Project title	An investigation into the effects of flue gas quality on tomato plants
Project number:	PC287
Project leader:	Tim Pratt, FEC Services Ltd
Report:	Final report, December 2009
Previous report	None
Key staff:	Jon Swain (FEC Services) Tim Pratt (FEC Services) Steve Adams (Warwick HRI) Gerry Hayman (Hayman Consulting)
Location of project:	FEC Services, Warwick HRI, Hayman Consulting and nursery locations in the UK
Project coordinator:	Dr David Hand
Date project commenced:	October 2008
Date project completed (or expected completion date):	December 2009

DISCLAIMER:

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

[Name]
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[Organisation]

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[Name]
[Position]
[Organisation]

Signature .... Date ....

Report authorised by:
[Name]
[Position]
[Organisation]

Signature .... Date ....

[Name]
[Position]
[Organisation]

Signature .... Date ....

CONTENTS

GROWER SUMMARY

Headline

The concentration of harmful pollutants in the greenhouse is dictated largely by the combustion system from which the flue gases are used. The hierarchy of bad to good is given below.

Kerosene burner	Engine CHP	Older gas burner	Gas turbine	Newer gas burner
Most pollutants	→	→	→	Least pollutants

The ‘safe’ concentration of NO_x in flue gases depends on the concentration of CO_2 in the flue gases, which varies according to the combustion system type and fuel used. It also varies according to the CO_2 concentration achieved in the greenhouse. If 1,000ppm of CO_2 is achieved in the greenhouse, the concentration of NO_x in the flue gases from a natural gas fuelled boiler should not exceed 30ppm.

Evidence also suggests that more precise control of CO_2 levels in the glasshouse could reduce crop risks from pollutants, optimise crop response to CO_2 and reduce unnecessary fuel use.

Background and expected deliverables

CO_2 enrichment using the flue gases from natural gas and to a lesser extent from kerosene fuelled heating systems are used extensively in the UK by growers of a wide range of protected horticultural crops. However, the flue gases do not consist entirely of CO_2; depending on the source they can include a range of pollutants which, if present in large enough amounts, can have a negative effect on plant growth. The pollutants of greatest interest in horticultural applications are:

- Oxides of Nitrogen - collectively known as NO_x
- Oxides of Sulphur - collectively known as SO_x
- Ethylene (an un-burnt Hydrocarbon C_2H_4).

PC 25 (1992) concluded that the risk of damage to plants from high levels of NO_x were slight providing the CO_2 concentration remained within the range of 300 – 500ppm which at the time represented commercial practice. However, the current practice of growers of edible crops in particular is to aim for 1,000ppm. This suggests that damage to plants due to high levels of NO_x may be occurring. This is compounded by the fact that the performance of plants can be affected by relatively low levels of NO_x without showing any visible signs of damage. Improved glasshouse designs which are better sealed, and the widespread use of thermal screens, both increase the risk from pollutants building up and persisting in the glasshouse atmosphere for longer. Evidence suggests that it is not only the actual level of pollutants which pose a risk, but the length of time for which this level exists. This makes elucidation of crop effects even more complex.

More recently PC 228 (2005) explored the reasons for yield increases occurring at a commercial tomato nursery following the installation of a natural gas fuelled micro turbine CHP unit (Guy & Wright, Green Tye, Hertfordshire). Analysis of the CO_2 levels, light levels and other parameters did not fully account for the increase in yield. This led scientists, consultants and growers to question if the quality of CO_2 produced from the micro-turbine CHP contributed to the yield improvement.

The objectives of this project are to:

1. Establish values for the concentrations of harmful gases in the environment of 5 representative commercial greenhouses.
2. Establish the effect of CO_2 enrichment system type on the presence of harmful gases.
3. Determine the effects of harmful gas concentrations on plant yield and quality.

Summary of the project and main conclusions

Sites were chosen to represent the different heating and CO_2 enrichment systems currently used in UK tomato production. These were:

- Modern / new gas burner
- Old gas burner
- Micro-turbine gas CHP
- Reciprocating gas engine CHP
- Kerosene fuelled burner.

Three rounds of measurements were taken for the periodic monitoring in October 2008, January 2009 and March 2009. These were chosen to coincide with periods of minimal venting and therefore when pollutant levels were likely to be highest.

At each site the following measurements / records were collected:

1. Flue gas quality directly measured at the flue
2. Concentration of NO_x and CO_2 in the greenhouse over a period of one week
3. Spot measurements of Ethylene concentration

4. CO_2 distribution in the greenhouse
5. CO concentration as spot measurements
6. Season long data collection of yield, CO_2 level and radiation.

In addition to carrying out these measurements, heating equipment manufacturers were contacted to determine the 'as new' performance of equipment commonly found on nurseries.

Main conclusions

- The maintenance and calibration of all CO_2 related equipment ranging from burners to sensors is a key part of any strategy to ensure low levels of pollutants in greenhouses.
- The concentration of ethylene measured in greenhouses on commercial nurseries showed that it was unlikely to cause any plant related problems. However, anecdotal evidence suggests that ethylene damage does occur especially on nurseries with reciprocating engine CHP and it should not be ignored.
- NO_x are the most likely cause of poor plant performance. In extreme cases plant growth can be reduced by as much as 24%.
- NO_x concentrations above 250 ppb in a greenhouse should be avoided. 'Safe' concentrations vary widely depending on factors as subtle as the specific cultivar; 400 ppb can be tolerated in certain circumstances.
- Any flue gas regardless of fuel or combustion system type containing more than 30ppm of NO_x should be avoided, especially if CO_2 concentrations above 800 ppm are required.
- Modern (low NO_x) natural gas fuelled burners are designed to produce less than 30ppm of NO_x in the flue gases and will deliver generally acceptable NO_x levels in a greenhouse.
- Well maintained flue gas cleaning equipment operated alongside reciprocating engine CHP should deliver less than 30ppm of NO_x. This will deliver acceptable levels in greenhouses as long as excessively high CO_2 levels are voided (<1,200ppm).
- Ultra low NO_x combustion technology (less than 10ppm of NO_x in flue gases) is unlikely to deliver sufficient additional benefit to justify their associated cost and reduced energy efficiency.
- Modern kerosene fuelled burners are likely to deliver excessively high NO_x levels in a greenhouse even at 700ppm of CO_2.

- Replacing an old burner with its modern equivalent will deliver energy savings in addition to reducing pollutant levels in a greenhouse. The pay back on energy savings alone is likely to be less than 7 years.
- When comparing different combustion systems e.g. micro-turbine vs. conventional boiler it is important to compare the concentration of pollutants relative to the concentration of CO_2.

Financial benefits

The inherent variation between nurseries and their heating sources means that accurately determining the financial impact is very difficult. In many cases, the benefits of CO_2 enrichment outweigh the cost of any associated pollutant damage. However, this should not be used to 'justify' acceptance of high pollutant levels as, without them, the benefits of CO_2 enrichment could be even greater.

NO_x

Although highly dependent on the stage of growth and even variety, the literature search revealed reductions in the growth of tomatoes ranging from 22 to 32% at NO_x levels as low as 250 ppb. Typically this was exceeded in all the greenhouses monitored especially when there was no venting and a CO_2 level of 1,000 ppm or more was achieved. In comparison it was rarely exceeded on the new burners and micro-turbine CHP sites at CO_2 concentrations of less than 800ppm.

Putting the potential yield cost into perspective:

- A portable CO_2 meter to check fixed sensors and variation of CO_2 levels within a greenhouse - £1,000.
- Replacing a leaking suction pipe / central CO_2 analyser based measurement system with individual electronic CO_2 sensors in each greenhouse - £1,000 per sensor.
- PC 265 (2007) suggests that the first ten weeks of a tomato crop's life would require around 18 tonnes of pure CO_2 per hectare - £5,000 p.a. (including annual tank rental).
- A new natural gas fuelled burner - £25,000 to £30,000. The energy savings alone (up to 5% p.a.) could pay back the cost within seven years, excluding the value of any improvement in yield.

Ethylene

Ethylene was only found on one nursery and even then it was below the levels believed to affect plant development. However, there is considerable anecdotal evidence to suggest that a small number of nurseries are affected each year. These nurseries almost exclusively have ageing reciprocating engine CHP and the problems normally occur early in the year when there is little venting. Putting this into perspective:

- The loss of one complete truss of tomatoes can represent 2% of the total yield but much more in financial terms as ethylene problems tend to occur early in the year when the value of produce tends to be higher - £10,000 /Ha.
- Prolonged miss-set of tomatoes can significantly affect the value of several trusses especially when they are vine tomatoes grown for highly selective markets - £20,000 to £30,000 /Ha.
- A new centralised ethylene analyser (gas chromatograph) capable of checking the output of several CHP engines - £15,000 to £20,000.

SO_x

SO_x is only present at the levels required to affect plant performance when kerosene is used. To minimise the risk of SO_x damage the CO_2 level I the greenhouse should not exceed 450ppm. However, it is likely that the yield benefit of allowing 600ppm of CO_2 will outweigh the SO_x damage.

Action points for growers

Direct measurement of pollutants in greenhouses is impractical for growers to carry out. Where a problem is suspected:

- Measure the composition of flue gases and compare with guidelines in this report.

To minimise the likelihood of pollutant related problems:

- Ensure you have an effective maintenance program in place for all CO_2 related infrastructure – burners through to CO_2 sensors.
- Obtain copies of the following for guidance on CO_2 measurement in particular:
    - HDC grower guide – Tomatoes: guidelines for CO_2 enrichment (2002)
    - DEFRA factsheet – Energy management in protected cropping: management of CO_2 enrichment, 10/09.

Where problems are identified and best practice maintenance does not solve them:

- Reduce the target CO_2 concentration
- Consider using pure CO_2 when there is minimal venting
- Investigate upgrade options such as new burners.

SCIENCE SECTION

Introduction

CO_2 enrichment using the flue gases from natural gas and to a lesser extent from kerosene fuelled heating systems are used extensively in the UK by growers of a wide range of protected horticultural crops. However, the flue gases do not consist entirely of CO_2; depending on the source they can include a range of pollutants which, if present in large enough amounts, can have a negative affect on plant growth. The pollutants of greatest interest in horticultural applications are:

- Oxides of Nitrogen - collectively known as NO_x
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PC 25 (1992) concluded that the risk of damage to plants from high levels of NO_x were slight providing the CO_2 concentration remained within the range of 300 – 500ppm which was commercial practice at the time. However, current practice of growers of edible crops in particular is to aim for 1,000ppm. This suggests that damage to plants due to high levels of NO_x may be occurring. This is compounded by the fact that the performance of plants can be affected by relatively low levels of NO_x without showing any visible signs of damage.
More recently PC 228 (2005) explored the reasons for yield increases occurring at a commercial tomato nursery following the installation of a natural gas fuelled, micro turbine CHP unit (Guy & Wright, Green Tye, Hertfordshire). Analysis of the CO_2 levels, light levels, etc., did not fully account for the increase in yield which led scientists, consultants and growers to question if less pollutants in the micro-turbine CHP flue gases contributed to the yield improvement.

As a result, this project was commissioned to:

- Review current scientific knowledge in relation to the ‘safe’ levels of known pollutants
- Measure the levels of pollutants in both the flue gases and greenhouses on commercial nurseries with a range of CO_2 sources (boilers, CHP, etc.).

The overriding objective of this project was to improve the profitability of growers of protected crops by reducing the incidence of plant damage from high levels of pollutants in flue gases used for CO_2 enrichment.

Specific objectives were to:

- Provide recommendations for limits on concentrations of harmful gases in the greenhouse environment.

- Give information to growers on the selection and operation of CO_2 enrichment systems for optimised performance.
- Provide information about the yield benefits of improved CO_2 systems.
- Provide information about the energy efficiency and environmental pollution benefits of improved CO_2 systems.
- Effectively communicate the results to HDC members.

Materials and methods

The project comprised three parallel work streams:

- Literature review.
- Periodic short-term continuous and spot measurements of pollutants on commercial nurseries.
- Season-long monitoring of yield and key growth factors (CO_2, light, etc.).

Literature review

This was delivered by Dr Steve Adams (WHRI). The purpose was to identify and summarise existing scientific knowledge in relation to the effect of NO_x, SO_x and ethylene on plant growth and development and the currently accepted safe levels within the growing environment. Current standards in relation to the health and safety of people working within greenhouses were also identified.

Measurement of pollutant levels on commercial nurseries

This was delivered by FEC Services Ltd. This included:

- Spot measurements of flue gas composition
- Short-term, continuous monitoring of pollutant levels in the greenhouse
- Samples of greenhouse air for laboratory analysis by WHRI
- Spot measurements of CO_2 and CO distribution in the greenhouse.

Flue gas composition

The composition of the flue gases from the primary CO_2 source was measured at the start of each short-term monitoring period. The sample was taken directly from the flue to ensure no dilution with fresh air.

A Kane and May Quintox flue gas analyser, as used for boiler maintenance / efficiency tests, was used. Table 1 below lists the relevant data recorded.

Table 1. Flue gas analyser gas measurement types

Description	Units of measurement	Instrument range
CO_2	%	0 – 100%
O_2	%	0 - 100%
CO	ppm	0 - 10,000 ppm
NO	ppm	0 - 5,000 ppm
NO_2	ppm	0 - 1,000 ppm
NO_x	ppm	0 – 6,000 ppm
SO_2	ppm	0 - 5,000 ppm

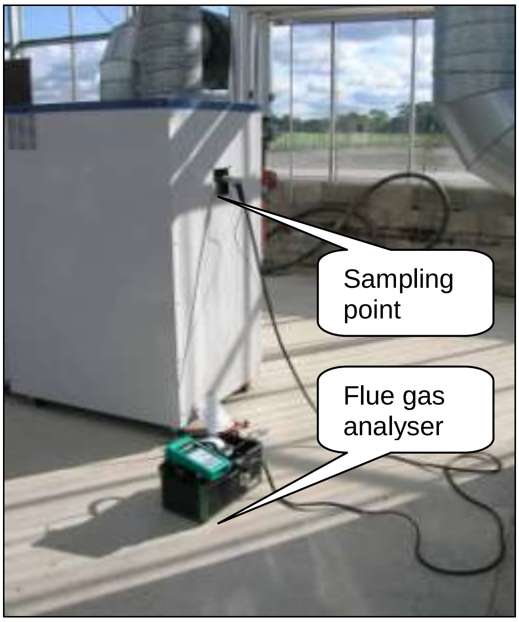

Figure 1. *Flue gas analysis on a micro-turbine CHP unit*

To ensure as representative a reading as possible:

- The boiler / CHP unit (Figure 1) was run for a minimum of 30 minutes before sampling started
- Five samples were taken at two minute intervals
- The flue gas analyser was purged before and after sampling.

Short-term monitoring of the greenhouse environment

Continuous monitoring

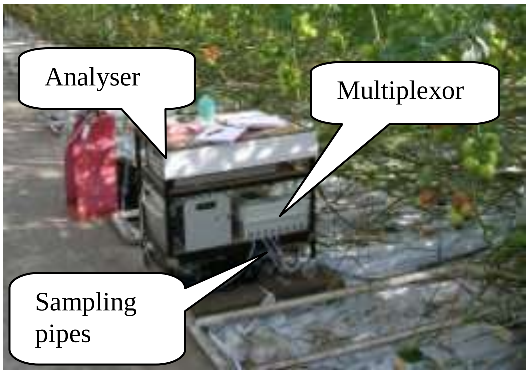

Figure 2. *Continuous monitoring in a greenhouse*

The monitoring equipment (Figure 2) was located at the side of the central path in each greenhouse and a multiplexor was used to allow air to be sampled from four different locations. The sampling points were:

- In the centre of the greenhouse (reducing potential effects of ambient air from doors)
- Half way along two rows approximately 4m apart
- One sampling point at the top of the crop canopy
- One sampling point at the base of the crop, close to the CO_2 enrichment pipes.

To give sufficient time for each sample to purge through the analysers, the multiplexor switched samples every five minutes. As a result measurements were recorded from each location every 20 minutes. Table 2 lists each of the gases measured in this way.

***Table 2**. Gases measured continuously*

Description	Units of measurement	Measurement method
CO_2	ppm	Edinburgh Instruments Guardian II Infra-red gas analyser
NO	ppb	Teledyne Instruments model 200E nitrogen oxides analyser
NO_2	ppb	

Due to the nature of its sensing elements the nitrogen oxides analyser had to be regularly calibrated. This was done using two reference points:

- A known concentration of NO_X (nominally 450 ppb NO) from a gas cylinder supplied for this purpose.

- Zero NO_x (0ppb) created by passing ambient air through a filter containing a NO_x absorbing material.

Spot measurements

Ethylene

It was not possible to continuously measure ethylene in the same way as for NO_x and CO_2. Samples were therefore taken each time the nurseries were visited according to the protocol below:

- 150 ml conical flasks were placed next to each of the sampling points used for the continuous monitoring
- The flasks were left for one hour and then sealed with turnover rubber stoppers
- The samples were analysed in WHRI laboratories using a Shimadzu GC-8A gas chromatograph.

CO_2 and CO measurements

The distribution of CO_2 and CO in the greenhouse was measured using a Kane and May model 100 handheld analyser. Measurements were taken at short intervals (<10 seconds) along six rows evenly distributed in the glasshouses.

The measurements were used to assess the variation in CO and CO_2 concentration and therefore by inference the variation in pollutant concentration.

Season-long monitoring

This was delivered by Gerry Hayman. Many of the participating nurseries already provided benchmarking data via the Tomato Working Party. The dataset was expanded slightly to include additional data required by this project. All of the data was collected as weekly averages and totals:

- Yield – kg/m^2
- CO_2 ppm during daylight hours only
- Temperature – 24-hour average
- Solar radiation – total MJ/cm^2.

Participating nurseries

In total seven nurseries took part in this project representative of the five CO_2 systems. Table 3 summarises each one. The nursery that was the subject of PC 228 was not included in this project as it was in the process of converting from natural gas to gas produced by an anaerobic digester. The variability in fuel quality was deemed to be too great to provide any clear results.

Due to the cost and maintenance requirements of the short-term, continuous pollutant monitoring equipment, each nursery was typically monitored for one week on three separate occasions. The site visits were planned to coincide with periods of no or minimal venting to identify 'worst case' pollutant levels:

- Autumn 2008.
- New year 2009.
- Spring 2009.

Table 4 lists each nursery and the dates during which monitoring was carried out.
All the data collected was collated by FEC Services' engineers and sent to WHRI for analysis and comparison with the findings of the literature review.

Table 3. *Commercial nurseries monitored*

Nursery project reference	**Reciprocating engine CHP 1**	**Reciprocating engine CHP 2**	**New gas burner (ornamentals)**	**New gas burner (edibles)**	**Kerosene burner**	**Micro-turbine CHP**	**Old gas burner**
Fuel	Natural gas	Natural gas	Natural gas	Natural gas	Kerosene	Natural gas	Natural gas
Primary CO_2 source	Reciprocating engine CHP with flue gas cleaning >10 years old	Reciprocating engine CHP with flue gas cleaning >10 years old	Low pressure hot water boiler 5 - 10 years old	Low pressure hot water boiler 5 - 10 years old	Low pressure hot water boiler >10 years old	Turbec micro-turbine CHP <5 years old	Low pressure hot water boiler >10 years old
Crop	Tomatoes cv Encore	Tomatoes cv Encore	Stem chrysanthemum various cultivars	Tomatoes cv Piccolo	Tomatoes cv Encore	Tomatoes cv Red Choice	Tomatoes cv Honey /Globo

Table 4. *Short-term monitoring schedule*

Nursery project reference	Reciprocating engine CHP 1	Reciprocating engine CHP 2	New gas burner (ornamentals)	New gas burner (edibles)	Kerosene burner	Micro-turbine CHP	Old gas burner
Autumn 2008	10/10/08 – 17/10/08	No measurements	No measurements	19/09/08 – 30/09/08	No measurements	No Measurements	17/10/08 – 24/10/08
New-year 2009	04/03/09 – 13/03/09 CHP not running, consider as an old burner site	No measurements	26/01/09 – 02/02/09	23/02/09 – 04/03/09	12/01/09 – 19/01/09	02/02/09 – 09/02/09	19/01/09 – 26/01/09
Spring 2009	CHP not running	07/05/09 – 20/05/09	No measurements	02/04/09 – 10/04/09	24/04/09 – 01/05/09	17/04/09 – 24/04/09	10/04/09 – 17/04/09
Additional notes	CHP failure prevented Spring measurements	Substitute for Reciprocating engine CHP 1	Late addition to investigate specific problems at this nursery		CO2 enrichment ended prior to Autumn measurements	CO2 enrichment ended prior to Autumn measurements	

Results

Literature review

Oxides of nitrogen (NO_x)

Various oxides of nitrogen can be formed when nitrogen and oxygen combine during combustion, although the principle gas is nitric oxide (NO). The rate at which NO forms is dependent on combustion temperature and this can then be oxidised to form nitrogen dioxide (NO_2). NO forms when the combustion temperature is above 1,100^oC and this commonly occurs in the combustion systems used on nurseries.

These two gases have rather similar harmful effects on crop photosynthesis and are often considered together under the collective name NO_x.

Effects on workers

In relation to human health, it is generally considered that NO_2 is the main threat because it is water soluble and can penetrate deeply into lungs and cause tissue damage (Krupa, 1997). Although NO, which is almost insoluble, may not pose such a direct threat, it is the main source of NO_2 in the atmosphere. The occupational exposure limit for NO_2 used to be 3 ppm long-term (averaged over eight hours), and 5 ppm short-term exposure (averaged over 15 minutes), although the Health and Safety Commission approved an updated list of Occupational Exposure Standards (OESs) in 2003 and the OES for nitrogen dioxide was withdrawn.

The National air quality objectives and the European Directive limit for the protection of human health specify an hourly limit of 105 ppb NO_2 (200 $\mu g\ m^{-3}$ NO_2 at 25^oC and 101 kPa) (Defra, 2007). This hourly limit is not to be exceeded more than 18 times in a calendar year. The Directive also specifies an annual limit value averaged over a calendar year of 21 ppb NO_2 (40 $\mu g\ m^{-3}$ NO_2 at 25^oC and 101 kPa).

