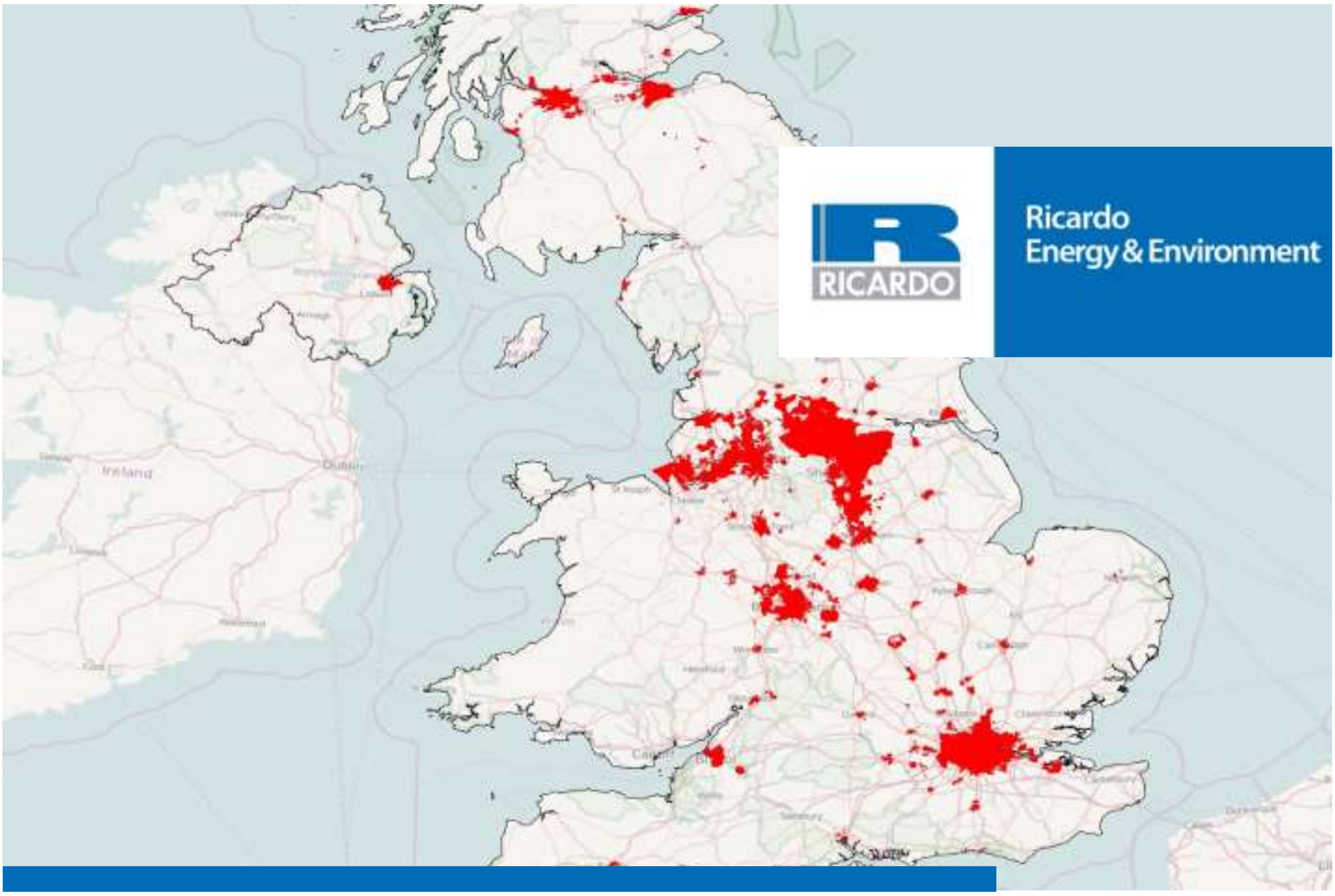

Ricardo
Energy & Environment

Assessment of particulate emissions from wood log and wood pellet heating appliances

A report of the National Atmospheric Emissions Inventory

The work is funded by the Department for Environment, Food and Rural Affairs

ED 59799021 | Issue 1 | Date 27/01/2017

Customer:

The Department for Environment, Food and Rural Affairs

Customer reference:

AQ0726

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27 January 2017

Ricardo Energy & Environment reference:

Ref: ED59799021- Issue 1

Executive Summary

Background

Small-scale and residential combustion sources including wood and solid mineral fuel heating appliances make a significant contribution to emissions of several pollutants in the UK according to the National Atmospheric Emissions Inventory, especially particulate matter (PM). The UK and several other countries have developed legislation to control PM emissions from these appliances, but the different approaches can report very different PM emission levels.

This work programme carried out a series of comparative and round robin tests to investigate the PM measurement issues to provide Defra with evidence to inform negotiation of Ecodesign Regulations including measurement technique and associated emission limits. Measurements were undertaken by accredited laboratories on a 200 kW pellet boiler and five residential roomheaters; three wood log stoves, a wood log stove boiler and a pellet stove boiler. Three measurement techniques were used for determining PM emissions:

- Electrostatic precipitator (ESP)
- Dilution tunnel
- Heated filter

Variability of measurements

There is evidence that repeatability of PM emission testing is better on automatic and semi-continuous automatic appliances than on batch-fed, manually-controlled natural draught log-burning roomheaters. The measurement of particulate emissions from log-burning roomheater appliances is much less consistent than measurement of burn rate, efficiency or heat output. Uncertainty of PM emission measurements can be significantly higher.

The study indicates variability in emissions over five repeat tests, variability between measurement campaigns and differences between PM emissions determined by different laboratories.

Standard deviations of five consecutive PM emission tests were generally over 20% of the average value reported – this represents a very wide range for the ‘true’ appliance emission.

The variability in PM emissions is a challenge both for manufacturers, market surveillance and policymakers for air emission and air quality policy development. This study has found that PM measurement techniques can provide low variability on a 200 kW automatic pellet boiler operating continuously. However, repeatability of PM measurements on wood log roomheaters is poor.

The greater variability found in emission concentrations of particulate (and CO and VOC) than found for burn rate (and NOx) suggests that there may be inherent challenges in PM emission testing of wood log roomheaters. This may suggest a need to adopt a different roomheater operating profile for particulate emission testing than the approach used for output and efficiency.

Comparability of measurement techniques for particulate matter

The data reported here do not allow comparison between national test methods (which include a range of different test protocols) but there is some indication that the ESP and dilution tunnel techniques report broadly similar and higher values than the heated filter technique but even this is not without individual exception. There were several instances where the average ESP and dilution tunnel results differed by a relatively large margin.

Comparison of the dilution tunnel and heated filter PM measurements which were undertaken simultaneously on the same burn cycles indicates that the ratio between dilution tunnel and heated filter PM measurements for the log appliances A to D (including tests at both Lab 1 and Lab 2) ranged from 0.4 to 21 with an average of about 5.

Inter-laboratory comparisons

The difference in average emissions determined by different laboratories using the same techniques can be substantial - even when the fuel was from the same batch, a technician provided guidance on appliance set-up and the PM sampling apparatus was identical. This may indicate that PM emissions from wood log roomheater appliance are inherently variable and/or, the current measurement procedures do not ensure repeatable measurements at different laboratories.

CEN TC295 is working to develop a common test procedure for PM emissions but current proposals are on a heated filter technique and a dilution tunnel technique that are aligned with the appliance performance tests. A proposed longer term method is based on limited testing of a heated filter technique and OGC measurement but still to be aligned with EN appliance performance tests.

Recommendations

Appliance emission testing

- There is a need for further research and understanding of particulate emissions from biomass appliances and, in particular, the features of automatic and non-automatic appliances that influence particulate emissions.
- Measurement of appliance performance parameters for wood log roomheaters show less variability – this may suggest that a separate test protocol is needed for PM emissions than is applied for energy performance which is contrary to the current CEN TC295 proposals.
- The implications for air quality of replacing national test methods with a single test method designed to demonstrate compliance with Ecodesign (or similar) type approval needs to be understood. It may be beneficial (for air quality) to encourage the Standardisation body and the European Commission to consider a test protocol and Ecodesign requirements that are more aligned with real-life operation of appliances.
- The variability in particulate emissions from wood log roomheaters may be improved by addressing weaknesses in current methodologies. There is scope for more consistency in the particulate measurement approaches to define more clearly the measurement techniques and the test protocols. This should allow lower variability and improved repeatability between laboratories. For example :
    - Clearer requirements on measurement equipment, fuel and test protocols;
    - There is evidence that the highest particulate emission concentrations occur during the initial period after refuel;
    - For the heated filter method (and by implication the dilution tunnel method) there is potential for significant deposition of particulate material upstream of the filter;
    - Consider whether additional repeat tests may reduce uncertainty;
    - Consider whether adopting a measurement protocol that assesses PM emissions across multiple burn cycles may reduce uncertainty.

UK emission inventory

- The UK emission inventory should consider the implications of the variability in PM emission measurements for residential wood combustion for uncertainty of emissions from this sector.
- The basis of the EMEP/EEA Guidebook emission factors for wood log roomheaters (as used in the UK emission inventory) need to be reviewed to assess whether they are based on type approval or real-life operation of appliances.
- Future measurement programmes for emission inventory development for residential wood combustion need to consider the variability in measured emissions carefully when developing a testing protocol for laboratory measurements.
- In the longer-term, alternative emission determination approaches such as in-situ measurements, air quality measurements or source apportionment may provide alternative means to validate or develop emission estimates.

Table of contents

Appendices

1 Introduction

1.1 Overview

Small-scale and residential combustion sources including wood and solid mineral fuel heating appliances are significant contributors to emissions of several pollutants in the UK[1] including particulate matter (PM). The UK and several other countries have developed legislation to control PM emissions from residential sources and other smaller scale combustion plants, including emission limits for heating appliances. A number of different approaches to measuring particulate emissions have been developed both qualitative and quantitative.

Unfortunately the quantitative approaches can report very different particulate matter (PM) emission values due to differences in:

- the sampling and measurement technique:
  sample of undiluted flue gases at stove outlet at 70°C (heated filter),
  sample of diluted flue gases on dilution tunnel at/near ambient temperature (dilution tunnel),
  electrostatic precipitator collecting PM from all flue gases at chimney outlet (ESP).
- the characteristics of the PM emitted:
  emissions from batch-fired, manually-controlled, natural draught appliances tend to include a substantial condensable material which may vary over the course of the burn cycle,
  automatically-stoked appliances have greater control of combustion conditions (including air supply), typically have a more constant operation and emit much less condensable material.
- the measurement protocol (scope of testing) which differ in many respects including:
  the range of outputs tested (1 to 4),
  aggregation of emission data,
  the number of measurements at each output (1 to 5),
  the extent of coverage of the burn cycle,
  natural or fixed draught,
  natural or artificial firebed.

Comparison of PM data from these methods is further complicated as the different methods traditionally report results in different units :

- an emission rate - g/h,
- concentrations - mg/m^3 at a variety of oxygen contents,
- emission factors for example g/kg fuel burned (on a dry or other basis).

Research papers in scientific literature often apply further test protocols and report emission data for a wider range of emission units including g/GJ energy input (on either a net or gross basis) or heat output.

Differences in national PM measurement and reporting approaches were not of great consequence when legislation was designed to address national requirements. However, increasingly appliance manufacturers sell into different countries and have burdens associated with the multiple regulatory requirements.

Although harmonised European Standards are in place for many solid fuel heating appliances, these generally have not covered PM emissions as a common measurement methodology which satisfied all national requirements could not be agreed A CEN Technical Specification[2] for emission testing includes an Annex describing national methods for PM applied by UK, Germany and Norway. Recent Regulations[3] under the Ecodesign Directive set emission and other requirements for new solid fuel roomheater and boiler appliances which will be applicable across the EU. However, in the

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[1] See key source analysis in NAEI Informative Inventory Report here http://uk-air.defra.gov.uk/reports/cat07/1603150959_GB_IIR_2016_Final.pdf
[2] CEN/TS 15883:2009 - Residential solid fuel burning appliances. Emission test methods
[3] Commission Regulations 2015/1189 and 2015/1185 setting out Ecodesign requirements for solid fuel boilers and Local Space Heaters respectively.

negotiations for the Regulation for Local Space Heaters (roomheaters) a common methodology for assessing PM emission from roomheaters was not available and could not be agreed. Consequently the Regulation incorporates approximations to the three national methods applied for assessing roomheater PM emissions in Europe.

This work programme carried out a series of comparative and round robin tests to investigate the PM measurement issues to provide Defra with evidence to inform negotiation of Ecodesign Regulations including measurement technique and associated emission limits.

1.2 Scope of work

Ricardo Energy & Environment was contracted to supervise a series of PM and other measurements undertaken by a UK testhouse (Lab 1) and two other EU testhouses (Lab 2 and Lab 3). All the testhouses are accredited for appliance testing to harmonised European Standards and for PM emission measurements to the national Standards. Tests were undertaken to determine PM emissions from a range of residential biomass appliances and a larger biomass boiler.

1.3 Report structure

This report summarises the measurement reports of the main testhouse which provide more detail of the measurements undertaken by all three testhouses. The detailed test reports are included in the appendices and cover comparative measurements using the national methods, inter-laboratory tests and investigative measurements .

1.4 Emission units

Unless noted otherwise, the emission data in this summary report are expressed as g/GJ net heat input.

2 Emission measurement methodologies

2.1 Particulate Matter measurement techniques

For type approval and related appliance testing, the measurement techniques used in national methods are periodic (non-continuous) gravimetric techniques and these are introduced below. Further detail is provided in CEN/TS 15883[4], in national Standards and related documentation.

2.1.1 Electrostatic Precipitator

The Electrostatic Precipitator (ESP) method is a UK method and the basis of the assessment of whether a small solid fuel heating appliance is suitable for use in Smoke Control Areas designated by Local Authorities from powers provided by the Clean Air Act 1993[5]. An ESP is fitted on a chimney section above the appliance under test. All the flue gases from the appliance pass through the ESP in which an electric field is applied to charge the particulate material and collect it on the internal surface of the ESP. The amount of smoke (PM) collected is determined gravimetrically. Although the ESP collects PM at a similar temperature as the heated filter approach (Section 2.1.2), the ESP is located further away from the appliance and this appears to encourage condensation of semi-volatile emission components and allows collection of more PM than is collected by the heated filter closer to the appliance. The equipment and methodology is described in CEN/TS 15883. The UK ESP (and alternative dilution tunnel method – see Section 2.1.3) and associated emission limit values are included in Ecodesign Regulation 2015/1185 for solid fuel Local Space Heaters.

2.1.2 Undiluted anisokinetic extractive sampling (heated filter)

The heated filter methodology is a methodology described in the 'DIN+' ecolabel and referenced in German national legislation to allow demonstration of PM emissions during type testing of appliances. The equipment and methodology is described in CEN/TS 15883. Measurements are undertaken on flue gases in a test section immediately downstream of the appliance. A fixed volume of flue gas is taken from the flue gases over a thirty minute period. This implies a constant anisokinetic sampling rate because measurement of velocity in small natural draught flues is difficult. A heated thimble filter is used (maintained at 70°C) to collect PM. The commercial equipment used by testhouses includes a short unheated sampling probe but the methodology includes provision for use of cooling systems where high flue gas temperatures are encountered. A PM concentration is calculated using the weight of collected PM and the volume of flue gas sampled. Simultaneous oxygen or carbon dioxide measurements are required to normalise the emission concentration to a 13% reference oxygen concentration. The heated filter method is included in Ecodesign Regulation 2015/1185 for solid fuel Local Space Heaters.

2.1.3 Full Flow Dilution Tunnel with extractive sampling

There are a variety of dilution tunnels in use internationally but the two considered in this study are those adopted in the Norway and UK Standards. In the full flow dilution tunnel (FFDT) measurement systems, all the flue gas from an appliance is mixed, diluted and cooled with ambient air. The cooling process allows condensation of semi-volatile emission components which, after a short mixing period, are sampled and collected on filters (a similar sampling train as used for the heated filter technique but unheated). Filter preparation and weighing procedures allow determination of low (diluted) PM concentrations. Measurements are needed to determine the dilution rate and hence determine an emission rate which is used to calculate an emission factor. Simultaneous oxygen or carbon dioxide measurements may be required to normalise the emission concentration to a 13% reference oxygen concentration. The method is included in Ecodesign Regulation 2015/1185 for solid fuel Local Space Heaters.

2.1.4 Undiluted isokinetic extractive sampling

A variation of the heated filter approach. This methodology is not generally appropriate for small residential heating appliances and was not undertaken during the measurement programme but is

[4] CEN Technical Specification (TS) 15883:2009 - Residential solid fuel burning appliances. Emission test methods

[5] BS PD 6434:1969 and BS3841 Part2

provided for completeness. The setting of an isokinetic sampling rate requires measurement of flue gas velocity at the sampling point and, the velocity of flue gases from natural draught appliances is usually too low to measure directly with sufficient accuracy. There are EN and ISO Standards[6] which can be applied which are the methodologies used for larger boilers and industrial processes. These differ from the heated filter method in some key respects including filter temperature, recovery of prefilter deposits, formal leak check criteria, weighing procedures and use of blanks. A benefit of a dilution tunnel approach is that there is potential to apply the existing EN or ISO Standards on the diluted flue gas flow (current dilution tunnel methods generally adopt a simplified PM sampling approach compared to the EN or ISO Standards for isokinetic sampling).

2.2 Gaseous emission measurements

The concentrations of selected gaseous pollutants were measured by extracting flue gas from the flue, close to the appliance and before any dilution air is introduced. The sample gases were filtered and conditioned (for example dried) to suit the analysis technique being employed. Measurement methods used were broadly in accordance with CEN/TS 15883.

It should be noted that the flame ionisation technique for hydrocarbons results in a measurement of the concentration of the total hydrocarbons in the sample, it does not determine the individual hydrocarbons present.

The details of the gas sampling arrangements are written into the testhouses' accredited testing procedures, these cover items such as:

- Use of zero and span gases (zero specification, span gas analytical uncertainty and certificates of analysis).
- System leak checks and frequency.
- Frequency of zero and span checks.
- Hydrocarbons span gas.
- For NOx – determination of converter efficiency.
- Pre and post-test zero and span checks (and acceptance criteria).
- Data logging frequency.
- Site/test record sheets.

An extract from the Lab 1 UKAS accredited testing procedures is provided in the detailed test reports in the appendices.

2.3 Other measurements

Other measurements undertaken to characterise the operation of the appliances included the suite of measurements for EN appliance testing including draught, flue gas temperature, weight of test rig + appliance (to provide fuel consumption). In addition fuels were sampled and analysed.

2.4 Appliances tested

The choice of appliances for the testwork was based on a number of criteria:

- all appliances are of modern design and on the market
- a range of different fuels should be used – logs and pellets
- a range of appliance outputs should be tested
- a range of appliance types should be tested, including roomheaters, roomheater / boilers, and boilers

[6] EN 13284-1, ISO 12141 and ISO 9096

- appliances producing a range of expected emissions concentrations should be tested; from those expected to burn very cleanly (large scale pellet boiler) to those expected to be relatively polluting (small scale roomheater / boiler)
- appliances meeting a range of PM emissions standards should be chosen

Appendix 1 shows the appliances chosen for the study which included three wood log roomheaters, one wood log roomheater boiler, a pellet stove boiler and a large pellet boiler.

2.5 Measurement programme

2.5.1 Objectives of measurement programme

The aim of the test programme was to assess variability in PM emissions and the differences between the measurement techniques (ESP, heated filter and dilution tunnel) at two output conditions (low and nominal or rated output) – the test protocols in the national methods are considered to be too different to allow meaningful comparison of the national methods. The main focus of the test programme was to assess :

- variation in PM emissions for a group of appliances which are currently available and of different characteristics and capabilities (see Section 2.4).
- relationship between emission data provided by the three main PM measurement techniques
- variation between test laboratories
- whether correlations exist between PM measurement techniques and other measurements
- differences in PM method performance between low and rated output operation

The test programme (Appendix 2) included replicate measurements on each appliance at rated and low output using the three measurement techniques with measurements on two wood log roomheater appliances at three testhouses (a ‘round robin’ test) and investigation of PM emissions during different points of the burn cycle.

2.5.2 Main test programme

As indicated in Section 1.1, the PM emission data provided by the national test methods are difficult to compare because the operation of the appliances during the tests and aggregation of emission data can be very different. Consequently, the test programme focussed on comparing the measurement techniques under common appliance operating conditions. However, operation was adjusted to match requirements of individual measurement techniques (for example draught and sampling period). The test protocol adopted is summarised below :

- Measurements were at nominal (rated) heat output and at a reduced (low) output.
- Five measurements were undertaken at each output for each appliance.
- Normal method draughts were applied – natural draught or at 12 Pa (the harmonised EN Standard reference draught).
- Normal measurement cycles were adopted - full cycle for ESP and dilution tunnel and 30 minute for heated filter.
- Natural wood log firebeds were used (this is a deviation for one of the dilution tunnel measurement techniques).

Variability of PM emissions was assessed by comparing the multiple measurements on each appliance under each measurement technique. Ideally, in order to assess the difference in PM emissions provided by the different techniques, the measurement techniques would all have been applied simultaneously and to the same test protocol however, the test protocols were slightly different to reflect the normal approach of each measurement technique and, it is not possible to operate the ESP and dilution tunnel techniques on an appliance at the same time so testing was undertaken separately. Where possible the heated filter and dilution tunnel measurements were undertaken simultaneously.

2.5.3 Inter-laboratory programme

Measurements were undertaken on two of the wood log appliances at two other testhouses. Both testhouses undertook heated filter measurements and one of the testhouses also undertook dilution tunnel measurements (simultaneously with heated filter tests). Fuel used for these measurements was shipped from the UK with the appliances and a test engineer from the UK testhouse attended the emission tests at the other testhouses to provide guidance on how the appliance was operated in the UK.

