[2].

Summary of main findings

The main findings of this study are summarised under the following headings.

<u>Background and printer contribution to particle concentrations</u>

1. Office workers are continually exposed to a background particle number concentration (PNC) within their office environment, predominantly within the nanoparticle[3] size range, with the source of these particles mainly from outside (vehicular) pollution. Therefore it is essential that this *local background particle exposure*[4] be accounted for when characterising the emission of particles, and assessing exposure of office workers, arising from the operation of laser printers. *Local background particle exposure* for 25 of the office environments included in

2 Usage of printers included in this study was such that the longest period of time that airborne concentrations of particles were elevated above background was 50 minutes in an eight hour period.
3 A particle with a nominal diameter smaller than about 100 nm.
4 Local office area eight-hour time-weighted average particle number concentration minus the eight-hour average particle number concentration from printing events. This value is specific to each office environment. The median of all values calculated for this report has been used as the basis for the recommended *particle reference value*.

this study ranged from 1.7 x 10^3 particles cm^{-3} to 1.2 x 10^4 particles cm^{-4}, with a median value of 4.0 x 10^3 particles cm^{-3}.

2. The particle size associated with the operation of the laser printers included in this study was predominantly less than 300 nm. This information when coupled with particle size characterised by SMPS reported in other studies leads us to the conclusion that the particle diameter associated with the operation of laser printers in office locations is within the ultrafine size range of less than 100 nm.

3. Laser printers that emit nanoparticles at concentrations greater than the local office background particle exposure are common within office workplaces, with 45 (42%) of the available printers initially surveyed for this work being classified as low to high emitters, and 62 (58%) of printers as non-emitters[5].

4. Of the 25 printers subjected to continuous particle measurement at one metre from the printer, 18 recorded a statistically significant increase in PNC associated with printing. In addition, four of five printers subjected to continuous particle measurement at two metres from the printer also recorded a statistically significant increase in particle number concentration (PNC) associated with printing. Therefore these printers increased exposure of office workers to particles above the *local background particle exposure* at both one and two metres respectively.

<u>Exposure characterisation</u>

5. All eight-hour time-weight average (TWA) *printer particle exposures*[6] except one were below the eight-hour TWA *local background particle exposure* for each office area, indicating that the majority of the average nanoparticle exposure experienced by workers in these offices over the course of a working day came from sources other than printers, such as vehicle emissions infiltrating the building. Eight-hour TWA *printer particle exposures* were calculated for 19 office environments and ranged from 4.3 x 10^1 particles cm^{-3} to 4.0 x 10^3 particles cm^{-3}.

6. In contrast, eight-hour TWA *local background particle exposure* ranged from 1.7 x 10^3 particles cm^{-3} to 1.2 x 10^4 particles cm^{-3}, with a median value of 4.0 x 10^3 particles cm^{-3}, indicating that exposure to particles from non-printer sources were in certain cases, significantly higher than particle exposure arising from the operation of laser printers.

7. Peak particle exposure was recorded one metre from printers during printing events at greater than five times that of the eight-hour TWA *local office background particle exposure* for 11 printers, at four times for one printer, three times for two printers, and between one and two times for eight other printers. The peak particle exposure measurements ranged from 3.3 x 10^3 particles cm^{-3} to 9.9 x 10^4 particles cm^{-3} (this is the particle saturation value of the CPC, and therefore particle exposure was greater than this value).

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5 Emission classification is based upon ratio of PNC emission to the background - non-emitters (ratio ≤ 1); low emitters (ratio > 1 and ≤ 5), medium emitters (ratio > 5 and ≤ 10 to background); and high emitters (ratio > 10 to background)
6 Particle number concentration resulting from printer operation multiplied by measurement time and divided by eight hours.

8. These results indicate that the eight-hour time-weighted average of printer particle number concentration is not the best method for assessing exposure. Instead peak and 30 minute short-term printer particle exposure assessment are a better measure, using the measurement methodology recommended in this report.

Mitigation and control

9. The methods used in this study, including the measurement locations and durations, and the use of a P-Trak were very reliable in characterising both spatial and temporal PNC arising from printer operation, with the P-Trak measurements characterising 79% of PNC associated with printing events at both one and two metres from the printers.

10. Proper positioning of printers with respect to office ventilation inlet and outlet grills assists in diluting the printer PNC.

11. Complex modelling of air flow and printer particle distributions within office locations is not essential for informing exposure control options. Exposure control decisions can be informed by the use of a robust particle assessment method and excursion guidance criteria such as that recommended in this report.

Advice on nanoparticle assessment and control strategies

Although little direct toxicological data exists regarding nanoparticles associated with laser printer operation, there is a wide body of literature regarding the link between nanoparticles (also known as ultrafine particles) and cardiovascular and respiratory health effects. Consistent with a precautionary approach to exposure to nanoparticles in general, the following advice on nanoparticle exposure control and assessment is provided.

Option 1 - Nanoparticle exposure control only, no assessment

This option provides a universal approach for control implementation based upon the findings of this study, and does not require assessment of particle emission from the printers of concern.

Locate the printer such that distance and/or local ventilation conditions dilute the printer particles. Examples of such include:

1. Locate the printer in proximity to a ventilation inlet or outlet grill. The release of artificial smoke can aid in visualising local air movement. Note the potential movement of the printer should not then result in printer particles increasing exposure to occupants of other work stations;

2. Reduce the number of laser printers located amongst work stations and locate remaining laser printers in a dedicated printer room, or an area of the office a sufficient distance away from occupied work stations. Ideally the local ventilation to either of these areas should have a higher velocity so as to provide a greater particle dilution to the area compared to the rest of the office.

Option 2 – Nanoparticle exposure assessment followed by control implementation

This option provides for assessment of particle emission from the printers of concern so as to inform whether controls are required for individual laser printers. Ideally, assessment should be conducted by someone competent in the area of emission evaluation such as an occupational hygienist.

1. Choice of instrumentation

Instrumentation for characterisation of nanoparticles emitted from laser printer operation within an office environment should include:

i. Particle number counting instrument that can characterise nanoparticles, such as a condensation particle counter that has a lower particle measurement range ≤ 20 nm, and

ii. Artificial smoke generator.

2. Identification of laser printers emitting at a particle ratio of > 2 to the background

i. Set the instrument to record one data reading per second.

ii. Position the instrument at the printer so as to characterise background particle number concentration, and particle emission number concentration from the printer during the operation of the printer.

iii. Before commencing printing, record the background particle number concentration on the sampling log sheet.

iv. Perform at least five printing events that are representative of typical printing for the printer with the duration for each test between 2-3 minutes, for example, different number of pages up to 50, single and double sided, black and white and colour if a colour printer. Sampling locations at the printer should include the paper exit tray and fan exhaust vents usually located at back or side of printer. For each printing event record the printing times, number of pages printed, print colour, and page sides (one or two sided) on the sampling log sheet.

v. Calculate the ratio of the peak printing PNC to the background PNC for each printing event.

vi. All printers with ratios > 2 will require further investigation regarding office occupant exposure as per step 3. This printer emission classification system is similar to the approach used by He et al. [3], who used a P-Trak to catalogue printers into four different classes, in terms of the ratio of particle emission concentration to background, including:

- non-emitters (ratio ≤ 1),
- low emitters (ratio > 1 and ≤ 5),
- medium emitters (ratio > 5 and ≤ 10 to background), and
- high emitters (ratio > 10 to background).

3. Assessment of office occupant exposure to laser printer particles

For those printers identified in step 2 as emitting particles at a ratio of > 2 to the background, carry out the following:

i. Set the instrument to function in continuous recording mode.

ii. Assess exposure to nanoparticles of occupants at (computer) work stations by placing the instrument in a static location that represents the seated breathing height of the workstation occupant. Carry out sampling for a period that is representative of an eight-hour period of particle exposure. Ensure the printer is used as per normal. Record the time of each printing event on the sampling log sheet.

iii. Download and chart the logged PNC data from the instrument.

iv. Notate the graph of the real-time data with information on the different printing events such as time of printing, etc.

4. Identifying if the peak particle reference value and/or the 30 minute short-term particle reference value have been exceeded at the location of the work station as follows:

i. Calculate the *local background particle exposure* value. Subtract this from measured values to give the component due to laser printer emissions.

ii. Identify if any 30 minute short term printer particle exposures exceed three times the value 4.0×10^3 particles cm^{-3}, i.e., 1.2×10^4 particles cm^{-3}.

iii. Identify if peak values exceeds five times the value 4.0×10^3 particles cm^{-3}, i.e., 2.0×10^4 particles cm^{-3}.

These excursion criteria are based on guidance on general variability in the concentration of airborne substances, as described in the document *Exposure Standards for Atmospheric Contaminants in the Occupational Environment Guidance Note* [4], which can be interpreted such that printer particle exposures may be significant in the following circumstances:

a. Where the 30 minute short-term printer particle exposures exceed three times a *particle reference value* for more than a total of 30 minutes per eight-hour working day, and/or where a single peak value exceeds five times a *particle reference value*, and

b. A *particle reference value* of 4.0×10^3 particles cm^{-3}, which is the median value of the *local background particle exposures* estimated for the 25 office environments included in this study.

5. Deciding upon and implementing exposure controls

Given the absence of a universal *particle reference value* or National Exposure Standard for nanoparticles arising from the operation of laser printers. Precautionary guidance may be based upon the typical office (non-printer related) background particle exposures.

i. In relation to type of laser printers, measurement results show that a number of printers do not emit particles above a peak particle exposure concentration of 2.0×10^4 particles cm^{-3}, and 1.2×10^4 particles cm^{-3} as averaged over any 30-minute period. This reference may be considered in a precautionary approach to choice of printers.

ii. Implementing the controls outlined in Option 1 can help reduce exposure at the occupied work stations to below a peak particle exposure concentration of 2.0×10^4 particles cm^{-3}, and 1.2×10^4 particles cm^{-3} as averaged over any 30-minute period.

6. Evaluation of the effectiveness of control decision/s:

After controls are modified, measurements can be repeated so as to assess the effectiveness of the control decision.

2. Introduction

Several papers published over the last few years described the results of investigations into particle emission arising during the operation of laser printers [3, 5, 6] and confirmed that laser printers are an important source of nanoparticles in indoor office environments. The printers were divided into four classes of non-emitters, low, medium and high emitters, based on the particle concentrations in the immediate vicinity of the printers, after a short printing job. It was found that about 60% of the investigated printers did not emit particles and of the 40% that did emit particles, 27% were high particle emitters [3]. These investigations have also provided valuable information as to the composition of the particles, their formation mechanisms, and why some printers are high emitters whilst others are low emitters.

Questions arising from these studies included:

- what impact does the operation of laser printers have on the background particle number concentration (PNC) of an office environment over the duration of a typical working day?
- what influence does the office ventilation have upon the transport and concentration of particles?
- is there a need to control the generation of, and/or transport of particles arising from the operation of laser printers within an office environment? and
- what instrumentation and methodology is relevant for characterising such particles?

This report expands upon the findings of these three papers by providing answers to these questions based upon the results of measurement and evaluation of emission and transport of nanoparticles arising from the operation of laser printers in multiple real office locations.

3. Overall Aim

The overall aim of this project was to utilise real-time particle measurement instrumentation to improve upon existing knowledge of particle emissions from laser printers operating in office locations in order to investigate particle temporal and spatial concentrations, to characterise exposure, and identify means to minimise such exposure.

4. Objectives

The objectives of the project were to:

1. Measure concentrations of printer emitted particles in the environment of operating machines.
2. Model air flow and particle distributions indoors.
3. Consider the impact of ventilation and filtration systems on particle spatial and temporal characteristics.
4. Assess associated human exposure and risk.

5. Develop guidance material, based upon the findings of the project, to minimise exposure to emissions during the use of laser printers

5. Research Methodology

General Information

The study was designed to cater for:

i. the most common minimum distance between an office worker and a laser printer;
ii. the average breathing zone height of a seated office worker;
iii. the influence of local ventilation upon the transport of particles from the laser printer;
iv. the influence of low, medium, and high emitting printers on particle concentration within an office;
v. differing air movement both within and between office locations; and
vi. background particle number and mass concentrations.

Instrumentation

1. Particle number and mass concentration: Three TSI Incorporated (St. Paul, MN) Condensation Particle Counters (CPCs) were used for measurements of particle number concentration: a TSI Model 3025A with a sampling time of 1 second and particle size range of 0.007 - 3 µm was used for continuous measurement of nanoparticles from the printers, and a TSI Model 3781 CPC, with a sampling time of 5 seconds, and particle size range of 0.006 - 3 µm was used to measure outdoor particle number concentration. A TSI Model 8525 P-Trak Ultrafine Particle Counter was used to measure total particle number concentration (sample time 1 second) in the size range 0.02 - 1 µm. Particle size distribution in six channels between 0.3 µm to 10 µm was measured by a TSI Model AeroTrak 9306 hand-held optical particle counter (OPC). Particle mass concentration was measured by a TSI Model 8520 DustTrak Aerosol Monitor using a 2.5 µm impactor at the aerosol inlet.

2. Air temperature, relative humidity (RH) and carbon dioxide (CO_2) concentration were monitored using a TSI Q-Trak Plus Indoor Air Quality Monitor (TSI Incorporated, St. Paul, MN).

3. Air velocity was measured by a TSI Velocicheck Model Anemometer.

Experimental design

A P-Trak was used to classify printers, operating in selected office buildings as emitters or non-emitters of nanoparticles as described by He et al., 2007 [3]. During this classification process it was identified that one metre was a typical minimum distance between an occupant of a computer workstation and a desk-located laser printer. Therefore, the investigation focused upon the potential worst case exposure scenario for office workers defined as a work station at one metre from an emitting printer. Measurement equipment, consisting of a TSI CPC 3025, DustTrak, and Q-Trak, was therefore located on a trolley one metre away from the laser printer and at an orientation to the printer such that the airflow in the room was most likely to transport particles to the equipment. In addition, for five laser printers, a P-Trak was also located at a distance of two metres from the printer to compare particle number concentration (PNC) at one and two metres from the printer in order to investigate the influence of distance, local ventilation, and dilution upon PNC and office worker exposure.

The location of the measurement equipment was informed by generating artificial smoke to visualise the likely predominant direction particles would move away from the printer, and to, where possible, locate the measurement equipment in a worst case position at one and two metres from the printers. The air inlets of the measurement instruments were situated on a trolley at a height of 1150mm from the floor to represent the height of the mouth/nose (potential entry route of particles to the respiratory system) of a seated office worker. The height of 1150mm is the approximate 50th percentile “sitting eye height” anthropometric data of British adults aged 19-65 years [7].

The instrumentation on the trolley was operated during office hours and also over the previous night to characterise the office hours and 24-hour real-time background PNC. Q-Trak data (changes in temperature and relative humidity) was used to identify the approximate times the heating and ventilation air-conditioning (HVAC) system commenced and stopped operation for each day. For the overnight measurements, as printers were not operating, other likely sources of particle generation such as cleaner activity were identified were possible. Measurements then continued throughout the working day and were stopped at the end of the working day, typically around 4.30pm. As observation of the working patterns of the office workers revealed 8.30am to 4.30pm as being the time period the majority of office workers occupied the offices, this time period was selected for calculation of eight-hour office hour printer particle exposures. During office hours other sources of particle emission, such as the operation of microwave ovens and sandwich toasters, were confirmed using a P-Trak and notated on the real-time measurement graphs.

Initially, persons using each printer were asked to record, on a form located at each printer, the time and number of pages printed for each printing episode. However due to a lack of consistency in such record keeping this changed to the investigator recording this data.

Outside particle number and mass concentration data was also simultaneously collected using a CPC 3781 and DustTrak located in the plant room through which the office area received its outside air intake in order to distinguish between outside particle events, and indoor particle emission events such as that arising from the operation of laser printers.

For selected printers only handheld instruments were used so as to evaluate the utility of such instruments in characterising the emission and transport of nanoparticles arising from the operation of laser printers. A P-Trak and OPC were used to simultaneously characterise PNC in the size range of 20 to 10,000 nm at the printer particle source, and at varying distances from the printers. A DustTrak was also used to characterise particle mass in the size range of less than 2.5 micrometres (2500 nms).

To identify the influence of the air-conditioning system upon the transport of particles the duct face velocity and face area of the air inlet and outlet ducts in the immediate vicinity of the printers, and the distance between the ducts and the printers were measured. Artificial smoke was generated at varying distances between ventilation inlet and outlet ducts and the laser printer so as to visualise and measure the zone of influence of the ducts upon particle movement from the printers. More quantitative data on the operation of the air-conditioning system, such as room air supply volumes, percentage of mixed and outside air were not available from the building maintenance managers.

Although the size measurement range of CPC's includes that greater than nanoparticle size, for the purpose of this report, particles measured by the CPC 3025 and P-Trak are referred to as nanoparticles, as evidenced by Morawska et al., 2009 [5] where the particle count median diameter for printer particles was reported as less than 100 nanometres. Particles measured by the DustTrak are referred to as supermicrometre particles, and particles measured by the OPC include both submicrometre and supermicrometre particles.

Selection of offices and printers

The managers of five government departments invited the researchers for this project to carry out measurements on printers within central business district (CBD) office buildings. Discrete business units within each building were nominated by the managers for participation in the study. The printer selection criteria as outlined below were then applied to all printers used by these business units.

To minimise researcher selection bias, printers were selected for the emission study using the following two selection criteria:

1. **Particle emission status**. A P-Trak was used to measure the PNC arising from the operation of *all* laser printers within the office area of the business unit and at all potential particle emission points of each printer during the printing of a single page. The background office PNC was measured when the printer was not printing and the measurement was then repeated immediately during and after the printer had printed one page. The P-Trak was set to record one data reading per second and the duration for each test was between 2-3 min. The ratio of the peak PNC, measured during the one page printing event, to the background PNC was calculated. All printers with ratios > 2 were selected for further investigation. This printer emission classification system is in keeping with that used by He et al. [3], who used a P-Trak to catalogue printers into four different classes, in terms of the ratio of particle emission concentration to background, including: non-emitters (ratio ≤ 1); low emitters (ratio > 1 and ≤ 5), medium emitters (ratio > 5 and ≤ 10 to background); and high emitters (ratio > 10 to background).

2. **Accessibility.** The trolley containing the measurement equipment was required to be located at the predetermined particle exposure measurement position of one metre from the printer. Some printers that met criteria (a) had to be excluded because the furniture configuration in the office area would not allow the trolley to be located at this distance.

The total number of laser printers located across all these business units and therefore potentially available for inclusion in the study was 107. All were surveyed using the investigation selection criterion a) and b). Of the 107 printers available, 25 (codified as LJ1 to LJ25) met both selection criteria and were admitted to the study. Table 1 provides further details of these printers with the manufacturer/model details codified. Printers included in the study were inclusive of multiple manufacturers and printer models.

Table 1: Printers meeting investigation selection criteria

Printer identification code	Emission classification*
LJ1	High
LJ2	Low
LJ3	Low
LJ4	Low
LJ5	High
LJ6	High
LJ7	Low
LJ8	High
LJ9	Low
LJ10	High
LJ11	Low
LJ12	High
LJ13	High
LJ14	High
LJ15	Low
LJ16	High
LJ17	High
LJ18	High
LJ19	High
LJ20	High
LJ21	High
LJ22	High
LJ23	Medium
LJ24	High
LJ25	High
LJ26	Medium
LJ27	High
LJ28	Medium

* ratio of particle emission to background: non-emitters (ratio ≤ 1); low emitters (ratio > 1 and ≤ 5), medium emitters (ratio > 5 and ≤ 10 to background); and high emitters (ratio > 10 to background) [3]

In addition, 20 other printers were found to have PNC emission > 2 to the background but were excluded because measurement equipment could not be located at the desired distance from the printer. Therefore, 45 (42%) of the available printers were classified as low to high emitters, and 62 (58%) of printers as non-emitters because the ratio of particle emission concentration to background was not ≥ 2. This proportion of emitters versus non-emitters is similar to that found by He et al., 2007 [3].

For one printer, LJ20, particle concentration was measured simultaneously at 0.1 metres from the paper exit tray and at one metre from the printer.

Two other printers, LJ27 and LJ28 located at a different building to the other 26 printers, were selected for particle measurement using only the P-Trak, DustTrak, OPC, and Q-Trak so as to evaluate the utility of these portable instruments for workplace particle measurement.

Description of office environment, including ventilation

All buildings were serviced by HVAC systems with outside air entrained into air handling units, filtered, and delivered to each occupied area through central ventilation ducting, along with remixed air. The predominant design of all the office locations was open plan with one laser printer typically shared amongst up to 6 computer work stations in each work pod, with the laser printer located amongst the workstations. Such a configuration typically resulted in varying distances between the laser printer and the various computer work stations, ranging from approximately one to three metres. Some laser printers were located in enclosed offices that were connected to the open plan areas by a single doorway.

Data Analysis

All statistical analyses (correlation, regression, t-test and analysis of covariance [ANCOVA]) were conducted using Microsoft Excel, and R (R Development Core Team, 2010). A level of significance of $p = 0.05$ was used for all statistical procedures. When the data was not normally distributed, a robust analysis (trimming off the maximum and minimum) or logarithmic transformation was employed.