Effects on plants

With reference to the cultivation of salad crops in glasshouses, it seems that the plants are more sensitive to NO_x than the humans who care for them and so it is the responses of the plants that should determine what is "acceptable". Unfortunately, it is not easy to define an "acceptable" NO_x concentration. For example, tomato cultivars apparently vary in their sensitivity to the gases and their sensitivity also varies with the stage of development of the crop and with other environmental conditions (Hand, 1986). In particular, the presence of other pollutants (Mansfield and McClune, 1988) and of carbon dioxide at above normal ambient concentrations will all influence the response of a crop to NO_x (Hand, 1986). As a result, there are few national air quality standards relating to plants. From 31 December 2000, however, the UK Government adopted a limit value for the protection of vegetation and ecosystems of 16 ppb NO_x (30 μg m^{-3} NO_2 at 25^{o}C and 101 kPa), averaged over a year (Defra, 2007), which is the same as the European Directive limit.

In tomato, leaves exposed to a high concentration of 2,000 ppb NO_2 for one to two hours show visible symptoms of acute injury in the form of water-soaked areas or "windows" that later turn white or brown. The leaves may also develop damaged margins (e.g. see Hand, 1979). Longer-term exposure to a lower concentration (500 ppb NO_2) can cause chronic injury, including a temporary increase in leaf greenness that is then followed by chlorosis and premature leaf fall.

It has been demonstrated that the effects of NO_x can be even more insidious when the oxides are present at yet lower concentrations due to a reduction in the effectiveness of photosynthesis (Hand, 1986). Capron and Mansfield (1976) examined effects of NO and NO_2 on leaf photosynthesis and found that these gases have a similar effect. Capron and Mansfield (1977) showed a 32% reduction in growth when tomatoes were exposed to either 400 ppb NO or 400 ppb NO combined with 100 ppb of NO_2. Taylor and Eaton (1966) showed that lower concentrations of NO_2 (150-260 ppb) for 10-22 days could reduce tomato leaf areas and dry weight, whereas Marie and Ormrod (1984) showed that 110 ppb did not have a significant effect. With regards to the impact on yield, Spierings (1971) showed a 22% loss of yield when tomatoes were grown with 250 ppb of NO_2 over a 17 week period. However, tomato cultivars vary in their sensitivity and cv. Sonata has been shown to be able to tolerate and even benefit from 400 ppb of NO, although higher levels (800 ppb) proved detrimental (Anderson and Mansfield, 1979). The beneficial effects of low NO_x concentrations observed with some cultivars were more pronounced under low soil fertility as the NO_x can act to feed the plants with nitrogen, although their ability to use nitrogen in this form is limited (Mansfield and Murray, 1984). Interestingly, Pandey and Agrawal (1994) showed that even when growth is stimulated by low levels of NO_2 (200 ppb), yield can be adversely affected due to more assimilates being partitioned for vegetative growth.

Thus, it seems that tomato plants are generally sensitive to very low concentrations of NO_x in the atmosphere. However, the response might not be as marked in the presence of an enriched concentration of CO_2. Anderson and Mansfield (1979) showed that at 350 ppm CO_2 growth in cv. Ailsa Craig was reduced when exposed to 400 ppb NO, although at a CO_2 concentration of 1,000 ppm the same concentration of NO (400 ppb) had no effect. Similarly Bruggink et al. (1988) showed that while 1,000 ppb of NO reduced net photosynthesis of tomato by 38% at 350 ppm of CO_2, when the environment was enriched to 1000 ppm of CO_2 the reduction in net photosynthesis was only 24%. Furthermore, Mortensen (1986) showed that NO_x was more detrimental when light levels were low. Under very low light levels (30 µmol/m^2/s) 1,500 ppb of NOx caused severe leaf injury and growth was greatly reduced in tomato, however, effects were less pronounced at higher light levels (up to 250 µmol/m^2/s in this experiment). Nevertheless it is possible that high NO_x levels could be reducing the benefit the grower would otherwise have obtained from CO_2 enrichment (Hand and Hannah, 1995).

Many species appear to be less sensitive to NO_x when compared with tomato. Mortensen (1985a) grew a range of species in growth chambers with CO_2 enrichment (1000 ppm), with and without 850 ppb NO_x. The presence of the NO_x proved detrimental in tomato, saintpaulia, and rose, but did not reduce growth in lettuce, cucumber, chrysanthemum, kalanchoe, common ivy or fern. Mortensen (1985b) grew eight tomato cultivars and six lettuce cultivars with CO_2 enriched air (1000 ppm CO_2) containing 700 ppb or 900 ppb NO_x. All of the tomato cultivars showed reduced growth with the addition of NO_x, to the extent that the benefits from CO_2 enrichment were virtually lost, but none of the lettuce cultivars were adversely affected by the NO_x.

Personal communication with Dutch companies involved in the installation of CHP and COdiNOx gas purification systems has revealed that they have set limits of 250 ppb NO and 132 ppb NO_2. The concentration that is required in the exhaust gas to achieve this is dependent on the ventilation and leakage characteristics of the glasshouse, the CO_2 concentration required in the greenhouse, etc., however, alarms are often set to go off if the exhaust gases contain more than 30 ppm NO.

Ethylene (C_2H_4)

Ethylene can be produced during combustion if there is insufficient air; it is also a naturally occurring plant hormone. Symptoms of ethylene injury include reduced apical dominance and shorter internodes, epinasty of leaves, premature senescence of leaves and flowers, delayed and malformed flowers, and abscission of flower buds. Epinasty may be induced in tomato at 100 ppb, and 500 ppb for four days is sufficient to cause two in every five flowers to either abort or drop off (Hand and Hannah, 1981). Work on a dwarf tomato cultivar (Red Robin) suggests that this is far more sensitive; there was virtually no fruit set at 100 ppb of ethylene, and even at 50 ppb fruit set was reduced (Blankenship and Kemble, 1996).

Figure 3: *Damage to tomato flowers after short-term exposure to a low concentration of ethylene.*

In chrysanthemum, the most sticking feature of ethylene is often delayed flower buds. Van Berkel (1987) showed that 50 ppb was sufficient to cause a marked delay in bud formation. Under higher ethylene concentrations (1 to 4 ppm) Tjia et al. (1969) showed that chrysanthemums failed to initiate buds even when exposed to short days. The plants also had shorter internodes, thickening of stems, smaller leaves, and loss of apical dominance.

Ethylene can also affect plant growth. Mortensen (1989) showed that 120 ppb of ethylene could reduce the dry matter of lettuce by between 25 and 50%. Even 55 ppb was enough to cause a significant reduction in growth. However, species vary in the sensitivity. In Canola (rapeseed) 126 ppb reduced growth, while 56 ppb had no significant effect, while in oats, dry weights increased with ethylene concentration up to 126 ppb (Reid and Watson, 1985). Reduced growth might be due to epinasty resulting in reduced light interception and direct effects of ethylene on stomata (Gunderson and Taylor, 1991). Madhavan et al. (1983) showed that 60-70 ppb could cause reduced stomatal conductance in tomato after 12 hours exposure. Ethylene has also been shown to affect assimilate partitioning (Woodrow et al., 1987).

Leaks in supply lines for propane can release propylene which can cause plant damage with very similar symptoms to that of ethylene, although the concentrations required are often much higher.

Carbon monoxide (CO)

Carbon monoxide is harmful to humans, but many plants seem tolerant of its presence in the atmosphere even at concentrations that are harmful to humans (e.g. Hand, 1986). However, as humans are required to work on the crops in glasshouses, it is the permissible limits for humans that must take priority.

When inhaled, CO is absorbed by haemoglobin to form carboxy-haemoglobin, which restricts the amount of oxygen that can be transported in the blood. As the concentration of carboxy-haemoglobin rises, oxygen starvation occurs in the brain and other organs. The national air quality objectives and the European Directive limit for the protection of human health specify a maximum running 8-hour mean of 9 ppm CO (10 mg m^{-3} at $25^{o}C$ and 101 kPa) (Defra, 2007). These environmental limits allow for an average population containing young children and the elderly as well as other groups that are known to be sensitive to CO. Occupational limits, on the other hand, are less stringent because it is assumed that the workforce does not include these vulnerable groups and is made up of individuals who are healthy, physiologically resilient and under regular supervision. The workplace exposure limits for CO are 30 ppm for 8 hours and 200 ppm for 15 minutes (HSE, 2007).

Some plants are able to absorb CO, although tomato is apparently not one of them (Bidwell and Fraser, 1972; Bidwell and Bebee, 1974). There is no evidence that photosynthesis of salad crops is impaired by CO at concentrations and exposure times that cause harm to humans (e.g. Bennett and Hill, 1973; Hand, 1986). Indeed, Wignarajah et al. (2000) demonstrated that the rate of fixation of carbon by lettuce was enhanced in a CO concentration as high as 512 ppm.

Sulphur dioxide (SO_2)

The risk of damage from SO_2 has been greatly reduced due to the use of low sulphur kerosene and more recently the shift to natural gas. Plants can often tolerate 200 to 300 ppb without showing symptoms (Zahn, 1961), although López et al. (2008) have shown 180 ppb to reduce growth in cucumbers, tomatoes and peppers. Pandey and Agrawal (1994) showed that low SO_2 concentrations (100 ppb) could initially increase growth, although longer term the effect was negative. Whereas Marie and Ormrod (1984) showed no significant effect of 110 ppb on growth of tomato in the absence of NO_2.

Long-term exposure to higher levels than mentioned above can result in chlorotic leaf spots. However, short-term exposure to much higher concentrations can result in interveinal necrotic spots (see photo). The gas enters leaves via the stomata and is then absorbed by the mesophyll cells which are damaged as a result. The reduction in photosynthetic leaf area can result in reduced growth and in very extreme cases death.

Figure 4: *Damage caused by short-term exposure to high SO_2 levels*

Species and cultivars do vary in their sensitivity to SO_2. Hand (1972) categorises tomato as being of intermittent sensitivity, and chrysanthemums as being fairly resistant. Brennan and Leone (1972) showed that when chrysanthemums were exposed to 4.5 ppm SO_2 for 4 hours this resulted in no damage on six cultivars and five cultivars showed only slight damage. In contrast, this SO_2 concentration resulted in severe damage in geraniums, zinnia and pinto beans. Howe and Woltz (1980) reported more severe damage in chrysanthemum at lower SO_2 levels; leaf 'scorch' appeared as tan-orange necrosis originating on leaf margins which eventually became interveinal. They compared 0.5 ppm for 8 hours, 1 ppm for 4 hours, 2 ppm for 3 hours and 4 ppm for 1 hour. Damage occurred in all treatments but was much more pronounced when there was a higher SO_2 concentration for a shorter period.

Data collected from commercial nurseries

Direct measurement of flue gases

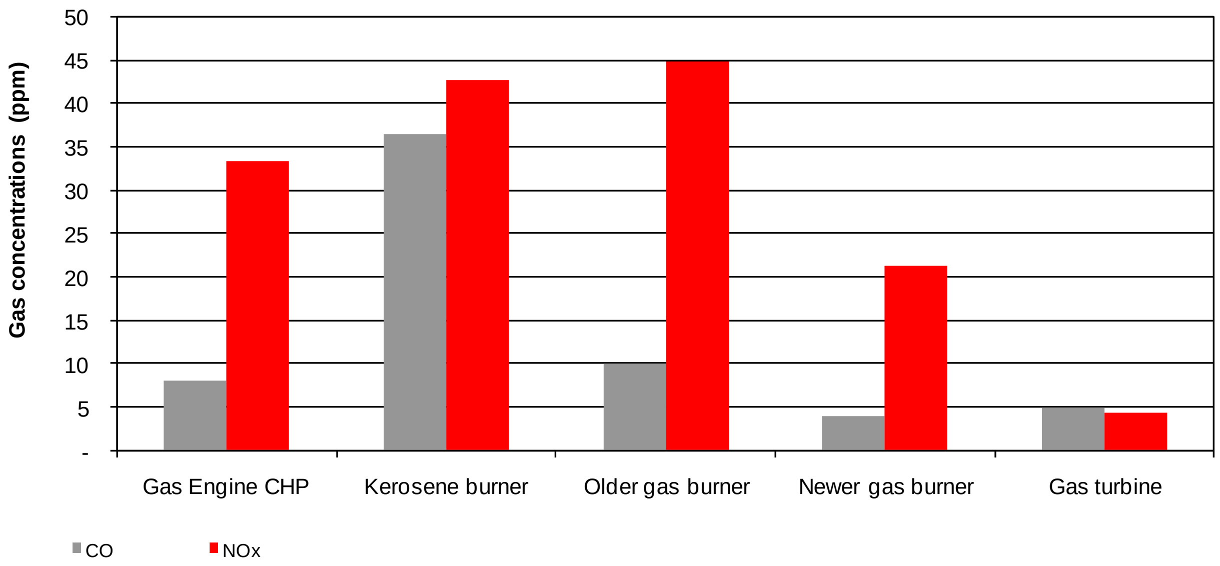

Figure 5: *Harmful gas concentrations measured in the flue gases*

Figure 5 above shows the average concentration of pollutants contained within the flue gases of the primary CO_2 source at each of the nurseries. On balance, the Kerosene burner exhibits the greatest amount of 'dirty' emissions. In isolation this data shows that the micro-turbine CHP unit is by far the 'cleanest' and this supports the hypotheses from PC 228. However, the concentration of CO_2 in flue gases varies according to the fuel burnt and the combustion system.

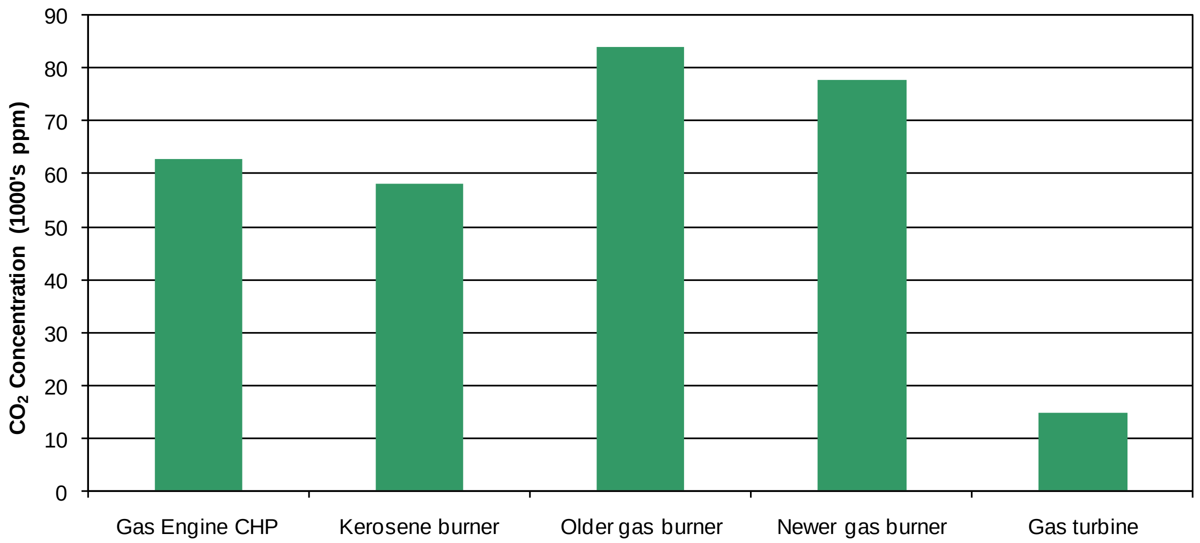

Figure 6.: *Quantity of CO_2 in the flue gases*

Figure 6 above, shows the concentration of CO_2 in the flue gases. The micro-turbine CHP unit produces significantly lower CO_2 concentrations than the others. This was expected due to the greater amount of excess combustion air required by the turbine compared to the other systems.

When using flue gases for CO_2 enrichment the lower concentration of CO_2 from the micro-turbine CHP unit means that a greater volume of flue gas is needed and therefore more pollutants will be added. As a result, comparing the concentration of pollutants in flue gases can be misleading. To address this Figure 7 shows the ratio between NO_X and CO_2 in the flue gases expressed as ppm of NO_x for each 10,000ppm of CO_2.

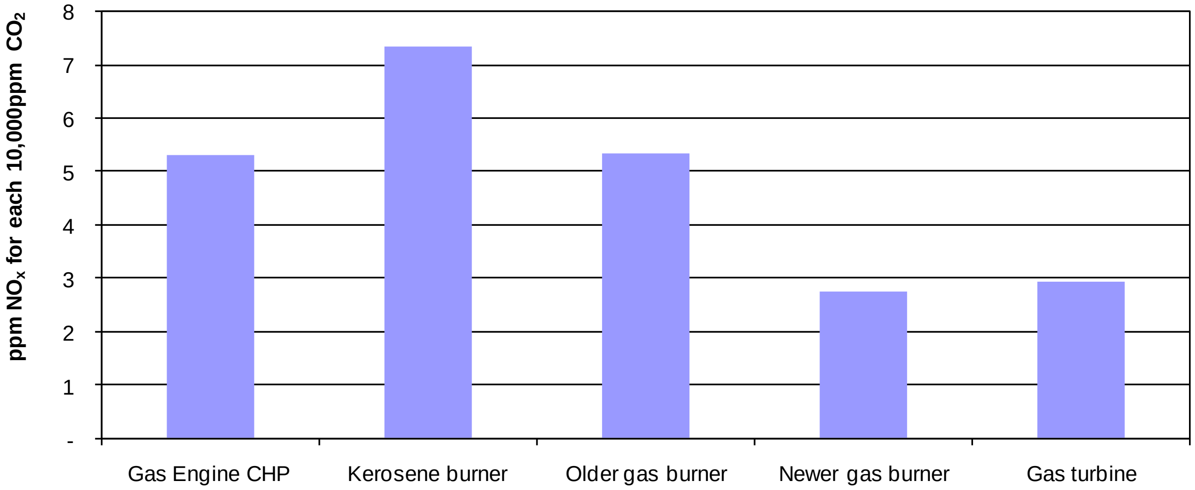

Figure 7. *Ratio of NO_X (PPM) to CO_2 (10,000 PPM)*

Presented in this way it is immediately obvious that the new gas burner and the gas turbine have the cleanest and broadly the same levels of NO_x (less than 3ppm NO_x/10,000ppm CO_2). The kerosene burner, as expected, is significantly higher and has in fact over double their quantity at 7ppm NO_X/10,000ppm CO_2.

Periodic greenhouse monitoring

Data from the analyser in the greenhouse was investigated and plots of CO_2 and NO_x levels were produced. Figure 8 below, is an example of one of these plots and shows the new burner site in April. Appendix 2 contains all of these plots for the other sites and measurement periods.

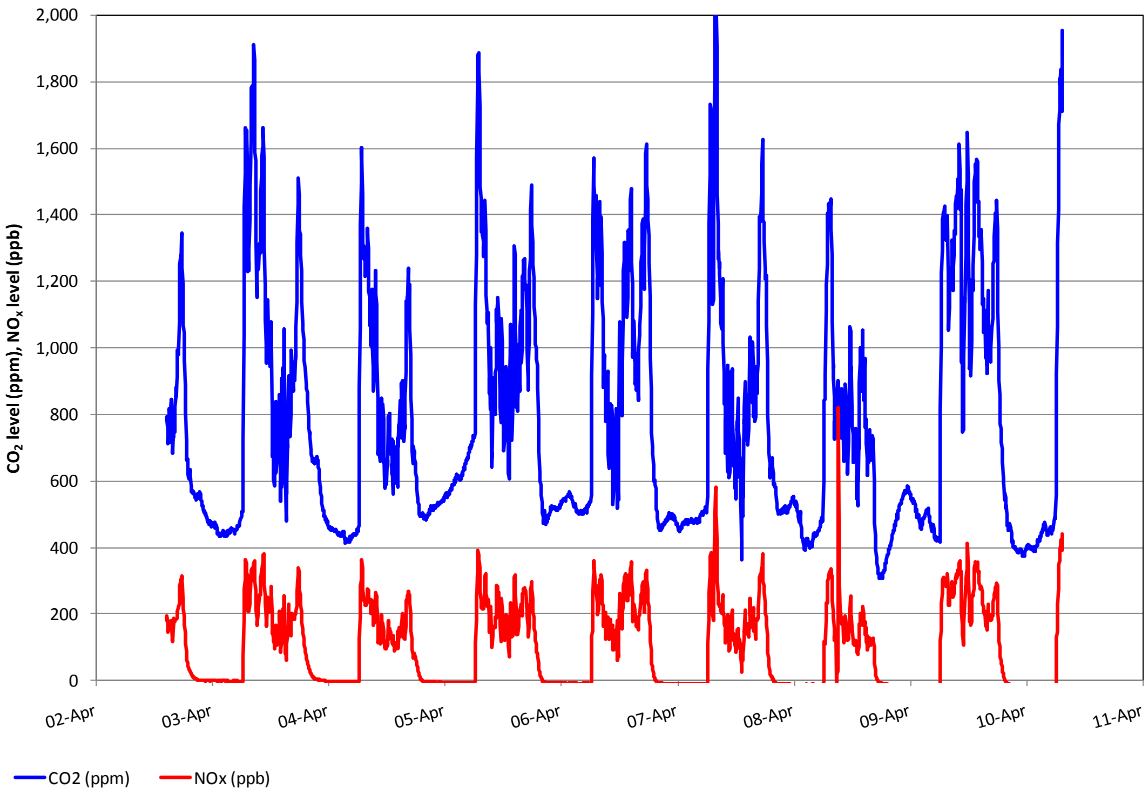

Figure 8. *Average NO_X and CO_2 concentrations recorded at the new gas burner site in April 2009*

From these graphs it is possible to see the variation of NO_X throughout the day and the maximum levels achieved. Analysis of these shows that the highest NO_X levels typically occurred during the early part of the year when CO_2 demand is relatively low but when there is almost no ventilation.

The NO_X comprised mainly NO, although some NO_2 was also present, especially at the engine CHP site which showed by far the highest NO_X concentrations. Values greater than 1,000 ppb NO_X were recorded, which is five times that typically seen on the sites with gas boilers. The gas turbine site also showed some moderately high values, although looking at the pattern this may have been, in part, due to enrichment over a longer period each day.
The concentration of NO_x varied greatly between the sites. The highest levels were seen during the early season (January/February 2009), coinciding with periods of high achieved

CO_2 concentrations and low ventilation rates. Figure 9 summarises the average values seen during this period.