2.5.4 Supplementary measurement programme

Further PM measurements were undertaken to assess slippage through the ESP, to assess repeatability of ESP measurements when an appliance was tested at a later date, to determine PM emission profiles during burn cycles on a wood log roomheater and to assess how differences in the measurement periods adopted in the national methods may influence measured PM data. In addition, changes in the filtration temperature and recovery of probe (pre-filter) washings were examined for the heated filter method.

2.5.5 Proposed CEN relationship between PM and hydrocarbon measurements

During the course of the measurement programme CEN Technical Committee 295 was working on how to address different national PM measurement methods in the harmonised EN appliance Standards. A proposal was made for measurement of :

- PM – filterable PM using a heated filter technique
- PME – 'total' PM by dilution tunnel
- OGC – a measurement of gaseous hydrocarbons[7]

A further proposal suggested a relationship between PM, PME and OGC broadly :

PME = PM + (0.4 x OGC)

The emission test results on the roomheaters were used to assess whether the proposed relationship was generally applicable.

2.5.6 Other measurements

Alongside the PM measurements, a range of measurements to assess operation of the appliance were also undertaken including flue gas temperature, draught, appliance/test rig weight, CO, O_2 (or CO_2), total hydrocarbon (THC), NOx and (in the UK testhouse) optical density. In addition fuel analysis was undertaken. Testing was undertaken by ISO 17025-accredited test organisations at test facilities used to undertaken EN appliance testing and testing to national PM methods. Details of these measurements are provided in the test reports in the appendices.

[7] Organic Gaseous Carbon (OGC) is a term used in EN303-5 for solid fuel central heating boilers and in the Ecodesign Regulations for solid fuel LSH and boilers – it is based on an total hydrocarbon (THC) or total organic compound (TOC) measurement by flame ionisation detection expressed as a carbon-equivalent mass concentration .

3 Results

3.1 Variability of PM emission measurements

3.1.1 Overall

The Standard Deviations (SD) of the PM measurements by the various methods in the different laboratories was found to be relatively large especially for the log burning appliances. The 95% confidence intervals (± 2 x SD) would show high levels of uncertainty for most of the measurements. The range of RSD[8] (the standard deviation of each group of measurements expressed as a percentage of the average result) for all appliances, outputs, measurement techniques and testhouses is from 1% to >100% of the averages for each set of measurements with a median of about 29%. For wood log roomheaters over 75% of the RSD values were greater than 20%.

The pellet stove results were generally less variable than the log wood appliances but gave substantial variations between PM test methods. The 200kW pellet boiler offered the most consistent and low PM emissions (RSD at high output 2% with ESP and 15% using heated filter).

Additional ESP, dilution tunnel and heated filter data from emission data submitted to Ricardo Energy & Environment for Clean Air Act Exemption were reviewed. The data cover a variety of wood log stove and insert roomheater appliances. These additional data are for different appliances to this study and include emission data from other test labs for the dilution tunnel and heated filter (but all accredited for PM emission testing). The additional data do not show as wide a range of RSD (5.5 – 57.2%) but over 65% of the RSD values were greater than 20% which confirms the variability observed in this study.

Note that the level of variability in appliance parameters such as burn rate, output and efficiency was generally much lower than for PM emissions.

3.1.2 Electrostatic precipitator

The Standard Deviations (SD) of the ESP PM measurements were found to be relatively large especially for the log burning appliances. The 95% confidence intervals (± 2 x SD) would show high levels of uncertainty for most of the measurements. The range of RSD for all appliances, outputs, and measurement techniques tested in Lab 1is from 2% to 64% of the averages for each set of measurements with a median of about 29%. For wood log roomheaters the RSD ranged from 16 to 64% with a median RSD of 30%. Over 85% of the RSD values were greater than 20%.

The pellet stove results were generally less variable than the log wood appliances and the 200kW pellet boiler offered the most consistent (and lowest) PM emissions (RSD at high output 2%).

[8] The standard deviation of the measurements expressed as a percentage of the average result. Note that care is needed in interpreting RSDs e.g. where SDs for separate data sets are similar but the average values differ significantly.

Table 3-1 Lab 1 ESP Results, g/GJ

Appliance		A	B	C	D	E	F
Output level	Statistic						
High	Average	86	126	115	96	32	18
	SD	24.4	20.6	34.8	60.8	5.8	0.4
	RSD	**28%**	**16%**	**30%**	**64%**	**18%**	**2%**
Low	Average	78	103	105	141	50	15
	SD	38.0	36.2	30.4	58.0	14.2	1.7
	RSD	**49%**	**35%**	**29%**	**41%**	**28%**	**12%**

A review of ESP emission data for wood log stoves and multifuel stoves burning wood logs submitted to Ricardo Energy & Environment for recent applications for Clean Air Act Exemption is summarised in Table 3-2 below and RSD ranged from 9 to 38% with a median RSD of 25%. 65% of the RSD values were greater than 20%. This suggests less variability than during the current study but may reflect a larger dataset and the relatively high variability of appliance D (a boiler stove). Note that only Lab 1 operates an ESP.

Table 3-2 Clean Air Act Exemption ESP PM Emission Results

Appliance	ESP1	ESP2	ESP3	ESP4	ESP5	ESP6	ESP7	ESP8	ESP9	ESP10
Type	Stove	Stove	Stove	Stove	Stove	Stove	Stove	Stove	Stove	stove
Size, kW	4.5	5.9	4.8	3.9	5.0	8.0	4.2	5.5	7.7	5.0
EN Efficiency, %	81.9	82.4	77.5	80.2	82.4	74.5	86.1	78.0	78.3	84.0
Nominal (high) output										
Average PM, g/GJ	93.3	64.7	89.6	191.8	137.0	80.1	112.0	106.6	63.7	97.9
Ratio max/min	1.8	1.9	1.3	1.4	1.4	2.6	1.9	2.1	1.8	1.2
SD, g/GJ	24.3	15.3	9.2	24.3	18.6	30.7	31.7	36.2	15.1	9.1
SD, % of average	26.0	23.6	10.3	12.7	13.6	38.3	28.3	33.9	23.7	9.3
Low output										
Average	123.9	121.2	106.0	96.2	129.2	88.0	126.9	127.0	57.6	115.7
Ratio max/min	1.4	1.9	2.9	2.1	3.3	2.7	1.4	1.6	1.7	1.8
SD	17.1	36.1	39.6	30.0	49.6	30.0	18.3	20.6	12.5	31.2
SD, % of average	13.8	29.8	37.4	31.2	38.4	34.1	14.4	16.2	21.7	27.0

3.1.3 Dilution tunnel

FFDT results are summarised in tables 3.3 and 3.4 for lab 1 and lab 2 respectively. The Standard Deviations (SD) of the FFDT PM measurements were found to be relatively large especially for the log burning appliances. The 95% confidence intervals (± 2 x SD) would show high levels of uncertainty for most of the measurements. The range of RSD for all appliances, outputs, measurement techniques and testhouses is from 1% to 50% of the averages for each set of measurements with a median of about 20%. For wood log roomheaters the RSD ranged from 1 to 50% with a median RSD of 27%. 50% of the RSD values were greater than 20%.

Table 3-3 Lab 1 FFDT Results, g/GJ

Appliance		**A**	**B**	**C**	**D**	**E**	**F**
Output level	Statistic						
High	Average	82	120	119	137	80	
	SD	22	48	59	26	8	
	RSD	**27%**	**40%**	**50%**	**19%**	**10%**	
Low	Average	168	77	97	402	79	
	SD	29	38	15	152	14	
	RSD	**17%**	**49%**	**15%**	**38%**	**18%**	

Table 3-4 Lab 2 FFDT Results, g/GJ

Appliance		**A**	**B**	**C**	**D**	**E**	**F**
Output level	Statistic						
High	Average		187	62			
	SD		58	1			
	RSD		**31%**	**1%**			
Low	Average		230	114			
	SD		45	13			
	RSD		**20%**	**11%**			

A review of dilution tunnel emission data for wood log and multifuel stoves and insert appliances submitted to Ricardo Energy & Environment for recent applications for Clean Air Act Exemption is summarised in Table 3-5 below. RSD ranged from 9 to 57% with a median RSD of 32%. 75% of the RSD values were greater than 20%. This suggests more variability than during the current study. . Note that the data are from several testhouses (but no data are for testhouses from this study) .

Table 3-5 Clean Air Act Exemption Dilution Tunnel PM Emission Results

Appliance	DT1	DT2	DT3	DT4	DT5	DT6	DT7	DT8	DT9	DT10
Type	Stove	Stove	Stove	Insert	Stove	Stove	Stove	Stove	Stove	Stove
Size, kW	4.9	6.5	10.0	11.0	5.0	8.0	4.6	7.6	8.7	4.5
EN Efficiency, %	76.7	77.2	78.3	80.0	81.0	83.0	83.0	77.0	79.0	79.0
Nominal (high) output										
Average PM, g/GJ	40.2	67.0	108.0	82.0	52.4	27.8	64.6	45.1	36.0	91.1
Ratio max/min	3.1	2.5	1.9	2.1	4.8	1.5	2.1	2.3	1.7	2.6
SD, g/GJ	13.1	23.4	26.5	25.0	30.0	3.9	24.4	17.4	8.9	34.9
SD, % of average	32.7	35.0	24.6	30.5	57.2	14.2	37.7	38.5	24.6	38.2
Low output										
Average	50.5	66.2	76.5	68.0	59.7	53.1	65.4	23.6	58.5	129.5
Ratio max/min	3.9	1.7	1.5	3.3	2.4	1.7	2.7	1.5	2.7	1.2
SD	28.6	14.6	11.2	31.7	18.8	9.8	25.2	4.2	28.9	11.2
SD, % of average	56.7	22.0	14.6	46.6	31.5	18.5	38.5	17.7	49.4	8.7

3.1.4 Heated filter

As expected from previous comparisons[9], the emission results from the heated filter measurements were generally lower than obtained using the ESP or dilution tunnel. However, higher emissions than the ESP and dilution tunnel were obtained during the low output tests on appliance D (the wood log roomheater boiler); the reason for this observation is not known.

FFDT results are summarised in tables 3.6, 3.7 and 3.8 for lab 1, lab 2 and lab 3 respectively. The Standard Deviations (SD) of the HF PM measurements were found to be relatively large especially for the log burning appliances. The 95% confidence intervals (± 2 x SD) would show high levels of uncertainty for most of the measurements. The range of RSD for all appliances, outputs, measurement techniques and testhouses is from 13% to 111% of the averages for each set of measurements with a median of about 40%. For wood log roomheaters the RSD ranged from 18 to 111% with a median RSD of 43%. 85% of the RSD values were greater than 20%.

Table 3-6 Lab 1 heated filter results, g/GJ

Appliance		**A**	**B**	**C**	**D**	**E**	**F**
Output level	Statistic						
High	Average	21	64	25	88	19	16
	SD	6	30	17	42	7	2
	RSD	**27%**	**47%**	**68%**	**48%**	**35%**	**15%**
Low	Average	18	28	59	607	15	4
	SD	6	11	29	375	4	1
	RSD	**32%**	**39%**	**49%**	**62%**	**28%**	**13%**

Table 3-7 Lab 2 heated filter Results, g/GJ

Appliance		**A**	**B**	**C**	**D**	**E**	**F**
Output level	Statistic						
High	Average		74	27			
	SD		13	5			
	RSD		**18%**	**20%**			
Low	Average		61	7			
	SD		21	2			
	RSD		**35%**	**27%**			

[9] For example, see Nussbaumer, T. et al Particulate Emissions from Biomass Combustion in IEA Countries Survey on Measurements and Emission Factors IEA Bioenergy Task 32, Swiss Federal Office of Energy, Zurich, 2008, ISBN 3-908705-18-5. Available here : http://www.ieabcc.nl/publications/Nussbaumer_et_al_IEA_Report_PM10_Jan_2008.pdf

Table 3-8 Lab 3 heated filter Results, g/GJ

Appliance		**A**	**B**	**C**	**D**	**E**	**F**
Output level	Statistic						
High	Average		91	32			
	SD		20	24			
	RSD		**22%**	**76%**			
Low	Average		115	22			
	SD		24	24			
	RSD		**21%**	**111%**			

NOTE: Measurements that Lab 3 excluded have not been included in these statistics.

Heated filter emission data for wood log stove and insert appliances submitted to Ricardo Energy & Environment for recent applications for Clean Air Act Exemption are summarised in Table 3-9 below. RSD ranged from 6 to 53% with a median RSD of 27%. 50% of the RSD values were greater than 20%. Note that the data are from several testhouses including data from Lab 2.

Note that although heated filter measurements typically include three measurements at rated output, the data provided include additional measurements for Clean Air Act (five tests at each output) but limited emission data for low output were available. Applicants often undertake low output measurements using a dilution tunnel to avoid application of an emission 'safety factor' to account for differences between PM emissions by heated filter and other measurement techniques[10]. The RSD values suggest less variability than during the current study but this may reflect several instances of particularly high RSD in the current study (Appliance D, the boiler stove, and Appliance C at Lab 1 and Lab3).

Table 3-9 Clean Air Act Exemption Heated Filter PM Emission Results

Appliance	HF1	HF2	HF3	HF4	HF5	HF6	HF7	HF8	HF9	HF10
Type	Inset	stove	stove	stove	stove	inset	stove	stove	stove	stove
Size, kW	11.7	5.5	7.0	7.2	5.0	7.0	7.5	8.0	5.0	5.3
EN Efficiency, %	80.0	79.0	79.1	81.0	81.0	82.0	79.0	80.5	78.0	82.0
Nominal (high) output										
Average PM, g/GJ	5.6	16.2	11.1	3.3	10.2	7.2	6.7	10.3	9.2	3.6
Ratio max/min	2.0	2.1	1.1	2.3	1.3	3.3	2.2	1.8	1.8	3.3
SD, g/GJ	1.3	4.4	0.6	1.2	1.3	2.9	2.2	2.9	1.9	1.9
SD, % of average	23.2	27.0	5.5	37.4	12.7	40.7	32.9	27.9	20.9	53.4
Low output										
Average	6.1		14.8		9.2			7.4		
Ratio max/min	1.4		1.2		2.0			3.4		
SD	0.9		1.1		2.6			3.2		
SD, % of average	14.2		7.4		28.7			42.9		

[10] See Clean Air Act guidance for Exemption applications (Section 3.2.2) https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/497436/Application_Pack_Ricardo_EE_Issue_v4_Final.pdf

3.2 Comparison of measurement techniques

Although results across the appliances at Lab 1 generally indicated that average results for the individual appliances and outputs were broadly similar for the ESP and dilution tunnel and that emission data were lower for the heated filter (as expected – see Section 3.1.4), there were several instances where the average ESP and dilution tunnel results differed by a relatively large margin. Also, for appliance D (a roomheater boiler) the average heated filter result at low output was higher than determined using the ESP or dilution tunnel.

Comparison of the dilution tunnel and heated filter PM measurements which were undertaken simultaneously on the same burn cycle indicates that the ratio between dilution tunnel and heated filter PM for the log appliances A to D and at both output conditions (including tests at both Lab 1 and Lab 2) ranged from 0.4 to 21 with an average of about 5 (see Table 3-10), see also Section 3.5.2.

Note that these data do not allow comparison between the full national test methods which incorporate different appliance operating conditions. Comparison for this study is limited to operation over individual burn cycles (either at rated or low output).

Table 3-10 Comparison of the dilution tunnel (FFDT) and heated filter (HF) PM measurements

Output	High			Low		
Appliance	HF	FFDT	Ratio (FFDT/HF)	HF	FFDT	Ratio (FFDT/HF)
Lab1						
A	28	113	4.04	17	143	8.41
A	16	69	4.31	10	107	10.70
A	15	66	4.40	19	173	9.11
A	21	64	3.05	16	119	7.44
A	26	98	3.77	26	168	6.46
B	30	161	5.37	36	60	1.67
B	72	157	2.18	27	38	1.41
B	75	142	1.89	10	123	12.30
B	94	81	0.86	30	111	3.70
B	138	57	0.41	38	52	1.37
C	11	223	20.27	56	82	1.46
C	11	85	7.73	90	105	1.17
C	16	77	4.81	77	116	1.51
C	47	100	2.13	14	82	5.86
C	39	112	2.87	59	98	1.66
D	53	155	2.92	458	472	1.03
D	113	150	1.33	526	465	0.88
D	32	96	3.00	1271	584	0.46
D	128	125	0.98	370	234	0.63
D	112	156	1.39	410	253	0.62
Lab 2						
B	90	134	1.49	82	284	3.46
B	75	199	2.65	61	226	3.70
B	78	276	3.54	69	261	3.78
B	54	138	2.56	25	212	8.48
B	71	189	2.66	67	168	2.51
C	24	62	2.58	7	108	15.43
C	30	62	2.07	5	107	21.40
C	35	63	1.80	8	131	16.38
C	21	63	3.00	10	123	12.30
C	26	61	2.35	6	100	16.67

3.3 Inter laboratory tests

The measurements were undertaken on appliances B and C. Standard deviations for most measurement series are high in comparison to the average concentrations indicating high variation in PM emissions between individual tests at each testhouse at notionally the same output. The fuel used in all tests was from the same batch (sourced by Lab 1) and a Lab 1 technician advised on appliance operation during the inter laboratory tests. The Lab 1 technician witnessed the tests at Lab 2 and Lab 3 and noted some small differences in procedures. For example, Lab 2 notched the faces of their logs (with an axe) to give faster ignition which might be expected to produce low emissions, however any effect is not clear from the results.

Note that these tests were not conducted on the same burn cycles so individual tests are not comparable and differences in emissions include differences arising from differences in measurement technique applied by the testhouses and they will also reflect variability in emissions from differences in operation at each testhouse or a combination of both factors.

3.3.1 Dilution tunnel

FFDT measurements carried out at two laboratories (Lab 1 and Lab 2) are summarised in Table 3-11 below. The dilution tunnels are not the same at each testhouse as they are compliant with different national standards.

Table 3-11 Particulate measurements by dilution tunnel technique made at two laboratories, g/GJ

Output	High				Low			
Appliance	B		C		B		C	
Laboratory	2	1	2	1	2	1	2	1
Test 1	134	161	62	223	284	60	108	82
Test 2	199	157	62	85	226	38	107	105
Test 3	276	142	63	77	261	123	131	116
Test 4	138	81	63	100	212	111	123	82
Test 5	189	57	61	112	168	52	100	98
Average	**187**	**120**	**62**	**119**	**230**	**77**	**114**	**97**
SD	**58**	**48**	**1**	**59**	**45**	**38**	**13**	**15**
Ratio average Lab 2/Lab 1	**1.56**		**0.52**		**3.00**		**1.18**	

Although the results of the five tests at higher output for appliance C at Lab 2 showed very low variation between tests, the standard deviations are, in most cases, very large compared to the measured and average emission values and thus the 95% confidence intervals (± 2 x SD) would show high levels of uncertainty for most of the measurements.

The differences in average particulate emissions between the two laboratories often exceed the standard deviations. The ratios of average PM data are not consistent for each appliance and output – for both appliances, Lab 1 determined that average PM emissions at low output were lower than at rated output but tests at Lab 2 indicated the opposite. This may indicate that there may not be a systematic error between the testhouses or measurement techniques but the variability within each measurement series makes conclusions difficult.

The differences between average results for the appliances at the different testhouses have implications for tolerances in Ecodesign market surveillance.

3.3.2 Heated filter

Heated filter measurements carried out at the three testhouses are summarised in Table 3-12 below.

The standard deviations are relatively large compared to the average PM emission data indicating high variability which limits conclusions. Some laboratories determined emissions falling on going from high fire to low fire whereas other laboratories determined an increase. Lab 2 and Lab 3 used identical proprietary sampling equipment for the heated filter measurements and this differed from the equipment used by Lab 1. However PM emission data determined by Lab 1 was not consistently lower (or higher) than the other testhouses.

At high/rated output, Lab 3 gave the highest particulate emissions and Lab 1 lowest but across all output and appliance combinations, none of the testhouses were higher (or lower) than the others. The differences between average results for the appliances at the different testhouses have implications for Ecodesign market surveillance.

Table 3-12 Particulate measurements by heated filter method made at three laboratories, g/GJ

Output	High						Low					
Appliance	B			C			B			C		
Laboratory	2	1	3	2	1	3	2	1	3	2	1	3
Test 1	82	30	93	7	11	*20***	90	36	*104**	24	56	*5****
Test 2	61	72	*115**	5	11	*2****	75	27	92	30	90	*25***
Test 3	69	75	102	8	16	56	78	10	*143**	35	77	32
Test 4	25	39	61	10	47	*56***	54	30	95	21	14	10
Test 5	67	106	*82**	6	39	*24***	71	38	*138**	26	59	36
Average	**74**	**64**	**91**	**7**	**25**	**39**	**74**	**28**	**115**	**27**	**59**	**26**
SD	**13**	**30**	**20**	**2**	**17**	**20**	**13**	**11**	**24**	**5**	**29**	**12**
Ratio average to Lab 1	**1.14**	**1.00**	**1.41**	**0.29**	**1.00**	**1.58**	**2.61**	**1.00**	**4.06**	**0.46**	**1.00**	**0.44**
Ratio highest average to lowest	**1.41**			**5.44**			**4.06**			**2.30**		

NOTES:
* Lab 3 reported that high particle loadings affected sample volume
** Lab 3 reported problems with fuel ignition /burnout
*** Lab 3 excluded these results because they considered them too low – and they have not been used in calculation of these statistics

3.4 Supplementary measurement programme

3.4.1 Repeat tests (ESP)

Appliance C was tested using the ESP in the same laboratory (Lab 1) several weeks apart (see Table 3-13). The average results differ, although almost within their respective standard deviations.

Table 3-13 Repeated ESP measurements

Appliance		**C**	***C Repeat tests***
Output level	Statistic		
High	Average	115	*124*
	SD	34.8	*44.8*
	RSD	**30%**	***36%***
Low	Average	105	*80*
	SD	30.4	*21.5*
	RSD	**29%**	***27%***

3.4.2 Slippage (ESP)

Slippage of PM material through the ESP was assessed by measuring PM in the flue gases downstream of the ESP during tests on appliance B. The ESP sampling was carried out in the usual way. Downstream of the ESP a heated filter sampling arrangement and procedure was used to determine levels of residual particulate matter in the flue gas. The results of these measurements are given in Table 3-14 below.