The eight-hour time-weighted average (TWA) particle exposures were calculated as per the following:

$$\text{8hr TWA} = \frac{(C1 \times T1) + (C2 \times T2) + \ldots(Cn \times Tn)}{\text{8 hours}}, \qquad \text{Eq.1}$$

where C = the concentration during the sampling interval – 1, 2…n; and T = the associated sampling period.

6. Results

Time series of particle number concentration in the offices

Shown below are several selected time-series plots of the PNC measured as part of the study. These graphs provide data on the nanoparticle and $PM_{2.5}$ mass concentration. The plotted measurement values reflect both the office particle background and the particle concentrations during the discrete print episodes so as to illustrate specific aspects of particle behaviour. Each printer in the particular office is identified on the graph by the code allocated. Appendices A, B, C, and D contain the graphs for the time series data for the other printers investigated.

Figure 1 shows the PNC measured at high-emitting printer LJ17. Note the steady background value of about 3.0 x 10^3 particles cm^{-3} with peaks associated with print jobs indicated by the vertical arrows. The heights of the peaks were highly variable. During six print jobs the CPC saturated as the PNC exceeded the maximum detectable value of $1x10^5$ cm^{-3}. There were nine other print jobs where the measured PNC was between background and 1.0 x 10^5 particles cm^{-3}. $PM_{2.5}$ peak values did not differ from the background values and were not associated with print jobs.

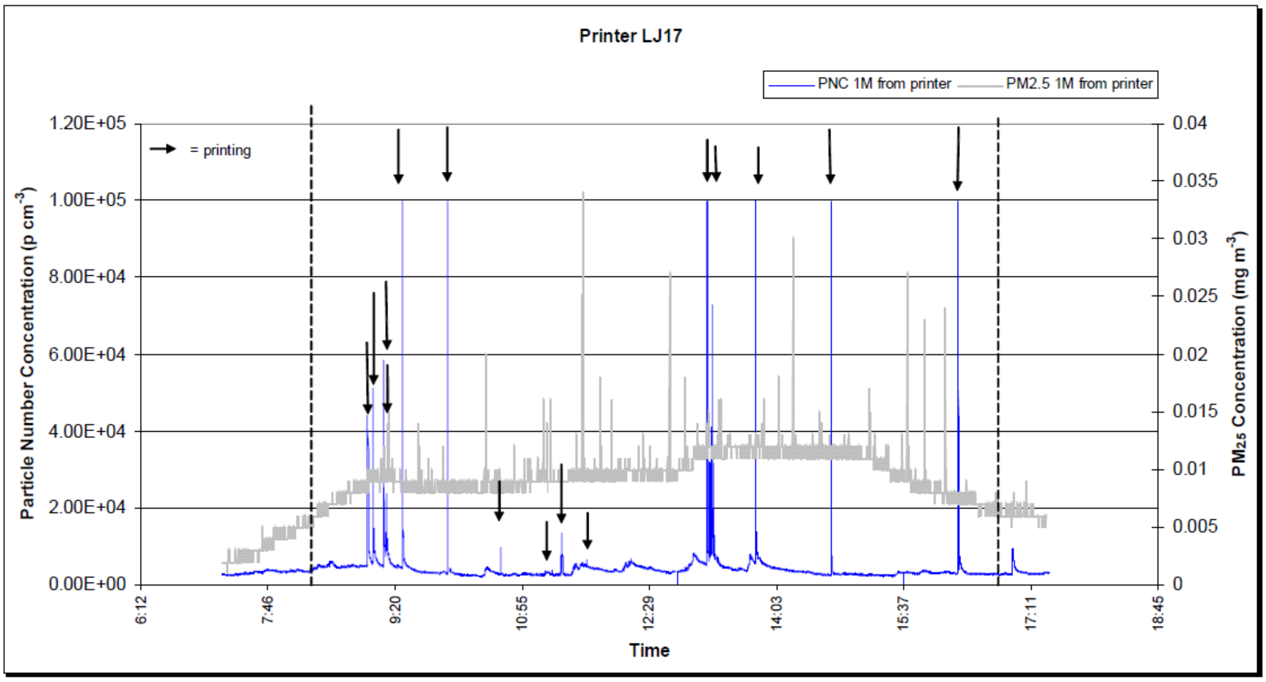

Figure 1: Particle number and mass concentration measured from printer LJ17 which was classified as a high-emitter. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

Figure 2 shows the corresponding graph for printer LJ2, which was classed as a low-emitting printer. The background PNC is seen to fluctuate between about 1.5 x 10^3 particles cm^{-3} and 7.5 x 10^3 particles cm^{-3}. There were nine print jobs during the period under consideration. The PNC peaks during each of these print jobs can be seen to be relatively small and only just distinguishable over the background. Again, $PM_{2.5}$ peak values did not differ from the background values and were not associated with print jobs.

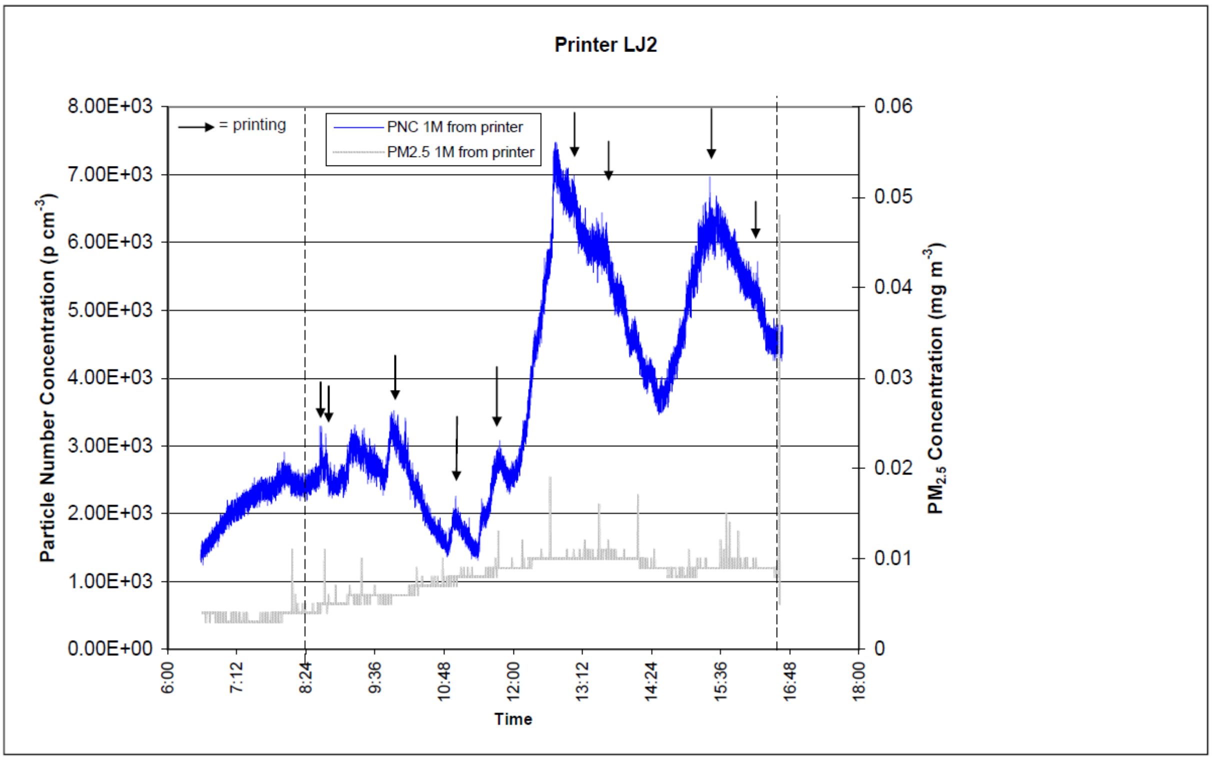

Figure 2: Particle number and mass concentration measured from printer LJ2 which was classified as a low-emitter. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

Figure 3 compares the PNC measured at two distances, one and two metres from printer LJ24. The PNC at the time of each print event at both one and two metres from the printer was higher than the background PNC between printing events. Note that the measurements at one metre were carried out with CPC 3025A, while those at two metres were done with a P-Trak. The minimum and maximum measurement size ranges of the two instruments differ. Therefore a correction factor, $F_{P\text{-}Trak}$, for the P-Trak PNC data was calculated as per equations 2 and 3 to account for the lower size range of the P-Trak.

$$F_{P-Trak} = \frac{TC_{P-Trak}}{TC_{CPC3025}} \qquad \text{Eq.2}$$

where $F_{P\text{-}Trak}$ is the correction factor for the P-Trak, and $TC_{P\text{-}Trak}$ and $TC_{CPC3025}$ are the total number concentrations measured by the P-Trak and CPC 3025, respectively, during selected periods for the printer emission measurements.

The corrected measurements for the P-Trak readings were then calculated as:

$$CTC_{P-Trak} = \frac{TC_{P-Trak}}{F_{P-Trak}} \qquad \text{Eq.3}$$

where, $CTC_{P\text{-}Trak}$ is the corrected total number concentration P-Trak data.

A $F_{P\text{-}Trak}$ correction factor of 0.78 was calculated for the P-Trak using ambient particle concentration time series data with both CPC's operated simultaneously and side by side. All P-Trak data is presented as the $CTC_{P\text{-}Trak}$.

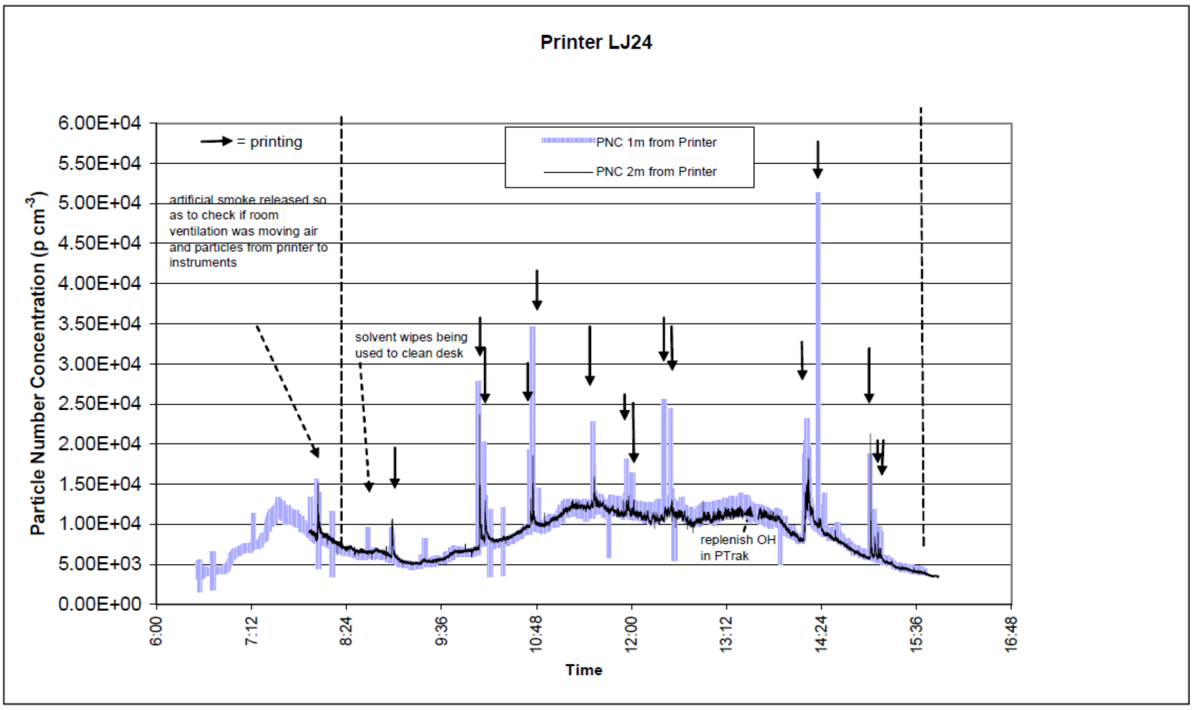

Figure 3: Particle number concentration measured at printer LJ24, a high-emitter. The P-Trak data are *$CTC_{P\text{-}Trak}$ values*. PNC one metre from the printer was measured using a CPC 3025A, and a P-Trak at two metres from the printer. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

Figure 3 clearly shows that the peak particle exposure at one metre as measured with CPC 3025A was greater than that at two metres as measured with the P-Trak. The figure also shows a clear difference in the heights of the PNC peaks during the print episodes with the peak particle exposure at 1 m being up to an order of magnitude greater than at two metres. As the difference in particle size measurement ranges between the two CPC's has been corrected for, most of this difference was due to the distance.

Figure 4 shows a comparison of the typical PNC concentration measured over a 24-hour period inside an office, and in the plant room providing outside air to the office. The office PNC is clearly higher during office hours compared to overnight. This is because the ventilation system provides filtered outside air to the office during office hours compared to at night when the ventilation system is typically not delivering air to the office. The outside PNC is clearly higher during the day compared to night and reflects the central business district location of the office with vehicle traffic patterns a major influence on the strength of outside PNC. Because the building ventilation system typically does not filter all the vehicle particles from the office air supply, office workers are constantly exposed to a background or ambient PNC.

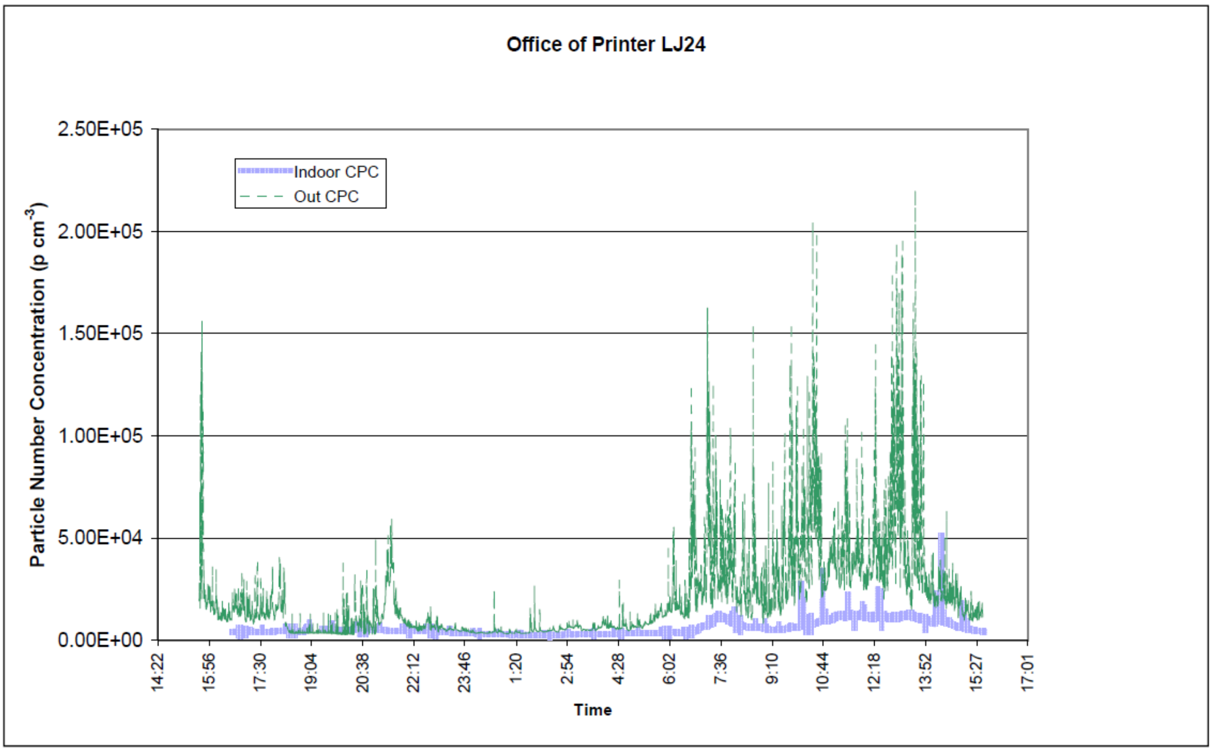

Figure 4: Comparison of indoor and outdoor particle number concentration for a 24 hour period. Indoor PNC was measured using a CPC 3025A, and outside PNC using a CPC 3781.

The significance of the ambient or background PNC to the characterisation of particles arising from sources such as laser printers and to the estimation of particle exposure from the operation of laser printers is central to the following sections of this report.

Contribution of particles from printing activities to the overall office background average particle number concentration

For each printer/office, a time series of the PNC and $PM_{2.5}$ was plotted for the hours 8.30am to 4.30pm. All peaks in PNC corresponding to printing episodes were identified.

The beginning time of the printing peak was identified by the sharp and sudden rise from background in the PNC associated with each print episode. In general, the measured PNC increased to its maximum value within five seconds and then decreased slowly over a period that ranged from about one to four minutes.

For some printers there was no obvious peak in PNC on the real-time data graph associated with the print times recorded on the log sheet. Therefore in order to capture all peak PNC associated with printing events, increases in PNC of 15% or more than the background immediately preceding the recorded printing time were counted as contributing to the total printing PNC. A time series sample was taken for five printers and the ratio of one standard deviation of the background PNC to the average of the background PNC was calculated. This ratio, the coefficient of variation, was found to be consistently 0.05 (or 5%) for these printers. This shows that the variability of these five printers is similar. Furthermore, increases of 15% or more are outside three standard deviations of the mean for the printers, indicating that less than 1% of CPC measurements not relating to printing will be included as being related to printing jobs (assuming background PNC is normally distributed). The end of the printing peak PNC was determined visually as the time at which the PNC first attained an approximate steady value over several seconds or when it drew level with the previous background value, whichever came first.

The determination of this end point, naturally, involved some uncertainty. In order to quantify this procedure, a time series sample with five print jobs was selected. For each of these printer PNC peaks, the end point cut-off was defined as the time at which the printer-induced PNC fell back to 2% of its pre-peak value. The average PNC values for:

i. the entire data set, and
ii. the data set excluding the printer PNC peak values,

defined by the 2% cut-off, were calculated. These values were found to be very close, well-within 1%, of the corresponding values calculated from the manual identification method described in the previous paragraph. As such, the manual method was adapted for all the data analysed.

A more sophisticated statistical procedure was trialled to distinguish between background PNC and that associated with printing. In this procedure a kernel density estimate of the probability density function was generated and overlayed on the histogram of PNC measurements. The fit was determined visually. There were two distinct peaks in the histogram and the associated kernel density estimate. Naturally, the peak at lower values was associated with background measurements and the peak at larger values associated with PNC from printing. Given the large amount of data (1 second interval over the period 8.30am to 4.30pm), there were more background measurements relative to the printing measurements. Thus the peak for printing was much smaller. The point at which the gradient of the density changed from negative to positive, where we assumed measurements began relating to printing, a threshold was placed. This was much larger than the baseline for background measurements and upon looking back at all the data it did not intuitively make sense to use this very high threshold. The distribution of the PNC measurements is more complicated than a two peaked density estimate in that some measurements in the right tail of the first peak are related to printing. Therefore a different statistical approach was required to explain what is occurring as the post printing measurements return to the background level. It is expected that a model based approach which fits a mixture of several distributions to the density would find a better estimate and realistic threshold for measurements associated with printing. However, development of this model based approach would be a separate project and is still a current research topic in the statistics literature [8], so the simple transparent approach described earlier was applied.

To determine if there were any differences between the mean CPC data that included and excluded printer PNC peaks a two sample t-test was performed. Table 2 summarises the average PNC at one metre both with and without the print PNC, and the calculated t-test p-values for 25 printers.

For the Student t-test the CPC data was log transformed to ensure the normality assumption of the test was valid. The t-test is such that unequal variance between the two samples is assumed. The t-test assumes independence between samples whereas in this case the CPC data not associated with printing is found in both samples. A two sided t test was conducted i.e.

$$H_0 : \mu_{all} = \mu_{no\_peaks}$$
$$H_1 : \mu_{all} \neq \mu_{no\_peaks}$$

At the 5% significance level, those printers with p-values < 5% from the associated t-tests are deemed to have significantly contributed to the office background.