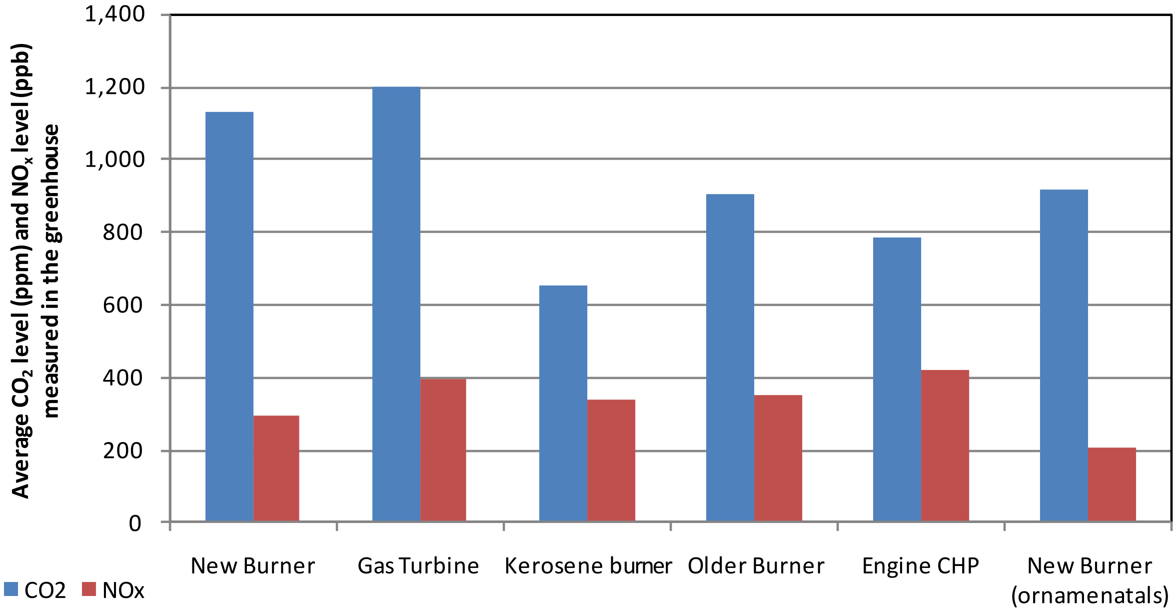

Figure 9. *Daytime average CO_2 and NO_x concentrations measured in the greenhouses in January/February 2009*

In the literature review it was evidenced that NO_X levels should be kept below approximately 250 ppb. However, in CO_2 enriched environments 400 ppb may be tolerable. Only the new gas burner (ornamentals) site was below 250 ppb on average. Apart from the engine CHP site, all of the rest had average values below 400 ppb.

Relationship between CO_2 and NO_X in the greenhouse

At a basic level, higher concentrations of CO_2 within a greenhouse require more flue gases to be added and therefore higher concentrations of pollutants can be expected. This was explored by plotting NO_x concentration versus CO_2 concentration for daylight hours.

Figure 10 shows good agreement with this hypothesis. However, the level of statistical agreement varied considerably between sites as demonstrated in Figure 11.

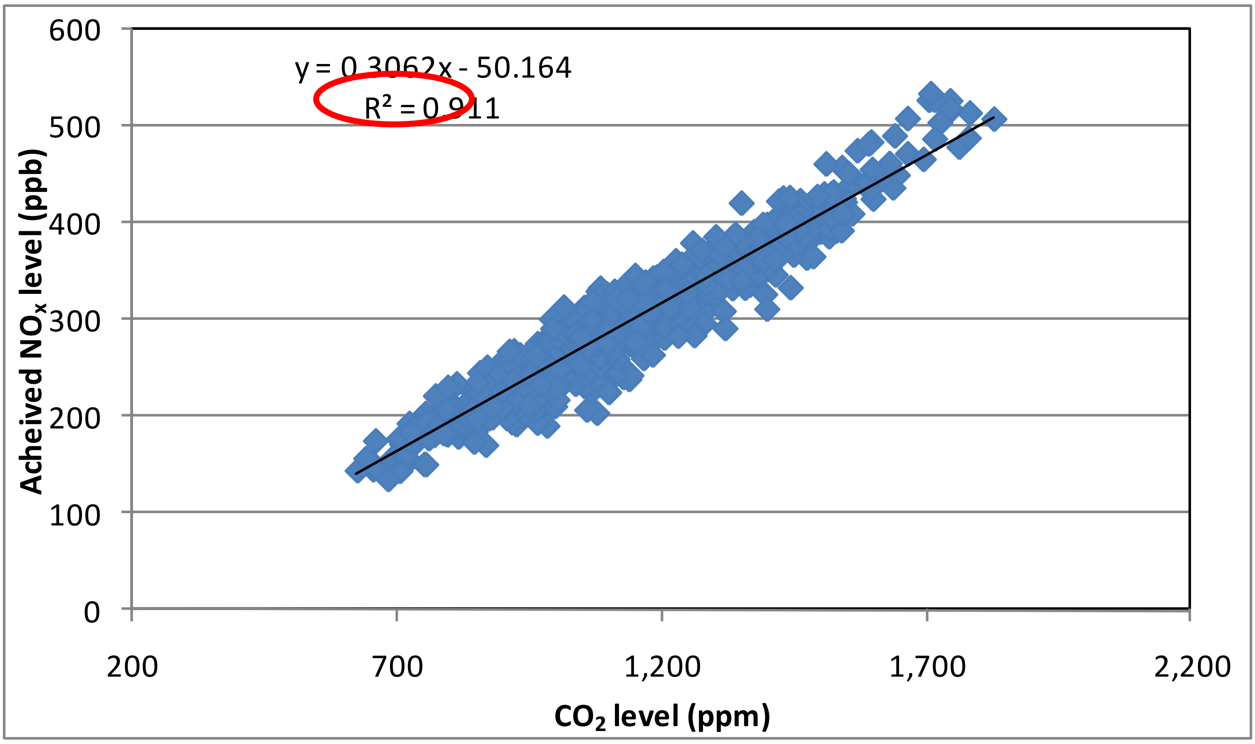

Figure 10. *Relationship betwwen NO_X (ppb) and CO_2 (ppm) in the greenhouse for the gas boiler site in January 2009, for daylight hours*

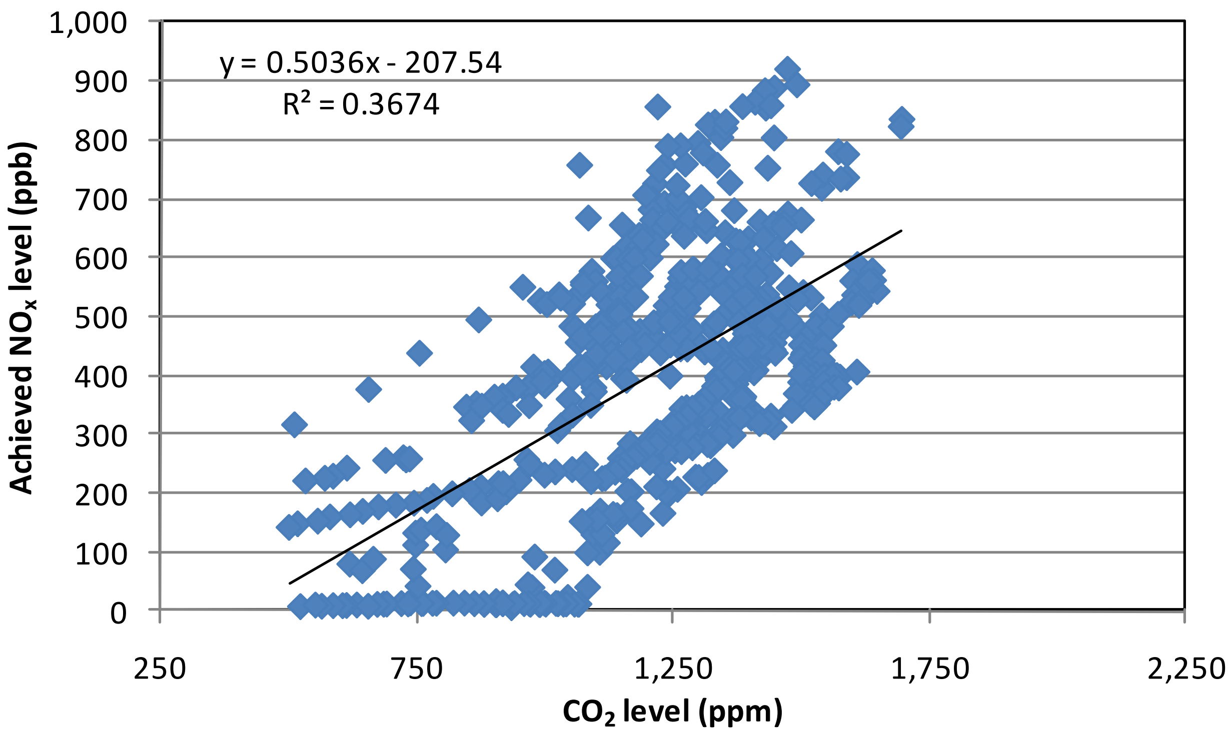

Figure 11. *Relationship betwwen NO_X (ppb) and CO_2 (ppm) in the greenhouse for the gas turbine site in February 2009, for daylight hours*

Accepting the inaccuracies associated with fitting a straight line to data such as that in Figure 11 above, Figure 12 below shows these relationships for all the sites in January / February 2009.

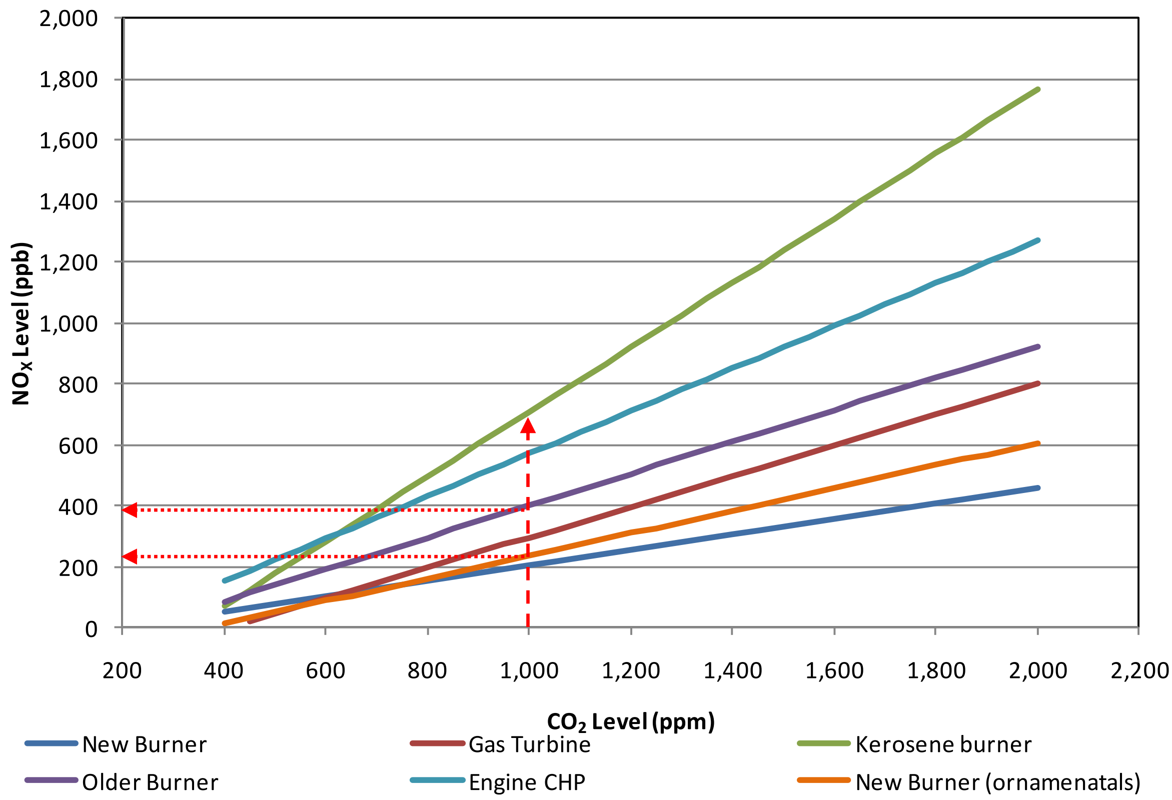

Figure 12. *Relationship between NO_X (ppb) and CO_2 (ppm) in the greenhouse for all sites in January/February 2009, for daylight hours*

Figure 12 can be used to indicate the likely NO_x concentration at any given CO_2 level for each nursery.

At a CO_2 level of 1,000 ppm:

- Kerosene burner and Engine CHP deliver greater than 400ppb NO_x
- Older burner and gas turbine deliver between 250ppb and 400ppb NO_x
- New gas burners deliver less than 250ppb.

Each site will have its own characteristic dependant on factors such as the sealing of the greenhouse, CO_2 enrichment strategy and even how windy it was when the measurements were taken. However, the trends identified in Figure 12 agree broadly with the cleanliness of the flue gas (see Figure 5).

Ethylene concentrations

The concentration of ethylene in the samples from the turbine and new burner sites were so low as to be undetectable. The samples from the engine CHP site showed a slight indication of ethylene but the concentration was probably no more than 20 ppb (the limit of detection), even from the samples at the bottom of the crop close to the CO_2 enrichment pipe.

'Safe' pollutant levels in flue gases

In practice it is not possible for growers to measure the concentration of pollutants in a greenhouse. It is however possible to check the concentration of NO_X and SO_X in the flue gases using commercially available flue gas analysers (cost around £3k) which boiler service engineers use. Ethylene can be measured but it is relatively expensive (£10-15k for an on-site analyser). As such ethylene monitoring only tends to be installed on sites with CHP where the risk is greatest.

Table 5 below summarises the 'safe' pollutant levels in greenhouses.

Table 5. *Safe pollutant concentration values*

Pollutant	**Level harmful to tomato plants**	**Suggested 'safe' level**
NO_x ($NO + NO_2$)	Although it does not result in visible damage, 250ppb may reduce growth and yield.	Aim for less than 250bbp
Ethylene (C_2H_4)	50ppb may reduce fruit set in some cultivars. Recommendations suggesting a 'safe' threshold of 10ppb appear sensible.	Aim for less than 10ppb
Sulphur dioxide (SO_2)	Following the introduction of low sulphur fuels this is rarely a problem. The harmful levels suggested vary from 100ppb to 500ppb.	Aim for less than 100ppb

The relationship shown in Figure 11 combined with the flue gas measurements allow an indication of the safe level of other pollutants in the flue gases to be determined. However, it should be noted that this approach does have its limitations and therefore serves to provide an indication rather than the definitive answer.

Figure 13 shows the concentration of NO_x in the undiluted flue gases from a natural gas fuelled boiler (8% CO_2) which would cause the NO_x concentration to exceed the threshold value (250ppb or 400ppb) in the greenhouse over a range of greenhouse CO_2 concentrations.

In this case, if a threshold of 250ppb is chosen there can be no more than 21ppm of NO_x in the flue gases. This increases to 33ppm if 400ppb is chosen.

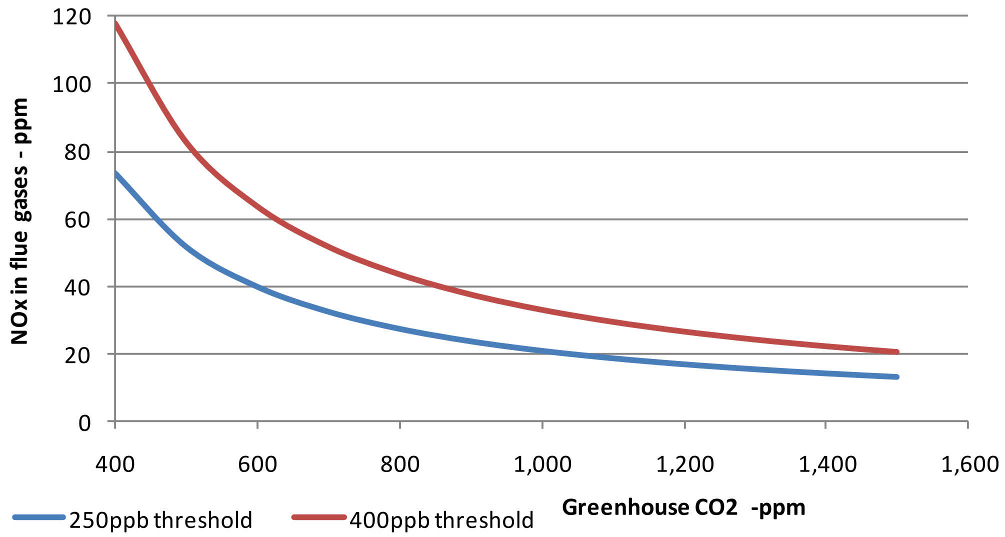

***Figure 13**. Relationship between NO_X (ppb) and CO_2 (%) and NO_x (ppm) in undiluted flue gases*

Taking this further, the flue gases from a reciprocating engine CHP typically contain 6% CO_2. To achieve the same CO_2 concentration in a greenhouse (compared to a boiler) more flue gases have to be added. The increase is equal to the ratio of CO_2 concentrations (8% : 6%). This also means that more NO_x are added so the 'safe' level of NO_x in the flue gases has to be reduced by the same proportion. So, if a threshold of 250ppb is chosen there can be no more than 16ppm of NO_x in the flue gases. This increases to 25ppm if 400ppb is chosen. The latter agrees well with industry wide targets for CHP installations of 30ppm.

The same process as described above can be applied to both SO_x and ethylene.

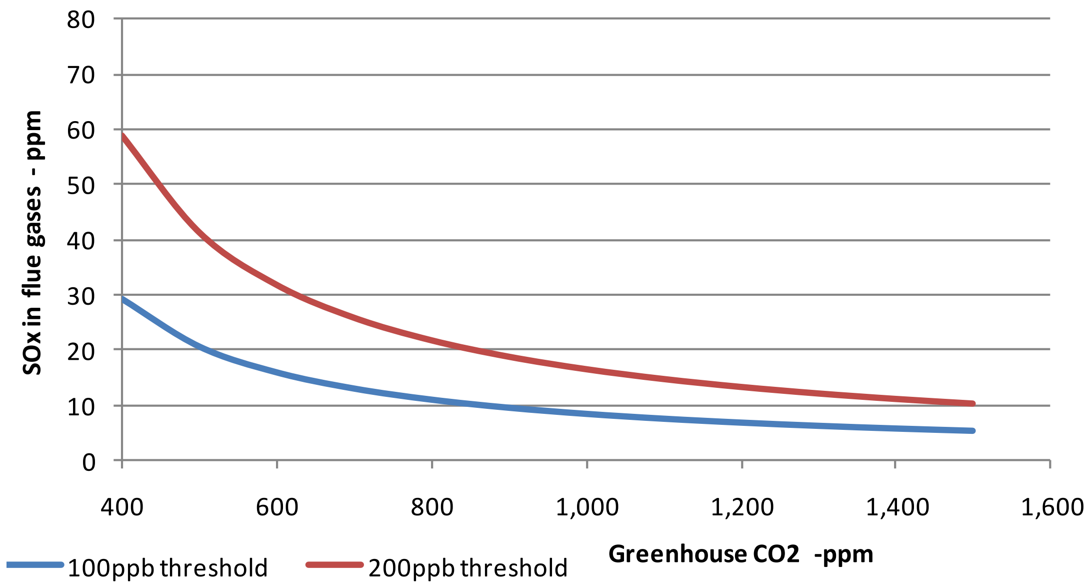

***Figure 14.** Relationship between SO_X (ppb) and CO_2 (%) and SO_x (ppm) in undiluted flue gases*

There are negligible amounts of sulphur in natural gas. As a result SO_x are only important when using kerosene. Although the specification for low sulphur kerosene is for a maximum of 0.1% of sulphur by weight it most commonly contains 0.05% sulphur. This produces around 25ppm of SO_x in the flue gases. Figure 14 above therefore shows that to have minimal risk of SO_x damage, the CO_2 concentration in the greenhouse should not exceed 450ppm. If 200ppm of SO_x is allowed, the CO_2 concentration increases to 700ppm. In this case it is likely that the increased yield due to higher CO_2 concentration will deliver greater benefits than the damage caused by SO_x.

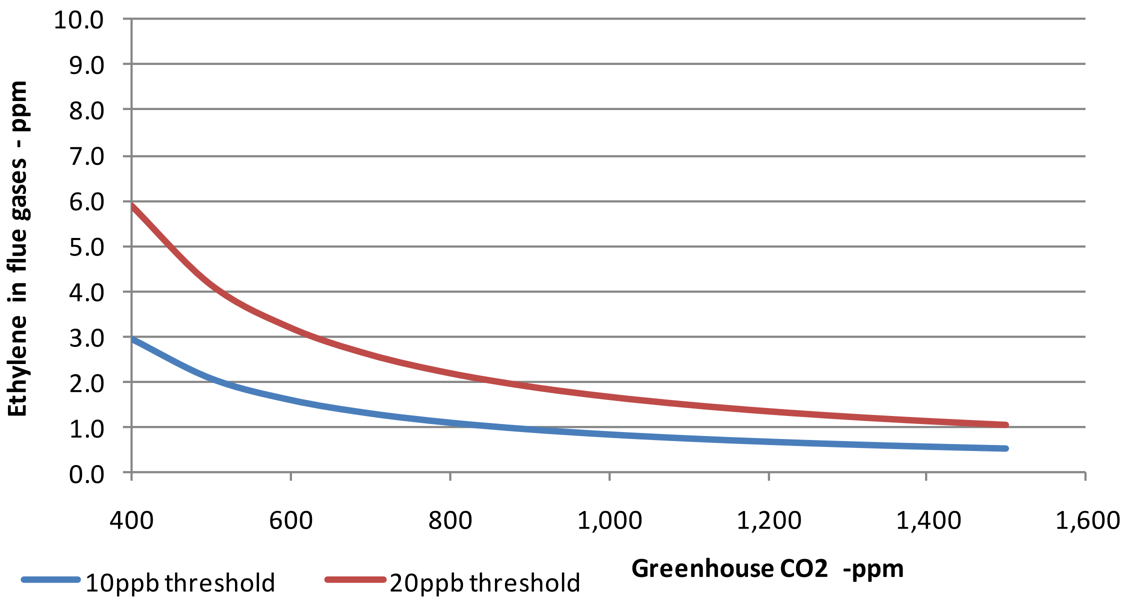

Figure 15. *Relationship between ethylene (ppb) and CO_2 (%) and ethylene (ppm) in undiluted flue gases*

As the effect of ethylene is so marked it is likely that growers would err on the side of caution and aim for 10ppb or less. Therefore when aiming for 1,000ppm CO_2 in the greenhouse no more than 0.8ppm should be allowed in the flue gases. This reduces to 0.6ppm with CHP. However, many growers with CHP regularly achieve 1,400ppm especially when CO_2 measurement error and control limitations are taken into account. This reduces the threshold to 0.45ppm in CHP flue gases. Once again this agrees well with industry wide targets for CHP installations of 0.4ppm. However, during the summer time when the vents are open and 600ppm of CO_2 in the greenhouse is commonly achieved 1.2ppm of ethylene in CHP flue gases may be acceptable.

