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Dust and odour emissions from layer sheds

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Foreword by the authors

At the commencement of this project there was a shortage of quality and relevant odour and dust emission rate data for layer farms and little understanding of the diurnal, seasonal, flock and inter-farm variability that may occur (especially for modern shed designs and management practices but also due to changes in odour analysis techniques). High quality odour and dust emission rate data was required to support improved planning for new and expanding farms by increasing the confidence in odour modelling, improve the calculation of separation distances and respond to community concerns. The measurement of volatile organic compounds (VOCs) was added to the project to improve understanding of the origins of the odour; and the identification of key odorants. In the longer term, these will be required to develop science based, targeted, odour mitigation strategies.

Six years after the commencement of this project, and many odour, dust and VOC measurements later, the research team are proud to have contributed to advancing knowledge of layer farm emissions and the refinement of associated measurement techniques. It is believed that the findings of this investigation will support the ongoing and sustainable development of layer farms and consequently the ongoing supply of quality eggs for Australian consumers.

Executive summary

Odour, dust and non-methane volatile organic compound (NMVOC) emissions were measured at tunnel ventilated layer (egg production) sheds over several seasons in Queensland and Victoria. Emission rates were found to vary between farms presumably due to management and environmental factors. Emissions data that has been collected will improve scientific understanding and support improved planning of new layer farms.

NMVOCs are the building blocks of odour—mixtures of specific odorous NMVOCs combine to form what people recognise as poultry odour—and influence its character and strength. NMVOC composition of layer shed odour samples was analysed to provide knowledge that will be vital for the strategic development of odour mitigation strategies and real time monitoring.

The successful completion of this project has been made possible through the collaboration of four research teams and co-ordination by the Australian Poultry CRC.

Background

Odour and dust emitted from layer sheds have the potential to impact on nearby residences, communities and the environment. Impacts due to odour and dust have been recognised by the poultry industries and regulatory authorities as a cause of concern. Consequently, new and expanding farms undergo rigorous assessments to investigate the likelihood of these emissions causing unnecessary impacts.

Impact assessments require accurate data for these emissions to enable modelling and prediction of impacts. Most of the published odour emission data for poultry production is no longer relevant due to recent changes in poultry production systems (new building designs, new management practices, new breeds and new diets) and advances in emission measurement practices including new olfactometry and dust measurement standards, improved sample collection methods and advancements in alternative measurement technologies such as electronic sensing arrays and gas chromatography-mass spectrometry/olfactometry (GC-MS/O).

This study has been undertaken to build a database of odour, dust and non-methane volatile organic compound emissions for modern intensive poultry farming in Australia. This data will improve estimation of emissions, improve prediction of impacts and enable improved planning for new poultry farms. Increased knowledge of the chemical composition of poultry odour (through NMVOC assessment) will be critical for identifying the origins of the odour and developing mitigation techniques.

Objectives

The project had the following objectives:

- Development of a database of odour and dust emissions from tunnel ventilated layer sheds.
- Identification of specific poultry shed non-methane volatile organic compounds and odorants.

Methods used

- Two tunnel ventilated layer farms were included in this project. Odour, dust and VOC emissions were measured over a 4–5 day period.
- 55 odour samples were collected from layer farms.
- Odour, dust and VOC samples were collected from within a temporary flexible duct that was attached to one of the tunnel ventilation fans at each farm.
- Odour concentration was measured using dynamic olfactometry to AS/NZS 4323.3:2001. Two laboratories were used, and comparative testing was conducted between the laboratories to ensure comparability of odour concentration measurement.

- Dust was measured using a DustTrak™ and an aerodynamic particle sizer (APS) and reported in terms of mass concentrations (PM_{10} and $PM_{2.5}$), particle number concentrations and count median diameters (mid-point of the number size distribution). Isokinetic sampling techniques were used.
- VOCs were collected using sorption tubes for subsequent analysis with a GC-MS/O.
- Ventilation rate was estimated by measuring fan airspeeds, or by calculating the flow rate through each active fan using manufacturer supplied fan flow rate date (and adjusting for shed static pressure), which was selected as the preferred method.
- All odour samples were analysed within 8.5 hours of collection.

Results/key findings

Odour emission rates

Odour emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight). Emission rates were normalised according to the number of birds in the shed or the total live weight to enable comparison with published emission rate data.

- Layer odour emission rates are summarised in the following table.

Units	Full measured range	Range for majority of data
ou/s	2882–24,907	2000–18,000
ou/s/1000 birds placed	58–512	50–500
ou/s/kg (total live weight)	0.03–0.27	0.03–0.26

- Odour emission the day following manure belt cleaning tended to be slightly higher than the following days when more manure had accumulated on the belts.
- Odour emission rate did not substantially increase as manure accumulated over the 4–6 day period between regular belt cleaning.
- Odour emission rates varied throughout the time that measurements were taken on each day.
- Comparison of Queensland and Victorian odour emissions was not possible due to unseasonal weather conditions experienced in Victoria during both summer (cooler than average) and winter (warmer than average).
- Odour emission rate tended to increase with increasing ventilation rate and ambient temperature whereas odour concentration tended to decrease.

Dust concentration and emission rates

Dust emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight).

- Layer shed dust concentration and emission rates are summarised in the following table.

Dust fraction	Units	Full measured range	Range for majority of data
PM_{10}	**mg/m³ (concentration)**	0.03–0.19	0.03–0.1
	mg/s (ER)	0.61–14.63	1–3
	mg/s/1000 birds placed (ER)	0.014–0.29	0.014–0.15
	mg/s/kg (total live weight) (ER)	(0.06–1.52) x 10^{-4}	(0.6–8) x 10^{-5}
$PM_{2.5}$	**mg/m³ (concentration)**	0.005–0.061	0.01–0.05
	mg/s (ER)	0.07–5.69	0.2–2
	mg/s/1000 birds placed (ER)	0.001–0.19	0.005–0.06
	mg/s/kg (total live weight) (ER)	(0.07–9.98) x 10^{-5}	(0.5–3) x 10^{-5}
Particle number	**particles/m³ (concentration)**	(0.015–1.92) x 10^{8}	(0.15–2) x 10^{7}
	particles/s (ER)	(0.004–1.78) x 10^{10}	(0.4–4) x 10^{8}
	particles/s/1000 birds placed (ER)	(0.008–5.93) x 10^{8}	(0.1–2) x 10^{7}
	particles/s/kg (total live weight) (ER)	(0.004–3.12) x 10^{5}	(0.04–1) x 10^{4}
Count median diameter (CMD)	**µm**	0.7–8	1–2.5

- The concentration of dust in the air exiting the layer sheds was variable. Consequently, dust emission rates from the sheds also varied widely. Dust emissions varied by ventilation rate, farm, season and microenvironment. Other factors that were unaccounted for were also likely to be involved.
- There were no discernible trends between dust concentrations or emission rates and the number of days after belt cleaning (manure removal).
- In general, dust emission rates tended to increase with increasing ventilation rate whereas dust concentrations tended to decrease.
- Seasonal differences in dust emissions could be partly explained by seasonal differences in ventilation rates.

Non-methane volatile organic compound NMVOC and odorant emissions

The following table lists the chemicals and odorants identified in the NMVOC samples collected at layer farms. Samples were dominated by 2-butanone, 1-butanol and 2,3-butanedione, however the chemical species identified were in lower concentrations. There was only a low presence of sulphide species. Only three compounds were able to be identified as odorants during the analysis. Some of the other NMVOCs identified are known to be odorants but their abundance in the sorbent tubes was

insufficient to elicit an olfactory response using the applied analytical methods. Ventilation rate did not impact significantly on the amount of NMVOCs measured from the layer house emissions; however, this may have been due to the overall low abundance of the compounds.

Chemical compounds frequently occurring in poultry house samples

Compound Family	Compounds Identified	Odorants Identified[1]	Odorant Descriptor[2]
Aromatics	Benzene Toluene Xylene (*o*-,*p*-) Styrene Acetophenone Benzaladehyde Phenol		
Alcohols	1-butanol 2-ethyl-1-hexanol 2-butoxy-ethanol	2-butoxy-ethanol	Solvent
Aldehydes	3-methyl-butanal Nonanal		
Ketones	2-butanone 2,3-butanedione 3-hydroxy-2-butanone Cyclohexanone	2,3-butanedione Cyclohexanone	Rancid, butter Solvent, chemical
Carboxylic Acids	Butanoic acid Acetic (Ethanoic) acid		
Sulphur	Dimethyl Sulphide		

[1]*The third column identifies which of the chemicals are also odorants; and*
[2] *provides a descriptor of the odorant*

Implications

The effect of variability and unpredictability of odour emission rates on industry planning and expansion

Odour emission rates were found to be variable but similar to the range of odour emission rate values reported in literature. Consequently, prediction of odour emission rates by consultants for dispersion modelling purposes is unlikely to significantly change.

Volatile organic compounds in odour

The identification and quantification of non-methane volatile organic compounds (NMVOCs) combined with the prioritisation of odorant species within these NMVOCs will support the development of tailored odour mitigation strategies. By focussing on nuisance odorants, researchers can develop odour abatement and mitigation strategies, with the aim of improving the management of poultry shed emissions.

Modelling of dust impacts

Further modelling work (e.g. dispersion modelling) will be required to use the database of dust emission rates obtained in this project to determine dust concentrations downstream of tunnel-ventilated poultry sheds as a function of distance. This information is necessary to determine dust concentrations in the areas surrounding poultry farms.

Recommendations

Measuring odour emissions at layer farms

- Odour sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because layer odour emissions are variable.
- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, fan details (dimension, manufacturer), mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, manure conditions (time since last cleaning, quantity, moisture content), lighting conditions and drinker type.
  - Flock information—bird age, bird numbers, bird live weight, total live weight, number of birds initially placed in the shed, bird breed.
- Daily fan activity should be understood/surveyed for that time of the flock and year. Odour sampling should be scheduled so that samples are collected at a representative ventilation rate or at several ventilation rates over the normal daily range. Efforts must be made to collect odour samples during the night when odour emission rates are lowest (and is also the time when atmospheric conditions are most stable and poor odour dispersion is likely).
- Fan activity **should not** be manually over-ridden, and stabilisation time should be allowed, if possible, following each change in fan activity. If fan activity changes during the collection of samples, it is recommended to record the changes in fan activity and calculate a time-weighted-averaged ventilation rate rather than manually lock-in the number of active fans. By locking in fans, abnormal shed conditions may be produced—especially in terms of temperature, bird activity and odour production/release mechanisms—that will result in the measurement of unrealistic odour emissions.
- Odour samples should be collected and analysed in duplicate to improve olfactometry confidence and accuracy. Samples should be analysed as soon as possible following collection.
- Efforts should be made not to disturb the chickens prior to, or during, sample collection as additional activity may increase the release of odour.

Measuring dust emissions at layer farms

- Dust sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because poultry dust emissions are highly variable.
- Continuous, size-resolved dust measurements are necessary for studies that attempt to characterise the mechanisms of dust generation in intensive poultry sheds.
- For studies that integrate dust measurements over extended periods of time (e.g. gravimetric filter analysis), it should be recognized that large variations in dust concentrations are likely to occur during the sample collection period.
- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, manure conditions (time since last cleaning, quantity, moisture content), lighting conditions, drinker type.

- Flock information—bird age, bird numbers, bird live weight, total live weight, number of birds initially placed in the shed, bird breed.

Sampling methodology

Dilution olfactometry analysis

- Odour samples should only be analysed at reputable, experienced olfactometry labs that can demonstrate compliance with AS/NZS 4323.3:2001. Olfactometry labs need to report the accuracy and precision of their laboratory, ensuring that $A \leq 0.217$ and $r \leq 0.477$.
- Odour samples are unstable and must be treated carefully. Odour samples should be analysed as soon as possible (preferably within 12 hours, maximum 24 hours) by:
  - choosing an olfactometry laboratory in close proximity to the test site;
  - transporting the samples to the olfactometry laboratory as soon as possible; and
  - pre-arranging delivery time to ensure the samples are analysed as soon as possible after delivery to the olfactometer.
- Where more than one olfactometry laboratory is used for a single trial, it is recommended that a test be performed to ensure similarity in results from all laboratories.

Ventilation rate measurement

- It is recommended that ventilation rate be estimated using manufacturer's performance data (from certified testing laboratories), number of active fans and shed static pressure. This method is recommended assuming that the following conditions are met:
  - fans are clean, well maintained and in good working order;
  - fan details are recorded including fan diameter, number of blades, blade pitch, blade material, motor manufacturer, motor power, voltage, pulley sizes, grills, shutter description, presence of a cone. A tachometer should be used to check rotational speed;
  - static pressure is recorded at the time of ventilation measurement (changes to fan activity and fluctuating wind conditions will affect the reading);
  - all active fan activity, including duty fans, is recorded; and
  - on-farm airspeed measurement inside the shed or across each fan face should ideally be made as a cross reference to the manufacturer's published fan performance data.
- Estimating ventilation rate using manufacturer's performance data is recommended because:
  - ventilation rate can be consistently estimated regardless of duty and tunnel fan activity as well as tunnel ventilation status (internal shed airspeed measurement is unsuitable when mini-vents are open or when duty fans are active);
  - manufacturer's fan performance data is usually obtained using standardised methods and certified laboratories (but you need to check which standard was used);
  - airspeed measurements across each active fan are time consuming and prone to errors due to fluctuating winds as well as non-uniform and turbulent air flow;
  - airspeed measurements across each fan face will be affected by the presence of grills and back-draft shutters; and
  - within the poultry shed environment, it is difficult to achieve the conditions required by AS4323.1:1995 when measuring airspeed inside the shed or across each fan face.
- When airspeed measurements are to be taken inside the shed or across each fan face, measurements must be made according to AS4323.1:1995.
- External fan measurements should be undertaken with caution because of turbulent fan air flow.
- External fan measurements should be avoided during gusty wind conditions.
- If measuring air velocity across the fan face, measurements need to be made at each active fan.
- Internal shed velocity measurements should not be undertaken while mini-vents or duty fans are active.

- Internal shed velocity measurements should be avoided during low levels of ventilation (when airspeed is minimal).
- Be aware that errors of 10–20% are likely regardless of the method used.

Using the odour emission rate data

- Odour emission rates vary diurnally, seasonally, throughout the life of the flock and will be different at different farms depending on management and infrastructure. **Calculation of daily average, flock average or constant odour emission rate is not appropriate—**unless for a specific purpose.
- Odour emission rates should be presented in terms of total OER (ou/s), OER per 1000 birds placed (ou/s/1000 birds placed) or OER per kg total live weight (ou/s/kg).

Using the dust emission rate data

- Dust emission rates vary diurnally, seasonally, throughout the life of the flock and will be different at different farms depending on management and infrastructure. Selection of a daily average, flock average or constant dust emission rate should be made with extreme care: considerable variation is likely to occur around the chosen average.
- If possible, dust emission rates should be presented in terms of total emission rate (ER) (e.g. mg or particles/s), ER per 1000 birds placed (e.g. mg or particles/s/1000 birds placed) and ER per kg total live weight (e.g. mg or particles/s/kg). This will enable easier comparison between different studies.

Future research

- Additional studies to quantify 'typical' odour emission rates from layer farms need to be made at multiple farms and on multiple days. Odour measurements must represent the full spread of 'normal' daily odour emissions, which will require odour samples to be collected at night.
- Future research should be directed at quantifying the specific biological, physical and chemical mechanisms that regulate the formation, release and transport of odour and dust within the shed and in the exhaust airstream.
- The effect of manure moisture content on odour formation is still largely unknown—including the delay between wetting and increased emission; changes to microbial community composition and activity; and changes to the manure physical odour release properties due to caking. Further research must investigate these relationships between manure moisture content and odour generation. Techniques to accurately measure the full moisture profile of the manure and to quantify the amount of caking will be required to achieve this.
- Future research should be directed at quantifying the conservation/degradation of odorants following emission from the shed (and before reaching receptors). Changes in odorant composition beyond the farm boundary may change the perception of odour by receptors.
- Investigation of the composition and NMVOC emissions from the manure material from layer houses would provide useful information relating to the principal odorant emissions.
- Moreover, the investigation of the microbial communities within the manure material and their corresponding NMVOC emissions would enable the elucidation of the species responsible for the key nuisance odorant formation.

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1 Introduction

In Australia, the egg industry annually produces approximately 2.6 billion eggs (from 13 million laying hens). The majority of birds are raised intensively in sheds that are either naturally ventilated, or mechanically ventilated with an automated climate control system to provide the chickens with an optimal growing environment. Aerial emissions from these sheds, including odour and dust, are a normal part of production.

Odour and dust emitted from layer (egg production) sheds have the potential to impact on nearby residences, communities and environment. Impacts due to odour, in particular, and dust have been recognised as a cause of concern. Consequently, proposals for new and expanding farms undergo rigorous assessments to ensure that emissions will not cause unnecessary impacts.

Impact assessments require accurate data for these emissions to enable modelling and prediction of impacts. Much of the published odour emission data for poultry production is not relevant due to recent changes in poultry production systems (new building designs, new management practices, new breeds and new diets) and advances in emission measurement practices including new olfactometry and dust measurement standards, improved sample collection methods and advancements in alternative measurement technologies such as electronic sensing arrays and gas chromatography-mass spectrometry-olfactometry GC-MS-O.

This study has been undertaken to build a database of odour, dust and volatile organic compound (VOC) emissions for modern intensive layer farming. This data will improve estimation of emissions, improve prediction of impacts and support improved planning for new layer farms. Increased knowledge regarding the chemical composition of poultry odour (through measuring VOCs) is considered critical for identifying the origins of the odour and developing mitigation techniques.

Similarly, detailed knowledge of dust emissions from modern, layer sheds is required to ensure sufficient separation distances to minimise impacts. Research regarding particle concentrations and emissions from poultry sheds has previously been conducted in the USA, Europe and Australia. There is still a requirement for high quality data to describe the dependence of particle emission rates from Australian tunnel-ventilated poultry sheds on a range of factors including, season, bird weight, bird age and manure management. The dust component of this research program will attempt to fill this gap in knowledge.

1.1 Research objectives

The focus of this research project was quantifying and improving understanding of the emission of odour, dust and VOCs from tunnel ventilated layer sheds in Australia—achieved by:

- Development of a database of odour and dust emissions from tunnel ventilated layer sheds—evaluating the influence of geographic location, season, management and environment on emission rates;
- Identification of specific poultry shed non-methane volatile organic compounds and odorants.

Researchers from the Department of Employment, Economic Development and Innovation; Queensland University of Technology; Department of Primary Industries, Victoria; and University of New South Wales collaborated to provide the skills and equipment necessary to undertake this project.

2 Background

Measurement and research of dust and odour emissions from intensive livestock farming has been undertaken internationally for many years. In Australia, impacts by odour emissions, in particular, have been the major driver for emissions research. In other countries, dust and ammonia are the primary interest for researchers due to environmental and health concerns. There is a large quantity of published information about poultry production systems; odour and dust generation in poultry production; odour and dust emissions from poultry; and odour and dust measurement methods. This chapter provides an introduction to these topics.

2.1 The egg production system

There are three main types of farms involved at different stages of the production cycle; breeder farms, pullet rearing farms and layer farms (where mature hens are housed and eggs are harvested for sale). Layer farms can be categorised into different production systems according to shed design and management; including free range, barn and caged systems. Where hens are housed in cages, shed designs vary with different cage, ventilation and manure management systems. The cages can be arranged in a single storey where the manure accumulates on the floor for a number of months before removal, or the cages can be multi-storey with belts under each storey for manure collection and removal on a regular basis. Caged sheds may be naturally or mechanically ventilated. In this investigation, only the caged production system with tunnel ventilation and manure belts were considered; as this is currently the preferred design for intensive egg production.

Most eggs produced in Australia are laid by hens that produce brown eggs. The three breeds most commonly found at Australian commercial farms are Hy-Line Brown (http://www.hyline.com.au/brown.htm), ISA Brown (http://www.hendrix-genetics.com/layerbreeding/template.php?sectionId=609) and Hisex Brown (http://www.hendrix-genetics.com/layerbreeding/template.php?sectionId=616). Specific and detailed management, nutrition and performance information can be accessed via their websites.

2.1.1.1 Production cycle

Breeder farms produce fertile eggs which are taken to a hatchery. The day old female chicks are either grown at pullet rearing farms and then sold to layer farms as point-of-lay pullets, or sold directly to layer farms where they are grown to maturity. The point-of-lay pullets are introduced to the tunnel ventilated production sheds just before they begin laying eggs; around the age of 18 weeks. Once introduced to the cage system, the hens may remain there till the age of 80 weeks.

During the time a hen is housed in the production shed, there is a 97% chance that she will lay an egg every day (combined data from Hy-Line, ISA and Hisex). A hen will generally grow from 1.5 kg to 2.0 kg over the 62 weeks of egg production, with an average feed conversion of 2.09 kg of feed consumed for every 1 kg of egg produced.

The temperature requirements for layers remains constant throughout their adult life, with optimum shed temperature being around 23 °C.

At the end of the productive life of the hens, they are removed from the cages and processed.

2.1.1.2 Shed design and ventilation system

Mechanically ventilated layer sheds are designed to provide the birds with a comfortable environment and many design features of modern sheds contribute to the control of odour and dust emissions. These sheds are typically 100–120 m long, 8–15 m wide and 5 m tall, which provide sufficient space for 30,000–50,000 hens. There will usually be 3–8 sheds on a typical farm.

The shed floor is concrete, with insulated roof and wall panelling.

The ventilation system installed into layer sheds is very complex and comprises a central control unit, ventilation fans, mini-vent inlets, tunnel ventilation inlets, and evaporative cool pads. Large diameter axial fans (1220–1397 mm diameter) provide the majority of the ventilation. The configuration of

layer sheds may be similar to broiler sheds in which the fans are installed on the narrow end of the shed with the cool pads at the opposite end. However, the sheds can also be designed so that the fans are located near the centre of the long side of the shed with the cool pads located on both narrow walls. In these sheds, instead of air being drawn down the length of the shed, air is drawn towards the centre of the shed and out each long wall.

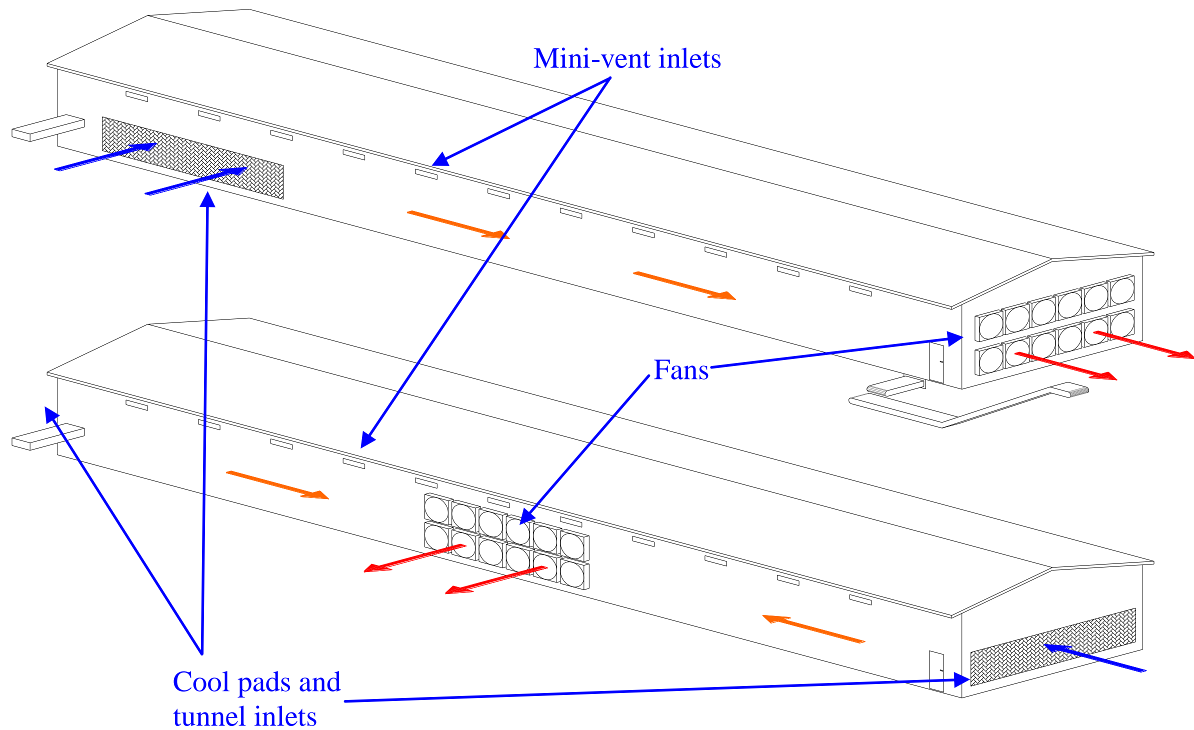

Figure 1: Components of layer shed ventilation systems (Top – single direction tunnel air flow, bottom – bi-directional tunnel air flow)

Maximum ventilation rate is approximately 106–131 m³/s. All fans are fitted with back-draft shutters to prevent fresh air entering the shed through the inactive fans. Mini-vent outlets are installed at equal intervals along the walls on each side of the shed. Air is drawn through these vents when low levels of ventilation are required and drawn through the tunnel inlets when more ventilation is required. When the weather is hot and maximum cooling is required, water runs down over the cool pads, creating a cooling effect as the air passes through them.

Hens are housed in a series of banks of cages. Depending on the physical size of the shed, the banks of cages can range from 5–8 storeys high, with 3–5 banks positioned along the width of the shed. A plastic belt runs under each storey to catch all manure deposited by the hens. The floor of the cages is sloped in order for the eggs to run out onto the egg belt positioned at the front of the cages. A feed channel also runs in front of the cages, with two nipple drinkers positioned along the centre of each cage. The feed and egg belt systems are automated.

2.1.1.3 Manure management

Manure belts are installed under each tier of cages, and are manually operated once or twice each week to remove the manure from the shed (see Figure 2). As the belt turns, the manure is cleaned by a scraper which ensures all manure is removed. The manure falls onto another conveyor belt built into the shed floor. The manure is either conveyed to a storage shed for later removal offsite, or loaded directly into a truck and stockpiled elsewhere.

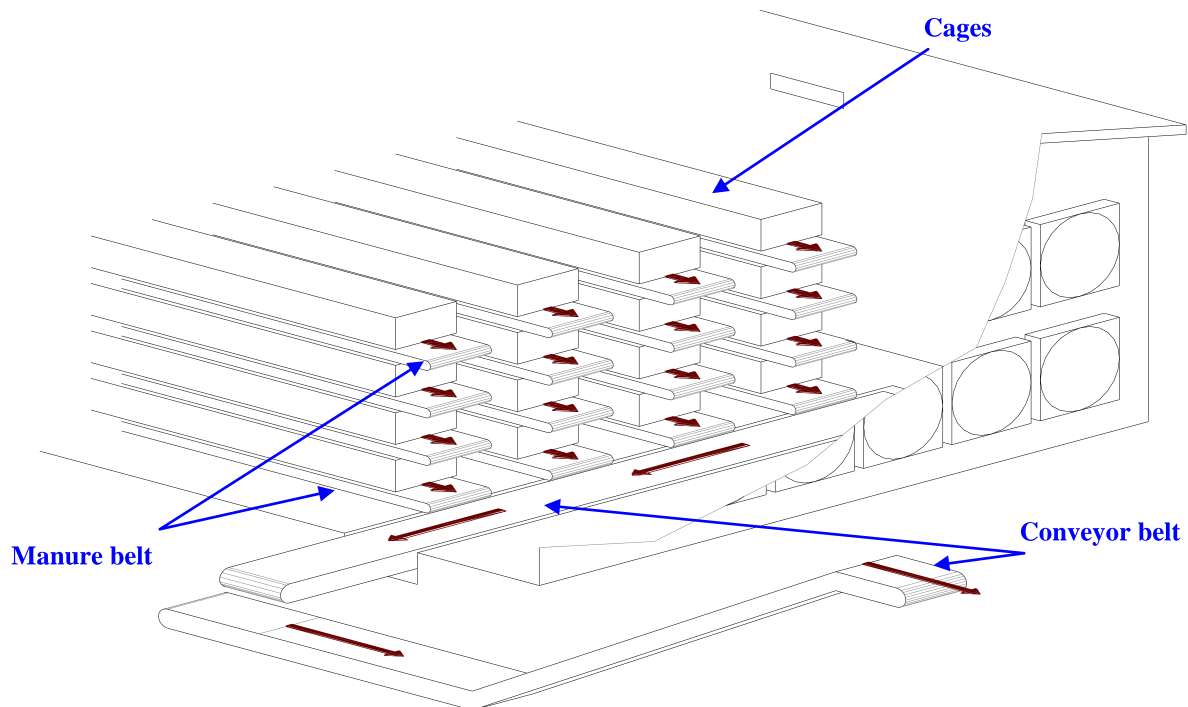

Figure 2: Manure belt system to remove manure from layer shed

A manure drying system is sometimes installed into sheds to improve management of manure moisture during the time it is in the shed, rather than relying on shed ventilation. Manure drying systems direct additional airflow onto the manure belts. This air may be conditioned to improve its moisture holding capacity and is either drawn from the external environment (used mostly during warmer conditions) or recirculated within the shed (used mostly during cooler conditions).

In addition to regularly removing manure from the shed, settled dust and feathers are regularly swept or blown out of the shed. This action may result in a temporary increase in particulate emissions.

2.1.2 Summary of the egg production system

- Only caged layer production sheds with tunnel ventilation and manure belts were considered in this investigation.
- Shed design, husbandry practices and farm management are likely to have an effect on odour and dust emissions.
- Laying hen manure is removed once or twice weekly using an automated belt system.
- Mechanical ventilation is used to create a comfortable environment (especially temperature) for the chickens, and is also used to remove excessive moisture, which is a contributing factor to odour generation. Mechanically ventilated poultry sheds use several modes of ventilation—mini-vent ventilation; tunnel ventilation; and tunnel ventilation with evaporative cooling—which change the in-shed aerodynamics and are therefore likely to influence odour and dust emissions and the measurement of these emissions.

2.2 Odour

2.2.1 Introduction

Odour is a property that gives a substance a characteristic smell. Odorous molecules are formed by combinations of volatile organic compounds (VOCs) (O'Neill and Phillips, 1992), which are often referred to as odorants. When these molecules are inhaled, they are received by the olfactory organ (an area in the upper nasal passage known as the olfactory epithelium) where they react with proteins and activate receptors that send signals to the brain. Within the olfactory region, there are millions of receptor cells that are classed according to their sensitivity to specific odorants (Standards Australia/Standards New Zealand, 2001). There are 100 to 300 classes of olfactory receptor, each of which is more or less sensitive to different odorants, enabling an extremely large number of combinations of odours that can be identified. It is believed that humans can differentiate about 10,000 different odour characters (Standards Australia/Standards New Zealand, 2001).

Odours can be described using four dimensions: detectability (or odour threshold); intensity; quality (or character) and hedonic tone (Standards Australia/Standards New Zealand, 2001). Detectability is the minimum chemical concentration of an odour at which a percentage of the population can sense the odour. Detectability is measured using a dynamic olfactometer (described in more detail in section 2.2.2) and is used to calculate odour concentration. Intensity is the perceived strength of the odour sensation. Intensity allows an odour to be rated as weak or strong. Intensity has a logarithmic relationship to odour concentration (small changes in odour concentration near the detection threshold make a relatively large difference in odour intensity, however at higher concentrations, larger concentration change is required to make small change in odour intensity). Odour quality is a descriptive dimension allowing odours to be described as, for example, floral, rancid, faecal, cardboard, wet socks or any combination of these and many other descriptors. The final dimension of odour description is hedonic tone, which rates the relative pleasantness or unpleasantness of an odour.

Odour is a mixture of many different compounds known as odorants (American Society of Agricultural and Biological Engineers, 2007; Cai *et al.*, 2006; Lacey *et al.*, 2004; O'Neill and Phillips, 1992). Table 1 shows a list of some of the compounds that are produced by the microbial decomposition of manure. It is important to understand these compounds in order to understand how odours are produced. The presence of these compounds in odour will be dependent on the chemistry of the manure and activity of the microbial communities.

Table 1: Compounds resulting from manure decomposition (American Society of Agricultural and Biological Engineers, 2007)

Volatile fatty acids	Mercaptans	Sulphides
Acetic	Methylmercaptan	Hydrogen sulphide
Propionic	Ethylmercaptan	Dimethylsulphide
Butyric	Propylmercaptan	Diethylsulphide
Isobutyric		Disulphides
Isovaleric	Esters	
Ammonia and Amines	Alcohols	Nitrogen Heterocyclyes
Ammonia		Indole
Methylamine	Phenols and Cresols	Skatole
Ethylamine	Phenol	
Dimethylamine	p-Ethyl-phenol	Aldehydes
Trimethylamine	p-Cresol	
Diethylamine		

2.2.2 Biochemical origins of odour

During periods of extended storage and/or treatment within animal housing, in anaerobic ponds, or on feedlot pads, complex wastes are transformed through chemical and microbiological processes to simpler molecules. Three basic steps are involved with the anaerobic digestion of waste materials:

1. Hydrolysis

2. Fermentation (or acidogenesis) and
3. Methanogenesis.

Hydrolysis is the conversion of complex or particulate materials to soluble compounds which can then be further degraded to simple monomeric substances suitable as substrates by bacteria. This process is particularly relevant to undigested feed materials. Extra-cellular enzymes are primarily responsible for this process (Hill and Cobb, 1993).

Fermentation involves degradation of sugars, amino acids and fatty acids to produce acetate, propionate, butyrate and hydrogen and carbon dioxide. Butyrate and propionate are generally fermented further to hydrogen, carbon dioxide and acetate.

During methanogenesis, the products of fermentation (i.e. acetate, carbon dioxide and hydrogen) are utilised to produce methane. A range of non-methanogenic organisms (acidogens) are responsible for hydrolysis and fermentation. These include *Clostridium spp*, *Bifidobacterium spp*, *Staphylococcus* and *E. coli*. Many other groups are also involved in the process through production of various enzymes.

The micro-organisms responsible for the production of methane (methanogens) are strict obligate anaerobes, many of which are similar to organisms isolated from the stomachs of ruminants or from sediments in lakes and rivers (Tchobanoglous *et al.*, 2003). A limited number of these organisms utilise acetate to produce methane directly, while the majority oxidise hydrogen with carbon dioxide to produce methane.

The methanogens and acidogens form a syntrophic relationship in which the methanogens convert fermentation end products to methane and CO_2. The ability of the methanogens to utilise the hydrogen formed during fermentation is critical—if the hydrogen produced is not utilised sufficiently quickly, propionate and butyrate fermentation slows and these volatile fatty acids (and other intermediate metabolic products) accumulate, reducing pH, further slowing the fermentation process. In addition to compromising waste treatment, accumulation of compounds such as butyrate and propionate increases odour emissions. In extreme circumstances, anaerobic treatment fails.

The biochemical basis for microbial odorant production was comprehensively reviewed by Hobbs *et al.* (2004), Mackie *et al.* (1998) and Spoelstra (1980). These reviews indicated:

- A close association between undigested protein and low molecular weight branched volatile fatty acids, some reduced sulphides and indoles and phenols. Specific amino acids were identified as precursors of key odorants (Hobbs *et al.*, 2004; Mackie *et al.*, 1998);
- Complex carbohydrates in particular were associated with volatile fatty acids (mainly C_2 to C_4, with smaller amounts of C_5 to C_7 acids) (Zhu *et al.*, 1999);
- Deamination of organic N-containing materials present in large amounts in excreta to form ammonia and volatile fatty acids (Mackie *et al.*, 1998);
- Other relationships clearly link specific precursor compounds with odorants, including tyrosine (phenol, 4-ethylphenol), tryptophan (indole and skatole) and phenylalanine (phenyl acetate, phenyl propionate and benzoic acid) (Mackie *et al.*, 1998);
- Assimilatory microbial processes result in formation of cysteine and methionine, breakdown of which releases hydrogen sulphide and mercaptans;
- For dissimilatory processes, sulphate is used as a terminal electron acceptor and is reduced to hydrogen sulphide directly (Mackie *et al.*, 1998);
- A range of microbes were identified which were able to produce a series of volatile amines (Spoelstra, 1980).

2.2.3 Key odorous chemicals

The nature of emissions described generically as odour has been extensively researched, particularly for piggery operations. O'Neill and Phillips (1992) identified 168 separate odorous compounds in pig wastes. More recently, Schiffman *et al.* (2001) identified 331 different volatile organic compounds

were responsible for odour from piggery operations. 203 of these chemicals were identified in air samples while 167 were recovered from anaerobic pond liquor samples.

Hobbs *et al.* (1997) proposed that odorants could be separated into four distinct chemical classes – reduced sulphur compounds, volatile fatty acids (VFAs), phenols and nitrogen heterocycles (indoles). Zahn *et al.* (2001a; 1997; 2001b) and Bicudo *et al.* (2002) have extensively researched odour emissions from piggery wastes. They were able to identify a strong correlation between odour intensity and the concentration of 19 volatile organic compounds present in ambient air samples (Zahn *et al.*, 2001a). They refined these findings to show that measurement of the concentration of nine specific odorants enabled an adequate correlation between odorant concentration and odour intensity ($r^2 = 87.6$). The odorants that could be related to odour intensity included VFAs, phenols and indole.

Less intensive research has been undertaken on the specific identity of odorants in cattle wastes. Bicudo *et al.* (2003) measured ambient concentrations of hydrogen sulphide downwind and from the surface of manure storage basins over a 30 day period. Odour samples were collected from the surface of the manure storage lagoon on two occasions. It was confirmed that manure storages were major sources of odour. Emission rates varied between 7 and 10 OU/s.

Baek *et al.* (2003) measured ammonia and hydrogen sulphide (H_2S) fluxes from the pen surface of Texas feedlots. They identified a weak relationship between ammonia emission rates and the pad temperature. They were unable to identify a similar relationship for H_2S following instrument failure. They were able however to identify increases in emission rates of both chemicals following rainfall events. Diurnal variation in emission rates of both variables were also observed, with emission rates peaking at about 13:00 for ammonia and at about 15:00 for H_2S. No odour samples were collected during this study.

More recently, measurement of ambient air concentrations of ammonia, VFAs and other odorants downwind of feedlots in Alberta, Canada were reported (McGinn *et al.*, 2003). A positive correlation between ambient ammonia concentrations and odour intensity was observed. It was concluded that ammonia was an indicator or surrogate for odour and the odour plume, rather than being a major odorant. Concentrations of VFAs measured adjacent to feedlot pens were thought to be high enough to create the potential for nuisance odour conditions. It was also shown that the concentrations of odorants fluctuated throughout the day. It was not clear whether these fluctuations arose from diurnal trends or were in response to atmospheric conditions and dispersion. The authors identified that odour emissions might be managed in part by stocking pens at appropriate rates.

In their investigations of emissions of odorants from 29 piggeries, Zahn *et al.* (2001b) highlighted the metabolic processes involved in the formation of volatile sulphur-containing compounds. The formation of complex sulphur-containing odorants (e.g. thiols and mercaptans) requires energy expenditure, whereas sulphate reduction to hydrogen sulphide yields energy, making it energetically more favourable. Assimilatory processes are also more sensitive to environmental factors, including piggery and waste management systems. It should therefore be anticipated that emissions of volatile sulphur would be dominated by hydrogen sulphide, with other compounds present in lower concentrations.

Independent investigations have confirmed that only a small fraction of the total number of volatile and odorous compounds emitted from manure storages have ever been detected and quantified downwind of the source:

- Zahn *et al.* (2001a) demonstrated that downwind concentrations of hydrogen sulphide were much lower than the detection threshold. This finding in part explained the previously observed lack of correlation between hydrogen sulphide concentrations and odour concentrations (Hobbs *et al.*, 1999; Hobbs *et al.*, 1998);
- Wright *et al.* (2005) did not detect hydrogen sulphide, dimethyl disulphide or methyl mercaptan in samples collected downwind of a major piggery. They identified 4-methylphenol, 2'-aminoacetophenone, *iso*-valeric acid and 4-ethylphenol as the most significant odorants;

- Trabue *et al.* (2008a) demonstrated that hydrogen sulphide was the dominant sulphur-containing odorant at piggeries, while methanethiol was the principal sulphur-containing odorant in poultry litter (discussed further below);
- Trabue *et al.* (2008b) showed that butanoic acid, 4-methylphenol, 4-ethylphenol, indole and 3-methylindole were the dominant odorants associated with piggery buildings, while butanoic acid, 3-methylbutanoic acid and 4-methylphenol were characteristic of poultry odour.

The work of Trabue *et al.* (2008a) demonstrated that sulphur-containing compounds probably do contribute to intensive livestock odour. They showed that very stringent sampling and storage techniques were required to reduce the impact of moisture on sample composition. By passing the sample through calcium chloride traps, thereby greatly reducing the humidity within the sample, it was possible to detect sulphur-containing compounds within the sample container up to 48 hours after sample collection.

A key outcome of these investigations was identification of the dominant chemical classes responsible for the characteristic livestock odour detected downwind of these operations. Many of the chemicals were polar, water soluble compounds with relatively high boiling points and low vapour pressures.

These chemicals also have low odour detection thresholds. Zahn *et al.* (1997) tabled odour detection thresholds for some of the odorants associated with livestock production, together with what they termed "transport efficiency". The latter term refers to the relative concentrations observed at the source of the odour and 100 m downwind. Selected examples from Zahn *et al.* (1997) are summarised in Table 2.

Table 2: Transport efficiencies and odour detection thresholds for selected odorants

Compound	Transfer efficiency (%)[a]	Odour threshold (µg/m³)[a]
Acetic acid	100	100
Propanoic acid	53	25
Butan-2-ol	89	908
Butanoic acid	76	2.5
Pentanoic acid	37	2.6
Decanol	198	[b]
Hexanoic acid	44	198
Benzyl alcohol	44	[b]
Phenol	12	226
4-Methylphenol	11	8.3

Notes: [a] (Zahn *et al.*, 1997); [b] Odour threshold not available.

More recently, Trabue *et al.* (2008a) tabulated selected chemical properties of a number of odorants. Some of these are reproduced in Table 3.

Table 3: Physical and organoleptic properties of selected odorants (de Vos *et al.*, 1990; Trabue *et al.*, 2008a)

Odorant	Molecular weight (g/mol)[a]	Boiling point (°C)[a]	Vapour pressure (kPa)[a]	Odour threshold (μg/m³)[a]
Acetic acid	60	118	2.33[b]	356.3
Propanoic acid	74	140	1.75[b]	108.3
2-methylpropanoic acid	88	155	1.68[b]	70.8
Butanoic acid	88	164	0.15[b]	14.1
3-methylbutanoic acid	102	177	0.07[b]	10.3
Pentanoic acid	102	186	0.04[b]	20.2
4-methylpentanoic acid	116	199	0.0008[b]	22.9
Hexanoic acid	116	205	0.006[b]	60.3
Heptanoic acid	130	222	0.0004[b]	147.4
Phenol	94	182	0.065[b]	424.9
4-methylphenol	108	22	0.017[b]	8.3
4-ethylphenol	122	218	0.029[b]	6.3
4-propylphenol	136	232	0.012[b]	
Indole	117	254	0.002[b]	0.15
3-methylindole	130	266	0.002[c]	3.0
Hydrogen sulphide	34	-59.6	1840[c]	24.9
Carbonyl sulphide	60	-50	1010[c]	135.4
Carbon disulphide	76	115	53[c]	296.4
Methanethiol	48	6.8	205[c]	2.2
Dimethyl sulphide	62	38	45[c]	5.6
Dimethyl disulphide	94	117	3[c]	47.5
Dimethyl trisulphide	126	41	0.8[c]	8.8

Notes: [a](Trabue et al., 2008a); [b] determined at 27 °C; [c] determined at 20 °C

2.2.4 Odour measurement

Odour has traditionally been assessed using olfactometry, which determines odour detection thresholds using a combination of gas dilution equipment and trained human assessors. In Australia, odour is assessed according to the Australian olfactometry Standard: AS/NZS 4323.3:2001 *Stationary source emissions - Part 3: Determination of odour concentration by dynamic olfactometry* (Standards Australia/Standards New Zealand, 2001). Odour concentration and emission rates determined using other olfactometry standards may not be comparable to values determined using the Australian olfactometry standard (Department of Environmental Protection, 2002).