Table 2: Average PNC at one metre from printers with and without print PNC, and t-test p-values

Printer identification code	t-test p-values	Average total office hours PNC including particle contribution from printing events [particles cm^{-3}]	Average office hours PNC with printer PNC subtracted (= office hours 8-hr *local background particle exposure*) [particles cm^{-3}]	Sample period
LJ1	*0.01*	3.1×10^3	3.0×10^3	08:30-16:30
LJ2	*<0.01*	4.0×10^3	3.9×10^3	08:30-16:30
LJ3	0.99	4.0×10^3	4.0×10^3	08:36-16:30
LJ4	*<0.01*	1.9×10^3	1.7×10^3	08:30-16:25
LJ5A*	*<0.01*	6.3×10^3	2.2×10^3	08:30-16:36
LJ5B*	*<0.01*	7.6×10^3	5.8×10^3	08:30-15:59
LJ6	0.60	2.2×10^3	2.2×10^3	08:30-16:27
LJ7	0.93	6.5×10^3	6.5×10^3	08:30-15:59
LJ8	*<0.01*	8.1×10^3	8.0×10^3	08:30-16:18
LJ9	*<0.01*	4.1×10^3	4.0×10^3	08:30-15:42
LJ10	*<0.01*	5.2×10^3	4.8×10^3	08:30-16:27
LJ11	*<0.01*	3.5×10^3	3.4×10^3	08:30-16:05
LJ12	*<0.01*	5.5×10^3	4.9×10^3	08:30-16:30
LJ13	*<0.01*	3.6×10^3	3.6×10^3	08:30-12:43
LJ14	0.49	4.1×10^3	4.1×10^3	08:30-16:32
LJ15	*<0.01*	6.3×10^3	6.1×10^3	08:30-16:30
LJ16	*<0.01*	4.2×10^3	4.0×10^3	08:30-16:30
LJ17	*<0.01*	4.2×10^3	3.6×10^3	08:30-16:29
LJ18	0.14	2.5×10^3	2.5×10^3	08:38-16:30
LJ19	*<0.01*	4.2×10^3	4.0×10^3	08:30-16:30
LJ20	*<0.01*	7.6×10^3	7.6×10^3	13:14-15:32
LJ21	*<0.01*	1.3×10^4	1.0×10^4	08:30-16:29
LJ22	0.29	1.0×10^4	1.0×10^4	08:30-15:48
LJ23	0.94	1.2×10^4	1.2×10^4	08:30-15:45
LJ24	*<0.01*	8.8×10^3	8.4×10^3	08:31-15:52
LJ25	<0.01	5.2×10^3	4.8×10^3	08:30 -16:27

*Printer LJ5 was measured on two separate days

Column 2 shows the associated p-values for the data in columns three and four. A 5% significance value was used so those printers with p-values < 5% from the associated t-tests are deemed to have significantly contributed to the office background PNC. Such significant values are shown in italics in this table.

It can be seen that, of the 25 printers, 18 showed a statistically significant increase in PNC associated with printing, at one metre from the printer, over the background PNC, indicating these 18 printers made a statistically significant contribution to the normal background PNC for that office area.

A comparison to the initial emission classification outlined in Table 1 reveals that of these 18 printers, 13 were classified as high emitters, whilst five were classified as low emitters. In addition, five printers that were initially classified as high emitters were found to not significantly contribute to the background PNC. This incongruity likely reflects the many factors contributing to printer particle emission variability such as the amount of printing and the local ventilation conditions. Other factors may include the amount of material deposited on fuser rollers, the fuser temperature, type of volatile organic compound in different cartridges contributing to particle formation, and the type of paper [5].

Eight-hour time-weighted average exposure of office workers to particles arising from printing activities

Airborne particles are abundant within the environment and arise from both natural and anthropogenic sources. Within areas of heavy human occupancy a major source of particles is from combustion processes such as the operation of motor vehicles [9]. Such particles infiltrate buildings and are the major source of background or ambient particle concentration that office workers are exposed to. Therefore it is essential to measure the background particle concentration so as to establish a *particle reference value* to guide exposure assessment.

In the absence of a National Exposure Standard for laser printer particle emissions the eight-hour TWA *local background particle exposure* to which office workers are subjected to has been used as the comparative for exposure to laser printer particles. The *local background particle exposure* for each office was calculated by subtracting the average PNC associated with printing from the total PNC for each office hour period and applying an eight hour weighting period. These values are shown in column four of Table 2, and have been used to calculate the eight-hour TWA *local background particle exposure* for all 25 printer locations.

The eight-hour TWA *local background particle exposure* value reflects the exposure to nanoparticles arising from non-printer sources such as from vehicle emissions outside the building that subsequently infiltrate the building ventilation system and to which the workers in that office are constantly exposed.

In addition, for those 18 printers shown by t-test to contribute significantly to the office background PNC, the eight-hour time-weighted average (TWA) *printer particle exposure*[7] has been calculated, using equation 1, for office workers whose computer work station places them at one metre from the printer during their working day. This value reflects the printer particle exposure that was additional to the *local background particle exposure* for the office workers.

7 The measured values are not personal exposure measurements. However as the measurement equipment was located to replicate a seated worker at one metre from the printer the values give a reliable estimate of exposure.

Table 3: Estimated 8-hr TWA printer PNC exposures

Printer Identifier	8-hr TWA[a] *printer particle exposure* at one metre from printer [particles cm^{-3}]	8-hr TWA *printer particle exposure* as a percentage of the *local background particle exposure* [%]	8-hr TWA *local background particle exposure* (from column 4 of Table 2) [particles cm^{-3}]
LJ1	5.1×10^1	2	3.0×10^3
LJ2	6.8×10^1	2	3.9×10^3
LJ3	b	b	4.0×10^3
LJ4	2.4×10^2	14	1.7×10^3
LJ5A*	4.0×10^3	175	2.2×10^3
LJ5B*	1.6×10^3	28	5.8×10^3
LJ6	b	b	2.2×10^3
LJ7	b	b	6.5×10^3
LJ8	8.1×10^1	1	8.0×10^3
LJ9	8.2×10^1	2	4.0×10^3
LJ10	4.1×10^2	9	4.8×10^3
LJ11	7.3×10^1	2	3.4×10^3
LJ12	6.3×10^2	12	4.9×10^3
LJ13	4.3×10^1	1	3.6×10^3
LJ14	b	b	4.1×10^3
LJ15	2.1×10^2	3	6.1×10^3
LJ16	1.5×10^2	4	4.0×10^3
LJ17	6.1×10^2	17	3.6×10^3
LJ18	b	b	2.5×10^3
LJ19	1.3×10^2	3	4.0×10^3
LJ20	2.8×10^1	1	7.6×10^3
LJ21	3.0×10^3	28	1.0×10^4
LJ22	b	b	1.0×10^4
LJ23	b	b	1.2×10^4
LJ24	3.6×10^2	4	8.4×10^3
LJ25	3.4×10^2	7	4.8×10^3

a Calculated using equation 1. For the purposes of this calculation the concentration value "c" was estimated by subtracting the value in column 4 of Table 2 from the value in column 3 of Table 2. This value represents the contribution of particles from all printer events. Where the sampling interval for the printer was less than 8-hours an assumption has been made that the exposure in the non-sampling period was similar to the period sample. Therefore all "T" values = 8-hours. However as indicated in Table 3 the sampling periods in most case were 8-hours or close to such.

b Not calculated as printer was shown by t-test to not contribute significantly to the office background PNC.

Table 3 contains the results of the calculation of both the estimated eight-hour TWA *printer particle exposure* for a person seated one metre from the printer for 18 of the 25 printers, and the eight-hour TWA *local background particle exposure* for the offices in which printers LJ1 to LJ25 were located.

The concept of the eight-hour time-weighted average exposure has been used in this report to describe exposure for the following reasons:

- It is common practice within workplace settings to describe occupational exposure to airborne substances in terms of a TWA,

- It allows the measured printer PNC to be weighted to an eight-hour office working time period and compared to the eight-hour TWA *local background particle exposure*,
- It provides a basis for making a judgement regarding excursions above the *local background particle exposure* in terms of the particle indoor air quality of the office and whether control strategies are required, and
- It allows the precautionary principle to be applied within the context of accepted occupational hygiene practice.

From Table 3 it can be seen that 16 of the eight-hour TWA *printer particle exposures* were less than 20% of the *local background particle exposure*, two were 28%, and one was 175%. However it is clear that such results are relative to the local background particle concentration for that office area.

This is illustrated in the following example. From Table 3 the eight-hour TWA *printer particle exposure* arising from printer LJ5A was 4.0 x 10^3 particles cm^{-3}, and the eight-hour TWA *local background particle exposure* was 2.2 x 10^3 particles cm^{-3}, leading to a conclusion that *printer particle exposure* was greater than the *local background particle exposure*. However, had printer LJ5A been operated in an office with a higher eight-hour TWA *local background particle exposure*, for example the office for Printer LJ8 where the eight-hour TWA *local background particle exposure* was 8.0 x 10^3 particles/cm^3, the conclusion would have been that eight-hour TWA *printer particle exposure* was less than the eight-hour TWA *local background particle exposure*. The impact of such differences in eight-hour TWA *local background particle exposure* is further illustrated when comparing Figures 10 and 23 (Appendices A and B respectively), both for Printer LJ5 but on two different days, where the eight-hour TWA *local background particle exposure* differs by 3.5 x 10^3 particles cm^{-3}.

Clearly, as indicated by the values in Table 3, the eight-hour TWA *printer particle exposures* are a small fraction of the eight-hour TWA *local background particle exposure* for each office, except for Printer LJ5 where exposure exceeded the eight-hour TWA *local background particle exposure* on one day and was 28% of the eight-hour TWA *local background particle exposure* on another day. The results for this printer reflects the influence of frequent printing events, combined with a high PNC for each printer event, and within an office area which has a constant relatively low background PNC between printing events. The very low eight-hour TWA *printer particle exposure* results for the other 18 printers indicates that the majority of the average nanoparticle exposure experienced by workers in these offices came from sources other than printers, such as vehicle particle emissions infiltrating the building.

The importance of the variability in eight-hour TWA *local background particle exposure*, both within and between office locations, to the establishment of particle concentration guidance or reference values and indeed whether the TWA exposure approach is valid, are discussed in section 7.

Peak and 30 minute short-term exposure to particles arising from printer activities

To evaluate peak exposure to laser printer particles the guidance on general variability in the concentration of airborne substances, as described in the documents *Exposure Standards for Atmospheric Contaminants in the Occupational Environment Guidance Note* [4] and the *Threshold Limit Values for Chemical Substances and Physical Agents* [10], has been utilised in keeping with the normal occupational hygiene approach to such evaluation. Therefore, in the absence of a national exposure standard for printer particle emissions, and utilising the guidance in the two documents listed above on excursions of airborne substances greater than reference concentrations, a printing process could be considered to not be under reasonable control if:

- short term exposures exceed three times the eight-hour TWA *local background particle exposure* for more than a total of 30 minutes per eight-hour working day, or
- a single short term value exceeds five times the eight-hour TWA *local background particle exposure*.

To evaluate peak and 30 minute short-term exposure to particles arising from the operation of laser printers the total number of printing events, including those that did not register a significant increase in PNC above background, was tallied from the printing log sheet. In addition, the total time, during the eight-hour office hours period that the PNC arising from printing events was greater than the *local background particle exposure* was summed from the real time measurement data, the maximum PNC for each print event was identified for each printer, and the median of the total peak values for each printer were calculated. Table 4 provides a summary of these calculations and a comparison to the 8-hour TWA *local background particle exposure* for each printer.

It can be seen from Table 4 that a peak greater than the *local background particle exposure* was not identified for all printing events. This is because:

i. relatively high PNC background in some offices likely occluded the printer PNC, and
ii. particle emission from laser printers is variable, which has been shown by other researchers to occur [5].

Comparison of the data in columns one and two of Table 4 shows that 79% of print events where characterised by the particle measurement method indicating that i) operation of laser printers commonly results in peak particle exposure, and ii) this measurement method is valid for characterising exposure to particles arising from the operation of laser printers in office locations.

Did 30 minute short-term exposure exceed three times the eight-hour TWA *local background particle exposure* for more than a total of 30 minutes per eight hour working day?

No. Printer particle exposure greater than three times the *local background particle exposure* for a period of ≥ 30 minutes was recorded for any printer. From Table 4, it can be seen that although for printers LJ5, 11, 15, and 21 the total printing time during the eight-hour office hours period was greater than 30 minutes, the total printer particle exposure was not greater than three times the *local background* *particle exposure*. The closest printer particle exposure to this excursion guidance limit was for Printer LJ5A for which total *printer particle exposure* over the eight-hour office period was twice the *local background particle exposure* Further discussion on the application of this 30 minute short-term excursion guidance criteria is included in section 7.

Did any single short term value exceed five times the eight-hour TWA *local background particle exposure*?
From Table 4 it can been seen that 11 of the printers (LJ4, 5, 9, 11, 16, 17, 19, 20, 21, 24, 25) caused *peak particle exposures* greater than five times the eight-hour TWA *local background particle exposure*. This indicates that at one metre from these printers *peak particle exposure* was in excess of the excursion guidance.

In addition, eight printers (LJ1, 2, 6, 8, 10, 13, 18, and 23) contributed a *peak particle exposure* at between one and two times the eight-hour TWA *local background particle exposure*. Printers LJ14 and 15 contributed a *peak particle exposure* at approximately three times the eight-hour TWA *local background particle exposure* . Printer LJ12 contributed a *peak particle exposure* at approximately four times the eight-hour TWA *local background particle exposure*. Printer LJ7 contributed a *peak particle exposure* below the eight-hour TWA *local background particle exposure*, whilst the peak particle emission for printer LJ3 could not be distinguished from the *local background particle exposure*.

In summary, the printers were found to contribute *peak particle exposure* at one metre from the printers. One metre is a common distance between printer and occupied work stations.

Table 4: Summary of data used for calculating peak particle exposure and 30 minute short-term exposure

Printer ID	Number of printing events during office hrs (8 hr)	Number of printing events for which *peak particle exposure* was >15% back-ground PNC@	Time period for which PNC associated with print events was elevated above *local background particle exposure* [mins]	Number of pages printed during office hours	8 hr TWA *printer particle exposure* one metre from printer [particles cm^{-3}]	Highest *peak particle exposure* of all printing events [particles cm^{-3}]	Median of *peak particle exposure* for all printing events during office hours [particles cm^{-3}]	8-hour TWA *local background particle exposure* # (from Table 2) [particles cm^{-3}]
LJ1	3	2	1	8	5.1×10^{1}	7.1×10^{3}	4.8×10^{3}	3.0×10^{3}
LJ2	15	8	9	47	6.8×10^{1}	6.9×10^{3}	3.3×10^{3}	3.9×10^{3}
LJ3	9	Cannot distinguish printer events from background PNC		23	Cannot distinguish printer events from background PNC			4.0×10^{3}
LJ4	3	3	2	5	2.4×10^{2}	9.9×10^{4}*	2.3×10^{4}	1.7×10^{3}
LJ5A^	23	23	*50*	129	4.0×10^{3}	9.9×10^{4}*	9.9×10^{4}	2.2×10^{3}
LJ5B^	48	48	*40*	101	1.6×10^{3}	9.9×10^{4}*	9.9×10^{4}	5.8×10^{3}
LJ6	8	7	5	18	c	3.3×10^{3}	2.3×10^{3}	2.2×10^{3}
LJ7	11	3	2	28	c	5.5×10^{3}	4.3×10^{3}	6.5×10^{3}
LJ8	33	21	21	85	8.1×10^{1}	1.2×10^{4}	9.7×10^{3}	8.0×10^{3}
LJ9	39	37	25	116	8.2×10^{1}	8.6×10^{4}	1.4×10^{4}	4.0×10^{3}
LJ10	39	21	22	168	4.1×10^{2}	7.5×10^{3}	6.0×10^{3}	4.8×10^{3}
LJ11	45	30	*32*	143	7.3×10^{1}	9.9×10^{4}*	1.4×10^{4}	3.4×10^{3}
LJ12	13	11	10	73	6.3×10^{2}	1.9×10^{4}	7.5×10^{3}	4.9×10^{3}
LJ13	12	7	8	23	4.3×10^{1}	7.5×10^{3}	4.0×10^{3}	3.6×10^{3}
LJ14	10	8	4	16	c	1.6×10^{4}	5.8×10^{3}	4.1×10^{3}
LJ15	36	36	*33*	92	2.1×10^{2}	2.1×10^{4}	1.1×10^{4}	6.1×10^{3}
LJ16	11	7	12	63	1.5×10^{2}	3.8×10^{4}	2.2×10^{4}	4.0×10^{3}
LJ17	16	22	18	97	6.1×10^{2}	9.9×10^{4}*	5.1×10^{4}	3.6×10^{3}
LJ18	10	9	7	14	c	6.5×10^{3}	2.7×10^{3}	2.5×10^{3}
LJ19	26	11	18	59	1.3×10^{2}	1.9×10^{4}	9.1×10^{3}	4.0×10^{3}
LJ20	25	13	22	133	2.8×10^{1}	6.7×10^{4}	3.0×10^{4}	7.6×10^{3}
LJ21	20	16	*43*	122	3.0×10^{3}	6.4×10^{4}	2.8×10^{4}	1.0×10^{4}
LJ22	24	16	17	55	c	1.7×10^{4}	1.2×10^{4}	1.0×10^{4}
LJ23	15	10	18	38	c	1.7×10^{4}	1.4×10^{4}	1.2×10^{4}
LJ24	19	15	18	42	3.6×10^{2}	5.1×10^{4}	2.2×10^{4}	8.4×10^{3}
LJ25	8	8	5	39	3.4×10^{2}	9.9×10^{4}*	9.9×10^{4}	4.8×10^{3}

@ see text in section 3 for explanation of the significance of the 15% value
\# these values are the exposure to nanoparticles arising from *non-printer* sources such as from vehicle emissions outside the building that subsequently infiltrate the building ventilation system and to which the workers in that office are constantly exposed.
^ this printer was measured on two separate days
* these values represent particle saturation for the CPC so real values are likely higher
c Not calculated as printer was shown by t-test to not contribute significantly to the office background PNC

Difference in spatial particle exposure at one and two metres from printers
For five printer/offices, a time series of the PNC was plotted for the hours 8.30am to 4.30pm at both one and two metres from the printer and all peaks corresponding to printing episodes were identified. These time series graphs can be found in Figure 3 and in Appendix B at Figures 23 to 26.

To determine if the PNC corresponding to each print event was statistically different to the *local background particle exposure*, the beginning and end points of each increase in PNC associated with printing episodes was identified as per the method described in section 6. Table 5 provides the t-test results for any differences between:

1) the mean PNC including printer particles, and
2) the mean PNC with printer PNC subtracted, at both one and two metres from five printers.

The corrected P-Trak values, $CTC_{P\text{-}Trak}$ as calculated in section 6, have been used to inform these differences in spatial PNC associated with printing.

Table 5: Average PNC at 1 and 2 metres from printers with and without print PNC, and t-test p-values

Printer identification code	One metre			Two metres			Sample period
	t-test p-values (of columns 3 & 4)	Average total office hours PNC including printer PNC values [particles cm^{-3}]	Average PNC with printer PNC values subtracted [=*local background particle exposure*] [particles cm^{-3}]	t-test p-values (of columns 6 & 7)	Average PNC including printer PNC values [particles cm^{-3}]	Average PNC with printer PNC values subtracted [=*local background particle exposure*] [particles cm^{-3}]	
Printer LJ5B	*<0.01*	7.6×10^3	5.8×10^3	*<0.01*	8.5×10^3	5.4×10^3	8:30 – 15:59
Printer LJ21	*<0.01*	1.3×10^4	1.0×10^4	*<0.01*	1.2×10^4	1.0×10^4	8:30 – 16:22
Printer LJ22	0.29	1.0×10^4	1.0×10^4	*0.12*	9.9×10^3	9.9×10^3	8:30 – 15:48
Printer LJ23	0.94	1.2×10^4	1.2×10^4	*<0.01*	1.2×10^4	1.1×10^4	8:30 – 15:46
Printer LJ24	*<0.01*	8.8×10^3	8.4×10^3	*<0.01*	8.6×10^3	8.5×10^3	8:30 – 15:52
The slight difference in background PNC at one and two metres likely reflects the spatial influence of the office ventilation system between printing events. However the temporal differences associated with printing events at both one and two metres are statistically significant reflecting the strength of the printers as sources of particles compared to other office particle sources.							

It can be seen from Table 5 that, of the five printers, three (LJ5B, LJ21, LJ24) showed a statistically significant (p-value < 0.01) increase in particle exposure associated with printing over the *local background particle exposure*, at both one and two metres indicating that at both one and two metres from the printer the *printer particle exposure* was greater than the *local background particle exposure*. For Printer LJ22 the *printer particle exposure*, at both one and two metres, was not statistically significant and this result reflects the influence of the relatively high *local background particle exposure* for this office.

For Printer LJ23, *printer particle exposure* was statistically significant at two metres but not at one metre. The reason for this is likely due to the influence of local ventilation conditions that may have dispersed the particles predominantly to the position of the P-Trak at the two metre location in contrast to the CPC 3025 at the one metre location. As described in section 6 the release of artificial smoke within the office areas indicated that in general printer particles would first disperse upwards from the printer and then mix with the surrounding air.

The *printer particle exposure* is lower at two metres than at one metre (p-value <0.01) for printers LJ21, 22, 23, and 24 reflecting the spatial change over the one metre distance. However, for printer LJ5B the *printer particle exposure* at two metres is higher (p-value <0.01) than at one metre. This is because printer LJ5B emitted high particle concentrations resulting in the CPC 3025A located at a distance of one metre experiencing particle saturation at 1.0×10^5 particles cm^{-3} for nearly every printing event, whilst the P-Trak located at two metres distance registered higher PNC associated with the same printing events because of its higher particle saturation point. This also indicates that the *printer particle exposure* associated with printing at one metre was likely to be much higher than that recorded by the CPC 3025A.