CO and CO_2 distribution in the greenhouses

The minimum CO value detectable by the analyser is 1ppm. The safe human exposure limit is 30ppm. The analyser did not register any CO in the greenhouses. Even allowing for instrument measurement error, CO is not considered a problem.

Spot measurements of CO_2 concentration were taken at short intervals during or just after CO_2 enrichment. The data was analysed and surface plots of the results were created. Two sample plots of the results from the CO_2 distribution measurements are shown in Figure 16 below and Figure 17.

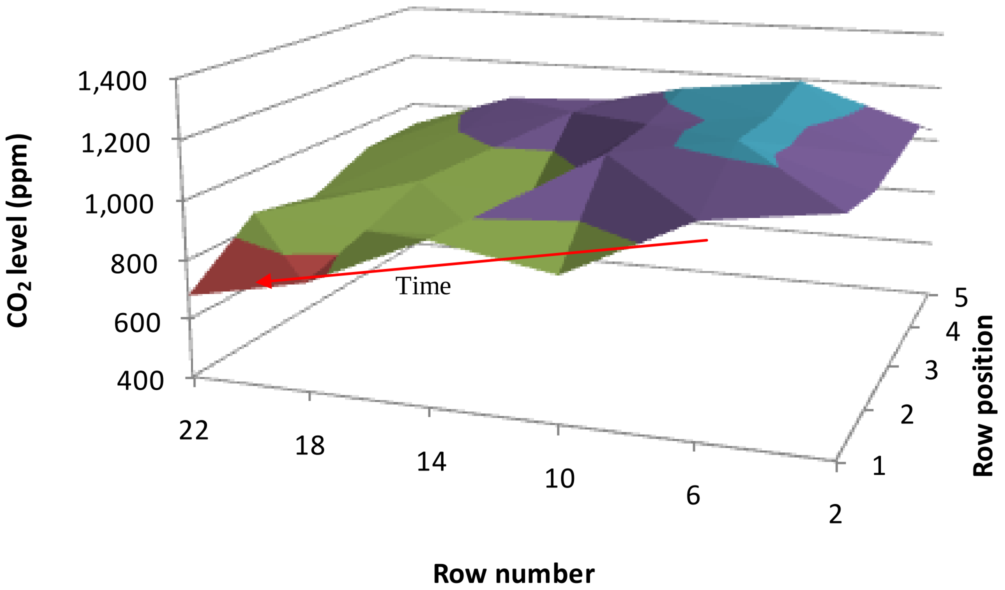

Figure 16. *Surface plot of the CO_2 distribution for the old burner site in January 2009*

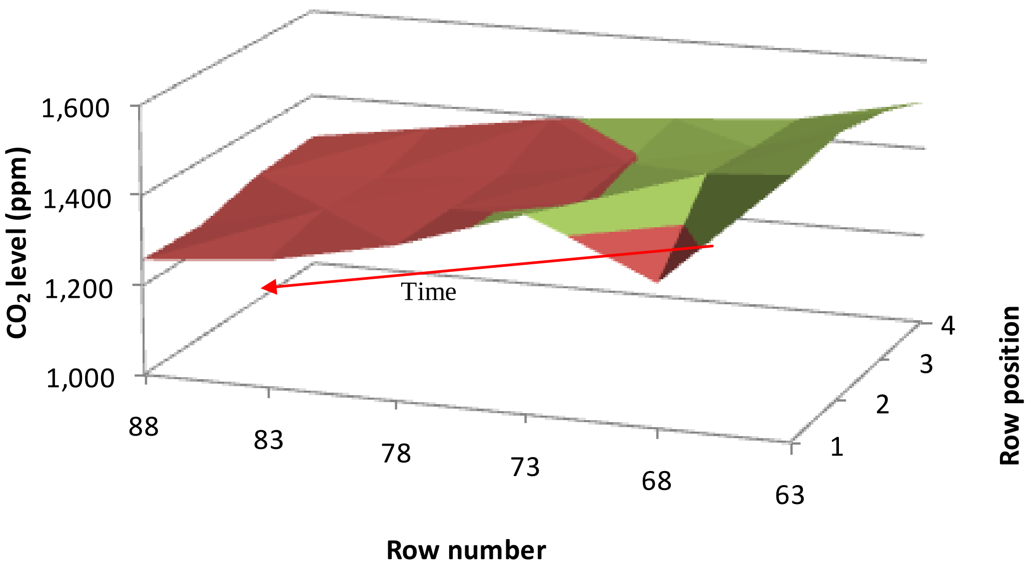

Figure 17. *Surface plot of the CO_2 distribution for the Turbine site in January 2009*

As the graphs show, the uniformity of CO_2 concentration measured within individual greenhouses varied significantly. This was largely due to the natural depletion of CO_2 which occurred very rapidly (within 2 to 3 minutes) and so it is difficult to make any firm conclusions.

Assuming that the distribution of CO_2 within a greenhouse was perfect, the effect of natural depletion of CO_2 would mean that every measurement would be lower than the one taken before it. Therefore any increase would suggest less than perfect uniformity. Even with this somewhat tenuous form of analysis the maximum variation was in the order of 200ppm of CO_2. Referring back to Figure 12 this has little effect on the pass / fail with regards to the level of NO_x within the greenhouses.

Long term yield and greenhouse environment

Table 6 details the results from the long term monitoring of the nurseries (excluding the ornamentals nursery)

Table 6. *Results from season data collection*

	Site	Engine CHP	New Burner	Kerosene Burner	Gas Turbine	Older Burner	Group Averages
Planting details	**Variety**	Encore	Piccolo	Encore	Red Choice	Honey /Globo	
	Sowing date	26/10/08	10/12/08	06/11/08	31/10/08		
	Growing system	NFT	NFT	Coir	Rockwool	Rockwool	
Plant population - heads/m^2	**Initial**	2.00	2.20	2.00	2.34	2.14	**2.14**
	Added	2.00	2.20	1.50	1.74	1.41	**1.77**
	Final	4.00	4.40	3.50	4.08	3.55	**3.91**
	Final - % of group average	102.4	112.6	89.6	104.5	90.9	
	Yield - kg/m^2	58.68	25.54	48.80	34.58	45.41	**42.60**
	Yield - % of group average	137.7	60.0	114.5	81.2	106.6	
CO_2 ppm	**Yearly day average**	994	762	611	798	676	**768**
	Yearly % of group average	129.4	99.2	79.5	103.9	88.0	
	Average wks 14-36	747	603	478	569	597	**599**
	% of group average wks 14-36	124.7	100.7	79.8	95.0	99.7	
Temp - average ^oC	**Day**	21.50	n/a	20.60	20.80	21.70	**21.15**
	Night	18.00	n/a	17.10	17.70	17.90	**17.68**
	24 hr	19.90	n/a	19.00	19.30	19.90	**19.53**
	24 hr - % of group average	101.9	n/a	97.3	98.8	101.9	
Solar Radiation	**MJ/m^2**	3641	3513	3273	4512	4365	**3861**
	% of group average	94.3	91.0	84.8	116.9	113.1	

The variables affecting yield are considerable and there was no facility within this project to replicate the results over time. Among the significant variables between sites are:

- Crop management
- Tomato variety
- Growing system
- Glasshouse design
- CO_2 source
- CO_2 input capacity
- CO_2 control strategy
- Solar radiation receipt.

Additionally, although some analyses were recorded for the engine CHP site when the CHP was operational in the autumn of 2008 and the early part of 2009, the system was not functioning for the whole of the 2009 crop season because of maintenance problems. The results shown here for 2009 therefore relate to the use of an older conventional gas fired hot water system with CO_2 extracted from its exhaust flue gases.

The same variety (Encore) was grown on only two locations, the engine CHP site (considered here as an older burner site) and the kerosene burner site. Comparisons in yield, solar radiation and recorded CO_2 levels for these sites are in Table 7.

Table 7. *Comparison of recorded yields, solar radiation and CO_2 for the engine CHP and Kerosene burner sites*

Site	**Engine CHP site (old burner)**	**Kerosene burner site**
Yield - kg/m^2	58.68	48.80
Yield - %	100	83.2
Solar radiation - MJ/m^2	3,641	3,273
Solar radiation - %	100	89.9
CO_2 – whole season - recorded ppm	994	611
CO_2 – whole season - %	100	61.5
CO_2 – weeks 14-36 - recorded ppm	747	478
CO_2 – weeks 14-36 - %	100	64.0

One might expect more pollutants to be associated with the burning of kerosene than natural gas, especially in an older burner, as has been proven earlier in this report. However, it could be argued that the differences in solar radiation receipt and achieved CO_2 levels between the two sites would more than account for the yield differences. Although not recorded, the older glasshouses on the kerosene burner site will also have lower light transmission levels than those on the engine CHP (old burner) site and would be expected to produce lower yields as a result.

Whilst the monitoring equipment was present on test sites in this project, the opportunity was taken to measure CO_2 levels as well as pollutants. These figures are included in Appendix 3. Recording was for relatively short periods so caution needs to be exercised in drawing conclusions. However, comparisons of grower climate computer records with analyser recorded values showed the following:

- Engine CHPsite. Figures overstated by an average of 110 ppm (2 records).
- New burner site. Figures understated by an average of 245 ppm (4 records).
- Kerosene burner site. Figures overstated by an average of 294 ppm (2 records).
- Gas Turbine site. Figures understated by an average of 36 ppm (4 records).
- Old burner. Figures overstated by an average of 132 ppm (2 records).

In two cases, new burner site and old burner site, control was exercised, at least in part, by running burners at a set rate until buffer tanks were full. In the case of the new burner site, no actual CO_2 set point was indicated. This would seem to incur the risks of both overdosing under low uptake and ventilation conditions and of under-dosing in high demand periods; neither being desirable.

In Appendix 3, achieved levels are expressed as a percentage of the desired set-point. These figures need to be interpreted with care as a disparity between the two could indicate some inaccuracy in dosing control or limitations in the capacity of the dosing system to meet high set-point targets.

CO_2 sources – manufacturers data

The results of this project show that NO_x continue to pose the greatest 'unseen' risk to plant growth and that levels considered to be harmful do occur on commercial nurseries. Ethylene causes the most visible and potentially catastrophic effect on plants but the concentrations measured during this project were so low as to be considered harmless. However, as a general rule measures taken to reduce the concentration of NO_x, such as improved monitoring and maintenance are likely to reduce the concentration of all pollutants.

Four key factors affect the concentration of NO_x in flue gases:

- Fuel

- Combustion system type / design
- The presence of flue gas cleaning equipment
- Maintenance.

As a means of further validating the results obtained and demonstrating what is possible in ideal operating conditions manufacturer's data was collated and compared with the measurements taken (see Table 8 and Figure 18 overleaf).

Once again the trends in terms of NO_x concentration agree well with the measurements taken on commercial nurseries.

An interesting comparison is between the different Hamworthy burners and the site measurements:

- The standard gas burner (SLN denotes 'ultra-low NO_x') produces NO_x levels similar to the new boiler site which has been shown to deliver acceptable NO_x levels in the greenhouse.
- The low NO_x fuel oil (kerosene) burner has *the* ***potential*** to produce significantly higher NO_x levels than those found on the kerosene boiler site. Therefore higher concentrations of NO_x in greenhouses using kerosene could exist.

Figure 18, shows the measurements of NO_x taken at each site compared to manufacturers stated data for that type of heating system. With the exception of the Engine CHP (most likely due to the reduced effectiveness of the COdiNox plant) and the older burner, the sites showed better than stated NO_x emissions.

***Table 8**. Some common heat sources and their NO_x emissions*

Type	**Make/model**	**Size**	**Fuel**	**NO_x mg/m^3**	**NO_x ppm**
Reciprocating Engine	Jenbacher J320GS	1 MW electrical	Natural Gas	<500	<243[1]
Reciprocating Engine	Jenbacher J320GS low nox	1 MW electrical	Natural Gas	<250	<122[2]
Reciprocating Engine	Caterpillar DM5489	1.1 MW electrical	Natural Gas	<500	<243[2]
Reciprocating Engine	Caterpillar DM5490 low nox	1.1 MW electrical	Natural Gas	<250	<122[2]
Gas burner standard low NO_x	Hamworthy eco-jet	6-100 MW	Natural Gas	<62	<30
Gas burner ultra low NO_x	Hamworthy eco-jet-SLN	6-100 MW	Natural Gas	<21	<10
Fuel oil burner	Hamworthy eco-jet-SLN	6-100 MW	Fuel oil	<144	<70
Gas Turbine	Turbec T100	100 kW electrical	Natural Gas	<31	<15
Capstone	C200	200 kW electrical	Natural gas	18.5	9
Capstone	C200 (2008 CARB certified)	200 kW electrical	Natural gas	8	4

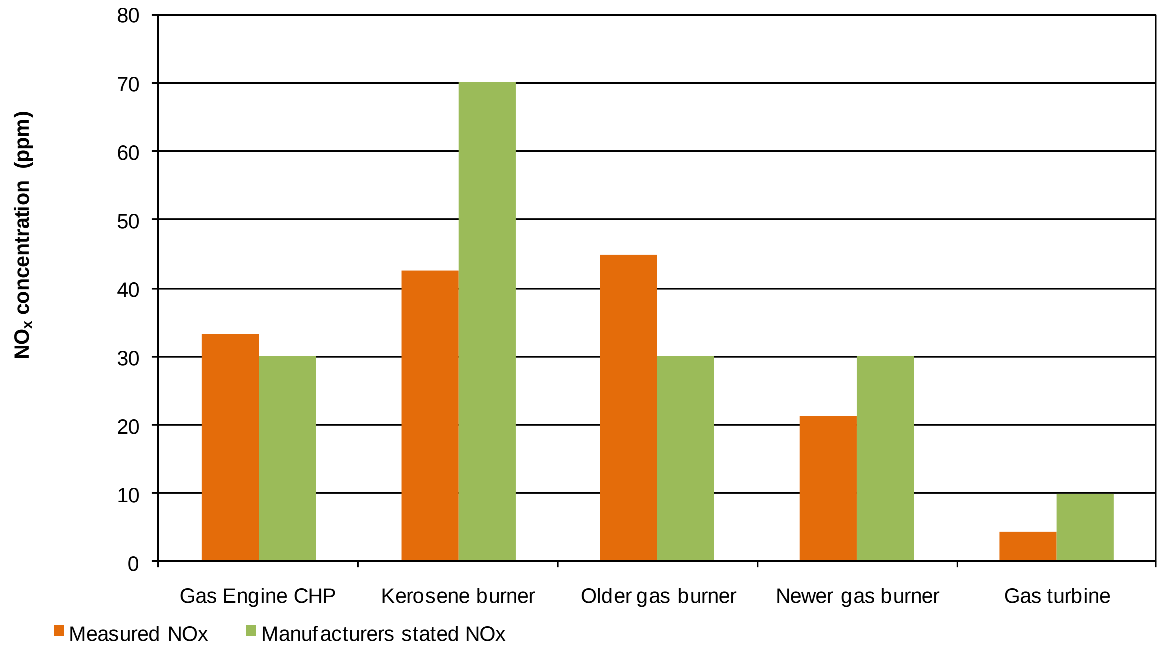

***Figure 18.** Comparison of measurements to manufacturers data*

[1] This value will be less than 30ppm when a well maintained COdiNox or equivalent gas scrubber is in place.

NO_x from gas burners

It is widely accepted that UK standards for NO_x emissions will align with Europe in the next year or two. These standards are likely to be in the region of:

Less than 40 ppm for gas fired plant

Less than 73 ppm for fuel oil plant.

As can be seen from Table 8 above, most burner manufacturers offer two types of product – the ‘standard’ low or the ultra-low NO_x.

New burners are inherently low NO_x through a combination of good design e.g. axial flow combustion and by clever control. This means that their NO_x emissions are typically <30 ppm. As seen in this project at the new boiler site the emissions from such burners can often be less than this (<20 ppm). Standard low NO_x burners can be retrofitted to existing boiler shells if required. In addition energy efficiency improvements are possible from replacing older burners with modern equivalents. Efficiency improvements of 5% are often quoted[2].

Ultra low NO_x equipment is also widely available and aims to reduce the NO_X emissions through either flue gas regeneration (FGR) or water / steam injection. Both of these aim to cool the flame temperature and create sub stochiometric combustion. By doing this, the production of NO_x is limited. There are however two major disadvantages to these solutions; either reduced boiler capacity or reduced energy efficiency.

NO_x from reciprocating engines

When considering the NO_x emissions from a reciprocating engine, for the flue gases to be clean enough for CO_2 enrichment, a flue gas scrubber must be in place and this is common practice. Gas scrubbers such as COdiNOx aim to reduce the NO_x concentration to <30 ppm and some of the other harmful pollutants such as CO. However, a gas scrubber will only perform if it is well maintained and operated.

Alternative CO_2 sources

One option would be to use pure CO_2 which is effectively pollutant free; some growers still use it. The cost (typically £100 per tonne) is prohibitive when the demand for CO_2 is high. However, the greatest problems with pollutant damage to plants occur when there is little venting i.e. when the demand for CO_2 is low. PC 265 (2007) showed that as little as 3 tonnes of pure CO_2 would be required per hectare per week when there is no / little venting.

[2] Carbon Trust publication – CTV018, Technology Overview.

Control and monitoring of CO_2 concentration

In the majority of cases the concentration of CO_2 is measured at a single point within a greenhouse. The uniformity measurements taken as part of this project were of limited accuracy. However, there was no indication that levels of variation likely to cause localised pollutant damage occurred.

The accuracy of the measurement of CO_2 is much more likely to cause over-dosing and therefore widespread pollutant damage within a greenhouse. This was demonstrated when comparing growers data with a calibrated 'laboratory standard' measurement system earlier in this report. This can be due to:

- Sensor calibration - CO_2 sensors are complex / sensitive and prone to 'drift'. As a result they can read low or high.
- Sampling system – sampling tubes connecting back to a single CO_2 analyser are still used. Leaks in pipes and connectors in particular can lead to significant underestimation of the actual CO_2 level in the greenhouse.

Considering pollutants, low readings are worst as they lead to over-dosing of CO_2 and therefore higher levels of pollutants. Personal communication with growers and 'stories' within the industry often highlight cases where actual CO_2 concentrations have reached 1,500 – 2,500 ppm.

This subject is covered in greater detail in:

- *HDC grower guide – Tomatoes:guidelines for CO_2 enrichment (2002)*
- DEFRA factsheet – *Energy management in protected cropping: management of CO_2 enrichment*, *10/09*

Financial

The inherent variation between nurseries and their heating sources mean that accurately determining the financial impact is very difficult. In many cases, the benefits of CO_2 enrichment outweigh the cost of pollutant damage. However, in the absence of pollutant damage the benefits of CO_2 enrichment could be even greater.

NO_x

Although highly dependent on the stage of growth and even variety, the literature search revealed reductions in the growth of tomatoes ranging from 22 to 32% at NO_x levels as low as 250 ppb. This was exceeded by varying degrees in all the greenhouses monitored especially when there was no venting and a CO_2 level of 1,000 ppm or more was achieved.

In comparison it was rarely exceeded on the new burners and micro-turbine CHP sites at CO_2 concentrations of less than 800ppm.

Putting the potential yield cost into perspective:

- A portable CO_2 meter to check fixed sensors and variation of CO_2 levels within a greenhouse - £1,000
- Replacing a leaking suction pipe / central CO_2 analyser based measurement system with individual electronic CO_2 sensors in each greenhouse - £1,000 per sensor
- PC 265 (2007) suggests that the first ten weeks of a tomato crop's life would require around 18 tonnes of pure CO_2 per hectare - £5,000 (including annual tank rental)
- A new natural gas fuelled burner - £25,000 to £30,000. The energy savings alone (up to 5% p.a.) could pay back the cost within seven years, excluding the value of any improvement in yield.

Ethylene

Ethylene was only found on one nursery and even then it was significantly below the levels believed to affect plant development. However, there is considerable anecdotal evidence to suggest that a small number of nurseries are affected each year. These nurseries almost exclusively have ageing reciprocating engine CHP and the problems normally occur early in the year when there is little venting. Putting this into perspective:

- The loss of one complete truss of tomatoes can represent 2% of the total yield but much more in financial terms as ethylene problems tend to occur early in the year when the value of produce tends to be higher - £10,000 /Ha.
- Prolonged miss-set of tomatoes can significantly affect the value of several trusses especially when they are vine tomatoes grown for highly selective markets - £20,000 to £30,000 /Ha.
- A new centralised ethylene analyser (gas chromatograph) capable of checking the output of several CHP engines - £15,000 to 20,000.

SO_x

SO_x is only present at the levels required to affect plant performance when kerosene is used. To minimise the risk of SO_x damage the CO_2 level I the greenhouse should not exceed 450ppm. However, it is likely that the yield benefit of allowing 600ppm of CO_2 will outweigh the SO_x damage.