While still regarded as the only standardised method for odour measurement, olfactometry is limited when trying to determine the origins and constitution of a particular odour or trying to measure odour in real-time or over an extended period. To achieve these outcomes, technologies such as a non-specific electronic sensor array (sometimes referred to as an artificial olfaction system (AOS) or electronic nose (Sohn *et al.*, 2007; Sohn *et al.*, 2008)) or gas chromatograph-mass spectrometer-olfactometer (GC-MS-O) are required. The GC-MS-O can be used to identify the chemicals that make up an odour, primarily VOCs, which provides opportunities to identify odour sources and develop specific mitigation techniques. Electronic sensor arrays attempt to replicate the human olfactory response by using multiple sensors, each sensitive to a range of different compounds. By identifying patterns in the sensor responses (magnitude of individual responses and relative difference between sensors), and calibrating these responses against olfactometry measurement (to AS/NZS 4323.3:2001), these sensor arrays are capable of continuously measuring odour concentration in real time with reasonable accuracy.

2.2.4.1 Olfactometry standards

The determination of odour is dependent on the method by which it is analysed and calculated. When reviewing existing odour concentration and emission data, it is critical to understand the method by which the odour samples were analysed, as quite different values will be obtained for the same odour by using alternate methods. Current olfactometry standards also have defined accuracy and precision criteria, which must be met in order for the olfactometry laboratory to be compliant. Similar levels of accuracy and precision were not required by older olfactometry standards.

The Australian/New Zealand Standard AS/NZS 4323.3:2001, is the current standard for dynamic olfactometry. Prior to the development of this standard, several standards had been used in Australia including the Dutch method for olfactometry (NVN2820), the Victorian B2 method and a draft European CEN method, (now EN 13725, *Determination of odour concentration by dynamic olfactometry*).

The Australian and European standards are very similar (with the AS/NZS 4323.3:2001 based on a draft version of the CEN method) and consequently odours measured according to these standards will have comparable odour concentrations and the olfactometers must meet specific accuracy and precision criteria (van Harreveld *et al.*, 2008). The NVN2820 standard defined the odour unit differently to the current Australian Standard, and consequently the odour values measured according to NVN2820 are not directly comparable to odour measurements made according to AS/NZS 4323.3:2001. According to Robertson *et al.* (2002), NVN2820 odour units need to be divided by a factor of approximately two for them to be comparable with the European (and consequently the Australian) olfactometry standards. Demetriou and Bardsley (cited by The Department of Environmental Protection (2002)) found that NVN2820 produced results approximately twice as high as the Victorian B2 method. Consequently, odour measurements made according to the Victorian B2 should be roughly comparable to AS/NZS 4323.3:2001, however comparative testing between the two methods has shown that greater variability occurred when odours were determined with the B2 method (Bardsley, 2002).

2.2.4.2 Odour decay in sampling bags

Odour is a mixture of volatile chemical compounds. Once collected and stored in a sampling vessel, the volatile compounds comprising odour may change over time. To overcome this issue, the olfactometry standard recommends that samples be collected and stored in polytetrafluoroethylene (PTFE, Teflon®), polyvinylfluoride (PVF, Tedlar ®) or polyethylene terephthalate (PET, Nalophan®, Melinex®) bags.

Van Harreveld (2003) investigated the stability of tobacco odour in sample drums and found that odour concentration changed considerably over a 30 hour period. Consequently, it was recommended to undertake olfactometry analysis within 12 hours of collection. Van Harreveld also recommended the use of PET bags over PVF bags for sample storage.

Pollock and Friebel (2002) undertook a similar investigation as van Harreveld, but used broiler odour. In this investigation, the authors found that odour concentration changed as sample storage time increased, but the changes were dependent on the time of year that the samples were collected, odour laboratory and sample bag. While no firm conclusions were drawn, it was recommended that samples be collected using PVF bags.

Parker *et al.* (2003) and Koziel *et al.* (2004) tested a selection of sample bag materials for suitability to store odour samples. The authors found that Tedlar bags had a background odour due to release of phenol and acetic acid from the bag material, which was sufficient to affect the measurement of odour concentration following 4–24 hours of sample storage. Koziel *et al.* (2004) reported that PET bags (Nalophan® or Melinex®) provided the best sample recovery of a range of VOCs and semi-VOCs and had no residual interfering compounds that would influence the measurement of odour concentration.

Agreement between the van Harreveld and Koziel *et al.* studies supports the use of PET bags to for the collection of odour samples; however, lack of agreement with the Pollock and Friebel study highlights the need for further research into the stability of odour samples in sample drums for different sources of odour.

2.2.5 Odour and dust relationship

The air in poultry sheds contains a mixture of odorous gases and dust particles. It has been demonstrated that dust particles collected in animal houses carry odorant molecules (Cai *et al.*, 2006; Das *et al.*, 2004; Heber *et al.*, 1988; Lee and Zhang, 2008; Oehrl *et al.*, 2001; Williams, 1989). It is believed that odorants can absorb onto dust particles and produce a much stronger and longer-lasting olfactory response than an equivalent volume of odorous air (Hammond *et al.*, 1981). It has been suggested that odour emissions from animal houses may be reduced by removing dust from the air (Briggs, 2004; Carey *et al.*, 2004; Cargill, 2001; Lacey *et al.*, 2004; McGahan *et al.*, 2002; Ministry of Agriculture and Food, 1999). There is, however, some doubt that removing dust will significantly reduce the detection threshold for odour (Williams, 1989). To date, attempts to correlate dust removal and subsequent odour reduction using olfactometry have been unable to demonstrate any correlation between dust removal and subsequent odour reduction (Simons, 2006; Williams, 1989).

The relationship between dust and odour is very complicated. While it has been confirmed that dust particles carry odorant molecules—adsorbed onto the surface or absorbed into the particle—it is unclear how much of the odour bound to the dust contributes to the total perceived odour emitted from a poultry shed. Olfactometry is unlikely to be an appropriate instrument for resolving this question because the olfactometer instrument almost certainly filters out dust particles—only allowing measurement of odours in the gas phase only, not odours associated with particulates. In addition, Williams (1989) found that dust concentration in odour sample bags quickly diminished due to static attraction of dust to the plastic bag material. It was proposed that particles were electrostatically attracted to the plastic bag material.

A methodology is yet to be developed that will enable the contribution of odour laden dust to the total perceived odour to be quantified.

2.2.6 Layer shed odour emissions

Odour generation and emission is a normal part of layer hen rearing. Odours are produced in poultry operations primarily from the microbial decomposition of faeces (Jiang and Sands, 2000); some odours may also be emitted from the birds themselves (Lacey *et al.*, 2004). Odours generated in the shed are emitted from the shed through the ventilation fans. The generation and emission of odour is presumed to be regulated by numerous factors relating to: manure properties and moisture content; temperature; ventilation; dust levels; the birds (age, live weight, activity, health status, stocking density); and weather. The diagram in Figure 3 attempts to demonstrate the complex and intertwined relationship between these factors and odour emission rate. These factors often interact with each other, and some are dependent on each other. These interactions and dependencies make it very difficult to identify the causes of increased odour emission. The generation of odour is usually influenced by factors that will affect microbial activity, while emission rates are affected by odour generation as well as the factors that influence the capture, mixing and transport of odour from the shed.

Odours have the potential to create a nuisance for nearby neighbours. The most effective ways to prevent odour or dust nuisance is to ensure adequate buffer distance between farms and receptors (McGahan and Tucker, 2003) and to prevent excessive odour generation through good management practices. The potential for odour nuisance to occur is investigated during odour impact assessments, and results in the calculation of separation distance between farms and neighbours. Separation distances are determined using either: approved guidelines for recommended distances (Department of Primary Industries - State Government of Victoria, 2009); simple formulas incorporating features of the farm, landscape and receptor (Environment Protection Authority South Australia, 2007); or estimating emission rates and using atmospheric dispersion modelling to predict impacts.

Accurately measuring representative odour emission rates from layer farms can be challenging. Previous attempts to measure emission rates have demonstrated the influence of the factors shown in Figure 3 on odour emission rates. When reviewing published odour emission rate data, these factors require careful consideration.

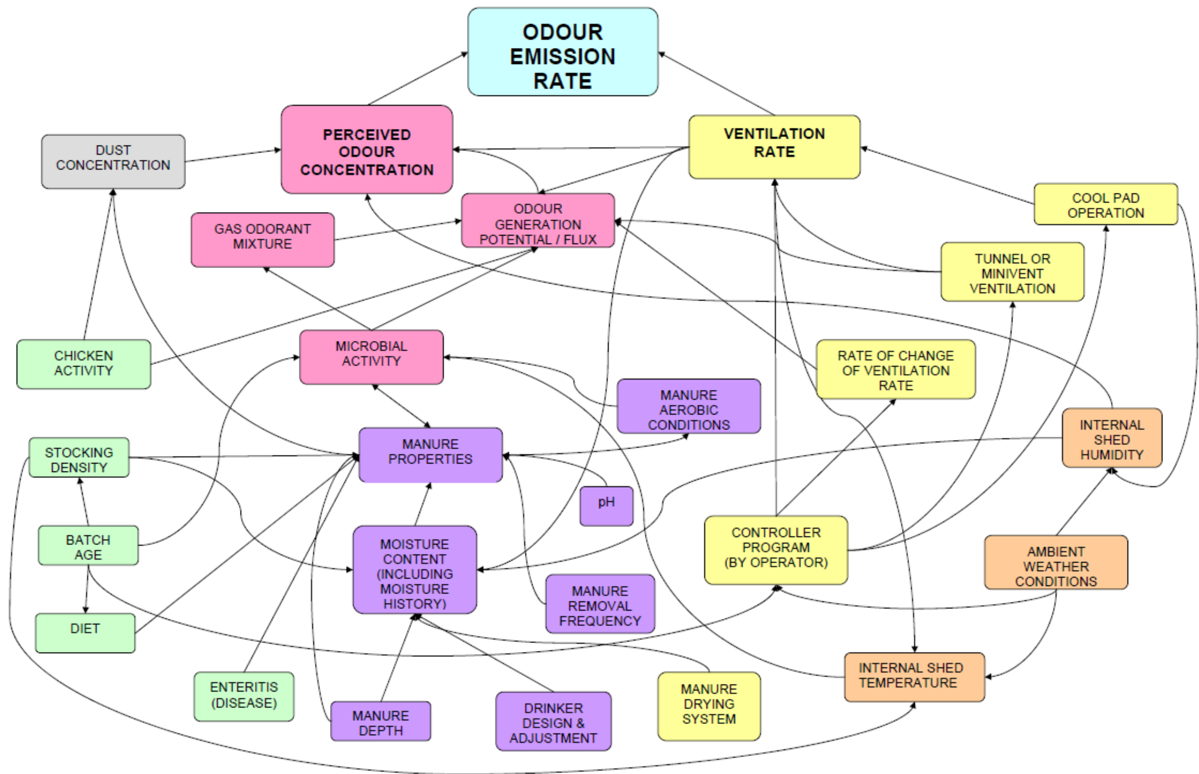

Figure 3: Diagram illustrating the interaction between layer farm conditions, environmental conditions and odour emission rate

2.2.6.1 Factors influencing odour generation at layer farms

There are several properties of manure that will influence odour generation including chemical composition, quantity, aeration, pH and moisture content. Conditions that favour microbial activity are likely to increase odour emissions. *(Note: some of the following information is based on research involving meat chickens and it is assumed that the underlying mechanisms are equally applicable to layer production.)*

Chemical composition of the manure will be influenced by bird diet and stage of decomposition. Gates (cited in McGahan *et al.* (2002)) found that reducing crude protein levels in the diet reduced pH, moisture content and ammonia in the poultry litter, resulting in a reduction of ammonia gas production. Reduction in ammonia may not necessarily equate to a reduction in odour emissions (Briggs, 2004); however, it demonstrates that diet will influence microbial activity and the subsequent generation of gasses during the litter decomposition process. Turan *et al.* (2007; 2009) measured VOC emissions during broiler litter composting and found that VOC emission rates changed significantly over time, as the decomposition of the litter progressed. Consequently, odour emission rates would be expected to change as manure decomposes.

A review by Cargill (2001) found that live weight density was a cause of increased odour production in poultry houses. Jiang and Sands (2000) also reported that as bird age increased, manure accumulation also increased leading to greater odour generation. Increased live weight density (by increasing bird numbers or bird age) will increase manure deposition leading to increased nutrient and moisture levels and, presumably, increased odour emissions.

Jiang and Sands (2000) reported that odour generation will take place under aerobic and anaerobic conditions. Aerobic decomposition will occur in the presence of oxygen and anaerobic decomposition is more likely to occur in very wet manure where oxygen supply is reduced. Anaerobic decomposition is often attributed to the production of highly odorous (and unpleasant) sulphurous compounds, but

odorous compounds containing nitrogen will still be produced during aerobic biodegradation (McGahan *et al.*, 2002).

Jiang and Sands (cited in McGahan *et al.* (2002)) reported that pH was an important factor for odour emissions because it influenced the formation of anaerobic conditions; microbial activity; and chemistry within the manure. Moore *et al.* (1995), Moore *et al.* (2006) and Gates (cited in McGahan et al. (2002)) reported changes in ammonia emissions with changes in litter pH.

Possible influence of manure moisture content on odour emissions

Manure moisture content is presumed to be one of the most critical factors affecting odour production in poultry sheds (Carey *et al.*, 2004; Clarkson and Misselbrook, 1991; Jiang and Sands, 2000; McGahan *et al.*, 2002; Scottish Environment Protection Agency (SEPA), 2008). Moisture content is expected to affect odour generation because water acts as a catalyst in the processes of odour generation, transfer and transport (Jiang and Sands, 2000); will increase microbial activity (Carey *et al.*, 2004); and high levels of moisture content will tend to increase anaerobic bacterial activity (McGahan *et al.*, 2002). Excessive manure moisture can occur for a variety of reasons including high ambient humidity; poor ventilation system design or operation; high stocking density; flock health problems; leaking drinkers; leaking shed or from poor management of evaporative coolers and fogging systems.

There is likely to be a time delay between wetting of the manure and the increase of odour emission. Lunney and Lott (1995) and Watts *et al.* (1994) reported that feedlot odour emissions peaked approximately one to five days following rainfall. The delay occurs because the microbial community requires time to increase activity, and it takes time for the manure to become anaerobic. In addition, Klieve *et al.* (1995) found that this microbial activity in the wet feedlot manure pad forms a polymer-like sheet on the surface which may reduce evaporation and prolong the manure drying process—which also prolongs the production of odours. Whilst there are differences between the feedlot and layer shed situations, odours in both cases are generated through microbial activity. It is therefore likely that there may be a delay between the wetting of poultry manure, and an increase in odour emission. This delay is likely to vary according to temperature, moisture content, microbial activity and manure composition.

The surface of the manure stored on the belts may dry and form a crust due to normal shed ventilation or the use of a manure drying system. This crusting restrict the transfer of odorants into the air stream (the mechanism of restricting gas exchange is presumed to be similar to the explanation provided by Simons (2006) for wet, caked broiler litter).

Further research is required to completely understand the relationship between manure moisture content and odour generation in poultry farms.

Possible influence of ventilation on odour emissions

Ventilation influences odour generation, transfer and transport.

Layer shed ventilation is primarily controlled to remove heat from the shed, maintaining a comfortable and healthy environment for the birds. As the internal temperature of the shed increases, more fans are activated to remove the heat and maintain the temperature.

Effective ventilation management will contribute to controlling manure moisture content, reducing anaerobic microbial activity and generation of odours (McGahan *et al.*, 2002).

Ventilation is a critical factor influencing odour emissions from poultry sheds. Odour emission rate (OER) is the product of odour concentration (OC) and ventilation rate. Assuming that odour concentration remains constant, changes to ventilation rate will result in proportional changes to odour emission rate.

Ventilation will also influence the transfer or release of odorants from emitting surfaces to the air (manure, building surfaces and the birds). These processes are controlled by physical air movement as well as the concentration of odorants in the air. Hudson *et al.* (2009) and Hudson and Ayoko (2009) demonstrated that emission of odour from area sources—such as poultry manure—are strongly related

to wind speed. Therefore, the mass transfer of odorants from the manure is very likely to be primarily controlled by advection processes (driven by wind speed).

Jiang and Sands (2000) explained the relationship between ventilation rate and the emission of odour from the broiler litter using boundary layer theory (as defined by Schilichting and Gersten (2000); and Incropera *et al.* (2007)). Boundary layer theory explains the mass transfer process at the solid/air and liquid/air interface and may be used to relate the rate of evaporation of an odorant to its diffusion characteristics, temperature, air velocity across the surface and the geometric dimensions of the source. Using this theory, the airborne chemical concentration for each odorant is a function of the air velocity across the surface of manure and birds.

The concentration of odorants in the shed may also be an important factor for regulating the transfer of compounds from the manure surface into the gas phase, especially when in-shed airspeed is negligible. Gholson *et al.* (1989) and Gholson *et al.* (1991) (in describing the operation of a flux chamber) reported that as the gas phase concentration increases, the liquid/gas phase equilibrium will be affected and the transfer of compounds from the surface to the air will be reduced. The transfer rate will be different for every odorant compound, depending on its Henry's Law constant. This equilibrium theory can be equally applied to poultry sheds where variable ventilation rates will result in different gas concentration within the shed, and presumably the emission rate of odorants from the manure and other surfaces into the air will also vary.

The mechanisms described by Hudson *et al.* (2009) and Hudson and Ayoko (2009), and to a lesser extent Jiang and Sands (2000) and Gholson *et al.* (1989), provide a overall description of the transfer of odorants from emitting surfaces into the airstream, and the importance of ventilation to the odour transfer process. In plain English, odorants produced by microbial degradation (Jiang and Sands, 2000) are adsorbed onto manure surfaces (and moisture contained within the manure), building surfaces and the birds. When the concentration of odorants in the shed is high and airspeed low, the transfer of these odorants into the air will reduce until equilibrium is achieved. When the odorant concentration is reduced or airspeed increases, presumably by introducing fresh air into the shed with increased ventilation, the transfer rate of odorants into the airstream will increase (possibly only temporarily) until a new equilibrium is achieved. Considering the highly variable ventilation activity in poultry houses, it would be expected that the transfer of odorants into the air, in-shed odour concentration, and subsequent emission of odour from the shed will be highly variable.

2.2.6.2 Previously reported layer shed odour emission rates

Accurately measured odour emission rates are essential for providing realistic predictions of impacts using odour dispersion modelling. Only limited odour emission rate data has been published for intensive poultry production. Much of the previously measured odour emission rate data has unfortunately lost relevance due to changes in olfactometry standards and recent changes to poultry farm design and management.

There is very limited available data regarding odour emission rates from layer farms. Pollock and Anderson (2004) reported emission rates of 80–85 $ou/s_{1000\ birds}$ for mechanically ventilated, multi-tiered layer sheds located near Melbourne.

Enviroscan Industrial and Marine Surveys (2005) measured odour emissions from a tunnel ventilated, manure belt layer shed and found that odour emission rates ranged from 48–70 $ou/s_{1000\ birds}$.

Hayes *et al.* (2006) measured odour emissions from two mechanically ventilated layer sheds in Ireland; one with manure belts and the other using a deep litter manure system. In the shed with manure belts, odour emission rates ranged from 260–620 $ou/s_{1000\ birds}$ (mean odour emission rate was 470 $ou/s_{1000\ birds}$). In the shed with deep litter, emission rates ranged from 1060–1470 $ou/s_{1000\ birds}$ (mean odour emission rate was 1350 $ou/s_{1000\ birds}$). These authors found that their odour emission rate measurements were similar to previously reported values of 80–520 $ou/s_{1000\ birds}$ for manure belt layer sheds; and 200–760 $ou/s_{1000\ birds}$ for litter floor sheds (citing Ogink and Groot Koerkamp; and Martinec *et al.*). Olfactometry was presumably conducted according to the 2003 CEN standard *'Determination of Odour Concentration by Dynamic Olfactometry – EN13725'*, which is comparable to Australian/New Zealand Standard for olfactometry (AS/NZS 4323.3:2001).

2.2.7 Summary of background information on odour

Odour in general

- Odour is extremely complex—measured in four dimensions: odour threshold, intensity, character and hedonic tone—and is usually comprised of numerous odorous compounds (odorants).
- Odour threshold is measured using olfactometry according to the Australian/New Zealand Standard AS/NZS 4323.3:2001. Gas chromatography–mass spectrometry–olfactometry (GC–MS/O) is a complementary instrumental method that can provide additional detail about odour.
- Odour measurement standards have changed over time so prior odour measurement may not be comparable to current values.
- Odorous gas mixtures are not stable, which can change the nature of an odour and also necessitates timely analysis of odour samples.
- Relationships between odour and dust have been hypothesised, but the effect of dust on perceived odour had not been quantified.

Layer farm odours

- Odour is produced by the microbial degradation of organic matter (manure).
- Factors influencing odour generation include: chemical composition; manure loading; temperature; manure moisture; aerobic/anaerobic status; manure physical properties and disturbance (influence odour release); ventilation and shed aerodynamics; and many other factors. **It is therefore likely that odour emission rates will vary between farms, diurnally, throughout the life of the flock and throughout the year.**
- Manure moisture has been reported as a contributing factor to excessive odour generation and further research needs to be conducted to quantify the delay between wetting of the manure and increased formation of odour.

Continued over the page.

Summary of layer farm odours continued from previous page

- Previously reported layer shed odour emission rates have not included essential supporting data—odour emission rate data MUST be supported by information including shed dimensions, ventilation system description (including maximum possible ventilation rate), bird age, bird numbers, bird weights, ventilation rate, ambient temperature, odour concentration and preferably manure conditions. This information must be recorded at the time of each odour sample and is required to put the odour emission rates in context with weather conditions and production factors.

Previously published layer odour shed emission rates

- Previously reported layer shed odour emission rates ranged from 48–620 $OU/s_{1000\ birds}$ for sheds with manure belts and 200–1470 $ou/s_{1000\ birds}$ for sheds with deep litter floors—based on very limited data.

2.3 Dust

Dust emissions from layer sheds occur due to two general processes. Firstly, animal activity or the movement of air causes the mechanical breakdown of mineral and organic material and entrainment of this material into the air. Secondly gaseous emissions, such as nitrous oxide (N_2O) and ammonia (NH_3), may be converted to the particle phase under the right conditions, adding to the total dust emissions from a poultry shed.

This section will highlight these possible health and environmental impacts and introduce some concepts used to characterise and measure particulates.

2.3.1 Measurement of particle concentrations—mass or number?

Particles suspended in the air can vary in size by many decades from ~10^{-9} m up to ~10^{-3} m. Particles in different size ranges will contribute to different health and environmental impacts. For this reason dust measurements are generally classified by particle size. Airborne particles that are less than ~100 µm in diameter are collectively referred to as total suspended particulate matter (TSP). Particles that are less than 10 µm are defined as PM_{10}. The PM_{10} size fraction is usually grouped into two size categories: coarse particles, with a diameter from 2.5–10 µm, and fine particles, with a diameter of up to 2.5 µm ($PM_{2.5}$). Even smaller size fractions are becoming increasingly important and many studies now report the concentration of particles smaller than 1 µm (PM_1), or even particles smaller than 0.1 µm (ultra-fine particles). The definitions of particle size ranges can vary between countries and particle sampling devices. For example, many European studies of dust emissions from intensive livestock production refer to the 'inhalable' and 'respirable' particles, referring to the particles less than 30 µm and 5 µm, respectively. Although the size ranges do not match exactly, inhalable particles can be compared to TSP.

Particle or dust levels in the air are generally measured as either a mass concentration or number concentration. Mass concentration refers to the mass of PM per unit volume of air and is commonly expressed in units of mg/m^3. Number concentration refers to the number of particles per unit volume of air and is commonly expressed in units of $particles/m^3$. Which concentration metric is used in a given environment will primarily depend on the size distribution of particles in that environment. For example if a given sample of air contains a large number of ultra-fine particles (diameter < 0.1 µm) and only a very small number of larger, coarse particles (diameter > 2.5 µm) then the total mass of the particles will still be dominated by the small number of larger particles. To 'see' the ultra-fine particles it would be more appropriate to measure their number concentration. Traditionally, allowable particle concentration levels expressed in air quality guidelines have been expressed as mass concentrations. However with a consensus emerging that fine and ultra-fine particles are more damaging to human health than coarse particles, it is becoming more common to measure particle number concentrations. In many situations it is most desirable to measure both particle mass and number concentration.

2.3.2 Potential health effects of dust

Dust particles can act as a reservoir for bacteria, other disease carrying agents and noxious gasses, such as ammonia. Dust concentrations in intensive animal production sheds can build up to levels that are high enough to adversely affect animal health and productivity. However, there is doubt regarding the specific levels required to induce these adverse effects. In tunnel ventilated poultry sheds, the ventilation rate of air through a tunnel shed is highly variable, with higher rates of ventilation in warm summer weather; and the opportunity for high dust concentrations will also be variable depending on ventilation rate, manure conditions and bird activity. These factors can contribute to amount of dust being emitted from the exhausts of tunnel ventilated sheds into the ambient air.

The effects of dust on health and the environment are dependent on the size of the particles; categorised in terms of TSP, PM_{10} and $PM_{2.5}$. TSP is typically associated with adverse aesthetic effects rather than human health effects because these particles tend to settle out on surfaces causing soiling and discolouration. Larger particles (> 10 µm) are usually trapped in the human nose and throat before being swallowed. PM_{10} particles (particles < 10 µm) travel further down the human airway into the lungs and they are associated with increases in respiratory illnesses such as asthma, bronchitis and emphysema. Particles in the PM_{10} size fraction have been associated with increases in the daily prevalence of respiratory symptoms, hospital admissions and mortality (Pope *et al.*, 1995). The people most sensitive to these conditions include the elderly, children and those with pre-existing heart problems or respiratory diseases. Particulates can accumulate in the lungs after repeated, long-term exposure causing respiratory distress and other health problems. Specific health effects of dust will depend on composition, concentration and the presence of other pollutants.

Particles in the $PM_{2.5}$ size fraction have been associated with health effects similar to those of PM_{10} (Pope and Dockery, 2006). When inhaled, the weak gravitational force felt by these small particles enables them to inside the lungs to be deposited in the alveoli.

Particle composition, especially the presence of microbial organisms, can influence the health effects of particulate matter. For example, both harmless and pathogenic bacteria are known to be emitted in the exhaust of tunnel ventilated broiler sheds (Blackall *et al.*, 2008). This study concluded that the pathogenic bacteria were emitted rarely from broiler sheds and concentrations were too low to cause any significant human health effects.

2.3.3 Dust concentrations and emissions from poultry farms

Dust emissions from poultry farms have been studied for at least three decades. However, ongoing research is required due to recent advances in large-scale poultry production and increasing recognition of the potential health effects of particulate matter. In addition, the mechanisms behind dust generation from poultry sheds are not yet completely understood. These mechanisms need to be elucidated in order to design strategies for reducing dust emissions.

Poultry dust consists of feathers, dander, faeces, and crystalline urine. This suggests that dust is generated from birds, manure in poultry sheds. Many interdependent factors can affect poultry dust levels including:

- bird age;
- ventilation rate;
- shed design (ventilation system, manure removal system, feeding system);
- in-shed microenvironment (temperature, relative humidity, light levels);
- season;
- time of day;
- stocking density;
- cleaning practices;
- bird handling;
- residual dust levels;
- moisture content of manure and feed; and
- nearby dust sources.

Much of the research concerning dust concentrations and emissions from poultry sheds has been conducted in the USA or Europe, although some has also been conducted in Australia. The results from studies have been tabulated in Appendix 1; and a combined summary of the particulate concentrations and emission rates is provided in Table 4. It should be noted that variations between dust concentrations and emissions measured in different studies could be due to all of the factors listed above, as well as differences in instrumentation and methodologies. As can be seen in the table, studies have been conducted at layer sheds with natural and mechanical ventilation systems. In-shed TSP concentrations range from 0.38–12 mg/m³. PM_{10} or PM_5 concentrations are generally lower and vary from 0.1–0.9 mg/m³. Recently, a number of studies have measured the concentrations of the smaller particle size fractions ($PM_{2.5}$ and PM_1) in recognition of the greater health effects of these particles. Results from these studies are included in Appendix 1.

Dust emission rate from a poultry shed is calculated by multiplying dust concentration by ventilation rate. Emission rates are generally expressed in units of mass of PM emitted per unit time. Many studies also calculate the emission rate per 500 kg live weight in order to compare rates between different sheds. Table 4 displays emission rates per 500 kg live weight in square brackets.

Table 4: Summary of reported particulate concentrations and emission rates for layers

	Ventilation type	Country	Concentration (mg/m³)				Emission rate, ER (mg/s) [ER per 500kg live weight (mg/s/500kg)]			
			TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$
Layer	Various#	Australia	0.38–4.45		0.094–0.863		3.4–98 [0.024–0.7]		0.88–18.8 [0.006-0.13]	
Layer	Mechanical	Overseas	1.0–5.5	0.44–0.59	0.15–0.55	0.031–0.047	40.3–130 [0.28–0.9]	3.3–32.4 [0.05–0.23]	3.6–11.5 [0.03–0.08]	1.3–7.6 [0.01–0.05]
Layer	Various#	Overseas	0.86–12		0.1-0.8		25.5–123.2 [0.18–0.86]	0.4–4.3 [0.003–0.03]	3.1–23.8 [0.02–0.17]	
Not specified	Various#	Overseas	0.02–81.3		0.01–7.73					

#measurements collected from both mechanically and naturally ventilated buildings; or ventilation type not specified
*not reported

Bull (2008) performed a study to measure ambient PM_{10} concentrations near a broiler farm in the United Kingdom that housed approximately 250,000 birds. A monitoring station was established and PM_{10} concentration was measured for approximately 7 months over a 12 month period. This study found that daily average PM_{10} concentrations were typically about half of the ambient objective value (50 µg, 24-hour average) and whilst there were a few occasions when the daily average exceeded the objective, occurrence was much less often than what was allowable. The authors concluded that ambient PM_{10} concentrations around broiler farms (at typical receptor distances) are unlikely to exceed the daily mean ambient air quality objective for PM_{10}. It is assumed that the same conclusions are applicable to layer farms.

2.3.4 Summary of background information on dust

Dust in general

- Airborne dust originates from suspension of mineral and organic materials or by the conversion of gases.
- Dust concentration is measured in terms of mass and/or number of particles.
- Dust is categorised according to particle size ranges (especially TSP, $PM_{2.5}$, and PM_{10}).
- Dust has been linked to health and environmental effects.

Poultry farm dust

- Dust originates from the manure, feed and the birds (skin and feathers particles).
- Factors influencing dust generation include: physical manure properties and moisture content; bird activity; stage of production (number and size of birds); contribution of feathers; shed design; shed cleaning and management; ventilation; and feed properties.
- Studies have shown that air surrounding poultry farms is unlikely to be significantly affected by dust emitted from the sheds, and ambient air quality objectives for particulates are unlikely to be exceeded.

Layer dust emission rates

- Previously measured dust concentrations have been highly variable, and categorised according to the various size categories. Refer to Table 4 for summary of reported values.

2.4 Non-methane volatile organic compounds

Odour has traditionally been assessed using olfactometry, which determines odour detection thresholds using a combination of gas dilution equipment and trained human assessors. While still regarded as the only standardised method for odour measurement, olfactometry is limited when trying to determine the origins and constitution of a particular odour or trying to measure odour in real-time or over an extended period. To achieve these outcomes, technologies such as a non-specific electronic sensor array and/or gas chromatograph-mass spectrometer-olfactometer (GC-MS/O) have more recently been applied to the assessment of emissions from intensive livestock operations. GC-MS/O allows the chemical compounds to be separated and identified, with simultaneous identification and characterisation of the odorants according to their perceived intensity and character.

2.4.1 Gas Chromatography analysis of odours

Emissions from different intensive livestock operations comprise different chemicals and odorants. Wright *et al.* (2005), Hobbs *et al.* (2004) and Jacobson *et al.* (2006) studied the different compounds that were identified in the emissions for different intensive livestock facilities; the comparisons drawn by Hobbs *et al.* (2004) serve to highlight these differences. As different compounds have different odour detection thresholds, some species that gave an olfactometry response did not always correspond to a response from any other detector, conversely some compounds with large detector responses gave little or no olfactometry response. Speculation is often made as to the identity of the compound based upon it odour characteristic and associated compounds within the matrix.

Studies have been undertaken that focus on particular intensive livestock operations. Studies carried out by Kai & Schäfer (2004), Blunden *et al.* (2005) and Bulliner *et al.* (2006) focussed upon the chemical analysis of emissions from swine facilities, while Rabaud *et al.* (2003) analysed the emissions from dairy facilities. Work specifically relating to intensive poultry production has primarily focused on the general quantification of the odour emissions and not the identification of the odorants; Hayes *et al.* (2006) and Pescatore *et al.* (2005) reported ammonia emissions from intensive poultry facilities, whilst Williams (1989) reported the relationship between dust and odour from poultry houses.

Table 5 lists recent publications that focussed on the investigation of odorant emissions from intensive livestock operations.

Table 5: Chemicals reported in different intensive livestock operation emissions

Reference	Chemical Observations
Zahn *et al.* (2001a)	Reported that downwind concentrations of hydrogen sulphide were much lower than the detection threshold.
Wright *et al.* (2005)	Identified 4-methylphenol, 2-aminoacetophenone, iso-valeric acid and 4-ethylphenol as major odorants in piggery emissions.
Trabue *et al.* (2008a)	Reported hydrogen sulphide was the dominant sulphur-containing odorant at piggeries, while methanethiol was the principal sulphur-containing odorant in poultry litter.
Trabue *et al.* (2008b)	Reported butanoic acid, 4-methylphenol, 4-ethylphenol, indole and 3-methylindole were the dominant odorants associated with piggery buildings, while butanoic acid, 3-methylbutanoic acid and 4-methylphenol were characteristic of poultry odour.

2.4.2 **Olfactory-GC-MS analysis of odorants**

Olfactory-GC (GC/O) and GC-MS/O is a well established techniques in other science fields, such as food aromas and taste and odours in drinking water, but has had limited application to environmental odour analysis. In drinking water, taste and odour (or off-flavours) monitoring using GC-MS/O analysis has been successfully applied to the characterisation of common earthy and musty off-flavours compounds such as geosmin and MIB (2-Methylisoborneol) (Hochereau and Bruchet, 2004). These studies have enabled the development of odour wheels for drinking water olfactory assessment (Figure 4) to relate odour descriptors to the chemical composition of odorants (Suffet *et al.*, 1999). Odour wheels are used by water operators and in customer complaint evaluations to determine a cause-and-effect relationship between the water quality and operational failures.

Figure 4: Taste and odour wheel for off-flavours in drinking water (Suffet *et al.*, 1999) showing the highlighted relationship between earthy – musty odours and compounds, geosmin and MIB (2-Methylisoborneol)

GC-MS/O applications for the assessment of odorous emissions has mainly focused on the simple qualitative characterisation of odours from various agricultural operations such as swine finishing, dairy processing facilities and poultry sheds (Kai and Schäfer, 2004; Kleeberg *et al.*, 2005; Parcsi and Stuetz, 2007; Wright *et al.*, 2005). Results have shown that emissions are composed of several hundred compounds; some species give intense olfactory responses whereas others give little or no

olfactometry response (Figure 5). Additionally, speculation is often made as to the identity of the compound based upon its odour characteristic (Rosenfeld and Suffet, 2004). These studies have shown that GC-MS/O can be successfully used for the analysis and identification of odorous compounds but that more attention needs to directed toward understand the formation of key odorants and their fate in the environment.

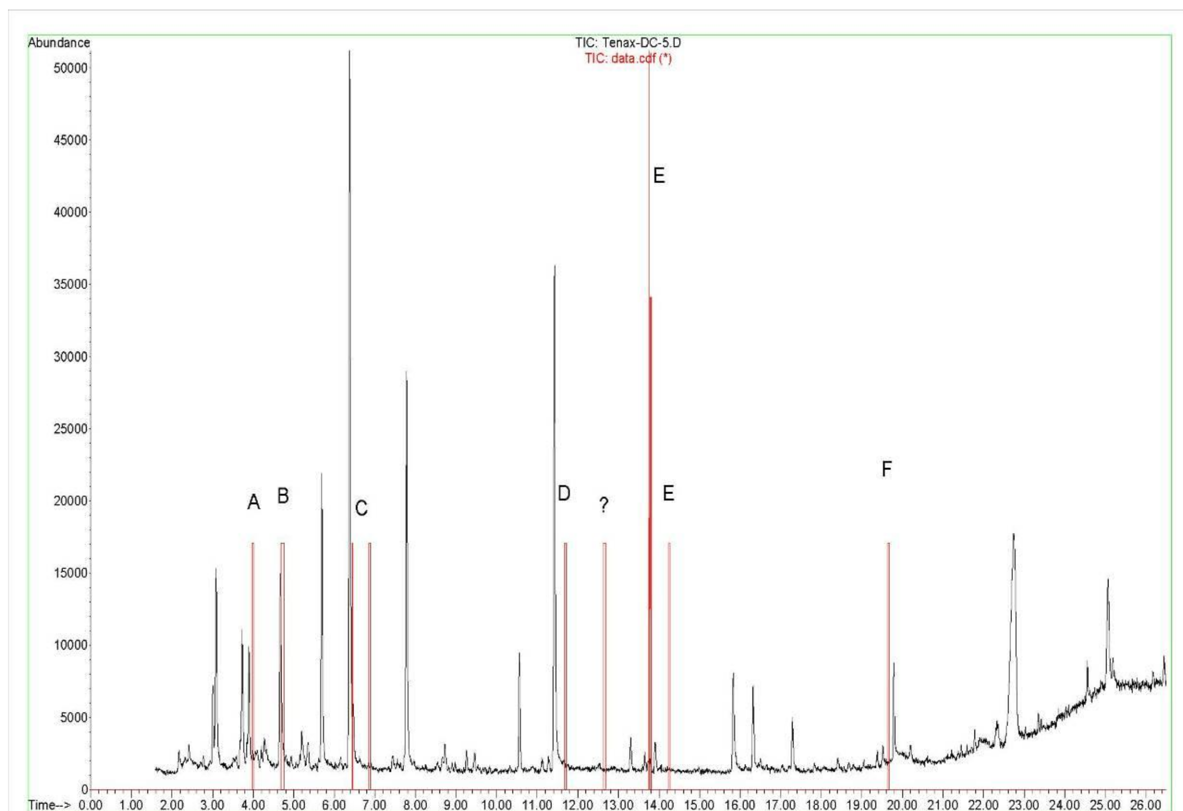

Figure 5: GC-MS/O analysis showing total ion chromatogram and odour chromatogram (A – 2-butanone, B – 2, 3-butanedione, C – dimethyl disulphide D – 3-hydroxy-2-butanone E – dimethyl trisulphide and F – acetophenone) (Parcsi and Stuetz, 2007)

2.4.3 Summary of background information on odorant analysis

Odorants in General

- Odours are composed of a mixture of odorous and non-odorous compounds
- Odorants identified in intensive livestock operations include 2-butanone, indole, skatole and various sulphides

Poultry house odorants

- Existing work focuses on quantification of chemicals from poultry houses
- Limited information is available on dominant odorants within the emissions from poultry facilities
- Factors influencing NMVOC emissions include: physical manure properties; manure moisture content; bird activity; stage of production (number and size of birds); shed cleaning and management; ventilation; and feed properties.

Poultry VOC emission rates

- Previously published material investigated the emissions of ammonia and hydrogen sulphide with little focus on the chemical composition of VOCs with odorant impact.

2.5 Application of background information to this project

- Odours and dust will need to be sampled and measured to the AS/NZS 4323 series of standards.
- For layer sheds, regular sampling will be required to relate the effect of manure removal on odour and dust emissions.
- Emission measurements will need to be repeated as ventilation requirements change throughout the day.
- Ventilation mode (i.e. tunnel or mini-vent) and rate will need to be recorded while measuring dust and odour emissions.
- Manure moisture content will need to be measured throughout the life of the flock due to the reported effect of this on odour and dust emissions. Moisture content in the days leading up to odour measurements will need to be understood because of delayed effects—increased moisture leads to growth of microbial community (2-5 days) and potentially increased odour generation.
- Dust will need to be measured in terms of mass and particle number and categorised in terms of particle size ranges (i.e. $PM_{2.5}$ and PM_{10}).

3 Methodology

Odour, dust and non-methane volatile organic compound (NMVOC) samples were collected from layer sheds in Queensland and Victoria during summer and winter. Sampling was scheduled around the operation of the manure belts in the sheds. It had been assumed that as this is the time when there would be the greatest variability in odour emissions.

3.1 Farm selection

3.1.1 Farm selection criteria

Farms were selected for monitoring based on the following criteria:

- Shed age 0–5 years
- Shed tunnel ventilated (not a naturally ventilated shed retrofitted with tunnel ventilation fans)
- Terrain at tunnel ventilation fan end to be flat enough for attachment of a sample duct
- Management practices to be industry standard – no additional procedures taken place that are not part of typical day-to-day management
- Within workable distance to the olfactometry laboratory for odour sample analysis

Farms were selected in Queensland and Victoria in an attempt to ensure that odour, dust and volatile organic compound (VOC) emission measurements would be representative of poultry sheds in sub-tropical and temperate regions.

3.1.2 Farm descriptions

The details of shed are summarised in Table 6.

Table 6: Description of farms

Farm Label	Location	Shed Dimensions (m)			Shed Description		Ventilation System		Bird Breed	Manure management	
		Width	Length	Wall height	Shed Walls	Shed Age	Tunnel fans	№		Type	Frequency
Farm D	Pittsworth, QLD	8.5	107	4.5	Solid walls	2005	Multifan 50” (1270 mm), 3 blade	11	Hyline Brown	Manure Belt	Every 3-4 days
Farm E	Pakenham, Vic	10	120	5.3	Solid walls	1995	Munters EM50, 1270 mm, 1.0hp	16	Hyline Brown	Manure Belt	Weekly

Note that emissions measurements from these layer farms formed part of a larger project. Farms A to C and F to M were broiler farms and have been reported separately.

3.2 Sample collection

Odour, dust and NMVOC samples were collected during summer and winter seasons. Samples were collected over a four to five day period to assess the change in odour emissions for different belt cleaning intervals.

Collection times for odour samples are constrained by the need to transport and analyse the samples as soon as possible following collection to ensure sample integrity. Samples needed to be delivered to the olfactometer in the early afternoon to ensure they would be analysed on the same day as collection. Consequently, samples needed to be collected in the morning.

Ventilation control systems were left in automatic mode. Samples were collected at different ventilation rates by waiting until the ventilation system automatically turned on more fans. The sampling team usually waited for the number of fans to stabilise before collecting samples. If the number of active fans changed during sample collection (usually only during VOC collection, because odour samples only required 10 minutes for collection), a time weighted average ventilation rate was recorded. At very low levels of ventilation, it was occasionally necessary to manually turn on the fan to which the sampling duct was attached. This was to ensure that the fan did not turn off mid-sample.

When this was done, care was taken to match the required ventilation rate at the time (usually required manually turning off one of the fans in the next stage of ventilation).

Odour, volatile organic compound and dust samples for the seasonal and location variability studies were collected from within a polyethylene duct (Figure 6). The duct was manufactured from a transparent polyethylene material (clear Gale Pacific Ltd. Solarweave®Q). The use of a duct enabled air samples to be collected at a sampling plane in accordance with AS 4323.1 (Standards Australia, 1995a). It was especially important for collecting dust samples isokinetically.

Ducts were custom designed for each farm to ensure that minimal backpressure was applied to the fan. For fans fitted with a cone, duct diameter was equal to the cone diameter. For fans without cones, the duct was made the same diameter as the fan impeller. Duct length and position of sampling plane was calculated according to AS 4323.1 (Standards Australia, 1995a). Duct length was equal to eleven duct diameters. Samples were drawn from a hole cut in the duct at a distance of eight duct diameters from the fan face.