Comparison of submicrometre and supermicrometre sized particles during printing

In order to characterise supermicrometre PNC, the particle emission for two printers, coded as printers LJ27 and LJ28, were measured using an Optical Particle Counter, which was operated simultaneously with the P-Trak and DustTrak. Figure 5 illustrates the real-time PNC size response for printer LJ28 in the particle bin sizes of 20 to 1000 nm (as measured by the P-Trak), 300 to 500 nm (as measured by the OPC), and > 500 nm (also as measured by the OPC). PNC > 300 nm was extremely low and not associated with print events, whilst PNC recorded by the P-Trak was four orders of magnitude higher and associated with print events. This indicates the predominant particle size associated with printing is less than 300 nm and concurs with the findings of Morawska et al. [5] who concluded the particle size range associated with printing was within the nanoparticle size range.

This finding of insignificant particle size in the supermicrometre size range is supported by Figures 1 and 2 which show typical printer $PM_{2.5}$ values do not differ significantly from background and are not associated with print jobs. Appendix D contains a graph of similar real-time measurements for the printer LJ27.

Influence of local ventilation upon particle number concentration

In an endeavour to characterise the influence of the office local ventilation upon particle transport and dispersion away from the printers, the face velocity - *v* (m/s) - at the inlet and outlet HVAC grills was determined by multiple anemometer (TSI VelociCheck hot wire anemometer) measurements. These measurements were taken over a grid pattern and the average of these measurements calculated. Artificial smoke was also released so as to visualise the predominant direction of air movement in the vicinity of the printers and the grills.

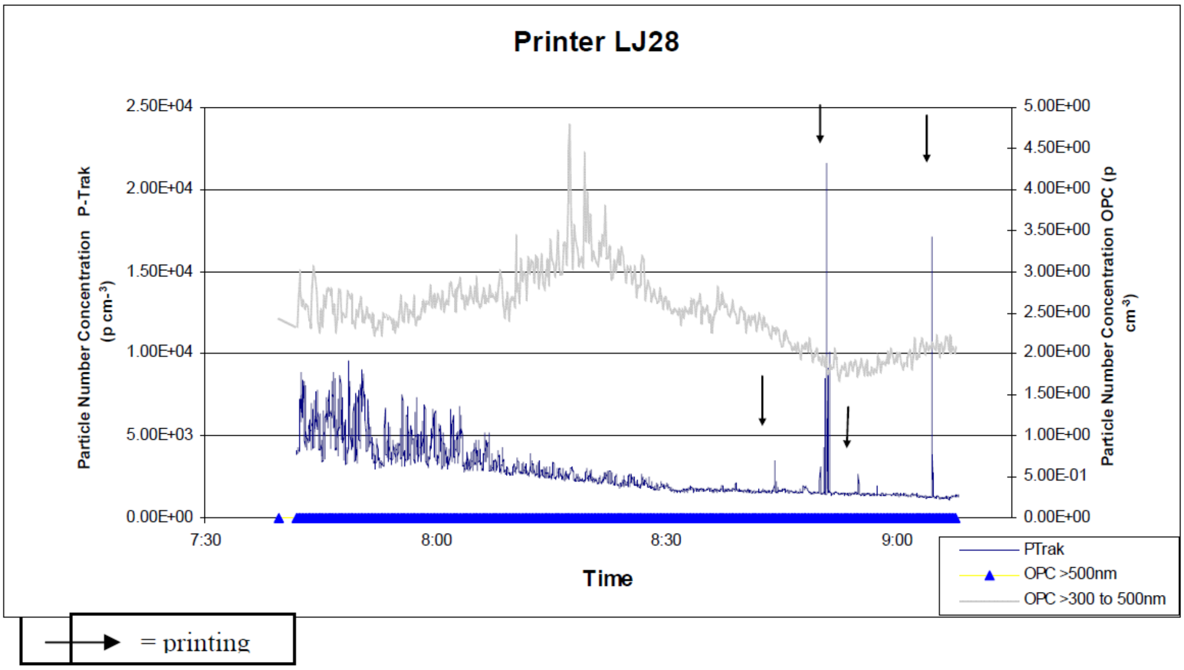

Figure 5: Supermicrometre and submicrometre particle number concentration. The PNC > 300nm recorded by the OPC does not change in response to recorded printing events in contrast to the PNC < 300nm as recorded by the P-Trak. The higher PNC > 300nm for period prior to 8.30am reflects the ventilation system starting up for the day and automatically venting the room with outside air.

For all office locations the average face velocity at the inlet vents nearest to each of the printers was fairly similar within the range of 0.2 m/s to 0.5 m/s for all printers except Printer LJ20 where the average velocity at the inlet grill was 1.7 m/s. The ceiling height in the offices ranged from 2.4 to 2.7 metres. The horizontal distance of the inlet vents to the printers ranged from one to two metres. Because of the combination of distance and low airflow velocity, release of artificial smoke at the printer paper exit trays of all printers except one, revealed negligible influence of local ventilation on the movement of the smoke (and so also PNC arising from printing processes). The smoke migrated upward from the printer and very gradually dispersed in all directions. The local ventilation only noticeably influenced the movement direction of the smoke when the smoke was generated at approximately 0.2 metres from the inlet grills.

The exception to this was with Printer LJ20 where the release of smoke at the printer resulted in immediate movement in a direction away from the inlet grill. The configuration of the office in which printer LJ20 was located was such that the occupied computer work station was located *between* the printer and the unusually high velocity inlet ventilation grill, with the inlet grill approximately two metres on one side of the computer work station, and the printer approximately one metre from and on the opposite side of the computer work station.

Because this unusually high velocity inlet grill and printer were positioned on opposite sides of the computer workstation an opportunity presented to characterise the influence of the local ventilation upon the transport of particles in the vicinity of a printer. Therefore a P-Trak was located at 0.1 metres from the paper exit tray of the printer, and the CPC 3025 at the computer workstation (one metre from the printer), both in a straight line with the inlet grill. The results of the real time measurements are graphed in Figure 6.

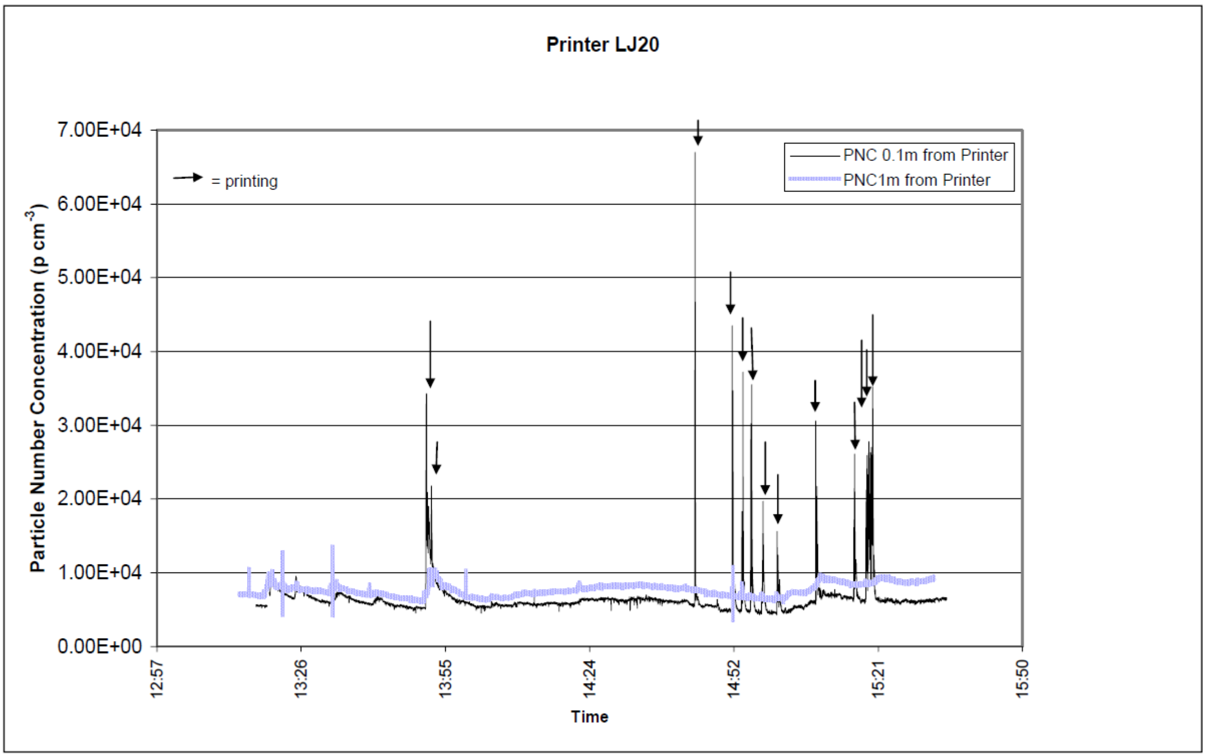

Figure 6: Influence of office local ventilation upon the movement of printer particles as measured with a P-Trak at printer particle source, and a CPC 3025A at distance of one metre from particle source.

Figure 6 shows that whilst a PNC's of up to almost 7.0 x 10^4 particles cm^{-3} were generated during printing events, the particles were not transported to the computer work station one metre from the printer and "upwind" from the printer. This finding is discussed in section 7. The influence of local ventilation upon the transport of particles within office environments is also discussed below.

Effect of type of printing and ventilation upon particle number concentration
To determine if the variation in the *peak printer emission* can be explained using selected explanatory variables an analysis of covariance (ANCOVA) model was conducted. An exploratory analysis of the data and description of the ANCOVA method and analysis can be found in Appendix E.

Type of printing: The dataset consisted of variables associated with emissions during printing jobs. The six variables used were:

- Peak – the maximum PNC value from the printing job,
- Printer – which of the 25 sampled printers the peak is associated with,
- Type – whether the printer is classified as a high, medium or low emitter,
- Colour – whether the print job was colour or black and white,
- Sided – whether the print job was single or double sided, and
- Pages – the number of pages in the print job.

Colour was the only significant variable found to explain the variation in peaks of printer emissions based on the ANCOVA. All other variables, and the interactions between these variables, were also tested for their impact on PNC values. The ANCOVA showed them to be insignificant and thus not useful in explaining the variation on maximum PNC value.

Local ventilation: Unfortunately ventilation could not be tested as a variable influencing PNC values because of the large difference in local office ventilation conditions. Conditions that are thought to affect PNC include the:

- size of the office,
- number of ventilation grills,
- distance of ventilation grills from printers, and
- direction of air dispersion near printers.

These conditions are not easily coded into variables. As such these variables could not be tested for their influence on PNC in the modelling.

Results of Computational Fluid Dynamics modelling

Computational Fluid Dynamics (CFD) modelling was used to model air flow and particle distribution within the three office locations containing printers LJ3, LJ16, and LJ27.

Computational Fluid Dynamics (CFD) models numerically solve a set of partial differential equations for the conservation of mass, momentum (Navier–Stokes equations), energy, chemical-species concentrations, and turbulence quantities. The solution provides the field distributions of air pressure, air velocity, air temperature, the concentration of water vapour (relative humidity) and contaminants, in addition to air turbulence parameters for both indoor and outdoor spaces.

Temperature, relative humidity, air velocity, and PNC data from field measurements within the office locations and positional information regarding the office furniture, ventilation inlet and outlet grills, printer, and work stations were inputted to the CFD software in order to predict the movement of printer emitted particles within the offices.

The specific modelling conclusions included:

1. The positioning of the air inlets and outlets in the office of printer LJ27 were not effective for immediate removal of printer particles from the immediate zone of the printer,
2. The main ventilation inlet for the office of printer LJ27 was too close to the main outlet resulting in most of the inlet airflow moving directly to the outlet;
3. In the offices of printers LJ3 and LJ16 the printer emitted particles first disperse upward and then spread to all directions within the offices,
4. Obstacles, such as furniture and a person sitting near the printer, influence the distribution of particles,
5. The location of the printer influenced the particle distribution within the offices, for example, the presence of a printer LJ16 in the inner corner of the office caused localisation of the particle concentration, and
6. Airflow movement within the offices becomes increasing complex when more partitions and furniture are present.

In summary, complex modelling of air flow and printer particle distributions within office locations is not essential for informing exposure control options because exposure control decisions can be informed by the use of a robust particle assessment method, and excursion control criteria such as that recommended in this report.

7. Discussion and Conclusions

The results described above will now be used to address the objectives of the project and to provide answers to the key questions regarding the temporal and spatial characteristics of particles arising from the operation of laser printers within the office environment and subsequent likely exposure of office occupants to particles.

Note: following the completion of this study, a separate review of the health risk associated with laser printer emissions concluded the health risk associated with the levels of emissions measured in the original study to be low, although this does not exclude the possibility of health effects for highly sensitive people [2], or those people exposed to higher levels (i.e. higher particle concentration and duration of exposure) of printer emissions to that characterised in the initial study.

Concentrations of printer emitted particles in the environment of operating laser printers

Estimated eight-hour time-weighted printer particle exposure, peak exposure, and 30 minute short-term exposure

Calculations of the estimated eight-hour TWA *printer particle exposure* for a person seated one metre from the printer were performed for 19 of the 25 printer measurement days. Using the eight-hour TWA *local background particle exposure* calculated for each office as the *particle reference value*, it was concluded that 16 of the results were less than 20% of the *local background particle exposure*, two were 28%, and one was 175%. However, if the median *local background particle exposure* of all offices studied, i.e., 4.1 x 10^3 particles cm^{-3}, is used then the conclusions are – 16 of the results remain at less than 20% of the *local background particle exposure*, the two 28% values increase to 48% and 75%, and the 175% decreases to 98%. Closer analysis of the frequency of printing for these 19 printers revealed that the three values greater than 20% of the *local background particle exposure* were all associated with high emitting printers operated for more than 40 minutes in the eight-hour period. Clearly, except for situations where high emitting printers are being used frequently the exposure to particles averaged over eight-hours arising from the operation of printers is very low.

However, short-term printer particle exposure and in particular peak printer particle exposure is evident. Eleven printers caused *peak particle exposure* greater than five times the eight-hour TWA *local background particle exposure* for that office.

Relationship between particle size range and printer operation

$PM_{2.5}$ and PNC in supermicrometre size range did not correlate with printing events and nor were such significantly elevated. Increases in nanoparticle emission did however correlate well with printing events at both one and two metres from printers. These particles associated with printing events are dominated by the nanoparticle (< 100 nm) size range. The evidence for this comes from the simultaneous measurement of printer emissions using both a P-Trak and an OPC which revealed increases in PNC during printing events to occur only below 300nm. This finding is supported by that of Morawska et al. [5] who concluded that the initial count median diameter of submicrometre particles during a print run was approximately 63 nm, which gradually decreased to approximately 28 nm.

Variables influencing printer particle number concentration emission and emission classification
Five printers that were initially assessed as being high emitters were found to exhibit variable particle emission during eight-hour real-time PNC measurement. This indicates decisions on exposure control implementation should not be based upon short-term particle measurements but rather upon a robust method such as that recommended in section 7.

Four of the printers studied, LJ5, LJ9, LJ11, and LJ25, were black and colour font printers. Colour printing was found to have a strong association with elevated PNC, however for these four printers black printing was also associated with elevated PNC during printing events. During assessment of printer emissions both colour and black printing modes should be assessed.

PNC varied by orders of magnitude between printing events for the same printer, and between different printer models and also varied between different printers of the same model. Single or double-sided and number of pages was not predictive for PNC. This indicates that printers can vary in particle emission intensity which is not explained by the variables tested above. Morawska et al. [5] indicated that printers do differ in particle emission intensity and the cause of particle emission in printers is complex and related to the speed and sophistication of the printer fuser temperature control which varies from model to model.

Modelling of air flow and particle distributions indoors
Generally, Computational Fluid Dynamics is considered an effective tool in predicting airflow, particle transport and number concentrations. However, it is also time consuming. For each of the three printer office scenarios modelled, the whole modelling process required the building of the model, defining the boundary conditions, grid generation, and testing the grid and simulation.

It was concluded CFD modelling is not required for assessing relatively simple printer emission scenarios because similar conclusions should be reached without significant difficulty through logical interpretation of information such as the location of inlet and outlet ventilation ducts, visualisation of air flow direction using artificial smoke, measurement of duct face air velocity, and particle measurement.

However, for some more complicated scenarios, such as those listed below, CFD modelling could be utilised:

- in large office spaces,
- where the printer needs to be close to all the occupants,
- where there are several air inlets and outlets mounted on the ceiling, and
- where airflow in an office is complex because of partitions and large amounts of furniture.

In these circumstances, CFD modelling could be applied to give an accurate airflow pattern of the offices and hence to inform the best location of the printer.

Impact of ventilation and filtration systems on particle spatial and temporal characteristics

18 out of 25 printers emitted an average PNC that was significantly different to the background at one metre from the printer. In addition, four of the five printers monitored at a position two metres from the printer also emitted an average PNC that was significantly different to the background with three of these printers also showing an average PNC that was significantly different to the background at one metre.

The measurement findings for printer LJ20 (Figure 6) indicate that where:

i) the velocity from nearby supply air inlet grills is sufficient, and
ii) the grill is positioned close enough and so as to push air across a computer workstation toward a printer;

then although a printer may emit at high PNC, the particles are diluted and not transported in significantly high concentrations toward the occupant of the nearby (computer) workstation.

Therefore, local conditions within the office have a strong influence on the transport of particles from printing processes and are important for informing decisions on where printers should be located relative to ventilation grills and occupied work stations.

Although data was collected regarding local office ventilation conditions such as size of office, number of ventilation grills, and distance of grills from printers, these variables could not be easily coded so as to fit the ANCOVA model.

8. Human Exposure and Risk

Local background particle exposure as a reference value for printer particle control decision making

Office workers are constantly exposed to particles both within and outside their office environment. Morawska et al. [11] found that the average outdoor particle concentration in the lower submicrometre range for the city of Brisbane, Australia was 7.4×10^3 particles cm^{-3}, and the average number median diameter was 40 nm. Because outdoor particles infiltrate office environments, assessment of particle emission and exposure arising from the operation of laser printers must account for local office background particle exposure.

Reasons for measuring particle emission from a laser printer include:

- evaluating the relative and absolute PNC associated with printing events, and
- estimation of exposure of office occupants to such particles.

However, in addition to a valid sampling methodology, the following is also required:

1. a particle number concentration value that reflects the *local background particle exposure* and that can be used as a *particle reference value* for control decision making,
2. a method of describing exposure such as time-weighted averages and peak concentrations, and
3. criteria for determining acceptable exposure excursions relative to the *particle reference value*.

Over the period of a day, where background particles (e.g. from outdoors) are on average a significantly higher contributor to particle exposure than laser printers, printer *peak particle exposure or 30 minute exposures* should be used when assessing such exposure. The use of eight-hour TWA *printer particle exposure* is not useful to guide control decision making regarding laser printer particle emission and exposure as it is difficult to quantify emissions due to variation in background levels.

The findings on health risk associated with printer emissions [2] is reassuring. However, the uncertainty in regard to health risks across the population e.g. for more sensitive people or those with higher levels of exposure to printer emissions than characterised in the initial study, would indicate that a precautionary approach[8] is prudent regarding exposure to particles associated with the operation of laser printers. Underpinning the application of the precautionary approach is the need for a *particle reference value* that would guide consideration of exposure levels.

It is possible to utilise the normal occupational hygiene protocol for determining when excursion from this particle reference value may be significant. Based upon the guidance principles on excursions of atmospheric contaminants within the occupational environment as outlined by both the *Australian National Occupational Health and Safety Commission* (now Safe Work Australia) [4] and the *American Conference of Governmental Industrial Hygienists* [10], a printing process could be

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8 Underpinning the precautionary approach is the precautionary principle set out in Principle 15 of the *United Nations Rio Declaration on Environment and Development* which indicates that where there are threats of harm lack of full scientific certainty shall not be used as a reason for postponing cost-effective control measures.

considered to not be under reasonable control if short term exposures exceed three times the *particle reference value* for more than a total of 30 minutes per eight-hour working day, or if a single short term value exceeds five times the *particle reference value*.

For the offices studied, the *local background particle exposure*, i.e. the office particle number concentration minus particles attributed to the printing episodes, was found to vary by an order of magnitude (in the range of 1.7×10^3 to 1.2×10^4 particles cm^{-3}), with an average value of 5.2×10^3 particles cm^{-3}, and a median value of 4.1×10^3 particles cm^{-3}. The main reasons for such a large range in *local background particle exposure* included:

1. the strength of the outdoor ambient pollution source, and
2. the relative differences in the filtration efficiency of the office HVAC systems that allowed varying concentrations of outside vehicle derived combustion particles to infiltrate the office areas.

A major implication of this is that if the printer is operating in an office with a relatively high *local background particle exposure*, particle exposure contribution from the printer will be overshadowed by non-printer particles. This important concept is illustrated in the following examples.

Local background particle exposures vary from day to day. The *local background particle exposure* over two separate days for printer LJ5 were, day one: 2.2×10^3 particles cm^{-3}, and for day two: 5.5×10^3 particles cm^{-3}. Calculation of the average outdoor ambient PNC revealed, for day one 1.9×10^4 particles cm^{-3} and day two 2.3×10^4 particles cm^{-3}. From this it can be concluded that office *local background particle exposure* is related to the outside ambient PNC and in addition to this, variation in *local background particle exposure* will occur between buildings in the same city (reflecting differing filtration efficiencies of building HVAC) and from city to city (reflecting differences in ambient vehicle pollution concentrations).