Table 3-14 ESP sample slippage results

Output	Test	ESP smoke	ESP slippage (heated filter)	ESP Slippage
		g/GJ	g/GJ	%
High	1	169.94	0.00	0.0
	2	155.00	0.00	0.0
	3	106.83	0.00	0.0
Low	1	183.35	0.29	0.2
	2	150.97	0.00	0.0
	3	86.27	0.38	0.4

3.4.3 Method adjustments (Heated Filter)

A series of tests were undertaken using appliance B to assess changes to the heated filter test procedure and also more general test approaches as detailed below:

- Baseline measurements (filter at 70°C, tests start 3 minutes after refuelling and 30 minute test period)
- Increased filter temperature (filter at 160°C to match EN 13284-1; reference Standard for PM measurement)
- Starting measurement immediately after refuelling
- Extending 30 minute test period to cover full burn cycle
- Recovery of pre-filter deposits (acetone and water wash as used in EN13284-1)
- Short-term measurements to assess variation in PM over burn cycle

These measurements were undertaken at rated output with some additional measurements at low output to assess effects of filter temperature and pre-filter deposits. Note that PM emission results are provided as concentrations (mg/m^3 for a dry gas at 13% O_2 and STP - 0°C, 101.3kPa).

The PM emission concentrations determined for the method adjustments generally show less variability at high output than found for the baseline measurements which may indicate some benefit for repeatability in adopting one or more of the adjustments. The change in average concentrations at high output compared to the baseline are broadly consistent with expected changes:

- Slight reduction in average measured concentration at higher filter temperature – possibly due to non-collection of some PM at higher temperature.
- Increase in average measured particulate when including initial period after refuelling – the period immediately after refuelling includes poor combustion where increased PM emission concentrations would be expected.
- Reduction in average measured concentration when measurement period extended to collect PM at end of burn cycle – the PM emission concentrations are likely to be lower at the end of the burn cycle and inclusion of such periods be expected to decrease the average PM concentration compared to the baseline.

However, the measured average PM concentrations are all within the Standard Deviation of the baseline measurements and the measured concentrations at low output are inconsistent (Table 3-15).

Table 3-15 Results of method adjustments for Appliance B, mg/m^3 @ 13% O_2

Method		**DIN+ 70°C (baseline)**	**DIN+ 160°C**	**DIN+ 3 mins**	**DIN+ full cycle**
Output level	Statistic				
High	**Average**	**81**	**77**	**94**	**62**
	SD	38	20	28	16
	RSD	47%	26%	30%	26%
Low	**Average**	**36**	**105**		
	SD	14	55		
	RSD	39%	42%		

The contribution of the prefilter deposits to measured PM concentrations was variable (Table 3-16), the data suggest that at rated output, the potential average contribution of PM deposited upstream of the filter was significant at almost 20%. The proportion of deposited material was much lower at low output which is surprising.

Table 3-16 Recovery of prefilter deposits, mg/m^3 @ 13% O_2

Output	High		Low	
Sample system washings included?	NO	YES	NO	YES
Test 1	38	53	46	48
Test 2	91	107	34	35
Test 3	95	111	13	14
Test 4	49	66	38	39
Test 5	133	150	48	49
Average	81	97	36	37
SD	38	39	14	14
RSD (%)	47	40	39	38
Average pre-filter deposit, %	20		3	

A series of short-term heated filter measurements were undertaken to assess variation in PM emission during the burn cycle. Two separate measurements of ten minute duration each were carried out in each of six burn cycles. The measurement periods were arranged to provide coverage of the full burn cycle (approximately forty minutes)

The highest measured particulate concentration was found during the initial ten minutes of a burn cycle, this period also had the highest average particulate concentration of the burn cycle (Table 3-

17). The lowest particulate concentrations were found during the third interval (21-30 minutes into the burn cycle).

Measured particulate concentrations in the final interval sampled (31-40 minutes of the burn cycle) increased compared to the preceding interval. The particulate concentrations measured when carbon monoxide (CO) and hydrocarbon (THC) levels are elevated are higher than when these levels are low. However, even when CO / THC levels have dropped to a relatively low level the levels of particulate concentrations measured remained significant.

Table 3-17 Comparison of heated filter method applying multiple sample periods and a baseline measurements for Appliance B, High Output – Particulate concentrations, mg/m^3 at 13% O_2

Test	1	2	3	4	5	6	Average	DIN+ 70°C (Baseline)
0-10 mins	47		75		95		72	
11-20 mins		72		33		55	53	
21-30 mins	17		15		14		15	
31-40 mins		41		27		57	42	
Average							**46**	**81**
SD							26	38
RSD							57%	47%

3.5 PM and correlations with other parameters

3.5.1 ESP measurements

Correlations were examined by Lab 1 between PM (ESP) and parameters which indicate combustion efficiency (CO and hydrocarbons), NOx and optical density (OD). The results are summarised in Table 3-18.

None of the parameters give uniformly good correlations with the ESP measured smoke emission rates. There may be insufficient evidence to draw strong inferences from these results. Strong correlations were observed for individual combinations of appliance, output and parameters, however these were not achieved for other combinations. In some instances, strong correlations were found for a particular appliance and parameter at one output condition but weak correlation at the other output condition.

Table 3-18 Comparison of correlation coefficients (r^2) for linear regression between ESP smoke emission and other measured parameters

Appliance	Firing level	Smoke vs OD	Smoke vs CO	Smoke vs NOx	Smoke vs THC
A	High	0.86	0.00	nd	nd
A	Low	0.15	0.25	nd	nd
B	High	0.33	0.66	0.00	0.59
B	Low	0.91	0.90	0.93	0.88
C	High	0.79	0.01	nd	nd
C	Low	0.60	0.38	nd	nd
C_{EXTRA}	High	nd	Nd	0.00	0.83
C_{EXTRA}	Low	nd	Nd	0.54	0.14
D	High	0.94	0.65	nd	nd
D	Low	0.50	0.31	nd	nd
E	High	nd	0.00	nd	nd
E	Low	0.69	0.02	nd	nd

NOTE: nd – not determined during ESP tests. NOx and THC were measured only for a limited number of the tests where ESP measurements were made. For appliance C, additional tests (marked "C_{EXTRA}") were undertaken to provide data for assessing correlation with ESP data.

3.5.2 Comparison of heated filter, hydrocarbon and dilution tunnel data

Technical Committee 295 of CEN developed a proposed relationship for the draft appliance Standard prEN16510 to link PM determined by dilution tunnel, PM determined using the heated filter and, Organic Gaseous Carbon (OGC).

$$PM_{FFDT} = PM_{HF} + (OGC \times 0.42)$$

In the study reported here, measurements of OGC and particulate by dilution tunnel and heated filter were determined simultaneously on a series of tests on five roomheater appliances. The applicability of the proposed CEN model has been tested using the data collected.

The data were collected by Labs 1 and 2. All three measurements were carried out in parallel for each test on each appliance (that is each group of dilution tunnel, heated filter and hydrocarbon data were on the same burn cycle).

Error! Reference source not found. Figure 3-1 compares the predicted dilution tunnel PM concentration (calculated from the PM data obtained from a heated filter measurement and OGC data from a hydrocarbons measurement) and the measured PM from the dilution tunnel techniques for the roomheater appliances A to E. These data indicate some correlation with the CEN model and the measured dilution tunnel but measured dilution tunnel data were generally lower than predicted data and there are also large variations between appliance and operating outputs.

Figure 3-2 illustrates the relationship between the measured OGC and the difference between the measured dilution tunnel and measured heated filter PM measurements – notionally the condensable fraction of the PM emission. The proposed CEN model essentially assumes that the OGC measurement can be used as a surrogate for the condensable PM fraction. The apparent absence of any evidence of a relationship is interesting and may reflect incomplete understanding of PM formation and measurement processes for residential solid fuel roomheaters.

The findings from the current study indicated that the proposed CEN TC295 model is not valid when applied to measurements covering a range of appliances (the proposal was subsequently removed from the draft Standard). Moreover, development of a widely applicable model for relating particulate measurements using different methods would need a robust theoretical basis, validated using extensive measurements.

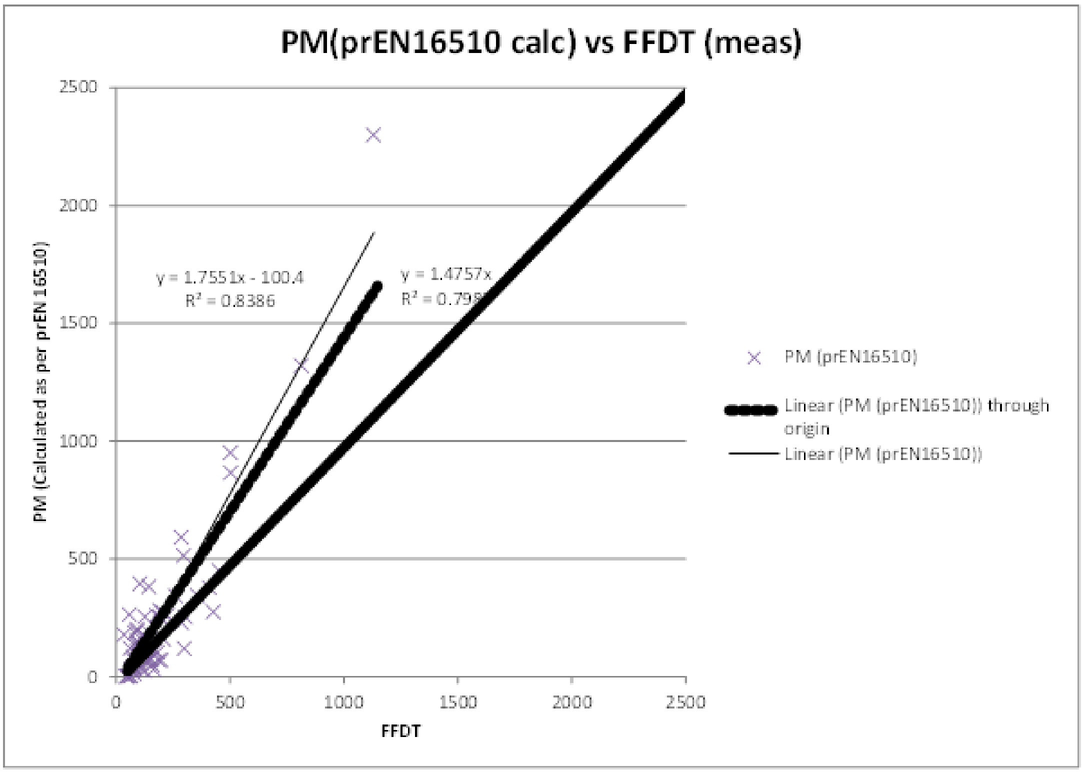

Figure 3-1 Comparison of PM calculated as per prEN16510 and PM measured by FFDT, Lab 1 appliances A to E, Lab 2 appliances B and C

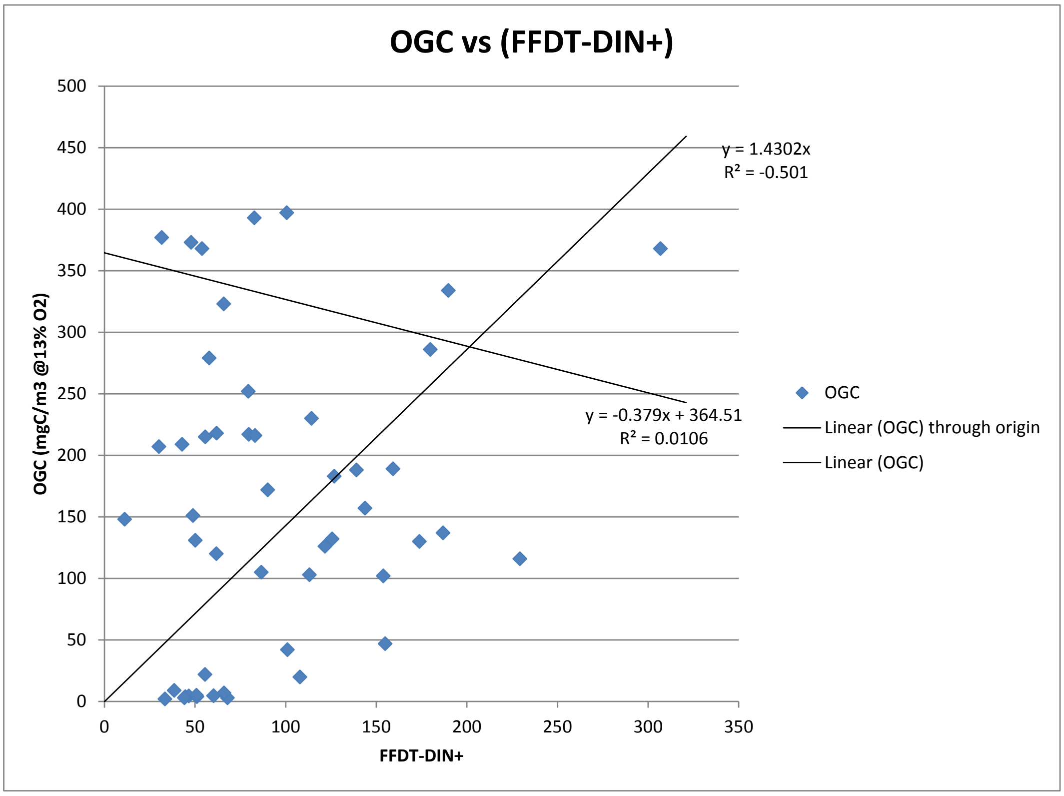

Figure 3-2 - Comparison of OGC and the difference between PM measured by dilution tunnel (FFDT) and heated filter (DIN+), Lab 1 appliances A to E and, Lab 2 appliances B and C

4 Conclusions and Recommendations

4.1 Variability of PM measurement results

There is evidence that repeatability of PM emission testing is better on automatic and semi-continuous automatic appliances than on batch-fed, manually-controlled natural draught log-burning roomheaters.

The measurement of PM emissions from log-burning roomheater appliances is much less consistent than measurement of burn rate, efficiency or heat output. Uncertainty of PM emission measurements can be significantly higher.

The study indicates variability in emissions over five repeat tests, variability between measurement campaigns and, differences between PM emissions determined by different laboratories.

Standard deviations of five consecutive PM emission tests were generally over 20% of the average value reported – taking the 95% confidence interval as double the standard deviation, this represents a very wide range for the 'true' appliance emission. This presents a substantial challenge to regulatory authorities trying to define appropriate emission limits and verification tolerances.

The variability in PM emissions is a challenge both for manufacturers, market surveillance and policymakers for air emission and air quality policy development. This study has found that PM measurement techniques can provide low variability on a 200 kW automatic pellet boiler operating continuously. However, repeatability of PM measurements on wood log roomheaters is poor.

The greater variability found in emission concentrations of particulate (and CO and VOC) than found for burn rate (and NOx) suggests that there may be inherent challenges in PM emission testing of wood log roomheaters. This may suggest a need to adopt a different roomheater operating profile for particulate than the approach used for output and efficiency.

4.2 Comparison of measurement techniques

The data reported here do not allow comparison between national test methods (which include a range of different test protocols) but there is some indication that the ESP and dilution tunnel techniques report broadly similar and higher values than the heated filter technique but even this is not without individual exception. There were several instances where the average ESP and dilution tunnel results differed by a relatively large margin.

Comparison of the dilution tunnel and heated filter PM measurements which were undertaken simultaneously on the same burn cycles indicates that the ratio between dilution tunnel and heated filter PM for the log appliances A to D (including tests at both Lab 1 and Lab 3) ranged from 0.4 to 21 with an average of about 5.

4.3 Inter-laboratory comparisons

The difference in average emissions determined by different laboratories using the same techniques can be substantial - even when the fuel was from the same batch, a technician provided guidance on appliance set-up and the PM sampling apparatus was identical, as in the heated filter tests at Labs 2 and 3. This may indicate that PM emissions from roomheater appliance are inherently variable and/or, the current measurement procedures do not ensure repeatable measurements at different laboratories.

CEN TC295 is working to develop a common test procedure for PM emissions but current proposals are on a heated filter technique and a dilution tunnel technique that are aligned with the appliance performance tests. A proposed longer term method is based on limited testing of a heated filter technique and OGC measurement but still to be aligned with EN appliance performance tests.

4.4 Recommendations

Appliance emission testing

- There is a need for further research and understanding of particulate emissions from biomass appliances and, in particular, the features of automatic and non-automatic appliances that influence particulate emissions.
- Measurement of appliance performance parameters for wood log roomheaters show less variability – this may suggest that a separate test protocol is needed for PM emissions than is applied for energy performance which is contrary to the current CEN TC295 proposals.
- The implications for air quality of replacing national test methods with a single test method designed to demonstrate compliance with Ecodesign (or similar) type approval needs to be understood. It may be beneficial (for air quality) to encourage the Standardisation body and the European Commission to consider a test protocol and Ecodesign requirements that are more aligned with real-life operation of appliances.
- The variability in particulate emissions from wood log roomheaters may be improved by addressing weaknesses in current methodologies. There is scope for more consistency in the particulate measurement approaches to define more clearly the measurement techniques and the test protocols. This should allow lower variability and improved repeatability between laboratories. For example :
    - Clearer requirements on measurement equipment, fuel and test protocols;
    - There is evidence that the highest particulate emission concentrations occur during the initial period after refuel;
    - For the heated filter method (and by implication the dilution tunnel method) there is potential for significant deposition of particulate material upstream of the filter;
    - Consider whether additional repeat tests may reduce uncertainty;
    - Consider whether adopting a measurement protocol that assesses PM emissions across multiple burn cycles may reduce uncertainty.

UK emission inventory

- The UK emission inventory should consider the implications of the variability in PM emission measurements for residential wood combustion for uncertainty of emissions from this sector.
- The basis of the EMEP/EEA Guidebook emission factors for wood log roomheaters (as used in the UK emission inventory) need to be reviewed to assess whether they are based on type approval or real-life operation of appliances.
- Future measurement programmes for emission inventory development for residential wood combustion need to consider the variability in measured emissions carefully when developing a testing protocol for laboratory measurements.
- In the longer-term, alternative emission determination approaches such as in-situ measurements, air quality measurements or source apportionment may provide alternative means to validate or develop emission estimates.

Appendices

Appendix 1: Appliances

Appendix 2: Measurement programme

Appendix 3: Test report 1 – ESP measurements

Appendix 4: Test report 2 – Comparative trials and inter-laboratory comparison

Appendix 5: Test report 3 – Method adjustments

Appendix 1 – Appliances

Table A1-1 summarises the appliances tested in the study.

Table A1-1 – Appliances tested

Appliance	A	B	C	D	E	F
Type	Roomheater	Insert Roomheater	Roomheater	Roomheater boiler	Pellet stove boiler	Boiler
EN Standard	13240	13229	13240	13240	14785	303-5
Output, kW	4.5	8	6	16	15	195
Fuel	logs	logs	logs	logs	pellet	pellet
UK Clean Air Act Exempt? Note 1	no*	yes	yes	no	no	not yet tested
BImSchV 2? note 2	no	no	yes	no	yes	no
RHI Certificate? Note 3	na	na	Na	no	yes	not yet tested
MCS Compliant? Note 4	na	na	Na	no	yes	na
Nordic Swan Ecolabel? Note 5	yes	no	No	no	no	no
Likely to burn clean / dirty?	Clean	Clean	Clean	Dirty	Clean	Clean

Notes:

1) Meeting the requirements for use in smoke control areas in the UK under the Clean Air Act 1993, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/497436/Application_Pack_Ricardo_EE_Issue_v4_Final.pdf
2) Meeting the requirements of legislation in Germany – the First Regulation implementing the Federal Pollution Control Act (Ordinance on small and medium-sized combustion plants - 1. BImSchV) – stage 2 requirement for new wood log stoves https://www.gesetze-im-internet.de/bundesrecht/bimschv_1_2010/gesamt.pdf (in German)
3) Meeting the emission requirements for PM and NOx of the UK Renewable Heating Incentive; https://www.ofgem.gov.uk/key-term-explained/emission-certificate-rhi
4) Microgeneration scheme – equipment approval and installation certification scheme for residential renewable technologies including biomass boilers (no emission criteria).
5) Nordic Swan Ecolabel – assessed as compliant with the Nordic Swan Ecolabel for stoves which includes PM emission criteria http://www.nordic-ecolabel.org/Templates/Pages/CriteriaPages/CriteriaGetFile.aspx?fileID=1423

* This appliance is a variant of a UK Clean Air Act exempt appliance
na not applicable

Appendix 2 – Measurement programme

The following tables summarise the measurement programme, the following abbreviations are used for the PM test methods :

- **HF – PM by heated filter**
- **FFDT – PM by dilution tunnel**
- **ESP – PM by Electrostatic Precipitator**

Table A2-1 - Test Matrix for Inter-method comparison tests

Laboratory	Appliance	Output	Method	Tests
LAB 2	B	High	HF	5
			FFDT	5
		Low	HF	5
			FFDT	5
	C	High	HF	5
			FFDT	5
		Low	HF	5
			FFDT	5
LAB 3	B	High	HF	5
		Low	HF	5
	C	High	HF	5
		Low	HF	5
LAB 1	A	High	HF	5
			FFDT	5
			ESP	5
		Low	HF	5
			FFDT	5
			ESP	5
	B	High	HF	5
			FFDT	5
			ESP	5
		Low	HF	5
			FFDT	5
			ESP	5
	C	High	HF	5
			FFDT	5
			ESP	5
		Low	HF	5
			FFDT	5
			ESP	5
	CEXTRA	High	ESP	5
		Low	ESP	5
	D	High	HF	5
			FFDT	5
			ESP	5
		Low	HF	5
			FFDT	5
			ESP	5
	E	High	HF	5
			FFDT	5
			ESP	5
		Low	HF	5
			FFDT	5
			ESP	5
	F	High	HF	5
			ESP	5
		Low	HF	5
			ESP	5

Table A2-2 - Test Matrix for Inter-laboratory comparison tests

Method	Appliance	Output	Laboratory	Tests
HF	B	High	LAB 3	5
			LAB 1	5
			LAB 2	5
		Low	LAB 3	5
			LAB 1	5
			LAB 2	5
	C	High	LAB 3	5
			LAB 1	5
			LAB 2	5
		Low	LAB 3	5
			LAB 1	5
			LAB 2	5
FFDT	B	High	LAB 3	5
			LAB 1	5
		Low	LAB 3	5
			LAB 1	5
	C	High	LAB 3	5
			LAB 1	5
		Low	LAB 3	5
			LAB 1	5

Table A2-3 - Test Matrix for method adjustment comparison tests carried out at Lab1 on Appliance B

Output	Method	Tests	Comment
High	HF 70°C	5	Baseline HF test.
	HF 160°C	5	Filter temperature raised to match EN13284-1 (reference Standard for PM measurement).
	HF +3min	5	Starting measurement when door closed after refuelling – HF starts 3 minutes after refuelling.
	HF full	5	Extending test period from 30 minutes to cover full (EN) burn cycle.
	HF prefilt	3	Recovery of prefilter deposits (acetone and water rinse) to match EN 13284-1.
	HF 10min	3 X 4	Short-term measurements to assess variability in PM emission over a burn cycle.
Low	HF 70°C	5	Applying HF test to a low output.
	HF 160°C	5	Filter temperature raised to match EN13284-1.
	HF prefilt	3	Recovery of prefilter deposits (acetone and water rinse) to match EN 13284-1.