The duct was suspended from the fan housing or shed wall with ten gauge wire, that was tensioned by a winch supported by a rigid frame (see Figure 6) attached to an adjustable frame to account for minor terrain variability. Sidewards movement of the duct was minimised with steel star pickets covered with polypropylene pipe.

Figure 6: Polyethylene duct attached to tunnel ventilation fan

3.2.1 Odour sample collection

Odour samples were collected according to AS/NZS 4323.3 (Standards Australia/Standards New Zealand, 2001).

Odour samples were drawn into rigid drums lined with a Melinex® bag (polyethylene terephthalate) using a vacuum pump as shown in Figure 7. All bags were preconditioned by filling with odorous air then emptied prior to the sample being collected. All components of the sampling train that were in contact with the poultry odour were manufactured from stainless steel or polytetrafluoroethylene (PTFE). The volume of sample collected in QLD was 120 L (Figure 7), and for Victoria was 15 L (Figure 8). The difference in sample volume was due to the use of different olfactometry laboratories.

All odour samples were collected simultaneously into two separate drums, effectively producing duplicate odour samples for individual analysis. Sampling in this manner is recommended by AS/NZS 4342.3 to reduce variability due to olfactometry analysis and improving confidence in the measured concentration.

All drums were filled over approximately ten minutes (sampling flow rate in QLD was approximately 20 L per minute and in Victoria was approximately 3.5 L per minute). Once filled, the drums were sealed and transported to the olfactometry laboratory for analysis. All samples were analysed within 8.5 hours of collection. Each bag was used once and discarded after analysis.

Figure 7: Odour sample collection from the polyethylene duct in Queensland

Figure 8: Odour sample collection from the polyethylene duct in Victoria

3.2.2 Dust sample collection

Previous research has shown that dust concentrations within a shed are generally higher than concentrations downstream from a shed (Visser *et al.*, 2006). The objective of this study was to measure representative emission rates. Therefore, dust measurements were conducted in the exhaust airstream, as it was exhausted from the building (within a temporary polyethylene duct designed in accordance with AS 4323.1:1995).

Dust samples were obtained by drawing air through an isokinetic sampling probe that was inserted into the polyethylene duct (see Figure 9). The isokinetic sampling probe obtained representative dust samples independently of the particle size distribution. The probe achieves this by ensuring that the air stream entering the particle samplers has a velocity (speed and direction) equal to that of the air in the gas stream just ahead of the sampling probe. This meant that all particles of all sizes entering the sampler have a collection efficiency of unity. The isokinetic probe was designed specifically for this project in accordance with AS 4323.2–1995 (Standards Australia, 1995b).

In this project, particle mass and number concentrations were measured to characterise poultry dust emissions (see section 2.3.1). In addition, particle number size distributions were also measured. PM_{10} and $PM_{2.5}$ particle mass concentrations were measured using two TSI model 8520 DustTraks (www.tsi.com) with appropriate inlets. Particle number concentrations and size distributions were measured with a TSI model 3320 Aerodynamic Particle Sizer (APS). The three particle sampling devices were operated in parallel downstream from the isokinetic sampling probe (see Figure 10).

Figure 9: Isokinetic sampler used for particulate measurement

Figure 10: Isokinetic sampler, APS and DustTraks

3.2.2.1 DustTrak: TSI model 8520

The DustTraks were used for on-line, real-time continuous measurements of particle mass emitted from the sheds. The DustTrak is a laser-scattering photometer and thus determines mass loading indirectly by light scattering. It measures particles in the size range from 0.1–10 µm within 0.001–100 mg/m³ load range. The unit is supplied with a cyclone and an inlet kit for measuring particle sizes corresponding to PM_{10}, $PM_{2.5}$ or $PM_{1.0}$ dust fractions.

In this study, two DustTraks sampled in parallel downstream from the isokinetic sampling probe. One DustTrak was fitted with a PM_{10} inlet and the other with a $PM_{2.5}$ inlet. This setup allowed simultaneous measurement of PM_{10} and $PM_{2.5}$ concentrations. Concentrations were logged every 30 seconds during sampling.

3.2.2.2 Aerodynamic particle sizer (APS): TSI model 3320

Particle size distributions and number concentrations were measured with the APS. The APS measures particle number size distribution continuously in real time over the size range 0.5–20 µm. The maximum concentration is 1000 particles/cm³ with maximum coincidence error of 6% at 10 µm. The instrument measures the time-of-flight of individual particles in an accelerating flow field. It achieves this by accelerating particles through a nozzle before they are detected by two broadly focused laser beams. A monotonic relationship between time-of-flight and particle aerodynamic diameter is then used to generate a particle size distribution in real time. Integration over the size distribution also yields a measurement of particle number concentration. In this project a particle size distribution was generated every 20 seconds.

3.2.3 Non-methane volatile organic compound sample collection

3.2.3.1 Introduction to methods—sorbent tubes

Non-methane volatile organic compounds (NMVOCs) were collected to identify and quantify the chemical components of the air exiting the poultry sheds. These can be collected by a variety of different methods; however, in consideration of logistical constraints and the project objectives, sorbent tubes were chosen because they provide robustness, sample stability, reliability, repeatability, ease of use, cost effectiveness and the ability to quantify NMVOCs.

Sorbent tubes are small inert tubes that come in a variety of sizes (see Figure 11). Markes International Limited (Pontyclun, UK) manufacture sorbent tubes that have been accepted across multiple disciplines involved in volatile and semi-volatile organic compound monitoring as the standard size of 6.35 mm outer diameter and 89 mm length.

Figure 11: An example of two sorbent tubes with brass caps—the upper tube is coated in an inert coating to prevent oxidation of highly volatile species during sampling

Each tube is packed with a measured amount of sorbent that collects and traps the target VOCs as the sample air is drawn through the tube, thus an effective sampling volume in the order of 10 litres may be collected in a tube no larger than a pencil. The tube itself is fabricated from either stainless steel or glass. Stainless steel tubes offered a much higher degree of robustness than glass and were chosen for use in this project.

To ensure that each sample remained free of contamination, inert fittings and sample flow paths were utilised—for example stainless steel sampling manifolds, polytetrafluoroethylene (PTFE) tubing and, most importantly, each tube was sealed with 2-piece brass screw caps with PTFE ferrules prior and post sample collection (Swagelok® caps with Teflon® ferrules: part numbers: B-400-C with T-400-SET respectively).

Sorbent tubes can be sampled and reliably analysed many times as the sorbent bed within the tube can be cleaned with relative ease and have consistently low carry over rates. As the analytes are captured on or within a sorbent they are readily liberated by gentle gas flow and heat. Thermostatically and flow rate controlled devices such as the Markes TC-20 (Markes Int'l. Ltd Pontyclun, UK) allow for sorbent tubes of the same sorbent bed to be batch conditioned simultaneously, providing efficient and timely turn around from analysis to re-deployment for field sampling.

Each sorbent tube is identified with a unique serial number, allowing identification of the sorbent contained within the tube, and when correct quality assurance and quality control strategies are implemented, the sampling, analysis and conditioning cycles that the tube has under gone can be readily recorded. This is of significance as the sorbents within the tube have a finite life and this must be acknowledged in order to have confidence that the results of tube analysis are reliable, precise and provide accurate representation of the NMVOC composition of an air sample.

3.2.4 Sorbent selection

The sorbent tubes contain a sorbent of known mass and composition, chosen specifically for the target analytes. During this project, it was decided that the use of sorbents that have been widely documented for other studies of livestock emissions would be ideal to capture the NMVOCs from poultry sheds.

Extensive studies of VOC emissions from bovine and porcine operations have used both carbon molecular sieves and graphitised carbon black sorbents. Carbon molecular sieves are porous materials that collect analytes by trapping them within the pores of the material, capturing analytes smaller than

the size of the pore in the material and allowing larger molecules to pass through the sorbent bed. Graphitised carbon black sorbents are generally nonporous materials that collect analytes on their surface by adsorption, thus their strength is considered to be a function of their specific surface area—the area analytes have to bind to—thus a lower specific area corresponds to a lower strength.

Detailed methodologies from the United Kingdom Health and Safety Laboratory (UK HSL Methods for the Determination of Hazardous Substances MDHS-72), the United States Environmental Protection Agency (USEPA Method TO-17) and technical notes available from Markes Int'l Ltd., led to the use of two different sorbent tubes to ensure accurate and reliable representation of the volatile organic compounds found in the gas phase emissions from the poultry houses.

The principal sorbent selected was Tenax TA—a widely used, inert, hydrophobic, weak sorbent, with a specific surface area of ~35m²/g. Tenax TA targets VOCs with boiling points between 100–450 °C or compounds n-C_7 to n-C_{30} for example aromatics, apolar and polar compounds, poly aromatic hydrocarbons and poly chlorinated biphenyls.

The second sorbent was Carbotrap 300, which provides an approximate analyte capture range of ethane (C2) to n-C20 and is a mixture of three different sorbents: Carbopack C; Carbopack B; and Carbosieve SIII (listed in increasing sorbent strength and packing order within the tube). Table 7 lists the properties of these three sorbents.

Table 7: Properties of the three sorbent types within the Carbotrap 300 sorbent tubes

Sorbent	Specific Surface Area	Target Compound Range	Sorbent Strength	Hydrophobic / Hydrophilic
Carbopack C	~12 m²/g	n-C_8 to n-C_{20}	very weak	hydrophobic
Carbopack B	~100 m²/g	n-$C_{5/6}$ to n-C_{14}	medium	hydrophobic
Carbosieve III	~800 m²/g	ethane to n-C_5	very strong	mildly hydrophilic

With the specific targeting of the Tenax TA sorbent tubes and the Carbotrap 300 sorbent tubes, it was anticipated that the significant majority of NMVOCs present in the gas phase emissions from the poultry sheds could be trapped for analysis.

For added redundancy a sorbent tube that contained a mixture of Tenax and Carbograph 1TD was occasionally used. Carbograph 1TD is a moderately weak hydrophobic sorbent with a specific surface area of ~100 m²/g and a target analyte range of n-$C_{5/6}$ to n-C_{14} including alcohols, aldehydes, ketones and apolar compounds.

3.2.5 Sorbent tube collection methodology

There are two methods of collecting NMVOCs with sorbent tubes: active sampling using a vacuum pump; and diffusive sampling (also refereed to as passive sampling). Throughout the project, the majority of samples were collected using active sampling; however, diffusive sampling was also occasionally used.

Active sampling was conducted using a calibrated air sampling pump and adjustable low-flow tube holders to draw sample air through the sorbent tube at a known flow rate and for a set duration (SKC Universal Pump 224-PCXR8 and 224-26-01 respectively, SKC Inc., Pennsylvania, USA, see Figure 12). This allows for the total volume of air passed through the sorbent to be recorded and the concentration of the analytes detected during subsequent analysis to be determined.

Figure 12: Vacuum pump used to draw the air samples through the sorbent tubes to collect the analytes

Appropriate sampling flow rate, duration and total sample volume is essential. An excessive sampling volume may result in the sorbent becoming saturated and VOCs passing through the tube unretained. A flow rate that is too high or too low may similarly result in the VOCs passing through the sorbent without sorption. It is for these reasons that double tubes were collected in series during the initial proof of concept field trials. These series tubes demonstrated that the sampling flow rates and volumes were suitable for the NMVOCs to be retained on the first (front) sorbent tube.

Air samples were drawn through a 1.5 m long, 6.35 mm diameter stainless steel probe that was either within the polyethylene duct as shown in Figure 13. The probe fed into a stainless steel manifold shown in Figure 14, onto which the sorbent tubes were attached with 60 mm lengths of Tygon® tubing (Saint-Gobain Performance Plastics Corporation Tygon® R–3603 vacuum tubing).

All tubes were individually calibrated using a flow meter (TSI Incorporated Model 4143) and individual low flow tube holders attached to Tygon® tubing. Samples were collected for 30 minutes at a maximum rate of 100 mL per minute.

Figure 13: VOC sampling from duct

Figure 14: Filtered VOC tubes and manifold

In comparison to the active sampling methods, diffusive samples do not require a sampling pump—the leading end of the sorbent tube is opened to the emission source whilst the trailing end of the sorbent tube remains capped (see Figure 15). Specifically designed diffusion caps must be placed over the open end of the sorbent tube to fix the cross sectional area of the sampling surface, and to prevent the ingress of dust, insects and other particulate matter to the tube.

Figure 15: Sorbent tube with diffusion cap in place

3.2.5.1 Filtering of pumped sorbent tubes

Throughout the initial stages of the field sampling a number of comparative samples were collected that were either filtered or unfiltered. This filtering was performed inline by way of a 0.2 µm PTFE disc filter housed within a stainless steel holder (see Figure 16). This inline filter was placed before the sampling manifold so each sorbent tube had one common filter.

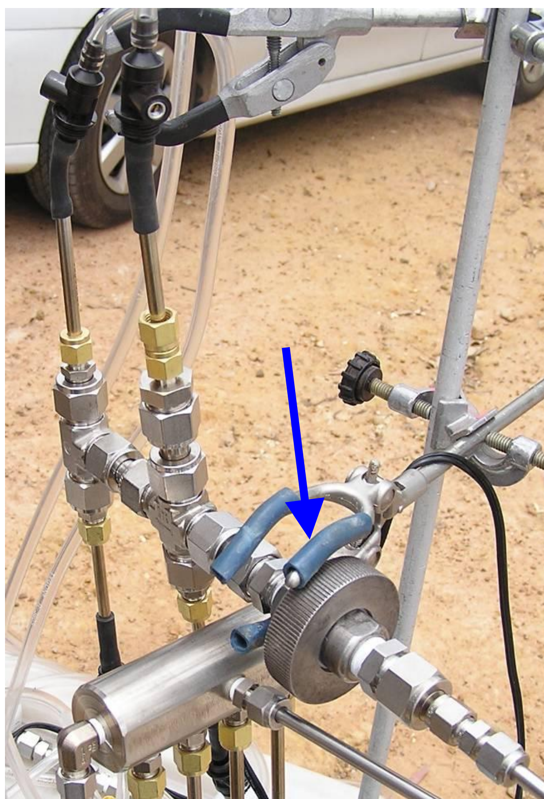

Figure 16: Sorbent tubes in place collecting filtered samples— arrow pointing to inline filter housing containing a Teflon filter. Lower manifold (obscured) for unfiltered sorbent tubes

The intention of this filtering was to prevent particulate matter from entering and contaminating the sorbent tube, and to provide consistency within samples by removing any error from differing levels of inadvertently collected particulate matter. After empirical analysis of the results obtained from these initial samples it became evident that there was significant variability within the unfiltered results and henceforth all samples collected would be filtered.

As the project progressed, two other filter materials were used to perform this filtering; mixed nitrocellulose fibre and resin free glass fibre. In difference to the single inline filter for all tubes as with the PTFE filter, the mixed nitrocellulose fibre and glass fibre filters were individually housed in clear polystyrene cassettes (SKC, AirMet Scientific, North Sydney, NSW, Australia). This allowed for investigation of NMVOCs trapped on the particulate matter for each individual sorbent tube.

Upon further detailed analysis of the results and specifically the results of laboratory based tests it was concluded that the use of resin free glass fibre filters provided the most reliable and consistent samples.

The analysis of collected particulate matter was performed in addition, albeit intrinsically parallel, to the gas phase NMVOC analysis to provide greater understanding of the chemical make up of the air exhausted from the poultry sheds and any chemical mechanisms that may be taking place during the transportation of particles.

Furthermore it should be accepted that there is a significant amount of *parasitic static cling* resulting from the movement of air over the various flow paths within the sampling setup, such as the polyethylene duct, stainless steel sampling lines and fittings and other inline features. This will reduce the amount of air borne particulate matter that will actually reach the filter and sorbent tube.

3.2.5.2 Sorbent tube storage and handling considerations

Extreme care was exercised throughout all stages of sample collection, transportation, analysis, conditioning, and re-deployment into the field to ensure that the tubes retain their integrity. Care was also taken when handling tubes to avoid contamination from human contact—as the skin contains numerous natural oils—by handling the tube only in the centre of the stainless steel body, well away from the tube openings.

Once a sample had been collected in a sorbent tube, it was immediately and cautiously sealed with its caps and wrapped in clean aluminium foil. The aluminium foil serves to identify the tube as having been exposed, to insulate the tube from rapid changes in temperature and to also act as a secondary contamination barrier.

Each sorbent tube was transported in a clean, translucent plastic container that held up to ten tubes. Aside from being a convenient way to package and ship the tubes, the case gave additional handling protection to the sorbent tubes.

The tubes were stored in refrigerators (between 1-5 °C) to conserve the integrity of the analytes captured on the sorbent. When in the field for sample collection or during transportation from the field locations to the laboratory for analysis, the tubes were kept in portable refrigerators or coolers with ice packs to keep their temperature sub-ambient. Although these measures may be considered superfluous, every attempt has been made throughout this project to guarantee the utmost integrity of the data obtained from the analysis of the NMVOCs collected on these sorbent tubes.

3.2.6 **Ventilation rate measurement**

Ventilation rate was measured by two methods throughout the project: at the fan face with a hot wire anemometer; or calculating ventilation rate from manufacturer’s fan performance data, fan activity and shed static pressure.

3.2.6.1 Measurement of ventilation at the external fan face

Airspeed measurements were taken in two perpendicular transects across the external face of each fan using a hot wire anemometer (TSI Incorporated VelociCalc® Model 8386–M–GB) as shown in Figure 17. Each transect consisted of 12 points, which were each measured over 2 s. The spread of measurement points over the fan face was calculated using AS 4323.1 (Standards Australia, 1995a). A 2 m length of small diameter PVC (polyvinyl chloride) pipe was marked with measurement points and attached to the fan housing with either clamps or metal hooks during airspeed measurement (see Figure 17). An average of all measurements from all active fans was used to calculate the shed ventilation rate. Ventilation rate (Q) was calculated by multiplying the average airspeed (m/s) by the fan cross-sectional area by the number of active fans (see Equation 1).

$$Q\ (m^3/s) = \text{Average airspeed}\ (m/s) \times \text{fan cross–sectional area}\ (m^2) \times \text{no. active fans} \qquad \textbf{Equation 1}$$

Figure 17: Measurement of airspeed at fan face (External)

Figure 18: Measurement of airspeed at fan face (Internal)

Where fan shutters were on the outside of the fan, measurements were taken from the internal fan face (Figure 18).

3.2.6.2 Estimating ventilation rate using fan activity, static pressure and manufacturer's performance information

Shed ventilation rate can be estimated using fan performance data (Dunlop and Duperouzel, 2008; Wilhelm *et al.*, 2001). Flow rate for each active fan was estimated using performance data provided by the fan manufacturer or from an independent testing laboratory (for example the BESS Laboratory at the University of Illinois http://www.bess.uiuc.edu/). Ventilation rate was calculated by multiplying the number of active fans by the estimated flow rate through each fan.

Calculating ventilation rate with this method assumes that the fan performance data is accurate and that the fans are clean and in good condition. It is essential that the fan performance data exactly matches the fans installed at the farm. It is therefore necessary to record details including; fan manufacturer; model number; number of blades; blade pitch (if adjustable); motor size and manufacturer; and pulley sizes. It is also advisable to supplement the estimation of flow rate through each fan with physical measurement of the velocity profile using techniques described above in Section 3.2.6.1.

Fan performance data was sourced from fan manufacturers or suppliers. Figure 19 displays the fan performance data for the fans installed on farms involved in this study. It can be seen that flow rate reduces as the magnitude of the static pressure increases (inside the shed is lower pressure than outside). The fan performance curve equations (see Table 8) were calculated using Microsoft® Excel 2003 by fitting a polynomial trend line to the flow rate data at different static pressure values.

For this method to be successful, it is essential to measure the shed static pressure at the time of ventilation measurement. Temperature and barometric pressure should also be recorded to enable the air flow to be adjusted to match the conditions under which the fans were evaluated and then, for the purposes of calculating emission rates, adjusted to match standard temperature and pressure conditions (see section 3.2.6.3).

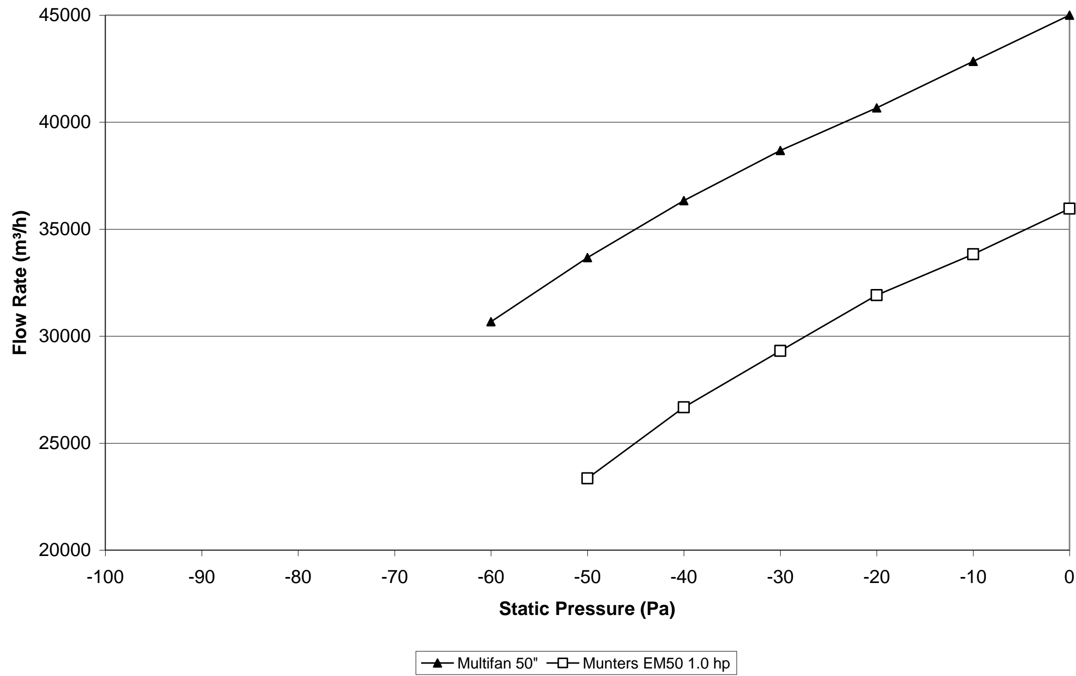

Figure 19: Fan performance curves as supplied by manufacturer

Table 8: Fan performance equations

Fan	Fan Performance Equation*
Multifan 50" (1270 mm) (Vostermans Ventilation B.V., 2004)	$Q = 0.023p^3 + 1.1965p^2 + 228p + 45000$
Munters EM50 (1270 mm) 1.0hp (University of Illinois Department of Agricultural Engineering BESS Lab, 2002)	$Q = 0.0234p^3 + 0.173p^2 + 201.77p + 35937$

* *Where:* *Q = ventilation rate, in m³/hour, and*
p = internal shed differential pressure, in Pascals (Pa).

3.2.6.3 Adjustment of ventilation rate for standard conditions

According to AS/NZS 4323.3 (Standards Australia/Standards New Zealand, 2001), the ventilation rate used to calculate an emission rate is to be standardised to standard temperature and pressure conditions (0 °C, 101.3 kPa). Each fan manufacturer was contacted, and details were recorded as to the temperature and pressure conditions under which the fans were tested. As a result, the flow rate of the fans was altered according to Equation 2 (sourced from Appendix G of AS/NZS 4323.3).

$$V_{R,0} = V_s \times \frac{(273+0)}{273+t} \times \frac{P_s}{101.3}$$ **Equation 2**

Where $V_{R,0}$ = volume flow at standard conditions
P_s = absolute pressure during fan performance testing, in kPa
V_s = measured flow rate
t = temperature during fan performance testing, in °C

3.2.6.4 Continuous monitoring of fan activity

At Farm D, ventilation rate was continuously monitored using fan activity sensors. The method used to monitor fan activity was similar to that used by Dunlop and Duperouzel (2008). The following section summarises the important components of the ventilation monitoring system.

Fan activity

Fan activity data, combined with fan performance data and other data such as shed static pressure and inlet vent positions, was used to continually estimate actual ventilation rate.

Mercury tilt switches were attached to the fan back-draft shutters to monitor fan activity, similar to the approach used by Wilhelm *et al.* (2001). The use of tilt switches was selected over other techniques due to low cost (sensors cost approximately $3.00 per fan), availability of components, expected reliability (when compared to more complex systems) and unobtrusiveness. The potential problems foreseen with the use of tilt switches included the possibility for false positive readings if the shutters did not close when the fan turned off. Additionally, if a wire broke during cleaning operations or through fatigue caused by repeated opening and closing of the shutter, a false positive reading would also be returned.

Mercury tilt switches were fitted onto an angled aluminium plate, which was then riveted onto the fan back draft shutters of every fan on the shed (see Figure 20 and Figure 21). The purpose of the angled plate was to avoid hysteresis issues associated with the switch only just (or just not) reaching a true horizontal position when the fan turned on and the shutter opened. The angle ensured the tilt switch passed beyond the horizontal position, whenever the louvers opened, so the switch would always activate.

Figure 20: Mercury tilt switch with fan turned off (shutters closed, switch closed)

Figure 21: Mercury tilt switch with fan turned on (shutters open, switch open)

Inlet vent opening

Inlet vents are an integral part of the ventilation system in a tunnel ventilated poultry shed. The mode of ventilation (tunnel or mini-vent), was determined by monitoring the position of the mini-vents and the fan activity.

To detect when mini-vents were open or closed, a Hall-effect sensor was used. A Hall-effect sensor is a digital semiconductor switch which responds to the presence of a magnetic field. To create a magnetic field, a magnet was fastened to the mini-vent shutter (see Figure 22). The voltage output of the Hall-effect sensor changed as the strength of the magnet moved away from the sensor and was recorded by the data logger. An assumption was made that if the mini-vents were open, the shed was operating in mini-vent mode. On the other hand, if the mini-vents were closed and a reasonable percentage of the fans were active, it was assumed that the shed was operating in tunnel ventilation mode.

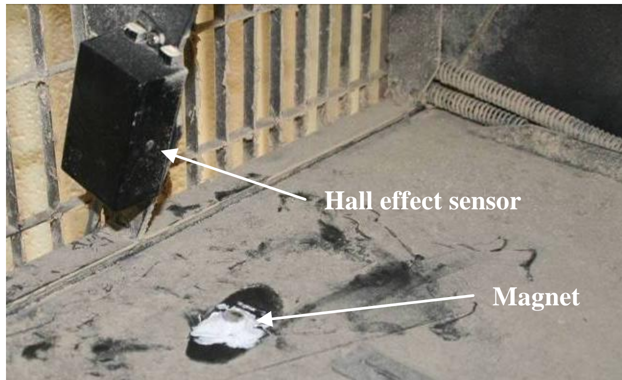

Figure 22: Mini-vent opening sensor (mini-vent in open position)

Figure 23: Setra ultra low differential pressure transducer used to measure the shed static pressure

Shed static pressure

The differential pressure between the inside and outside of the chicken shed affects the performance of the ventilation fans. Chicken sheds will normally have a differential pressure in the range of 0 Pa to -40 Pa relative to the outside. This differential pressure is often referred to as static pressure. The static pressure will vary due to the number of active fans, inlet vent position and by external forces such as wind. Consequently, the static pressure will fluctuate constantly. The ventilation controller monitors the static pressure and adjusts the inlet vents to maintain a suitable pressure. Because static pressure affects fan performance, it was essential to monitor the static pressure to allow calculation of ventilation rate with reasonable accuracy.

A differential pressure sensor (Setra brand model 264, ±63 Pa range, see Figure 23) was used to measure the pressure difference between the ambient environment and the internal shed environment. The reference pressure for the pressure sensor was the pressure measured inside a weatherproof box (which was vented, but protected the sensor from strong wind pressures) or from within the control room of the poultry shed.

Measurement frequency of each sensor

A data logger (dataTaker® DT500, dataTaker® Pty Ltd) was programmed to monitor and record the output of each sensor at specified intervals. Table 9 lists the monitoring and recording frequency for each of the sensors.

Table 9: Frequency of monitoring and recording for each sensor

Sensor	Monitoring Frequency	Recording Frequency
Fan activity (mercury tilt switches)	Six second	6 minute average; on change in fan activity
Mini-vent switches (Hall effect sensors)	Six second	6 minute average, on change in fan activity
Shed static pressure (differential pressure sensor)	Six second	6 minute average, on change in fan activity

3.2.7 Manure collection

Manure was collected directly from the belts on the day where most manure was present. For Farm D, this was the final day of sample collection, and for Farm E the second day of sample collection. Samples were taken from the end of the belts, where the manure was easily accessible and stored in individually marked WhirlPak® bags (710 mL, 0.076 mm thickness). Manure was collected from randomly selected rows from each bank of cages, namely from the bottom half of each bank due to the height of the structures.

Samples were stored in the laboratory and analysed within 7 days in accordance with AS 4454-2003 (Standards Australia, 2003).

3.2.8 Measurement of weather conditions

Weather conditions were monitored at Farms D with a 10 m portable automatic weather station (AWS) (See Figure 24).

Figure 24: Weather station used for this project

Weather information collected during the trials is displayed in Table 10. All data (except rainfall) was collected every second then averaged and reported every six minutes. Hourly and daily averages (and totals) were calculated during post processing. Specific information for the weather station sensors is displayed in Table 11.

Table 10: Weather information collected during the trials

Parameters measured by the AWS	
2 m wind speed	10 m wind speed standard deviation
2 m wind direction	2 m temperature (2 sensors)
10 m wind speed	2 m relative humidity
10 m wind direction	10 m temperature
2 m wind direction standard deviation	Total radiation
10 m wind direction standard deviation	Barometric pressure
2 m wind speed standard deviation	Rainfall

Table 11: Weather station sensor information

Sensor/Parameter	Brand	Model Number	Sensitivity	Range
Data Collection	DataTaker	DT500 (version7)	0.11% for Voltage 0.21% for Current	0-2500 mV 0.25-25 mA
Temperature (2 m)	Vaisala	50Y Humitter	±0.6°C at 20 °C	-10 to +60 °C
Temperature (2 m & 10 m)		PT100		-50 to +250 °C
Relative Humidity (RH) (2 m)	Vaisala	50Y Humitter	±3% at 90% RH	10 to 90%
Wind Speed	Gill Windsonic	1405-PK-040 Option 3	±4% at 20 m/s	0 to 60 m/s
Wind Direction	Gill Windsonic	1405-PK-040 Option 3	± 3° at 20 m/s	0 to 359°
Total Radiation	Li-Cor	LI200SZ	0.2 kW/m²/mV	
Barometric Pressure	Vaisala	PTB101B	±0.5 hPa at 20 °C ±2 hPa at 0-40 °C	600 to 1060 hPa
Rainfall	Hydrological Services	TB3	one tip/0.2 mm rain	0 to 700 mm/hr

The AWS was located and managed by DEEDI according to AS 2923–1987 (Standards Australia, 1987) wherever possible. It was not always possible to locate the weather station in strict accordance with the standard at some of the sites due to vegetation or geographical landforms. In these cases, the weather station was positioned as close as possible to the trial site, which occasionally meant small compromises in relation to these obstacles.

Data from the AWS was able to be used to calculate atmospheric stability class, described using Pasquill-Gifford stability categories. Stability class was calculated using the σ_A method (wind turbulence based method using wind direction standard deviation) as described in USEPA (2000).

3.2.9 Measurement of ambient and shed temperature and humidity

Ambient and in-shed temperature and relative humidity were measured with three instruments. During in-shed ventilation rate measurement, the hot wire anemometer (TSI Incorporated VelociCalc® Model 8386–M–GB) was used to measure temperature and relative humidity.

Ambient temperature and relative humidity were monitored with a Kestrel® Pocket Weather Tracker (Nielsen–Kellerman model 4500, see Figure 25). The Kestrel was suspended from DEEDI's sample collection trailer out of direct sunlight and influence from air exiting the shed. Readings were recorded every minute.

Temperature of the air exiting the shed was monitored from within the polyethylene duct using a Cox Tracer® (Cox Technologies, Inc., see Figure 26). The logger contains two temperature sensors, one inside the green body, and the other external sensor in the steel probe. The probe was suspended inside the duct for the duration of the sample days. Readings were recorded every minute.

Figure 25: Kestrel® Pocket Weather Tracker

Figure 26: Cox Tracer® Temperature Recorder

For measurement of ambient temperature and relative humidity, as mentioned in section 0, a 10 m weather station was used. It is possible to measure ambient conditions using portable instruments such as the Kestrel® and Cox Tracer®. However, it is important that the measurement point is located away from any interference from the air exiting the poultry shed. Figure 27 shows how ambient temperature measured with a Kestrel or Cox Tracer compared to ambient temperature measured at 2 m from DEEDI's weather station. Sixty-five percent of the portable instrument readings were within one degree Celsius and 34% of the readings were between 1.5 and 4 degrees Celsius above that measured by the weather station. The use of portable temperature instruments is good for measuring internal shed temperature, but care must be taken when measuring ambient temperature near the tunnel ventilation fans. The use of a weather station will reduce the possibility of these errors.

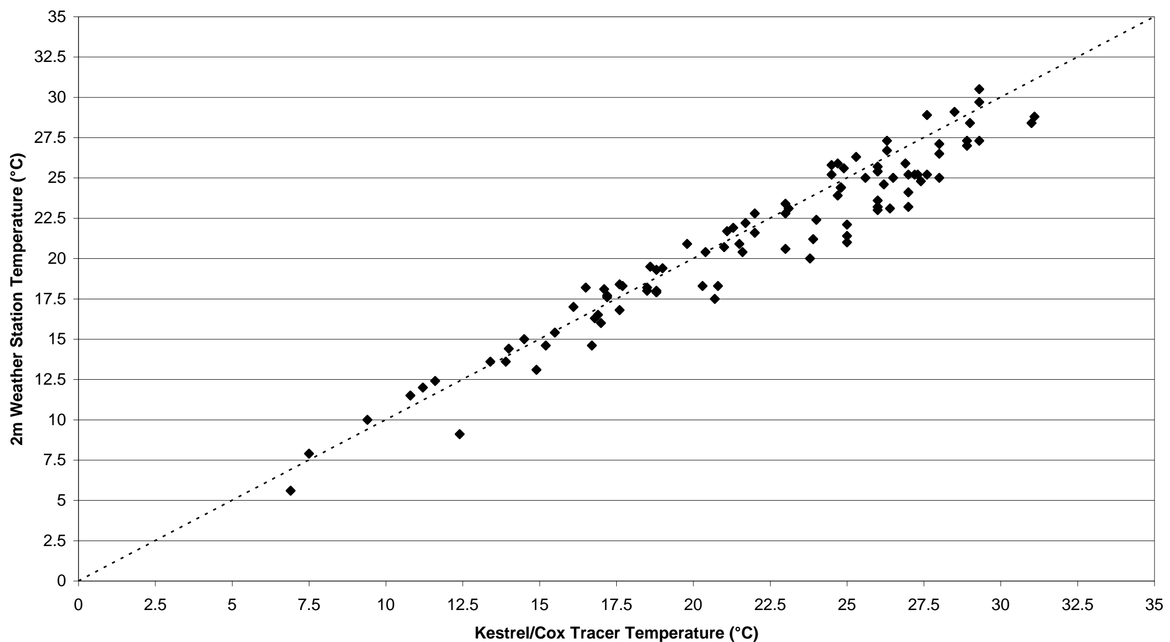

Figure 27: Comparison between weather station (2m) and Kestrel/Cox Tracer temperature

3.2.10 **Production parameters**

Production information was provided by the farm manager. Number of birds placed, number of birds present on each sample collection day, and average daily live weight were supplied. These parameters were assessed for their ability to influence air quality.

Details of bird weight were supplied by the producers using the weekly average weight.

The number of birds placed the number of birds present was provided by the producer. The number of birds present on each sampling day was estimated using the number of birds placed and estimated or recorded mortalities.

3.3 Analysis techniques

3.3.1 Olfactometry – odour concentration analysis

3.3.1.1 Department of Employment, Economic Development and Innovation (DEEDI) Olfactometer

Odour concentration from all Queensland farms was determined using the eight panellist, triangular, forced choice dynamic olfactometer developed by the Department of Employment, Economic Development and Innovation (DEEDI), which has been described previously (Nicholas *et al.*, 1999; Zeller *et al.*, 2002). This olfactometer was constructed and operated to comply with the Australian/New Zealand Standard for Dynamic Olfactometry AS/NZS 4323.3:2001 (Standards Australia/Standards New Zealand, 2001).

During a typical odour sample assessment routine, each panellist was first screened with the reference gas (n-butanol) to ensure that his or her detection threshold was within the required concentration range of 20–80 ppb (v/v). Thereafter, the odorous sample was diluted and presented to the panellists in one of three ports, while the other two ports emitted clean, odour-free air. The panellists were required to sniff from the ports and determine whether they could detect a difference between the three ports. Each panellist was allowed a maximum of 15 seconds for this assessment. The panellists indicated via a keypad whether they were certain, uncertain or guessing that one of the ports was odorous, as well as from which port the odour (if detectable) was emitted.

This process was repeated, doubling the concentration of odorous air of the previous presentation each time, until each panellist had entered a "certain and correct" response for two consecutive presentations. Each panellist's individual threshold estimate ($\overline{Z}_{ITE}$) was then determined by calculating the geometric mean of the dilution at which the panellist did not respond with certainty and correctly and the first of the two dilutions where the panellist did respond with certainty and correctly. A complete dilution series is defined as a round. Three rounds were completed for each sample provided sufficient sample was available.

At the end of the three rounds, the results of the first round were discarded in accordance with AS/NZS 4323.3. The results from rounds two and three were then geometrically averaged ($\overline{Z}_{ITE}$). The ratio between Z_{ITE} and $\overline{Z}_{ITE}$ is defined as ΔZ . The calculation of ΔZ is presented in the following equations:

$$if\ Z_{ITE} \geq \overline{Z}_{ITE},\ then\ \Delta Z = \frac{Z_{ITE}}{\overline{Z}_{ITE}}$$ **Equation 3**

$$if\ Z_{ITE} \leq \overline{Z}_{ITE},\ then\ \Delta Z = \frac{\overline{Z}_{ITE}}{Z_{ITE}}$$ **Equation 4**

If ΔZ is greater than ± 5 then all $\bar{Z}_{ITE}$ values of the panel member with the largest ΔZ were excluded from the data set. The screening procedure was then repeated, after re-calculation of $\bar{Z}_{ITE}$ for that measurement. If a panel member again did not comply, the results for this panel member (with the largest ΔZ) were omitted. This was repeated until all panel members in the dataset had an acceptable ΔZ value. The last value of $\bar{Z}_{ITE}$ was then defined as the odour concentration and expressed as odour units per cubic metre (ou m³).

3.3.1.2 Emission Testing Consultants (ETC) Olfactometer

The ETC olfactometer was designed and built to comply with the performance and design criterion of the Standard.

Six odour panellists were used to assess odour samples. Each odour panellist had two ports (left and right) in which odour samples were presented. One port always contained odour free air (reference air) and the other diluted sample air. The olfactometer was designed so that the reference air and the diluted sample air could be swapped randomly from one port to the other.

All odour panellists were screened to ensure their sensitivity to a reference odorant (*n*-butanol) was between 20 and 80 ppb. Odour panellists were assessed on a continuous basis to ensure they complied with the criterion for sensitivity and consistency stipulated in the Standard.

The olfactometer was calibrated on an annual basis using a NATA certified tracer gas (carbon monoxide) and assessed against the performance criterion of the Standard.

3.3.1.3 Compliance of olfactometers with accuracy and repeatability criteria

To be compliant with AS/NZS 4323.3:2001 (Standards Australia/Standards New Zealand, 2001), olfactometers must meet or exceed assessment criteria for accuracy and repeatability. Accuracy is a measure of how closely the olfactometer can measure the true value of a reference gas (40 ppb Butanol) and is defined by accuracy test variable A_{od}. Olfactometer must achieve $A_{od} \leq 0.217$ for compliance. For olfactometer precision (measured in terms of repeatability), olfactometers must achieve a value of $r \leq 0.477$ (resulting in $10^r \leq 3$). In plain English, this value implies that the difference between two single measurements, performed on the same material, in one laboratory, will not be greater than a factor of 3 in 95% of cases. An assumption is then made that this repeatability is transferable to unknown samples (Standards Australia/Standards New Zealand, 2001; van Harreveld *et al.*, 1999).

During this study, two olfactometry laboratories were used: DEEDI laboratory in Queensland and ETC in Victoria. DEEDI olfactometer accuracy ranged from $0.052 \leq A_{od} \leq 0.121$ with an average value of $A_{od} \approx 0.082$. Repeatability ranged from $0.259 \leq r \leq 0.318$ ($1.46 \leq 10^r \leq 2.08$). ETC olfactometer accuracy ranged from $0.098 \leq A_{od} \leq 0.216$. Repeatability ranged $0.251 \leq r \leq 0.465$ ($1.78 \leq 10^r \leq 2.92$).

3.3.1.4 Round robin testing of olfactometry laboratories

All odour samples could not be analysed by the same olfactometry laboratory. As farms in Queensland and Victoria were included in the study, it was not logistically possible to analyse the Victorian samples in Queensland within the required time frame. Hence an olfactometry laboratory was used to analyse the Victorian odour samples. To ensure comparability between laboratories, all participating olfactometry laboratories took part in an international round robin test in 2005.

An independent laboratory (OLFAtec GmbH, Honigsee, Germany) distributed gaseous samples to all participating laboratories. The samples were analysed on one day within a specified week determined by OLFAtec. Each laboratory calculated their odour concentration results and forwarded the results to OLFAtec, where odour threshold results were calculated. The results were then analysed by OLFAtec to determine the accuracy of each olfactometry laboratory.

The odour concentration and odour threshold results are shown in Table 12. The terms ‘pass’ and ‘fail’ indicate whether the concentration calculated by the laboratory fell within the set limits of accuracy.

Table 12: Olfatec 2005 round robin test results for DEEDI and ETC

Test №		Odour concentration (ou/m³)		Odour threshold (µg/m³)	
		DEEDI	ETC	DEEDI	ETC
1.	1–Butanol	378 (pass)	340 (pass)	95.24 (pass)	105.88 (pass)
2.	1–Butanol	1166 (pass)	900 (pass)	101.3 (pass	130.89 (pass)
3.	Tetrahydrothiopen	3158 (pass)	3800 (pass)	2.37 (pass)	1.97 (pass)
4.	SFREE – ethylacrylate, methylacrylate and 2–ethyl 3–methylpyrazine	7061 (pass)	8100 (pass)	0.14 (pass)	0.12 (pass)

The odour concentration and odour threshold results for the DEEDI and ETC olfactometers are shown in Figure 28 and Figure 29 respectively.