For printer LJ21, if the eight-hour TWA *local background particle exposure* value of 1.0×10^4 particles cm^{-3} is used as a *particle reference value* when assessing exposure then the conclusion is that the average and median values of the printer *peak particle exposure*, 2.7×10^4 particles cm^{-3} and 2.8×10^4 particles cm^{-3} respectively, were not greater than five times the *local background particle exposure* and therefore would be assessed as not violating the *excursion guidance criteria*. However, had this same printer been operated in an office with a lower *local background particle exposure*, for example 4.1×10^3 particles cm^{-3} which is the median value of all 25 office ambient PNC's, then the assessment would have concluded exposure exceeded the "5-times" *excursion guidance criteria*.

The *peak particle exposure* of 6.4×10^4 particles cm^{-3} for printer LJ21 was greater than five times the *local background particle exposure* value of 1.0×10^4 particles cm^{-3} and therefore violated the *excursion guidance criteria*. However, had a lower emitting printer been operated in this office, say with a peak particle exposure of 4.0×10^4 particles cm^{-3}, then the conclusion would have been that exposure did not violate the *excursion guidance criteria*.

Several options are available for a *particle reference value* that will guide assessment of control. These options include:

1. *Establishing a single particle reference value based upon the median value of eight-hour TWA local background particle exposure of a representative sample of office locations.* Therefore based upon 25 printers included in this study the median *local background particle exposure* value of 4.0×10^{3} particles cm^{-3} would be set as the *particle reference value* for all office workplaces. Application of the *excursion guidance criteria* would result in particle control strategies being implemented where the short term *printer particle exposures* exceeded 1.2×10^{4} particles cm^{-3} for more than a total of 30 minutes per eight-hour working day, or if a single peak value exceeded 2.0×10^{4} particles cm^{-3}.

2. *Establishing a single particle reference value based upon the maximum eight-hour TWA local background particle exposure value from a representative sample of office locations.* Therefore based upon 25 printers included in this study the *local background particle exposure* value of 1.2×10^{4} particles cm^{-3} would be set as the *particle reference value*. Application of the *excursion guidance criteria* would result in particle control strategies being implemented where the short term printer particle exposures exceeded 3.6×10^{4} particles cm^{-3} for more than a total of 30 minutes per eight-hour working day, or if a single peak value exceeded 6.0×10^{4} particles cm^{-3}.

3. *Using each individual office eight-hour TWA local background particle exposure as the printer particle reference value*. Therefore based upon 25 printers included in this study the *particle reference value* would vary from office to office and in the range of 1.7×10^{3} particles cm^{-3} to 1.2×10^{4} particles cm^{-3}. Application of the *excursion guidance criteria* would result in particle control strategies being implemented where the short term printer PNC exposures exceeded between 5.1×10^{3} particles cm^{-3} to 3.6×10^{4} particles cm^{-3} for more than a total of 30 minutes per eight-hour working day, or if a single peak value exceeded between 8.5×10^{3} particles/cm^{3} to 6.0×10^{4} particles cm^{-3}.

Table 6 provides a comparison of how many of the printer locations for printers LJ1 to LJ25 which would have exceeded the *excursion guidance criteria* for each of options one, two, and three outlined above.

These findings give two completely different conclusions, depending on whether the peak measurement excursion criteria is used (a number of excursions) or the 30 minute measurement criteria is used (no excursions). An explanation for this difference lies in frequency of use, i.e. it is low.

Table 6: Number of printer locations exceeding different options for particle reference values

	Particle reference values for option one		Particle reference values for option two		Particle reference values for option three	
	Three times the particle reference value of 4.0 x 10^3 particles cm^{-3}	Five times the particle reference value of 4.0 x 10^3 particles cm^{-3}	Three times the particle reference value of 1.2 x 10^4 particles cm^{-3}	Five times the particle reference value of 1.2 x 10^4 particles cm^{-3}	Three times the *local background particle exposure*	Five times the *local background particle exposure*
Number of printer locations that would have exceeded the excursion guidance criteria for each option	0	11	0	8	0	11

However it raises the question of which is the appropriate excursion criteria to use. Should it be based on consideration of peak measurement, or 30-minute measurement, or both?

The peak measurement outcomes, summarised in Table 6, for options one and three are the same because most of the local office printer reference values are close to the value of 4.0 x 10^3 particles cm^{-3} (which is the average value for all 25 offices). Option two resulted in an underestimation of the proportion of printers meeting the excursion guidance criteria because the value of 1.2 x 10^4 particles cm^{-3} is much higher than the majority of local office background particle exposure values. Therefore option two should be excluded.

Although options one and three are likely to result in a similar number of laser printers requiring an intervention to reduce particle exposure to office occupants, option one is recommended because it is less complex to implement as it relies on a single *particle reference value* to be used for all printers.

However, in order to utilise a single *particle reference value* for all printers, ideally the variability in local office background particle exposure both within the same office environment and between office environments should first be controlled, so as control decisions can be based primarily on the emission behaviour of the laser printers.

Such an approach reflects the sound principle of reducing *all* particle exposure to as low as reasonably practicable. The very low eight-hour TWA printer particle exposure results calculated for the printers included in this study indicate that the majority of the nanoparticle exposure experienced by workers in these offices over the course of a working day came from sources other than printers, such as vehicle emissions infiltrating the building. Vehicles are widely acknowledged in the literature as the principal source of ultrafine particles in urban areas [9]. However, office occupants are exposed to peak printer particle emissions arising from the operation of laser printers.

Health based arguments for controlling the *local background particle exposure* of office workers in addition to particle exposure arising from the operation of laser printers are contained within the scientific literature. Although the scientific evidence for such a link between nanoparticle exposure and ill-health remains largely unexplored, particles are known to cause oxidative stress and inflammation in the lungs and so contribution to illness, such as the exacerbation of asthma symptoms in susceptible individuals, is feasible. Weichenthal et al. [12] concluded that nanoparticles in general may play an important role in triggering asthma symptoms and that indoor nanoparticle exposures may be particularly important because people spend the majority of their time indoors where these contaminants are present. Knol et al. [13] reported upon the conclusions of a panel of experts regarding the likelihood of nanoparticle health effects and causal pathways associated with ambient particle pollution. These European experts with clinical, toxicological and epidemiological backgrounds in the field of nanoparticles concluded there was a medium to high likelihood of nanoparticle exposure causing cardiovascular and/or respiratory illness.

The main reason the link between nanoparticle exposure and ill-health remains largely unexplored is that the portable instrumentation necessary to characterise these particles has only become available within the last ten years. With the resultant increase in knowledge regarding nanoparticle concentrations within the environment, including that of offices, comes concerns about potential health effects of exposure, and demands for such exposure to be controlled.

The eight-hour TWA *local background particle exposure* for the office environments studied ranged from 1.7×10^3 particles cm^{-3} to 1.2×10^4 particles cm^{-3}. The median value of this range, i.e., 4.0×10^3 particles cm^{-3}, could be used as the basis for both the 30 minute short-term and peak *particle reference values* and that these *particle reference values* could be used for all laser printer particle exposure control decision making. Therefore, based upon the application of the *excursion guidance criteria*, printer particle exposure levels may be examined based on whether:

- the 30 minute short term printer particle exposures exceed three times the value 4.0×10^3 particles cm^{-3}, i.e., 1.2×10^4 particles cm^{-3}, for more than a total of 30 minutes per eight-hour working day, and/or
- a single peak value exceeds five times the value 4.0×10^3 particles cm^{-3}, i.e., 2.0×10^4 particles cm^{-3}.

The 30 minute short term *particle reference value* and the peak *particle reference value* allow primary decisions regarding control of printer particle exposure to be made based upon the emission characteristics of each printer, and the duration of exposure of office workers to printer emissions, with reference to a *background particle exposure*. A robust measurement methodology, as discussed below, will support this approach. These reference values may also be used in consideration of the performance of office HVAC systems.

Method for measuring particle emissions from laser printers and exposure within office locations

The ideal instrumentation for measurement of particle emission from laser printers operating in office locations would be portable and able to be used with minimal intrusion and disturbance to the office worker's immediate work environment. In addition the measurement methodology should reliably characterise temporal and spatial particle characteristics, and delineate amongst particles of interest and background particles.

The real-time data from the P-Trak and CPC 3025A correlated extremely well with 79% of the PNC arising from printing events being registered by the instruments at both one and two metres from the printers. OPC and DustTrak responses did not correlate with recorded printing events. Therefore it can be concluded that the temporal and spatial particle signature for printer particles within office locations is within the nanoparticle size of less than 300nm. In particular, a high PNC on the P-Trak in combination with a low PNC in the OPC small size range (300-500 nm) and at the time of printing events would indicate the particle source is the printer. Conversely a low PNC on the P-Trak in conjunction with a high PNC in the OPC large size band (> 1000 nm) would indicate a possible non-printer source of particles.

However, other non-printer sources of peak nanoparticle emission occasionally identified during the study came from the operation of nearby microwave ovens and sandwich toasters. Therefore, if measuring nanoparticle exposure associated with printer operation these possible sources of particles need to be demarcated from the printer results.

The CPC 3025A and P-Trak both demonstrated reliability in characterising particle exposure associated with printing events. However the use of the CPC 3025A is limited by its lack of portability, having to be operated on a trolley, and its particle saturation limit of 1.0×10^5 particles cm^{-3}, in contrast to the P-Trak which is a hand-held instrument and has a higher particle saturation limit of 9.9×10^5 particles cm^{-3}. The CPC 3025A also suffers from its relatively noisy pump operation which did cause stated annoyance to some office occupants. However, the CPC 3025A has a lower particle size measurement value of approximately 6 nanometres, compared to 20 nanometres for the P-Trak. This difference becomes important particularly in situations where the particle count median diameter is lower than 20 nanometres, which is rarely the case for laser printer emissions [5]. For accurate comparison of temporal PNC for the same printer it is therefore important that the same particle measurement instrument be used.

Both the 3025A and P-Trak CPC’s were found to be reliable and useful in characterising particles arising from laser printer operation within an office environment. Further support for the use of a P-Trak for characterising the release and exposure to nanoparticles comes from the Organisation of Economic Co-operation and Development [14] who have suggested the use of a P-Trak (and OPC) as a simple semi-qualitative nanoparticle emission technique for occupational hygienists when assessing the release of, and exposure to, nanoparticles arising from nanotechnology processes. This method was developed by the US National Institute of Occupational Safety and Health and titled the Nanoparticle Emission Assessment Technique and is reported to be useful in determining the release and exposure to engineered nanoparticles [15, 16].

Because of spatial differences in PNC between the printer and occupied computer workstations the instrumentation should be positioned so as to reliably estimate office worker particle exposure, such as at occupied work stations and at a height representative of the seated breathing zone. The generation of artificial smoke was useful in visualising air movement patterns so as to partly inform where to locate the instrumentation.

In conclusion, because the particle signature associated with the operation of laser printers is within the nanoparticle size range, the use of a particle counter that is able to characterise particles within the nanoparticle size range, for example a CPC, is recommended. Because such measurement is workplace based the particle counter should be relatively portable. Because the particle signature is within the nanoparticle size range, instruments that characterise particle number and mass above the nanoparticle size range are not required for workplace measurement of laser printer particles. In this study, the use of a DustTrak and OPC were found to be useful *research* tools for the characterisation of particle emission from the operation of laser printers, mainly in order to exclude the possible presence of particles larger than the nanoparticle size range.

Guidance on minimising exposure to emissions during the use of laser printers

Australian workplaces do not have wide experience of measurement and characterisation of nanoparticles despite numerous sources of nanoparticle exposure such as that from welding, smelting operations, and operation of combustion engines having occurred at workplaces for more than one hundred years. Therefore, the following advice regarding procedures for characterising and controlling exposure to particles emitted during the operation of laser printers within office environments is provided.

Option 1 - Nanoparticle exposure control only, no assessment

This option provides a universal approach for control implementation based upon the findings of this study, and does not require assessment of particle emission from the printers of concern. This is consistent with a precautionary approach to controlling exposure to nanoparticles in general.

Locate the printer such that distance and/or local ventilation conditions dilute the printer particles. Examples of such include:

1. Locate the printer in proximity to a ventilation inlet or outlet grill. The release of artificial smoke can aid in visualising local air movement. Note the potential movement of the printer should not then result in printer particles increasing exposure to occupants of other work stations;
2. Reduce the number of laser printers located amongst work stations and locate remaining laser printers in a dedicated printer room, or an area of the office a sufficient distance away from occupied work stations. Ideally the local ventilation to either of these areas should have a higher velocity so as to provide a greater particle dilution to the area compared to the rest of the office.

Option 2 – Nanoparticle exposure assessment followed by control implementation

This option provides for assessment of particle emission from the printers of concern so as to inform whether controls are required for individual laser printers. Ideally, assessment should be conducted by someone competent in the area of emission evaluation such as an occupational hygienist.

1. Choice of instrumentation

Instrumentation for characterisation of nanoparticles emitted from laser printer operation within an office environment should include:

i. Particle number counting instrument that can characterise nanoparticles, such as a condensation particle counter that has a lower particle measurement range ≤20nm.
ii. Artificial smoke generator.

2. Identification of laser printers emitting at a particle ratio of > 2 to the background

i. Set the instrument to record one data reading per second.

ii. Position the instrument at the printer so as to characterise background particle number concentration, and particle emission number concentration from the printer during the operation of the printer.

iii. Before commencing printing, record the background particle number concentration on the sampling log sheet.

iv. Perform at least five printing events that are representative of typical printing for the printer with the duration for each test between 2-3 minutes, for example, different number of pages up to 50, single and double sided, black or colour font. Sampling locations at the printer should include the paper exit tray and fan exhaust vents usually located at back or side of printer. For each printing event record the printing times, number of pages printed, print colour, and page sides on the sampling log sheet.

v. Calculate the ratio of the peak printing PNC to the background PNC for each printing event.

vi. All printers with ratios > 2 will require further investigation regarding office occupant exposure as per step 4. This printer emission classification system is similar in approach to that used by He et al. [3], who used a P-Trak to catalogue printers into four different classes, in terms of the ratio of particle emission concentration to background, including: non-emitters (ratio ≤ 1); low emitters (ratio > 1 and ≤ 5), medium emitters (ratio > 5 and ≤ 10 to background); and high emitters (ratio > 10 to background).

3. Assessment of office occupant exposure to laser printer particles

For those printers identified in step 2 as emitting particles at a ratio of > 2 to the background, carry out the following:

i. Set the instrument to function in continuous recording mode.

ii. Assess exposure to nanoparticles of occupants at (computer) work stations by placing the instrument in a static location that represents the seated breathing height of the workstation occupant. Carry out sampling for a period that is representative of an eight-hour period of particle exposure. Ensure the printer is used as per normal. Record the time of each printing event on the sampling log sheet.

iii. Download and chart the logged PNC data from the instrument.

iv. Notate the graph of the real-time data with information on the different printing events such as time of printing, etc.

4. Identifying if the peak particle reference value and/or the 30 minute short-term particle reference value as follows have been exceeded at the location of the work station

i. Calculate the *local background particle exposure* value. Subtract this from measured values to give the component due to laser printer emissions.

ii. Identify if any 30 minute short term printer particle exposures exceed three times the value 4.0×10^3 particles cm^{-3}, i.e., 1.2×10^4 particles cm^{-3}.

iii. Identify if peak values exceeds five times the value 4.0×10^3 particles cm^{-3}, i.e., 2.0×10^4 particles cm^{-3}.

These excursion criteria are based on guidance on general variability in the concentration of airborne substances, as described in the document *Exposure Standards for Atmospheric Contaminants in the Occupational Environment Guidance Note* [4], which can be interpreted such that printer particle exposures may be significant in the following circumstances:

a. Where the 30 minute short-term printer particle exposures exceed three times a *particle reference value* for more than a total of 30 minutes per eight-hour working day, and/or where a single peak value exceeds five times a *particle reference value*, and

b. A *particle reference value* of 4.0×10^3 particles cm^{-3}, which is the median value of the *local background particle exposures* estimated for the 25 office environments included in this study.

5. Deciding upon and implementing exposure controls

Given the absence of a universal *particle reference value* or National Exposure Standard for nanoparticles arising from the operation of laser printers precautionary guidance may be based upon the typical office (non-printer related) background particle exposures.

i. In relation to type of laser printers, measurement results show that a number of printers do not emit particles above a peak particle exposure concentration of 2.0×10^4 particles cm^{-3}, and 1.2×10^4 particles cm^{-3} as averaged over any 30-minute period. This reference may be considered in a precautionary approach to choice of printers.

ii. Implementing the controls outlined in Option 1 can help reduce exposure at the occupied work stations is below a peak particle exposure concentration of 2.0×10^4 particles cm^{-3}, and 1.2×10^4 particles cm^{-3} as averaged over any 30-minute period.

6. Evaluation of the effectiveness of control decision/s:

After controls are modified, measurements can be repeated so as to assess the effectiveness of the control decision.

9. References

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APPENDIX A – Graphs of time-series plots of nanoparticles and PM2.5 measured at one metre from the printers

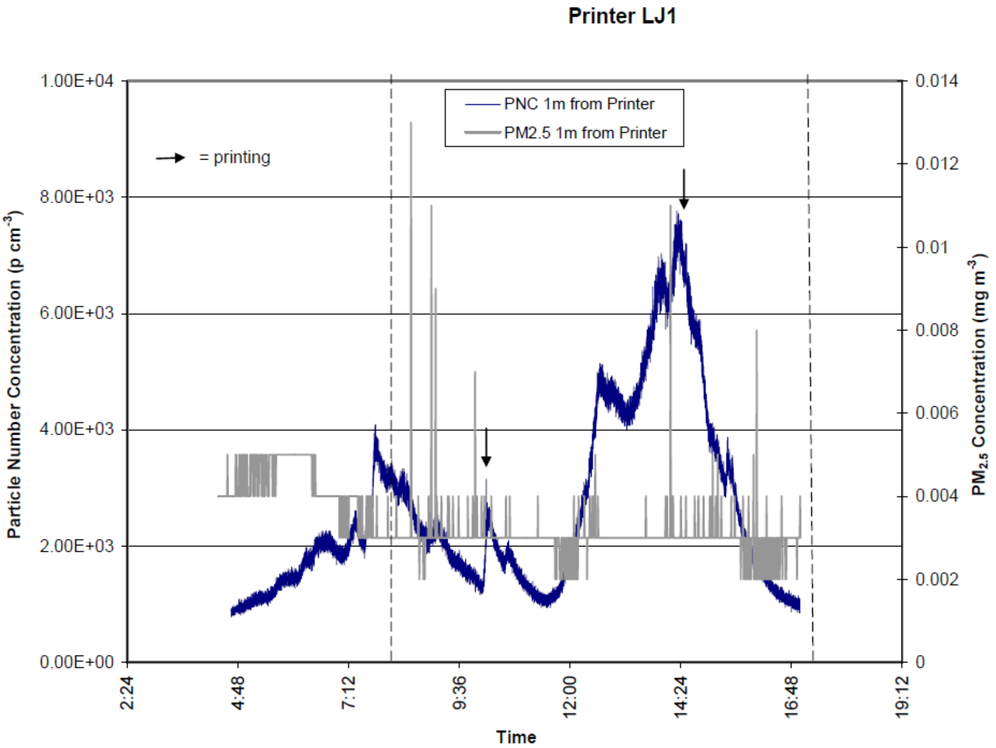

Figure 7: Particle number and mass concentration measured from printer LJ1. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

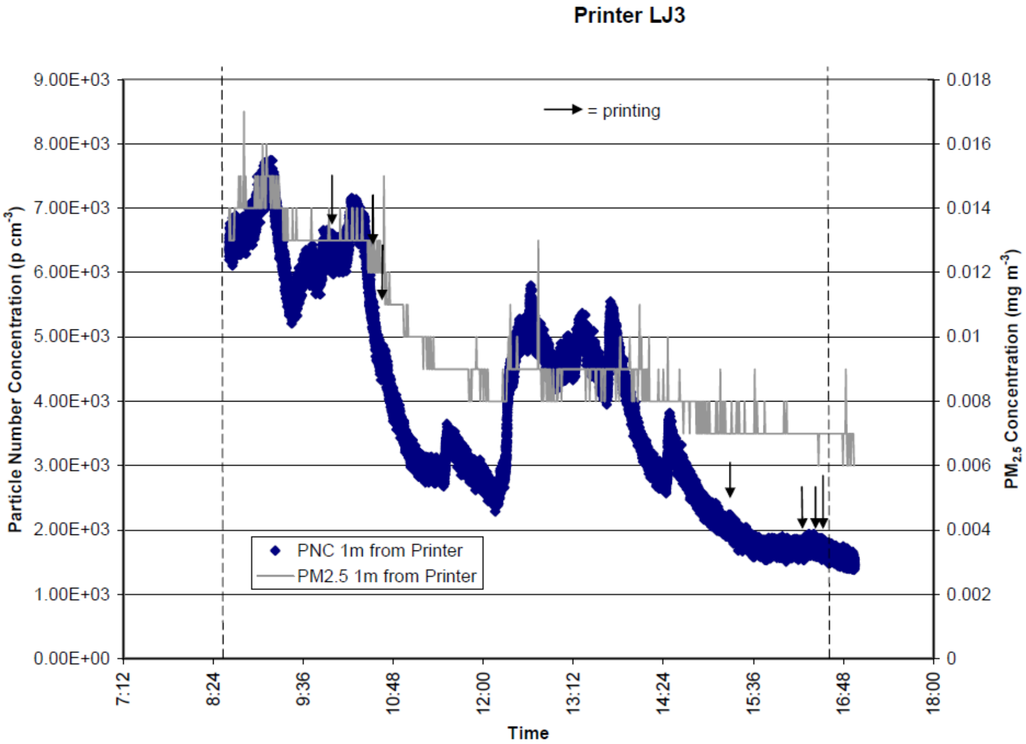

Figure 8: Particle Number and Mass Concentration measured from printer LJ3. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