Appendix 3 – Test report 1 (ESP measurements)

Assessment of particulate and NO_x emissions from a range of log and pellet appliances and boilers by a range of measurement techniques

Report on particulate emissions measurements using the ESP method

Prepared by: Kiwa GASTEC
Prepared for: Ricardo AEA for Defra
Report Number: 60097-2
Date: October 2016

Defra
60097-2

Assessment of particulate and NO_x emissions from a range of log and pellet appliances and boilers by a range of measurement techniques

Report on particulate emissions measurements using the ESP method

Prepared by

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Commercial in Confidence

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Table of Contents

1 Introduction

Particulate air pollution has been a recognised problem in urban centres and many of the countries in the EU have passed a wide variety of local legislation including controls on solid fuel heating appliances. This has resulted in a number of different approaches to measuring particulate emissions from such appliances, both qualitative and quantitative. Unfortunately, these approaches can report very different values. This is further complicated as the different methods traditionally report results in different units.

Such differences were not of great consequence when local legislation was written around the local measurement technique, but with the advent of the single market and the rise in interest in biomass, the situation is now changing. There is considerable evidence to indicate that different measurement techniques can collect and report widely varying quantities of particulate matter and NO_x.

There are two aspects to the smoke testing of biomass fired appliances which affect the individual results obtained:

- Smoke source characteristics and operation
- Smoke measurement method and execution

The factors affecting the smoke produced include:

- Fuel type
- Fuel condition and composition
- Characteristics of the combustion chamber (including the arrangements for air inlet, fuel bed and flue gas exhausting)
- Repeatability of control settings
- Operator practices

The factors affecting the measurement method include:

- Inherent characteristics of the method (flue gas sampling, particulate collection technique, measurements of temperatures, flows etc.)
- Operator practices

This work programme carried out a series of comparative and round-robin tests to investigate this issue to provide Defra with robust evidence to inform the choice of measurement technique to demonstrate compliance with emission limits.

The test matrix defined included measurements of particulates by three methods, total hydrocarbon (THC) and NO_x measurements from representative biomass appliances.

The smoke measurement methods used were the Electrostatic Precipitator (ESP), Full Flow Dilution Tunnel (FFDT) and the heated filter (‘DIN+’).

This report shows the results of tests carried out at Kiwa Gastec Laboratories near Cheltenham, UK using the ESP particulate emission measurement method on several wood-burning appliances at full and at reduced output.

2 Description of Appliances

Table 1 presents a summary of the characteristics of the appliances used for this study.

Table 1 Comparison of Appliance Features

Appliance	A	B	C	D	E	F
Type	Room-heater	Insert Room-heater	Room-heater	Room-heater boiler	Room-heater boiler	Boiler
Output, kW	4.5	8	6	16	15	200
Fuel	logs	logs	logs	logs	pellet	pellet
UK Clean Air Act Exempt?	no*	yes	yes	no	no	not yet tested**
BImSchV 2?	no	no	yes	no	yes	no
RHI Certificate?	na	na	na	no	yes	not yet tested**
MCS Compliant?	na	na	na	no	yes	na
Nordic Swan Ecolabel?	yes	no	no	no	no	no
Likely to burn clean / dirty?	Clean	Clean	Clean	Dirty	Clean	Clean

NOTES:
* This appliance is a variant of an appliance which is UK Clean Air Act exempt, and is likely to be clean burning
** These tests are likely to result in Clean Air Act exemption and RHI approval
na not applicable

3 Background on solid fuel combustion and emission measurement

Historically numerous studies of combustion processes in solid fuel appliances have been undertaken including development and verification of smoke emission measurements. For example, the Coal Research Establishment investigated the application of the ESP and Full Flow Dilution Tunnel methods for measurement of smoke emission rates from open fires burning manufactured solid fuels, which concluded that a good agreement between the methods in this application[i].

Current measurement techniques and methods are largely based on the information collected in such studies. However, these studies mainly focussed on fossil solid fuels or their derivatives (peat, lignite, and bituminous through to anthracitic coals and cokes).

3.1 Effects of fuel properties on smoke emission

Commercially-available fossil solid fuels, though heterogeneous in comparison to gaseous and liquid fuels are nonetheless, much more homogeneous and stable than biomass fuels.

Further their compositions and physical and chemical structures differ significantly from fresh biomass materials.

In a previous study of particulate emissions, sponsored by HETAS, determinations were made using the ESP method. 17 coal-fired and five wood-fired appliances were tested at high and low output levels. The results are summarised in Appendix 1, Table A1.1. They show, on average, lower levels of precision in the results for the wood fired appliances than for the coal fired appliances. However, there is wide variation between individual appliances with some wood-fired appliances showing lower variability than the average for the coal-fired appliances and similarly, individual coal-fired appliances show relatively high variability.

To some extent the consistency of the properties of biomass fuels can be improved through preparation processes, in particular comminution followed by reconstitution into briquettes or pellets. Where the 'raw' biomass is used as wood logs some improvement in consistency can be achieved by controlled sizing, removal of bark and selection of knot-free logs which are then stabilised under standard conditions. This helps to improve repeatability of combustion but does not represent the actual practices of end users.

The compositional differences between wood and solid fossil fuels result in different behaviours during combustion and hence to differences in amounts and types of products released.

The features of the combustion process can be summarised as:

1. Drying – as material is heated for ignition, free moisture evaporates
2. Pyrolysis – the chemical structure starts to break down in the presence of a limited oxygen availability. Initially smaller chemical groups (methyl, ethyl etc.) cleave from the structure. As the temperature rises larger groups are freed including longer chain and ring hydrocarbons and related species.
3. Volatile Combustion – as the gas and vapour species reach more oxygen rich environments they burn to a degree which depends on how much oxygen is available and temperature.
4. Char Combustion – the structure left once volatile matter has been released is a combination of a carbonaceous skeleton char and mineral ash. Once the temperature is high enough and oxygen is available the char burns to CO_2 or if the oxygen level is deficient to CO.

Potential sources of smoke include:

- Partially burned pyrolysis product – fine char particles
- Ash particles
- Incompletely burned char particles

- Pyrolysis products condensed on the surfaces of other solid particles

Annex B of EN 13240[ii] summarises the ranges of compositions for coals, cokes, peat and woods. Coals have low to moderate volatile matter (VM) contents from about 2 to 30% but low smoke coals are at the lower end of the range. Woods have high VM contents of 80% or more and yet are still able to be burned in a manner that produces low levels of smoke emission.

The explanation for this apparent contradiction lies in differences in the range of compound types released in each case. Fossil solid fuels tend towards release of higher molecular weight (MW) compounds including aromatics. Woods tend towards lower MW hydrocarbon species. Due to the high oxygen content of wood fuels they also produce light alcohols, aldehydes, acids etc. Overall a significant amount of the VM from wood is likely to be relatively volatile and less likely to condense.

Predicting the development of fume or droplets formation from condensation of unburned volatile matter onto particles in a flue gas stream is difficult. Knowledge at least, of the concentrations of the species present is required, so that the amount of condensable material present can be estimated. However, the conditions, species and concentrations change continuously during combustion and particularly for batch firing processes such as in log burning stoves.

Hydrocarbon emission analysers are used to measure ‘hydrocarbons’. However, the measurements are based on the detection of the carbon atoms present in the sample. They do not provide structural information and the concentration results they provide are referenced to the hydrocarbon species used to calibrate the analyser. Some measurement procedures use methane, CH_4. Other procedures use propane (C_3H_8 or 3 C atoms) as the reference hydrocarbon and report 1/3 the concentration indicated if methane is used. In fact, a range of species will be present with a range of numbers of C atoms. Many of these will also contain other atoms such as oxygen and nitrogen which can affect the response of the hydrocarbon analyser.

Hydrocarbon analyser measurements give no indication of the range and mass distribution of the species present. Similar numerical results could be obtained for a large amount of small hydrocarbons or oxy-hydrocarbons (such as CH_4, C_2H_6, H_2CO etc) or a small amount higher molecular weight species (such as benzene, phenol, pyridine, polycyclic aromatics etc) but only the latter would contribute significantly to smoke formation.

Ash from fuel contributes to the amount of smoke generated. For coals for small scale combustion the ash contents are typically in the 5 to 15% range whereas average ash contents for woods are less than 2%. However, ash in wood tends to be concentrated under the bark so logs with bark are likely to have significantly more ash. Wood ash is typically low density compared with coal and so under similar flue gas flow conditions is more likely to be entrained and carried up the flue. Ash particles provide nucleation centres for the condensation of volatile matter from the flue gases and play a key role in smoke development.

It is noted that for log-fired roomheaters visible luminous flames are considered a selling feature. However, as flame luminosity is caused by incandescing carbon particles it is at the same time an indication of potentially incomplete combustion. So, unless the appliance design guarantees effective burnout this characteristic will contribute to smoke formation as these carbon particles act as nucleation centres for condensation of volatile matter from the flue gases, similarly to ash particles as mentioned above. In contrast some pellet-fired appliances highlight the almost invisible flame achieved.

It is also noted that historically the emissions from fuel beds consisting of large numbers of small particles (e.g. small coal or pellets) are more consistent with time and more reproducible than those consisting of only two to four lumps (e.g. logs). This can be rationalised in that the large lumps are more likely to be affected by the way they fall onto the fire bed, thus affecting speed of ignition, likelihood of volatiles to be sheltered from thermal radiation etc. Thus pellet appliances are more likely to give consistent and reproducible emissions than batch fed log appliances.

The amount of smoke emitted depends on numerous factors. The air flow through an appliance is crucial but the effects are complex. Reducing the amount of air supply tends to decrease combustion performance and so increase particle formation through some routes. On the other hand the same action reduces velocities through combustion chambers and this tends to reduce particle carry over rates.

3.2 Optical density of flue gas

The gaseous and vapour species in flue gas have little effect on its transparency to visible light. The presence of translucent and opaque particles in flue gas reduces its ability to transmit light. Optical smoke meters use this to provide a continuous indication of the particulate concentrations in flue gas. This enables a profile of particulate emission throughout the burn cycle to be generated.

The measurement technique is discussed in Appendix 4.

3.3 NOx emissions

NOx formation in combustion systems is complex. A range of contributing mechanisms have been identified[lll]:

1. Fuel NOx - nitrogen in the fuel is converted to NOx during the combustion process
2. Thermal NOx - direct combination of oxygen and nitrogen in the combustion air and becomes significant above about 1,300°C

3. Prompt NO – indirect route where air nitrogen first combines with fuel and then behaves as fuel nitrogen

Temperature and nitrogen and oxygen availability are the main controlling factors. Based on the data in the ECN Phyllis 2 database[IV] coals contain up to about 3% nitrogen. The average is about 1.5% which is close to the British Coal figure of 1.6% for bituminous coal for domestic fuel[V]. According to Phyllis 2, woods contain up to about 3%, though the average is much lower at around 0.3%.

Some of the factors that affect smoke formation also influence NOx formation. However, the complexity of the overall NOx formation process makes it difficult to predict without detailed knowledge of the conditions in the combustion chamber.

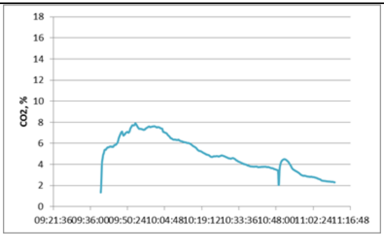
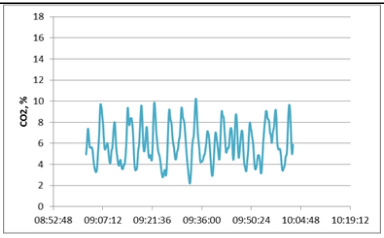
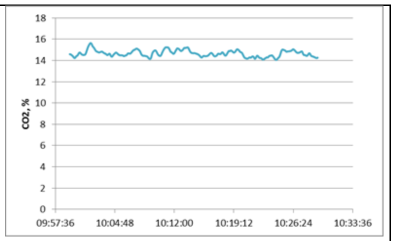
3.4 CO emission

CO is the result of incomplete combustion of carbon containing species. Various factors affect the level formed but in a combustion system, oxygen availability is very important. When insufficient oxygen is available for all the carbon present to be fully oxidised some will form CO and some will remain unoxidised. The amounts will depend on the specific local oxygen concentrations and temperatures. The observed behaviour is that there is a non-linear relationship between oxygen concentration and CO concentration. A wide range of oxygen concentrations produce similar low CO levels. However, below a critical oxygen level (generally termed the CO break-point) the CO level increases very greatly with only a small decrease in the oxygen available.

3.5 CO_2 Emission

Almost all the carbon in combustion systems is oxidised to form CO_2. Levels of CO and THC which are considered high in terms of emissions, usually account for a small fraction of the carbon. In intermittently-fuelled systems the CO_2 level reaches a peak as combustion of the fresh fuel is established and gradually declines as the fuel is consumed. This is clearly apparent in flue gas measurements for log fired appliances over a long period (of the order of hours) and low firing rate pellet appliances though over much shorter time periods (of the order of minutes). Where fuelling is continuous, as in Appliance F used in this project, the CO_2 level only fluctuates a little. The examples in Table 2 below, illustrate these behaviour types.

Table 2 Examples of CO_2 emission concentration profile from different types of appliance

		
Appliance D, High Output, Test 1 Log roomheater / boiler	Appliance E, Low Output, Test 1 Small pellet boiler	Appliance F, High Output, Test 1 Large pellet boiler

4 Test Work

4.1 Test Matrix – ESP method

Table 1Table 3 below summarises the firing levels at which each appliance was operated and the number of replicate measurements carried out in each case. It also shows which parameters were measured for each group of replicate tests.

Table 3 Test Matrix for Kiwa ESP Determinations

Appliance	Method	Firing Rate	Replicates	Measured parameters				
				Smoke	Optical density	CO	NOx*	THC*
A	ESP	Maximum	5	YES	YES	YES	NO	NO
		Minimum	5	YES	YES	YES	NO	NO
B	ESP	Maximum	5	YES	YES	YES	YES	YES
		Minimum	5	YES	YES	YES	YES	YES
	ESP + Filter**	Maximum	4	YES	NO	YES	YES	YES
		Minimum	4	YES	NO	YES	YES	YES
C	ESP	Maximum	5	YES	YES	YES	NO	NO
		Minimum	5	YES	YES	YES	NO	NO
	ESP Extra	Maximum	5	YES	NO	YES	YES	YES
		Minimum	5	YES	NO	YES	YES	YES
D	ESP	Maximum	5	YES	YES	YES	NO	NO
		Minimum	5	YES	YES	YES	NO	NO
E	ESP	Nominal	5	YES	YES	YES	NO	NO
		Low	5	YES	NO	YES	NO	NO
F	ESP	Nominal	5	YES	NO	YES	YES	YES
		Low	5	YES	NO	YES	YES	YES

NOTES:
* The test plan included a full suite of NOx and THC measurements for each condition for each appliance. These were made during the tests where DIN+ and FFDT measurements were made. A limited set collected on the tests where ESP measurements were undertaken to check the validity of the assumption that conditions

during tests on the same appliance with the same fuel would be comparable.
** ESP slippage test.

4.2 Test Equipment

For the smoke emission measurement work the appliances were installed with their flues connected to a brick chimney fitted with an electrostatic precipitator housing. The Kiwa method statement is reproduced in Appendix 2.

Smoke emissions were measured using the ESP equipment described in BS 3841: Part 2:1994[VI].

Optical density measurements were made using the British Coal Corporation, Coal Research Establishment (BCC, CRE) Optical Smoke Meter System. The characteristics of this instrument are described in Appendix 2.

4.3 Test Fuel

The test fuel used for the log boiler and stoves (appliances A, B, C, and D) was test wood logs conforming to the specification given in BS EN 13240:2001[II] for thermal performance testwork on roomheaters burning wood logs.

The Kiwa log selection method statement is reproduced in Appendix 2. In addition, for this work, efforts were made to select similar logs for each test within the constraints of a batch of commercial logs. The logs used were all of a similar length as supplied.

The analyses of the fuels used in the test programme are given in Table 4, below. The initial test programme used logs from the 1st batch. Additional tests carried out after the main programme had been completed used logs from the 2nd batch.

For the two pellet boilers (appliances E and F), the fuel was 6mm diameter wood pellets conforming to BS EN 14961 part 2[VII] (analysis provided at **Table 4**).

Table 4 Test fuel analyses

Parameter	Units	Wood Logs 1st batch		Wood Logs 2nd batch		Wood pellets	
		ar	db	ar	db	ar	db
Total moisture	%	32.4	-	23.6	-	-	-
Free moisture	%	4.51 (aa)	-	16.1	-	7.4	-
Ash content	%	0.1	0.2	0.4	0.5	0.4	0.4
Volatile matter	%	57.6	85.2	nd	nd	75.2	81.2
Fixed Carbon	%	9.9	14.6	nd	nd	nd	nd
Total Sulphur	%	<0.01	<0.01	0.01	0.01	0.02	0.03
Carbon	%	45.2	66.9	38.6	50.5	46.4	50
Hydrogen	%	6.06	8.96	4.62	6.05	5.62	5.62
Nitrogen	%	3.80	5.62	0.12	0.16	0.06	0.06
Oxygen by difference	%	12.4	18.3	32.7	42.8	40.1	43.51
Gross Calorific Value	MJ/kg	13.079	19.347	14.845	19.431	18.747	20.231
Net Calorific Value	MJ/kg	10.989	16.497	13.263	18.113	17.347	17.347

Notes:
ar as received
aa as analysed
db dry basis
nd not determined

4.4 Test Procedures

4.4.1 Log fired appliances

Particulate matter emissions from the appliances were measured using the ESP for two conditions, High Output and Low Output. For the log-fired appliances these outputs were attained through adjusting the air control settings

For High Output the primary and secondary air settings were those used for the nominal output tests. For Low Output a low setting for the secondary air that maintained clean combustion was determined and then used. The low setting used was not the minimum setting for the secondary air control.

The mass of fuel used as the refuel charge for each test was according to the appliance capacity and ranged from about 1kg (Appliance A) to about 5kg (Appliance D). The standard method was to use four evenly sized logs, three laid side-by-side on the fuel bed and the fourth rested diagonally on top. However, the number and arrangement used was adapted to meet the manufacturers' guidance for each appliance. The information provided in the appliance manuals is summarised in Table 5 below.

Table 5 Appliance fuel specifications

Appliance	Manufacturer specified wood length, cm	Manufacturer specified wood diameter, cm	Standard fuelling	Maximum firing rate, kg/h
A	25-30	7-9	2-3 logs of up to 1kg each	2.0
B	Up to 45	Not specified	Open stacking	2.6
C	Up to 35	Not specified	Not specified	Not specified
D	So as not to overhang grate bars	Not specified	Not specified	Not specified

For the tests on these appliances the refuelling procedure adopted was to allow the newly charged fuel to burn with the primary and secondary air controls set at maximum for a maximum period of 2 minutes. After this period, with flames from the logs fully established, the primary air and secondary air supplies were adjusted to provide the required operating level i.e. High Output or Low Output. The possibility of setting the air flow in an accurately repeatable way depended on the appliance controls[1].

Following this ignition period a pre-test period was used to establish a suitable firebed. For Appliance D difficulty was experienced in producing repeatable fire beds after each refuelling.

The test durations were not predefined. The fire was allowed to burn back to the initial level of embers established at the start of the test.

Approximately five minutes before the end of the pre-test period a weighed, clean and conditioned precipitator was placed in position on the chimney. Immediately after the refuel charge was added and the firedoor closed the power supply to the precipitator was turned on and maintained throughout the test. At the end of the test the precipitator was removed from the chimney and placed in the conditioning room overnight before being re-weighed to determine its increase in mass.

Close attention was paid to the manufacturer's recommended operating procedures with regard to use of the appliances.

The appliance operation method for the replicate tests was in as far as possible identical for each. However, this could not control all the factors which may affect particle emission. For example the presence of knots, or the presence/thickness of bark will affect this, although

[1] Operators noted that log appliances can have several independent controls for air. So the operator has considerable flexibility with a large number of air setting combinations possible.

efforts were made to minimise such effects during this work by log selection the progression of combustion will vary with every log. Individual log characteristics determine when events occur which are likely to cause short term fluctuations in particle pick up in the flue gas (such as the collapse of the partially burned logs). The split surface of logs inevitably varies and the way the logs lie can produce areas where one log shades another from the effect of full radiation. This will affect the way that volatiles are generated and ignited.