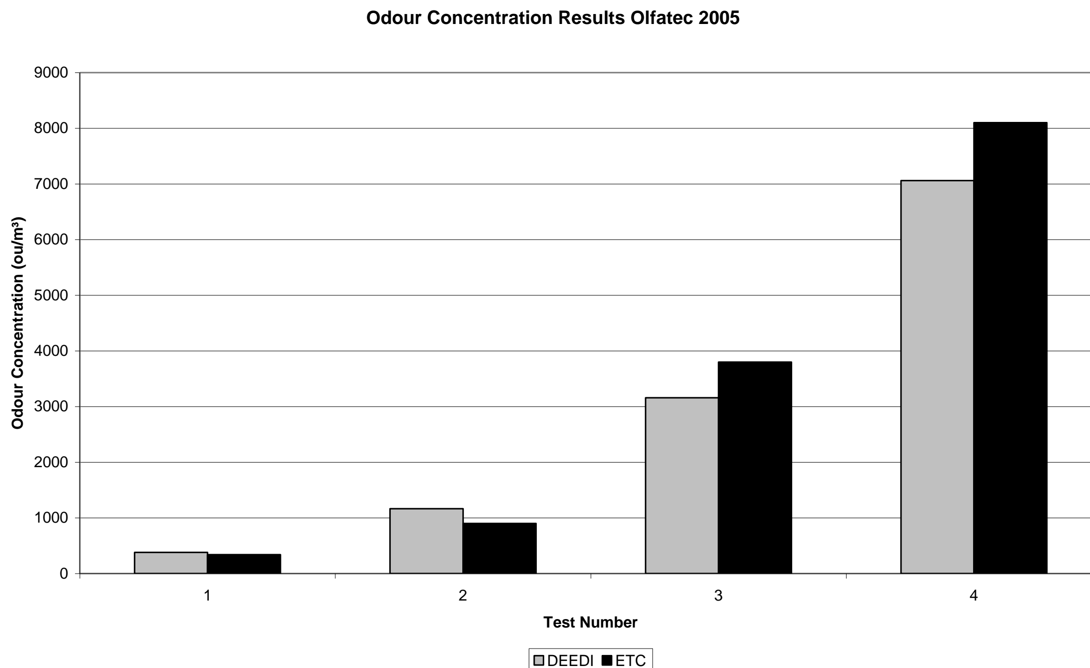

Figure 28: Odour concentration results for Olfatec Test 2005

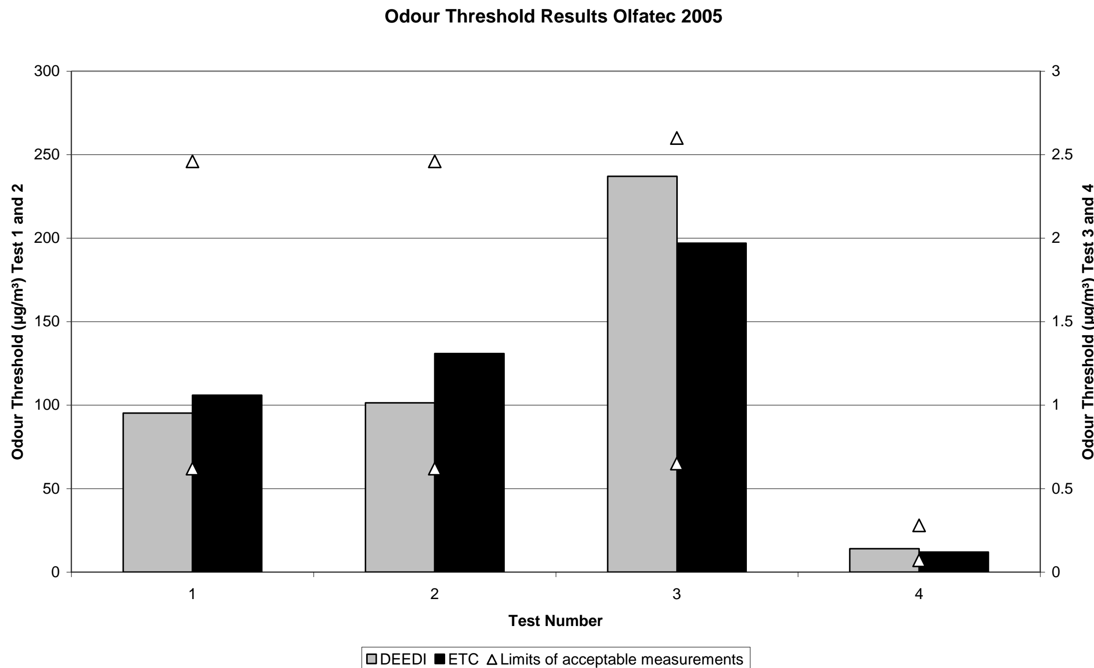

Figure 29: Odour threshold results for Olfatec Test 2005

Summary of round robin testing

The two olfactometry laboratories used during this project—ETC and DEEDI—were assessed using an international round robin compliance test conducted by OLFAtec and both laboratories passed each of the four assessment included with the test. Similar results by both olfactometry laboratories in this independent testing event demonstrated that odour measurements by both labs were comparable—when using standard gas mixtures. Consequently, assessment of poultry odour samples by either ETC or DEEDI olfactometers would also be expected to be comparable.

It is recommended that where more than one olfactometry laboratory is used for a single trial, that:

- a test be performed to ensure similarity in results from all laboratories; and
- all laboratories conform to AS/NZS 4323.3:2001 (Standards Australia/Standards New Zealand, 2001).

3.3.2 Dust analysis

Particle mass concentration (for PM_{10} $PM_{2.5}$ fractions) and particle number concentration were measured in the exhaust stream from layer sheds. These variables had units of mg/m³ and particles/m³ respectively. The data analysis procedure was identical for both concentration measurements. Concentrations were first corrected for dilution during the sampling process. Dilution with particle-free air during sampling was necessary to maintain isokinetic conditions. Particle number or mass emission rates were then obtained by multiplying average corrected concentrations by average ventilation rate, which was expressed in units of m³/s, producing emission rates in units of mg/s or particles/s. These rates represent the number or mass of dust particles emitted per second from the layer sheds. For comparison between different layer sheds, emission rates were normalised to emission rate per kg of live bird weight, and emission rate per 1000 birds placed, using the appropriate production parameters.

During the sample collection periods, continuous dust concentrations were recorded at the majority of farms. Therefore a choice had to be made regarding the time period over which concentrations were averaged. Two approaches were taken. Firstly, to directly compare dust and odour emission rates, particle mass and number concentrations were averaged over the times that odour samples were collected. Secondly, to investigate the relationship between dust emission rate and ventilation rate,

concentration measurements were averaged over the times when ventilation rate was relatively constant (i.e. when the number of active fans was constant).

Particle size distributions were also measured throughout this project. A very large number of size distributions were recorded at each farm so to easily represent this information a single parameter, Count Median Diameter, (CMD), was calculated for each distribution. The CMD represents the mid-point diameter of a particle number size distribution.

3.3.3 Non-methane volatile organic compound and odorant analysis

The laboratory analysis of the sorbent tubes for non-methane volatile organic compounds (NMVOCs) and odorants was performed in three unique and sequential stages:

1. Using a thermal desorber (TD) to liberate the analytes from the sorbent tube, focus and inject the NMVOCs;
2. Using a gas chromatograph (GC) to separate the NMVOCs on a chromatographic column; and
3. Using a mass selective detector (MSD)—alternatively known as a mass spectrometer (MS)—and olfactometry detection port (ODP) to detect, identify and quantify the NMVOCs and odorants.

The instrument series is frequently referred to as TD-GC-MS/O—the MS/O segment indicating that these two stages happen simultaneously. Figure 30 show the TD-GC-MS/O instrument setup as used in this investigation.

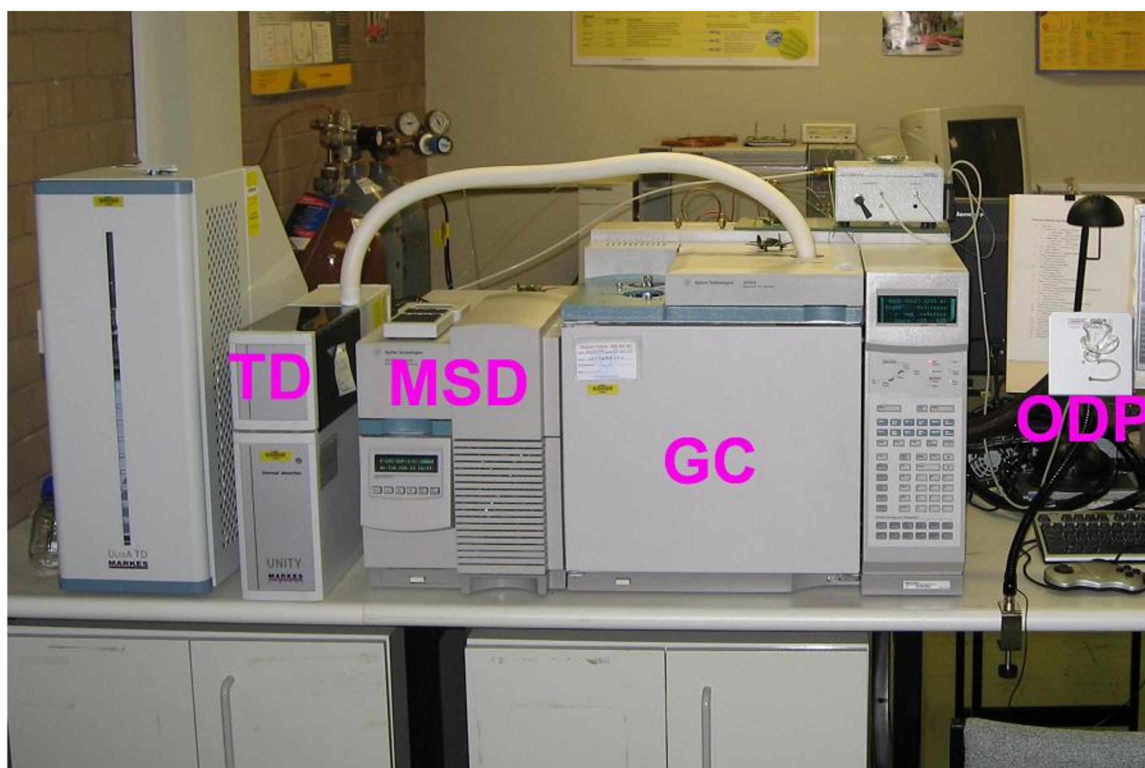

Figure 30: The instrument setup for the analysis of the thermal desorption tubes. *From left to right: Markes UltrA Autosampler, Markes Unity Thermal Desorber, Agilent 5973N Mass Selective Detector, Agilent 6890N Gas Chromatograph and Gerstel ODP2 Olfactory detection port*

The gas chromatograph-mass spectrometer (GC–MS) combination is one of the most powerful analytical tools available to most modern analytical chemists. The selectivity, flexibility, and sensitivity of GC–MS lend itself to the analysis of environmental samples, owing to the wide variety of analytes that are found within a particular matrix.

The chemical characterisation of the NMVOCs within the poultry shed emissions was performed using an Agilent 6890N gas chromatograph coupled to an Agilent 5973N mass selective detector

(Agilent Technologies, Nth Ryde, Sydney, Australia).Varying different operating parameters during the course of the research enabled an optimum method to be established for the efficient speciation of the analytes captured on the sorbent tubes.

The separation of the chemical species allows for their identification, numerous detectors are commercially available for integration into a chromatographic system; however, the mass selective detector has the benefit of providing rapid and flexible chemical speciation. For the purpose of characterising the odorants within the NMVOCs, an additional olfactory detection port is necessary. It is the combination of the mass spectrometer and the odour detection port that provide the unique data set for the characterisation of the NMVOCs and the odorants present within the gas phase poultry shed emissions.

The methods for each piece of analysis equipment are explained in the following sections. A summary of the NMVOC laboratory analysis equipment and operating parameters used throughout the project is provided in Appendix 2. The term volatile organic compound (VOC) refers to any organic compound that under normal conditions will be of sufficient volatility to enter the atmosphere; where normal conditions are typical atmospheric pressure (101.325 kPa) and temperature (~300 K). Correspondingly, NMVOC are all volatile organic compounds with the specific exclusion of methane (CH_4). For the purpose of this document the terms NMVOC and VOC have been used interchangeably; however, it should be expressly noted that where VOC is written, it is implied that it is the non-methane volatile organic compounds (NMVOC).

3.3.3.1 Thermal desorption—operation and control parameters

The initial stage of the laboratory analysis procedure, that of the thermal desorption, was performed with a Markes Unity Thermal Desorber (Markes Int'l. Ltd Pontyclun, UK). This instrument performs a series of sample preparation steps, focuses the volatile organic compounds and then injects them as an analyte slug into the GC. Clean, rapid injection of the analyte slug must be executed to enable the VOCs to be separated effectively by the chromatographic column. This is achieved using cryogenic trapping (also known as cryogenic focussing), which precipitates the volatiles into a liquid that can be injected onto the chromatographic column. In fundamental difference to the use of cryogenic fluids (LN_2) the Unity Thermal Desorber contains a narrow sorbent trap, known as the *cold trap*, which employs a Peltier device to maintain a desired temperature to focus the analytes from the sorbent tube. This cold trap is held at either ambient (25~30 °C) or sub-ambient (-10 °C) temperature whilst the analytes are thermally liberated from the sorbent tube. The use of a temperature controlled sorbent trap negates the use of cryogenic temperatures and the corresponding cryogenic fluids.

The operation of the TD is governed by numerous parameters controlled either by software or manual adjustment. There is a number of different modes of operation under which the TD can function—for the analysis of NMVOCs from sorbent tubes, the Standard 2(3) stage desorption is selected. Figure 31 illustrates the graphical user interface of the Markes Unity software that is used to control the different temperatures and times of the TD. The gas flow rates are controlled by needle valves on the instrument and verified by the flow rates reported on the GC.

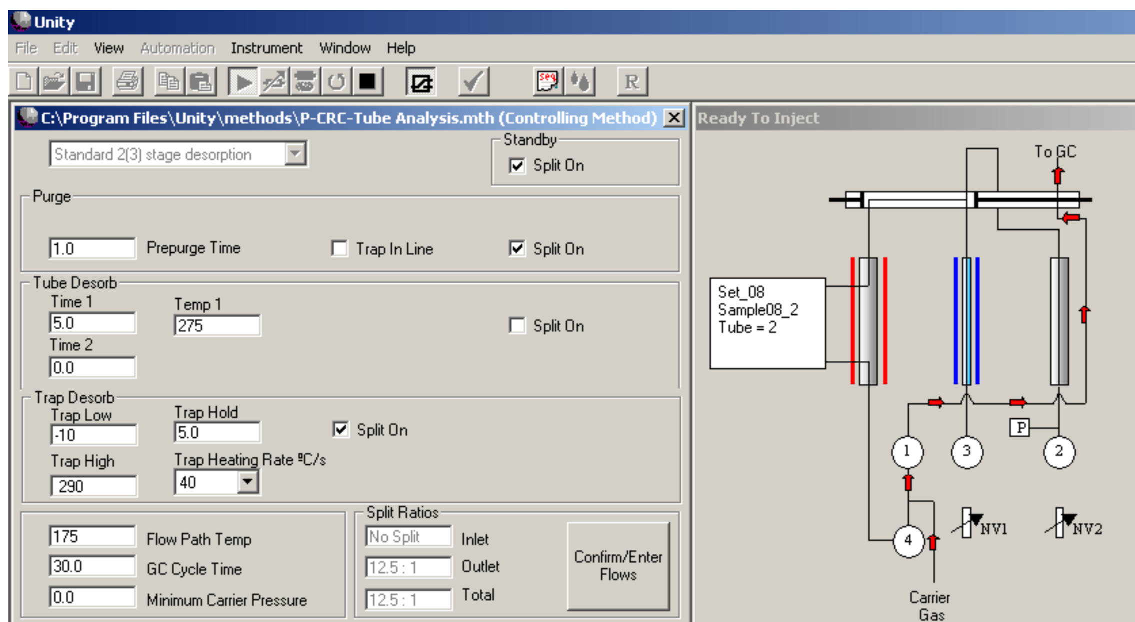

Figure 31: Markes Int'l. Unity software screen capture. *The left portion is the controlling method and the right portion illustrates the current flow path and instrument status (tube loaded, waiting to desorb)*

The Unity thermal desorber has three stages of operation:

1. tube purge;
2. tube desorb; and
3. trap desorb (including a default trap purge).

Tube purge

The tube purge is a critical component of the sample preparation, as it removes undesirable contaminants such as oxygen and water from the sorbent. This is vitally important when sampling from humid environments such as poultry sheds—if any moisture is passed to the cold trap and injected into the GC it can result in damage to the column and the detector as well as interfering with the signal from the detector. The presence of oxygen in the sorbent tube will result in oxidation of the volatiles within the sorbent tube upon heating.

The presence of both oxygen and water vapour in the sorbent tubes is unavoidable as they are collected from the atmosphere, thus careful sample preparation must be employed to minimise their harmful effects on the analysis. It should be recognised that thermally labile compounds may degrade during the heating stages of the thermal desorption; however, the use of gentle temperature ramps and effective pre-purging should minimise the risk.

During the tube purge, the tube is held at ambient temperature, the cold trap is kept at the trapping temperature (*trap low)* and the carrier gas is passed though the sorbent tube at a flow rate equal to that during the tube desorb stage, which is set by the needle valves. The time that the tube is purged for is set by the *prepurge time* and can optionally be captured inline (*trap in line*) by the cold trap and/or have some of the flow diverted into the recapture tube (s*plit on*). If the prepurge is not trapped in line it is passed through to the solvent vent of the gas chromatograph.

Tube desorb

Upon conclusion of the prepurge the tube desorb stage commences, with an electric heater (the *oven*) heating the sorbent tube to a preselected temperature (Temp 1) and maintaining this temperature for the preset time (Time 1). During this stage the carrier gas continues to flow through the sorbent tube and through to the cold trap where the analytes are captured and focussed. This stage thermally liberates the analytes from the sorbent tube and collects them on the cold trap. The flow from the

sorbent tube can either have all the sample passed onto the cold trap or split a certain ratio to the recapture tube for additional analysis with the *split on* function selected.

There can either be one or two temperatures to which the oven is heated, depending upon the characteristics of the NMVOCs that have been collected. The cold trap is maintained at its Trap Low temperature during the tube desorption stage in order to effectively capture all the NMVOCs from the flow.

Trap desorb—including trap purge

The conclusion of the tube desorb stage commences the trap purge, which is in essence identical to the tube purge and further ensures that there is minimal unwanted moisture or oxygen contamination within the analytes that have been captured on the cold trap before the heating of the trap is instigated. The cold trap is a narrow sorbent tube that acts as a cryogenic trap; the sorbent is contained in a quartz tube that can rapidly be heated by the Peltier device.

The sorbent contained within the cold trap should be selected based on the analytes that are to be focussed. The *trap low* temperature is the temperature at which the cold trap is maintained during standby, tube purge, tube desorb and trap purge. As indicated in the preceding text, this temperature is either ambient (25~30 °C) or sub-ambient (-10 °C) depending on the characteristics of the sample. The cold trap is designed to provide a focussed analyte *slug* that can quickly and cleanly be injected into the GC and this is achieved through rapid (*ballistic*) heating. The cold trap is heated from the *trap low* temperature to the *trap high* temperature in a matter of seconds—this heating rate can be customised to preserve sample integrity. As with the other two stages the complete sample can be injected into the gas chromatogram or a portion can be split into the recapture tube for additional analysis.

Miscellaneous parameters

The split ratio is controlled by the needle valves on the TD; however, the software contains a dialogue box pertaining to this ratio setting. The user must enter the flows as indicated by either the gas chromatogram or as measured with an accurate flow meter. In this way the amount of sample that is passed to the gas chromatogram or to the recapture tube can be calculated.

The sample flow path through which that the NMVOCs flow, most significantly along the transfer line, is also controlled from the TD software. The *flow path temp* is selected based upon the volatility of the compounds—a temperature that is too low may cause some of the analytes to condense along the flow path before reaching the GC, conversely a temperature too high may result in thermal degradation of the sample.

During automated operation (i.e. when the UltrA Autosampler is attached) the cycle time must be set according to the total run time of the GC and the time required for the oven to return to the initial temperature.

As mentioned in the preceding text, the cold trap of the TD is similar to a sorbent tube, although of a much narrower bore to allow the analytes to be rapidly released upon the ballistic heating. In similarity to the selection of sorbents for the sorbent tubes, the properties of the sorbent contained within the cold trap can be selected to best suit the analytes being assessed. During this project, a general purpose graphitised carbon sorbent was selected—suitable for the NMVOCs that were repeatedly detected in the tubes. In a similar method to the conditioning of the sorbent tubes, a cold trap can be conditioned if it becomes apparent that there is an undesirable level of carry over contamination between samples; however, this is not frequent as the higher trap desorb temperature than the tube desorb temperature ensures that all analytes released from the sorbent tube will be released from the cold trap upon heating.

Thermal Desorption Methods

During the initial sampling and method development stages of the project, the thermal desorption methods underwent minor revisions to accommodate the two different sorbent tubes that had been selected for the field sampling. The moderate hydrophilic Carbotrap 300 sorbent captured far more moisture during sampling then the Tenax TA tubes and this had a marked impact on the experimental

results. Two different methods were used to thermally desorb the analytes from the sorbent tubes, as seen in Table 13.

Table 13: Instrument controlling parameters for the thermal desorption of the Tenax TA and Carbotrap 300 sorbent tubes

Parameter	Tenax TA	Carbotrap 300
Purge (min.)	1.0	5.0
Tube Desorb Time (min.)	5.0	5.0
Temp. (°C)	250	250
Trap low (°C)	-10	+30
Trap High (°C)	290	300
Trap Hold (min.)	5.0	5.0
Trap Heating Rate (°C/s)	MAX	MAX
Flow Path Temp (°C)	150	150
Splits (Purge/Tube/Trap)	Y/N/Y	Y/N/Y

As the project developed and the sampling techniques were refined, the thermal desorption parameters were refined until one method was developed that was appropriate for both the Tenax TA and Carbotrap 300 sorbent tubes. As can be seen in Figure 32, it has been influenced strongly by the initial Tenax TA method; however, has been optimised for efficient analysis of Tenax TA, Carbotrap 300 and dual sorbent Tenax TA and Carbograph 1TD sorbent tubes.

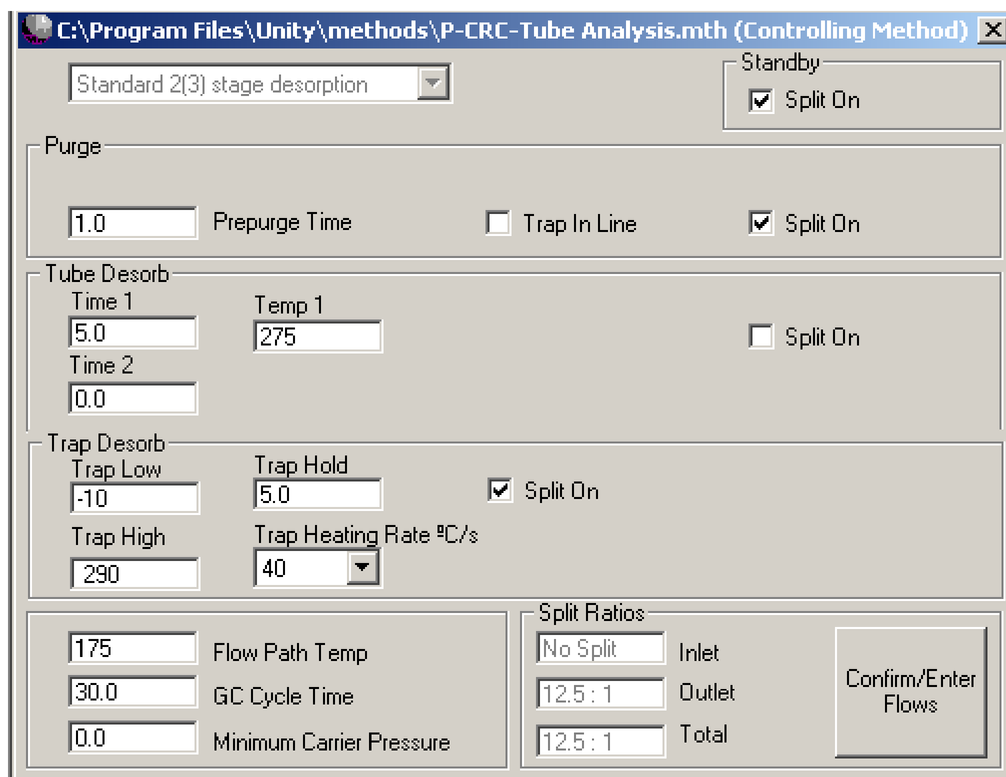

Figure 32: Screen capture of the TD software illustrating the final thermal desorption parameters that were used for all sorbent tube samples

3.3.3.2 Gas chromatograph operation and parameters

The unknown facets of the speciation lead to the use of very general GC operating parameters for the initial sample analysis; however, once the quantity and variety of compounds was understood, this method was refined to an optimal level to reduce total sample analysis time and increase peak separation.

Carrier Gas

The GC was supplied with ultra high purity helium carrier gas (He - 220G, BOC Gases, Sydney, NSW Australia). The electronic pneumatic control module of the GC controlled the gas pressure though the TD and through the GC. Helium has been extensively used in gas chromatography due to its very low molecular (cf. atomic) mass, inertness and non-polar properties.

Column type

The use of fused silica capillary columns in gas chromatography has resulted in increased accuracy and lower detection limits for trace level analysis. These columns are available in different polarities—the analyte mixture that is being separated will determine whether a polar, non-polar or an intermediate polarity column will be selected. The interactions of the analytes within the sample are responsible for the retention time of the particular molecule, and these interactions are physical more so than chemical—with adsorption/desorption (or simply sorption) and porous layer open tubular (PLOT) columns, the affinity for the chemical species is governed by the size, surface charge and van der Waals forces. Combining these factors determines the retention time and therefore elution order of the chemical species.

For the initial sampling, a general purpose (5%-Phenyl)-methylpolysiloxane (HP-5ms, Agilent Technologies, North Ryde, NSW Australia) column was used. This non-polar column is suitable for semi-volatiles, alkaloids, drugs, fatty acid methyl esters (FAMEs), halogenated compounds, pesticides and herbicides. It allowed for the initial identification of the varieties of species within the samples; however, as the results of the initial sampling became clear, and the characteristics of the species being detected were established, a column with a significantly higher polarity was installed.

The polar column that was subsequently chosen was a polyethylene glycol column (HP-INNOWax, Agilent Technologies, North Ryde, NSW Australia)—suitable for alcohols, aromatics, essential oils and solvents. This column was far more suitable to the low molecular mass mildly polar species that were consistently being detected in the samples and allowed for separation of the co-eluting peaks—leading to increased reliability and improved identification of odorants when used concurrently with the olfactory detection port.

During different sampling campaigns, replicate samples were collected in order to analyse them on different columns to ensure that polar column in use was most suitable. These duplicates were analysed on moderately polar columns (DB-VRX, J&W Scientific, and HP-624, Agilent Technologies) with essentially identical stationary phases.

The vast majority of the samples were analysed on the polar (HP-INNOWax) due to the late acquisition of the considerably more suitable DB-VRX column. Time restrictions did not permit repeat sampling or quantification of the DB-VRX data sets; however, it is strongly recommended that all future work would be carried out on this column.

Injection Method

One advantage of fused silica capillary columns over traditional packed columns is the small injection volumes that can be directly injected onto the column. This ensures that all the analytes within the sample matrix will pass to the detector ensuring the accurate representation of the emission source. With the use of the thermal desorber, a split-less injection was performed to ensure that all the analytes within the sample were injected onto the column to maximise the number of compounds identified within the samples.

Flow rate

The retention time and elution order of analytes within a given sample result from the interaction of the analytes and the stationary phase of the column. The flow rate of the carrier gas can influence the

elution time but not the order of elution—considerations must be given to the operation of the detector that is being used. This is of significance to the use of a MSD, which is under high vacuum—if the carrier gas flow rate is too high, the pumps of the MSD will not be able to create and maintain the level of vacuum required for proper operation.

Whilst the initial sample analysis only employed the MSD, the later sampling employed a second detector—the olfactory detection port (ODP) (Gerstel ODP2, Gerstel GmbH & Co., Germany) which consequently required the effluent from the GC column to be split between the two detectors. This dictated that the carrier gas flow provided sufficient pressure at the end of the column in order to maintain positive flow to the ODP, whilst preserving the vacuum of the mass selective detector. If this balance is not correctly maintained, the MSD could be effectively open to the atmosphere, creating an air leak and potentially damaging the instrument.

Oven Temperature Program

As mentioned in the introduction the GC section, the initial sample analysis employed a very general method—the oven temperature profile was initially a single temperature ramp from 50 °C to 250 °C, with a total run time of 44 minutes. Initial temperature (50 °C) was held for 2 minutes before the temperature was increased at 5 °C/min to the final temperature of 250°C which was held for 2 minutes. This programme appeared to be suitable for the elution of the compounds; however, there was a significant amount of free space (dead time) during which no compounds were eluting. Consequently the temperature programme was modified, to include two temperature ramps, and a lower final temperature. The initial temperature was kept at 50 °C and the first temperature ramp 5 °C/min to 125 °C, then a second temperature ramp of 10 °C/min to 200 °C, which was held for 2 minutes. The first allowed for the elution of the closely related n-C_4 compounds with adequate separation, and also gave enough time for the elution of the higher polarity (cf. higher boiling point) species to elute.

3.3.3.3 Mass selective detector (mass spectrometer) operation and parameters

The mass selective detector (MSD) provides chemical speciation as well as quantification; it is a flexible detector capable of characterising complex samples efficiently for a wide range of chemical compounds. The operating parameters are controlled by the ChemStation Software, and there are two modes of operation in which the MSD can operate; *scan* and s*elected ion monitoring* (SIM). Scan operates the MSD as a continuous scan from a preset range, whilst in SIM mode, the MSD is programmed to target specific m/z ions during specific time windows. The SIM mode is best when the composition of the samples that are being analysed is vaguely understood. This was not the case with the majority of the poultry samples; consequently the use of the scan mode was engaged for all the samples.

Manually controlled operating parameters

The scan parameters were initially set to 50–550 m/z, which was a basis for the initial results; however, upon the further interrogation of the preliminary results, it was determined that the scan range should be increased to detect the lower m/z fragments of many of the compounds. To avoid influence from any traces of air and moisture that may be present during the elution of the compounds, a lower m/z of 35 was chosen. This would allow for many of the n-C_4 fragments in the 40–50 m/z range to be detected and thus increase the reliability of the matches to the mass spectral databases.

Automatically configured operating parameters

The operating parameters pertaining to the stable function of the MSD were controlled automatically by the ChemStation (Agilent Technologies, North Ryde Sydney Australia) software, tuning the instrument allowed for the correct voltages to be configured to ensure the system functioned properly.

Databases, spectral matching and compound identification

Two databases were used for the identification of the compounds eluting from the samples: NIST02 database and Wiley275 database. The former is issued by the National Institute of Standards and Technologies and the other is produces by the science publishing house Wiley InterScience. Once a

reliable spread of compounds had been positively identified, several neat standards were purchased to provide retention time matches and also to perform the quantification of the method.

3.3.3.4 The olfactory detection port operation and parameters

The olfactory detection port (ODP) (see Figure 33) was operated in tandem to the MSD and allowed for the simultaneous identification of the odorants that were present among the suite of NMVOCs.

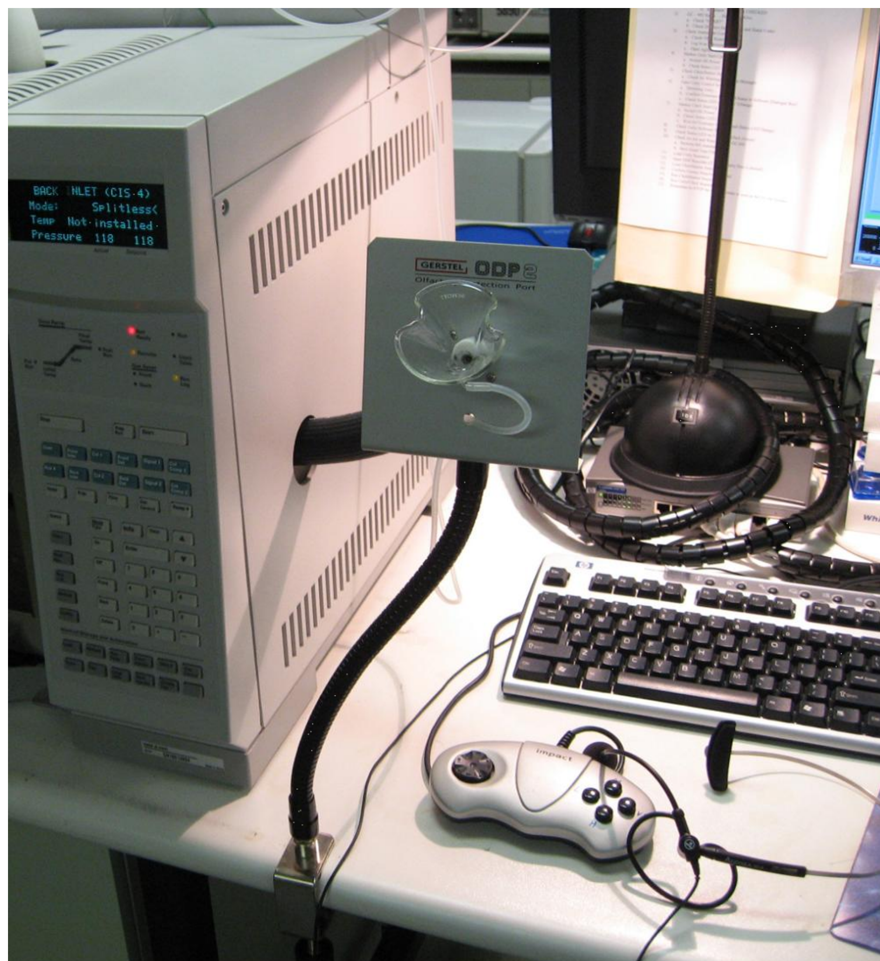

Figure 33: Gerstel olfactory detection port connected to the Agilent 6890N GC. *Seen in the lower frame is the Odour Input Device (OID) consisting of the control pad and headset microphone*

The function of the ODP, as implied by its name, is to detect compounds that promote an olfactometric response from an *operator*. This detection can occur as a presence/absence result or a relative quantity of odour—the quantity of which is described by five discrete levels: absence (0), barely detectable (1), easily discernable (2), significantly odorous (3) and highly odorous (4). The results are recorded using the Gerstel ODP Recorder which integrates with the Agilent ChemStation to provide chromatographic spectra for both the total ion chromatogram and the odorant profile chromatogram.

An additional function of the ODP is the ability to record an odorant descriptor to qualitatively characterise the odour, in similarity to recording a hedonic tone. This descriptor can be used to identify closely eluting peaks or empirically to global impact on the whole odour. Descriptors are used either to classify or specifically identify the odorant, the operator records a comment for later playback that describes the characteristic of the odour. As both the strength of the odour is recorded and the characteristic of the odorant, this is an empirical method to establish which of the compounds within the overall matrix may have the most impact on a receptor.

During the analysis of the samples, a small capillary splitter (Figure 34) diverted a calculated amount of the sample to the ODP, whilst the remainder of the flow continued to the MSD. This split ratio was calculated at the initial temperature of the oven. As the temperature of the oven increased, the volumetric flow rate was kept constant by the electronic pneumatic control module of the GC. This allowed for the flow rate of each of the effluent flow paths to be maintained at the desired ratio.

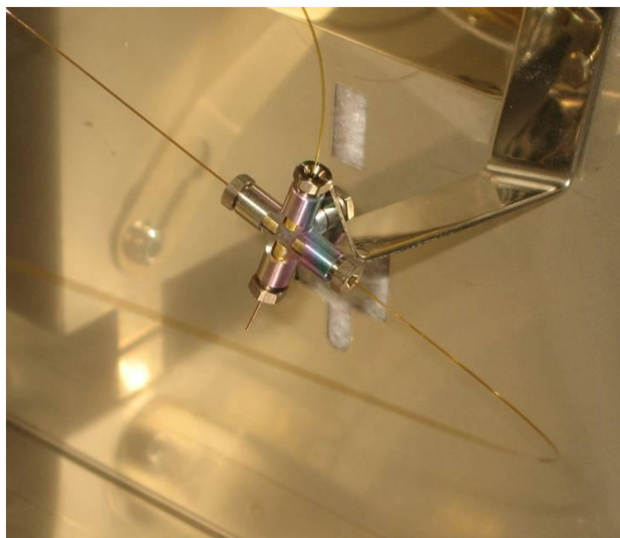

Figure 34: Capillary splitter; low volume cross piece

Although there is a calculated delay between the arrival of the compound at the MSD and the ODP, their respective detection times will differ. The calculated delay is substantiated by the flow of fluids through different capillaries, which are known, to the respective detectors; however, there is a secondary influence on the detection time of a given odorant at the ODP and that is the operators' response. This *operator delay* results from a combination of physiological factors including respiration rate, neural response times and reflex speeds.

The operator records their response to the odour using the odour input device (see Figure 33). Whilst recording their response, the operator can also record a descriptor of the odorant. This can be used to identify the compound from neighbouring non-odorous peaks in the total ion chromatogram, and it can also determine whether the compound is likely to contribute to the overall characteristic of the odour.

3.3.3.5 Quality assurance and quality control—blank samples

Consistent documentation of all samples collected, coupled with instrumentation logs, allowed for the scrutiny of the results. Of particular significance was the use of blank tubes to ensure the samples analysed were free from or contained minimal uncertain contamination. Each sorbent tube that was sampled in the field or the laboratory was thermally conditioned to the manufacturer's specifications and then analysed to confirm all traces of analyte had been removed before the sorbent tube was sampled. Additionally, field blanks, ambient samples and laboratory blanks were also collected. Field blanks being tubes that were transported with the actual samples but remained sealed during the return trip from the laboratory to the field. Ambient samples were pumped sorbent tubes collected from the ambient air stream immediately upwind of the poultry shed ventilation inlet. Laboratory blanks were sorbent tubes that remained sealed in the laboratory whilst the balance of the tubes were in the field. All of these blank tubes were analysed under identical conditions when the field samples were analysed. The importance of the collection of field blanks was the ability to determine what compounds were present in the ambient air entering the shed; to enable discrimination of compounds produced in the shed.

3.3.4 Manure moisture analysis

Manure moisture content was determined using Australian Standard 4454–2003 (Standards Australia, 2003).

A proportion of each sample (approximately 50 g) was placed in an individually identifiable 100 mL ceramic evaporating dish. Each dish was dried at 105 °C and weighed before the addition of manure. The manure was immediately weighed to ascertain a wet sample weight. All samples were dried in an oven at 105 °C overnight. After cooling in a desiccator cabinet, the dry manure samples were weighed. To calculate wet basis moisture content, Equation 5 was used.

$$\%\,Moisture\ content = \frac{m_2 - m_3}{m_2 - m_1} \times 100\% \qquad \text{Equation 5}$$

Where m_1 = mass of the dish (g)
m_2 = combined mass of the dish and manure (g)
m_3 = combined mass of the dried dish and manure (g)

All samples collected were analysed individually in order to assess intra-shed variability of moisture content.

Contour plots were drawn using Surfer® version 7 (Golden Software Inc. Colorado USA) to visually assess moisture content differences.

3.4 Data processing

3.4.1 Olfactometry data processing

3.4.1.1 Averaging of duplicates

Odour samples were collected into two drums (duplicate odour samples) and each drum was analysed independently by the olfactometer. The odour concentrations values for these duplicate samples were averaged using their geometric mean, producing a single odour concentration value for each sampling time.

Collection and analysis of duplicate samples is recommended by the AS/NZS 4323.4:2001 because it reduces variability in the measured odour concentration and improves confidence in the olfactometry result. Analysis of duplicate samples also provides one way to identify the amount of variability in olfactometry results. If the detection threshold for duplicate samples is measured to be exactly the same, it is reasonably likely that the olfactometer has measured the true result of the sample. However, if the detection threshold for duplicate (and assumed to be identical) samples is found to be quite different, confidence in the results may be reduced.

3.4.1.2 Removal of duplicates with excess variability

AS/NZS 4323.3:2001 (clause 8.3.2) requires calculation of repeatability and accuracy for an individual olfactometer. The olfactometer needs to comply with these requirements, which are measured using a reference testing material (40 ppb *n*-butanol gas). The assumption is then made that these repeatability and accuracy measurements are transferrable to the measurement of unknown samples. Accuracy defines the ability of the olfactometer to determine the ‘true’ result of an odour sample. Repeatability defines the ability of the olfactometer to measure the same sample multiple times and obtain the same result.

Exclusion of data from olfactometry analysis due to excessive variability is not covered in the Standard. However, if the ratio between duplicate odour samples was greater than the repeatability ratio of the olfactometer (given $r = 0.318$ and $10^r = 2.08$ for the DEEDI olfactometer) then we believe that the detection threshold for the duplicate samples was questionable, and it would be reasonable to exclude both duplicate results on the basis that they do not fit the 95% confidence band. Consequently, we applied this filtering rule to the olfactometry data analysed by the DEEDI olfactometer and 6.2%

of the total number of duplicate samples analysed during the project were excluded from further analysis. The duplicates discarded are shown in Appendix 3.

For the ETC olfactometry, variability between duplicates was within the repeatability value for the olfactometer, and within the Australian Standard requirements, and consequently no results were discarded.

3.5 Summary of methodologies

- Odour, dust and NMVOC emissions were measured at two tunnel ventilated layer farms over a 4 to 5 day period.
- Samples were collected from within a temporary flexible duct that was attached to one of the tunnel ventilation fans.
- Odour concentration was measured using dynamic olfactometry to AS/NZS 4323.3:2001. Two laboratories were used, and comparative testing was conducted between the laboratories to ensure comparability of odour concentration measurement.
- Dust was measured using a DustTrak™ and an aerodynamic particle sizer (APS). Isokinetic sampling techniques were used.
- NMVOCs were collected using sorption tubes for subsequent analysis with a TD-GC-MS/O. Sampling and analysis techniques, including the selection of sorbents, were refined during the project, resulting in the development of an improved method for measuring NMVOC emissions from poultry sheds.
- Ventilation rate was estimated by measuring fan airspeeds or by calculating the flow rate through each active fan using manufacturer supplied fan flow rate date (and adjusting for shed static pressure), which was selected as the preferred method.

4 Odour emission rates

From July 2007 to June 2008, 55 odour measurements were made at two layer farms, one located in southern Queensland (Farm D), the other located in southern Victoria (Farm E). Emissions from each shed were measured in summer (December in QLD and February in Victoria) and winter (July in QLD and June in Victoria).

Manure removal practices were slightly different for each farm. Farm D cleaned the manure belts twice per week, whereas Farm E cleaned the belts once per week. In order to integrate with the cleaning activities of each farm, samples were collected on different days in relation to the manure loading on the belts. Emissions were monitored on four days spanning the time between belt cleaning.

Odour, particulate number and concentration, volatile organic compounds, ventilation rate and manure moisture data was collected. The full dataset is provided in Appendix 4 to Appendix 7.

Figure 35 to Figure 37 display all odour emission data measured at the layer farms. The spread of data can be explained by the range of conditions expected from summer and winter. Each season will be discussed separately in Section 4.1.

Odour data can be displayed using different units: three have been chosen to display the total odour emission rate and odour emission rate according to the number of birds and total live weight.

Figure 35 displays the emission rate data using units of odour units per second (ou/s), which is the total emission rate from the shed. Emission rates ranged from 2882–24,907 ou/s.