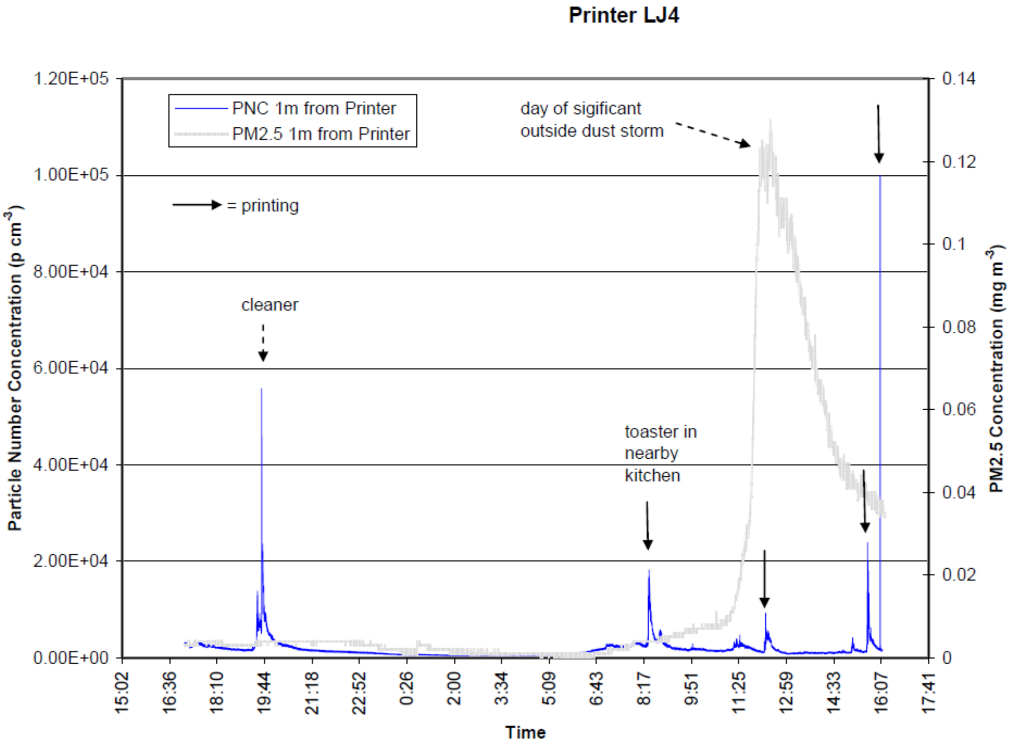

Figure 9: Particle Number and Mass Concentration measured from printer LJ4 which was classified as a low-emitter. This graph illustrates the PNC arising from cleaner activity and use of a toaster within the office area, and also the impact on inside supermicrometre particle size from significant external events involving supermicrometre particles such as a dust storm. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak.

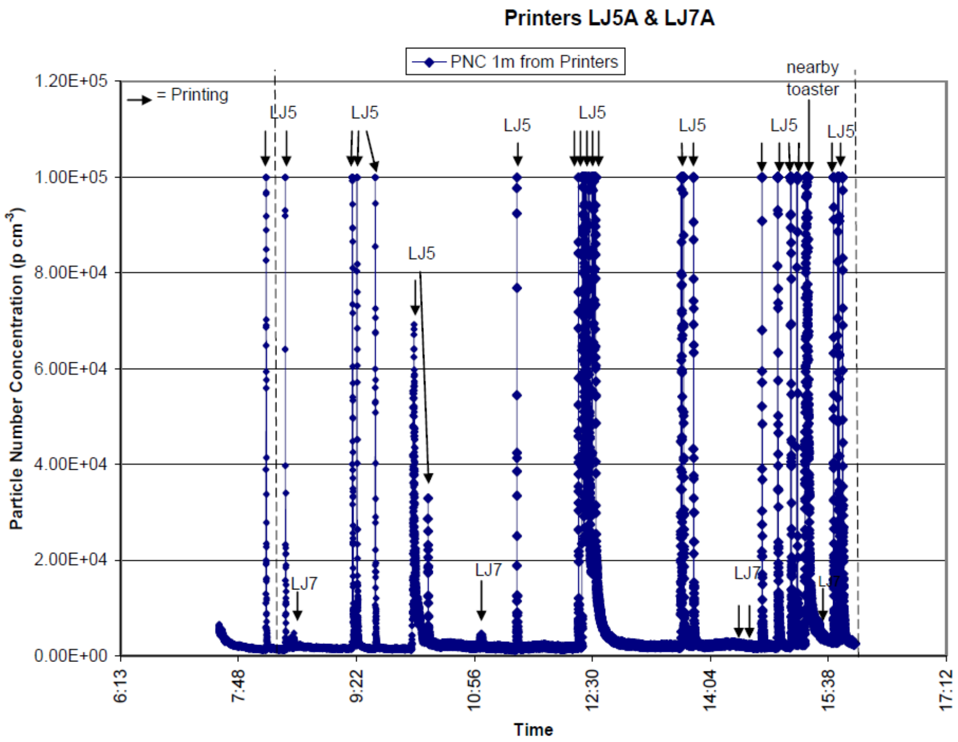

Figure 10: Particle Number Concentration measured from printer LJ5 which was classified as a high-emitter and LJ7 which was classified as a low-emitter. PNC one metre from the printer was measured using a CPC 3025A. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

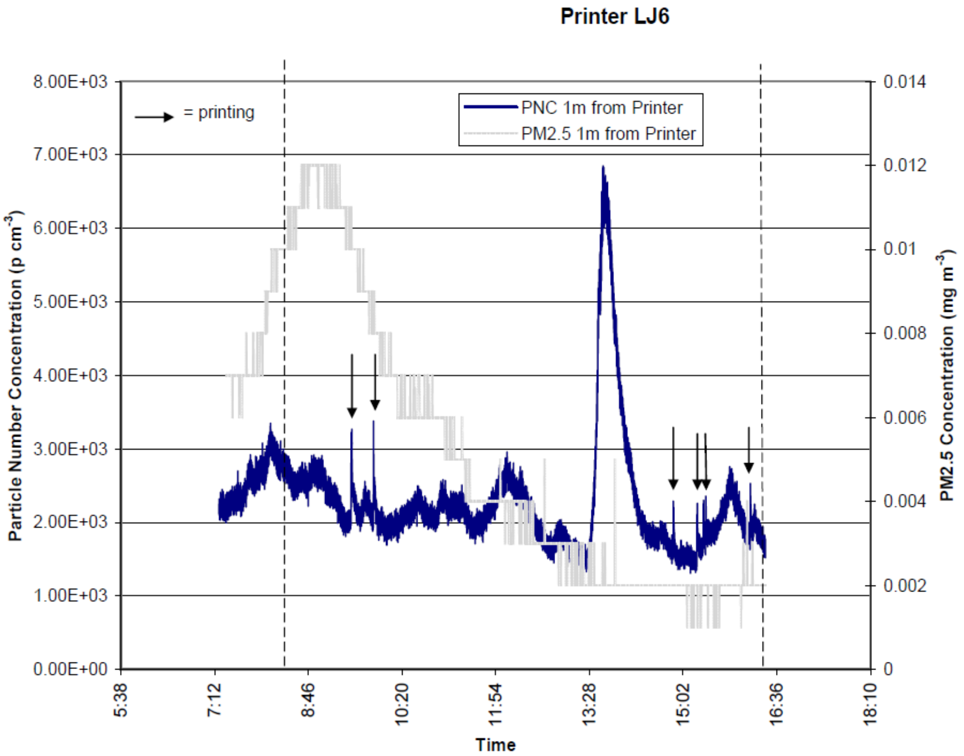

Figure 11: Particle Number and Mass Concentration measured from printer LJ6 which was classified as a high-emitter. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

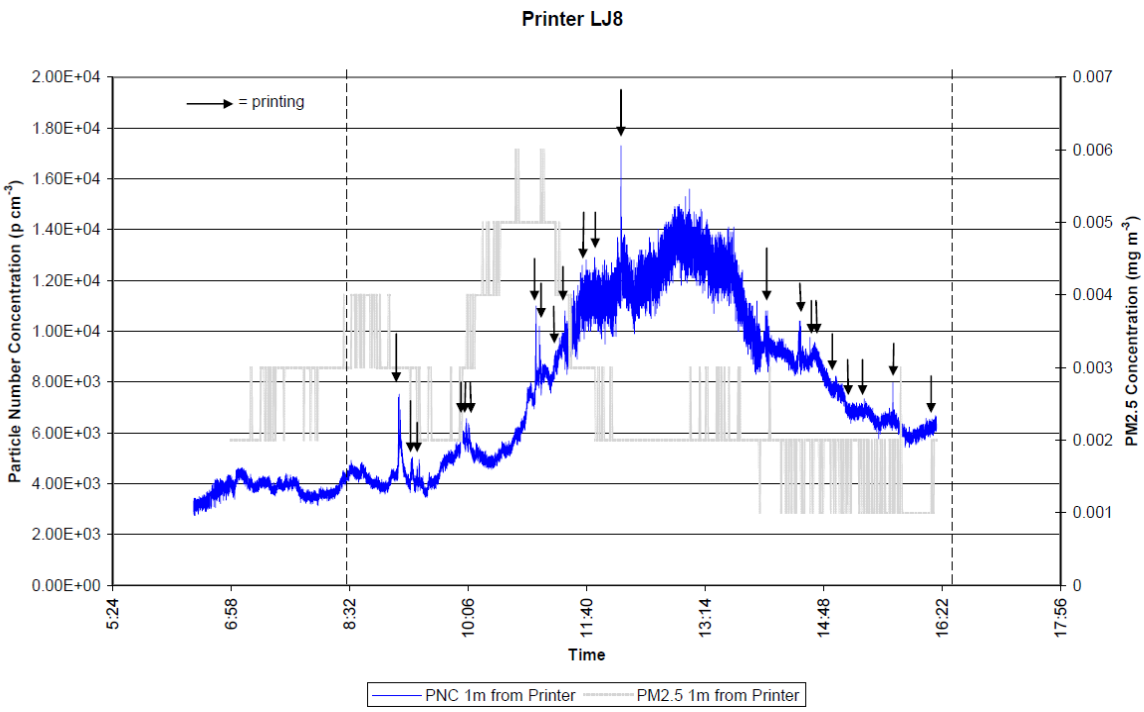

Figure 12: Particle Number and Mass Concentration measured from printer LJ8. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

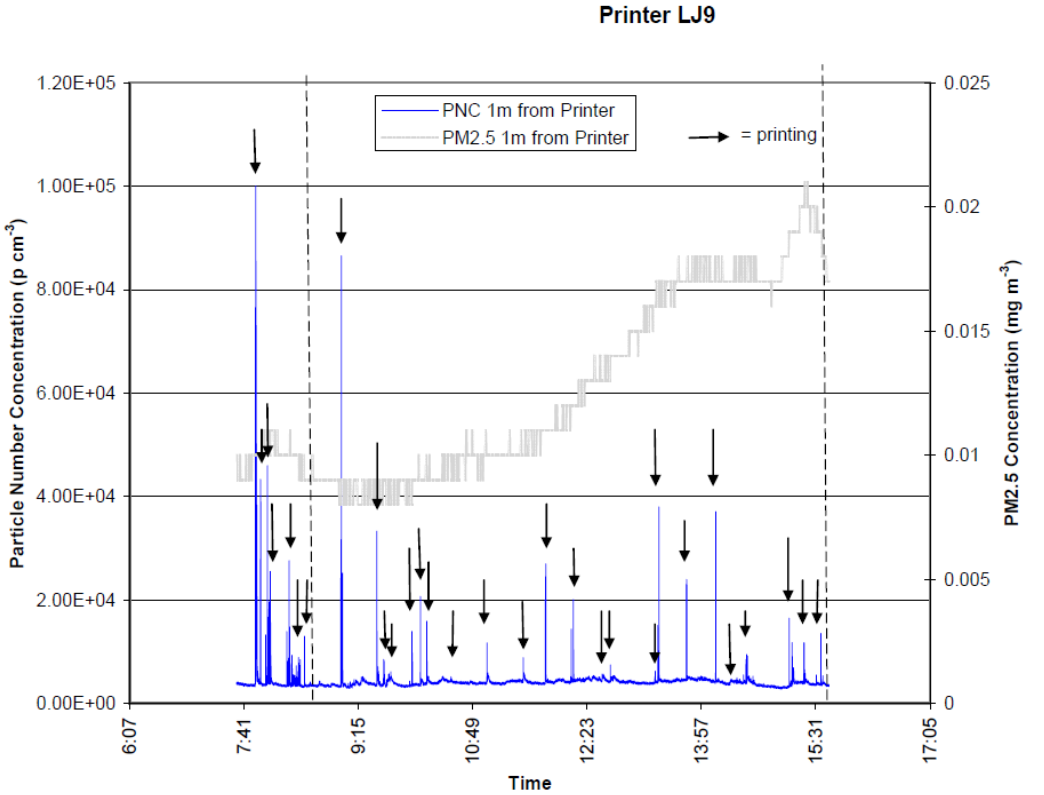

Figure 13: Particle Number and Mass Concentration measured from printer LJ9. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

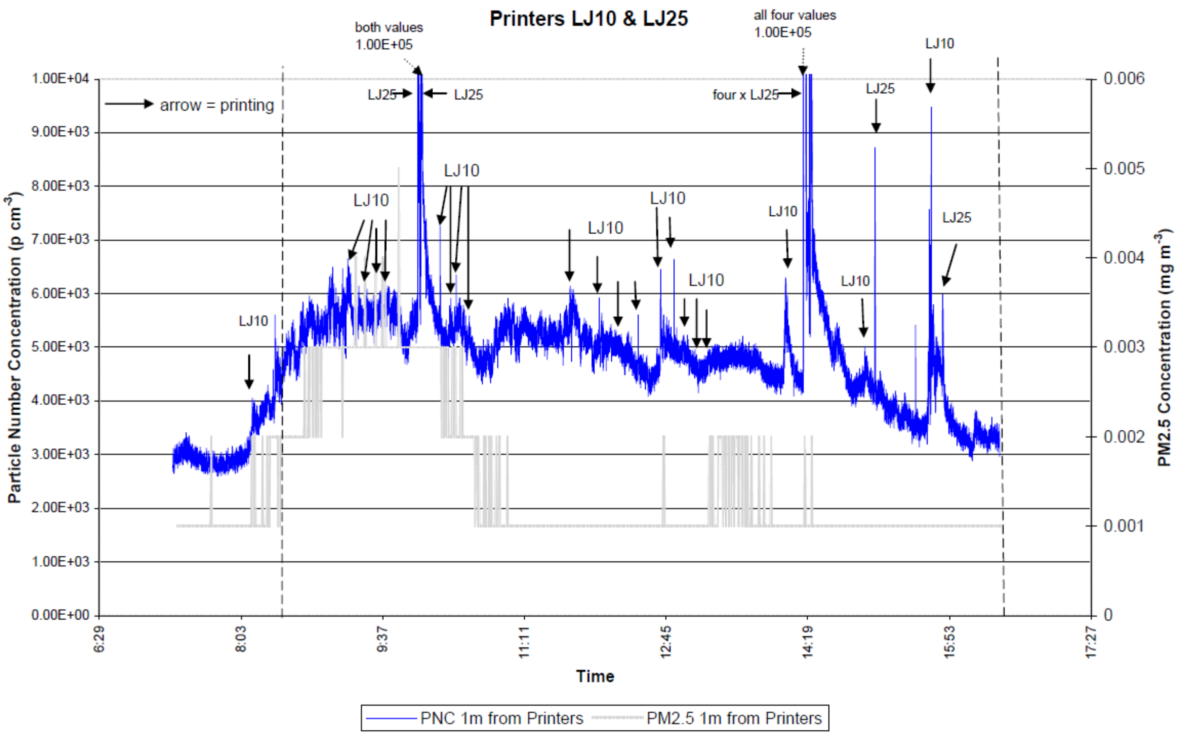

Figure 14: Particle Number and Mass Concentration measured from printers LJ10 and LJ25. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

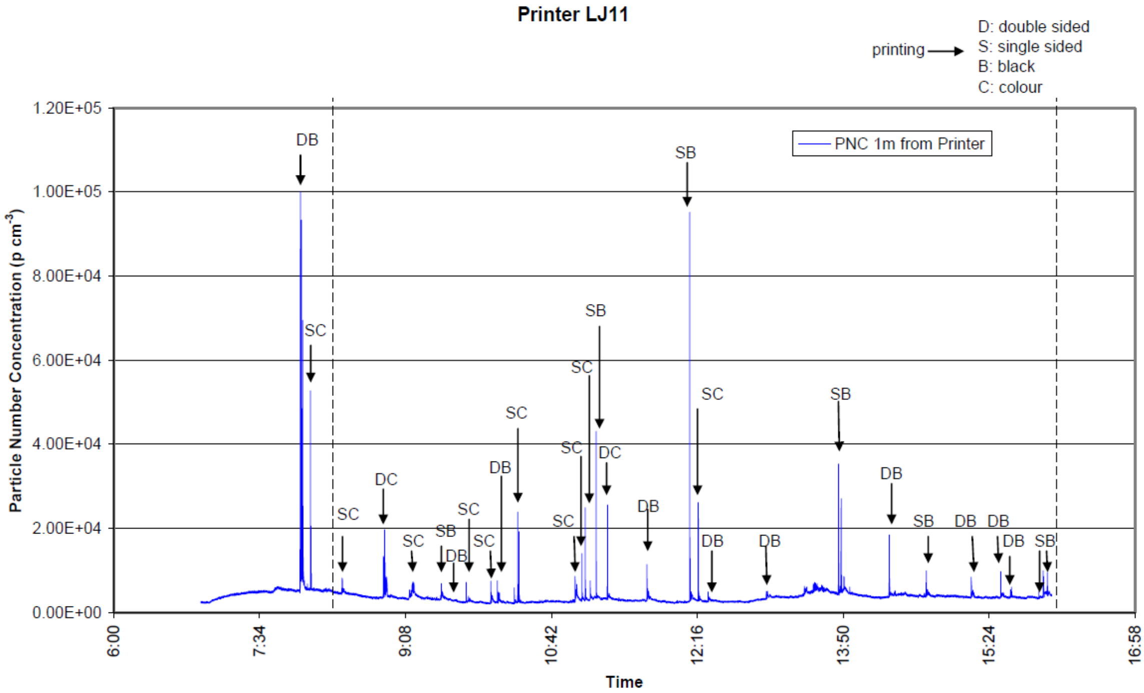

Figure 15: Particle Number Concentration measured from printer LJ11. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

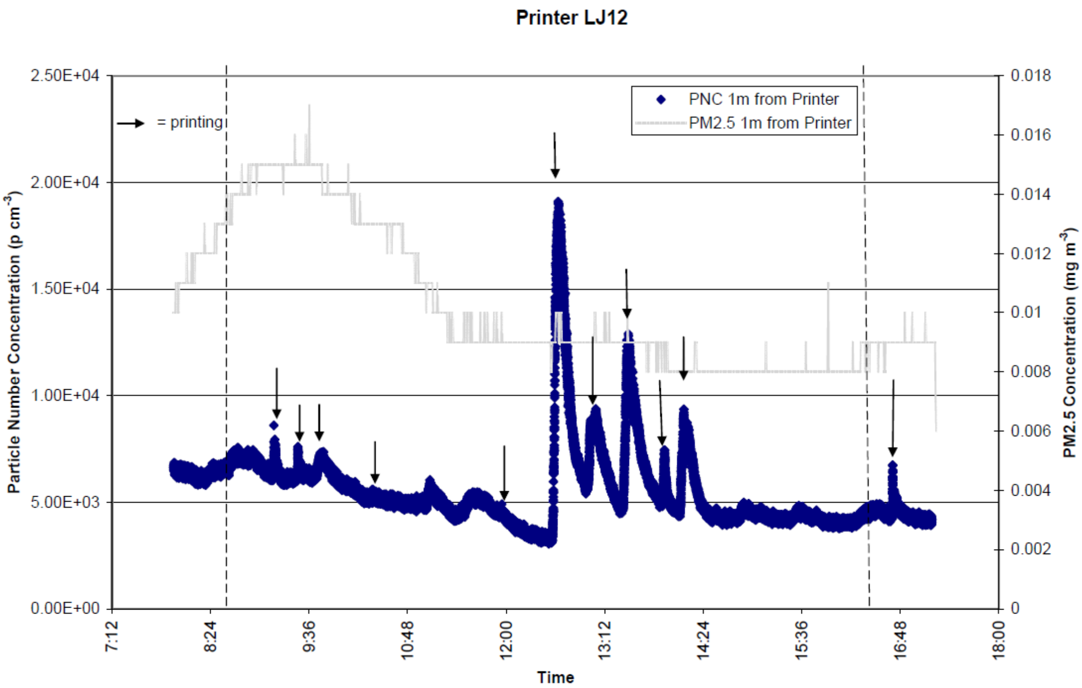

Figure 16: Particle Number and Mass Concentration measured from printer LJ12. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