4.4.2 Pellet fired appliances

Pellet-fired appliances can operate continuously and the output level is automatically controlled at the level set in the control system by the operator. Tests were carried out at High (in these cases the nominal appliance rating) and Low (or reduced) output conditions.

4.4.3 Particulate measurements

The particulate matter emission in all tests was measured using the ESP method described in BS 3841[VI]. The precipitators were conditioned using the hot room method. The Kiwa method summary is reproduced in Appendix 2.

In addition to the measurement by the ESP method determination of particulate matter emission, the optical density of the smoke emission was also measured using the BCC, CRE Optical Smoke Meter System (see Appendix 2). PD6434[VIII] requires that “in addition to the average rate of smoke emission being within acceptable limits, the emission over short periods, for example at the times of refuelling or de-ashing, does not reach objectionably high levels.” Although no definition of how this requirement is to be met appears in BS PD6434 or regulations it has, in the past, generally been interpreted as not exceeding optical density of 0.2 for more than 6 minutes.

For each test or test period the total mass of particulate collected by the ESP was determined. Average emission rates from the test periods were calculated.

Optical smoke measurements were collected during the ESP collection periods in most cases. From these data plots of optical density of the flue gas with time were produced

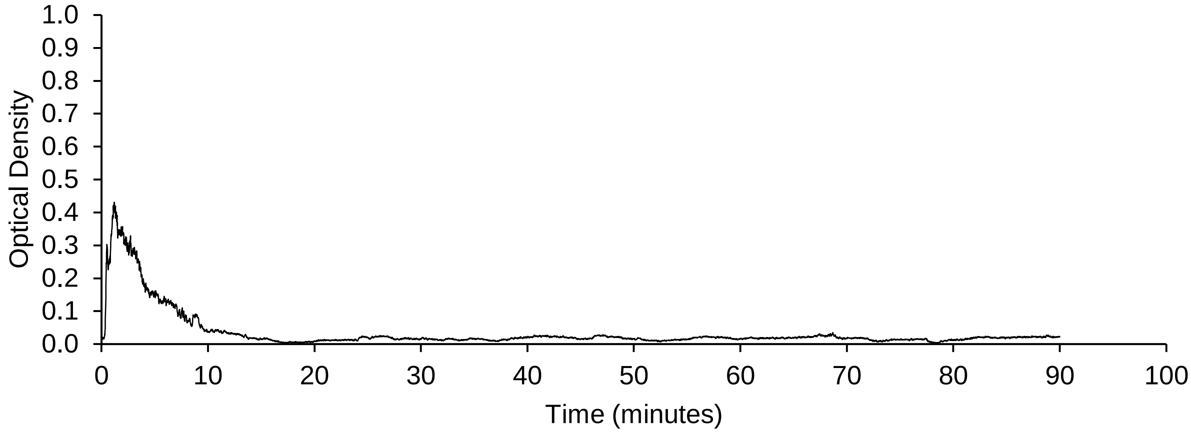


Figure 1 Optical density plot from High Output Test 1, Appliance D (log stove)

Examples for a log and a pellet fired appliance are presented in Figure 1 and Figure 2 respectively.

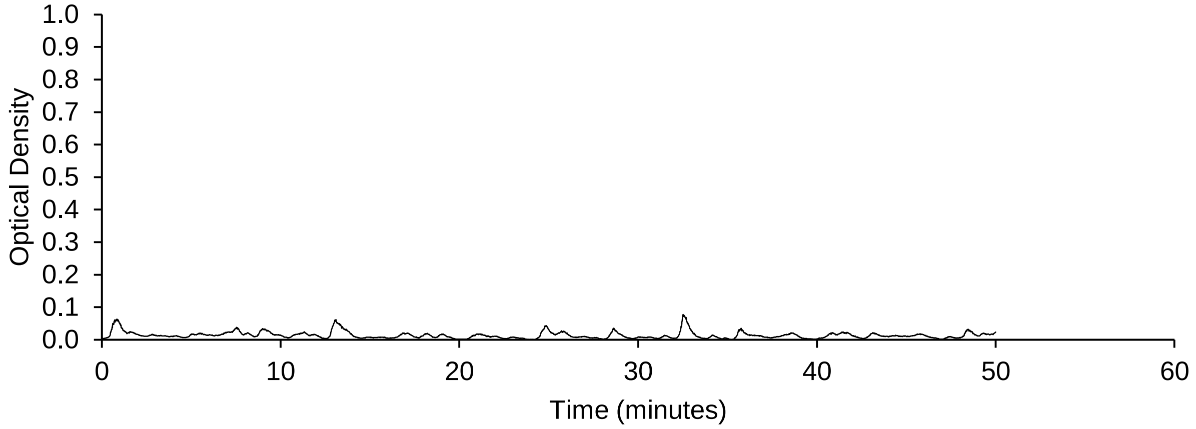


Figure 2 Optical density plot from Low Output Test 1, Appliance E (pellet stove)

The initial peak in smoke emission at the start of a firing period for log fired Appliance D is clearly visible in Figure 1. Such disturbances are not evident in the plot for the pellet fired Appliance E in Figure 2

5 Results and Discussion

5.1 Test results

The detailed results for each of the smoke emission tests listed in the test matrix in Table 3 above are shown in Appendix 3, Tables A3.2 to A3.6.

CO_2/O_2 and hydrocarbon, CO, NOx emission measurements were carried out at the same time as the smoke emission tests and these results are also shown in Appendix 3.

5.2 ESP slippage measurements

ESP technology in general is used widely for flue gas cleaning where high levels of particle capture are achieved. However, particle properties and in particular resistivity affects their response to the electric field in these devices determining whether they will be captured. ESPs only collect solid and condensed material.

As smoke measurement devices ESP collectors receive the full flow of flue gas from an appliance. Material in the flue gas such as vapours and gases and particles with low resistivity could pass through the collector.

To investigate the effectiveness of the collection by the ESP, slippage tests were undertaken.

The ESP sampling was carried out in the usual way. Downstream of the ESP a heated filter (DIN+) sampling arrangement and procedure was used to determine levels of residual particulate matter in the flue gas. The results of these measurements are given in Table 6 below.

Table 6 ESP sample slippage results

Output	Test	ESP smoke	ESP slippage by DIN+
		g/GJ net	g/GJ net
High	1	169.94	0.00
	2	155.00	0.00
	3	106.83	0.00
	Average	**143.92**	**0.00**
Low	1	183.35	0.29
	2	150.97	0.00
	3	86.27	0.38
	Average	**140.19**	**0.23**

These results suggest that slippage is insignificant. However, particulates are expected to develop continually as the flue gas passes along the flue and cools. So downstream of the

ESP the absence of particles to act as nucleation points for condensation, may have prevented further condensation of organic vapours. This could otherwise have occurred on particles as the temperature of the flue gas downstream of the ESP continued to fall.

5.3 Average emissions of smoke and gaseous pollutants

The results are summarised in Table 7 and Figure 3 below.

Table 7 Average Particulate (Smoke) Emissions measured by the ESP method

	Particulate Emission, g/GJ net						
Appliance	A	B	C	CEXTRA	D	E	F
High Output	86	127	115	124	96	32	19
Low Output	78	103	105	80	141	50	15

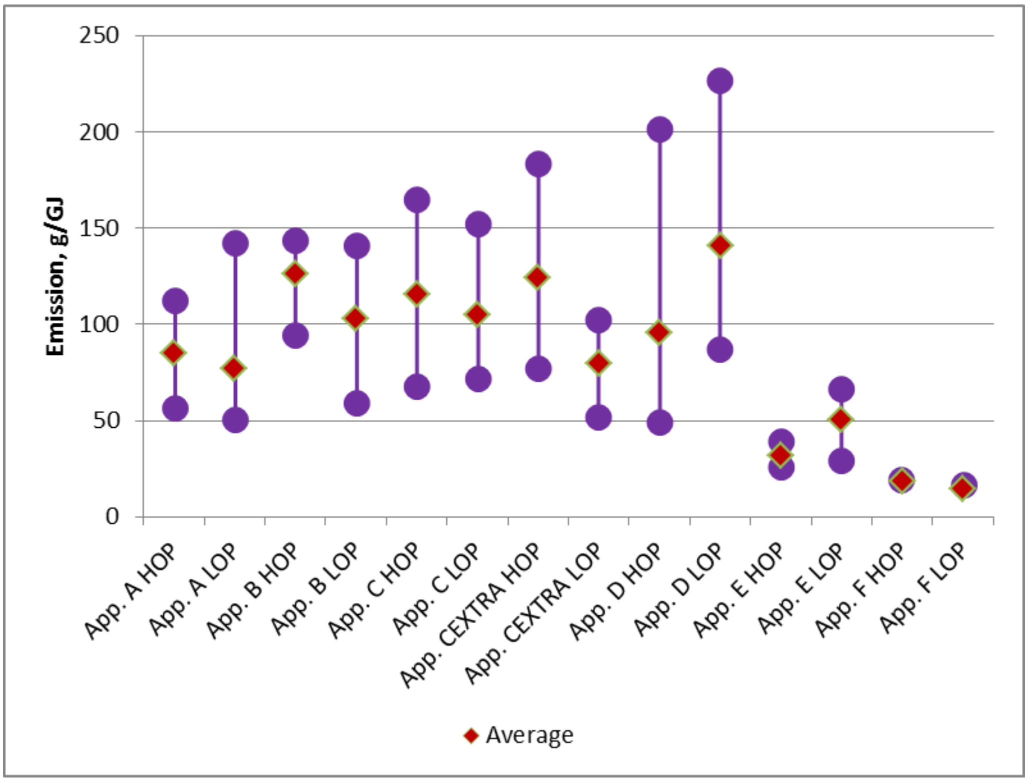


Figure 3 Average Particulate (Smoke) Emissions

The average smoke emissions results show that the difference between emission rates at High Output and Low Output is not very large, but in some cases the emission is greater at Low Output whilst in others it is greater at High Output.

Specific observations:

- The Appliance D shows the greatest ranges of emission levels under both conditions indicating that its operating behaviour is the least repeatable. This roomheater boiler appliance has a water cooled heat transfer surface in the combustion chamber which may have contributed to its unpredictability. This is a commonly observed phenomenon.

- The two sets of tests undertaken on Appliance C on different dates several weeks apart illustrate the difficulty in gaining reproducible results.

- The ranges give an impression of the variability in the emissions levels and are in line with the expectation that pellet fired appliances (Appliance E and Appliance F) would have relatively low and repeatable emission levels compared to the log fuelled appliances. This was broadly confirmed in the testwork but low output emission tests for the pellet stove (appliance E) were more variable than at nominal output and for the pellet boiler. Pellets are introduced to the combustion chamber in a (semi) continuous fuel feed whereas log fuelling is a batch process. Continuous fuel feed avoids such effects as sudden temperature changes during fuelling and large variations in air flow through the combustion zone. Whereas air flows to the log fired appliances were disrupted every time they were refuelled and conditions vary throughout each burn cycle.

5.4 Variability of particulate emission rates between replicate tests

The relative standard deviation (RSD) is a measure of the precision of multiple determinations of a parameter. It is the ratio of the standard deviation (SD) to the average (sample mean) value for the parameter. The lower the value of the RSD the greater is the precision of the determinations. For this investigation it has been used as an indicator of the repeatability of results from multiple determinations of particle loading. In the context of this work the level of precision indicated includes the entire system of appliance operation and particulate measurement[2].

Repeatability of operating conditions for manual feed log fired appliances is inherently lower than for automatically fed pellet fired appliances. This is because control of the fuel and air supplies to pellet fired appliances is much more consistent during operation and the high quality of modern automatic control systems mean that the same settings can easily be applied in separate periods of operation. Also pellet fuels are more homogenous than logs, even when care is taken in their selection and preparation. Finally, stability of appliance operation generally improves with increasing ‘fuel bed size’ to ‘fuel piece size’ ratio.

---

[2] Care is needed in interpreting RSDs e.g. where SDs for separate data sets are similar but the average values differ significantly as is the case for appliances A and B. The RSD approach assumes that the measurements were of a parameter with a single correct value.

Results of individual tests are given in Appendix 3. The results are summarised in Table 8 and Figure 4 below.

Table 8 Repeatability of ESP Results

Appliance		**A**	**B**	**C**	**CEXTRA**	**D**	**E**	**F**
Output level	Statistic							
High	Average, g/GJ	74	127	115	124	96	37	19
	SD, g/GJ	21	21	35	45	61	6.7	0.4
	RSD, %	**28**	**16**	**30**	**36**	**64**	**18**	**2**
Low	Average, g/GJ	67	103	105	80	141	58	15
	SD, g/GJ	33	36	30	21	58	16.4	1.7
	RSD, %	**49**	**35**	**29**	**27**	**41**	**28**	**12**

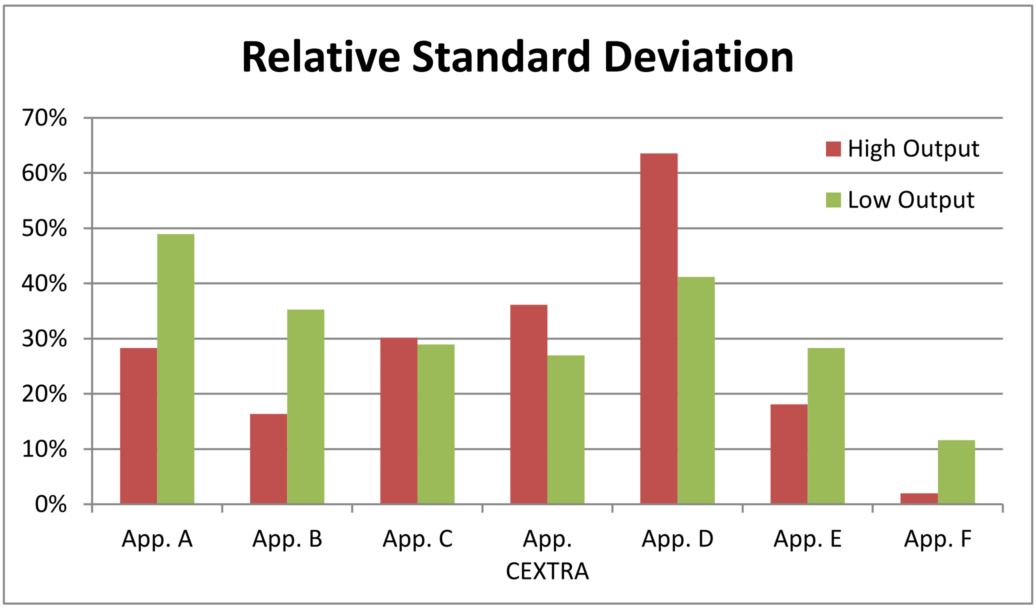


Figure 4 Repeatability of ESP Results

The good level of repeatability for the large pellet fired appliance (Appliance F), particularly at high output, indicates that where operating conditions can be well replicated (for the reasons outlined above) the variation attributable to the particulate emission measurement method (in this cases the ESP method) is relatively low.

The RSDs for all the other appliances are relatively high, suggesting that the repeatability of the overall tests was relatively poor. Previous testing (Appendix 1) has indicated similar variation for wood and mineral fuel roomheaters however, use of the ESP for other fuels and combustion appliances has shown good repeatability in the measurements. For example, tests to compare the ESP and FFDT methods using manufactured solid mineral fuels on open fireplaces gave results reproduced in Table 9[l].

Table 9 ESP results from manufactured solid mineral fuels (on open fires)

Test	Smoke from Fuel A, g/h	Smoke from Fuel B, g/h
1	4.72	1.75
2	4.54	2.49
3	4.65	2.09
4	4.22	1.84
5	4.02	1.99
Average	4.43	2.03
SD	0.30	0.29
RSD, %	**6.74**	**14.16**

NOTE: RSD added by author

The results for the pellet fired appliances and in particular for Appliance F gave comparable repeatability. This suggests that the wider variation in results from the other appliances and in particular, appliances fired with logs (being the most extreme for Appliance D - a roomheater boiler) is a result of differences in combustion conditions in the appliances.

The factors affecting the formation of particulates also affect the emission of NOx, CO and hydrocarbons. The presence of particulate in flue gas affects its optical density. The relationships between the measured smoke emission and these four parameters have been investigated with a view to gaining a clearer understanding of the contribution that operational variability makes to the overall degree of imprecision in the results from the tests.

The results are presented in graphs in Appendix 1. Note that the annotation on these plots of HOP and LOP indicate respectively High Output and Low Output operations. In Table 10 below, the findings are summarised. R^2 has been used as a measure of the degree of correlation[3] between ‘Smoke emission rate in g/h’ and:

- Average CO in mg/m^3 dry flue gas @13 $\%O_2$
- Average NO in mg/m^3 dry flue gas @13 $\%O_2$
- Average Total hydrocarbons (THC), mg/m^3 dry flue gas @13 $\%O_2$
- Optical density, integrated and normalised (OD), /h

[3] Caution must be exercised in the interpretation of R^2 as a measure of the relationship between parameters, particularly when they are grouped closely together as is the case for some of these data sets.

Table 10 Correlation coefficients (r^2) for linear regression between smoke emission and other measured parameters

Appliance	Firing level	Smoke vs OD	Smoke vs CO	Smoke vs NOx	Smoke vs THC
A	High	0.86	0.00	nd	nd
A	Low	0.15	0.25	nd	nd
B	High	0.33	0.66	0.00	0.59
B	Low	0.91	0.90	0.93	0.88
C	High	0.79	0.01	nd	nd
C	Low	0.60	0.38	nd	nd
CEXTRA	High	nd	nd	0.00	0.83
CEXTRA	Low	nd	nd	0.54	0.14
D	High	0.94	0.65	nd	nd
D	Low	0.50	0.31	nd	nd
E	High	nd	0.00	nd	nd
E	Low	0.69	0.02	nd	nd

NOTE: nd – not determined during ESP tests. As stated above NOx and THC were measured during the runs under the same nominal conditions for these appliances for the FFDT/DIN+ smoke measurements but only for a limited number of the tests where ESP measurements were made.

Some strong correlations were noted but these were appliance/pollutant/load specific. None of the parameters give uniformly good correlations with the ESP measured smoke emission rates. There is insufficient evidence to draw strong inferences from these results.

The inconsistency in the correlations with NOx at High and Low outputs is not surprising as the mechanisms for its formation are different to those for the release of hydrocarbons and the formation of ash and carbon particles.

5.5 Variability of other parameters between replicate tests

Detailed results for various parameters measured during each individual test, including burning rate, flue gas temperatures and gas composition are presented in Appendix 3.

The values presented include averages, SDs and RSDs for parameters measured during individual tests and for all data from repeats of each condition (High and Low output rates) for each appliance.

The information about flue gas composition and in particular CO and CO_2 presented in the tables in Appendix 1 show that there is considerable variability in conditions for replicate tests for the log fired appliances. The control of the combustion in the pellet fired appliances is much more consistent. Poorer combustion conditions are often present in the log fired appliances as evidences by the much higher levels of CO encountered (of the order of 1,000s ppm) when compared to the pellet fired appliances (of the order of 10s of ppm).

Flue gas temperatures at the ESP varied between ~60°C and 90°C, depending on the firing rate and the appliance.

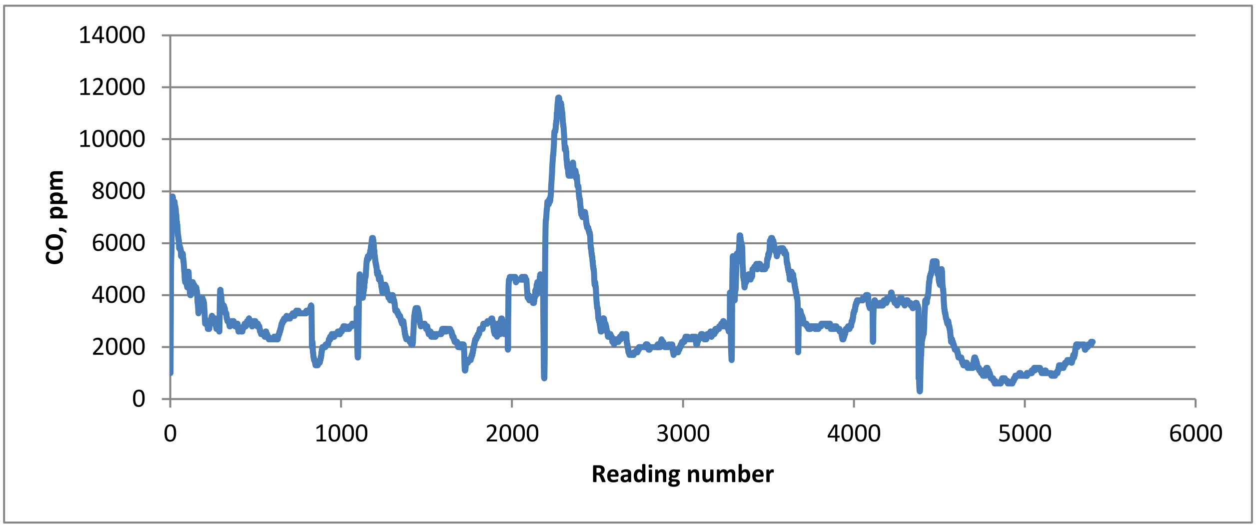


Figure 6 CO levels recorded for the five High Output tests with Appliance D

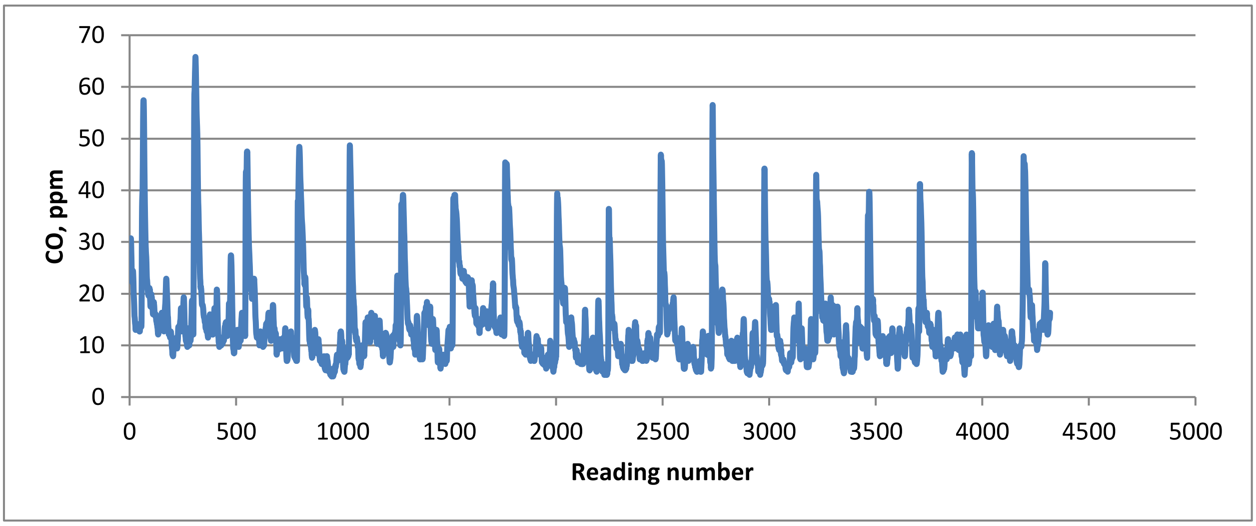


Figure 5 CO levels recorded for the Low Output condition for Appliance F

Figure 5 and Figure 6 show the measured CO levels for the tests for one condition for an appliance. The High Output conditions for log roomheater boilers should have the best combustion conditions with the maximum amount of air available. In spite of this Appliance D shows high levels of CO emission. In contrast Appliance F shows good control even at the Low Output condition producing low levels of CO emission. The regular minor CO excursions are expected as the pellet fuel is fed to the burner but in spite of this the levels remain below 100ppm.