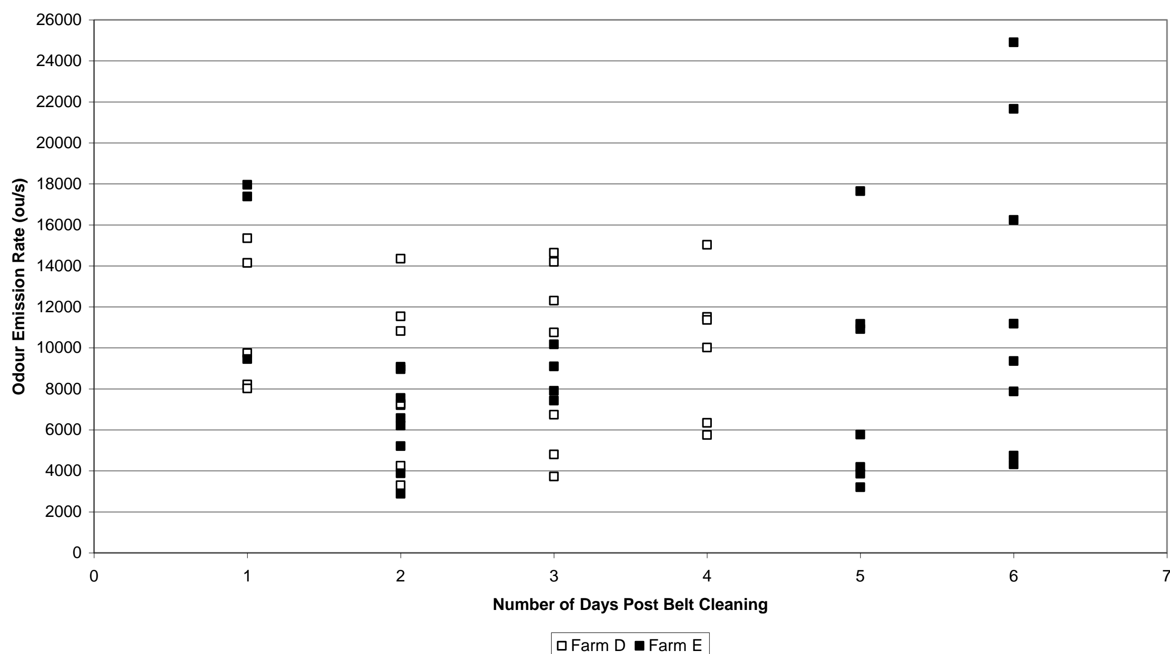

Figure 35: Odour emission rate per second for Farm D and Farm E

Figure 36 displays the emission rate data in terms of odour units per second per 1000 birds (ou/s/1000 birds), which is the total emission rate from the shed, taking into account the number of birds housed. This measure can be used to compare sheds of different sizes. Emission rates varied from 58–512 ou/s/1000 birds. Farm D housed less birds compared to Farm E (30,000 compared to 50,000). Figure 36 shows that the odour emission rate per bird at Farm D was higher than Farm E.

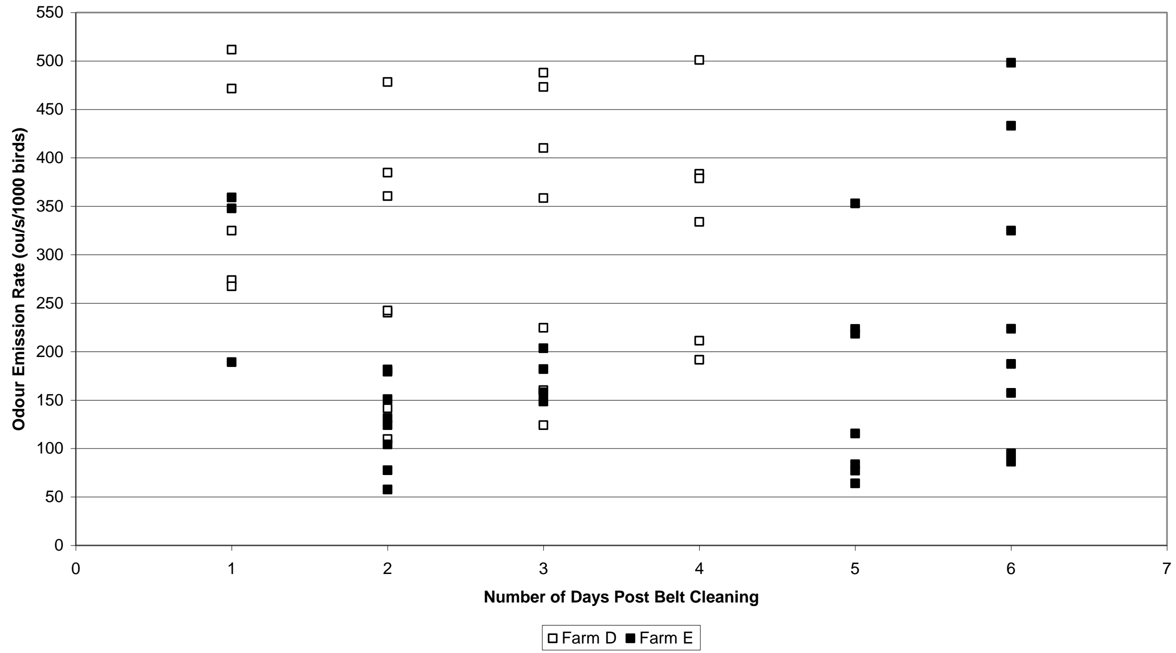

Figure 36: Odour emission rate per 1000 birds for Farm D and Farm E

Figure 37 displays the emission rate data using units of odour units per second per kilogram (ou/s/kg), which is the total emission rate from the shed, taking into account the total weight of the birds. This measure can be used to account for variation due to different shed sizes and bird age. Emission rates varied from 0.03–0.27 ou/s/kg.

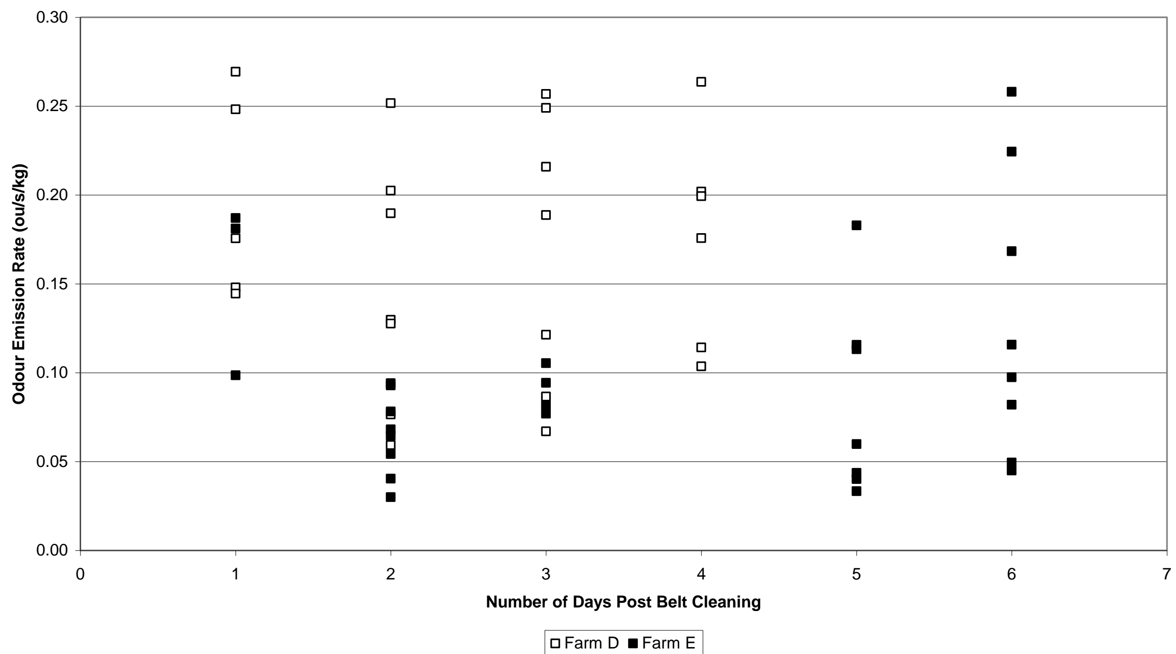

Figure 37: Odour emission rate per kilogram for Farm D and Farm E

4.1 Seasonal and location variability

4.1.1 Summer odour emission rates

Odour measurements collected in summer are shown in Figure 38. The emission rate from Farms D and E remained relatively constant over the monitoring period. The emission rate on the first day following belt cleaning was slightly higher than on the subsequent days. There was no apparent rise in emission rates as the quantity of manure accumulated in the shed (when manure accumulated for up to 6 days). The odour emission rate per 1000 birds measured at Farm D ranged from 242–512 ou/s/1000 birds, and for Farm E ranged from 58–359 ou/s/1000 birds.

A duplicate odour sample was collected from Farm E while the farm staff were cleaning the shed of accumulated feathers and dust. The data point circled in Figure 38 indicates the measurement from this time. This management activity did not appear to cause a substantial elevation in odour emissions.

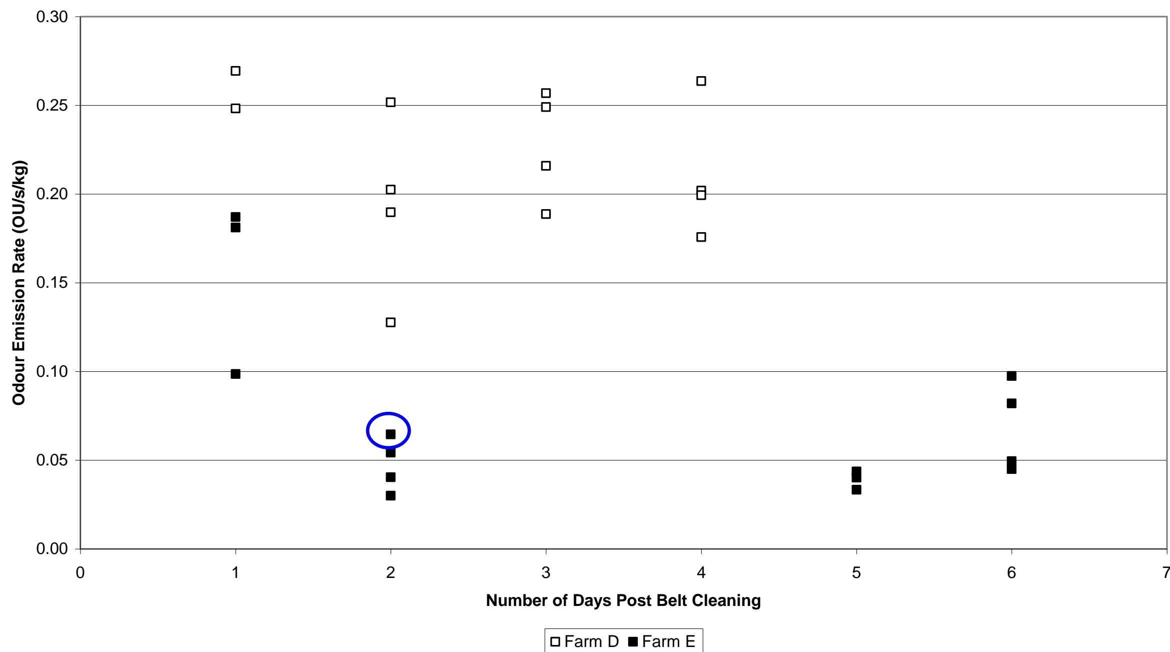

Figure 38: Summer odour emission rate per 1000 birds for Farm D and Farm E

The comparatively low emission rates measured at Farm E may have been due to the unseasonably cold weather experienced during this week. Figure 39 illustrates the 25 year mean maximum temperature for the weather station located near Farm E. For February (circled), the long term mean maximum temperature was 25.2 °C, whereas the mean maximum temperature recorded for February 2008 was 22.9 °C (http://www.bom.gov.au/jsp/ncc/cdio/cvg/av, accessed 23 March 2009). As a result of the cooler weather conditions, ventilation rates were lower than expected and therefore calculated odour emission rates were lower.

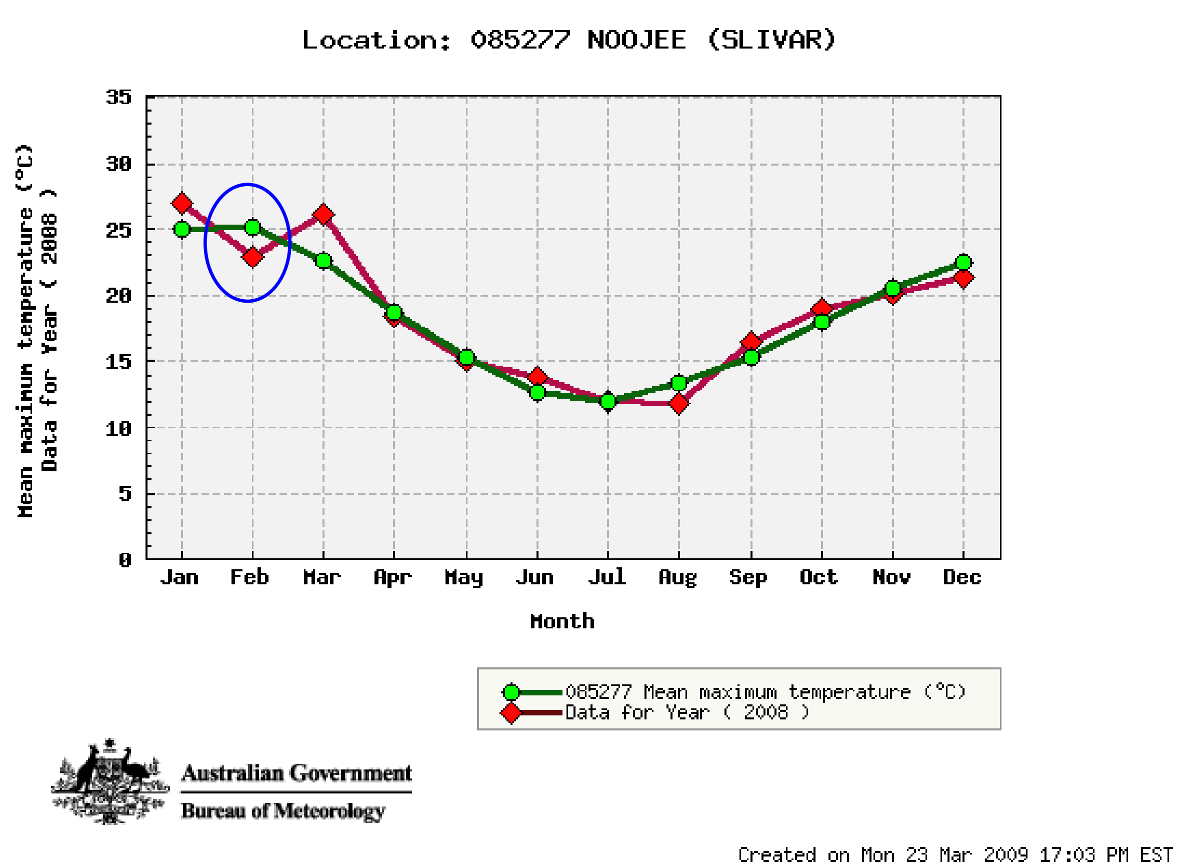

Figure 39: 2008 temperatures compared to long term mean maximum temperature for the Victorian location

Figure 40 illustrates the ventilation rates under which odour measurements were taken. It can be seen that for Farm D, the range of ventilation rate was 27–91% of maximum ventilation rate, whereas for Farm E, the range of ventilation rate was 13–38%. The exception to this is one measurement taken during shed cleaning where a ventilation rate of 62.5% was obtained due to the fans being manually increased by the farm staff (while they used motorised garden blowers to blow dust and feathers out of the shed) (see circled point in Figure 38 and Figure 40).

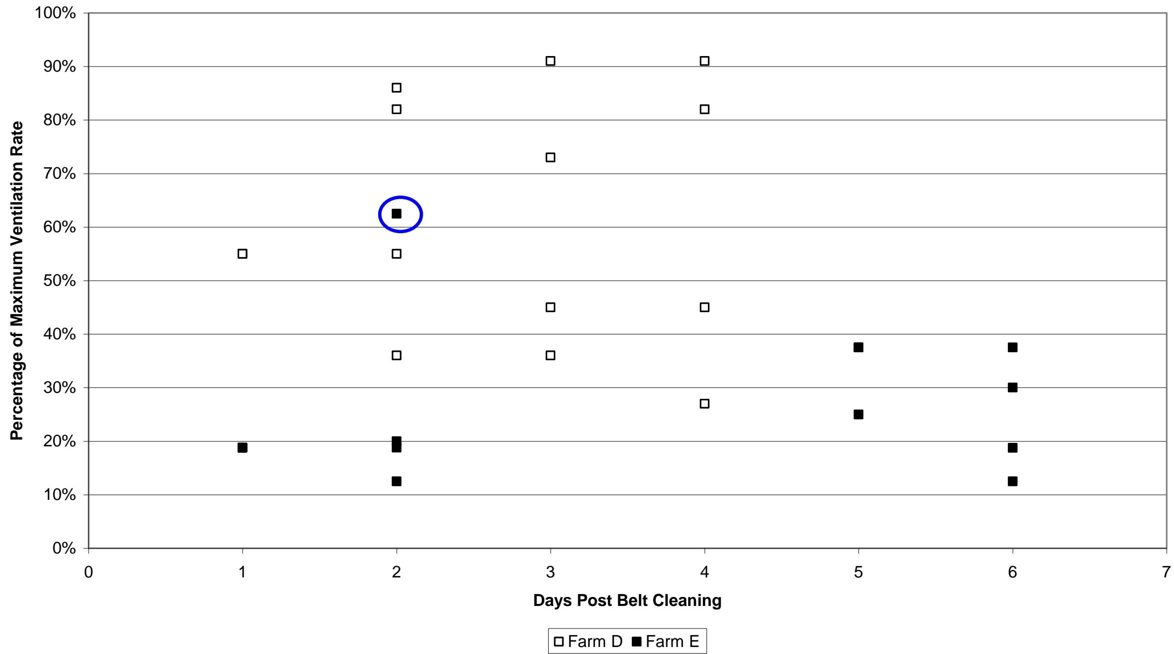

Figure 40: Summer Percentage of Maximum Ventilation Rate for Farms D and E

The data collected from the continuous ventilation monitoring equipment installed at Farm D is shown in Figure 41. Apart from the first day (where the ventilation rate did not increase during the time when measurements were collected), data was collected over the range of morning ventilation rates.

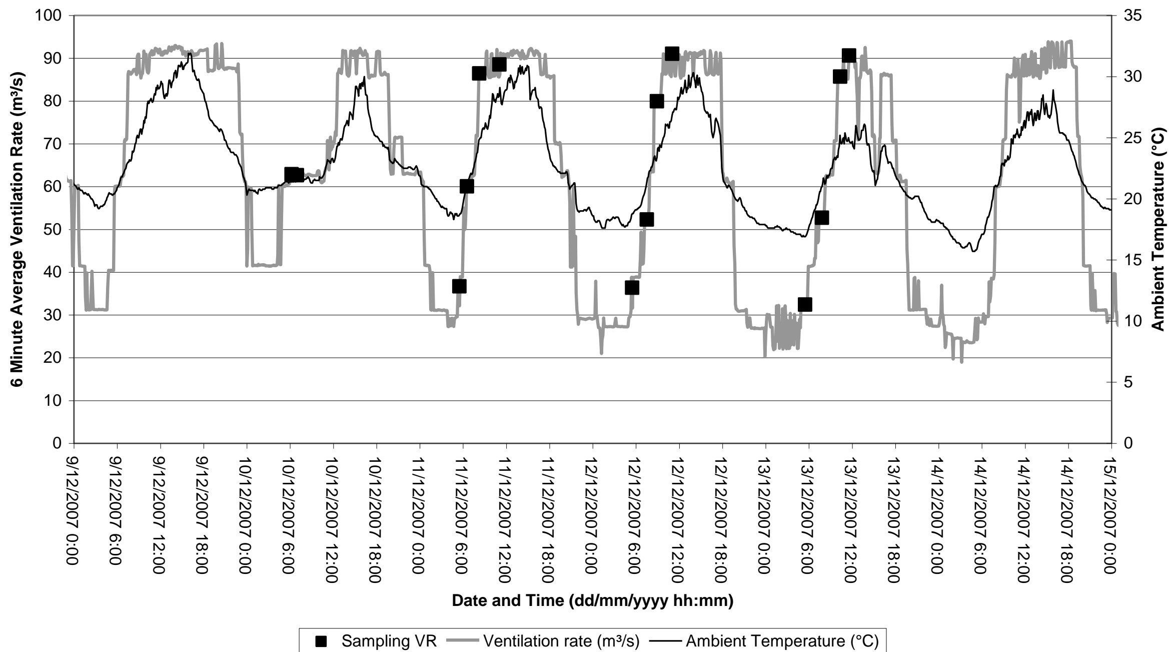

Figure 41: Summer ventilation rate and ambient temperature measured at Farm D

It is difficult to compare the emission rates measured in terms of farm location due to the unseasonal climatic conditions experienced at Farm E. The lower odour emission rates measured at Farm E may not have occurred if the unusual weather conditions had not occurred. However, from the data collected during summer, it can be said that odour emission did not appear to increase as manure accumulated on the belts.

4.1.2 Winter odour emission rates

Odour measurements collected in winter are shown in Figure 42. The emission rate from Farms D and E were more variable than what was measured during summer. For Farm D, odour emission rates were highest the day following cleaning of the manure belts. For Farm E, odour emission rate increased with each day of additional manure accumulation. Odour emission rate per 1000 birds measured at Farm D ranged from 110–325 ou/s/1000 birds, and for Farm E ranged from 115–498 ou/s/1000 birds.

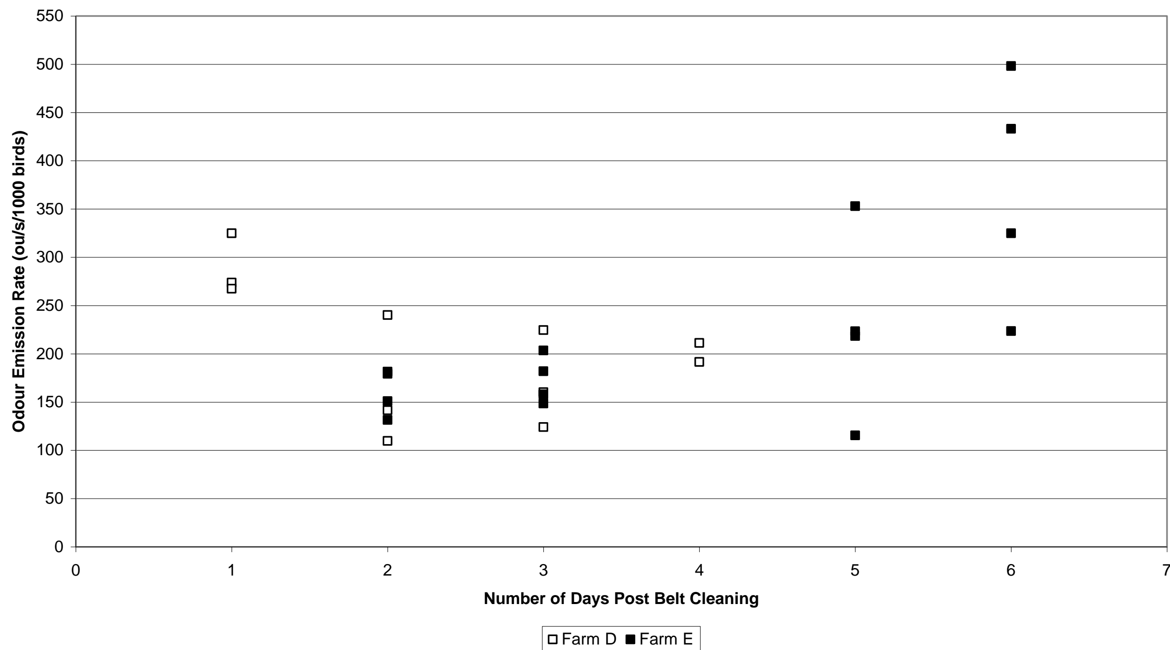

Figure 42: Winter odour emission rate per 1000 birds for Farm D and Farm E

The climatic conditions for the week that measurements were collected at Farm E were unseasonably warm. Figure 43 illustrates the 25 year mean minimum temperature for the weather station located near Farm E. For June, the long term mean minimum temperature was 4.0 °C, whereas the mean minimum temperature recorded for June 2008 was 6.5 °C (http://www.bom.gov.au/jsp/ncc/cdio/cvg/av, accessed 23 March 2009). As a result of the warmer weather conditions, ventilation rates were higher than expected and therefore odour emission rates were higher.

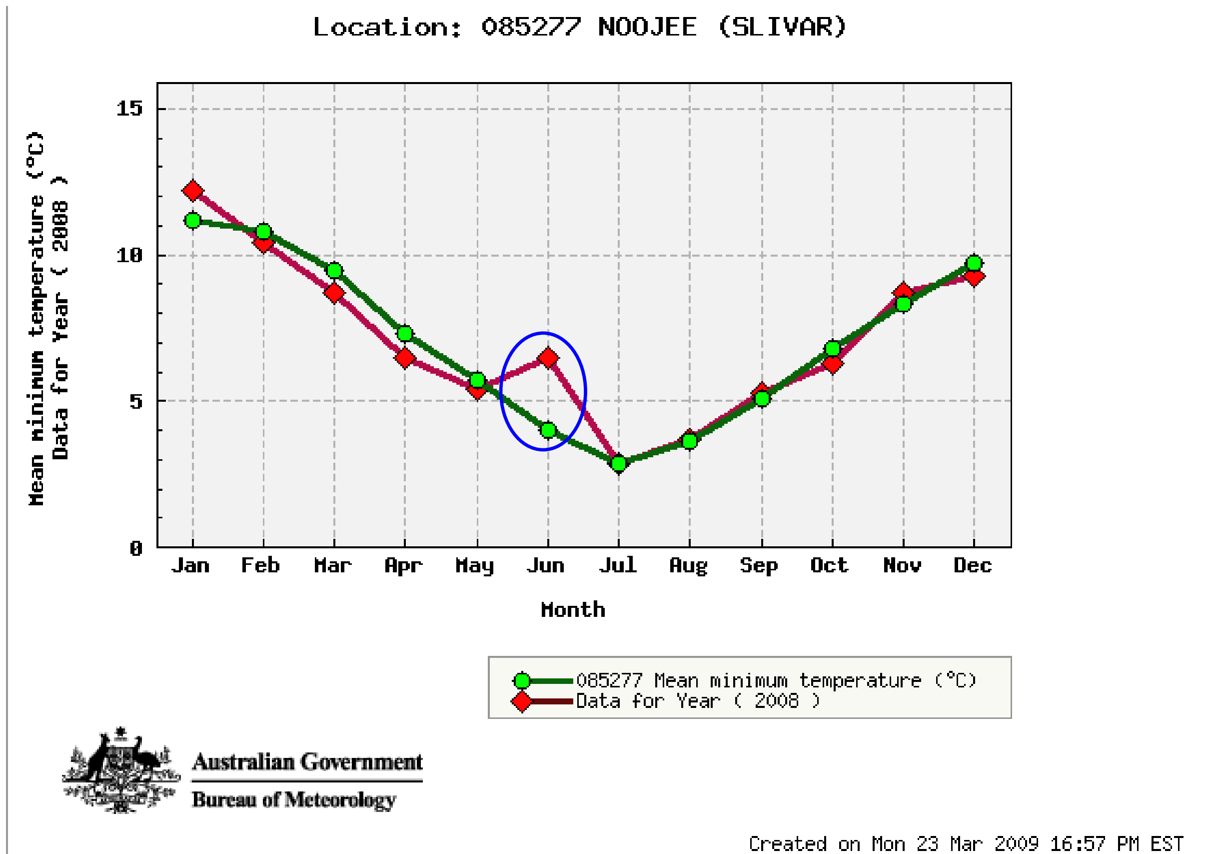

Figure 43: 2008 temperatures compared to long term mean minimum temperature for the Victorian location

Figure 44 illustrates the ventilation rates under which odour measurements were taken. It can be seen that for Farm D, ventilation rates varied from 9–27% of maximum ventilation rate, and for Farm E, varied from 9–25%. Anecdotal evidence provided by farm staff at Farm E indicated that the typical winter ventilation rate was approximately 6% of maximum possible ventilation rate.

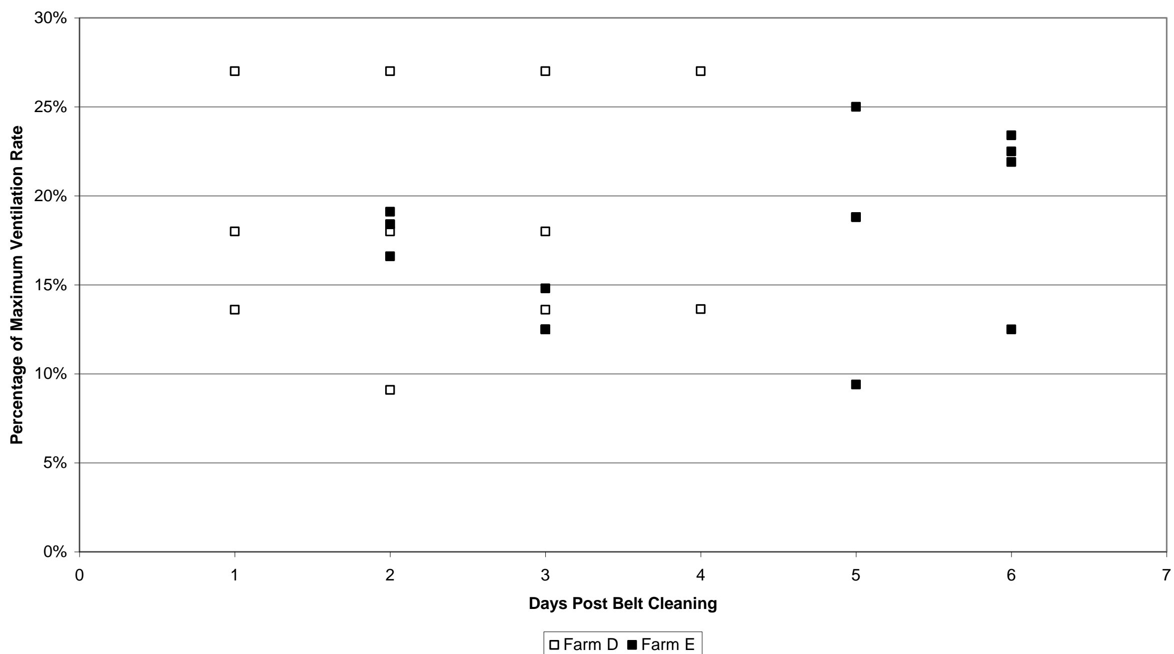

Figure 44: Winter percentage of maximum ventilation rate for Farms D and E

The data collected from the continuous ventilation monitoring equipment installed at Farm D is shown in Figure 45. Odour measurements were made over a reasonable range of the recorded ventilation rates.

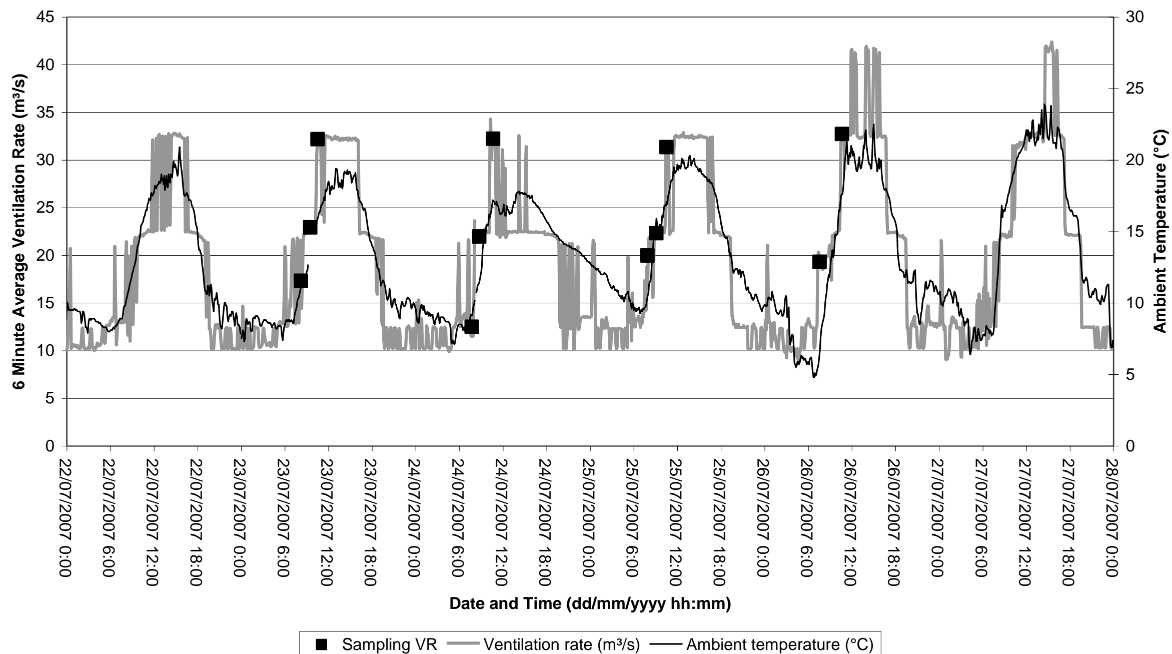

Figure 45: Winter ventilation rate and ambient temperature measured at Farm D

Variability of winter odour emissions due to farm location is difficult to assess due to the unseasonably warm conditions experienced at Farm E. The data collected indicates that in Queensland, where trends in ventilation rate were repeated over consecutive days, odour emission declined as manure accumulated in the shed. In Victoria, where the ventilation rate increased with each additional day of manure accumulation, odour emission rate also increased. Statistical analysis of the layer odour data was not recommended due to the unseasonal weather conditions experienced at Farm E.

4.2 Odour emission rate relationships

Data was analysed to identify any relationships that may exist between odour emission rate and other variables measured on–farm. The effect of ventilation rate and ambient temperature on odour emissions is discussed below.

4.2.1 Effect of ventilation rate on odour emissions

The ventilation rate measured at the time of each odour sample collection was assessed in order to identify any possible relationships between odour and ventilation rate. The relationship between odour concentration and ventilation rate is shown in Figure 46. Odour concentration was considerably less when ventilation rate increased above 30 m³/s.

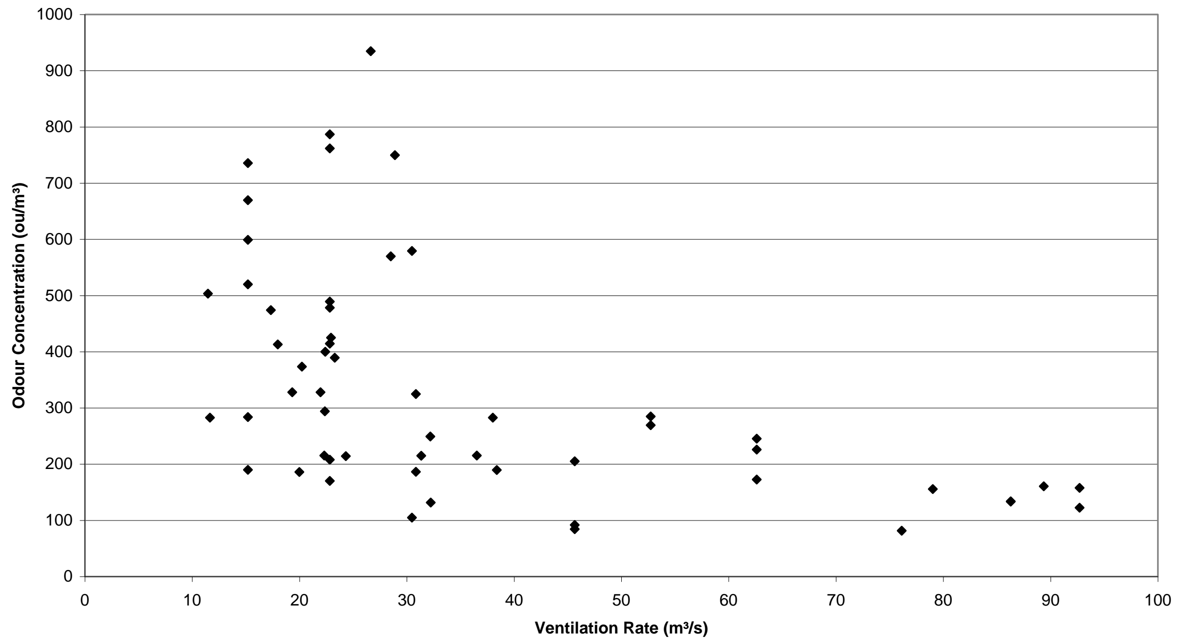

Figure 46: Layer odour concentration with increasing ventilation rate

The relationship between OER per 1000 birds placed and ventilation rate is shown in Figure 47. Emission rate tended to increase as ventilation rate increased up to approximately 40 m^3/s, after which emission rate levelled out as ventilation rate continued to increase.

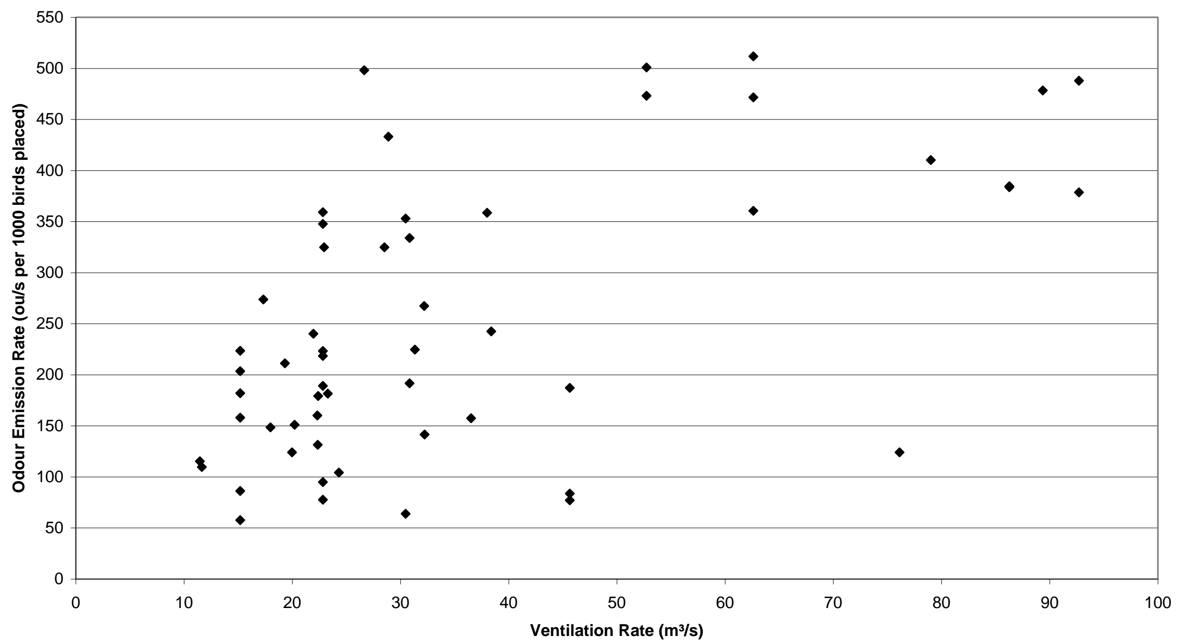

Figure 47: Layer odour emission rate per 1000 birds placed with increasing ventilation rate

4.2.2 Effect of ambient temperature on odour emissions

The relationship between ambient temperature (°C) and odour concentration is shown in Figure 48. There is a downward trend in odour concentration as ambient temperature increases.

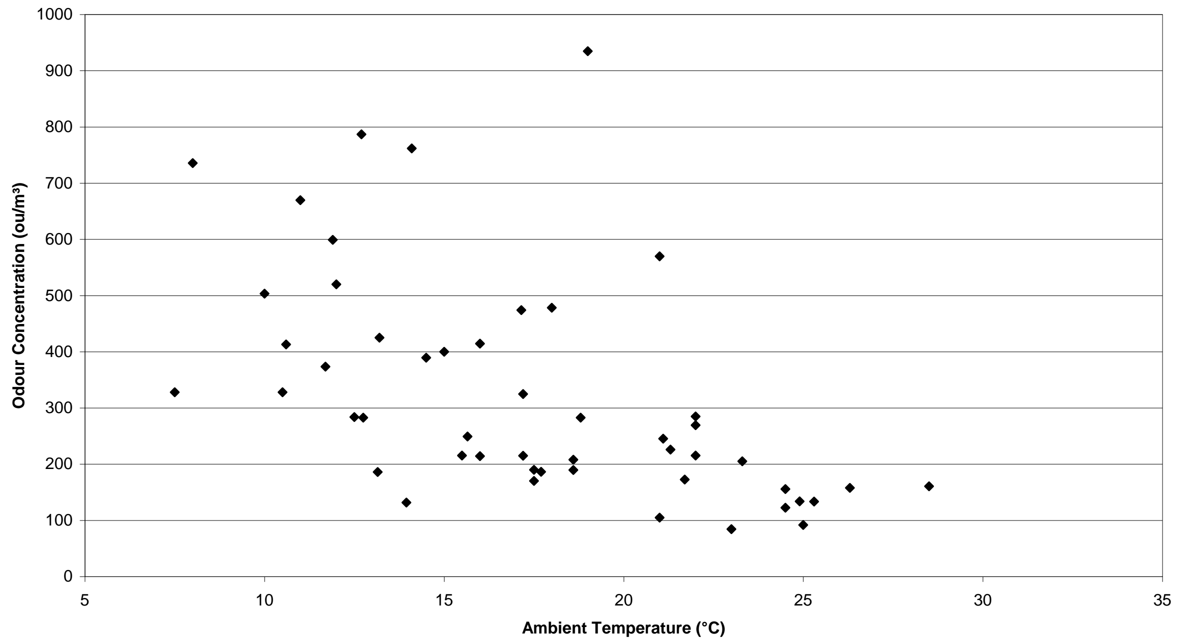

Figure 48: Layer odour concentration with increasing ambient temperature

The relationship between ambient temperature (°C) and odour emission rate per 1000 birds placed is shown in Figure 49. Odour emission rate tended to increase with ambient temperature. This was expected to occur as ventilation rate generally increases with ambient temperature in order to maintain correct target temperature for optimal bird performance (see Figure 50). As a result, increasing ventilation rate usually results in increased odour emission rate.

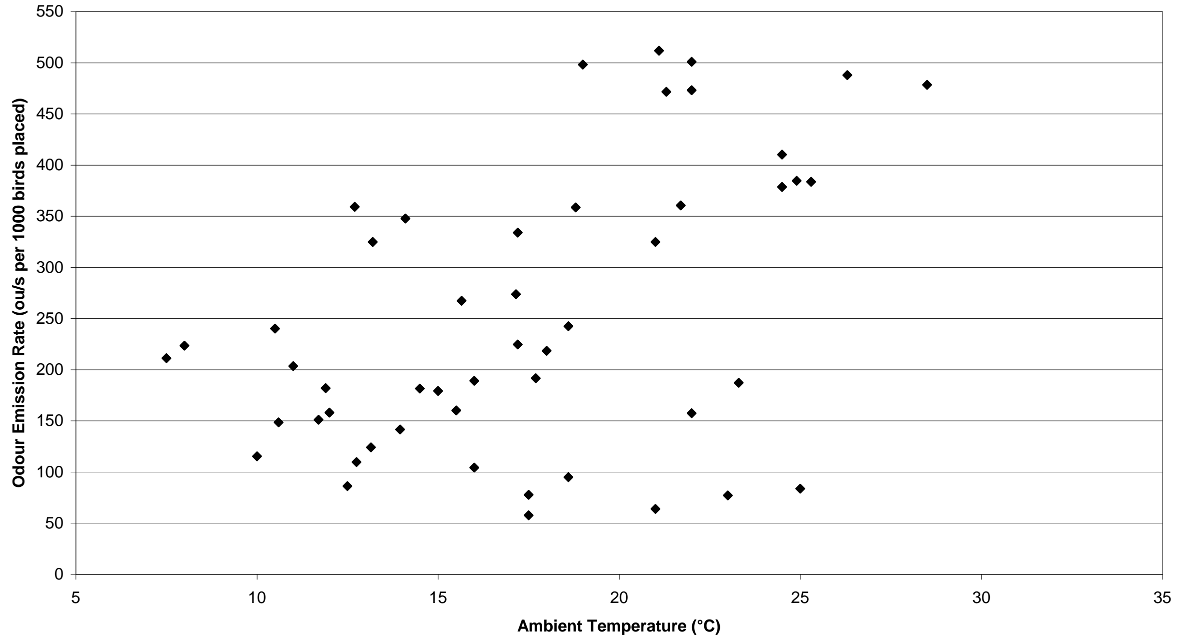

Figure 49: Layer odour emission rate per 1000 birds placed with increasing ambient temperature

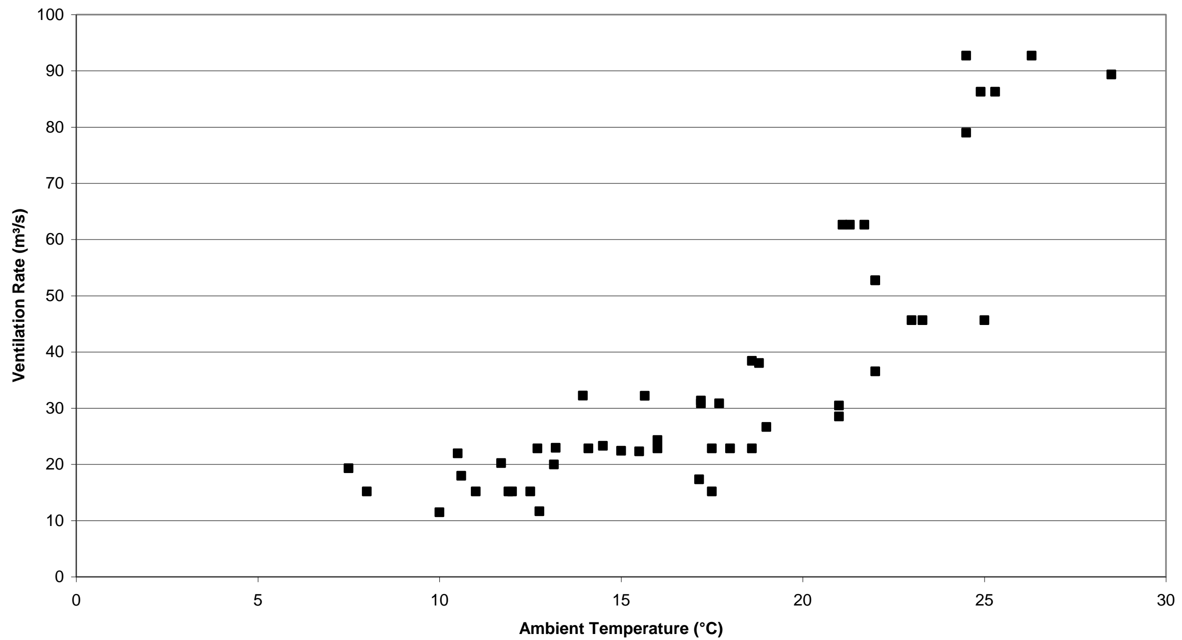

Figure 50: Layer ventilation rate with increasing ambient temperature

4.3 Summary of layer odour emissions

Odour emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight).