Discussion

The literature search and measurements taken on commercial nurseries confirm that the levels of pollutants in flue gases used for CO_2 enrichment in greenhouses do not pose a threat to the heath of people working in glasshouses. This remains the case even if the CO_2 concentration achieved was double current targets (2,000ppm).

The susceptibility of plants to damage from pollutants (NO_x, SO_x and ethylene) varies according to the specific crop, its growth stage, the variety and many other growth factors. Consequently there is no single, broadly applicable concentration limit that each of the pollutants should be kept below, to avoid harm. Similarly it is not possible to provide simple 'sliding scales' or rules of thumb to quantify the effect on plant performance.
It can be argued that the negative effects of various pollutants are more than offset by the benefits given by higher CO_2 levels. However, this should not be used as an excuse to ignore the pollutants as, if they can be reduced cost effectively; improved yield is likely.

SO_x

Since the introduction of low sulphur fuel oils and natural gas, SO_x are rarely considered as a problem. The lowest level reported in the literature review found that concentrations of 500 ppb for eight hours caused leaf damage on chrysanthemum. By inference (derived from NO_x levels measured in greenhouses and NO_x and SO_x measured in flue gases) the worst case (Engine CHP nursery) would have achieved SO_x levels in the greenhouse of 366 ppb for brief periods and an average of only 140 ppb.

Ethylene

Ethylene can have the most catastrophic effect on plant development in so far as it can delay flowering and cause flowers to abort at very low concentrations; 50 ppb has been shown to affect the most sensitive crops and varieties.

Laboratory analysis of samples of air taken within greenhouses from directly above the CO_2 distribution pipes only found ethylene at one site and even then it was only just detectable - about 20 ppb. This does not say that there is no risk from ethylene in greenhouses; there is considerable anecdotal evidence suggesting that a small number of nurseries are affected each year. These nurseries almost exclusively have reciprocating engine CHP and the problems normally occur early in the year when there is no venting.

A single relatively high ethylene 'event' can cause the complete failure of flower buds. This is highly visible and at the very least prompts further investigation by the grower. However, lower levels over longer time periods can cause some bud abortion which may go undetected for considerable periods and cause greater financial loss to growers than a single high level vent.

NO_x

At low levels NO_x restrict photosynthesis causing a reduction in yield whilst the plants may show no visible signs of damage. ‘Safe’ concentrations appear to range from 150 ppb to 400 ppb. On balance 250 ppb seems to be a reasonable target.

Measurements on commercial nurseries showed that 250 ppb was regularly exceeded on all nurseries. This was in part due to CO_2 concentrations above 1,000 ppm being achieved. However, even with modern combustion equipment (new burner, micro-turbine CHP) 250 ppb of NO_x was exceeded at 1,000 ppm CO_2.

As NO_x levels largely follow CO_2 concentration it is possible that the benefits of higher CO_2 outweigh the disadvantages of high NO_x. However, it should be noted that increasing the CO_2 concentration from say 800 ppm to 1,000 ppm delivers relatively modest increases in yield. Therefore accepting lower CO_2 levels as a means of reducing NO_x levels could deliver a net benefit.

Yield

Comparison of season-long yield gave no conclusive evidence of yield effects at the sites where pollutant levels were highest. This should not be interpreted as saying that pollutants are not a problem on commercial nurseries. The lack of any conclusive evidence is more indicative of the difficulties in comparing individual nurseries because of variation in facilities, growing methods, equipment and varieties.

CO_2 systems

The levels of pollutants as measured in the flue gases on commercial nurseries fell broadly in line with the trends expected and manufacturers stated data; the concentration of pollutants within the greenhouses followed a similar pattern.

A number of ‘housekeeping’ issues were identified especially in relation to the measurement of CO_2 within the greenhouses. This has been the subject of several HDC publications and reports in the past and they remain as relevant as when they were written. For ease of reference they include:

- HDC grower guide – Tomatoes: guidelines for CO_2 enrichment (2002)
- DEFRA factsheet – Energy management in protected cropping: management of CO_2 enrichment, 10/09.

Regular checking and calibration of CO_2 sensors will help ensure the best conditions for the plants and that harmful pollutants remain within acceptable limits.

For most commercial nurseries NO_x are the biggest potential problem. Clearly, regular maintenance and flue gas analysis, whatever the CO_2 source, are vital. Beyond this, if pollutants remain high, the options are:

- Accept lower CO_2 concentrations which will lead to lower pollutant levels
- Use pure CO_2
- Invest in new equipment such as a newer burner.

In most cases, replacing an older burner which produces high levels of NO_x with a modern version will deliver energy savings which go a long way to justifying the cost incurred. However, the opportunity to replace an older boiler at the same time should also be seriously considered. Total energy savings of 10% are possible and in some cases can be much more than this.

Conclusions

- The maintenance and calibration of all CO_2 related equipment ranging from burners to sensors is a key part of any strategy to ensure low levels of pollutants in greenhouses.

- The concentration of ethylene measured in greenhouses on commercial nurseries showed that it was unlikely to cause any plant related problems. However, anecdotal evidence suggests that ethylene damage does occur especially on nurseries with reciprocating engine CHP and it should not be ignored.

- NO_x are the most likely cause of poor plant performance. In extreme cases plant growth can be reduced by as much as 24%.

- NO_x concentrations above 250 ppb in a greenhouse should be avoided. 'Safe' concentrations vary widely depending on factors as subtle as the specific cultivar; 400 ppb can be tolerated in certain circumstances.

- Any flue gas regardless of fuel or combustion system type containing more than 30ppm of NO_x should be avoided, especially if CO_2 concentrations above 800 ppm are required.

- Modern (low NO_x) natural gas fuelled burners are designed to produce less than 30ppm of NO_x in the flue gases and will deliver generally acceptable NO_x levels in a greenhouse.

- Well maintained flue gas cleaning equipment operated alongside reciprocating engine CHP should deliver less than 30ppm of NO_x. This will deliver acceptable levels in greenhouses as long as excessively high CO_2 levels are voided (<1,200ppm).

- Ultra low NO_x combustion technology (less than 10ppm of NO_x in flue gases) is unlikely to deliver sufficient additional benefit to justify their associated cost and reduced energy efficiency.

- Modern kerosene fuelled burners are likely to deliver excessively high NO_x levels in a greenhouse even at 700ppm of CO_2.

- Replacing an old burner with its modern equivalent will deliver energy savings in addition to reducing pollutant levels in a greenhouse. The pay back on energy savings alone is likely to be less than 7 years.

- When comparing different combustion systems e.g. micro-turbine vs. conventional boiler it is important to compare the concentration of pollutants relative to the concentration of CO_2.

Technology transfer

The following technology transfer activities were carried out:

- HDC News – May 2009
- Tomato Conference – September 2009
- Pepper Technology Day – September 2009
- Horticulture Week – October 2009
- HDC News – November 2009

Various informal updates at TGA technical committee, Pepper Technology Group and BPOA meetings.

Glossary

NO_X General term used to describe the oxides of nitrogen commonly containing nitrogen dioxide (NO_2) and nitric oxide (NO)

SO_2 General term used to describe the oxides of sulphur

CO_2 Carbon dioxide

ppb Parts per billion, a unit of measure for gas volume concentrations equal to 1×10^{-9} % (10,000,000 ppb = 1%

ppm Parts per million, a unit of measure for gas volume concentrations equal to 1×10^{-6} % (10,000 ppm = 1%)

Ethylene More commonly called ethene, a hydrocarbon with the chemical formula C_2H_4

CO Carbon monoxide

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Dunphy – environment and engineering data for clean, efficient combustion

APPENDICES

Appendix 1

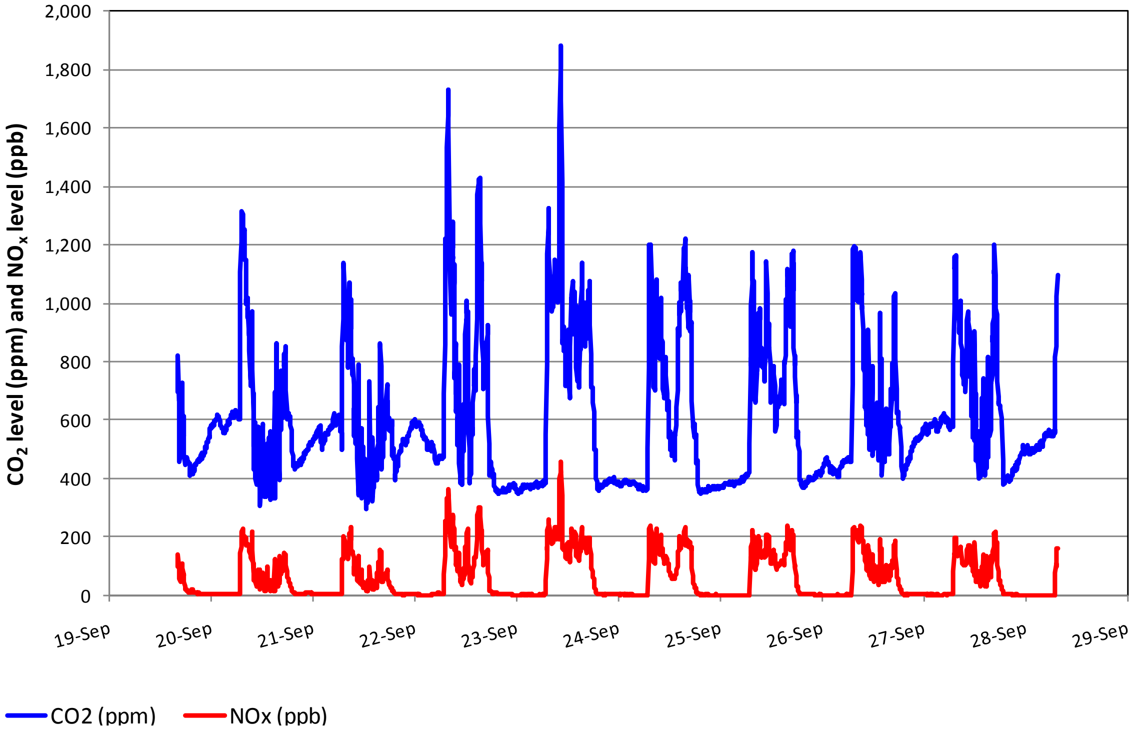
Teledyne Instruments model 200E - Equipment operation

This instrument measures the chemiluminescence, which occurs when nitrogen oxide (NO) reacts with ozone (O_3). In order to measure the concentration of NO_X (and derive the concentration of NO_2) the analyser periodically switches the sample gas stream through a converter cartridge filled with heated molybdenum chips which reacts with NO_2 in the sample gas and produces a variety of molybdenum oxides and NO which can be measured.

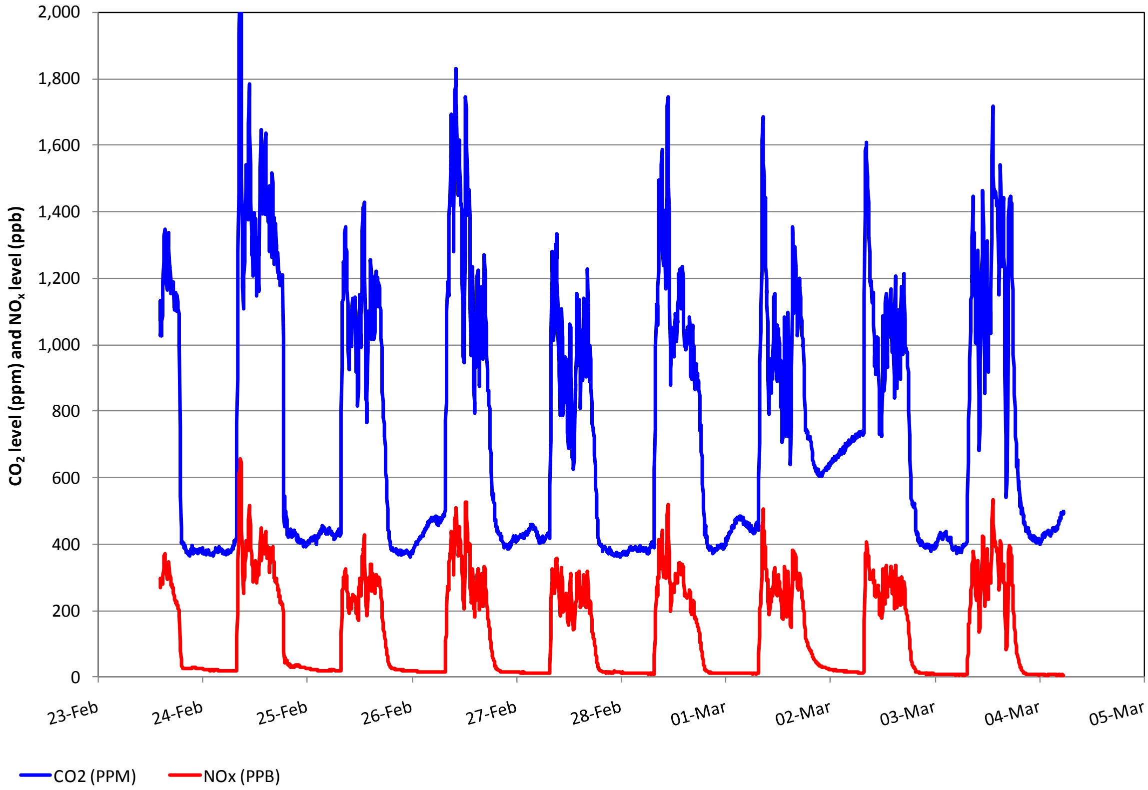
Appendix 2

Periodic monitoring results

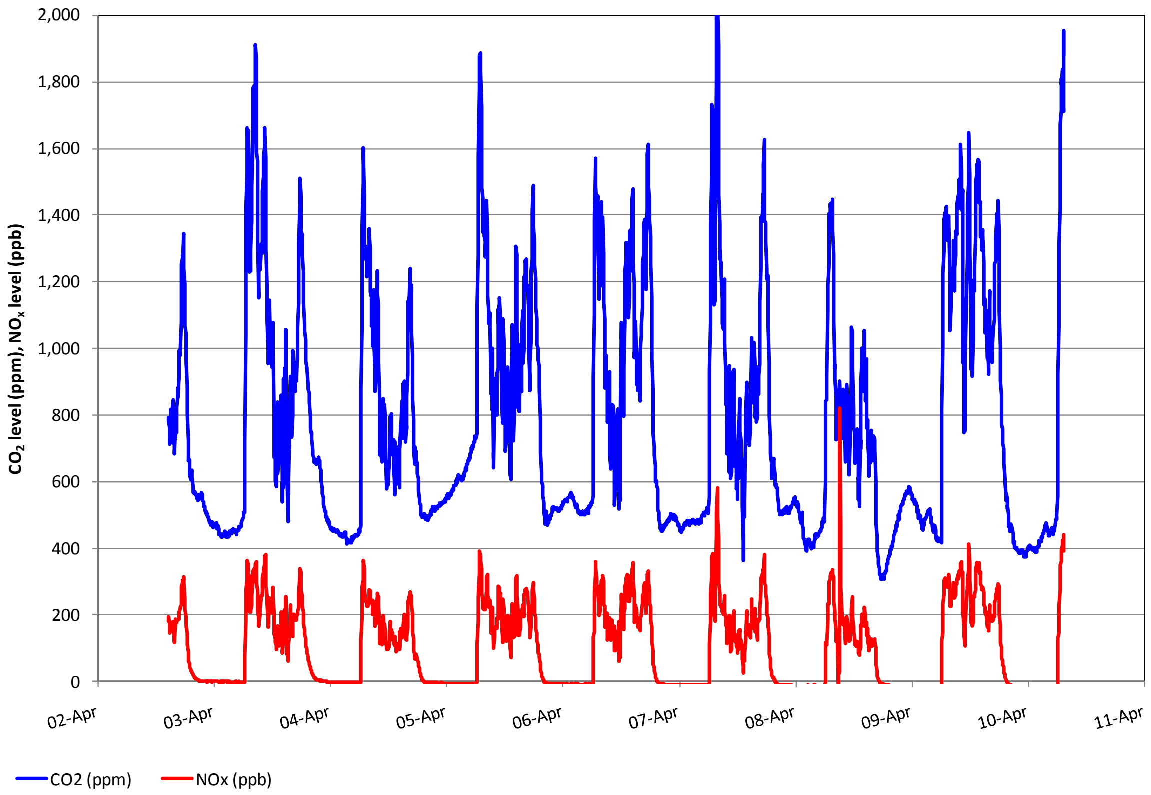
New burner site



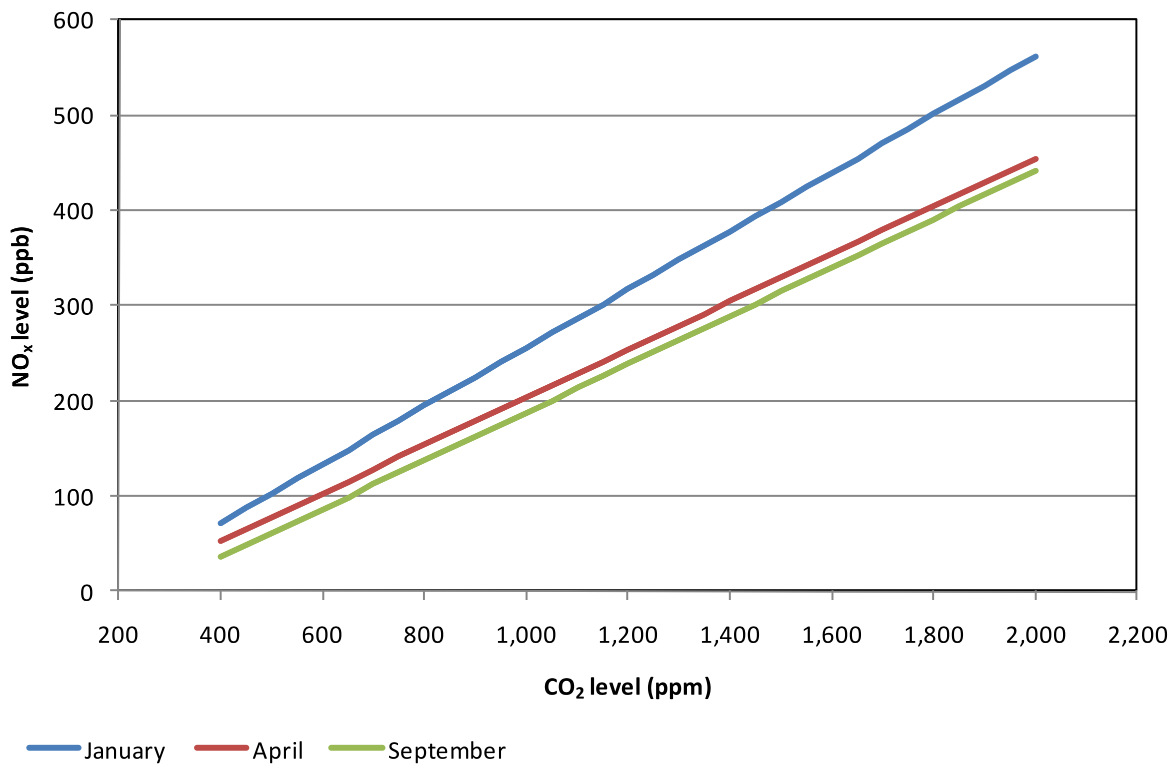
***Graph 1** – New burner site 19th Sept to 28th Sept 2008*