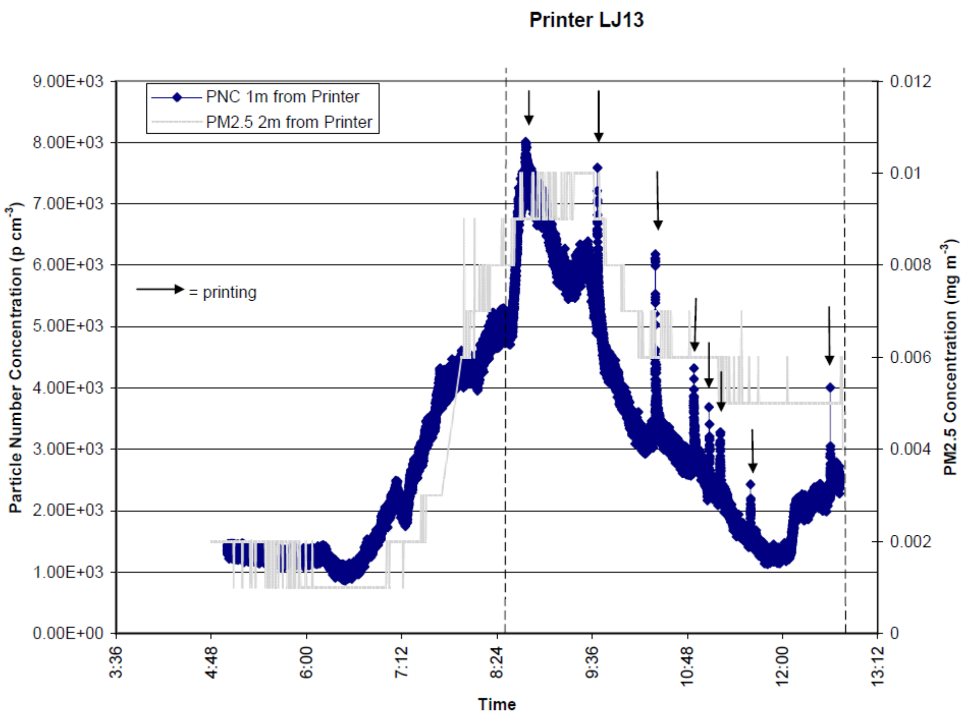

Figure 17: Particle Number and Mass Concentration measured from printer LJ13. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

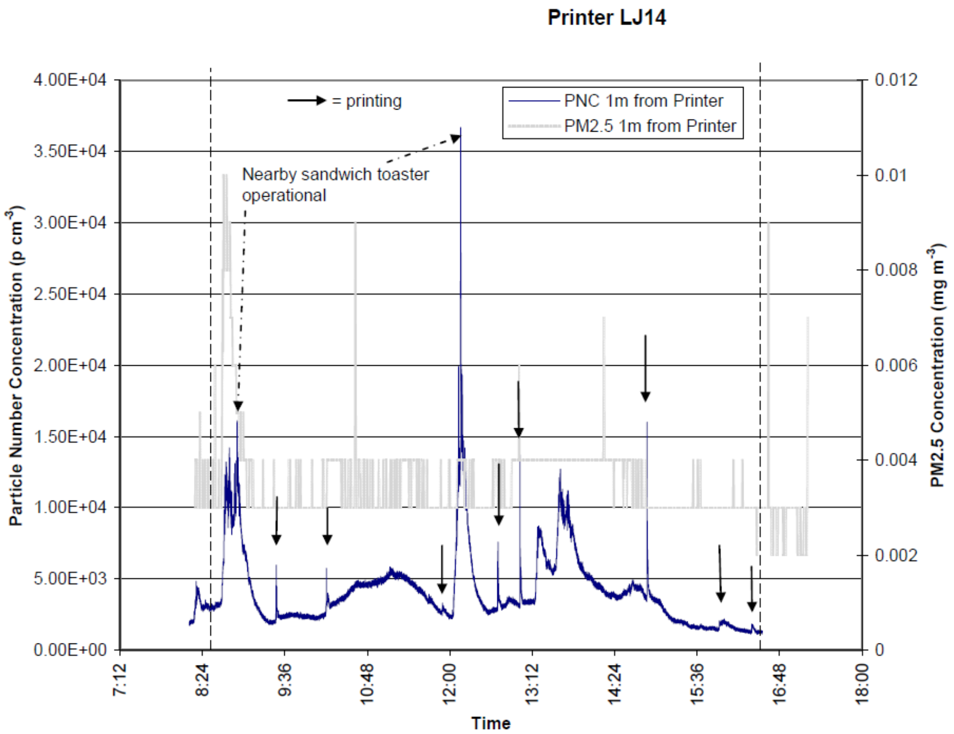

Figure 18: Particle Number and Mass Concentration measured from printer LJ14. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

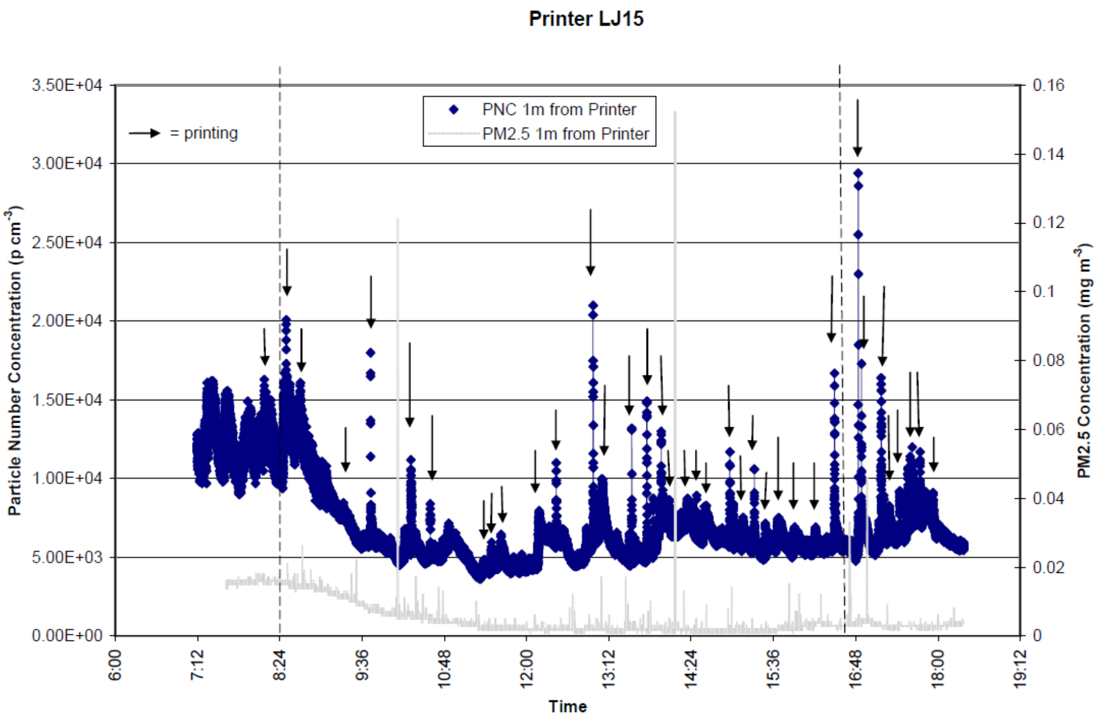

Figure 19: Particle Number and Mass Concentration measured from printer LJ15. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

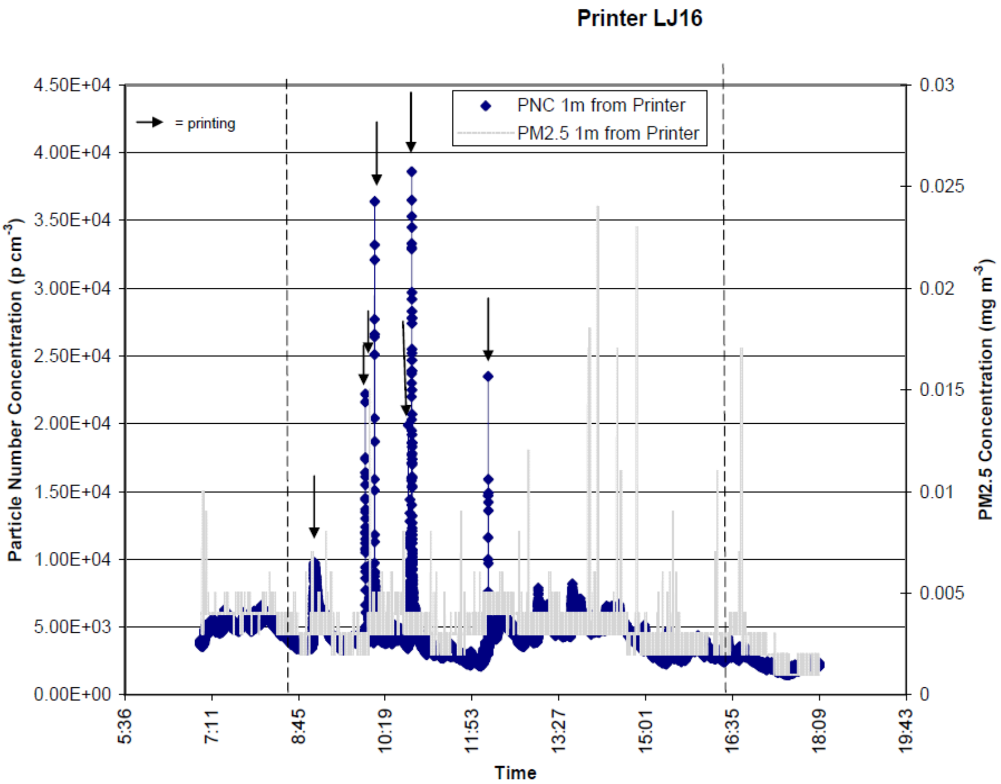

Figure 20: Particle Number and Mass Concentration measured from printer LJ16. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

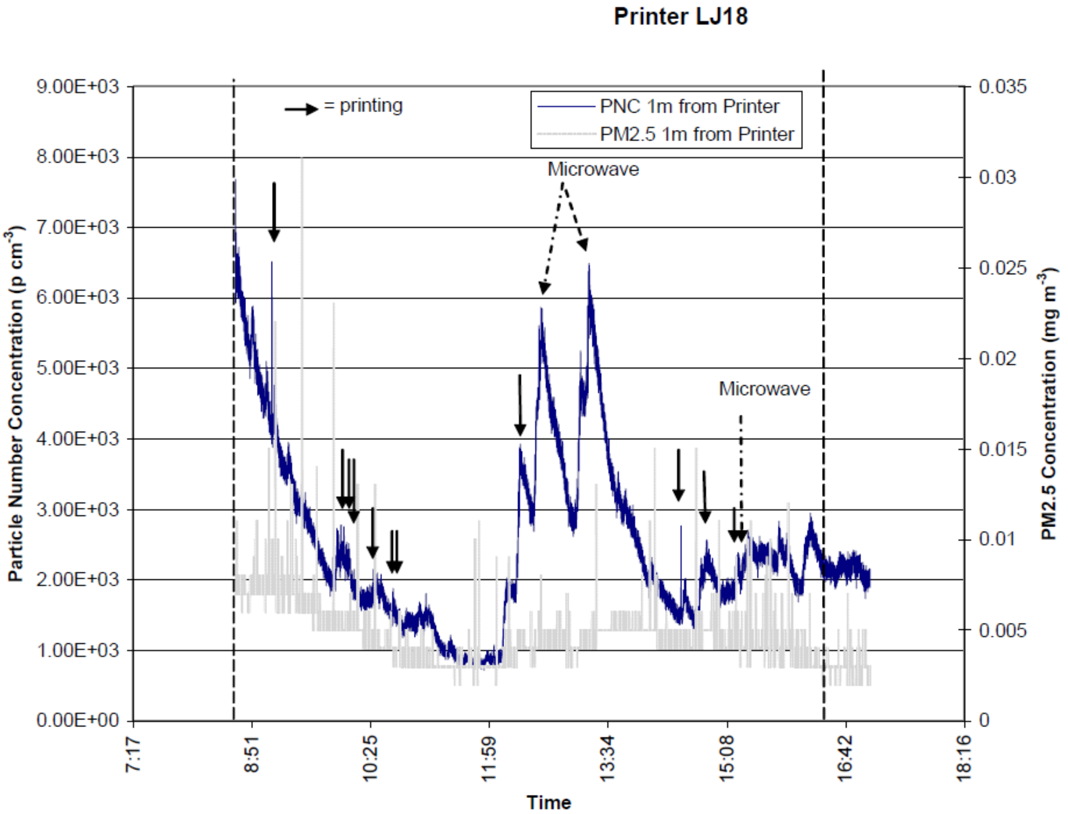

Figure 21: Particle Number and Mass Concentration measured from printer LJ18. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

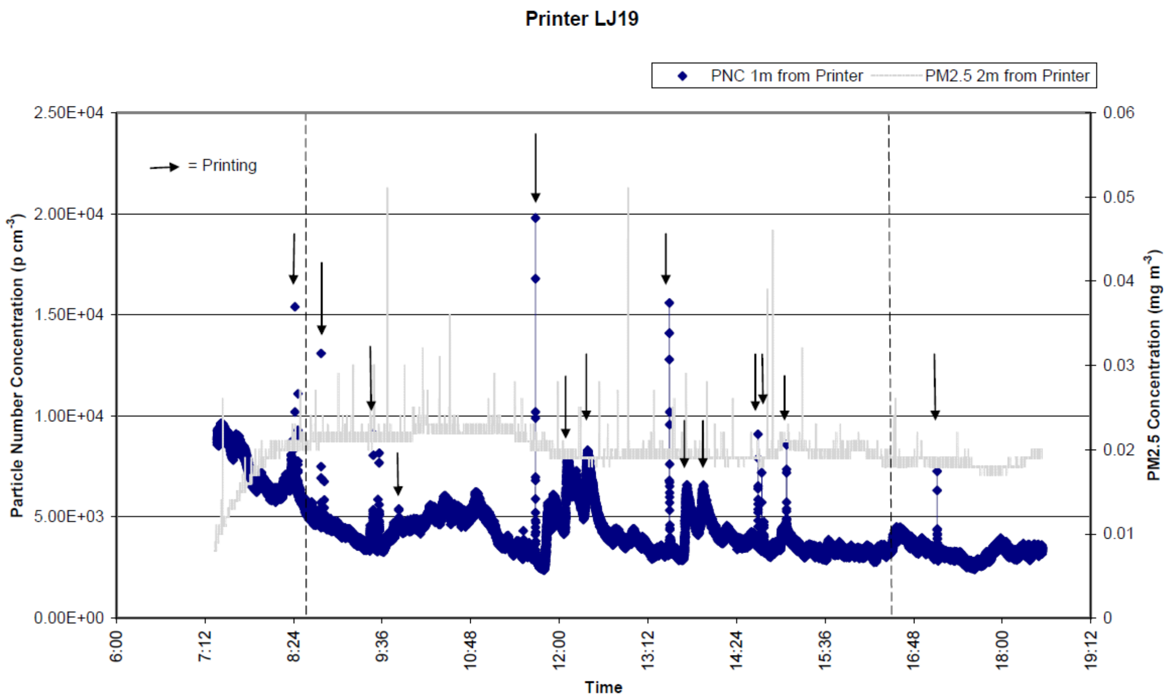

Figure 22: Particle Number and Mass Concentration measured from printer LJ19. PNC one metre from the printer was measured using a CPC 3025A, and PM2.5 using a DustTrak. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

APPENDIX B - Graphs of time-series plots of nanoparticles measured simultaneously at one and two metres from the printers

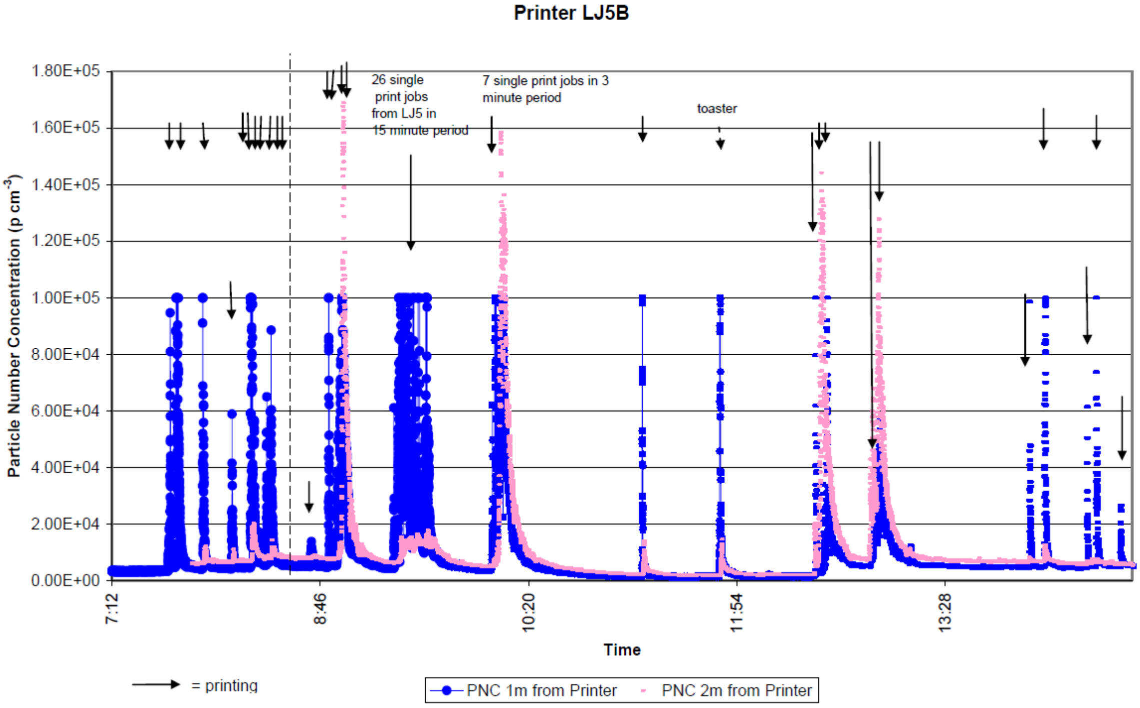

Figure 23: Particle Number Concentration measured at printer LJ5, a high-emitter. The P-Trak data are $CTC_{P\text{-}Trak}$ values. PNC one metre from the printer was measured using a CPC 3025A, and a P-Trak at two metres from the printer. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

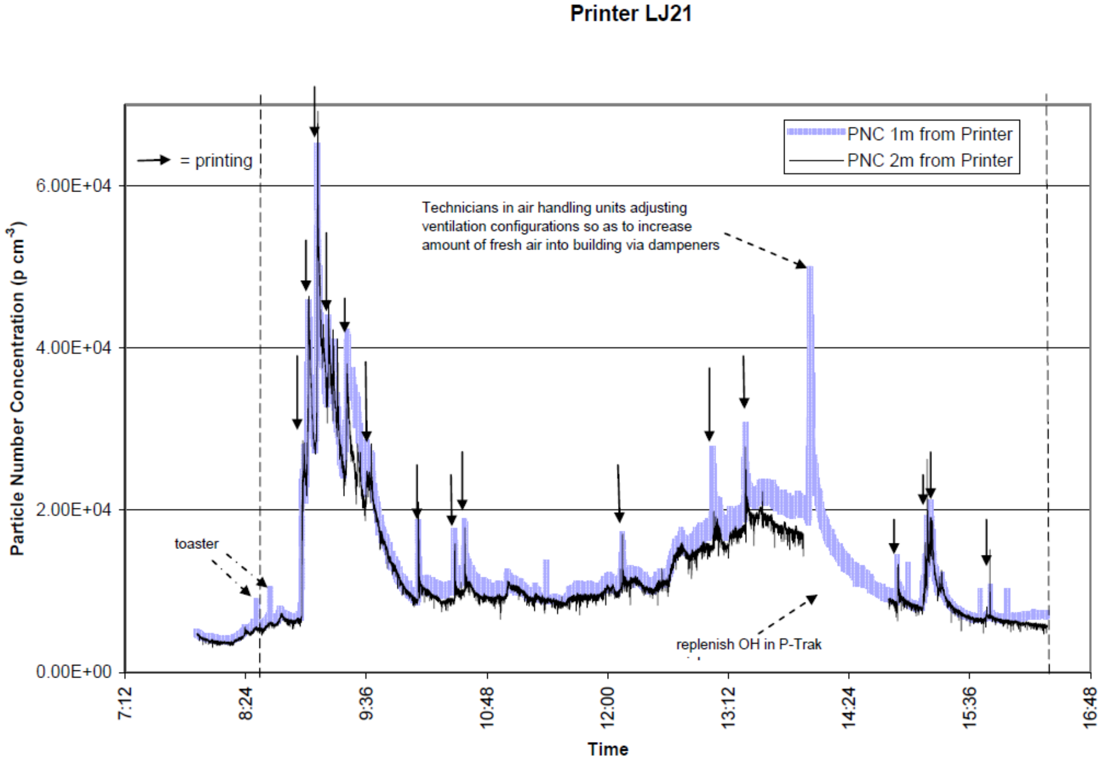

Figure 24: Particle Number Concentration measured at printer LJ21, a high-emitter. The P-Trak data are $CTC_{P\text{-}Trak}$ values. PNC one metre from the printer was measured using a CPC 3025A, and a P-Trak at two metres from the printer. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