- From July 2007 to June 2008, 55 odour emission measurements were made at two layer farms located in Queensland and Victoria.
- Odour emissions were measured over four days in conjunction with manure belt cleaning – either four consecutive days following belt cleaning, or two days before and two days after belt cleaning.
- The majority of layer odour emission rates ranged from:
    - 2000–16,000 ou/s
    - 50–500 ou/s per 1000 birds placed
    - 0.03–0.26 ou/s per kg live weight (of birds in the shed at the time of measurement)
- Odour emission rates varied throughout the time that measurements were taken on each day.
- Comparison of Queensland and Victorian odour emissions was not possible due to unseasonal weather conditions experienced in Victoria during both summer (cooler than average) and winter (warmer than average).
- Odour emission rate did not substantially increase as manure accumulated over the 4–6 day period between regular belt cleaning.
- Odour emission rate tended to increase with increasing ventilation rate and ambient temperature whereas odour concentration tended to decrease.

5 Layer dust emissions

5.1 Overview of layer dust results

Dust was measured at two layer farms (Farm D and E) in two states during summer and winter. Manure removal practices were slightly different for each farm. Farm D cleaned the manure belts twice per week, whereas Farm E cleaned the belts once per week. Dust emissions were measured on four selected days spanning the time between belt cleaning of the manure management cycle.

Particle mass concentration (for both PM_{10} and $PM_{2.5}$ size fractions), particle number concentration and count median diameter (mid-point of the size distribution) were recorded at both farms. Concentration measurements were combined with ventilation rates to calculate particle number and mass emission rates (see Section 3.3.2). All of the layer dust data collected as part of this project is included in Appendix 8 to Appendix 11. The values in these appendices are themselves averages of hundreds of dust measurements taken over time intervals when ventilation rate was relatively constant (this interval varied from ~10 mins up to a few hours).

The following section summarises the average dust data from layer sheds in graphical form. As the graphs will show, there is considerable spread in the measured dust concentrations and emission rates. This is presumably due to the complex interaction of a range of factors including ventilation rate, shed design, time of day and microenvironment. Care should be taken to consider all of these factors and more when interpreting the dust measurements.

5.1.1 PM_{10} concentration and emission rates for all layer farms

Figure 51 displays the PM_{10} concentrations measured at Farms D and E against the number of days post belt cleaning (manure removal). PM_{10} concentrations varied from 0.03 to 0.19 mg/m³. These values fall below the majority of layer shed PM_{10} or PM_5 concentrations found in the literature (see Appendix 1). There is a lot of scatter observed in Figure 51, which was expected because of variation in the range of factors (ventilation rate, season, time of day) for each data point. There was no discernible pattern between layer PM_{10} concentrations and the number of days post belt cleaning.

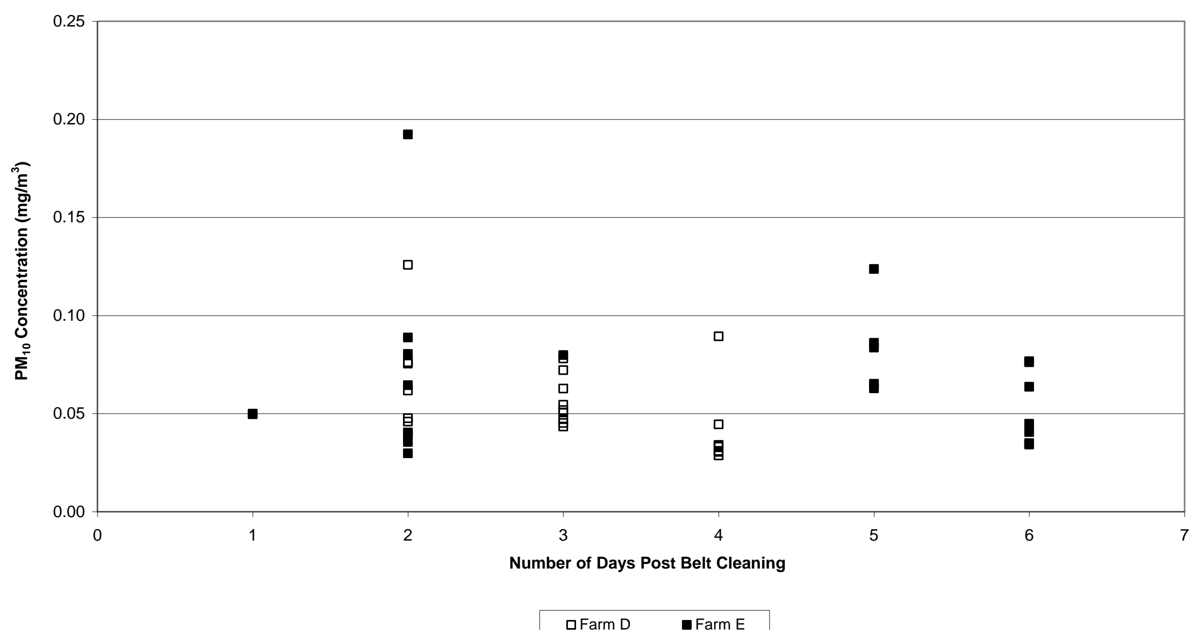

Figure 51: PM_{10} concentrations for layer farms

Figure 52 displays the PM_{10} emission rates measured at Farms D and E against the number of days post belt cleaning (manure removal). The maximum PM_{10} emission rate measured at a layer farm was 14.63 mg/s. This was far higher than all other emission rates during the project and was the result of

high PM_{10} concentrations during high ventilation. To improve the presentation of the remaining data in Figure 52, this maximum value was written above the graph instead of presenting it as a data point. All the other emission rates measured at layer farms during this project varied from 0.61 to 5.52 mg/s. These values are towards the lower end of PM_{10} emission rates from layer farms found in the literature (see Appendix 1). Again, no clear pattern was observed between PM_{10} emission rate and the number of days since removal of manure.

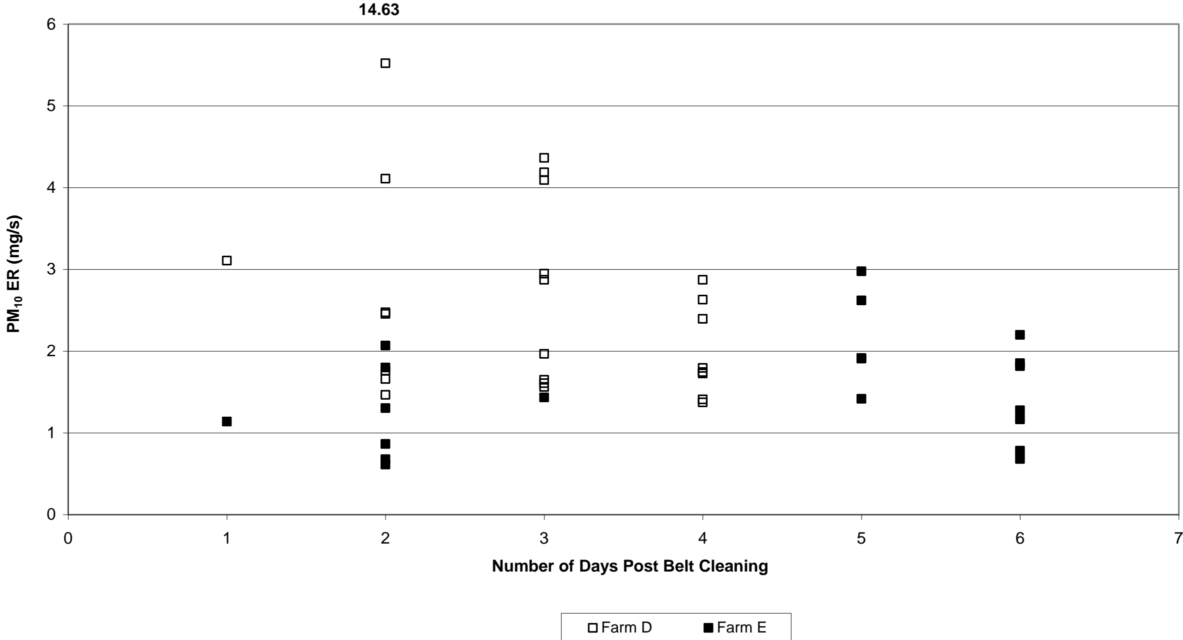

Figure 52: PM_{10} emission rates for layer farms

Figure 53 displays the PM_{10} emission rates per 1000 birds placed measured at Farms D and E against the number of days post belt cleaning (manure removal). The PM_{10} emission rates per 1000 birds placed varied from 0.014–0.3 mg/s per 1000 birds placed at the layer farms. In this report emission rates will be expressed as 'per 1000 birds placed' when rates from different sized sheds are being compared.

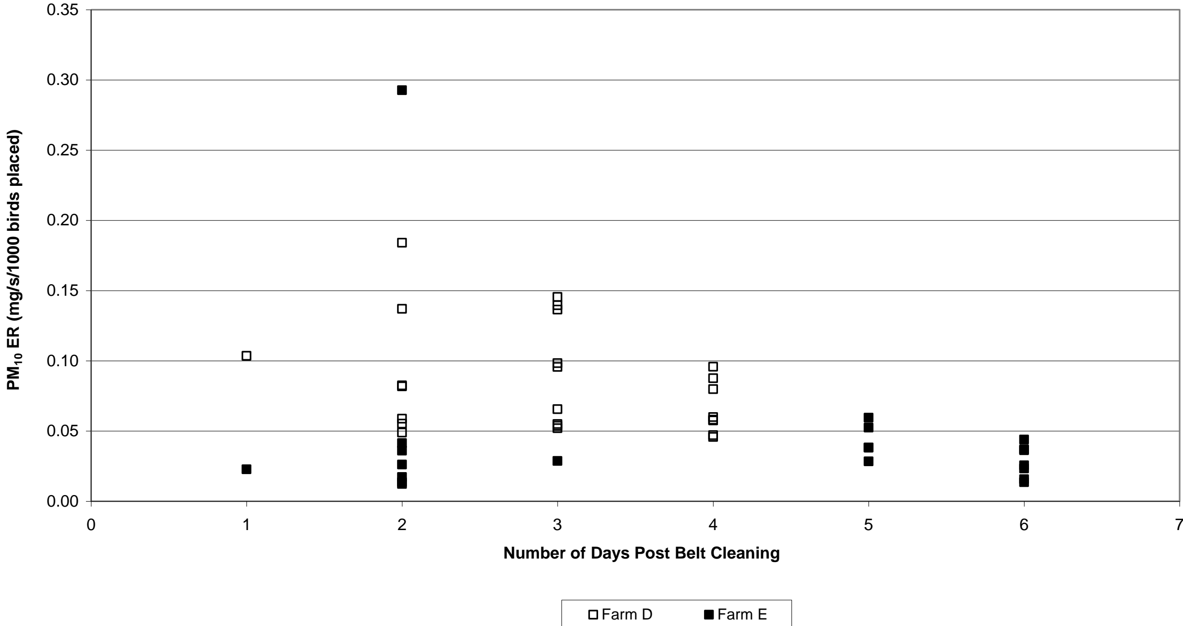

Figure 53: PM_{10} emission rates per 1000 birds placed for layer farms

5.1.2 $PM_{2.5}$ concentration and emission rates for all layer farms

Figure 54 displays the $PM_{2.5}$ concentrations measured at Farms D and E against number of days post belt cleaning (manure removal). $PM_{2.5}$ concentration varied from 0.005 to 0.06 mg/m³ at the layer farms. Only one measurement of $PM_{2.5}$ concentration in a layer shed was found in the literature: 0.039±0.008 mg/m³ (Lim *et al.*, 2003). The literature value falls within the range of concentrations measured during this project. Similarly to PM_{10} concentration (Figure 51), there was no trend between $PM_{2.5}$ concentration and the number of days after belt cleaning.

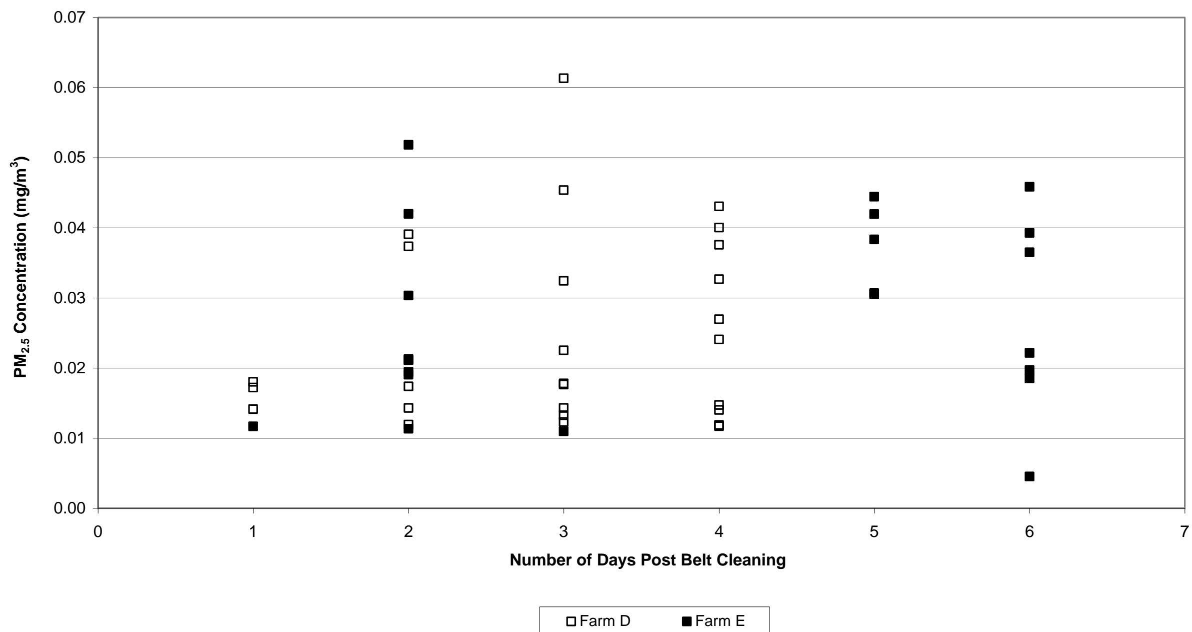

Figure 54: $PM_{2.5}$ concentrations for layer farms

Figure 55 displays the $PM_{2.5}$ emission rates measured at Farms D and E against number of days post belt cleaning (manure removal). $PM_{2.5}$ emission rates generally varied from 0.07 to 5.69 mg/s at the layer farms, although it should be noted that the majority of the measurements were less than 2 mg/s. This range of values is comparable to the range of values found in the literature (see Appendix 1).

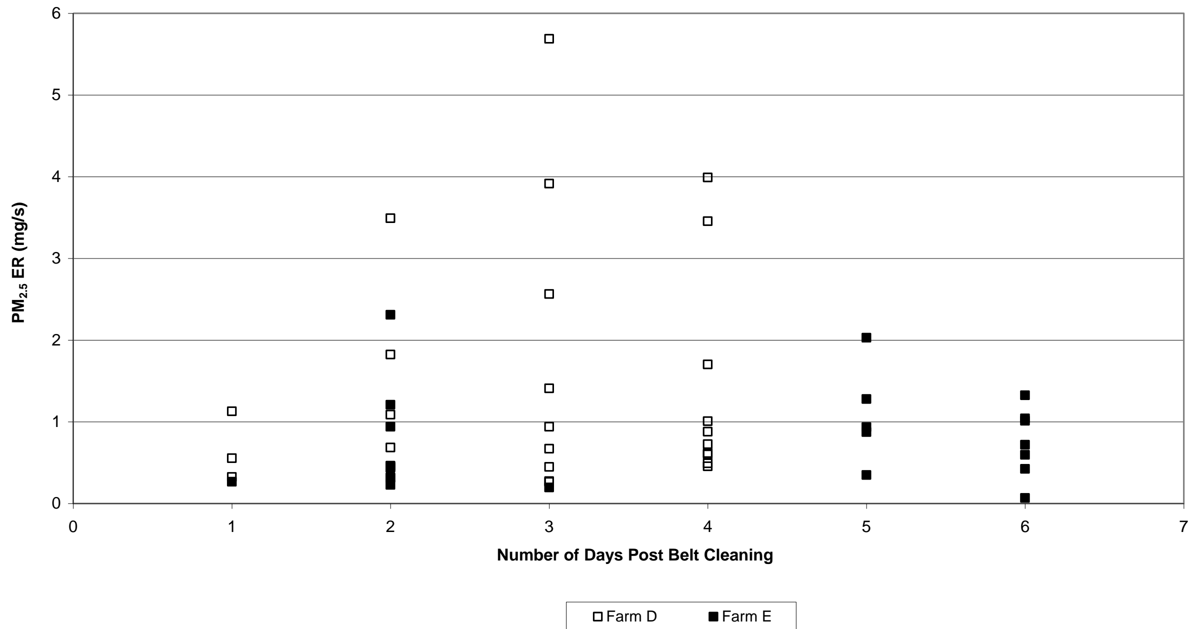

Figure 55: PM$_{2.5}$ emission rates for layer farms

Figure 56 displays the PM$_{2.5}$ emission rates per 1000 birds placed measured at Farms D and E against the number of days post belt cleaning (manure removal). The PM$_{2.5}$ emission rates per 1000 birds placed varied from 0.001–0.19 mg/s per 1000 birds placed at the layer farms.

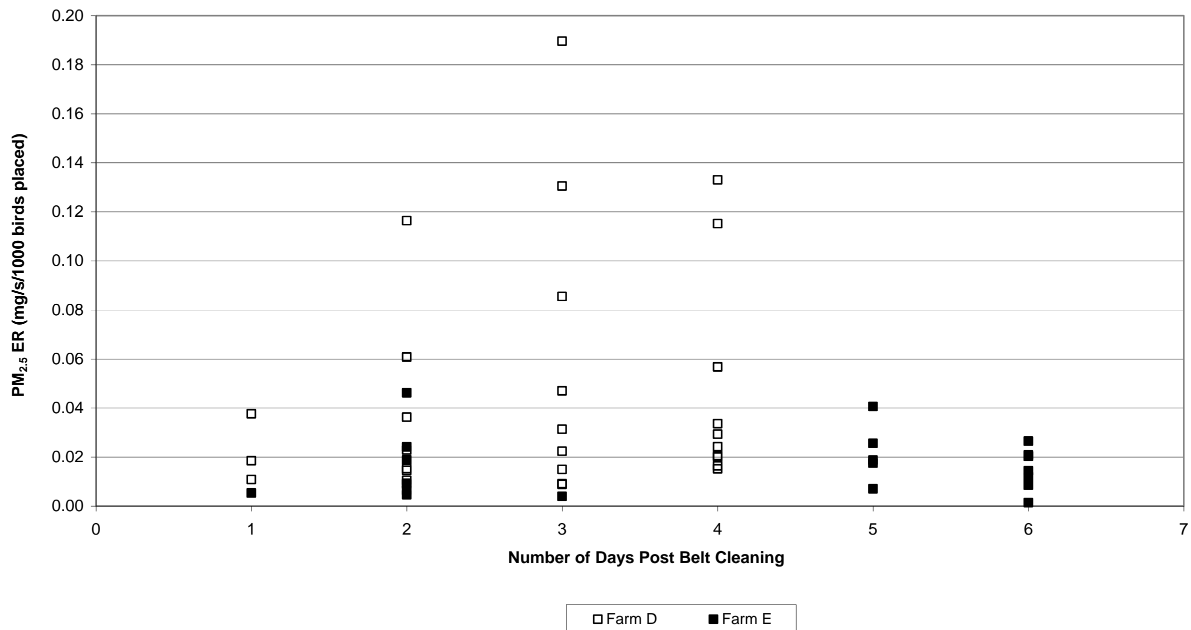

Figure 56: PM$_{2.5}$ emission rates per 1000 birds placed for layer farms

5.1.3 Particle number (PN) concentration and emission rates for all layer farms

Figure 57 displays the PN concentrations measured at Farms D and E against the number of days post belt cleaning (manure removal). PN concentrations were generally below ~1 x 10^7 particles/m³. However, the variable was prone to large spikes leading to concentration measurements of up to 1.92 x 10^8 particles/m³ (value written but not displayed in Figure 57) Corresponding spikes were not observed in particle mass concentration measurements (see Figure 51 and Figure 54), which suggests

that the spikes in number concentration were the result of bursts of large numbers of small particles (< ~1 μm) with relatively little mass.

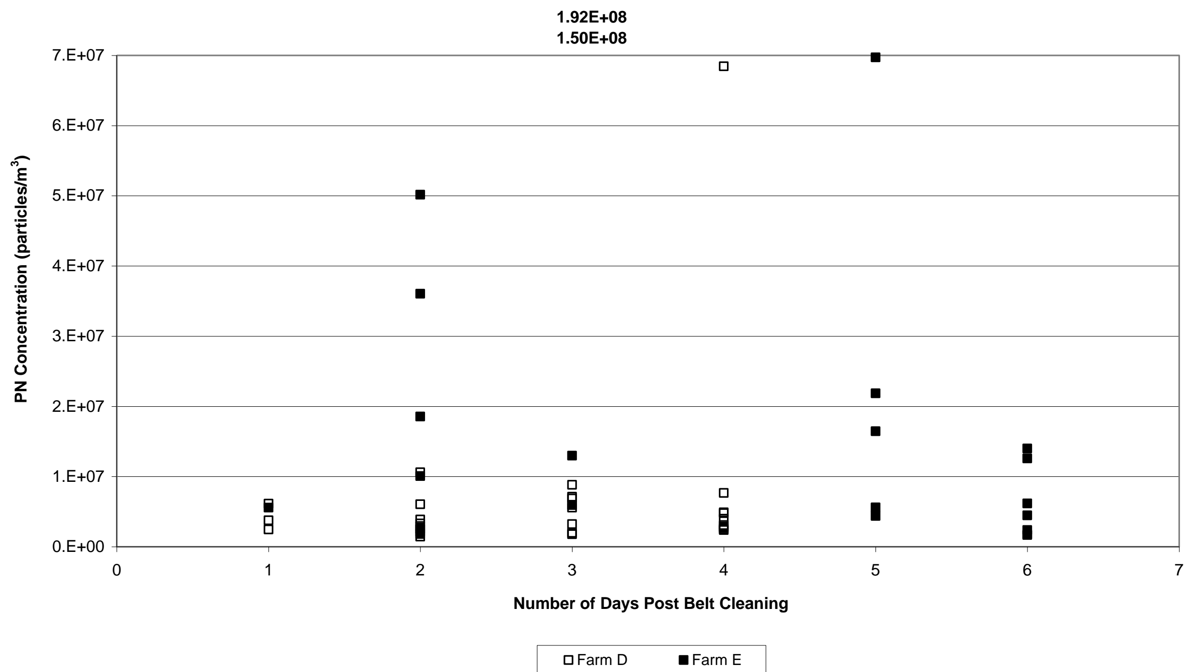

Figure 57: Particle Number (PN) concentrations for all layer farms

Figure 58 displays the PN emission rates measured at Farms D and E against number of days post belt cleaning (manure removal). PN emission rates were generally below 4 x 10^8 particles/s. However the large spikes in PN concentration (Figure 57) led to corresponding large spikes in PN emission rate. The highest layer PN emission rate measured during this project was 1.78 x 10^{10} particles/s.

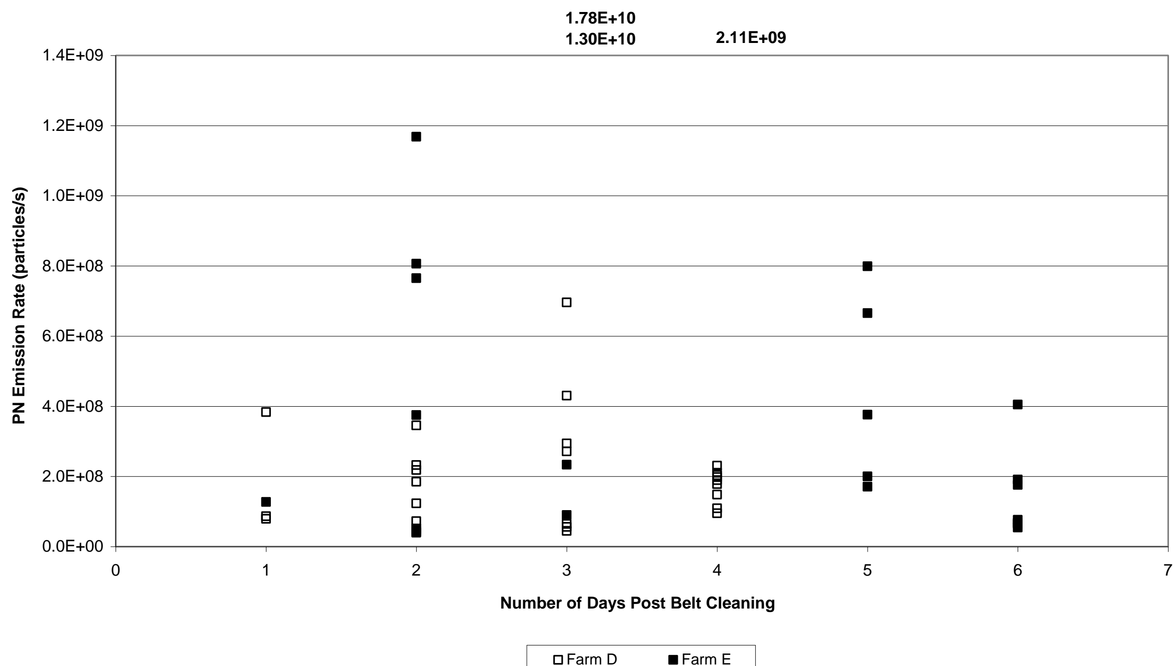

Figure 58: Particle Number (PN) emission rates for all layer farms

Figure 59 displays the PN emission rates per 1000 birds placed at Farms D and E against the number of days post belt cleaning (manure removal). PN emission rates per 1000 birds placed were generally

below 3 x 10^7 particles/s per 1000 birds placed. However, three emission rate values of 0.7, 4.3 and 5.9 x 10^8 mg/s per 1000 birds placed were also recorded.

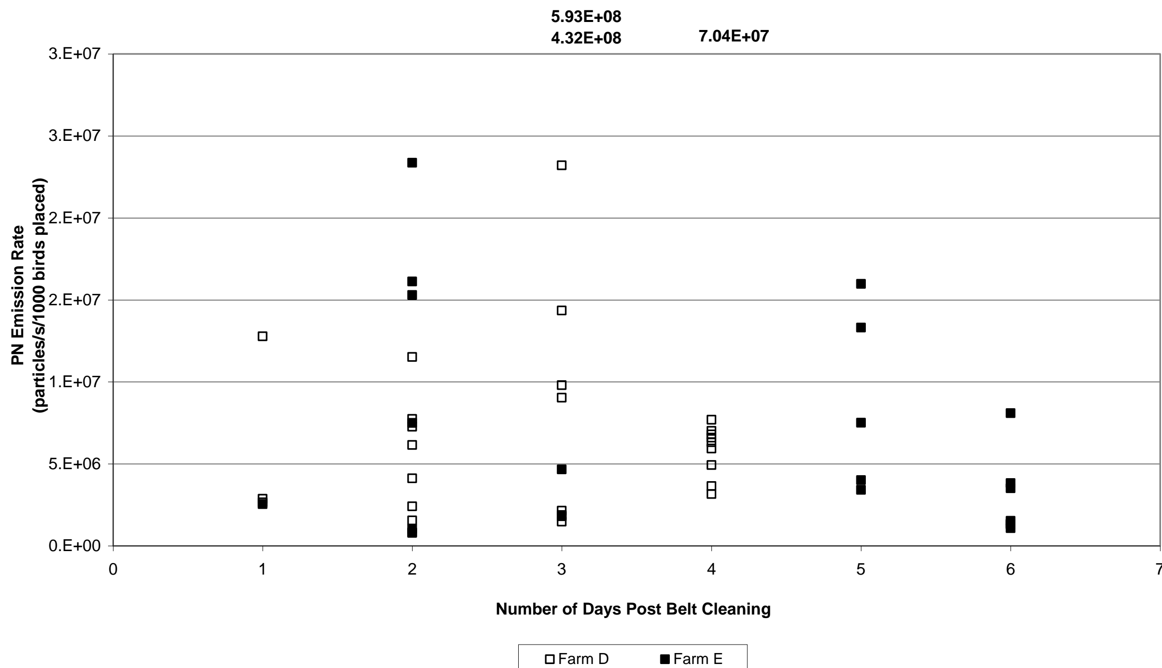

Figure 59: Particle Number (PN) emission rates per 1000 birds placed for all layer farms

5.1.4 Count median diameter (CMD) for all layer farms

Figure 60 displays the CMDs measured at Farms D and E against the number of days post belt cleaning (manure removal). The CMD represents the midpoint diameter of a particle number size distribution. The majority of CMD values for the size distributions of dust particles emitted from the layer sheds were below 3 µm. However one CMD measurement of 8.01 µm was recorded. This CMD was measured at Farm D during summer sampling (13 December 2007) and it is far higher than any other CMD measured during sampling at layer sheds during this project. It indicates that the particle size distribution during this measurement was dominated by large dust particles. It would be expected that these large particles would have a major impact on PM_{10} concentration; however no corresponding increase in PM_{10} concentration was observed on 13 December 2007 (see **Appendix 9**). This is probably because the large particles dominating the particle size distribution were greater than 10 µm in diameter, and therefore not detected by the DustTrak that sampled with a PM_{10} inlet.

The other interesting feature of Figure 60 is the regular occurrence of relatively small CMD values for the size distributions of dust particles emitted from the layer sheds. Many were less than 1.5 µm, including nine measurements of CMD less than 1 µm. The eight lowest CMD values were measured at Farm E during winter (see section 5.2.2). Low CMDs indicate particle size distributions that contained large numbers of small, light particles. These could be the particles responsible for the large spikes that were observed in particle number concentrations measured at the layer sheds (Figure 57) but not observed in the corresponding particle mass concentrations (Figure 51 and Figure 54).

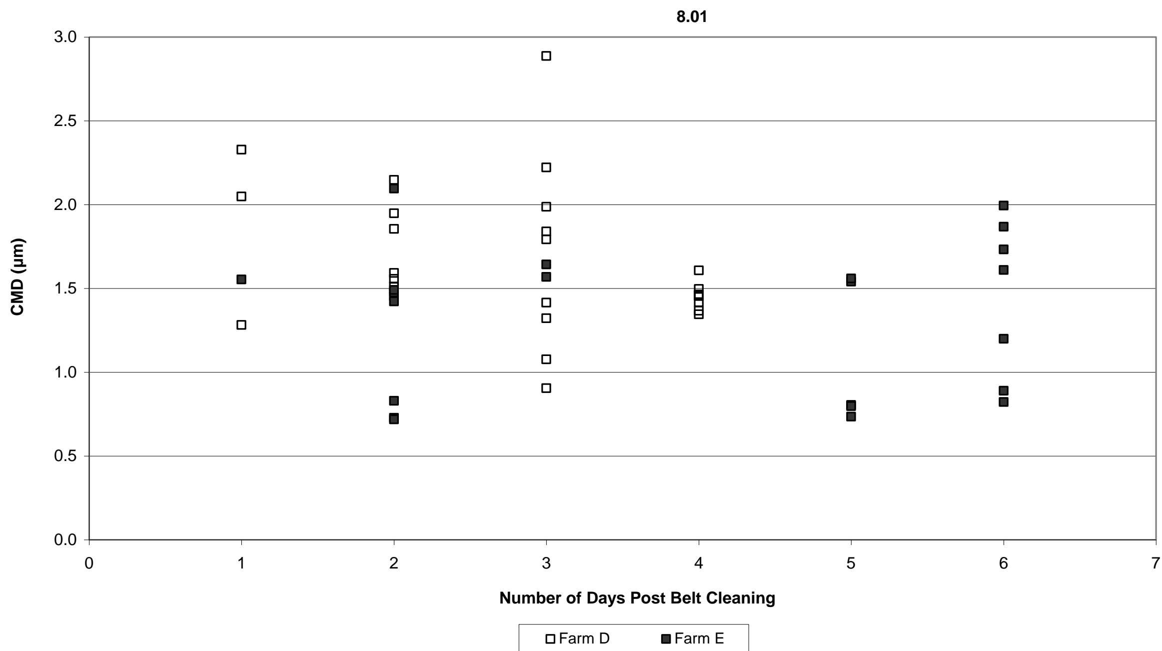

Figure 60: Count Median Diameter (CMD) for all layer farms

5.1.5 The effect of ventilation rate on layer dust concentrations and emissions

High concentration values tended to occur when ventilation rate was low. However, as the ventilation rate increased, dust concentrations generally decreased presumably due to increased dilution of the shed air with relatively clean upstream air. At the same time, dust emission rates tended to increase presumably because the greater movement of air agitated and entrained more dust into the shed airstream. At ventilation rates above 30–40 m³/s the relative changes in layer dust concentrations and emissions seemed to stabilise. In this section we will investigate the relationship between ventilation rate and layer dust concentrations and emissions. PM_{10} will be used as the dust variable in this investigation. Although a similar number of PM_{10}, $PM_{2.5}$ and PN concentrations were recorded for the layer farms, PN concentrations were prone to large and unexplained spikes (see section 5.1.3) and $PM_{2.5}$ concentrations were low, making it difficult to observe relative changes in this variable. Therefore PM_{10} was chosen as the most appropriate variable for this comparison.

PM_{10} concentrations and emission rates (per 1000 birds placed) are categorised according to ventilation rate in Figure 61. The graph clearly shows that higher dust concentrations were measured at the layer farms when ventilation rate was low. As the ventilation rate increased there was a steady decline in average dust concentration. In contrast, average dust emission rates increased with ventilation rate. The highest dust emission rates occurred when ventilation rate was at or near maximum. It needs to be stressed that farm specific and environmental factors could also be contributing to the variations seen in Figure 61. For example, ventilation rates were generally lower during winter than summer at both Farms D and E. Therefore microclimatic effects related to season could be contributing to the patterns observed in the graph. Because this dataset is quite small (45 average PM_{10} measurements) the contribution of these extra factors is potentially quite large.

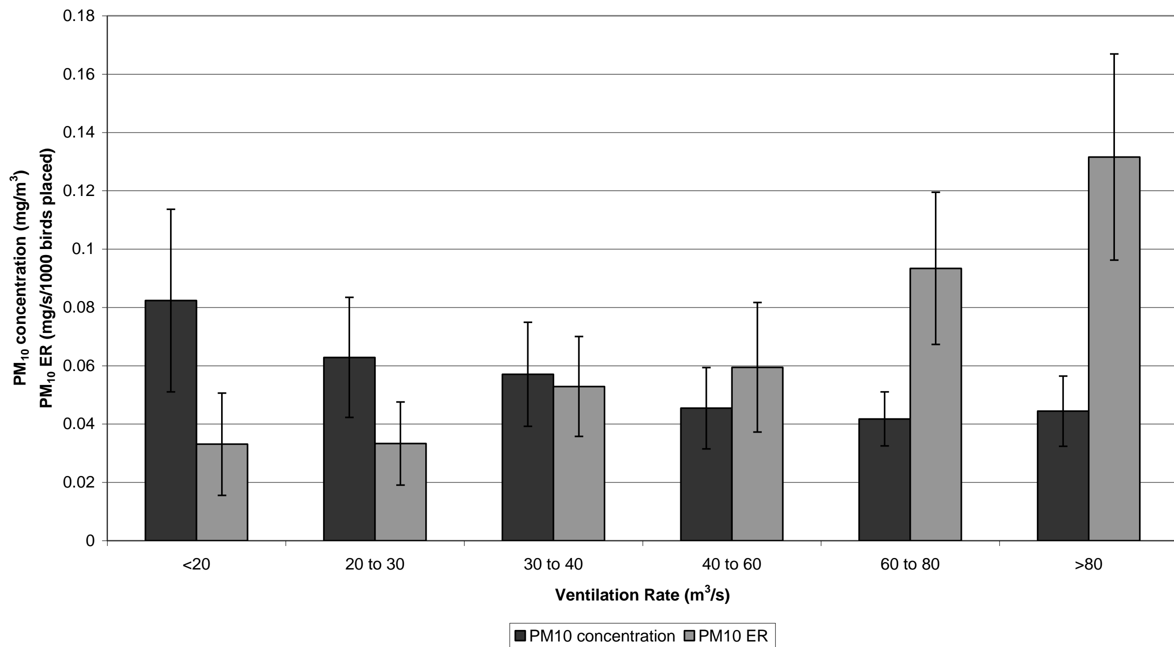

Figure 61: PM_{10} concentration and emission rate versus ventilation rate for the layer farms

5.2 Layer seasonal variability

This section investigates the differences in dust emissions when comparing seasons and states.

At each farm during each season, samples were collected on four days spanning the time between belt cleaning. To assess the seasonal variability of dust emissions from the layer farms we will compare the averages of all dust concentrations and emission rates measured during each 4 day sampling period. This is permissible because Figure 51 to Figure 59 indicate that there was no discernible relationship between dust concentrations and emissions and the number of days after belt cleaning. Nevertheless, the variation in factors such as ventilation rate and microenvironment between individual data points should be kept in mind when considering the average values graphed in this section.

5.2.1 QLD seasonal study

Figure 62 and Figure 63 display the average of all $PM_{2.5}$, PM_{10} and PN concentration measurements conducted at Farm D during the summer and winter sample collection periods. Three unusually high outlying measurements of PN concentration that were recorded on December 12 and 13, 2007 have not been included in the summer average PN concentration.

There is no clear difference between the average $PM_{2.5}$ and PN concentrations from summer and winter. However, the average PM_{10} concentration during the winter sample collection was far higher than the average PM_{10} concentration for the summer period. The most likely explanation for this difference is ventilation rates. Ventilation rates were considerably higher in summer than winter, which means the dilution effect was greater in summer than winter at this farm (see section 5.1.5).

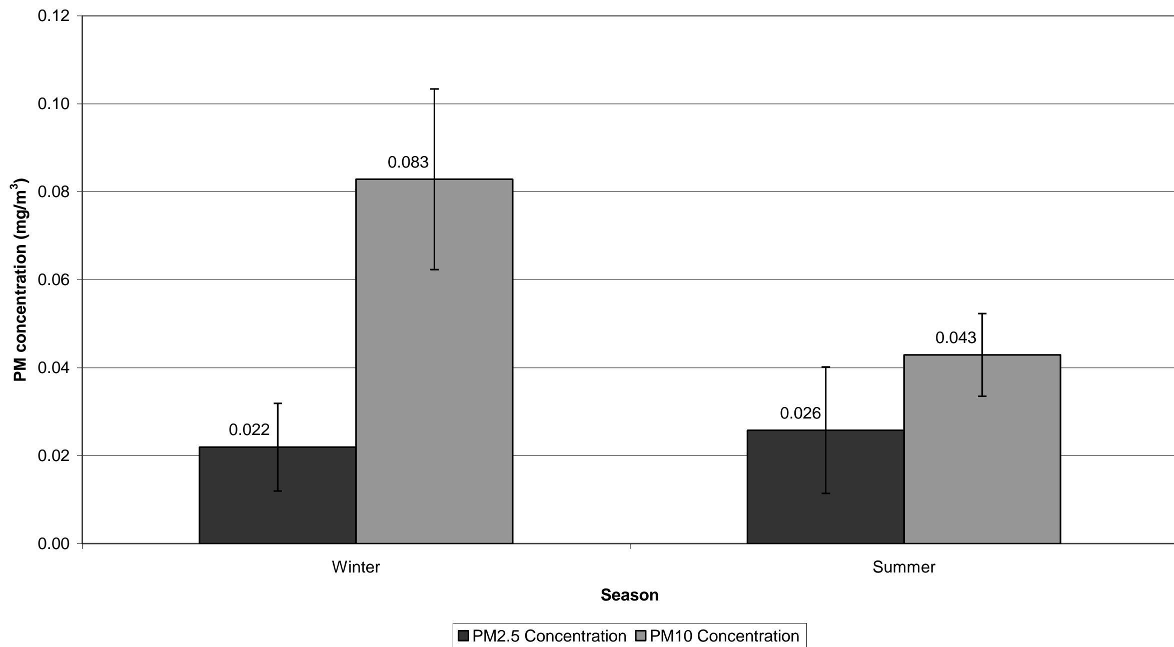

Figure 62: Average $PM_{2.5}$ and PM_{10} concentrations at Farm D during summer and winter sampling

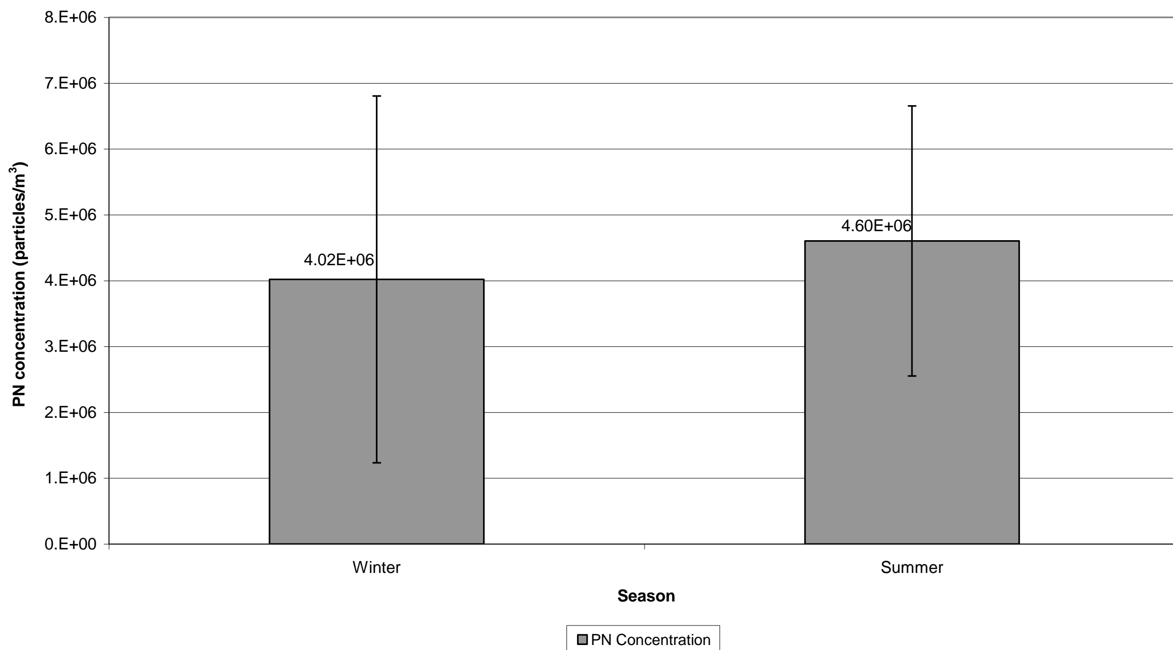

Figure 63: Average particle number concentrations at Farm D during summer and winter sampling

Figure 64 and Figure 65 display the average of all $PM_{2.5}$, PM_{10} and PN emission rate per 1000 birds placed measurements conducted at Farm D during the summer and winter sample collection periods. Three unusually high outlying measurements of PN emission rate that were recorded on December 12 and 13, 2007 have not been included in the summer average PN emission rate. The emission rate of all dust fractions was higher during the summer period than the winter period. Again, this is because ventilation rates were higher during the summer sample collection.