***Graph 2** – new burner site 23rd Feb to 4th March 2009*

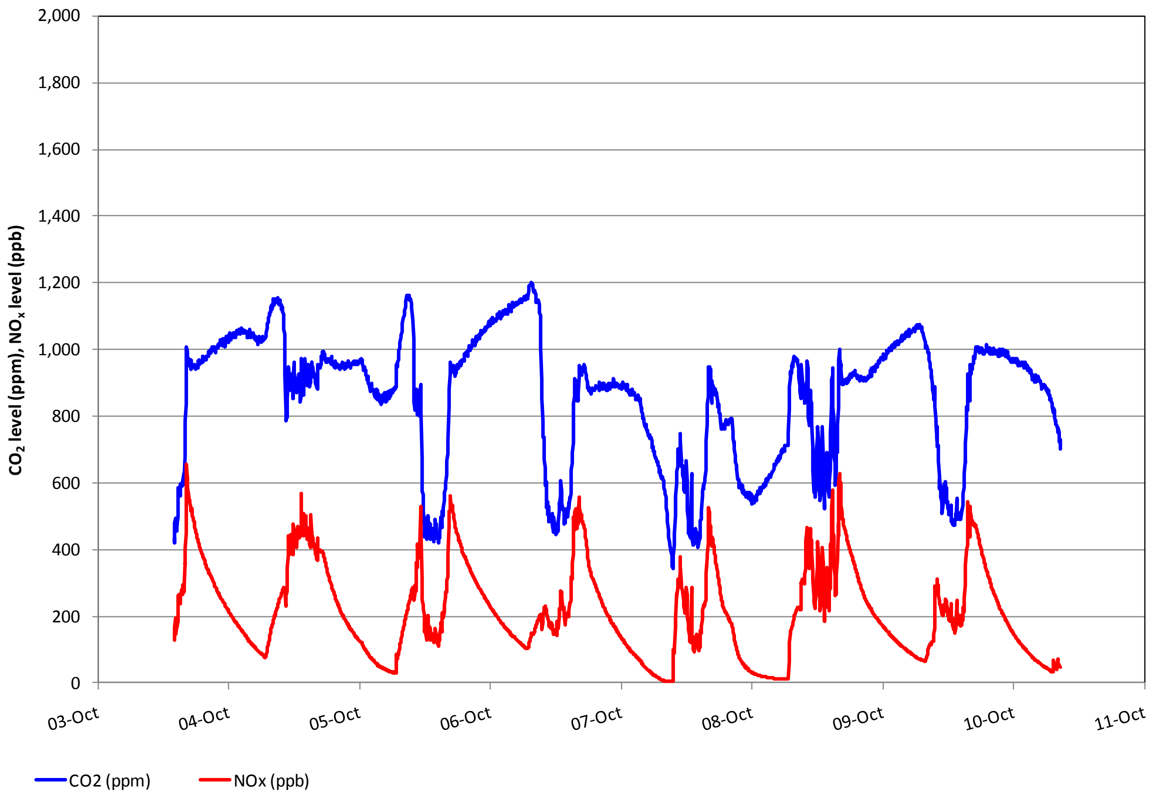


***Graph 3** – New burner site 2nd April to 10th April 2009*

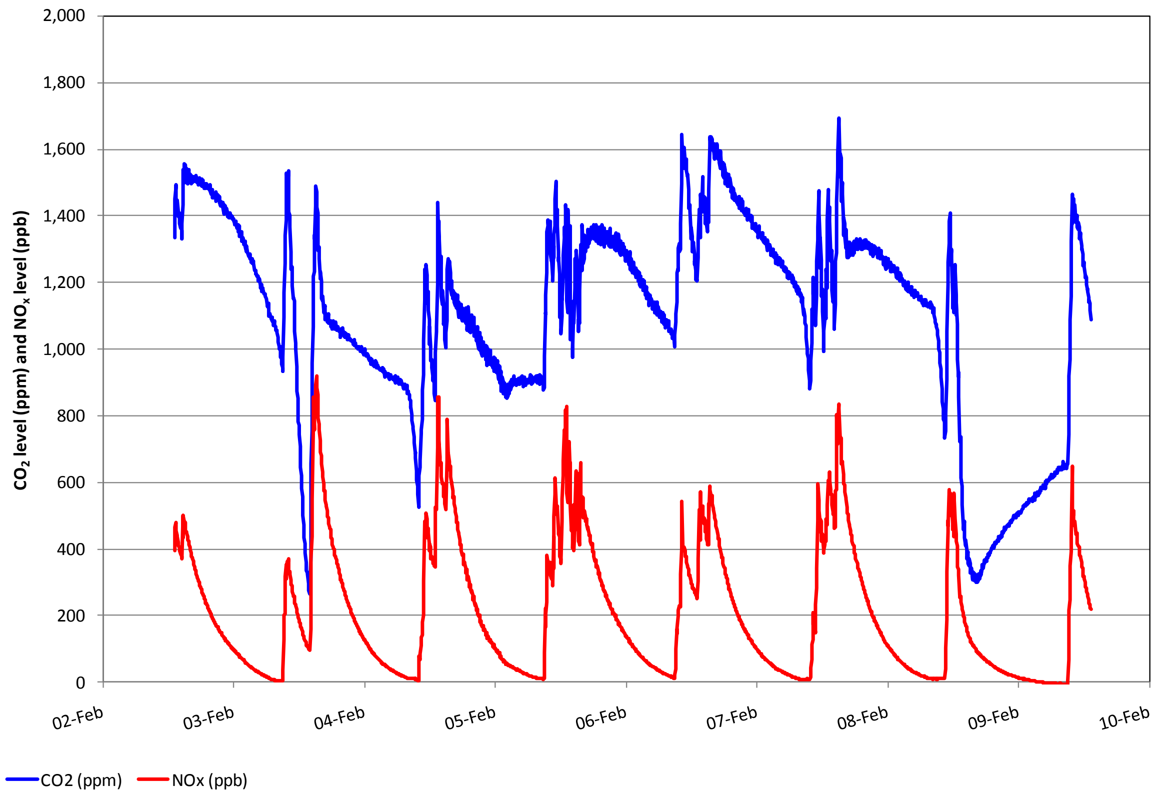


***Graph 4** – New burner site, comparison of achieved CO_2 to NO_X*

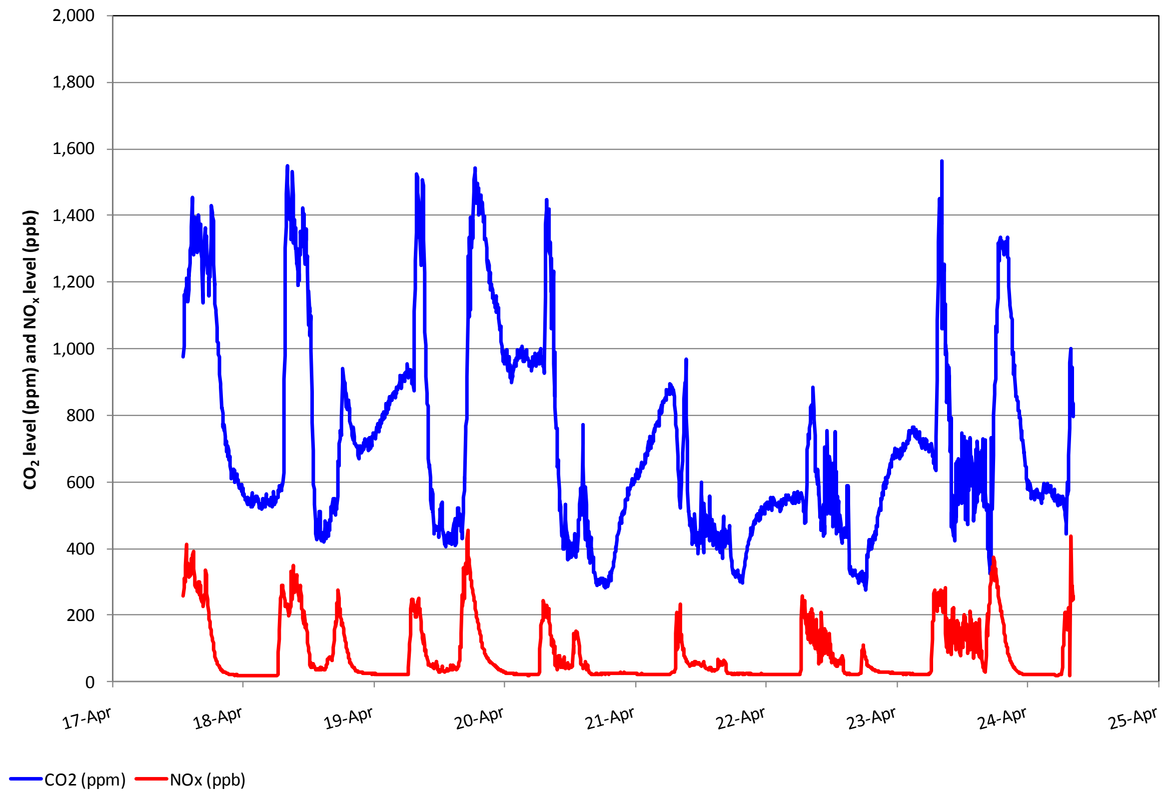
Gas Micro Turbine site



***Graph 5** – Gas turbine site 3rd October to 10th October 2008*

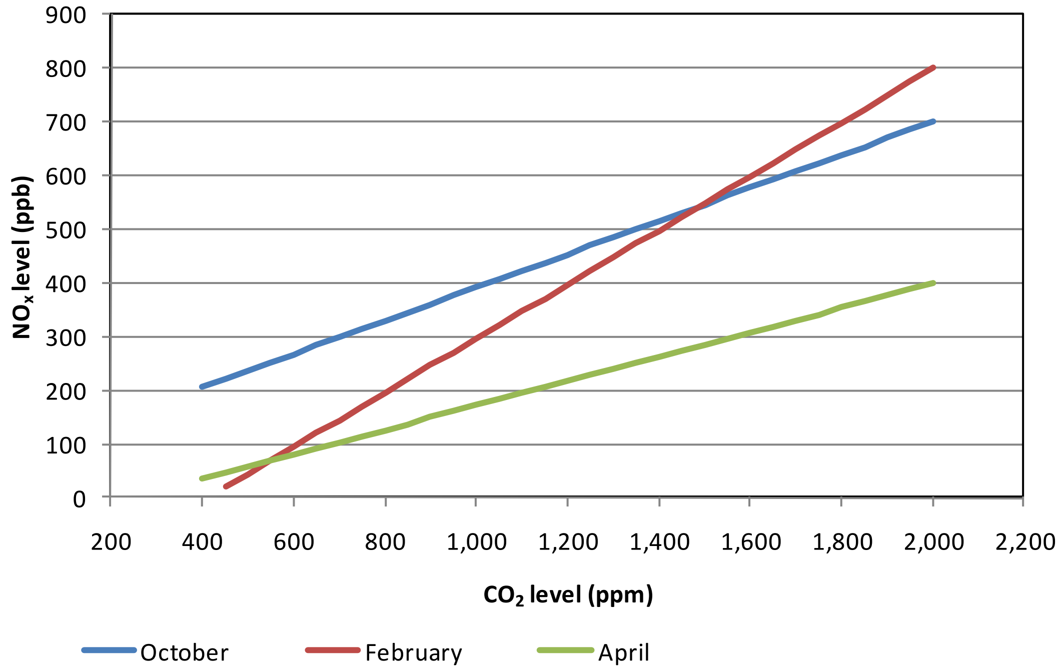


***Graph 6** - Gas turbine site, 2nd February to 9th February 2009*



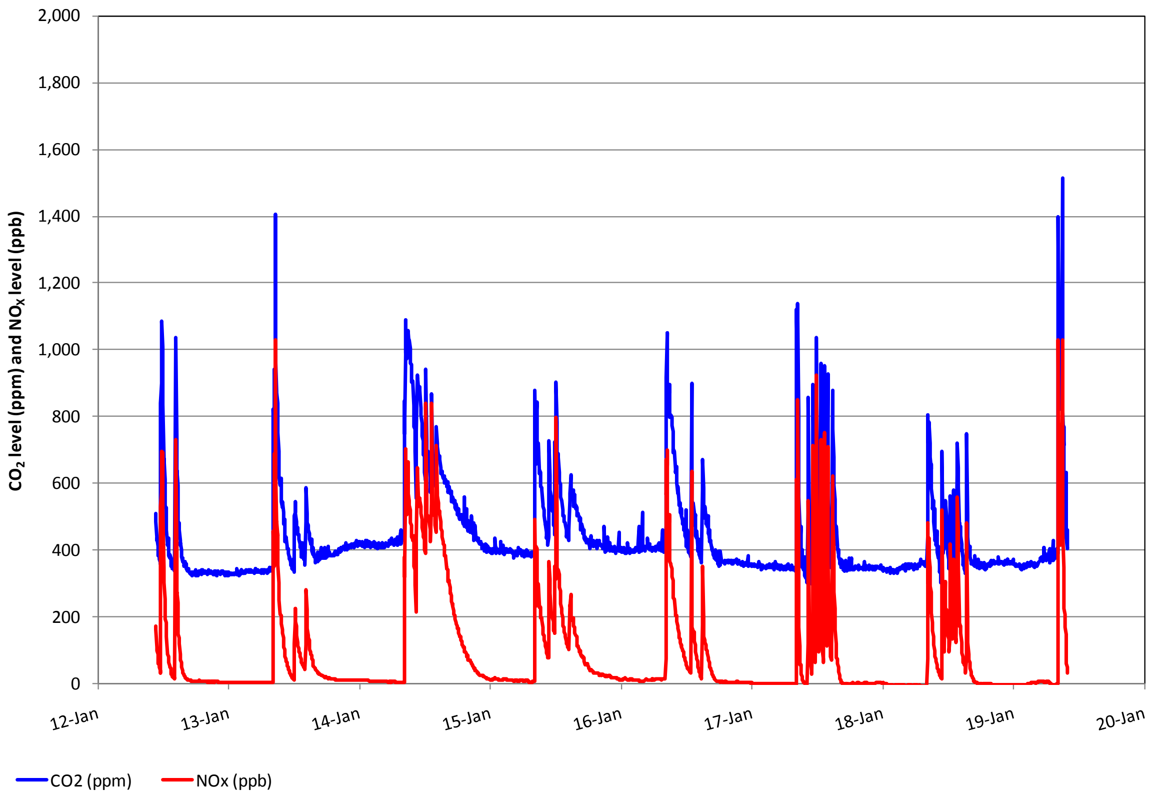
Graph 7 *– Gas turbine site 17th April – 25th April 2009*

The CO_2 data for this round of measurements was taken from the climate control computer as the analyser malfunctioned.

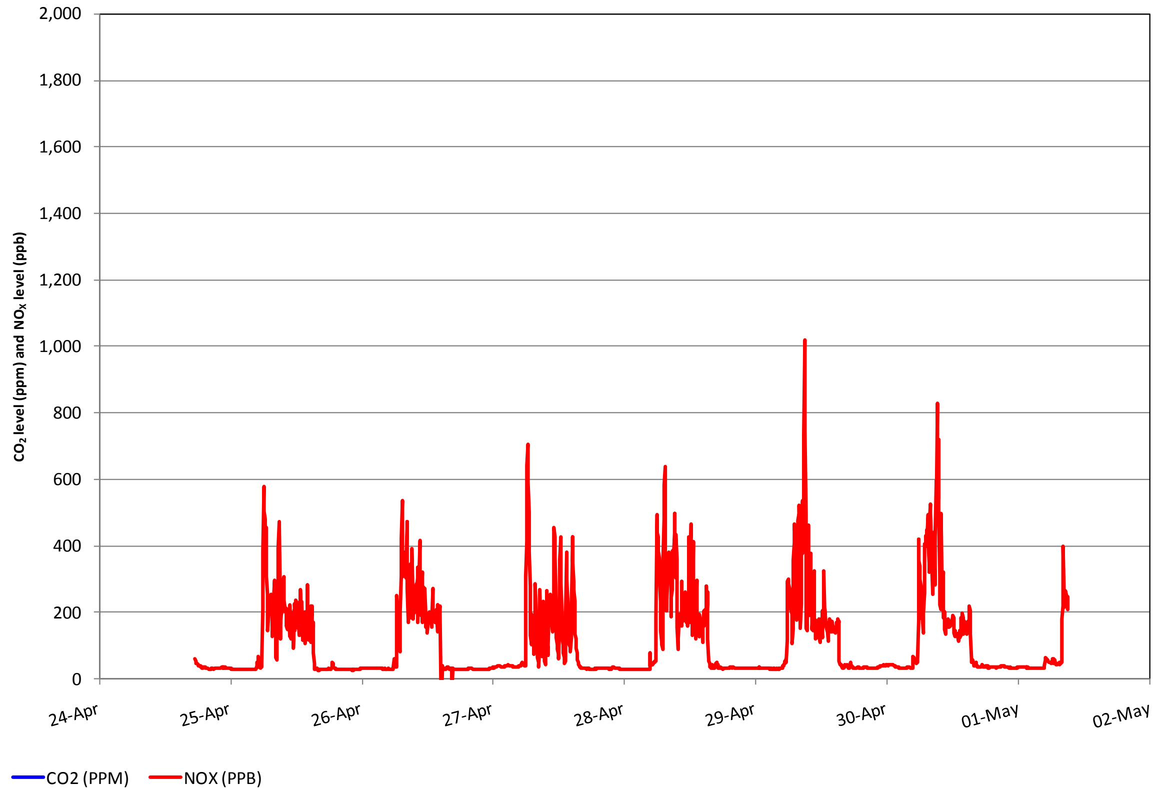


Graph 8 *– Gas turbine site, comparison of achieved CO_2 to NO_X*

Kerosene burner site

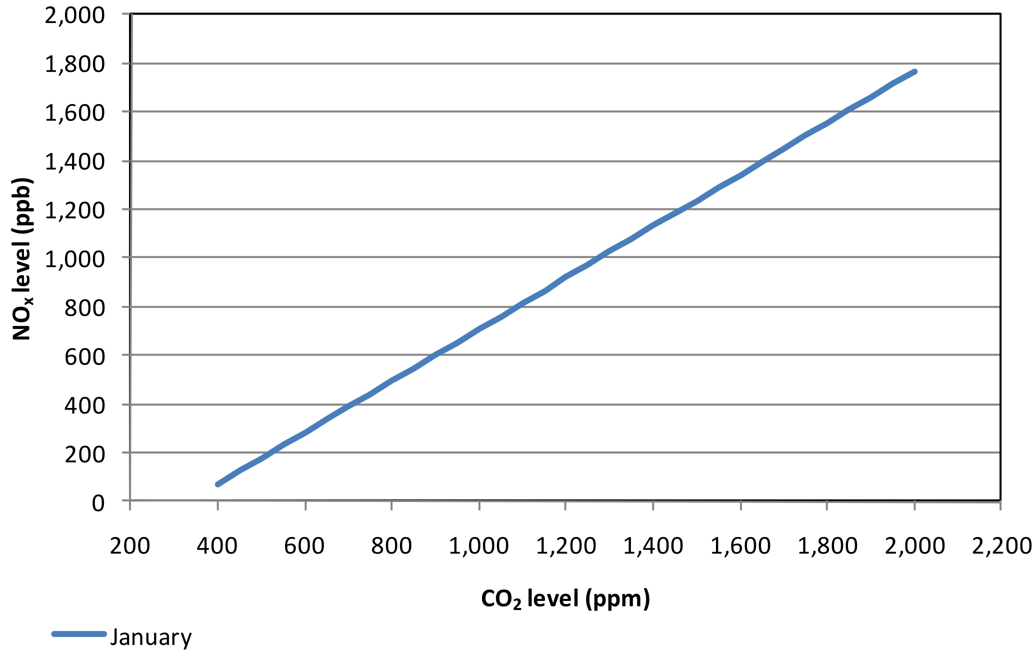


***Graph 9** – Kerosene burner site 12th January to 19th January 2009*



***Graph 10** – Kerosene burner site 24th April to 1st May 2009*

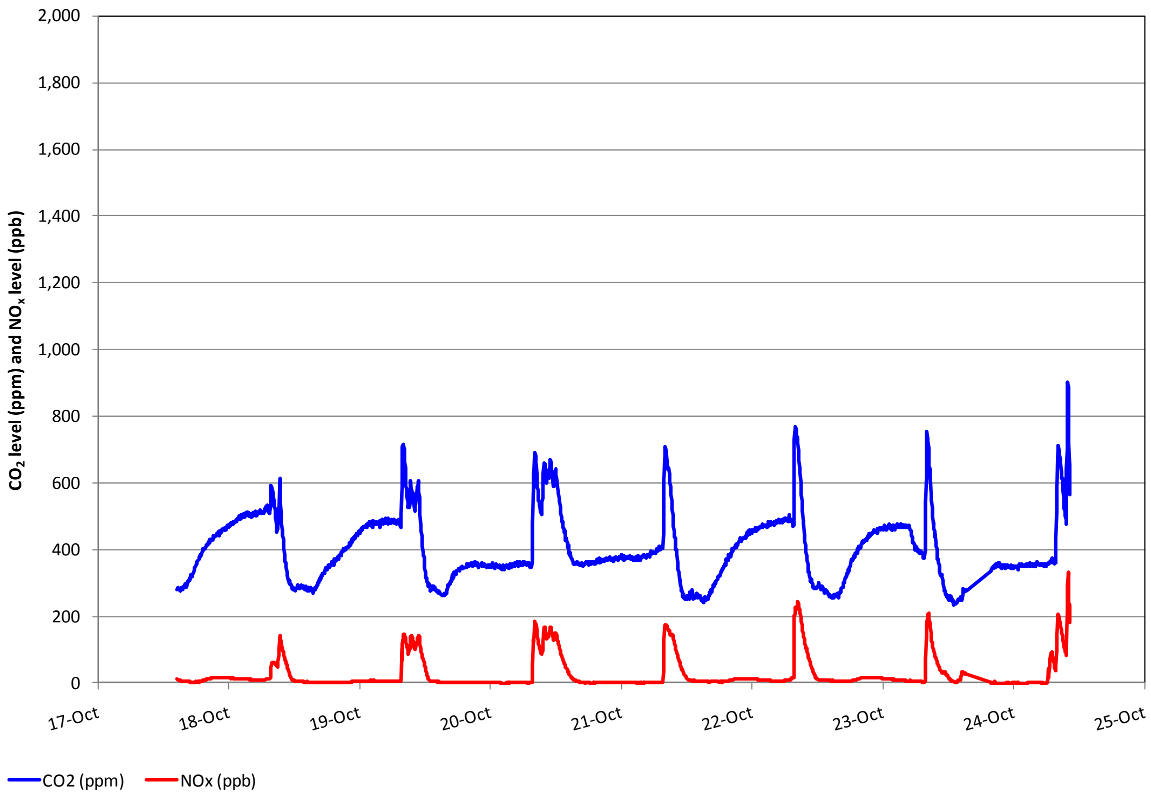
No CO_2 data was available for this period because of the anaylser malfunction and the inability of the climate control computer to record CO_2 levels.



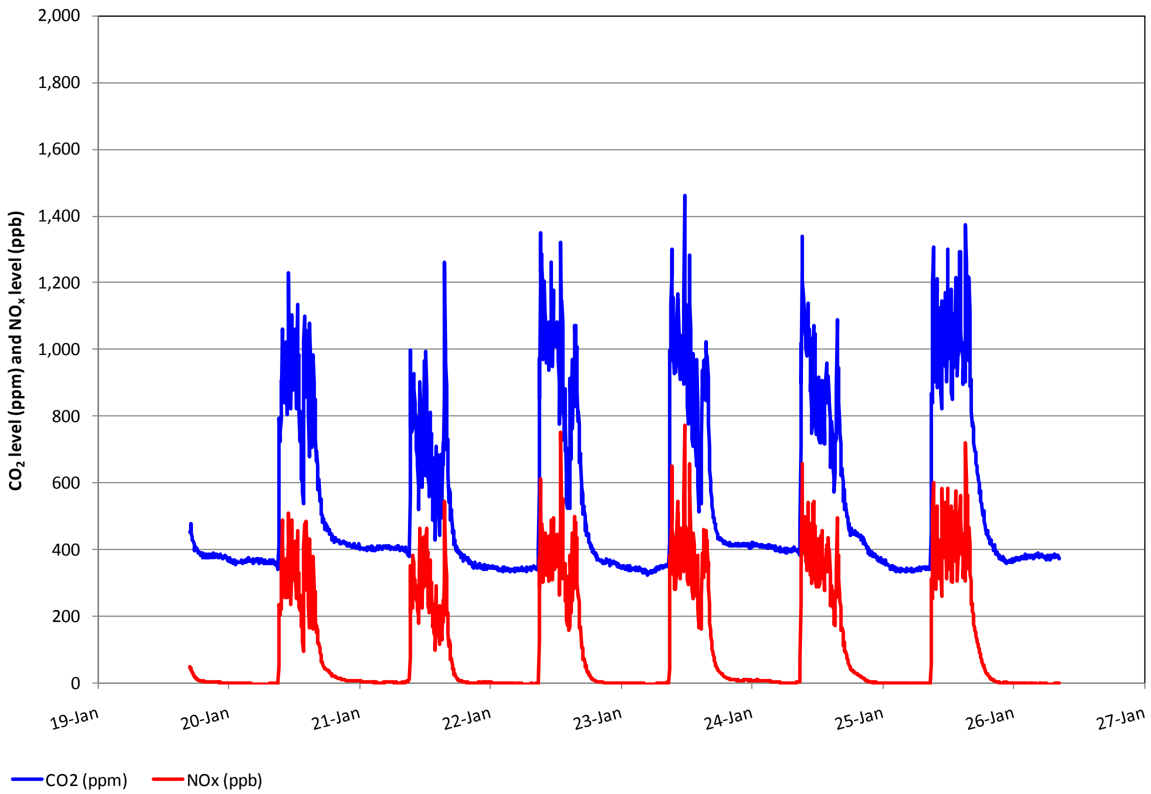
***Graph 11** – Kerosene burner site, comparison of achieved CO_2 to NO_X*

January data only was available for this site.