This observation tends to support the theory that a large proportion of the variation in smoke test results particularly for log fired appliances results from the difficulty in closely replicating combustion conditions rather than from variability in the application of the measurement technique.

6 Conclusions

-

1. The fuel types used were in accordance with the relevant specifications.

2. Efforts were made to select similar logs for each test and they were positioned in a consistent way for each fuelling of each appliance. However, the recorded data indicates that this was not enough to replicate combustion conditions in each test. For Appliance D in particular the operators noted problems with establishing a consistent bed. It is clear this is inherent in using logs as a fuel and will of course occur in the home so the test laboratory is reproducing some elements of real use however it is a significant constraint in producing repeatable test conditions.

3. The consistency of the performance of the pellet fired appliances indicated that the fuel used was of a consistent quality and provided a less variable firebed than for log appliances.

1. The ESP methodology is well defined and in these laboratory trials was carried out by experienced trained operatives. The ESP sees the whole flue gas flow and the slippage tests indicate that slippage is insignificant.

2. The particulate matter emissions determined on wood log appliances were variable however, lower variability was found on pellet appliances and has been observed in other fuel/appliance combinations which indicates that much of the variability in particulate emissions arises from the difficulty in replicating combustion conditions.

3. No evidence was found of correlation between smoke emission and optical density

4. No evidence was found of correlation between smoke emission and CO emission

5. No evidence was found of correlation between smoke emission and NOx emission

6. No evidence was found of correlations between smoke emission and THC

7 References

[I] Keeling J W, Wilkins D, Comparison of dilution tunnel and electrostatic precipitator methods for the measurement of smoke mass emission rate from manufactured solid fuels for domestic open fires. Coal Research Establishment, British Coal Corporation, FAT 66, January 1992

[II] BS EN 13240:2001:Roomheaters fired by solid fuel - Requirements and test methods.

[III] US EPA Technical Bulletin – Nitrogen oxides (NOx) why and how they are controlled. EPA 456/F-99-006R, November 1999

[IV] ECN Phyllis 2 database – interrogated 23/11/2013. https://www.ecn.nl/phyllis2/Browse/Standard/ECN-Phyllis

[V] unpublished internal British Coal Corporation note on coal properties for use in flue gas calculations, 1989

[VI] BS 3841-2 1994 Determination of smoke emission from manufactured solid fuels for domestic use – Part 2: Methods for measuring the smoke emission rate

[VII] BS EN 14961-2:2011 Solid biofuels — Fuel specifications and classes - Part 2: Wood pellets for non-industrial use

[VIII] PD 6434:1969 Recommendations for The design and testing of smoke reducing solid fuel appliances

Appendix 1 Historical Test Results

Table A1.1 Summary of HETAS comparisons

	Smoke at high output, g/h			Smoke at low output, g/h		
Appliance ID	Average	SD	RSD, %	Average	SD	RSD, %
Ac	4.58	0.99	21.7	2.73	0.38	13.9
Bc	7.57	1.04	13.8	2.83	0.22	7.8
Dc	6.48	0.99	15.2	1.58	0.30	19.0
Ec	6.02	0.84	14.0	1.53	0.49	31.9
Fc	11.10	0.74	6.6	2.60	0.17	6.7
Gc	2.53	0.55	21.7	3.46	0.32	9.3
Hc	2.73	0.38	13.9	4.46	0.69	15.4
Hc	2.66	0.95	35.8	4.22	0.96	22.8
Ic	2.58	0.85	33.2	1.44	0.44	30.5
Jc	1.38	0.65	47.4	0.96	0.48	50.3
Kc	1.30	0.42	32.2	0.86	0.29	33.5
Lc	3.84	0.82	21.3	3.92	0.86	21.9
Mc	3.12	0.36	11.6	3.00	0.38	12.7
Nc	2.96	0.65	22.0	2.26	0.68	30.3
Oc	3.10	1.73	55.9	2.94	0.60	20.5
Pc	3.44	1.01	29.4	3.16	0.93	29.5
Qc	3.22	1.18	36.6	2.60	0.44	17.0
Average			**25.4**			**21.9**
Aw	2.84	0.54	18.9	0.34	0.09	26.3
Bw	2.30	1.44	62.4	3.44	2.17	63.0
Cw	4.90	2.62	53.4	5.08	3.91	77.0
Dw	4.42	0.73	16.6	2.40	1.44	59.9
Ew	3.82	1.28	33.4	1.98	0.33	16.9
Average			**35.0**			**44.2**

NOTE: For these tests the investigators used an identification code of A to Q for the coal fired appliances and A to E for the wood fired appliances. To avoid confusion as they are reiterated in this report they have been recoded with the addition of a c for coal and w for wood.

Appendix 2 Methods and Equipment

A2.1 Kiwa Roomheater test procedure

Gastec at CRE Testing Services Solid Fuel Appliance Testing Procedures Manual	SECTION 9 Procedure No.: 9.2 Page 2 of 6
Title Of Section **NOMINAL HEAT OUTPUT AND EFFICIENCY TEST FOR ROOMHEATER TO BS EN 13240**	Issue No.: 2.2 Issue Date: 15/10/10

8

Appliance No.:		Test No.:	A13/469
Appliance Name:		Date:	21/11/13
Test Engineer:			

1. METHOD

The Efficiency Test at nominal heat output is carried out in accordance with the method described in clause A.4.7 of BS EN 13240 as appropriate to the appliance type being tested and the test fuel being used. Due account shall also be taken of the test procedures given in A.4.1 to A.4.6 of BS EN 13240. The appliance must be tested in its fully assembled state as detailed by the manufacturer in the appliance instructions.

The test environment and test assembly shall be in accordance with clauses A.1 and A.2 respectively of BS EN 13240. For appliances with boiler the valves on the test water circuit should be set to cold water input (continuous flow circuit). All pipework should be insulated to prevent extraneous heat loss.

The measurement of the surface temperature of the operating components and the measurement of the trihedron hearth and wall temperatures must be carried out under the nominal heat output test conditions as specified in clauses 5.5 and 5.6 of BS EN 13240 and separate test sheets are required for these measurements. The clearance distances to the trihedron wall and any hearth protection, if applicable, should be recorded on those sheets.

Ensure that the standardised test conditions relevant to the method used are met before starting the test. The burning rate of the appliance should be set during the installation/set up procedure to give at least the nominal rated output declared by the manufacturer. The applied flue draught shall be in accordance with the flue draught declared by the appliance manufacturer and this shall be kept constant in accordance with the requirements of clause 6.4 of BS EN 13240.

NOTE: For appliances with boiler the control thermostat may need to be disabled, by removing the sensor from its pocket, in order to achieve the conditions specified in the standard method.

The test period duration shall be the refuelling interval declared by the manufacturer for the appliance being tested which shall be not less than the minimum refuelling interval for the appliance type as specified in Table 10 of BS EN 13240. The mass of basic firebed for refuelling purposes shall be in accordance with clause 6.6 of BS EN 13240 or such greater mass declared by the appliance manufacturer.

At least 2 consecutive determinations of efficiency and heat output shall be undertaken and the requirements of clauses A.4.7.3 and A.5 of BS EN 13240 in respect of total heat output and test duration shall be met. The test result for efficiency and heat output shall be reported as the mean value of at least two valid and consecutive test runs provided the requirements of clauses A.4.7.3 and A.5 of BS EN 13240 are met.

A2.2 Log fuel selection method

Date: 08 May 2006	BS EN Standards 12815, 12809, 13229 & 13240,	GASTEC at CRE
	Tests with wood	Page: AII/02

Issue
SIZE OF WOOD LOGS

The test fuel specifications state that all fuels, including wood logs, should be "of commercial size in accordance with manufacturer's instructions". Potentially, this gives the manufacturer considerable leeway in describing the fuel size in its operating instructions.

Interpretation

The standards are not really ambiguous. Whilst they can be of the size in accordance with the manufacturer's instructions they also have to be "logs" and of "commercial size".

Thus the sizes allowable for wood logs are limited in range to the smallest (~300 mm) and largest (0.5 metre) available in the European market

Policy

Gastec at CRE will purchase logs on the commercial market. Whilst some selection can be made of these logs to suit the physical size of the appliance and the manufacturer's instructions no further size reduction of the logs will be permitted, eg to produce slivers, to generate wood pieces which could not sensibly be sold as "wood logs"

Author John Tucker		Initials:

A2.3 Kiwa Electrostatic Precipitator smoke emission measurement method summary

APPENDIX A

SUMMARY OF TEST METHOD: FUEL TESTING PROCEDURE NUMBER 18 GRAVIMETRIC MEASUREMENT OF SMOKE EMISSION FROM DOMESTIC SOLID FUELS

An ignition charge of fuel equivalent to 0.007 m^3 is placed on the grate and arranged as an even layer by hand. This ignition charge is lit using 4220 kJ of gas passed over a period of approximately ten minutes. When the radiation output from the fire attains 1.15 kW the air control plate is placed in position on the firefront. The opening in this air plate is carefully set in order to obtain a second peak radiation output (i.e. peak radiation after the first refuel) within the range 1.80 kW to 2.30 kW. If the second peak radiation falls outside this range the test is either abandoned or allowed to continue for the purpose of sighting but cannot be used as a valid test. It is not permitted to adjust the air plate opening during the test. Furthermore if during the ignition period the radiant output takes longer than 50 minutes to attain 1.15 kW then the test is abandoned and all further tests are ignited using the greater quantity of gas of 7440 kJ passed over a period of approximately 17.5 minutes.

The ignition charge is allowed to burn until the radiant output has attained a peak and fallen again to either 1.45 kW or 75 % of the peak, whichever is the lowest value. Approximately ten minutes prior to this, a pre-conditioned and weighed electrostatic precipitator (EP) is placed on top of the chimney and briefly tested to ensure it is functioning properly.

When the radiation output from the ignition charge has dropped to the pre-determined level, as specified above, the fire is carefully de-ashed, the EP is turned on and a refuel charge of fuel equivalent to 0.005 m^3 is added to the fire. The fire is then allowed to burn until the radiation output from this first refuel charge has peaked and fallen again to 1.45 kW.

The EP is turned down to approximately 1/3 of its normal operating power, the fire is carefully de-ashed and the EP is turned back up to full power. A further refuel charge of fuel equivalent to 0.005 m^3 is then added to the fire.

When the radiation output from this second refuel charge has peaked and fallen again to 1.45 kW the EP is switched off and placed in the conditioning room. After a period of at least 2 hours in the conditioning room the EP is re-weighed to determine the total mass of smoke collected. This is converted to a mean smoke emission rate over the length of the test period i.e. the time period between addition of the first refuel and turning off the EP when the radiation output from the second refuel has fallen to 1.45 kW following its peak.

A2.4 Optical Density method

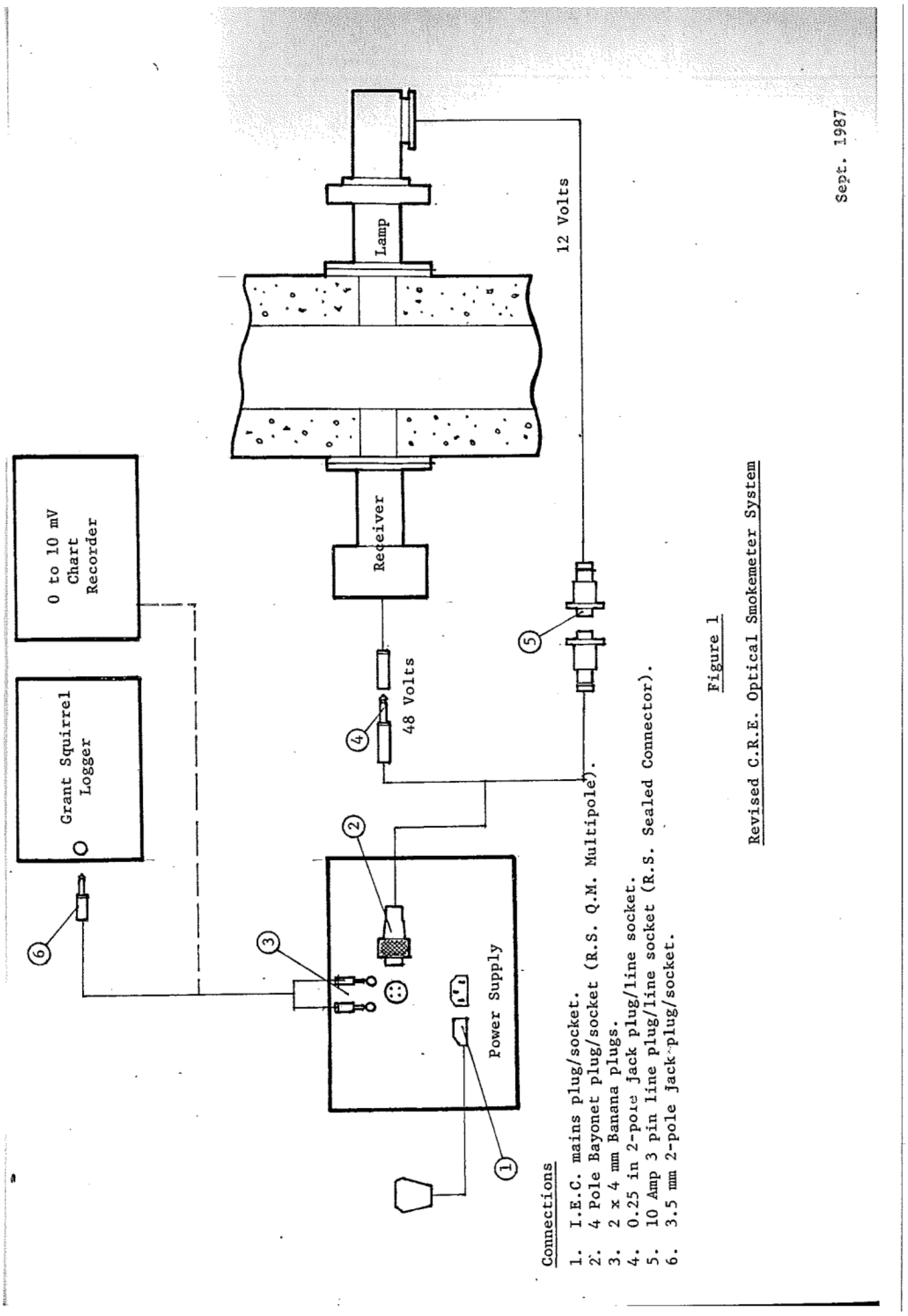


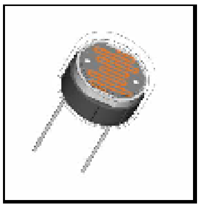
Figure A2.1 Arrangement of the CRE Optical Smoke Meter System

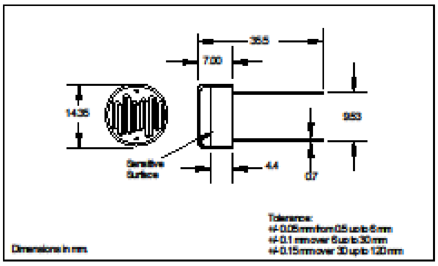
Component characteristics

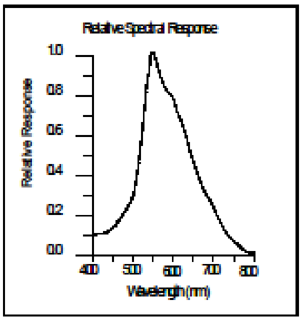
- Light source: Thorn EMI Halogen lamp M32, 12V, 50W
- Detector: Light sensitive resistor ORP12 – detects in the visual spectrum

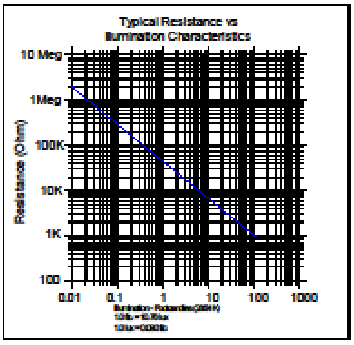
NORPS-12

Plastic Packaged CdS Photocell
104510 Rev 04









Description

The NORPS-12 is a CdS photoconductive cell with a spectral response similar to that of the human eye, encapsulated in a moisture-resistant coating and enclosed in a plastic casing.

Absolute Ratings Maximum

Operating Temperature	-60 to +75°C
Storage Temperature	-60 to +75°C
Voltage (peak AC or DC)	250 Volts
Power Dissipation at 30°C (1)	250mW

Electrical Characteristics (T_A=25°C, source at 2854°K)

Symbol	Parameter	Min.	Typ.	Max.	Units	Test Conditions
R_L	Light Resistance	5.4		12.6	kΩ	1 ftc. (2)
R_D	Dark Resistance	1.0			MΩ	15 sec. after removal of test light.
λ_P	Spectral Peak		550		nm	

Specifications subject to change without notice

Notes: (1) Derate linearly to zero at 75°C.
(2) Cells light adapted at 30 to 50 Ftc for 16 hrs minimum prior to electrical tests.