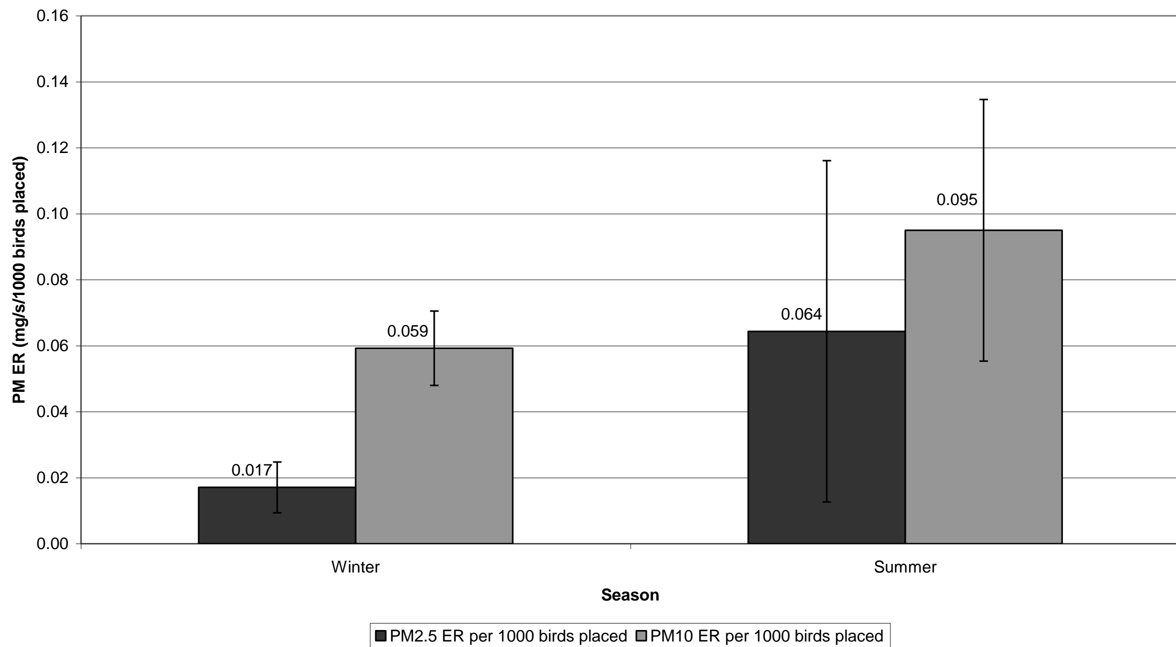

Figure 64: Average $PM_{2.5}$ and PM_{10} emission rates per 1000 birds placed at Farm D during summer and winter sampling

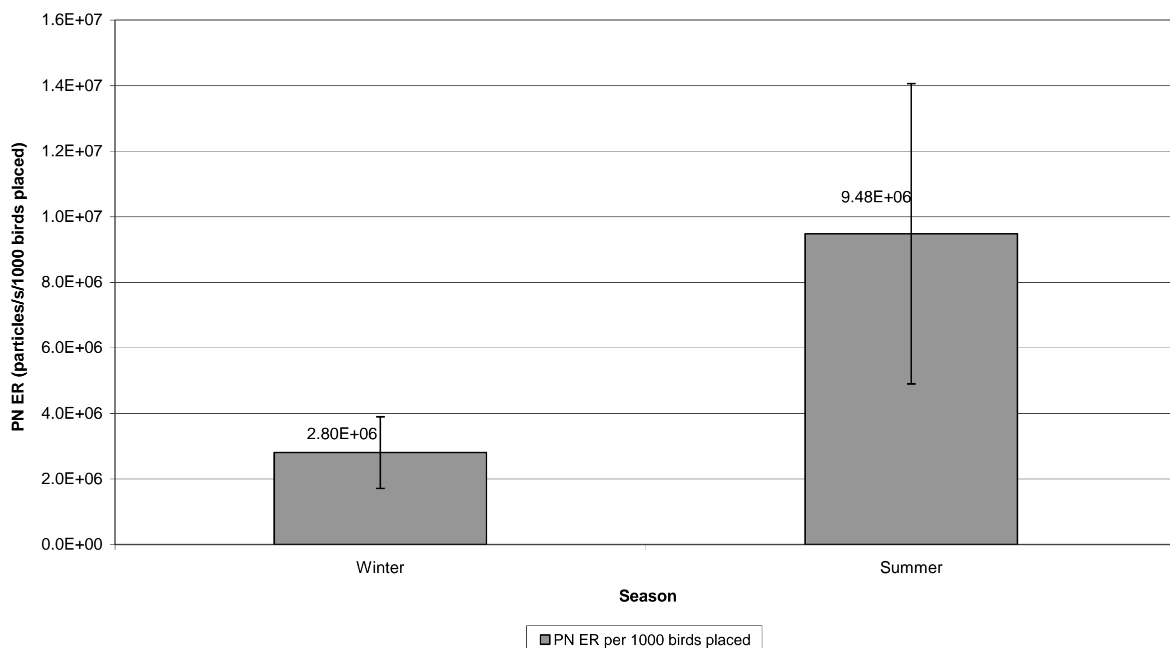

Figure 65: Average particle number (PN) emission rates per 1000 birds placed at Farm D during summer and winter sampling

5.2.2 Victoria seasonal study

Figure 66 and Figure 67 display the average of all $PM_{2.5}$, PM_{10} and PN concentration measurements conducted at Farm E during the summer and winter sample collection periods. The average winter $PM_{2.5}$ and PM_{10} concentrations were slightly higher than the corresponding summer averages. However the difference between the average $PM_{2.5}$ concentrations was only small and there was considerable variation in the average PM_{10} concentrations, particularly the summer average. On the other hand, the average PN concentration during winter sampling was considerably higher than the summer average. The large seasonal difference observed between the particle number, but not particle

mass, concentrations was due to small, light particles that had a strong effect on total particle number but minimal effect on total particle mass. The average count median diameter (CMD) of all the size distributions measured during winter was only 0.98 ± 0.34 µm. This average includes the eight lowest CMDs measured during this whole project (see section 5.1.3). It is not known why large numbers of small, light dust particles were emitted from Farm E during the 4-day winter sampling period.

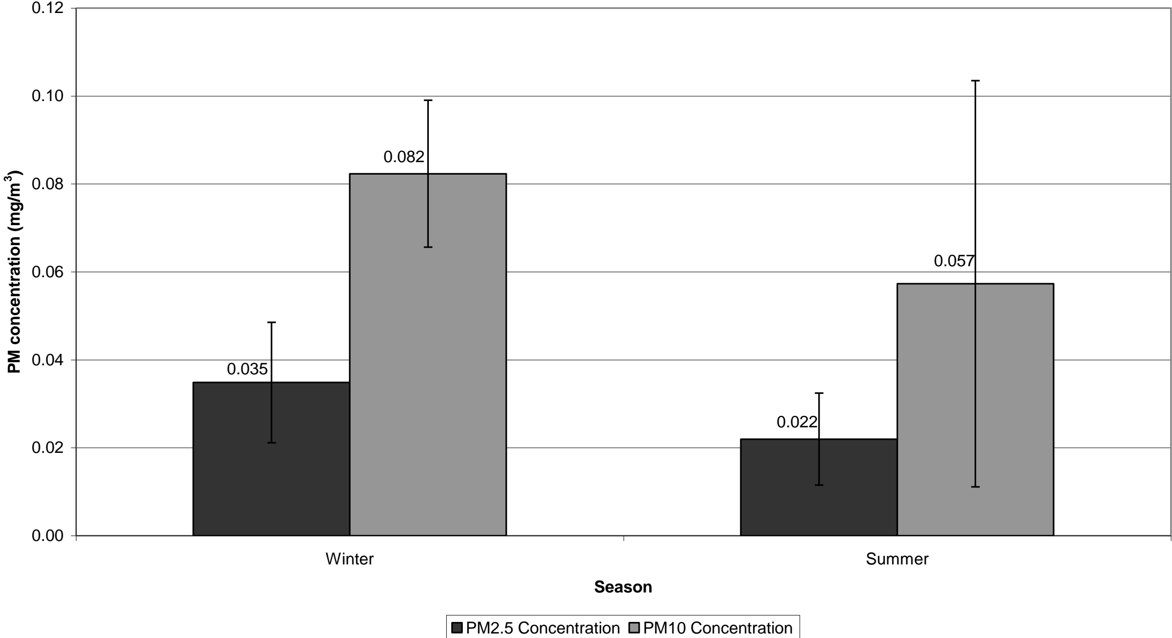

Figure 66: Average $PM_{2.5}$ and PM_{10} concentrations at Farm E during summer and winter sampling

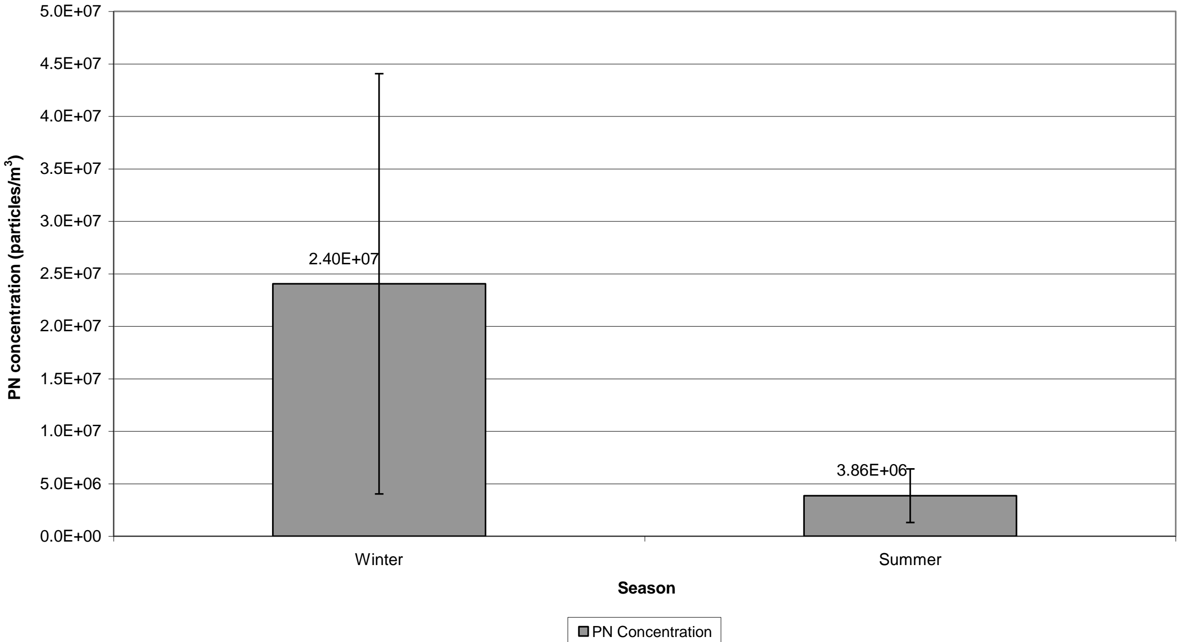

Figure 67: Average particle number (PN) concentrations at Farm E during summer and winter sampling

Figure 68 and Figure 69 display the average of all $PM_{2.5}$, PM_{10} and PN emission rate per 1000 bird placed measurements conducted at Farm E during the summer and winter sample collection periods. The average $PM_{2.5}$ and PM_{10} emission rates in summer and winter were fairly similar. This was expected because summer and winter $PM_{2.5}$ and PM_{10} concentrations were fairly similar (Figure 66) and, on average, ventilation rates were only slightly higher in summer. In contrast, PN concentrations

were far higher in winter than summer at Farm E (Figure 67). Despite the slightly higher ventilation rates in summer this meant that PN emission rates were still considerably higher in winter compared to summer.

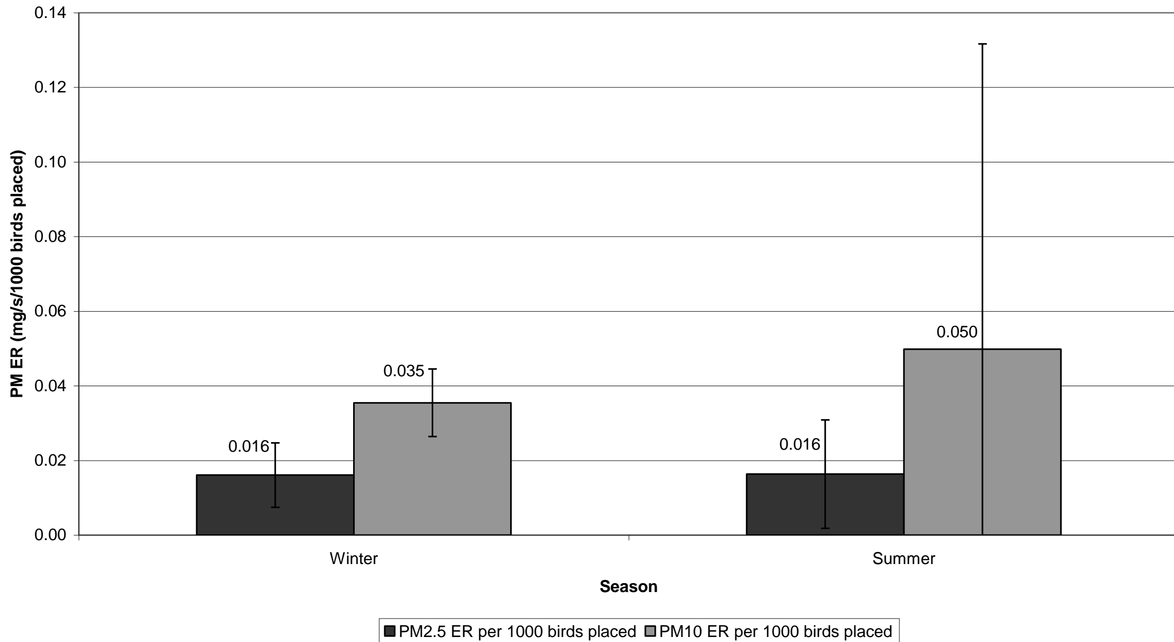

Figure 68: Average $PM_{2.5}$ and PM_{10} emission rates per 1000 birds placed at Farm E during summer and winter sampling

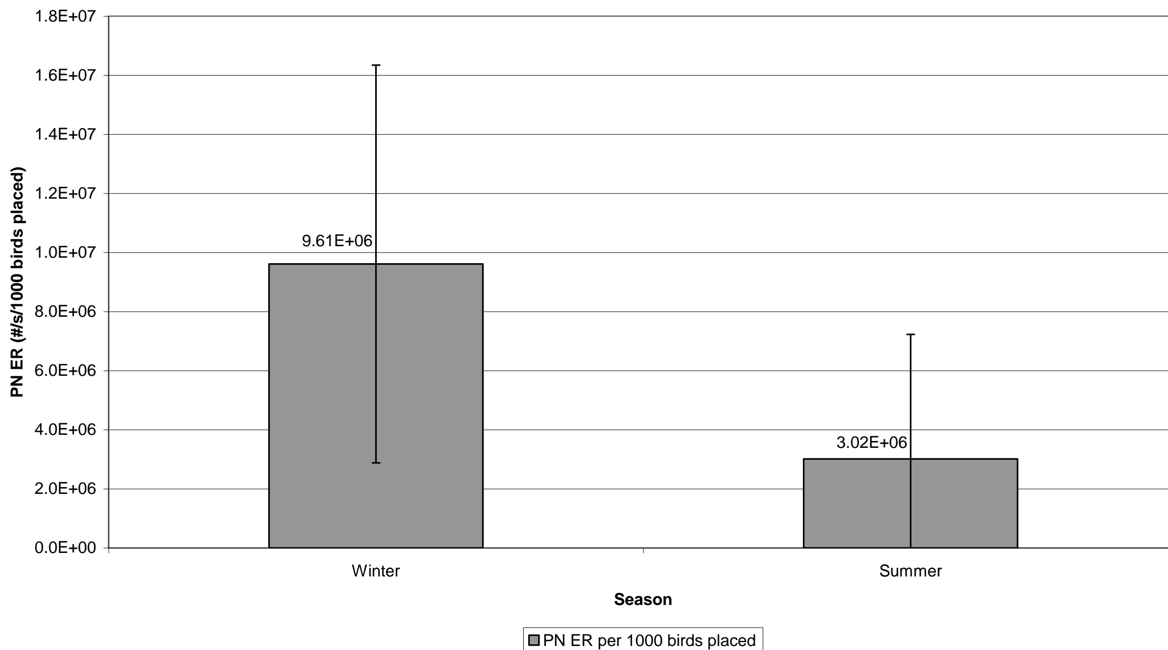

Figure 69: Average PN (PN) emission rates per 1000 birds placed at Farm E during summer and winter sampling

5.2.3 Summary and conclusions from the layer seasonal study

At Farm D, $PM_{2.5}$ and particle number concentrations during the winter and summer sampling periods were relatively similar. PM_{10} concentrations were considerably higher in winter than summer. However, temperatures, and therefore ventilation rates, were much higher during the summer. This

meant that the emission rates of all dust-related variables were noticeably greater in summer than winter.

Seasonal differences in particle mass (PM_{10} and $PM_{2.5}$) concentrations and emission rates at Farm E were less pronounced because ambient temperatures and therefore ventilation rates were unusually similar. On the other hand, particle number concentrations and emission rates were far higher during the winter sampling period. This is because large numbers of small, light dust particles were emitted during the winter period and these had a strong effect on particle number but minimal effect on particle mass. It is not known why these smaller particles were emitted from the shed in winter and not summer.

5.3 Summary of layer dust emissions

Dust emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight).

- From July 2007 to June 2008, dust emission measurements were made at two layer farms located in Queensland and Victoria.
- Dust emissions were measured over four days in conjunction with manure belt cleaning – either four consecutive days following belt cleaning, or two days before and two days after belt cleaning.
- The majority of layer dust emission rates per 1000 birds placed ranged from:
    - 0.014–0.15 mg/s per 1000 birds placed for PM_{10}
    - 0.005–0.06 mg/s per 1000 birds placed for $PM_{2.5}$
    - (0.1–2.0) x 10^7 particles/s per 1000 birds placed for particle number
- The count median diameter for the majority of measurements ranged from 1.0–2.5 μm.
- Dust concentration and emission rate were highly variable due to ventilation rate, farm, season, microenvironment and other unidentified factors.
- There were no discernible trends between dust concentrations or emission rates and the number of days after manure belt cleaning.
- In general, dust concentrations tended to decrease with increasing ventilation rate and dust emission rates tended to increase with increasing ventilation rate.
- Seasonal differenced in dust emissions could be partly explained by seasonal differences in ventilation rates in Queensland. No obvious seasonal differences in dust particle mass concentrations and emissions were observed in Victoria. However, a much larger number of fine dust particles were emitted from the Victorian farm during winter than summer. It is not known why this occurred.

6 Layer NMVOC emissions

6.1 Overview of NMVOC & odorant emissions from layer sheds

To facilitate the non-methane volatile organic compound (NMVOC) and odorant assessment from layer facilities, thermal desorption sorbent tubes were collected at two layer farms, one located in southern Queensland (Farm D), the other located in southern Victoria (Farm E) during summer and winter. Layer house samples were analysed with gas chromatography-mass spectrometry/olfactometry (GC-MS/O) to provide simultaneous chemical speciation and odorant identification.

There was limited diversity in the chemical species present within the layer sheds and the abundance of the chemicals that were present was low. The results of the mass spectral analysis were not dominated by sulphide species; however, trace levels of dimethyl disulphide were detected in a few of the layer house samples

The predominant compounds present within the NMVOC suite were 2-butanone and 1-butanol. In addition to the these two compounds, there were minor levels of 3-hydroxy-2-butanone, 2,3-butanedione, and 3-methyl-2-butanone. Owing to the substantially lower abundances of the chemical species present they frequently did not elicit an olfactory response. It is also for this reason that the emissions from the layer facilities can not be quantified with scientific certainty.

The results of the odorant identification were limited owing to the low chemical abundances of the species present frequently being below the level of olfactory detection.

6.2 NMVOC analysis

The results of the NMVOC analysis of the layer shed samples is shown in Figure 70 to Figure 73, the dual chromatograms represent the exhaust emissions (upper total ion chromatogram) from the specific shed sampled and the corresponding ambient (inlet) air sample (lower inverted chromatogram). The observations reveal that for the majority of samples analysed there was little difference between the chemical composition of the ambient air entering the layer house and that of the exhaust emissions from the layer house.

Figure 70 shows the total ion chromatograms from two samples, an inlet and outlet to a layer shed from Farm D, which shows that there was little difference between shed exhaust and ambient air.

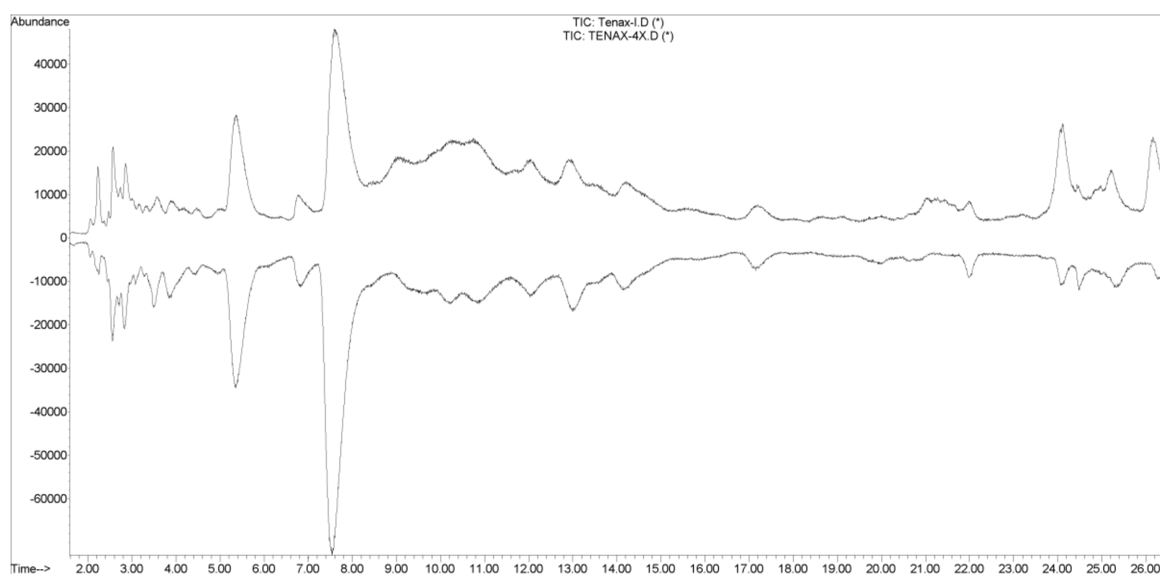

Figure 70: The total ion chromatogram from an ambient sample (lower, inverted) and the emissions from a layer house sampled during summer at Farm D

Figure 71 shows the total ion chromatograms from two samples, an inlet and outlet to a layer shed from Farm D during winter, which shows that there was little difference between shed exhaust and ambient (outside the shed) air.

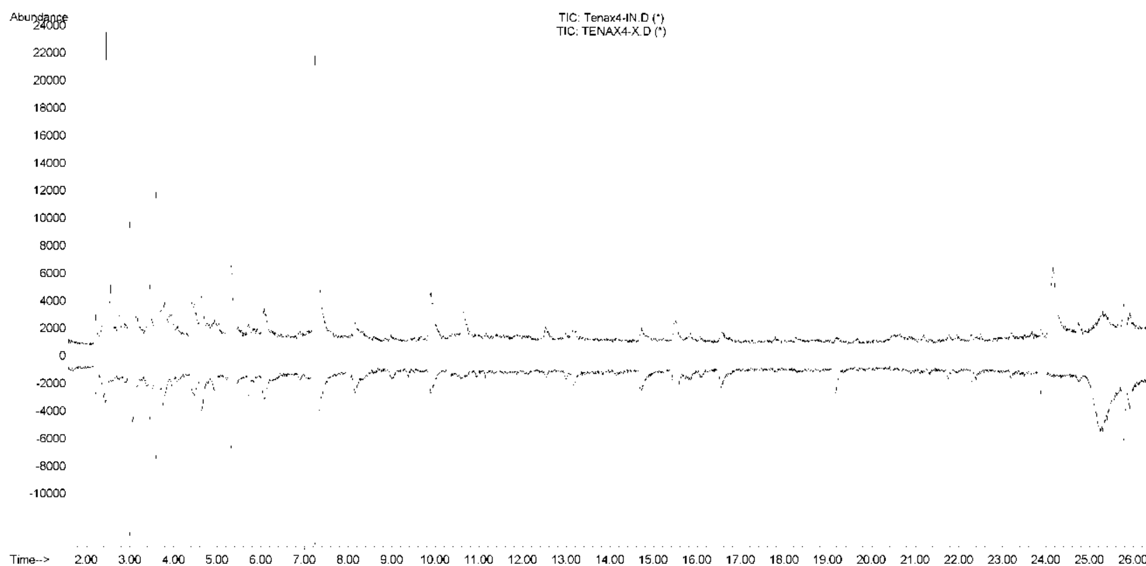

Figure 71: The total ion chromatogram from an ambient sample (lower, inverted) and the emissions from a layer house sampled during winter at Farm D

Figure 72 shows the total ion chromatograms from two samples, an inlet and outlet to a layer shed from Farm E during summer, which shows that there was little difference between shed exhaust and ambient (outside the shed) air.

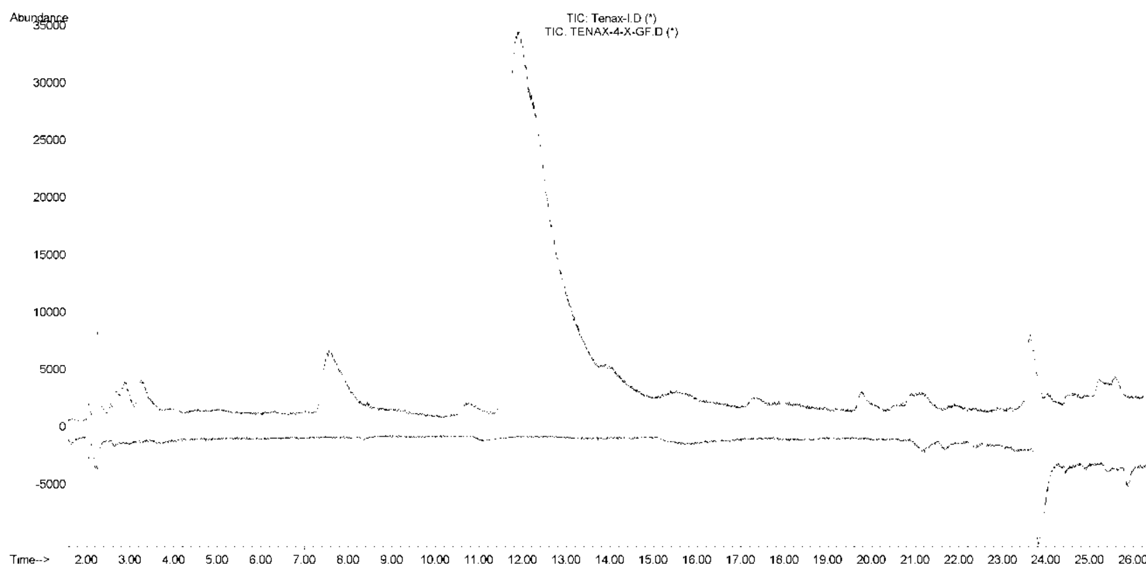

Figure 72: The total ion chromatogram from an ambient sample (lower, inverted) and the emissions from a layer house sampled during summer at Farm E

Figure 73 Figure 287 shows the total ion chromatograms from two samples, an inlet and outlet to a layer shed from Farm E during winter, in contrast to the previous layer house samples analysed there was a significant difference between the inlet and outlet samples for this series.

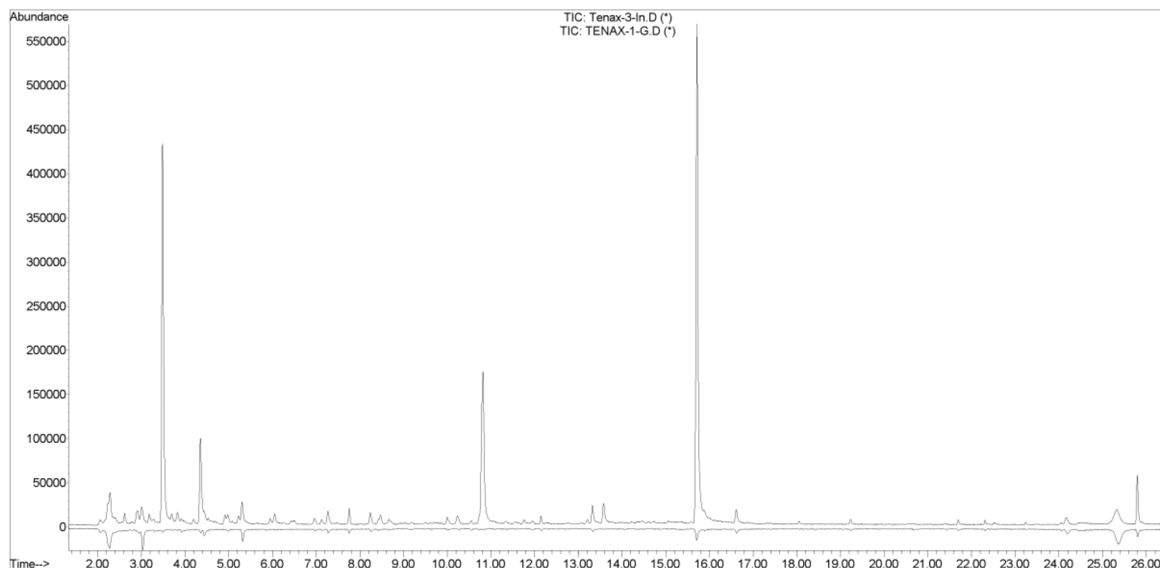

Figure 73: The total ion chromatogram from an ambient sample (lower, inverted) and the emissions from a layer house sampled during winter at Farm E

It should be noted that there is a significant difference in the results obtained from the analysis of the samples collected at Farm E during winter due to instrumentation configuration changes. This explains the graphical differences between Figure 70, Figure 71, Figure 72 and Figure 73. This also partially explains the greater diversity in chemical species detected in these samples.

The NMVOCs identified in the layer sheds are listed in Table 14, grouped by farm and season.

Table 14: NMVOC identified in the emissions from layer sheds

Farm D		Farm E	
Summer	**Winter**	**Summer**	**Winter**
1-butanol	1-butanol	1-butanol	1-butanol
2-butanone	2-butanone	2-butanone	2-butanone
2-ethyl-1-hexanol		3-hydroxy-2-butanone	3-methyl-butanal
Acetic Acid	2-ethyl-1-hexanol	2,3-butanedione	Acetic Acid
Butanoic Acid	Acetic Acid	Toluene	2,3-butanedione
Toluene		Cyclohexanone	2-butoxy-ethanol
Styrene	Toluene	2-ethyl-1-hexanol	2-ethyl-1-hexanol
Phenol	Styrene	Dimethyl Sulphide	nonanal
Benzaldehyde			Benzene
Acetophenone	Benzaldehyde		Toluene
			Styrene
			o-xylene
			p-xylene
			Benzaldehyde
			Acetophenone
			Dimethyl Sulphide

6.3 Odorant analysis

The sorbent tube samples that were collected at the layer facilities in Queensland and Victoria were all analysed with simultaneous mass spectrometry/olfactometry, yielding dual data sets for each sample—the total ion chromatogram from the chemical species present and the odorant chromatogram from the chemical species that effect an olfactory response from the operator.

Figure 74 illustrates a typical example of one of the few samples that contained chemicals of adequate abundance to elicit an olfactory stimulus response from an operator.

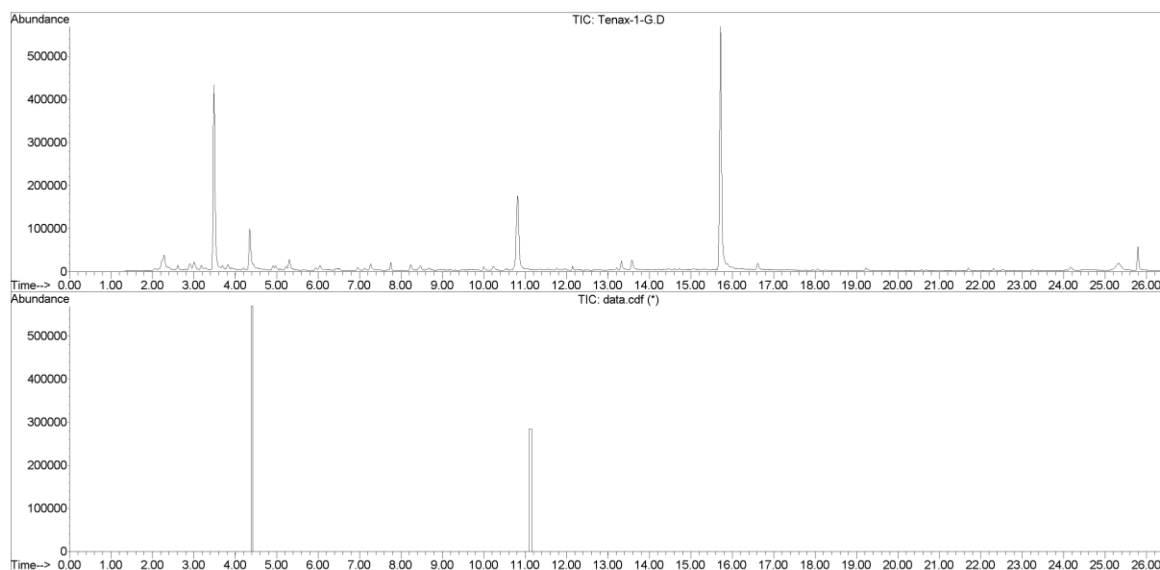

Figure 74: The total ion chromatogram and olfactory stimulus chromatogram from a sample collected during winter from Farm E

Table 15 lists the odorants identified during GC-MS/O analysis of the layer shed samples.

Table 15: Odorants identified from GC-MS/O analysis of layer shed samples

Odorant compound	Descriptor
2,3-butanedione	Rancid, butter
2-butoxy-ethanol	Solvent
Cyclohexanone	Solvent, chemical

6.4 Summary of layer NMVOC results

NMVOC emission need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight)

- NMVOC data was collected from layer houses between July 2007 and June 2008.
- The ventilation rate did not impact significantly on the amount of NMVOCs measured from the layer house emissions.
- Key NMVOCs within the layer house emissions included 2-butaneone, 1-butanol, 2,3-butanedione, cyclohexanone and toluene.
- Key odorants were limited to 2,3-butanedione, cyclohexanone and 2-butoxy-ethanol.

7 Conclusions

This project had a number of objectives:

- *Development of a database of odour and dust emissions from tunnel ventilated layer sheds.*
- *Identification of specific poultry shed non-methane volatile organic compounds and odorants.*

Achievement of these objectives is summarised in the following sections.

7.1 Development of an odour and dust emission database

7.1.1 Summary of methods and sampling program

- Two tunnel ventilated layer farms were included in this project. Odour, dust and VOC emissions were measured over a 4–5 day period.
- 55 odour samples were collected from layer farms.
- Odour, dust and VOC samples were collected from within a temporary flexible duct that was attached to one of the tunnel ventilation fans at each farm.
- Odour concentration was measured using dynamic olfactometry to AS/NZS 4323.3:2001. Two laboratories were used, and comparative testing was conducted between the laboratories to ensure comparability of odour concentration measurement.
- Dust was measured using a DustTrak™ and an aerodynamic particle sizer (APS) and reported in terms of mass concentrations (PM_{10} and $PM_{2.5}$), particle number concentrations and count median diameters (mid-point of the number size distribution). Isokinetic sampling techniques were used.
- VOCs were collected using sorption tubes for subsequent analysis with a GC-MS/O.
- Ventilation rate was estimated by measuring fan airspeeds, or by calculating the flow rate through each active fan using manufacturer supplied fan flow rate date (and adjusting for shed static pressure), which was selected as the preferred method.
- All odour samples were analysed within 8.5 hours of collection.

7.1.2 Odour emissions summary

Odour emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight).

- Layer odour emission rates are summarised in Table 16.

Table 16: Summary of measured layer odour emission rates using olfactometry

Units	Full measured range	Range for majority of data
ou/s	2882–24,907	2000–18,000
ou/s/1000 birds placed	58–512	50–500
ou/s/kg (total live weight)	0.03–0.27	0.03–0.26

- Odour emission the day following manure belt cleaning tended to be slightly higher than the following days when more manure had accumulated on the belts.
- Odour emission rate did not substantially increase as manure accumulated over the 4–6 day period between regular belt cleaning.
- Odour emission rates varied throughout the time that measurements were taken on each day.

- Comparison of Queensland and Victorian odour emissions was not possible due to unseasonal weather conditions experienced in Victoria during both summer (cooler than average) and winter (warmer than average).

- Odour emission rate tended to increase with increasing ventilation rate and ambient temperature whereas odour concentration tended to decrease.

7.1.3 Dust concentration and emission summary

Dust emission rates need to be individually considered along with environmental and in-shed conditions at the time of measurement (for example ambient temperature, ventilation rate, manure moisture content, bird age and total bird live weight).

- Layer dust concentration and emission rates are summarised in Table 17.

Table 17: Summary of measured layer dust concentrations and emission rates

Dust fraction	Units	Full measured range	Range for majority of data
PM_{10}	**mg/m^3 (concentration)**	0.03–0.19	0.03–0.1
	mg/s (ER)	0.61–14.63	1–3
	mg/s/1000 birds placed (ER)	0.014–0.29	0.014–0.15
	mg/s/kg (total live weight) (ER)	$(0.06–1.52) \times 10^{-4}$	$(0.6–8) \times 10^{-5}$
$PM_{2.5}$	**mg/m^3 (concentration)**	0.005–0.061	0.01–0.05
	mg/s (ER)	0.07–5.69	0.2–2
	mg/s/1000 birds placed (ER)	0.001–0.19	0.005–0.06
	mg/s/kg (total live weight) (ER)	$(0.07–9.98) \times 10^{-5}$	$(0.5–3) \times 10^{-5}$
Particle number	**$particles/m^3$ (concentration)**	$(0.015–1.92) \times 10^{8}$	$(0.15–2) \times 10^{7}$
	particles/s (ER)	$(0.004–1.78) \times 10^{10}$	$(0.4–4) \times 10^{8}$
	particles/s/1000 birds placed (ER)	$(0.008–5.93) \times 10^{8}$	$(0.1–2) \times 10^{7}$
	particles/s/kg (total live weight) (ER)	$(0.004–3.12) \times 10^{5}$	$(0.04–1) \times 10^{4}$
Count median diameter (CMD)	**µm**	0.7–8	1–2.5

- The concentration of dust in the air exiting the layer sheds was variable. Consequently, dust emission rates from the sheds also varied widely. Dust emissions varied by ventilation rate, farm, season and microenvironment. Other factors that were unaccounted for were also likely to be involved.

- There were no discernible trends between dust concentrations or emission rates and the number of days after belt cleaning (manure removal).

- In general, dust emission rates tended to increase with increasing ventilation rate whereas dust concentrations tended to decrease.

- Seasonal differences in dust emissions could be partly explained by seasonal differences in ventilation rates.

7.2 Identification of NMVOCs and poultry shed odorants

Table 18 lists the chemicals and odorants identified in the NMVOC samples collected at layer farms. Samples were dominated by 2-butanone, 1-butanol and 2,3-butanedione, however the chemical species identified were in lower concentrations. There was only a low presence of sulphide species. Only three compounds were able to be identified as odorants during the analysis. Some of the other NMVOCs identified are known to be odorants but their abundance in the sorbent tubes was insufficient to elicit an olfactory response using the applied analytical methods.

Ventilation rate did not impact significantly on the amount of NMVOCs measured from the layer house emissions; however, this may have been due to the overall low abundance of the compounds.

Table 18: Chemical compounds frequently occurring in poultry house samples

Compound Family	Compounds Identified	Odorants Identified[1]	Odorant Descriptor[2]
Aromatics	Benzene Toluene Xylene (*o*-,*p*-) Styrene Acetophenone Benzaladehyde Phenol		
Alcohols	1-butanol 2-ethyl-1-hexanol 2-butoxy-ethanol	2-butoxy-ethanol	Solvent
Aldehydes	3-methyl-butanal Nonanal		
Ketones	2-butanone 2,3-butanedione 3-hydroxy-2-butanone Cyclohexanone	2,3-butanedione Cyclohexanone	Rancid, butter Solvent, chemical
Carboxylic Acids	Butanoic acid Acetic (Ethanoic) acid		
Sulphur	Dimethyl Sulphide		

[1]The third column identifies which of the chemicals are also odorants; and
[2] provides a descriptor of the odorant

8 Implications

8.1 The effect of variability and unpredictability of odour emission rates on industry planning and expansion

Odour emission rates were found to be variable. Additionally, the range of odour emission rates was similar to values reported in literature. Consequently, prediction of odour emission rates by consultants for dispersion modelling purposes is unlikely to significantly change.

8.2 Volatile organic compounds in odour

The identification and quantification of non-methane volatile organic compounds (NMVOCs) combined with the prioritisation of odorant species within these NMVOCs will support the development of tailored odour mitigation strategies. By focussing on nuisance odorants, researchers can develop odour abatement and mitigation strategies, with the aim of improving the management of poultry shed emissions.

8.3 Modelling of dust impacts

Further modelling work (e.g. dispersion modelling) will be required to use the database of dust emission rates obtained in this project to determine dust concentrations downstream of tunnel-ventilated poultry sheds as a function of distance. This information is necessary to determine dust concentrations in the areas surrounding poultry farms.