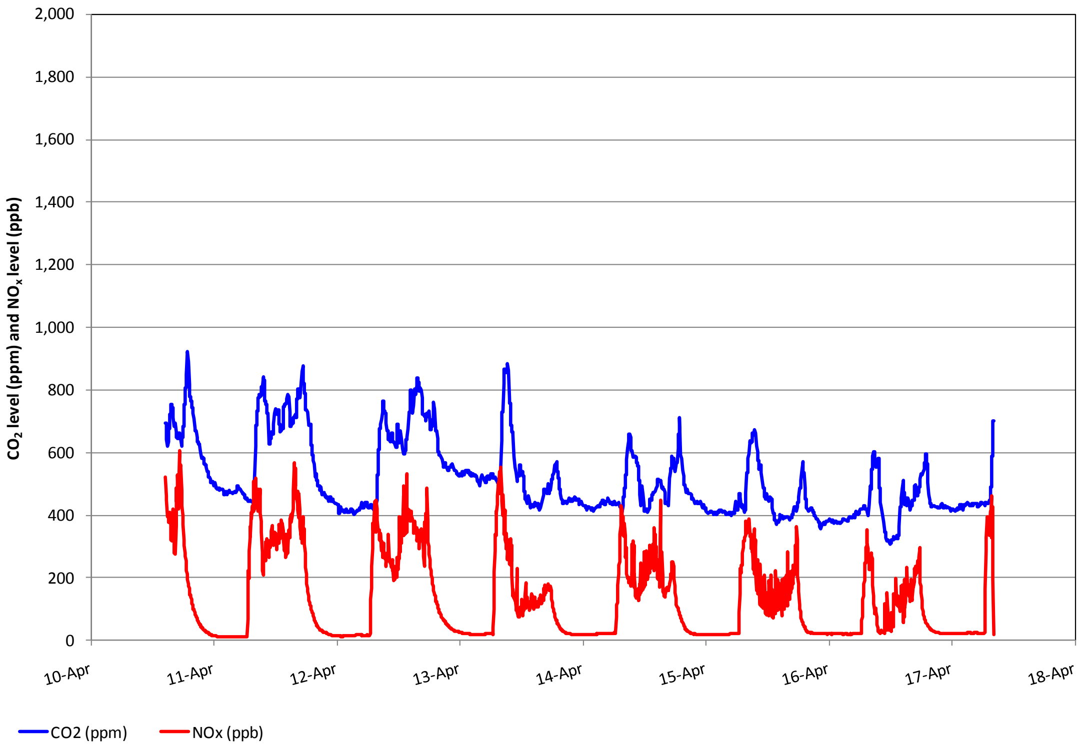
Old Burner site



***Graph 12** – Old burner site 17th October – 24th October 2008*

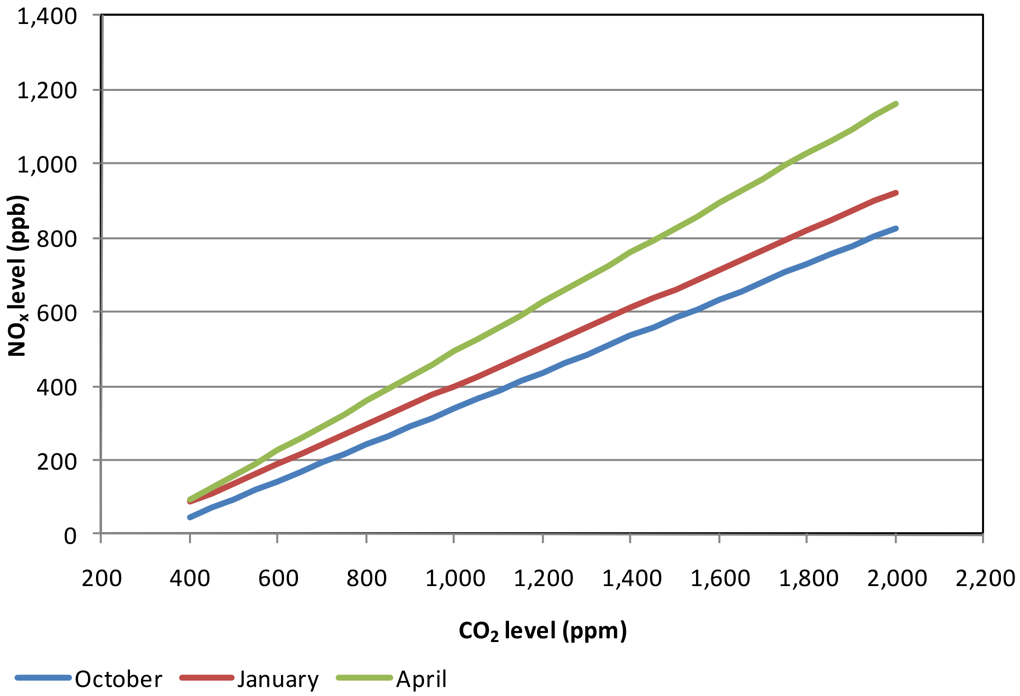


***Graph 13** – Old burner site 19th January to 26th January 2009*



***Graph 14** – Old burner site 10th April to 17th April 2009*

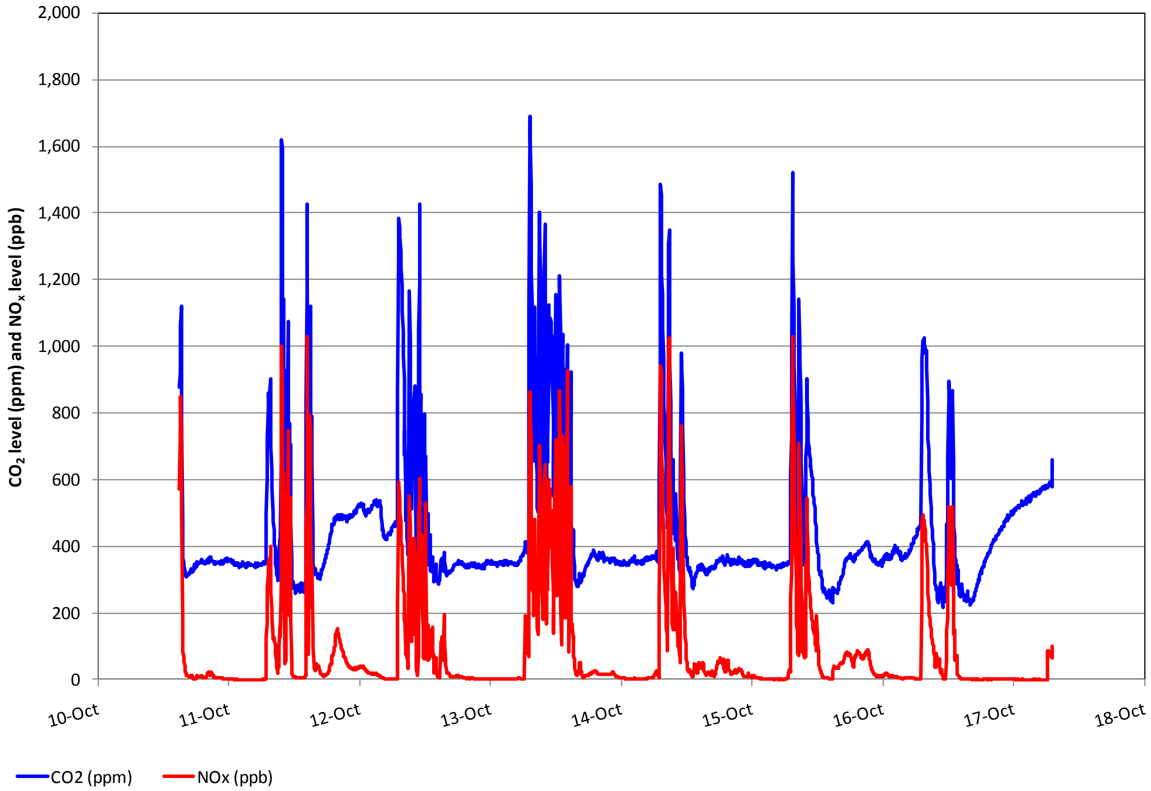
The CO_2 data used for this graph was supplied by the climate control computer because of an equipment malfunction with the CO_2 analyser.



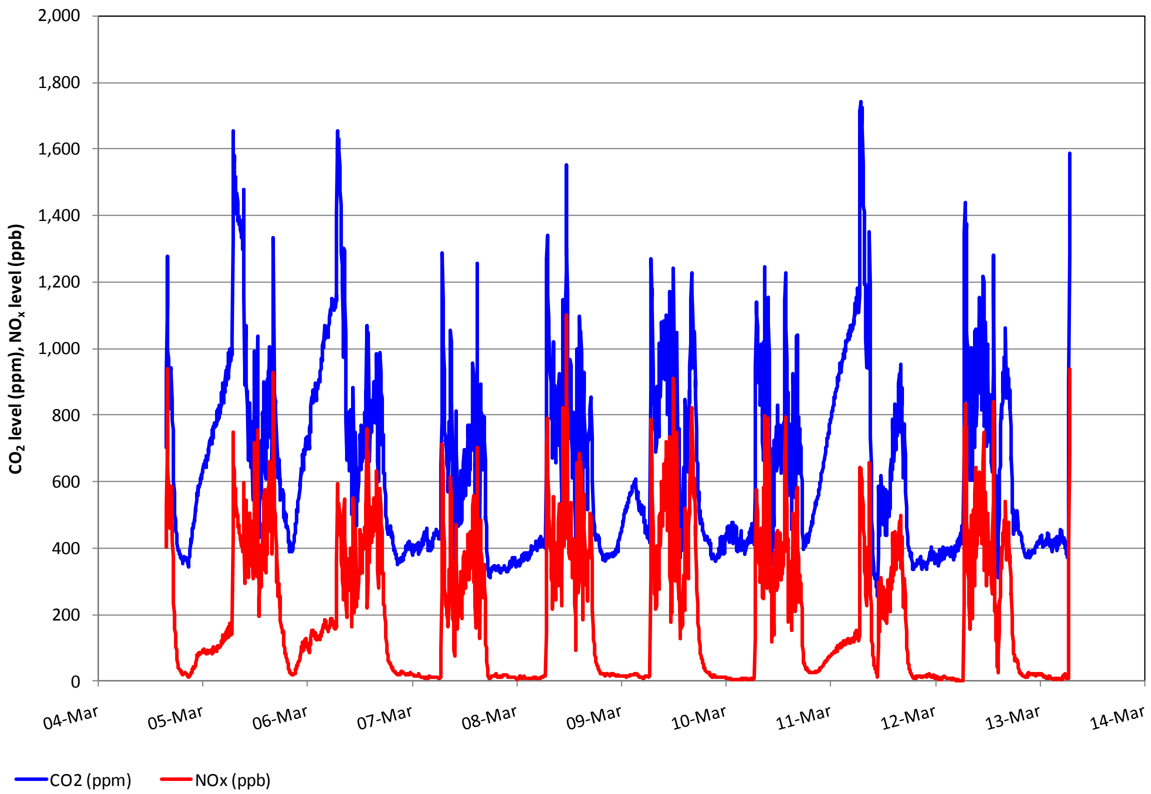
***Graph 15** – Old burner site, comparison of achieved CO_2 to NO_X*

The trace for April must be used with caution because the CO_2 data used for this was supplied by the climate control computer and its accuracy cannot be guaranteed.

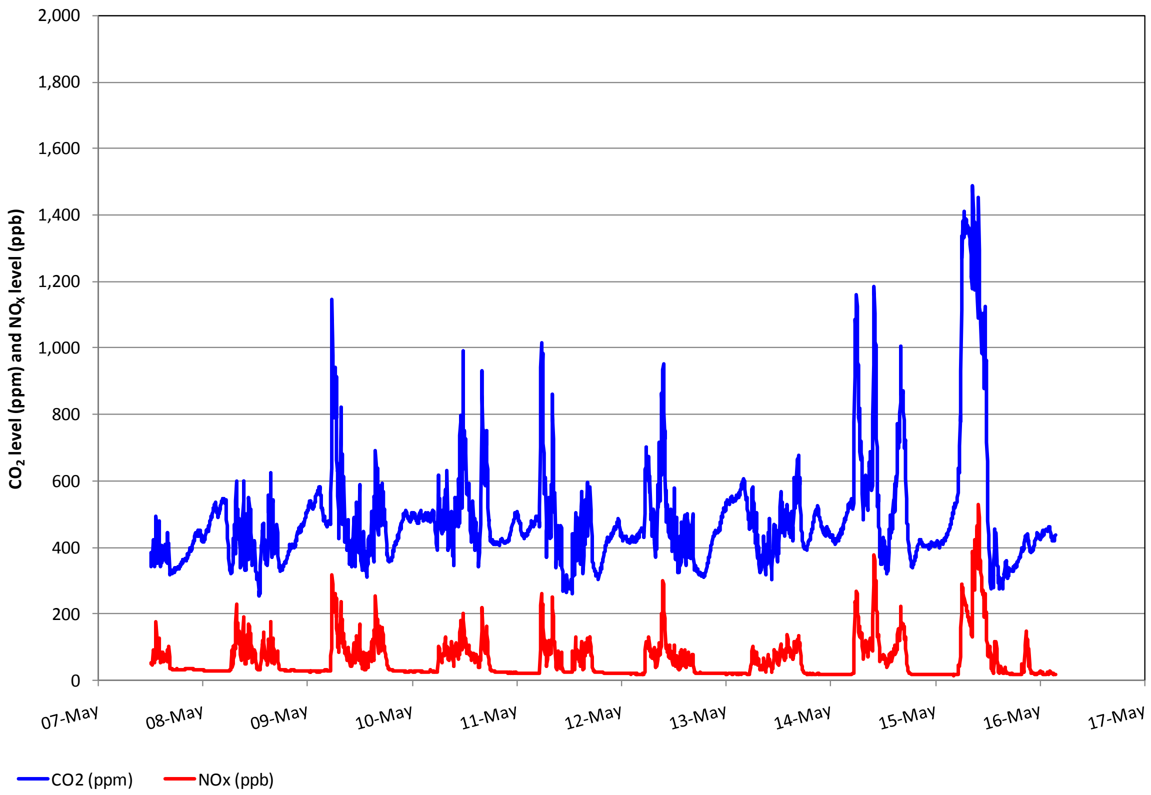
Engine CHP sites



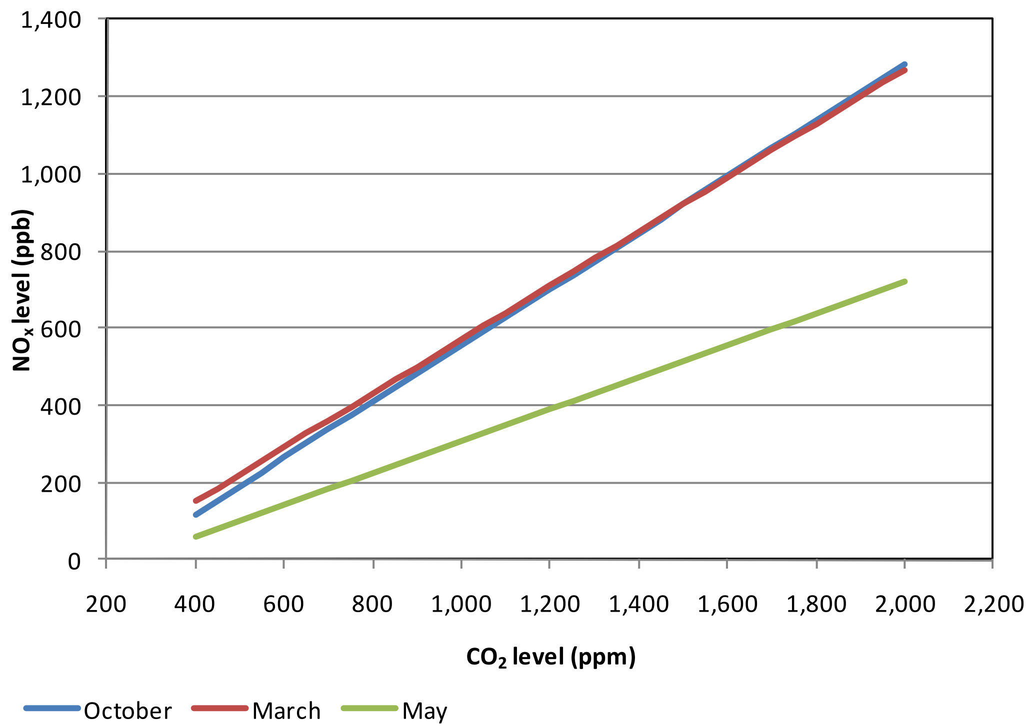
Graph 16 *– 1st Engine site 10th October to 17th October 2008*



Graph 17 *– 1st Engine site 4th March to 14th March 2009*



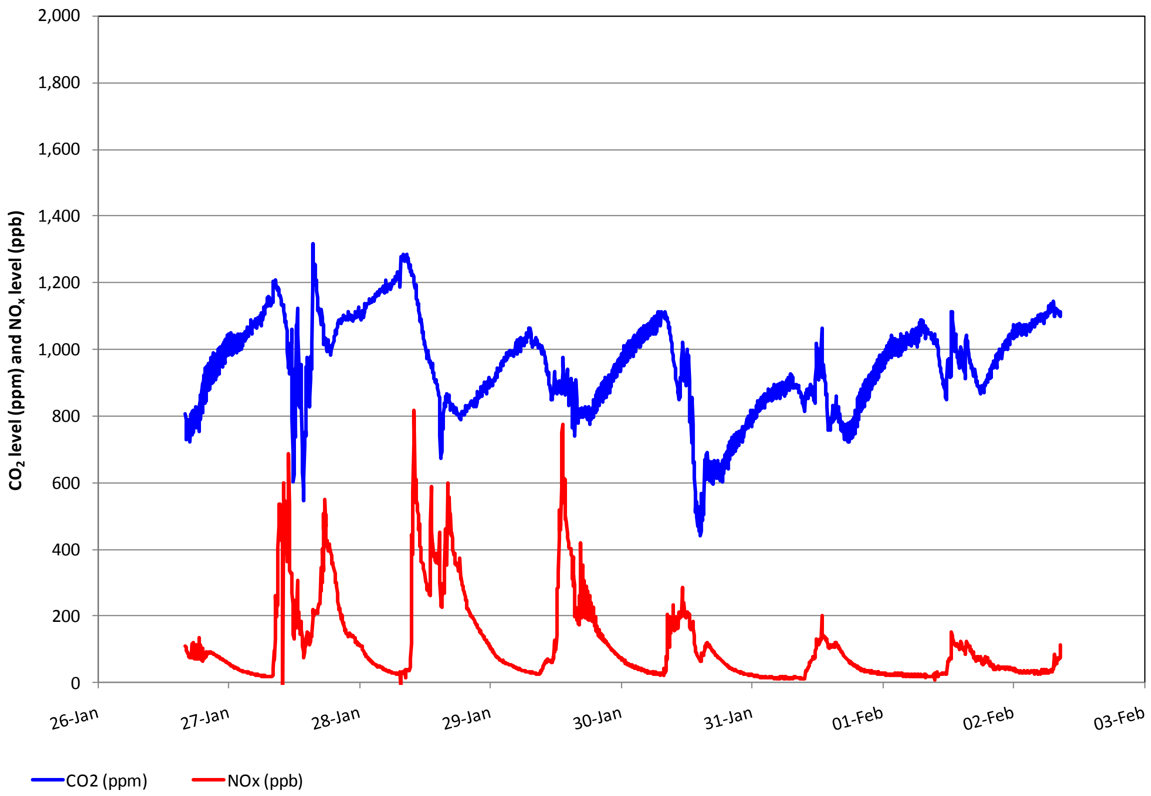
***Graph 18** – 2nd New Engine site 7th May to 16th May 2009*



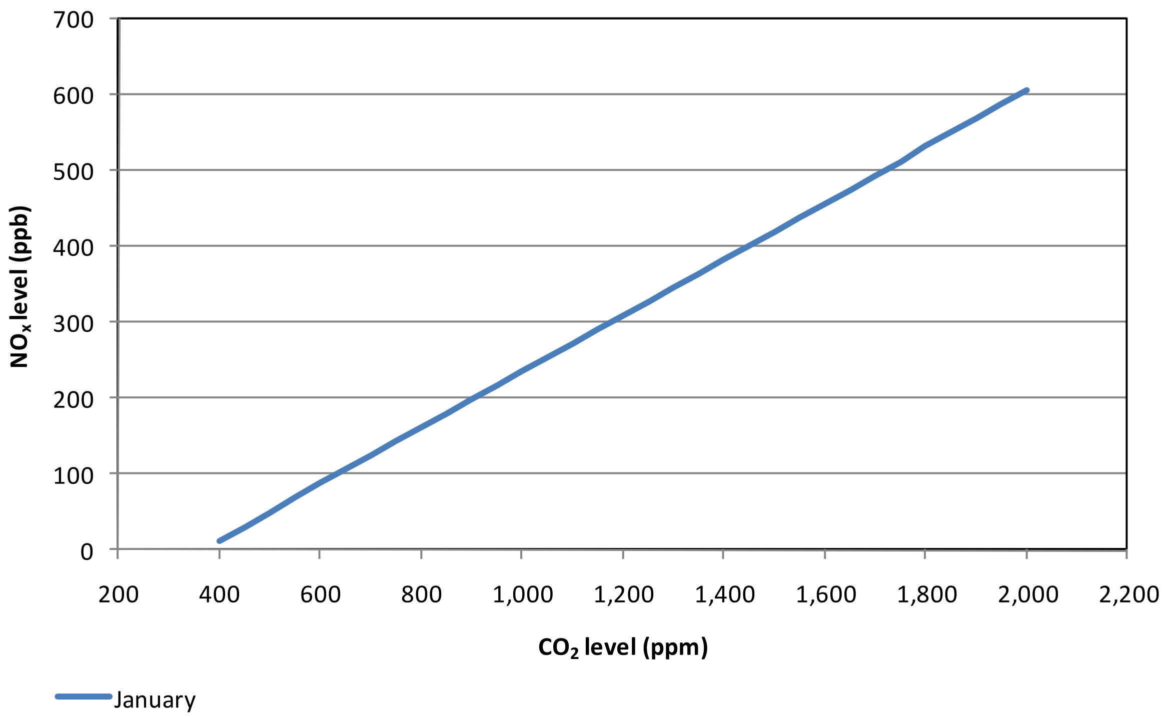
***Graph 19** – Engine CHP sites, comparison of achieved CO_2 to NO_X*

The engine CHP data used for May was taken from a different site to the October and March sets. This shows the differences between sites.