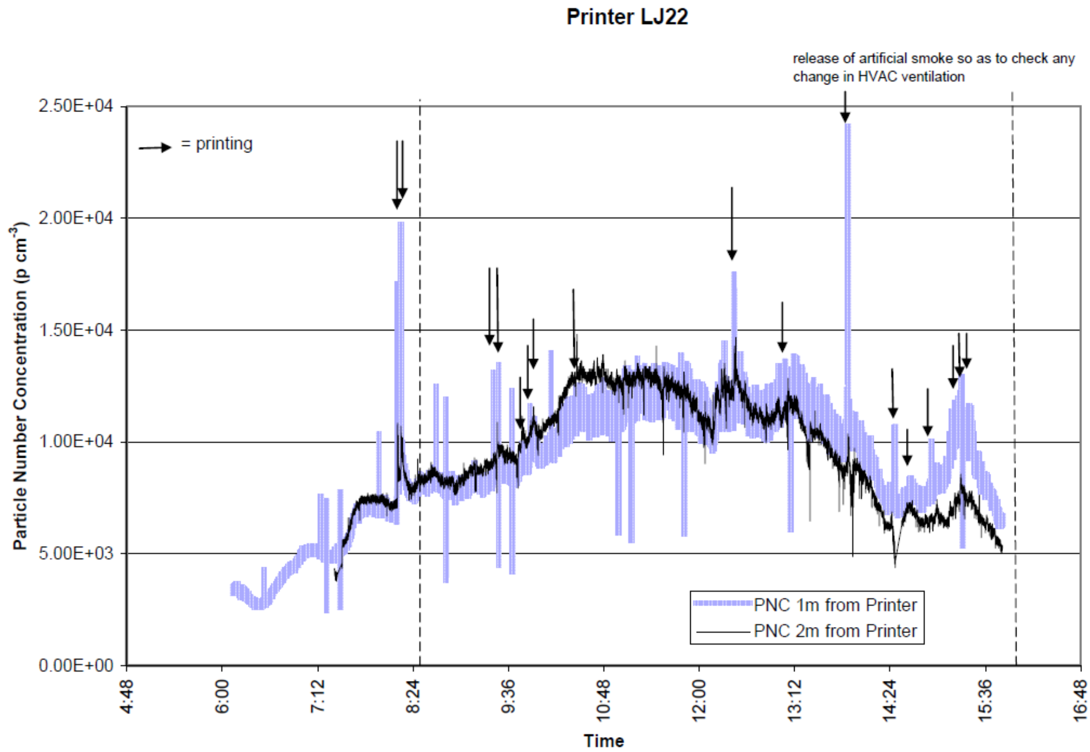

Figure 25: Particle Number Concentration measured at printer LJ22, a high-emitter. The P-Trak data are $CTC_{P\text{-}Trak}$ *values*. PNC one metre from the printer was measured using a CPC 3025A, and a P-Trak at two metres from the printer. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

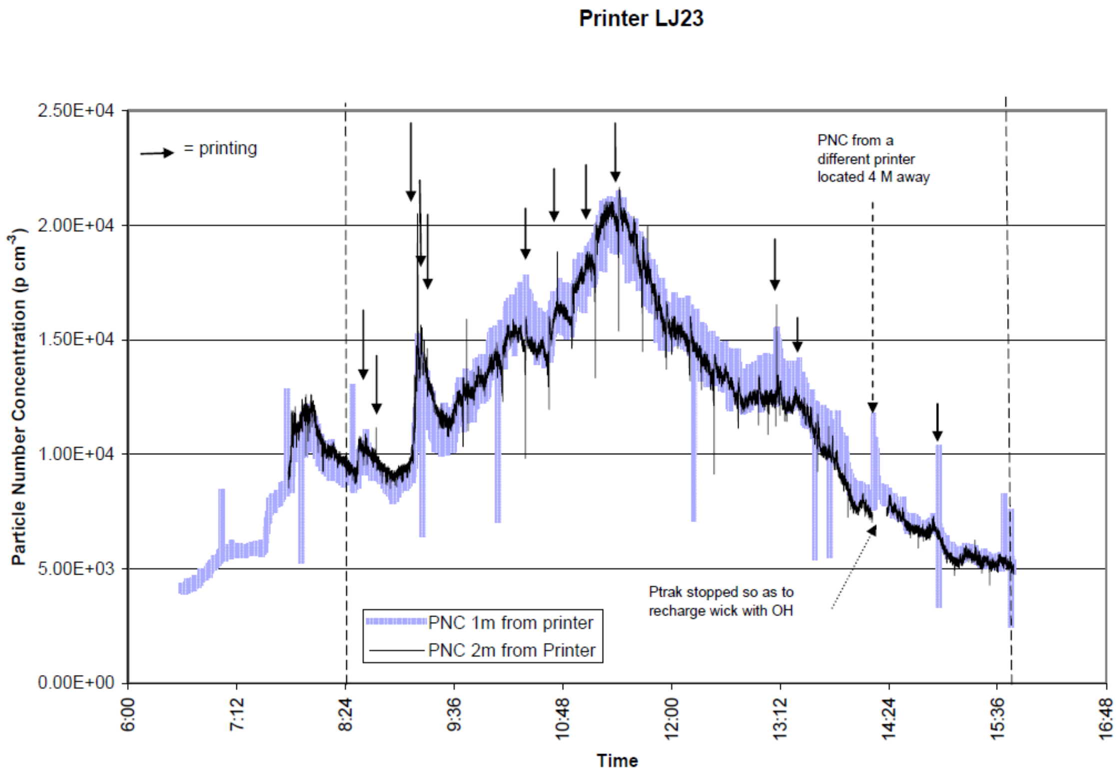

Figure 26: Particle Number Concentration measured at printer LJ23, a high-emitter. The P-Trak data are $CTC_{P\text{-}Trak}$ *values*. PNC one metre from the printer was measured using a CPC 3025A, and a P-Trak at two metres from the printer. The vertical dotted lines demarcate the time period used for calculating office hour particle exposure.

APPENDIX C - Graph of time-series plots of nanoparticles measured simultaneously at 0.1 metre and one metre from printer

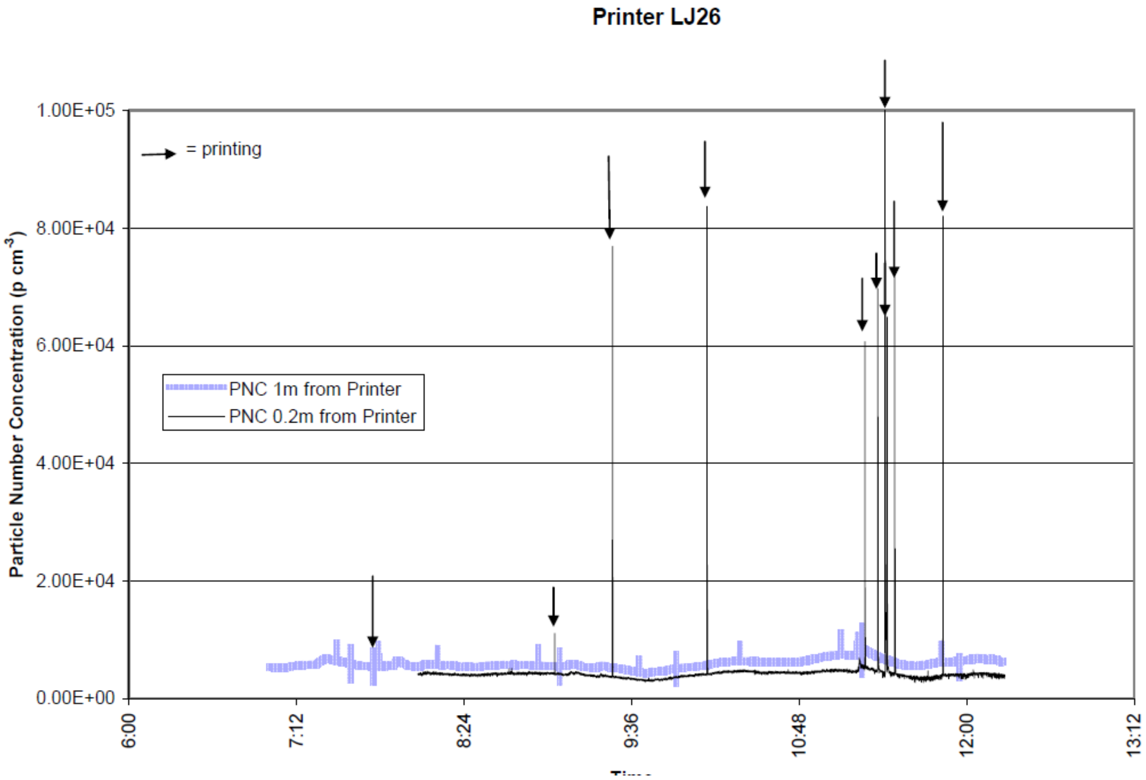

Figure 27: Particle Number Concentration from printer LJ26 as measured with a P-Trak at printer particle source, and a CPC 3025A at distance of one metre from particle source.

APPENDIX D - Graph of time-series plots of submicrometre and supermicrometre particle number count during printing

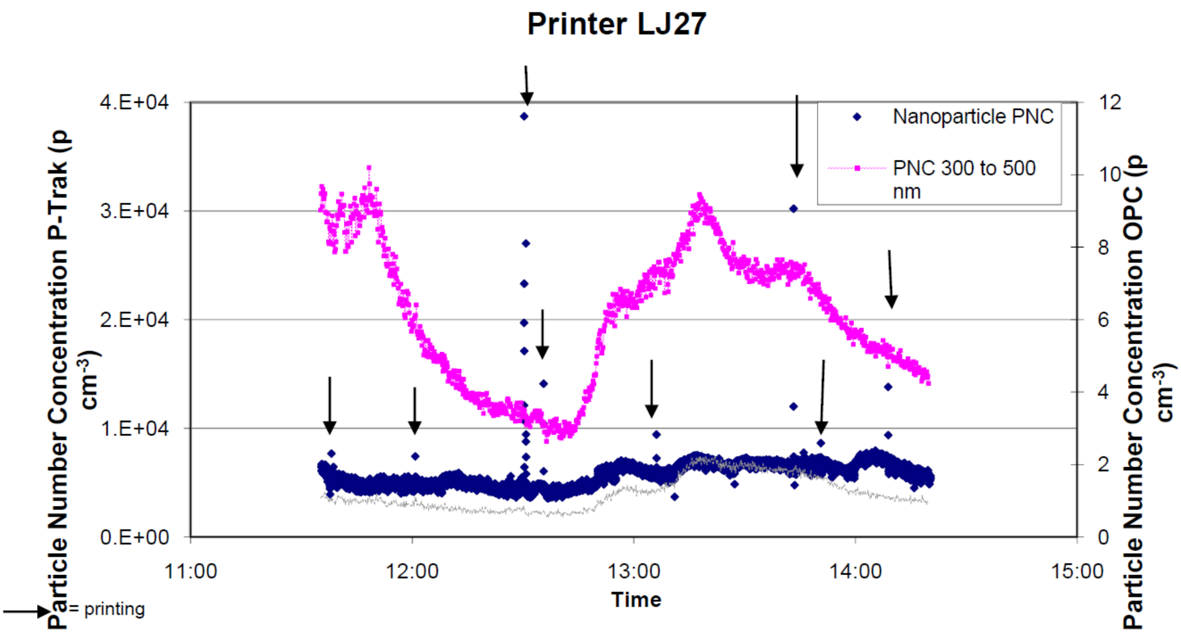

Figure 28: Supermicrometre and submicrometre particle number concentration. Nanoparticle concentration as measured by a P-Trak increases in response to printing events. The PNC > 300nm recorded by the OPC does not change in response to recorded printing events.

APPENDIX E – Description of ANCOVA Method and Analysis

Description of Method

The analysis of covariance (ANCOVA) model used [17] assumes a linear relationship between a continuous response (Peak PNC) to both categorical (Colour, Sided) and continuous (Pages) explanatory variables. Essentially it combines an analysis of variance (ANOVA) and a linear regression. It also allows for investigation as to whether there is any significant interaction for the covariates in explaining the variation in Peak PNC (i.e. Colour*Sided, Colour*Pages, Sided*Pages). Printer was not included as an explanatory variable as this was used for identification purposes. If y_{ij} is considered as the *j*th print job emission observation for the *i*th type (group, i.e. high, medium or low emitter) of printer and x_{ij} the corresponding value of an explanatory variable, an ANCOVA model with a random effect for the intercept is:

$$y_{ij} = \beta_1 + b_i + \beta_2 x_{ij} + \varepsilon_{ij}\,, \qquad i = 1,2\,,\ j = 1,\ldots,n_i\,,$$

$$b_i \sim N(0,\sigma_b^2)\,,\ \varepsilon_{ij} \sim N(0,\sigma^2)$$

Because there can be more than a single explanatory variable x_{ij} and there can be interaction terms between explanatory variables, additional x and β terms were added to the model and estimated. Only the intercept term was considered as random nested in Type of printer because the usual emissions were considered to be different between high and low emitting printers. The analysis gave a parameter which estimates the variance between Types of printer (σ_b^2) along with an estimate of the variance within each Type of printer (σ^2).The maximum likelihood method was used to estimate parameters. The model was fitted using the nlme R package [18]

The original dataset contained only one printer classified as ‘medium’ type (LJ23). This printer was re-categorised as a ‘high’ emitter to allow parameter estimation in the analysis below. To check that the re-categorisation did not adversely skew the results from the ANCOVA analysis, the printer was also re-categorised as a ‘low’ emitter and the analysis redone, with minimal impact upon the results.

Exploratory Analysis

Graphical methods were used to explore any relationships and summary statistics. Firstly, Figure 29 is a plot of peaks (natural log transformed for normality) versus the number of pages. This shows that there is no obvious relationship between the two variables which is reinforced by a small correlation at 0.0782. This suggests that there is a weak linear relationship between peaks and number of pages.

Figures 30, 31, and 32, contains box plots of peaks (log transformed for normality) by type, colour and sided. There appears to be minimal differences in peaks for the type and sided variables. The only difference in Peak appears to be due to whether the print job is coloured or not. These box plots suggest that only the colour variable only appears to be influencing the variation of the peaks. The ANCOVA statistical analysis section below will formally test whether these variables significantly impact the peak emissions.

Peaks vs # of Pages

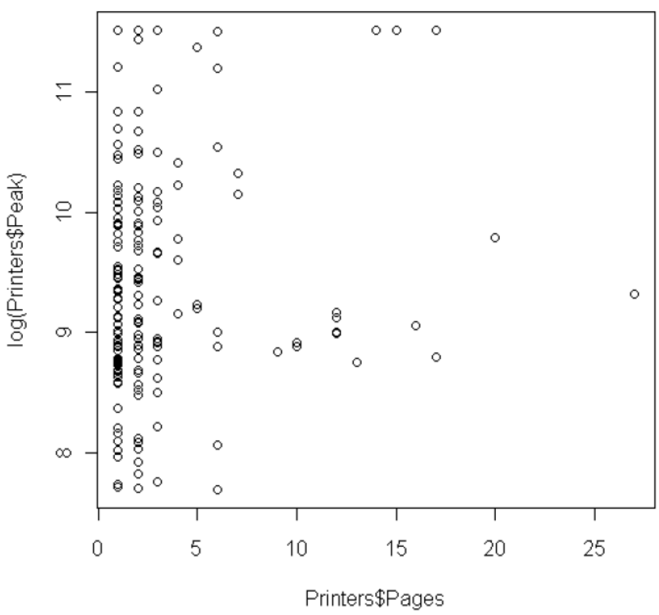

Figure 29: plot of peaks (natural log transformed for normality) versus the number of pages

Although the type of printer doesn't appear to impact on the peak emission, the 'baseline' emission was considered to be different between 'high' and 'low' emitting printers based on their classification. This influence was considered in the ANCOVA modelling outlined below. Because of the possible interaction between the explanatory variables Colour, Sided and Pages and thus influence on the response peak variable, these were also considered in the analysis as outlined below.

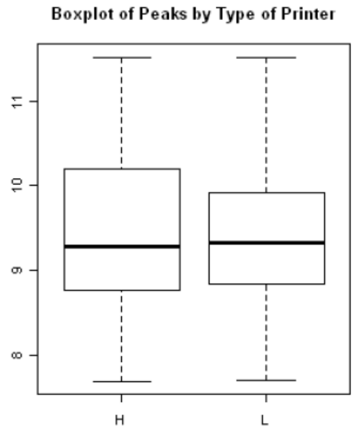

Figure 30

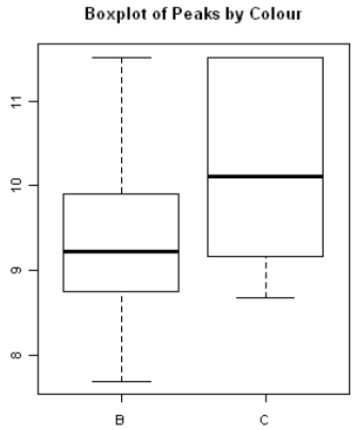

Figure 31

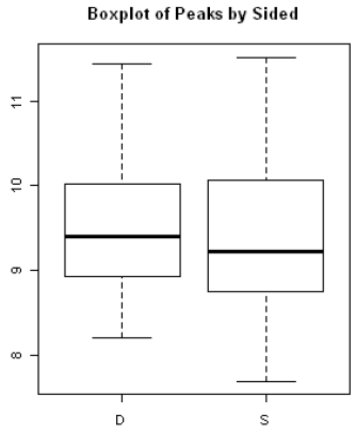

Figure 32

Statistical Analysis

The analysis commenced with a saturated model in which all explanatory variables (Sided, Colour, Pages) and interactions (Colour*Sided, Colour*Pages, Sided*Pages and Colour*Sided*Pages) were included. When the p value of an interaction term was found to be greater than 0.05 this term was dropped from the model. First the highest level interaction terms (Colour*Sided*Pages) was found to have a p value greater than 0.05 and this term was hence dropped from the model. Next the two term interactions were considered and the most insignificant (highest p value) being dropped and a new model was fitted. At each stage the Likelihood Ratio Test (LRT) was performed to determine the better of the two models after a term was removed. In each case as an insignificant variable was removed from the model the simpler model was neither better nor worse as per the LRT but was preferred to it because it was a simpler model. After performing this variable selection criteria it was only colour that was recognised as a significant variable ($p < 0.01$). The between Types estimates for the variance was $\hat{\sigma}_b \approx 0.0517$ and the within Types variances estimate was $\hat{\sigma} \approx 0.9547$. The coefficients were estimated as $\hat{\beta}_1 = 9.3684$ and $\hat{\beta}_2 = 0.7828$.

Linear mixed-effects model fit by maximum likelihood
Data: Printers

AIC	BIC	logLik
477.8652	490.4318	-234.9326

Random effects:
Formula: Printer ~ 1 | Type

	(Intercept)	Residual
StdDev:	**0.05167263**	**0.9546906**

Fixed effects: log(Peak) ~ Colour

	Value	Std.Error	DF	t-value	p-value
(Intercept)	**9.36843**	0.08710559	168	107.55257	**0e+00**
ColourC	**0.78275**	0.21971366	168	3.56259	**5e-04**

Correlation:

	(Intr)
ColourC	-0.328

Standardized Within-Group Residuals:

Min	Q1	Med	Q3	Max
-1.7710054	-0.6638041	-0.1388019	0.5794038	2.2694001

Number of Observations: 171 Number of Groups: 2

Assumptions and Cautions

The model assumptions of within-group errors being normally distributed seem slightly violated, due to the response variable not being exactly normal. Although a log transformation was performed, the data still appeared slightly non-normal. There were no other alarming patterns in residuals.

Further analysis using all the emissions that are allocated due to the printing job would give more data and may yield more light on explaining the variation in Peaks using the explanatory variables. The data is censored at the maximum emission value registered by machine and this may also cause problems

The within group error was much smaller than the between group error indicating that by grouping the type of printers did not necessarily add much to the analysis. A general linear model could be applied here with very similar result.