5200 St. Patrick St., Montreal
Que., H4E 4N9, Canada
Tel: 514-768-8000
Fax: 514-768-8889

QF-84 Rev 3

Figure A2.2 Detector Data sheet

Appendix 3 Detailed Test Results

Table A3.1 ESP smoke measurements

Appliance	Output	Smoke measured by ESP, g/GJ					Average	SD
		Test 1	Test 2	Test 3	Test 4	Test 5	Average	SD
A	Maximum	113	89	57	65	105	86	24
	Minimum	72	51	54	144	67	78	38
B	Maximum	143	139	116	94	138	126	21
	Minimum	132	110	141	71	59	103	36
C	Maximum	165	112	123	67	109	115	35
	Minimum	152	86	72	107	110	105	30
CEXTRA	Maximum	183	113	156	90	77	124	45
	Minimum	103	52	66	99	79	80	21
D	Maximum	84	201	83	61	49	96	61
	Minimum	90	87	136	164	227	141	58
E	Maximum	34	35	26	26	39	32	6
	Minimum	44	59	52	30	66	50	14
F	Maximum	18	19	19	18	18	18	0
	Minimum	15	16	14	12	16	15	2

Table A3.2 Fuel and energy information for individual tests

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
A	HIGH	1	1.124	0.67	1.68	5.54	78.0
A	HIGH	2	1.132	0.63	1.80	5.94	78.0
A	HIGH	3	1.170	0.73	1.60	5.30	78.0
A	HIGH	4	1.128	0.70	1.61	5.33	78.0
A	HIGH	5	1.146	0.70	1.64	5.41	78.0
A	LOW	1	1.118	0.77	1.45	1.45	78.0
A	LOW	2	1.124	0.77	1.36	1.36	78.0
A	LOW	3	1.115	0.78	1.43	1.43	78.0
A	LOW	4	1.107	0.77	1.39	1.39	78.0
A	LOW	5	1.098	0.78	1.41	1.41	78.0
B	HIGH	1	1.801	0.68	2.65	8.87	80.0
B	HIGH	2	1.822	0.68	2.68	8.97	80.0
B	HIGH	3	1.820	0.68	2.68	8.96	80.0
B	HIGH	4	1.824	0.75	2.43	8.14	80.0
B	HIGH	5	1.827	0.70	2.61	8.74	80.0
B	LOW	1	1.804	0.78	2.31	7.74	80.0
B	LOW	2	1.798	0.80	2.25	7.53	80.0
B	LOW	3	1.786	0.78	2.29	7.67	80.0
B	LOW	4	1.766	0.82	2.15	7.21	80.0
B	LOW	5	1.789	0.88	2.03	6.81	80.0
C	HIGH	1	1.446	0.72	2.01	6.98	83.0
C	HIGH	2	1.458	0.70	2.08	7.24	83.0
C	HIGH	3	1.396	0.63	2.22	7.70	83.0
C	HIGH	4	1.472	0.73	2.02	7.01	83.0
C	HIGH	5	1.456	0.75	1.94	6.74	83.0
C	LOW	1	1.264	0.82	1.54	5.36	83.0

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
C	LOW	2	1.393	0.85	1.64	5.69	83.0
C	LOW	3	1.292	0.87	1.49	5.16	83.0
C	LOW	4	1.304	0.83	1.57	5.46	83.0
C	LOW	5	1.269	0.90	1.41	4.90	83.0
C_{EXTRA}	HIGH	1	1.443	0.70	2.06	6.24	72.5
C_{EXTRA}	HIGH	2	1.438	0.75	2.04	6.11	72.3
C_{EXTRA}	HIGH	3	1.455	0.73	1.92	5.79	70.7
C_{EXTRA}	HIGH	4	1.410	0.85	1.96	5.84	76.3
C_{EXTRA}	HIGH	5	1.410	0.90	1.99	5.88	75.6
C_{EXTRA}	LOW	1	1.466	0.72	1.79	5.77	71.9
C_{EXTRA}	LOW	2	1.468	0.75	1.66	5.28	71.5
C_{EXTRA}	LOW	3	1.485	0.83	1.61	5.08	77.3
C_{EXTRA}	LOW	4	1.399	0.87	1.57	4.95	75.7
C_{EXTRA}	LOW	5	1.425	0.97	1.47	4.61	75.1
D	HIGH	1	7.922	1.50	5.28	16.61	75.0
D	HIGH	2	7.582	1.50	5.05	15.89	75.0
D	HIGH	3	7.869	1.50	5.25	16.50	75.0
D	HIGH	4	7.540	1.52	4.96	15.60	75.0
D	HIGH	5	7.653	1.43	5.35	16.83	75.0
D	LOW	1	7.720	1.65	4.68	14.71	75.0
D	LOW	2	7.390	2.02	3.66	11.50	75.0
D	LOW	3	7.492	1.95	3.84	12.08	75.0
D	LOW	4	7.661	1.78	4.30	13.53	75.0
D	LOW	5	7.440	2.08	3.58	11.25	75.0
E	HIGH	1	2.280	0.75	3.09	12.50	83.6

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
E	HIGH	2	2.240	0.75	3.09	12.50	83.6
E	HIGH	3	2.300	0.75	3.09	12.50	83.6
E	HIGH	4	2.300	0.75	3.09	12.50	83.6
E	HIGH	5	2.240	0.75	3.09	12.50	83.6
E	LOW	1	0.740	1.00	0.78	3.10	81.3
E	LOW	2	0.760	1.00	0.78	3.10	81.3
E	LOW	3	0.780	1.00	0.78	3.10	81.3
E	LOW	4	0.800	1.00	0.78	3.10	81.3
E	LOW	5	0.780	1.00	0.78	3.10	81.3
F	HIGH	1	46.493	0.50	46.49	203.94	88.8
F	HIGH	2	46.493	0.50	46.49	203.94	88.8
F	HIGH	3	46.493	0.50	46.49	203.94	88.8
F	HIGH	4	46.493	0.50	46.49	203.94	88.8
F	HIGH	5	46.493	0.50	46.49	203.94	88.8
F	LOW	1	13.148	0.50	13.15	56.93	90.0
F	LOW	2	13.148	0.50	13.15	56.93	90.0
F	LOW	3	13.148	0.50	13.15	56.93	90.0
F	LOW	4	13.148	0.50	13.15	56.93	90.0
F	LOW	5	13.148	0.50	13.15	56.93	90.0

Table A3.3 Conditions recorded for individual tests

Appliance	Output	Test #	CO_2, %		CO, %		O_2, %		Flue draught		Flue temp bottom		Flue temp top		Ambient temp	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
A	HIGH	1	3.39	0.91	0.13	0.19	ND	ND	9.52	0.76	122.15	11.33	ND	ND	ND	ND
A	HIGH	2	8.44	2.47	0.62	0.94	ND	ND	10.77	0.82	228.05	21.64	ND	ND	ND	ND
A	HIGH	3	7.52	1.75	0.44	0.42	ND	ND	10.29	1.03	202.31	20.75	ND	ND	ND	ND
A	HIGH	4	6.25	1.63	0.16	0.22	ND	ND	9.72	1.02	205.94	19.46	ND	ND	ND	ND
A	HIGH	5	6.05	1.77	0.31	0.61	ND	ND	10.15	0.87	208.10	17.19	ND	ND	ND	ND
A	LOW	1	5.10	1.84	0.06	0.07	ND	ND	9.70	0.76	116.01	15.32	ND	ND	ND	ND
A	LOW	2	7.03	2.27	0.14	0.12	ND	ND	10.00	0.78	202.78	21.40	ND	ND	ND	ND
A	LOW	3	6.57	2.32	0.12	0.11	ND	ND	10.47	0.86	191.91	20.12	ND	ND	ND	ND
A	LOW	4	6.65	2.71	0.13	0.13	ND	ND	9.56	0.98	193.39	23.74	ND	ND	ND	ND
A	LOW	5	5.67	1.65	0.08	0.07	ND	ND	10.22	0.73	210.92	27.75	69.26	5.74	22.70	0.19
B	HIGH	1	11.38	3.15	0.70	0.98	ND	ND	13.93	1.15	276.13	21.48	93.52	6.84	24.11	0.55
B	HIGH	2	10.71	3.37	0.50	0.57	ND	ND	13.72	0.98	266.64	20.81	94.42	5.18	26.32	0.59
B	HIGH	3	10.59	3.32	0.30	0.35	ND	ND	13.47	0.84	258.27	18.55	94.13	4.54	28.12	0.26
B	HIGH	4	10.16	2.62	0.28	0.34	ND	ND	12.38	0.75	238.02	17.09	79.73	4.71	21.69	0.10
B	HIGH	5	11.46	3.46	0.42	0.51	ND	ND	13.08	0.87	248.72	18.65	86.48	4.82	22.36	0.09
B	LOW	1	11.70	3.88	0.88	1.02	ND	ND	10.97	1.17	221.73	24.40	76.17	6.74	25.15	0.37
B	LOW	2	11.74	3.66	0.87	0.94	ND	ND	10.82	1.19	214.99	24.27	77.91	6.13	27.78	0.29
B	LOW	3	11.40	4.34	1.22	0.96	ND	ND	11.22	1.42	215.10	30.15	81.33	7.59	27.78	0.24
B	LOW	4	11.31	2.94	0.50	0.65	ND	ND	10.58	1.23	191.70	24.71	67.44	6.84	22.21	0.23
B	LOW	5	10.84	3.04	0.45	0.57	ND	ND	10.59	1.07	190.31	21.47	69.26	5.74	22.70	0.19
C	HIGH	1	8.57	2.70	0.26	0.61	11.77	2.83	9.06	1.38	211.08	29.62	64.81	8.92	23.30	0.86
C	HIGH	2	8.41	3.04	0.39	0.92	11.67	3.27	9.26	1.59	212.22	37.93	68.91	12.79	25.85	0.94
C	HIGH	3	8.86	2.57	0.41	0.86	11.19	2.86	9.29	1.57	202.71	37.79	68.26	11.95	27.58	0.45
C	HIGH	4	6.09	1.98	0.21	0.24	14.28	2.16	8.74	1.35	187.29	33.00	65.42	9.73	25.28	0.26
C	HIGH	5	7.13	2.69	0.24	0.58	12.86	2.91	9.50	1.67	208.03	37.30	71.84	16.83	26.74	0.40

Appliance	Output	Test #	CO_2, %		CO, %		O_2, %		Flue draught		Flue temp bottom		Flue temp top		Ambient temp	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
C	LOW	1	7.34	3.06	0.76	1.22	12.71	3.65	7.70	2.57	166.44	62.32	58.18	19.04	24.63	0.69
C	LOW	2	7.63	2.80	0.55	0.82	12.48	3.08	7.71	1.94	159.53	49.16	57.79	15.31	26.89	0.69
C	LOW	3	7.51	2.65	0.49	0.81	12.51	3.08	8.18	2.18	169.28	54.05	62.00	16.76	28.25	0.44
C	LOW	4	7.60	2.63	0.34	0.57	12.52	2.66	7.47	1.62	159.29	40.13	57.76	10.77	25.98	0.39
C	LOW	5	6.48	2.49	0.41	0.61	13.53	2.76	7.41	1.84	146.33	48.51	57.39	14.14	27.30	0.62
C_{EXTTRA}	HIGH	1	10.96	4.06	0.24	0.32	9.44	4.05	16.93	1.16	368.70	29.05	ND	ND	20.38	0.49
C_{EXTTRA}	HIGH	2	9.25	3.23	0.11	0.18	11.44	2.91	16.14	1.32	333.45	19.49	ND	ND	19.80	0.06
C_{EXTTRA}	HIGH	3	9.32	3.63	0.14	0.19	11.14	3.33	16.59	1.53	329.74	23.50	ND	ND	19.99	0.15
C_{EXTTRA}	HIGH	4	8.76	3.29	0.09	0.15	11.60	3.03	16.83	1.59	325.43	18.26	ND	ND	20.62	0.22
C_{EXTTRA}	HIGH	5	8.56	3.35	0.08	0.12	11.53	3.08	16.64	1.34	328.67	20.01	ND	ND	21.57	0.24
C_{EXTTRA}	LOW	1	9.30	2.60	0.08	0.12	10.82	2.40	13.92	1.47	286.84	14.83	ND	ND	20.11	0.14
C_{EXTTRA}	LOW	2	9.30	2.60	0.08	0.12	10.82	2.40	13.92	1.47	286.84	14.83	ND	ND	20.11	0.14
C_{EXTTRA}	LOW	3	8.83	2.94	0.11	0.11	11.22	2.72	14.04	1.45	280.83	15.26	ND	ND	20.61	0.21
C_{EXTTRA}	LOW	4	8.99	3.81	0.17	0.21	10.83	3.62	13.03	1.22	283.06	19.99	ND	ND	21.39	0.24
C_{EXTTRA}	LOW	5	8.34	3.11	0.14	0.11	11.39	2.90	13.95	1.54	273.15	18.48	ND	ND	21.87	0.12
D	HIGH	1	4.96	1.63	0.32	0.11	ND	ND	15.58	2.25	224.93	46.45	ND	ND	ND	ND
D	HIGH	2	3.17	1.33	0.33	0.11	ND	ND	15.82	3.46	226.68	72.80	ND	ND	ND	ND
D	HIGH	3	5.78	2.31	0.39	0.28	ND	ND	17.92	2.90	279.76	68.44	ND	ND	ND	ND
D	HIGH	4	5.57	2.32	0.39	0.10	ND	ND	17.42	2.96	262.86	70.11	ND	ND	ND	ND
D	HIGH	5	4.74	2.04	0.17	0.12	ND	ND	18.33	2.99	285.80	75.11	ND	ND	ND	ND
D	LOW	1	6.07	3.15	0.48	0.40	ND	ND	14.67	3.12	224.61	77.00	ND	ND	ND	ND
D	LOW	2	4.56	1.43	0.44	0.17	ND	ND	12.76	1.86	170.40	41.02	ND	ND	ND	ND
D	LOW	3	5.07	1.59	0.46	0.18	ND	ND	12.77	3.09	173.54	39.92	ND	ND	ND	ND
D	LOW	4	6.07	1.79	0.58	0.32	ND	ND	14.84	1.59	201.19	33.96	ND	ND	ND	ND
D	LOW	5	3.97	1.45	0.27	0.12	ND	ND	13.03	2.49	171.77	50.75	ND	ND	ND	ND

Table A3.4 Repeatability of test conditions - flue gas composition

Appliance	Output level	% CO2			% CO			% O2			NOx ppm			THC ppm		
		Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD
A	High	6.32	2.44	0.39	0.326	0.570	1.75	13.63	2.74	0.20	ND	ND	ND	ND	ND	ND
A	Low	6.20	2.30	0.37	0.106	0.108	1.02	13.75	2.41	0.18	ND	ND	ND	ND	ND	ND
B	High	10.85	3.23	0.30	0.436	0.611	1.40	ND	ND	ND	47.69	19.08	0.40	873.87	1886.23	2.16
B	Low	11.39	3.60	0.32	0.773	0.884	1.14	ND	ND	ND	50.89	11.89	0.23	1551.62	2801.83	1.81
C	High	7.77	2.82	0.36	0.300	0.681	2.27	12.40	3.03	0.24	ND	ND	ND	ND	ND	ND
C	Low	7.30	2.76	0.38	0.509	0.848	1.67	12.76	3.09	0.24	ND	ND	ND	ND	ND	ND
C_{EXTRA}	High	9.34	3.62	0.39	0.13	0.21	1.61	11.05	3.39	0.31	44.5	13.4	0.30	227.6	711.7	3.13
C_{EXTRA}	Low	8.93	3.08	0.35	0.12	0.14	1.20	11.04	2.87	0.26	47.5	17.3	0.36	124.1	595.1	4.80
D	High	4.85	2.17	0.45	0.323	0.181	0.56	15.69	2.49	0.16	ND	ND	ND	ND	ND	ND
D	Low	5.08	2.11	0.41	0.441	0.271	0.61	15.26	2.34	0.15	ND	ND	ND	ND	ND	ND
E	High	12.00	1.05	0.09	0.002	0.005	2.07	ND	ND	ND	ND	ND	ND	ND	ND	ND
E	Low	5.95	1.95	0.33	0.048	0.042	0.89	ND	ND	ND	ND	ND	ND	ND	ND	ND
F	High	14.84	0.32	0.02	0.002	0.001	0.66	ND	ND	ND	89.96	2.70	0.03	6.05	2.66	0.44
F	Low	9.95	0.60	0.06	0.001	0.001	0.61	ND	ND	ND	58.31	3.08	0.05	0.85	0.54	0.64

Note: These statistics are calculated from whole data set recorded for the multiple tests of each appliance at each output level.

Table A3.5 Repeatability of test conditions – draft and temperatures

Appliance	Output level	Flue draught, Pa			Flue temp bottom / Flue temp, °C			Flue temp top, °C			Ambient, °C		
		Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD
A	High	10.08	1.01	0.10	193.00	40.80	0.21	ND	ND	ND	ND	ND	ND
A	Low	9.99	0.89	0.09	183.15	40.62	0.22	ND	ND	ND	ND	ND	ND
B	High	13.29	1.08	0.08	257.07	23.53	0.09	89.44	7.88	0.09	24.46	2.45	0.10
B	Low	10.83	1.24	0.11	206.17	28.33	0.14	74.20	8.47	0.11	25.03	2.41	0.10
C	High	9.17	1.54	0.17	204.22	36.41	0.18	67.86	12.67	0.19	25.72	1.57	0.06
C	Low	7.69	2.07	0.27	160.00	51.90	0.32	58.63	15.52	0.26	26.64	1.35	0.05
C_{EXTRA}	High	16.62	1.43	0.09	336.70	27.36	0.08	ND	ND	ND	20.47	0.68	0.03
C_{EXTRA}	Low	13.77	1.48	0.11	281.78	17.74	0.06	ND	ND	ND	20.86	0.73	0.04
D	High	17.00	3.14	0.18	255.64	72.02	0.28	ND	ND	ND	ND	ND	ND
D	Low	13.55	2.66	0.20	186.58	54.14	0.29	ND	ND	ND	ND	ND	ND
E	High	ND	ND	ND	122.43	2.75	0.02	ND	ND	ND	21.30	0.71	0.03
E	Low	ND	ND	ND	49.41	1.31	0.03	ND	ND	ND	20.87	0.42	0.02
F	High	ND	ND	ND	178.62	2.75	0.02	ND	ND	ND	21.12	0.50	0.02
F	Low	ND	ND	ND	98.72	3.82	0.04	ND	ND	ND	20.84	0.54	0.03

Note: These statistics are calculated from whole data set recorded for the multiple tests of each appliance at each output level.

Figure A3 ESP tests

Figure A3.1a Flue gas measurement traces of OD, CO and CO2 for Appliance A, High Output

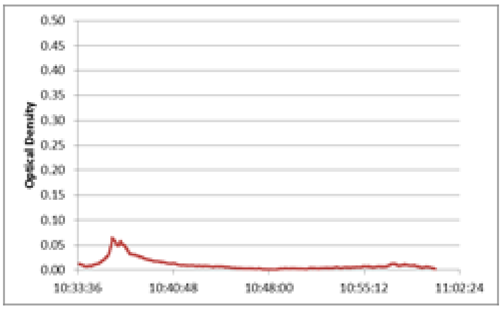
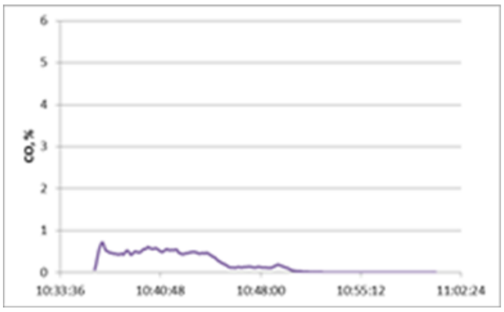
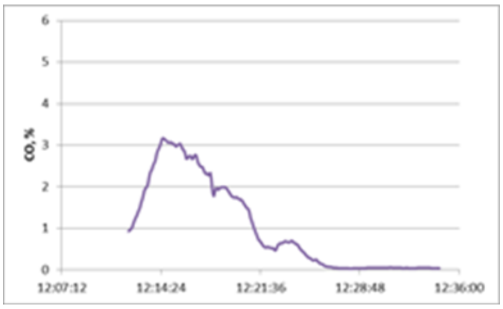
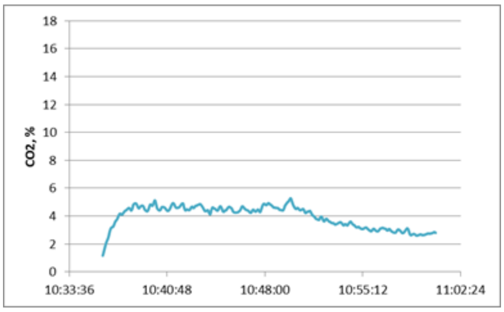
Test 1	Test 2
	
	
	

Figure A3.1b Flue gas measurement traces of OD, CO and CO_2 for Appliance A, High Output

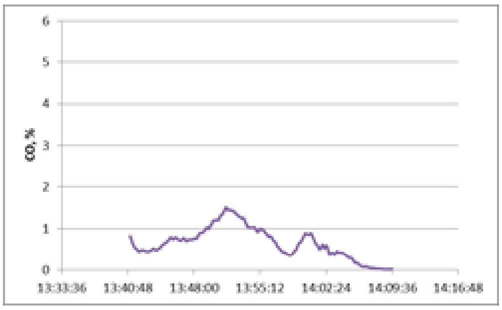
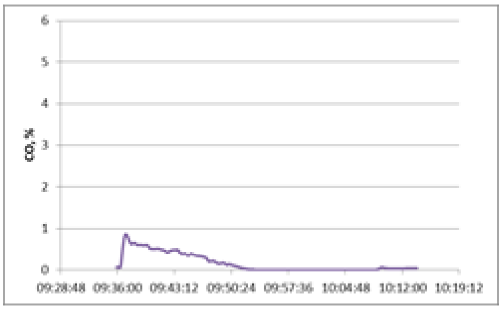
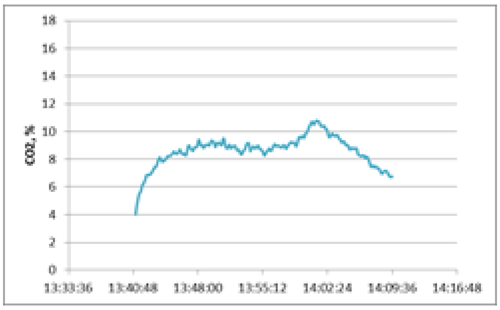
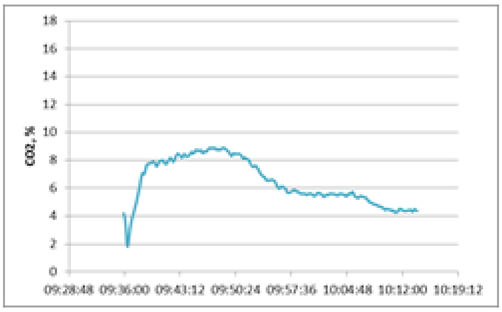
Test 3	Test 4
	
	
	