New Burner - ornamentals site



Graph 20 *– New Burner, ornamentals site 26th January to 2nd February 2009*



Graph 21 *– New burner ornamentals site, comparison of achieved CO_2 to NO_X*

Appendix 3 Weekly data records- Engine CHP site 1

Week	Yield / m^2		Average temp ^0C			Daytime CO_2				Light - MJ/m^2
	Units kg	Ave g / unit	Day	Night	24 hr	Setpoint vpm	Achieved vpm	% achieved	PC287 record	
45										20
46										19
47										21
48										18
49			18.1	16.7	17.1	700	752	107.4		22
50			17.7	16.5	16.9	1000	906	90.6		12
51			18.3	17.1	17.5	1000	892	89.2		15
52			18.9	17.0	17.6	1000	928	92.8		14
1			18.2	16.2	16.9	1000	947	94.7		15
2			18.9	16.3	17.1	1000	883	88.3		21
3			19.3	16.8	17.6	1000	958	95.8		21
4			19.5	16.8	17.7	1000	916	91.6		27
5			18.3	16.3	17.4	1000	991	99.1		23
6			18.5	16.0	17.3	1000	1023	102.3		29
7			20.1	16.5	17.9	1000	997	99.7		32
8			20.7	17.1	18.5	1000	939	93.9		41
9	0.01	n/a	20.4	17.2	18.5	1000	963	96.3		35
10	0.30	n/a	21.2	17.0	18.9	1000	937	93.7	816	61
11	0.47	n/a	21.0	17.2	19.1	1000	934	93.4	835	56
12	0.70	n/a	22.3	17.4	19.7	1000	830	83.0		94
13	0.60	n/a	21.4	17.3	19.4	1000	916	91.6		74
14	0.60	n/a	21.9	17.4	19.7	1000	855	85.5		82
15	0.80	n/a	21.5	17.3	19.6	1000	873	87.3		79
16	1.10	n/a	21.0	17.2	19.4	1000	691	69.1		81
17	1.70	n/a	22.1	17.3	20.1	1000	633	63.3		136
18	2.10	n/a	22.3	17.6	20.4	1000	825	82.5		114
19	2.10	n/a	22.4	17.5	20.5	1000	789	78.9		116
20	1.90	n/a	21.7	17.4	20.1	1000	850	85.0		106
21	2.00	n/a	22.7	17.8	20.9	1000	753	75.3		140
22	2.20	n/a	23.0	18.3	21.4	1000	745	74.5		95
23	2.60	n/a	22.9	18.1	21.1	1000	819	81.9		141
24	2.30	n/a	22.9	18.4	21.4	1000	798	79.8		132
25	2.10	n/a	22.8	18.4	21.2	1000	755	75.5		114
26	2.50	n/a	23.4	19.4	22.0	1000	715	71.5		130
27	2.70	n/a	24.1	21.0	23.1	1000	626	62.6		139
28	2.40	n/a	22.1	18.8	21.0	1000	654	65.4		110
29	1.60	n/a	22.3	19.0	21.2	1000	826	82.6		107
30	1.70	n/a	22.8	19.1	21.5	1000	850	85.0		117
31	2.10	n/a	22.5	19.0	21.2	1000	821	82.1		104
32	2.20	n/a	23.5	20.0	21.9	1000	629	62.9		99
33	1.80	n/a	23.3	20.3	22.0	1000	649	64.9		99
34	1.60	n/a	23.5	19.9	21.9	1000	641	64.1		112
35	2.30	n/a	22.6	19.2	21.1	1000	692	69.2		90
36	1.70	n/a	22.4	18.9	20.9	1000	691	69.1		79
37	1.60	n/a	23.1	19.3	21.2	1000	682	68.2		102
38	1.60	n/a	22.6	19.4	21.1	1000	960	96.0		64
39	1.30	n/a	22.5	19.1	20.7	1000	989	98.9		62
40	1.70	n/a	22.3	19.3	20.7	1000	1042	104.2		56
41	1.30	n/a	21.9	19.2	20.3	1000	1051	105.1		41
42	1.10	n/a	22.5	19.4	20.7	1000	1101	110.1		51
43	1.10	n/a	21.6	19.1	20.0	1000	969	96.9		36
44	2.80	n/a	2 1.8	18.1	19.7	1000	499	49.9		36
45										
46										
47										
48										
Total / ave	**58.68**	**n/a**	**21.5**	**18.0**	**19.9**	**994**	**837**	**84.2**		**3641**
Wks 14-36							**747**	**75**		

Weekly data records- New Burner site

Week	Yield / m^2		Average temp ^{0}C			Daytime CO_2				Light - MJ/m^2
	Units kg	Ave g / unit	Day	Night	24 hr	Setpoint vpm	Achieved vpm	% achieved	PC287 record	
45			n/a	n/a	n/a	None	1000			21
46			n/a	n/a	n/a	None	1200			18
47			n/a	n/a	n/a	None	1200			21
48			n/a	n/a	n/a	None				17
49			n/a	n/a	n/a	None				16
50			n/a	n/a	n/a	None				14
51			n/a	n/a	n/a	None				14
52			n/a	n/a	n/a	None				16
1			n/a	n/a	n/a	None				12
2			n/a	n/a	n/a	None	740			18
3			n/a	n/a	n/a	None	1419			20
4			n/a	n/a	n/a	None	1476			26
5			n/a	n/a	n/a	None	1254			20
6			n/a	n/a	n/a	None	1373			29
7			n/a	n/a	n/a	None	1281			30
8			n/a	n/a	n/a	None	790			37
9			n/a	n/a	n/a	None	853		1130	35
10			n/a	n/a	n/a	None	818		1062	60
11			n/a	n/a	n/a	None	806			55
12			n/a	n/a	n/a	None	748			77
13			n/a	n/a	n/a	None	899			75
14			n/a	n/a	n/a	None	733		973	78
15	0.28	n/a	n/a	n/a	n/a	None	793		1011	77
16	0.43	n/a	n/a	n/a	n/a	None	709			82
17	0.70	n/a	n/a	n/a	n/a	None	608			131
18	0.80	n/a	n/a	n/a	n/a	None	889			108
19	1.10	n/a	n/a	n/a	n/a	None	621			116
20	0.89	n/a	n/a	n/a	n/a	None	863			99
21	1.04	n/a	n/a	n/a	n/a	None	631			138
22	1.06	n/a	n/a	n/a	n/a	None	490			132
23	1.32	n/a	n/a	n/a	n/a	None	562			133
24	1.17	n/a	n/a	n/a	n/a	None	498			126
25	0.92	n/a	n/a	n/a	n/a	None	500			118
26	1.07	n/a	n/a	n/a	n/a	None	532			123
27	1.01	n/a	n/a	n/a	n/a	None	421			106
28	0.96	n/a	n/a	n/a	n/a	None	433			109
29	0.82	n/a	n/a	n/a	n/a	None	520			100
30	0.81	n/a	n/a	n/a	n/a	None	590			110
31	0.73	n/a	n/a	n/a	n/a	None	602			98
32	0.91	n/a	n/a	n/a	n/a	None	590			107
33	0.73	n/a	n/a	n/a	n/a	None	530			94
34	0.74	n/a	n/a	n/a	n/a	None	552			104
35	0.69	n/a	n/a	n/a	n/a	None	590			81
36	0.62	n/a	n/a	n/a	n/a	None	612			75
37	0.71	n/a	n/a	n/a	n/a	None	632			100
38	0.72	n/a	n/a	n/a	n/a	None	650			62
39	0.63	n/a	n/a	n/a	n/a	None	612			59
40	0.61	n/a	n/a	n/a	n/a	None	627			54
41	0.49	n/a	n/a	n/a	n/a	None	752			37
42	0.60	n/a	n/a	n/a	n/a	None	711			49
43	0.55	n/a	n/a	n/a	n/a	None	710			32
44	0.55	n/a	n/a	n/a	n/a	None	624			44
45	0.57	n/a				None				
46	0.66	n/a				None				
47	0.65	n/a				None				
48						None				
Total /ave	**25.54**	**n/a**	**n/a**	**n/a**	**n/a**	**None**	**762**			**3513**
Wks 14-36							**603**			

Weekly data records- Kerosene Burner site

Week	Yield / m^2		Average temp ^{0}C			Daytime CO_2				Light - MJ/m^2
	Units kg	Ave g / unit	Day	Night	24 hr	Setpoint vpm	Achieved vpm	% achieved	PC287 record	
45										13
46										18
47										15
48										8
49			18.5	17.6	17.9	1,000	933	93.3		16
50			17.5	16.7	17.0	1,000	1014	101.4		11
51			18.4	16.7	17.3	1,000	940	94.0		11
52			18.2	16.0	16.7	1,000	935	93.5		10
1			18.5	15.9	16.5	1,000	1037	103.7		14
2			18.6	15.2	16.3	1,000	950	95.0		16
3			19.2	16.6	17.5	1,000	968	96.8	544	11
4			19.0	16.7	17.5	1,000	958	95.8	795	10
5			19.5	15.7	17.0	1,000	997	99.7		21
6			19.6	16.6	17.8	1,000	927	92.7		25
7			19.6	16.1	17.5	1,000	959	95.9		24
8			20.2	16.0	17.8	1,000	988	98.8		29
9			19.1	16.5	17.6	800	730	91.3		26
10			20.5	16.7	18.4	800	775	96.9		50
11			21.1	16.6	18.7	800	766	95.8		51
12			21.8	16.2	18.8	800	733	91.6		89
13	0.40	n/a	19.7	16.3	18.2	800	560	70.0		53
14	0.80	n/a	21.8	17.2	19.8	800	672	84.0		79
15	1.00	n/a	21.7	17.7	20.0	800	577	72.1		79
16	1.10	n/a	21.2	17.2	19.6	800	672	84.0		76
17	1.60	n/a	22.2	17.1	20.2	800	541	67.6		126
18	1.80	n/a	21.6	17.1	19.9	800	591	73.9		112
19	1.90	n/a	20.8	17.0	19.3	800	512	64.0		97
20	1.80	n/a	20.9	17.5	19.7	800	436	54.5		96
21	1.90	n/a	21.9	17.5	20.5	800	451	56.4		132
22	2.00	n/a	21.4	17.6	20.2	800	532	66.5		109
23	2.40	n/a	20.5	16.9	19.4	800	431	53.9		111
24	1.70	n/a	21.4	17.6	20.1	800	469	58.6		111
25	2.20	n/a	20.5	16.9	19.4	800	449	56.1		114
26	1.60	n/a	21.4	17.6	20.2	800	439	54.9		133
27	1.90	n/a	21.9	17.5	20.5	800	397	49.6		149
28	2.50	n/a	20.9	17.5	19.7	800	380	47.5		97
29	1.40	n/a	21.6	18.1	20.5	800	395	49.4		111
30	1.70	n/a	22.0	18.0	20.3	800	456	57.0		94
31	1.70	n/a	22.0	17.9	20.6	800	431	53.9		106
32	2.00	n/a	23.7	19.1	22.0	800	439	54.9		104
33	1.80	n/a	22.3	18.2	20.6	800	328	41.0		82
34	1.30	n/a	22.7	18.3	21.0	800	454	56.8		103
35	1.60	n/a	21.2	17.5	19.8	800	457	57.1		83
36	1.40	n/a	21.2	17.4	19.7	800	477	59.6		80
37	1.30	n/a	21.0	17.7	19.5	400	336	84.0		73
38	1.60	n/a	19.5	17.4	18.5	400	327	81.8		51
39	1.30	n/a	21.2	17.4	19.4	400	327	81.8		65
40	1.00	n/a	21.5	17.9	19.6	400	319	79.8		55
41	0.80	n/a	20.9	18.2	19.4	400	345	86.3		27
42	1.30	n/a	20.8	16.3	18.3	400	318	79.5		47
43	1.30	n/a	19.2	15.7	17.1	400	342	85.5		24
44	0.70	n/a	20.0	16.4	18.2	400	339	84.8		26
45										
46										
47										
48										
Total / ave	**48.80**	**n/a**	**20.6**	**17.1**	**19.0**	**783.3**	**611**	**76**		**3273**
Wks 14-36							**478**	**60**		

Weekly data records- Gas turbine site

Week	Yield / m^2			Average temp ^0C			Daytime CO_2				Light - MJ/m^2
	Units trusses	Ave g / unit	Est kg	Day	Night	24 hr	Setpoint vpm	Achieved vpm	% achieved	PC287 record	
45				18.4	14.9	16.3	1500	1379	91.9		23
46				18.0	15.7	16.6	1500	1036	69.1		29
47				16.8	13.9	14.9	1500	1253	83.5		26
48				17.7	15.7	16.4	1500	1505	100.3		18
49				19.2	16.9	17.7	1500	1490	99.3		31
50				18.7	16.6	17.3	1500	1420	94.7		19
51				19.0	16.6	17.4	1500	1210	80.7		17
52				18.6	16.5	17.2	1500	1234	82.3		19
1				18.9	16.7	17.4	1500	1317	87.8		19
2				19.2	16.3	17.2	1500	1252	83.5		29
3				19.3	16.8	17.6	1500	1246	83.1		23
4				19.5	16.7	17.7	1500	1316	87.7		22
5				20.0	16.9	18.0	1500	1233	82.2		26
6				20.2	17.1	18.2	1500	1167	77.8	1151	34
7				20.5	17.2	18.5	1500	1196	79.7	1099	41
8				20.8	17.2	18.7	1500	1032	68.8		42
9	0.03	n/a	0.01	20.6	17.3	18.7	1500	946	63.1		71
10	0.93	n/a	0.33	20.9	17.7	19.2	1500	899	59.9		74
11	2.62	n/a	0.92	21.2	17.8	19.4	1500	775	51.7		115
12	2.75	n/a	0.97	21.9	18.0	19.9	1500	752	50.1		92
13	1.94	n/a	0.68	20.5	17.3	19.0	1500	707	47.1		109
14	1.93	n/a	0.68	21.6	17.9	19.8	1500	758	50.5		90
15	2.90	n/a	1.02	21.3	17.9	19.7	1500	864	57.6		112
16	3.49	n/a	1.23	21.8	18.0	20.2	1500	774	51.6	978	159
17	2.70	n/a	0.95	21.5	17.4	19.8	1500	592	39.5	611	131
18	2.91	n/a	1.03	21.3	17.9	19.9	1500	728	48.5		127
19	3.14	n/a	1.11	21.4	18.0	20.1	1500	688	45.9		105
20	3.26	n/a	1.15	21.0	17.9	19.9	1500	777	51.8		198
21	3.39	n/a	1.19	21.3	18.1	20.1	1500	487	32.5		152
22	4.79	n/a	1.69	21.6	18.0	20.4	1500	542	36.1		177
23	4.13	n/a	1.46	21.5	18.1	20.3	1500	501	33.4		139
24	4.35	n/a	1.53	21.0	18.3	20.1	1500	561	37.4		165
25	2.61	391	0.92	21.8	18.2	20.6	1500	462	30.8		166
26	3.05	n/a	1.07	22.6	18.7	21.4	1500	467	31.1		182
27	4.35	342	1.53	23.3	19.3	22.0	1500	439	29.3		129
28	3.92	316	1.38	21.3	18.5	20.4	1500	440	29.3		145
29	2.61	337	0.92	21.6	18.6	20.6	1500	513	34.2		143
30	3.26	388	1.15	21.7	18.8	20.7	1500	498	33.2		138
31	3.94	332	1.39	21.6	18.6	20.5	1500	518	34.5		121
32	2.40	364	0.85	22.7	19.4	21.4	1500	513	34.2		111
33	3.48	349	1.23	22.5	19.7	21.3	1500	486	32.4		141
34	3.34	373	1.18	22.5	18.6	20.9	1500	492	32.8		117
35	3.14	335	1.11	21.5	18.6	20.3	1500	468	31.2		113
36	1.14	343	0.40	20.7	18.6	19.7	1500	521	34.7		114
37	3.56	380	1.25	22.0	18.6	20.4	1500	471	31.4		78
38	1.81	393	0.64	21.4	18.7	20.1	1500	577	38.5		97
39	2.14	302	0.75	21.6	18.8	20.2	1500	469	31.3		71
40	2.47	335	0.87	21.3	18.3	19.7	1500	458	30.5		38
41	2.29	n/a	0.81	21.0	18.8	19.8	1500	508	33.9		63
42	1.85	357	0.65	22.1	17.8	19.6	1500	538	35.9		37
43	1.52	n/a	0.54	21.8	18.8	20.0	1500	502	33.5		36
44				22.3	19.1	20.3	1500	525	35.0		38
45											
46											
47											
48											
Total / ave	**98.14**	**352**	**34.58**	**20.8**	**17.7**	**19.3**	**1500**	**798**	**53**		**4512**
Wks 14-36								**569**	**38**		

Weekly data records- Older burner site

Week	Yield / m^2		Average temp ^0C			Daytime CO_2				Light - MJ/m^2
	Units kg	Ave g / unit	Day	Night	24 hr	Setpoint	Achieved	% achieved	PC287 record	
45										20
46										25
47										27
48										19
49										44
50										17
51			19.0	18.1	18.4	700	654	93.4		24
52			18.7	17.4	17.9	700	665	95.0		27
1			18.4	16.8	17.3	700	668	95.4		20
2			18.7	15.2	16.4	700	672	96.0		29
3			18.7	15.8	16.9	700	637	91.0		21
4			18.6	15.4	16.6	1000	858	85.8	841	23
5			18.1	15.1	16.3	1000	973	97.3		27
6			18.3	14.9	16.3	1000	972	97.2		34
7			19.2	15.6	17.1	1000	1032	103.2		43
8			20.0	16.3	17.9	1000	987	98.7		41
9			19.7	16.5	17.9	1000	972	97.2		44
10			20.0	16.4	18.1	1000	882	88.2		66
11			20.9	17.0	18.8	1000	847	84.7		69
12	0.05	85	22.1	17.3	19.6	1000	661	66.1		111
13	0.37	85	20.4	16.9	18.7	1000	788	78.8		89
14	0.97	80	20.9	17.1	19.1	1000	675	67.5		110
15	1.25	80	20.5	17.4	19.1	1000	793	79.3	676	86
16	1.27	77	21.0	17.9	19.6	1000	745	74.5	484	108
17	1.42	77	22.0	18.0	20.3	1000	657	65.7		153
18	1.87	76	21.0	17.7	19.7	1000	792	79.2		123
19	1.69	76	21.0	17.7	19.7	1000	792	79.2		120
20	1.76	75	20.4	17.8	19.4	1000	734	73.4		112
21	1.77	76	22.6	17.9	20.9	1000	504	50.4		174
22	1.90	75	23.0	17.3	21.3	1000	592	59.2		145
23	2.17	n/a	22.7	17.8	20.9	1000	522	52.2		169
24	1.84	n/a	22.2	18.4	20.9	1000	594	59.4		138
25	1.38	n/a	23.1	18.3	21.5	1000	540	54.0		162
26	1.82	n/a	23.8	19.4	22.2	1000	489	48.9		160
27	2.04	n/a	25.2	20.5	23.6	1000	446	44.6		182
28	1.46	n/a	22.3	19.1	21.2	1000	548	54.8		116
29	1.19	n/a	22.4	19.0	21.2	1000	514	51.4		136
30	2.06	n/a	22.8	19.3	21.5	1000	514	51.4		132
31	1.35	n/a	22.9	18.9	21.4	1000	546	54.6		134
32	1.33	n/a	24.6	20.4	22.9	1000	521	52.1		121
33	1.24	n/a	23.9	20.5	22.5	1000	518	51.8		106
34	1.40	n/a	24.5	19.6	22.4	1000	539	53.9		137
35	1.58	n/a	23.0	19.3	21.3	1000	572	57.2		101
36	1.49	n/a	22.6	19.0	20.7	1000	585	58.5		103
37	1.16	n/a	23.3	18.9	21.2	1000	545	54.5		110
38	0.70	n/a	22.4	18.9	20.7	1000	733	73.3		76
39	1.13	n/a	24.8	18.9	21.8	1000	725	72.5		93
40	1.08	n/a	24.2	18.7	21.3	1000	797	79.7		69
41	1.59	n/a	22.7	18.4	20.7	1000	876	87.6		38
42	1.26	n/a	22.9	17.9	19.7	1000	613	61.3		62
43	1.06	n/a	24.1	20.1	21.8	1000	388	38.8		36
44	0.76	n/a	22.4	16.7	19.0	1000	428	42.8		34
45										
46										
47										
48										
Total / ave	**45.41**	**78**	**21.7**	**17.9**	**19.9**	**967**	**676**	**69.9**		**4365**
Wks 14-36							**597**	**60**		