9 Recommendations

9.1 Measuring odour emissions at layer farms

- Odour sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because layer odour emissions are variable.
- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, fan details (dimension, manufacturer), mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, manure conditions (time since last cleaning, quantity, moisture content), lighting conditions and drinker type.
  - Flock information—bird age, bird numbers, bird live weight, total live weight, number of birds initially placed in the shed, bird breed.
- Daily fan activity should be understood/surveyed for that time of the flock and year. Odour sampling should be scheduled so that samples are collected at a representative ventilation rate or at several ventilation rates over the normal daily range. Efforts must be made to collect odour samples during the night when odour emission rates are lowest (and is also the time when atmospheric conditions are most stable and poor odour dispersion is likely).
- Fan activity **should not** be manually over-ridden, and stabilisation time should be allowed, if possible, following each change in fan activity. If fan activity changes during the collection of samples, it is recommended to record the changes in fan activity and calculate a time-weighted-averaged ventilation rate rather than manually lock-in the number of active fans. By locking in fans, abnormal shed conditions may be produced—especially in terms of temperature, bird activity and odour production/release mechanisms—that will result in the measurement of unrealistic odour emissions.
- Odour samples should be collected and analysed in duplicate to improve olfactometry confidence and accuracy. Samples should be analysed as soon as possible following collection.
- Efforts should be made not to disturb the chickens prior to, or during, sample collection as additional activity may increase the release of odour.

9.2 Measuring dust emissions at layer farms

- Dust sampling programs and methodologies need to be carefully chosen to provide meaningful and representative emission rates because poultry dust emissions are highly variable.
- Continuous, size-resolved dust measurements are necessary for studies that attempt to characterise the mechanisms of dust generation in intensive poultry sheds.
- For studies that integrate dust measurements over extended periods of time (e.g. gravimetric filter analysis), it should be recognized that large variations in dust concentrations are likely to occur during the sample collection period.
- At the time of sample collection, it is essential to record information including:
  - Sampling conditions—time, date, and sampling position.
  - Ambient conditions—ambient temperature, ambient humidity, internal shed temperature, and internal shed humidity.
  - Shed dimensions and conditions—ventilation rate, number and position of active fans, mode of ventilation (tunnel or mini-vent), shed length, shed width, wall height, roof apex height, ceiling baffle height, manure conditions (time since last cleaning, quantity, moisture content), lighting conditions, drinker type.

- Flock information—bird age, bird numbers, bird live weight, total live weight, number of birds initially placed in the shed, bird breed.

9.3 Sampling methodology

9.3.1 Dilution olfactometry analysis

- Odour samples should only be analysed at reputable, experienced olfactometry labs that can demonstrate compliance with AS/NZS 4323.3:2001. Olfactometry labs need to report the accuracy and precision of their laboratory, ensuring that $A \leq 0.217$ and $r \leq 0.477$.
- Odour samples are unstable and must be treated carefully. Odour samples should be analysed as soon as possible (preferably within 12 hours, maximum 24 hours) by:
  - choosing an olfactometry laboratory in close proximity to the test site;
  - transporting the samples to the olfactometry laboratory as soon as possible; and
  - pre-arranging delivery time to ensure the samples are analysed as soon as possible after delivery to the olfactometer.
- Where more than one olfactometry laboratory is used for a single trial, it is recommended that a test be performed to ensure similarity in results from all laboratories.

9.3.2 Ventilation rate measurement

- It is recommended that ventilation rate be estimated using manufacturer's performance data (from certified testing laboratories), number of active fans and shed static pressure. This method is recommended assuming that the following conditions are met:
  - fans are clean, well maintained and in good working order;
  - fan details are recorded including fan diameter, number of blades, blade pitch, blade material, motor manufacturer, motor power, voltage, pulley sizes, grills, shutter description, presence of a cone. A tachometer should be used to check rotational speed;
  - static pressure is recorded at the time of ventilation measurement (changes to fan activity and fluctuating wind conditions will affect the reading);
  - all active fan activity, including duty fans, is recorded; and
  - on-farm airspeed measurement inside the shed or across each fan face should ideally be made as a cross reference to the manufacturer's published fan performance data.
- Estimating ventilation rate using manufacturer's performance data is recommended because:
  - ventilation rate can be consistently estimated regardless of duty and tunnel fan activity as well as tunnel ventilation status (internal shed airspeed measurement is unsuitable when mini-vents are open or when duty fans are active);
  - manufacturer's fan performance data is usually obtained using standardised methods and certified laboratories (but you need to check which standard was used);
  - airspeed measurements across each active fan are time consuming and prone to errors due to fluctuating winds as well as non-uniform and turbulent air flow;
  - airspeed measurements across each fan face will be affected by the presence of grills and back-draft shutters; and
  - within the poultry shed environment, it is difficult to achieve the conditions required by AS4323.1:1995 when measuring airspeed inside the shed or across each fan face.
- When airspeed measurements are to be taken inside the shed or across each fan face, measurements must be made according to AS4323.1:1995.
- External fan measurements should be undertaken with caution because of turbulent fan air flow.
- External fan measurements should be avoided during gusty wind conditions.
- If measuring air velocity across the fan face, measurements need to be made at each active fan.

- Internal shed velocity measurements should not be undertaken while mini-vents or duty fans are active.
- Internal shed velocity measurements should be avoided during low levels of ventilation (when airspeed is minimal).
- Be aware that errors of 10–20% are likely regardless of the method used.

9.4 Using the odour emission rate data

- Odour emission rates vary diurnally, seasonally, throughout the life of the flock and will be different at different farms depending on management and infrastructure. **Calculation of daily average, flock average or constant odour emission rate is not appropriate—**unless for a specific purpose.
- Odour emission rates should be presented in terms of total OER (ou/s), OER per 1000 birds placed (ou/s/1000 birds placed) or OER per kg total live weight (ou/s/kg).

9.5 Using the dust emission rate data

- Dust emission rates vary diurnally, seasonally, throughout the life of the flock and will be different at different farms depending on management and infrastructure. Selection of a daily average, flock average or constant dust emission rate should be made with extreme care: considerable variation is likely to occur around the chosen average.
- If possible, dust emission rates should be presented in terms of total emission rate (ER) (e.g. mg or particles/s), ER per 1000 birds placed (e.g. mg or particles/s/1000 birds placed) and ER per kg total live weight (e.g. mg or particles/s/kg). This will enable easier comparison between different studies.

9.6 Future research

- Additional studies to quantify 'typical' odour emission rates from layer farms need to be made at multiple farms and on multiple days. Odour measurements must represent the full spread of 'normal' daily odour emissions, which will require odour samples to be collected at night.
- Future research should be directed at quantifying the specific biological, physical and chemical mechanisms that regulate the formation, release and transport of odour and dust within the shed and in the exhaust airstream.
- The effect of manure moisture content on odour formation is still largely unknown—including the delay between wetting and increased emission; changes to microbial community composition and activity; and changes to the manure physical odour release properties due to caking. Further research must investigate these relationships between manure moisture content and odour generation. Techniques to accurately measure the full moisture profile of the manure and to quantify the amount of caking will be required to achieve this.
- Future research should be directed at quantifying the conservation/degradation of odorants following emission from the shed (and before reaching receptors). Changes in odorant composition beyond the farm boundary may change the perception of odour by receptors.
- Investigation of the composition and NMVOC emissions from the manure material from layer houses would provide useful information relating to the principal odorant emissions.
- Moreover, the investigation of the microbial communities within the manure material and their corresponding NMVOC emissions would enable the elucidation of the species responsible for the key nuisance odorant formation.

10 Glossary

10.1 Abbreviations

ANOVA	Analysis of Variance
AOS	Artificial Olfaction System (electronic nose; non-specific electronic sensor array)
APS	Aerodynamic Particle Sizer
AS	Australian Standard
AS/NZS	Australian/New Zealand Standard
AWS	Automatic Weather Station
CEN	European Committee for Standardisation
CMD	Count Median Diameter
DEEDI	Department of Employment, Economic Development and Innovation (Queensland)
ER	Emission Rate
ETC	Emission Testing Consultants
GC	Gas Chromatograph
GC-MS/O	Gas Chromatograph-Mass Spectrometer/Olfactometer
HEPA filter	High Efficiency Particulate Air filter
IR	Infra-Red
Lpm	Litres per minute (sampling rate measurement)
MS	Mass spectrometer
MSD	Mass selective detector
N_2O	Nitrous Oxide
NER	Number Emission Rate
NH_3	Ammonia
NMVOC	Non-Methane Volatile Organic Compound
OC	Odour Concentration
ODP	Odour Detection Port
OER	Odour Emission Rate
OID	Olfactory input device
ou	Odour Concentration in Odour Units per m^3
PM	Particulate Matter
PM_1	Particulate Matter less than or equal to 1 micron
PM_{10}	Particulate Matter less than or equal to 10 microns
$PM_{2.5}$	Particulate Matter less than or equal to 2.5 microns
PN	Particle Number
PPB	parts per billion (µg/l)
PPM	parts per million (mg/l)
PTFE	Polytetrafluoroethylene (Teflon®)
PVC	Polyvinyl Chloride
QUT	Queensland University of Technology
r^2	Correlation Coefficient Value
RH	Relative Humidity
TD	Thermal desorption/Thermal desorber
TIC	Total Ion Chromatogram
TSP	Total Suspended Particulates
UNSW	University of New South Wales
VOC	Volatile Organic Compound
VR	Ventilation Rate

10.2 Definitions

Broiler	Meat chicken
Count Median Diameter	The mid-point of the size distribution of measured particles
Dry bulb temperature	Air temperature measured by a thermometer
Dynamic Olfactometer	Dilution system used to calculate odour concentration with the use of human panellists
Fogger	High pressure fogging nozzle designed to atomise water droplets and create a fine mist
Layer	An egg laying hen (or layer hen)
Live weight density	Unit weight of birds housed in a prescribed area, normally kg per m^2
Pickup	An event when some or all of the meat chickens will be harvested for processing
Stocking density	Number of birds housed in a prescribed area, normally birds per m^2
VOC and NMVOC	The term volatile organic compound (VOC) refers to any organic compound that under normal conditions will be of sufficient volatility to enter the atmosphere; where normal conditions are typical atmospheric pressure (101.325kPa) and temperature (~300K). Correspondingly non-methane volatile organic compounds (NMVOC) are all volatile organic compounds with the specific exclusion of methane (CH_4). **For the purpose of this document the terms NMVOC and VOC have been used interchangeably, however it should be expressly noted that where VOC is written it is implied that it is the non-methane volatile organic compounds.**
Wet Basis	Volume of moisture present in a sample compared to the total sample weight (can be compared to Dry Basis, which is the volume of dry matter present in the total sample weight)

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Appendix 1 – Summary of reported dust concentrations and emission rates

Reference	Type of operation	Ventilation type	Country	House and manure system	Sampling location	Concentration (mg/m^3)					Emission rate, ER (mg/s) [ER per 500kg live weight (mg/s/500kg)]				
						TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	PM_1	TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	PM_1
(Wathes et al., 1997)	Layer	Mechanical	UK	Perchery	7 sites within the shed (inc. 1 site at shed exhaust)	1.0 - 5.5		0.3 - 0.55			60.5-87.8 [0.42-0.61]		7.2-11.5 [0.05-0.08]		
(Wathes et al., 1997)	Layer	Mechanical	UK	Battery cages	7 sites within the shed (inc. 1 site at shed exhaust)	1.5 - 3.0		0.15 - 0.4			40.3-44.6 [0.28-0.31]		3.6-8.6 [0.03-0.06]		
(Takai et al., 1998)	Layer	Various	Denmark, Germany, England, Netherlands	Perchery	7 sites within the shed (inc. 1 site at shed exhaust)	5.3		0.8			123.2 [0.86]		23.8 [0.17]		
(Takai et al., 1998)	Layer	Various	Denmark, Germany, England, Netherlands	Battery cages	7 sites within the shed (inc. 1 site at shed exhaust)	1.2		0.1			25.5 [0.18]		3.1 [0.02]		
(Takai et al., 1999)*	Layer			Perchery	Within shed	2.82 - 7.33									
(Takai et al., 1999)*	Layer			Battery cages	Within shed	0.86 - 1.51									
(von Wachenfelt, 1999)*	Layer			Aviary	Within shed	2.4 - 12.0									
(Banhazi et al., 2003)	Layer	Various	Australia (SA)	Cage	Within shed	0.38		0.094			3.4 [0.024]		0.88 [0.006]		
			Australia (SA)	Bedding	Within shed	4.454		0.863			98 [0.7]		18.8 [0.13]		

Reference	Type of operation	Ventilation type	Country	House and manure system	Sampling location	Concentration (mg/m^3)					Emission rate, ER (mg/s) [ER per 500kg live weight (mg/s/500kg)]				
						TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	PM_1	TSP	PM_{10}	Respirable (PM_5)	$PM_{2.5}$	PM_1
(Lim et al., 2003)	Layer	Mechanical	USA	Battery cages	Within shed at exhaust	0.518 ± 0.074		0.039 ± 0.008		105 ± 25 [0.73±0.17]	105 ± 25 [0.73±0.17]	26.7 ± 5.7 [0.19±0.04]		1.8 ± 0.5 [0.013±0.003]	
(Jacobson et al., 2004)	Layer	Mechanical	USA	High-rise								3.3-16.7 [0.02-0.12]			
(Fabbri et al., 2007)	Layer	Mechanical	Italy	Battery cages- Deep pit manure system	Within shed at exhaust							25.7 [0.18]		7.6 [0.05]	
	Layer	Tunnel	Italy	Battery cages- Ventilated belt manure removal	Within shed at exhaust							7.4 [0.05]		2.5 [0.02]	
(Van Der Hoek, 2007)	Layer	Various	The Netherlands	Battery cages								0.4 [0.003]			
(Van Der Hoek, 2007)	Layer	Various	The Netherlands	Litter floor								4.3 [0.03]			
(Lim et al., 2003)	Layer	Mechanical	USA	Battery cages	Within shed at exhaust	0.518 ± 0.074		0.039 ± 0.008		105 ± 25 [0.73±0.17]		26.7 ± 5.7 [0.19±0.04]		1.8 ± 0.5 [0.013±0.003]	
(Takai et al., 1999)*	Broiler and Layer			Various	Within shed	2.22 - 4.58		0.19 - 0.64							
(Donham and Cumro, 1999)*	Broiler and Layer			Various	Within shed	0.02 - 81.33		0.01 - 7.73							

These references can be found within (Ellen et al., 2000). They are taken from the conference proceedings of the international symposium on "Dust Control in Animal Production Facilities"

** As referenced by Pollock and Anderson (2004)

*** This study reports average values from the (Redwine et al., 2002) study

Appendix 2 – Summary of the NMVOC laboratory techniques

Sampling Campaign	Date (MM/YYYY)	Gas Chromatograph Flow	Gas Chromatograph Column	Gas Chromatograph Temperature	Mass Spectrometer (m/z)	% Split to ODP
Qld. Winter Layer	Jul-07	1.6 ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35	66.67%
Qld. Summer Layer	Dec-07	1.6 ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35	66.67%
Vic. Summer Layer	Feb-08	1.6 ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35	66.67%
Vic. Winter Layer	Jun-08	1.6 ml/min Constant Pressure	HP-INNOWax	50 °C 2 min, 5 °C/min 125 °C, 10 °C/min 200 °C 2 min	Scan 35	66.67%

Appendix 3 – Odour samples discarded due to excess variability within the duplicate, or below detection limit or not analysed to standard

Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m^3/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %
158	D	Manure Belt	Winter	240707	2 days post belt run	8:45	18.00%	22	12.4	76	64.84	-	20.5	-
164	D	Manure Belt	Winter	260707	4 days post belt run	9:33	18.00%	22.9	14.4	67.9	64.84	-	21.8	-
164	D	Manure Belt	Winter	260707	4 days post belt run	9:33	18.00%	22.9	14.4	67.9	64.84	-	21.8	-

Appendix 4 – Farm D, winter odour and dust

Sample Number	Property	Manure Managment	Season	Date (ddmmyy)	Sample timing	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m^3/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
154	D	Manure Belt	Winter	230707	1 Day Post Belt Run	8:12	13.6%	17.3	17.2	70.6	64.84	-	21.3	-	55500	30000
155	D	Manure Belt	Winter	230707	1 Day Post Belt Run	9:29	18.0%	22.9	13.2	69.8	64.84	-	22.7	-	55500	30000
156	D	Manure Belt	Winter	230707	1 Day Post Belt Run	10:30	27.0%	32.2	15.7	58.2	64.84	-	23.5	-	55500	30000
157	D	Manure Belt	Winter	240707	2 Days Post Belt Run	7:43	9.1%	11.6	12.8	71.6	64.84	-	22	-	55500	30000
158	D	Manure Belt	Winter	240707	2 Days Post Belt Run	8:45	18.0%	22.0	10.5	82.4	64.84	-	20.5	-	55500	30000
159	D	Manure Belt	Winter	240707	2 Days Post Belt Run	10:38	27.0%	32.2	14.0	69.7	64.84	-	23.5	-	55500	30000
160	D	Manure Belt	Winter	250707	3 Days Post Belt Run	7:52	13.6%	20.0	13.2	69.1	64.84	-	22.4	-	55500	30000
161	D	Manure Belt	Winter	250707	3 Days Post Belt Run	9:06	18.0%	22.3	15.5	59.2	64.84	-	22.7	-	55500	30000
162	D	Manure Belt	Winter	250707	3 Days Post Belt Run	10:30	27.0%	31.3	17.2	53.2	64.84	-	23	-	55500	30000
163	D	Manure Belt	Winter	260707	4 Days Post Belt Run	7:34	13.6%	19.3	7.5	86.5	64.84	-	20.5	-	55500	30000
165	D	Manure Belt	Winter	260707	4 Days Post Belt Run	10:38	27.0%	30.8	17.7	55.5	64.84	-	23.1	-	55500	30000

Sample Number	Odour concentration* (ou/m^3)	ou Min[#]	ou Max[#]	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* ($ou/s/kg/m^2$)	NER[##] (particles/s/1000 birds placed)	$PM_{2.5}$ ER[##] (mg/s/1000 birds placed)	PM_{10} ER[##] (mg/s/1000 birds placed)
154	474	420	535	8213	0.27	274	274	0.15	127	-	-	-
155	425	304	594	9747	0.32	325	325	0.18	150	3,147,596	0.01	-
156	249	197	315	8019	0.27	267	267	0.14	124	2,381,859	0.02	-
157	283	256	312	3292	0.11	110	110	0.06	51	4,726,202	0.01	0.05
158	328	328	328	7202	0.24	240	240	0.13	111	2,324,034	0.01	0.06
159	132	114	152	4243	0.14	141	141	0.08	65	1,515,631	0.01	0.08
160	186	152	228	3721	0.12	124	124	0.07	57	1,692,661	0.01	0.04
161	215	181	256	4803	0.16	160	160	0.09	74	1,480,314	0.01	0.05
162	215	215	215	6739	0.22	225	225	0.12	104	1,606,265	0.01	0.06
163	328	269	400	6336	0.21	211	211	0.11	98	5,279,123	0.02	0.05
165	186	171	203	5746	0.19	192	192	0.10	89	3,101,046	0.03	-

* Geomean of duplicate olfactometry measurements
[#] Maximum or minimum olfactometry values
[##] Average values from corresponding odour collection times. Averaging time ~10 minutes.
Number of birds placed 30,000

Appendix 5 – Farm D, summer odour and dust

Sample Number	Property	Manure management	Season	Date (ddmmyy)	Sample timing	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m^3/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
166	D	Manure Belt	Summer	101207	1 Day Post Belt Run	6:12	55.0%	62.6	21.1	90.4	66.59	-	25.6	-	57000	30000
167	D	Manure Belt	Summer	101207	1 Day Post Belt Run	6:57	55.0%	62.6	21.3	88.1	66.59	-	25.8	-	57000	30000
168	D	Manure Belt	Summer	111207	2 Days Post Belt Run	5:30	36.0%	38.4	18.6	95.2	66.59	-	25.3	-	57000	30000
169	D	Manure Belt	Summer	111207	2 Days Post Belt Run	6:32	55.0%	62.6	21.7	82.5	66.59	-	24.9	-	57000	30000
170	D	Manure Belt	Summer	111207	2 Days Post Belt Run	8:15	82.0%	86.3	24.9	70.2	66.59	-	26.3	-	57000	30000
171	D	Manure Belt	Summer	111207	2 Days Post Belt Run	11:03	86.0%	89.4	28.5	59.1	66.59	-	27.1	-	57000	30000
172	D	Manure Belt	Summer	121207	3 Days Post Belt Run	5:28	36.0%	38.0	18.8	92.8	66.59	-	25.3	-	57000	30000
173	D	Manure Belt	Summer	121207	3 Days Post Belt Run	7:31	45.0%	52.7	22.0	81.8	66.59	-	26.6	-	57000	30000
174	D	Manure Belt	Summer	121207	3 Days Post Belt Run	8:55	73.0%	79.0	24.5	69.5	66.59	-	26.4	-	57000	30000
175	D	Manure Belt	Summer	121207	3 Days Post Belt Run	11:02	91.0%	92.7	26.3	59.6	66.59	-	26.8	-	57000	30000
176	D	Manure Belt	Summer	131207	4 Days Post Belt Run	5:28	27.0%	30.8	17.2	89.0	66.59	-	23.9	-	57000	30000
177	D	Manure Belt	Summer	131207	4 Days Post Belt Run	7:48	45.0%	52.7	22.0	70.3	66.59	-	25.2	-	57000	30000
178	D	Manure Belt	Summer	131207	4 Days Post Belt Run	10:21	82.0%	86.3	25.3	58.8	66.59	-	26.7	-	57000	30000
179	D	Manure Belt	Summer	131207	4 Days Post Belt Run	11:35	91.0%	92.7	24.5	59.8	66.59	-	26.5	-	57000	30000

Sample Number	Odour concentration* (ou/m^3)	ou Min[#]	ou Max[#]	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* ($ou/s/kg/m^2$)	NER[##] (particles/s/1000 birds placed)	$PM_{2.5}$ ER[##] (mg/s/1000 birds placed)	PM_{10} ER[##] (mg/s/1000 birds placed)
166	245	189	318	15350	0.51	512	512	0.27	231	-	-	-
167	226	220	232	14146	0.47	472	472	0.25	212	10,277,059	0.03	0.11
168	189	171	210	7274	0.24	242	242	0.13	109	-	-	-
169	173	157	190	10814	0.36	360	360	0.19	162	6,138,231	0.02	0.07
170	134	104	172	11539	0.38	385	385	0.20	173	6,567,724	0.05	0.11
171	161	135	191	14348	0.48	478	478	0.25	215	8,169,170	0.11	0.18
172	283	244	328	10754	0.36	358	358	0.19	162	-	-	-
173	269	256	283	14195	0.47	473	473	0.25	213	10,257,427	0.03	0.09
174	156	134	181	12305	0.41	410	410	0.22	185	23,145,617	0.07	0.13
175	158	152	164	14637	0.49	488	488	0.26	220	586,031,904	0.21	0.14
176	325	279	378	10015	0.33	334	334	0.18	150	66,369,778	0.02	0.05
177	285	279	291	15027	0.50	501	501	0.26	226	5,971,690	0.02	0.07
178	133	114	156	11506	0.38	384	384	0.20	173	6,353,947	0.11	0.08
179	123	105	143	11360	0.38	379	379	0.20	171	7,713,674	0.15	0.10

* Geomean of duplicate olfactometry measurements
[#] Maximum or minimum olfactometry values
[##] Average values from corresponding odour collection times. Averaging time ~10 minutes.
Number of birds placed 30,000

Appendix 6 – Farm E, summer odour and dust

Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m³/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m²)	Manure moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
180	E	Manure Belt	Summer	250208	5 Days Post Belt Run	11:50	25%	30.5	21.0	60.0	80.00	-	26	67	96000	50000
181	E	Manure Belt	Summer	250208	5 Days Post Belt Run	12:46	38%	45.7	23.0	-	80.00	-	26.9	-	96000	50000
182	E	Manure Belt	Summer	250208	5 Days Post Belt Run	14:05	38%	45.7	25.0	47.0	80.00	-	28.2	50.5	96000	50000
183	E	Manure Belt	Summer	260208	6 Days Post Belt Run	8:19	13%	15.2	12.5	89.6	80.00	-	24.9	62.2	96000	50000
184	E	Manure Belt	Summer	260208	6 Days Post Belt Run	9:19	18.8%	22.8	18.6	69.0	80.00	-	25.4	-	96000	50000
185	E	Manure Belt	Summer	260208	6 Days Post Belt Run	10:43	30.0%	36.5	22.0	57.8	80.00	-	26.1	54.5	96000	50000
186	E	Manure Belt	Summer	260208	6 Days Post Belt Run	11:31	37.5%	45.7	23.3	50.0	80.00	-	27.2	49.1	96000	50000
187	E	Manure Belt	Summer	280208	1 Day Post Belt Run	8:34	18.8%	22.8	12.7	87.7	80.00	-	23.9	57.7	96000	50000
188	E	Manure Belt	Summer	280208	1 Day Post Belt Run	10:22	18.8%	22.8	14.1	82.0	80.00	-	24.8	50.2	96000	50000
189	E	Manure Belt	Summer	280208	1 Day Post Belt Run	11:54	18.8%	22.8	16.0	58.6	80.00	-	25	51	96000	50000
190	E	Manure Belt	Summer	290208	2 Days Post Belt Run	8:20	62.5%	76.1	-	-	80.00	-	17.4	60.7	96000	50000
191	E	Manure Belt	Summer	290208	2 Days Post Belt Run	10:27	12.5%	15.2	17.5	55.0	80.00	-	25.7	-	96000	50000
192	E	Manure Belt	Summer	290208	2 Days Post Belt Run	11:41	20.0%	24.3	16.0	51.0	80.00	-	25.2	51.5	96000	50000
193	E	Manure Belt	Summer	290208	2 Days Post Belt Run	12:53	18.8%	22.8	17.5	41.0	80.00	-	25.4	39.7	96000	50000

Sample Number	Odour concentration* (ou/m³)	ou Min#	ou Max#	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m²)	NER## (particles/s/1000 birds placed)	$PM_{2.5}$ ER## (mg/s/1000 birds placed)	PM_{10} ER## (mg/s/1000 birds placed)
180	105	100	110	3196	0.06	64	64	0.03	80.42	3,412,554	0.02	0.04
181	84	84	85	3858	0.08	77	77	0.04	80.42	3,895,420	0.03	0.06
182	92	84	100	4184	0.08	84	84	0.04	80.42	4,115,261	0.05	0.06
183	284	260	310	4312	0.09	86	86	0.04	80.42	1,355,814	0.00	0.01
184	208	180	240	4745	0.09	95	95	0.05	80.42	1,083,298	0.01	0.02
185	215	160	290	7868	0.16	157	157	0.08	80.42	1,290,060	0.01	0.03
186	205	200	210	9357	0.19	187	187	0.10	80.42	1,528,294	0.02	0.04
187	787	680	910	17957	0.36	359	359	0.19	80.42	2,117,267	0.00	0.02
188	762	580	1000	17385	0.35	348	348	0.18	80.42	2,715,712	0.01	0.02
189	414	390	440	9456	0.19	189	189	0.10	80.42	2,796,052	0.01	0.02
190	81	79	84	6201	0.12	124	124	0.06	80.42	15,302,628	0.05	0.29
191	190	180	200	2882	0.06	58	58	0.03	80.42	790,316	0.01	0.01
192	214	170	270	5210	0.10	104	104	0.05	80.42	1,033,309	0.01	0.02
193	170	170	170	3881	0.08	78	78	0.04	80.42	822,432	0.01	0.01

* Geomean of duplicate olfactometry measurements
# Maximum or minimum olfactometry values
Average values from corresponding odour collection times. Averaging time ~10 minutes.
Number of birds placed 50,000

Appendix 7 – Farm E, winter odour and dust

Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Collection time (hh:mm)	Ventilation status (% of max fan activity)	Ventilation rate (m^3/s)	Ambient Temperature (°C)	Ambient Relative Humidity (%)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	In-shed temperature °C	In-shed relative humidity %	Total Live weight (kg)	№ Birds Present
194	E	Manure Belt	Winter	160608	5 Days Post Belt Run	9:35	9.4%	11.5	10.0	93.0	80.42	-	19.7	66	96500	50000
195	E	Manure Belt	Winter	160608	5 Days Post Belt Run	11:27	18.8%	22.8	18.0	60.0	80.42	-	-	-	96500	50000
196	E	Manure Belt	Winter	160608	5 Days Post Belt Run	11:52	18.8%	22.8	-	-	80.42	-	-	-	96500	50000
197	E	Manure Belt	Winter	160608	5 Days Post Belt Run	13:09	25.0%	30.5	-	-	80.42	-	-	-	96500	50000
198	E	Manure Belt	Winter	170608	6 Days Post Belt Run	8:39	12.5%	15.2	8.0	91.0	80.42	-	23.8	70.1	96500	50000
199	E	Manure Belt	Winter	170608	6 Days Post Belt Run	11:06	21.9%	26.6	19.0	69.0	80.42	-	22.3	-	96500	50000
200	E	Manure Belt	Winter	170608	6 Days Post Belt Run	11:37	22.5%	28.9	-	-	80.42	-	27.4	-	96500	50000
201	E	Manure Belt	Winter	170608	6 Days Post Belt Run	12:48	23.4%	28.5	21.0	55.0	80.42	-	25.6	-	96500	50000
202	E	Manure Belt	Winter	190608	2 Days Post Belt Run	9:00	16.6%	20.2	11.7	94.0	80.42	-	24.3	-	96500	50000
203	E	Manure Belt	Winter	190608	2 Days Post Belt Run	11:10	18.4%	22.4	-	-	80.42	-	19.5	-	96500	50000
204	E	Manure Belt	Winter	190608	2 Days Post Belt Run	11:37	18.4%	22.4	15.0	86.6	80.42	-	22.7	-	96500	50000
205	E	Manure Belt	Winter	190608	2 Days Post Belt Run	13:01	19.1%	23.3	14.5	86.0	80.42	-	23.3	-	96500	50000
206	E	Manure Belt	Winter	200608	3 Days Post Belt Run	8:27	14.8%	18.0	10.6	89.9	80.42	-	24.5	-	96500	50000
207	E	Manure Belt	Winter	200608	3 Days Post Belt Run	10:49	12.5%	15.2	11.0	91.0	80.42	-	13.4	-	96500	50000
208	E	Manure Belt	Winter	200608	3 Days Post Belt Run	11:12	12.5%	15.2	12.0	93.0	80.42	-	20.6	-	96500	50000
209	E	Manure Belt	Winter	200608	3 Days Post Belt Run	11:38	12.5%	15.2	11.9	87.0	80.42	-	23.6	-	96500	50000

Sample Number	Odour concentration* (ou/m^3)	ou Min[#]	ou Max[#]	Odour Emission Rate OER* (ou/s)	OER* (ou/s/bird)	OER* (ou/s/1000 birds)	OER* (ou/s/1000 birds placed)	OER* (ou/s/kg)	OER* (ou/s/kg/m^2)	NER[##] (particles/s/1000 birds placed)	$PM_{2.5}$ ER[##] (mg/s/1000 birds placed)	PM_{10} ER[##] (mg/s/1000 birds placed)
194	503	390	650	5770	0.12	115	115	0.06	72	15,980,698	0.01	0.03
195	478	440	520	10919	0.22	218	218	0.11	136	-	-	-
196	489	460	520	11165	0.22	223	223	0.12	139	7,514,765	0.02	0.04
197	579	550	610	17648	0.35	353	353	0.18	219	13,311,033	0.03	0.05
198	736	660	820	11173	0.22	223	223	0.12	139	3,825,656	0.01	0.02
199	935	910	960	24907	0.50	498	498	0.26	310	-	-	-
200	750	730	770	21655	0.43	433	433	0.22	269	8,091,288	0.03	0.04
201	570	550	590	16241	0.32	325	325	0.17	202	3,516,327	0.02	0.04
202	373	340	410	7549	0.15	151	151	0.08	94	7,501,601	0.00	0.03
203	294	240	360	6573	0.13	131	131	0.07	82	-	-	-
204	400	390	410	8957	0.18	179	179	0.09	111	16,124,749	0.02	0.04
205	389	370	410	9073	0.18	181	181	0.09	113	23,365,501	0.02	0.04
206	413	310	550	7425	0.15	149	149	0.08	92	4,668,161	0.00	0.03
207	670	650	690	10171	0.20	203	203	0.11	126	-	-	-
208	520	520	520	7897	0.16	158	158	0.08	98	1,777,599	-	-
209	599	520	690	9097	0.18	182	182	0.09	113	1,823,494	-	-

* Geomean of duplicate olfactometry measurements
[#] Maximum or minimum olfactometry values
[##] Average values from corresponding odour collection times. Averaging time ~10 minutes.
Number of birds placed 50,000

Appendix 8 – Farm D, winter dust

Dust Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Ventilation Status (% of max fan activity)	Ventilation rate (m^3/s)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (µm)	Number conc. (particles/m^3)	NER (particles/s)	$PM_{2.5}$ conc. (mg/m^3)	$PM_{2.5}$ ER (mg/s)	PM_{10} conc. (mg/m^3)	PM_{10} ER (mg/s)
80	D	Manure Belt	Winter	230707	1 Day Post Belt Run	18.0%	22.94	64.84	-	55500	30000	2.33	3,761,865	86,284,605	0.014	0.324	-	-
81	D	Manure Belt	Winter	230707	1 Day Post Belt Run	27.0%	32.19	64.84	-	55500	30000	2.05	2,466,561	79,403,564	0.017	0.554	-	-
82	D	Manure Belt	Winter	240707	2 Days Post Belt Run	9.1%	11.65	64.84	-	55500	30000	2.15	10,600,811	123,465,082	0.037	0.435	0.126	1.466
83	D	Manure Belt	Winter	240707	2 Days Post Belt Run	18.0%	21.96	64.84	-	55500	30000	1.95	3,299,261	72,441,045	0.014	0.314	0.075	1.658
84	D	Manure Belt	Winter	240707	2 Days Post Belt Run	27.0%	32.23	64.84	-	55500	30000	1.86	1,445,459	46,594,175	0.021	0.685	0.076	2.455
85	D	Manure Belt	Winter	250707	3 Days Post Belt Run	13.6%	19.99	64.84	-	55500	30000	1.99	3,222,315	64,407,268	0.013	0.265	0.078	1.561
86	D	Manure Belt	Winter	250707	3 Days Post Belt Run	18.0%	22.31	64.84	-	55500	30000	1.84	1,991,769	44,442,613	0.012	0.274	0.072	1.609
87	D	Manure Belt	Winter	250707	3 Days Post Belt Run	27.0%	31.34	64.84	-	55500	30000	1.79	1,791,079	56,137,313	0.014	0.448	0.063	1.967
88	D	Manure Belt	Winter	260707	4 Days Post Belt Run	13.6%	19.32	64.84	-	55500	30000	1.61	7,657,940	147,928,674	0.038	0.726	0.089	1.727
89	D	Manure Belt	Winter	260707	4 Days Post Belt Run	18.0%	22.31	64.84	-	55500	30000	1.50	4,895,978	109,244,627	0.027	0.601	-	-
90	D	Manure Belt	Winter	260707	4 Days Post Belt Run	27.0%	30.84	64.84	-	55500	30000	1.46	3,080,473	95,003,690	0.033	1.007	-	-

Appendix 9 – Farm D, summer dust

Dust Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Ventilation Status (% of max fan activity)	Ventilation rate (m^3/s)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (µm)	Number conc. (particles/m^3)	NER (particles/s)	$PM_{2.5}$ conc. (mg/m^3)	$PM_{2.5}$ ER (mg/s)	PM_{10} conc. (mg/m^3)	PM_{10} ER (mg/s)
91	D	Manure Belt	Summer	101207	1 Day Post Belt Run	55.0%	62.61	66.59	-	57000	30000	1.28	6,120,771	383,239,662	0.018	1.129	0.050	3.106
92	D	Manure Belt	Summer	111207	2 Days Post Belt Run	36.0%	38.39	66.59	-	57000	30000	1.51	6,049,866	232,240,525	0.012	0.458	0.046	1.761
93	D	Manure Belt	Summer	111207	2 Days Post Belt Run	55.0%	62.61	66.59	-	57000	30000	1.59	2,950,022	184,709,664	0.017	1.087	0.040	2.475
94	D	Manure Belt	Summer	111207	2 Days Post Belt Run	82.0%	86.28	66.59	-	57000	30000	1.56	2,526,975	218,025,299	0.021	1.822	0.048	4.110
95	D	Manure Belt	Summer	111207	2 Days Post Belt Run	86.0%	89.35	66.59	-	57000	30000	1.45	3,868,983	345,708,843	0.039	3.491	0.062	5.520
96	D	Manure Belt	Summer	121207	3 Days Post Belt Run	36.0%	38.02	66.59	-	57000	30000	1.32	7,134,667	271,224,475	0.018	0.670	0.043	1.650
97	D	Manure Belt	Summer	121207	3 Days Post Belt Run	45.0%	52.74	66.59	-	57000	30000	1.42	5,575,933	294,055,295	0.018	0.939	0.054	2.871
98	D	Manure Belt	Summer	121207	3 Days Post Belt Run	55.0%	62.61	66.59	-	57000	30000	1.08	6,876,675	430,548,621	0.023	1.410	0.047	2.947
99	D	Manure Belt	Summer	121207	3 Days Post Belt Run	73.0%	79.01	66.59	-	57000	30000	0.90	8,808,650	695,985,575	0.032	2.563	0.052	4.092
100	D	Manure Belt	Summer	121207	3 Days Post Belt Run	82.0%	86.28	66.59	-	57000	30000	2.22	150,228,105	12,961,680,921	0.045	3.914	0.051	4.364
101	D	Manure Belt	Summer	121207	3 Days Post Belt Run	91.0%	92.71	66.59	-	57000	30000	2.89	192,007,192	17,800,639,457	0.061	5.687	0.045	4.187
102	D	Manure Belt	Summer	131207	4 Days Post Belt Run	27.0%	30.84	66.59	-	57000	30000	8.01	68,435,936	2,110,606,305	0.015	0.454	0.045	1.373
103	D	Manure Belt	Summer	131207	4 Days Post Belt Run	36.0%	41.45	66.59	-	57000	30000	1.35	4,777,664	198,034,185	0.012	0.492	0.034	1.409
104	D	Manure Belt	Summer	131207	4 Days Post Belt Run	45.0%	52.74	66.59	-	57000	30000	1.37	3,991,342	210,489,481	0.012	0.616	0.033	1.743
105	D	Manure Belt	Summer	131207	4 Days Post Belt Run	55.0%	62.61	66.59	-	57000	30000	1.42	2,845,634	178,165,114	0.014	0.878	0.029	1.795
106	D	Manure Belt	Summer	131207	4 Days Post Belt Run	61.0%	70.72	66.59	-	57000	30000	1.46	2,682,212	189,686,005	0.024	1.702	0.034	2.394
107	D	Manure Belt	Summer	131207	4 Days Post Belt Run	82.0%	86.28	66.59	-	57000	30000	1.45	2,360,933	203,699,339	0.040	3.454	0.030	2.628
108	D	Manure Belt	Summer	131207	4 Days Post Belt Run	91.0%	92.71	66.59	-	57000	30000	1.46	2,488,511	230,705,356	0.043	3.990	0.031	2.872

Appendix 10 – Farm E, summer dust

Dust Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Ventilation Status (% of max fan activity)	Ventilation rate (m^3/s)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (µm)	Number conc. (particles/m^3)	NER (particles/s)	$PM_{2.5}$ conc. (mg/m^3)	$PM_{2.5}$ ER (mg/s)	PM_{10} conc. (mg/m^3)	PM_{10} ER (mg/s)
109	E	Manure Belt	Summer	250208	5 Days Post Belt Run	25%	30.47	80.00	-	96000	50000	1.54	5,600,241	170,627,693	0.031	0.935	0.063	1.914
110	E	Manure Belt	Summer	250208	5 Days Post Belt Run	38%	45.66	80.00	-	96000	50000	1.56	4,386,502	200,267,024	0.044	2.029	0.065	2.975
111	E	Manure Belt	Summer	260208	6 Days Post Belt Run	13%	15.19	80.00	-	96000	50000	1.61	4,463,624	67,790,715	0.005	0.068	0.045	0.681
112	E	Manure Belt	Summer	260208	6 Days Post Belt Run	18.8%	22.83	80.00	-	96000	50000	1.73	2,372,776	54,164,888	0.019	0.423	0.034	0.781
113	E	Manure Belt	Summer	260208	6 Days Post Belt Run	30.0%	36.52	80.00	-	96000	50000	1.87	1,766,032	64,502,980	0.020	0.719	0.035	1.275
114	E	Manure Belt	Summer	260208	6 Days Post Belt Run	37.5%	45.66	80.00	-	96000	50000	1.99	1,673,731	76,414,678	0.022	1.011	0.041	1.852
115	E	Manure Belt	Summer	280208	1 Day Post Belt Run	18.8%	22.83	80.00	-	96000	50000	1.55	5,570,024	127,150,538	0.012	0.266	0.050	1.139
116	E	Manure Belt	Summer	290208	2 Days Post Belt Run	62.5%	76.12	80.00	-	96000	50000	2.10	10,051,224	765,131,402	0.030	2.310	0.192	14.634
117	E	Manure Belt	Summer	290208	2 Days Post Belt Run	12.5%	15.19	80.00	-	96000	50000	1.48	2,601,885	39,515,798	0.021	0.320	0.040	0.613
118	E	Manure Belt	Summer	290208	2 Days Post Belt Run	20.0%	24.32	80.00	-	96000	50000	1.49	2,124,538	51,665,439	0.019	0.463	0.036	0.864
119	E	Manure Belt	Summer	290208	2 Days Post Belt Run	18.8%	22.83	80.00	-	96000	50000	1.42	1,801,394	41,121,584	0.019	0.444	0.030	0.679

Appendix 11 – Farm E, winter dust

Dust Sample Number	Property	Manure Management	Season	Date (ddmmyy)	Sample timing	Ventilation Status (% of max fan activity)	Ventilation rate (m^3/s)	Bird weight distribution (kg/m^2)	Manure moisture content % (wet basis)	Total live weight (kg)	№ Birds Present	CMD (µm)	Number conc. (particles/m^3)	NER (particles/s)	$PM_{2.5}$ conc. (mg/m^3)	$PM_{2.5}$ ER (mg/s)	PM_{10} conc. (mg/m^3)	PM_{10} ER (mg/s)
120	E	Manure Belt	Winter	160608	5 Days Post Belt Run	9.4%	11.46	80.42	-	96500	50000	0.73	69,721,321	799,034,893	0.031	0.350	0.124	1.418
121	E	Manure Belt	Winter	160608	5 Days Post Belt Run	18.8%	22.83	80.42	-	96500	50000	0.80	16,459,790	375,738,239	0.038	0.875	0.084	1.908
122	E	Manure Belt	Winter	160608	5 Days Post Belt Run	25.0%	30.47	80.42	-	96500	50000	0.80	21,844,342	665,551,637	0.042	1.278	0.086	2.621
123	E	Manure Belt	Winter	170608	6 Days Post Belt Run	12.5%	15.19	80.42	-	96500	50000	0.82	12,594,858	191,282,787	0.039	0.596	0.077	1.165
124	E	Manure Belt	Winter	170608	6 Days Post Belt Run	22.5%	28.88	80.42	-	96500	50000	0.89	14,006,543	404,564,407	0.046	1.324	0.076	2.200
125	E	Manure Belt	Winter	170608	6 Days Post Belt Run	23.4%	28.51	80.42	-	96500	50000	1.20	6,166,557	175,816,330	0.037	1.041	0.064	1.815
126	E	Manure Belt	Winter	190608	2 Days Post Belt Run	16.6%	20.22	80.42	-	96500	50000	0.83	18,551,080	375,080,046	0.011	0.229	0.064	1.303
127	E	Manure Belt	Winter	190608	2 Days Post Belt Run	18.4%	22.36	80.42	-	96500	50000	0.73	36,054,269	806,237,443	0.042	0.939	0.080	1.799
128	E	Manure Belt	Winter	190608	2 Days Post Belt Run	19.1%	23.29	80.42	-	96500	50000	0.72	50,154,519	1,168,275,051	0.052	1.208	0.089	2.067
129	E	Manure Belt	Winter	200608	3 Days Post Belt Run	14.8%	17.98	80.42	-	96500	50000	1.57	12,979,664	233,408,029	0.011	0.197	0.080	1.435
130	E	Manure Belt	Winter	200608	3 Days Post Belt Run	12.5%	15.19	80.42	-	96500	50000	1.64	5,927,774	90,027,313	-	-	-	-