Figure A3.1c Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance A

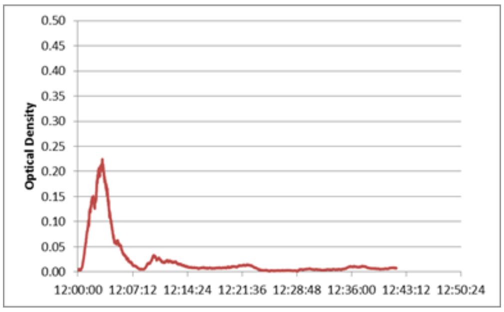
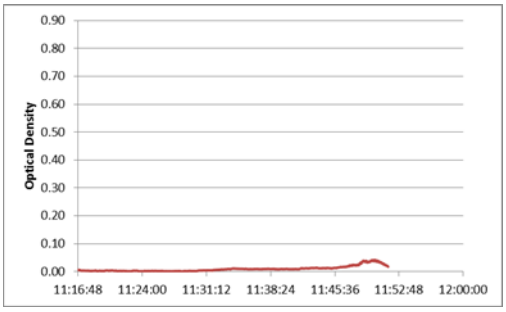
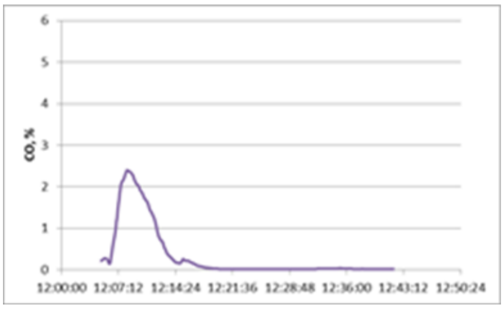
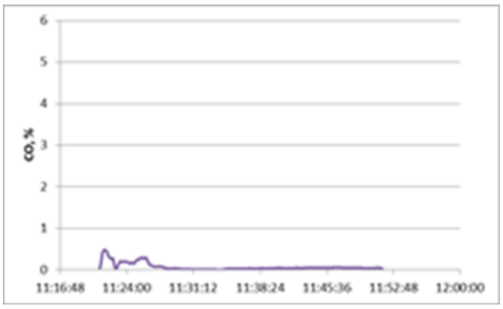
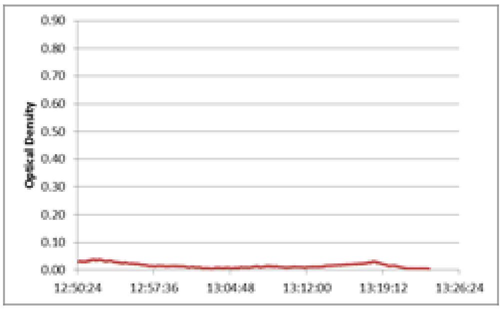
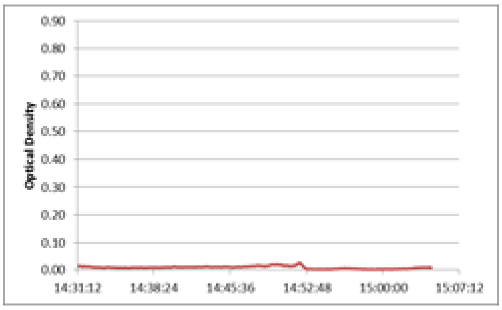
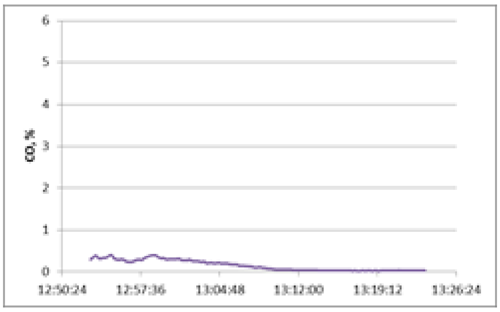
High output Test 5	Low output Test 1
	
	
	

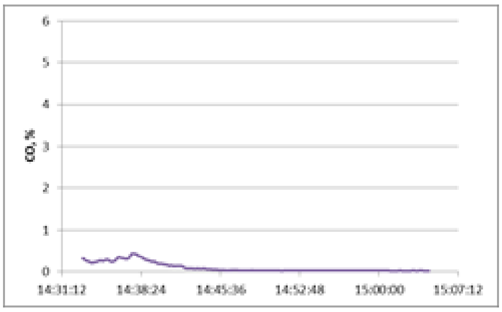
Figure A3.1d Flue gas measurement traces of OD, CO and CO2 for Appliance A, Low Output

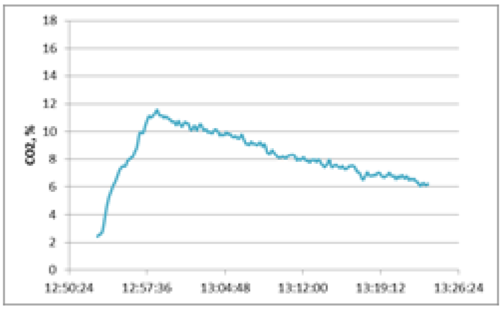
Test 2	Test 3











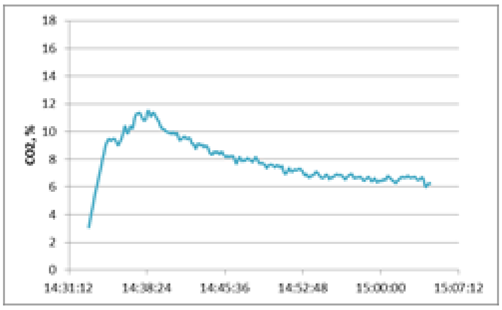


Figure A3.1e Flue gas measurement traces of OD, CO and CO2 for Appliance A, Low Output

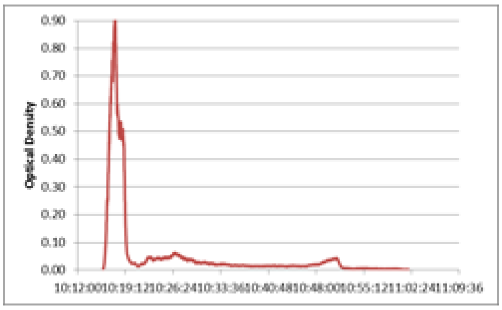
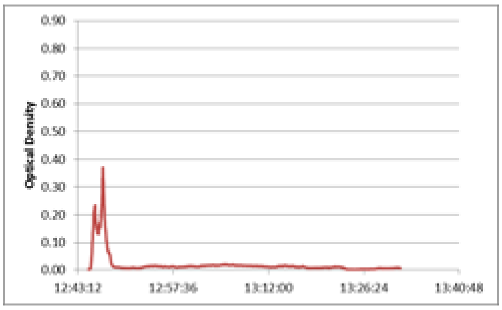
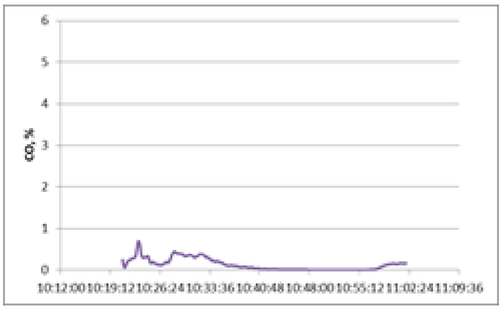
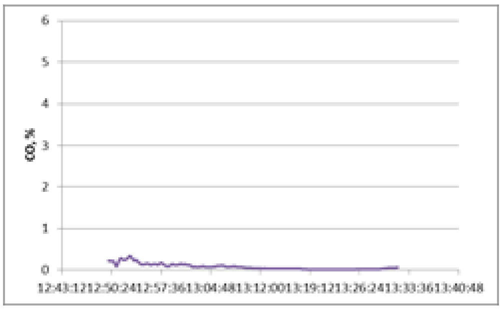
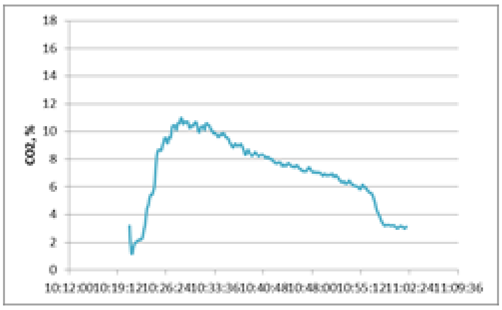
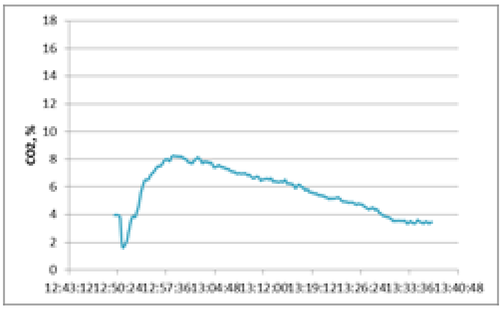
Test 4	Test 5
	
	
	

Figure A1.1f Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance B, High output

Test 1	Test 2

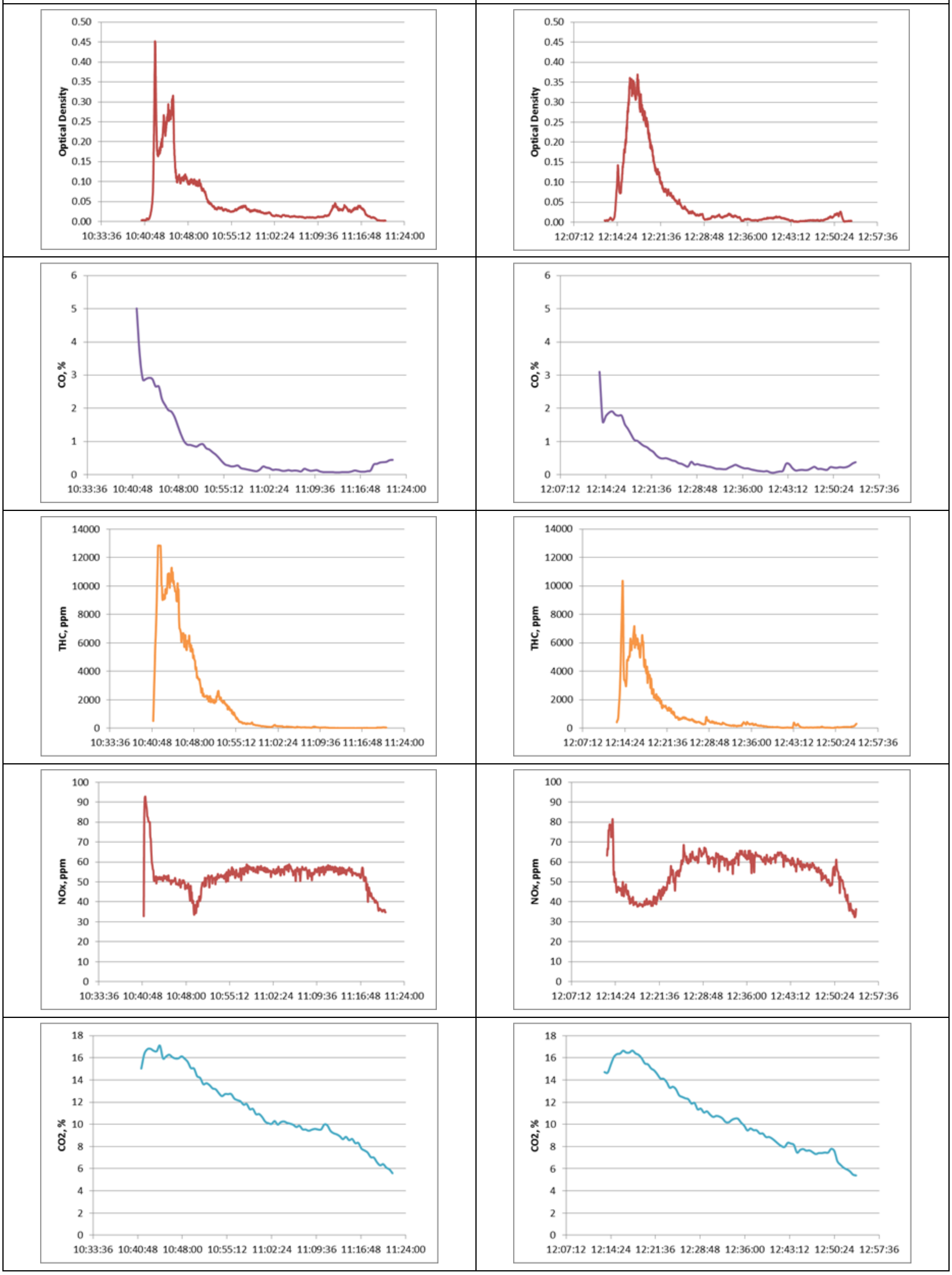


Figure A3.1g Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance B, High Output

Test 3	Test 4

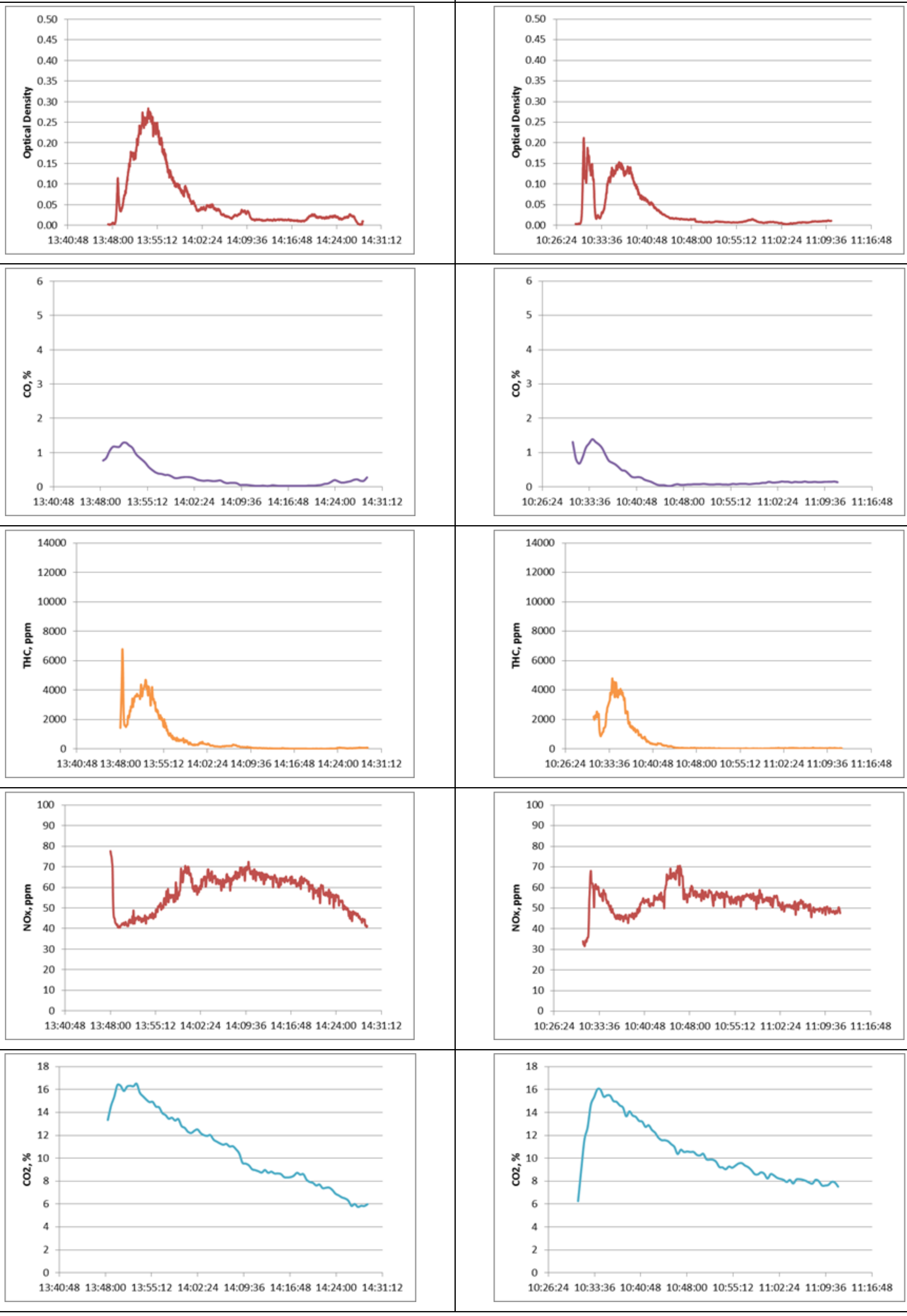


Figure A3.1h Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance B

High output Test 5	Low output Test 1

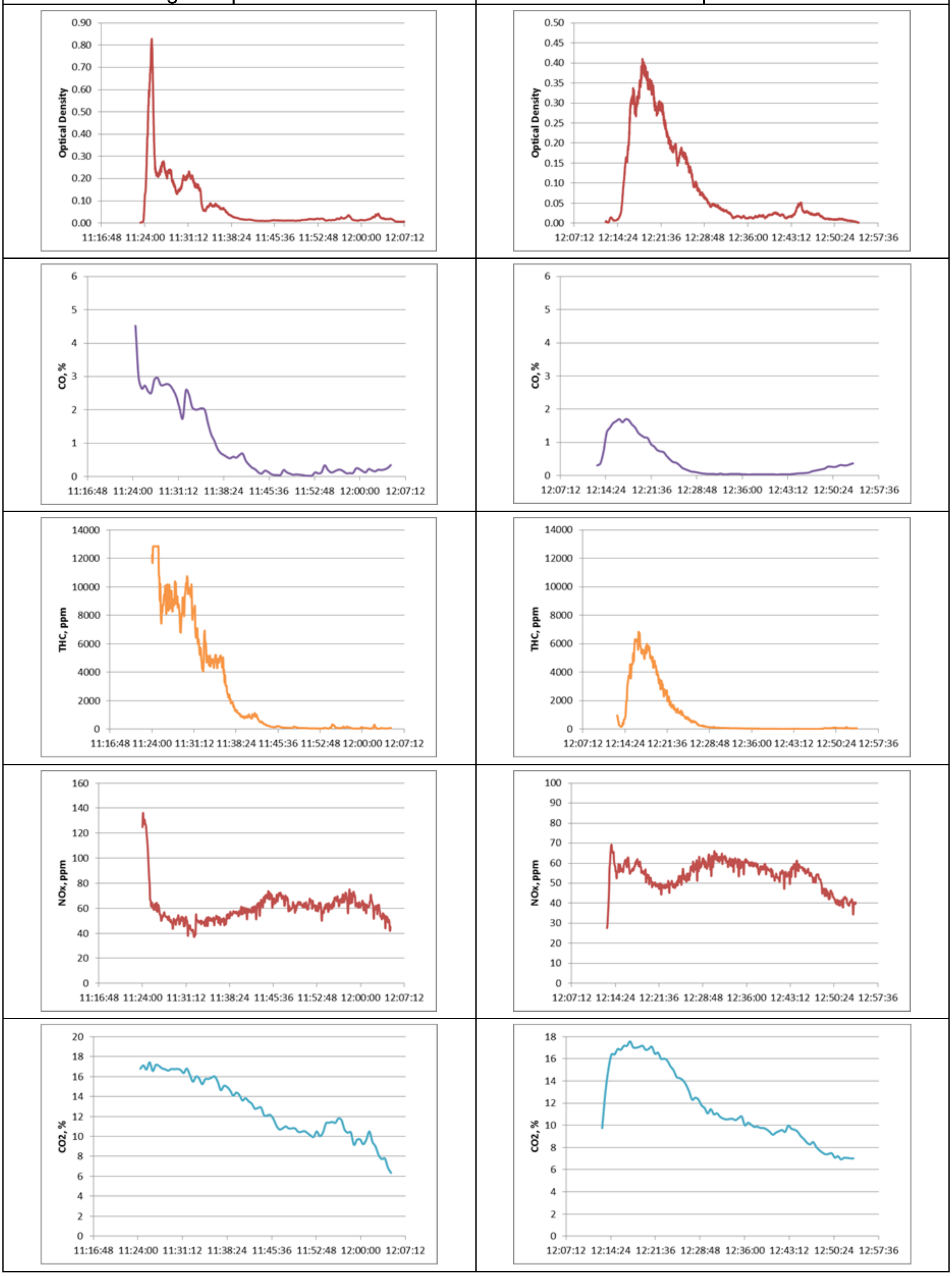
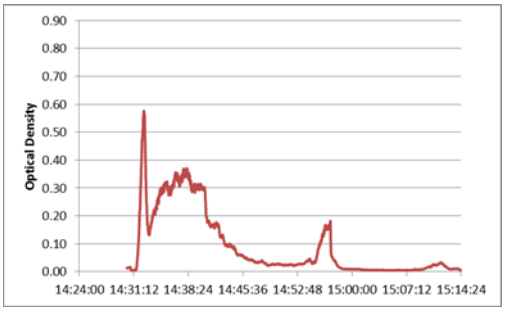
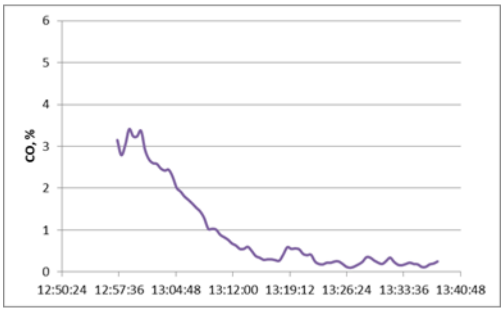
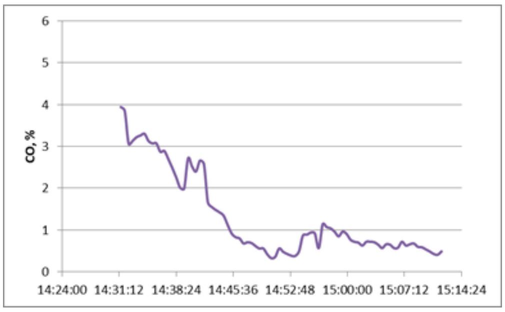


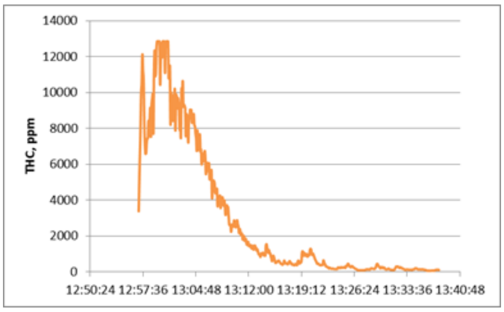
Figure A3.1i Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance B, Low Output

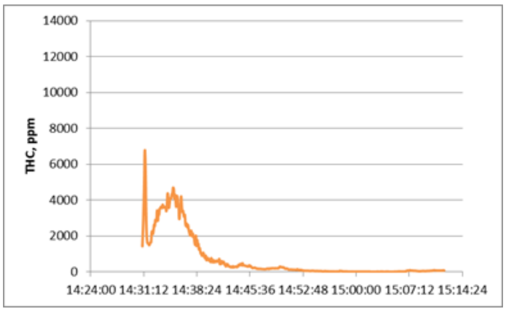
Test 2	Test 3

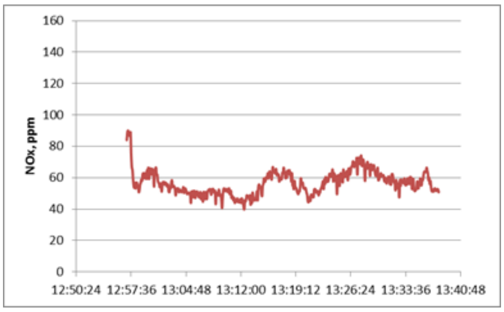


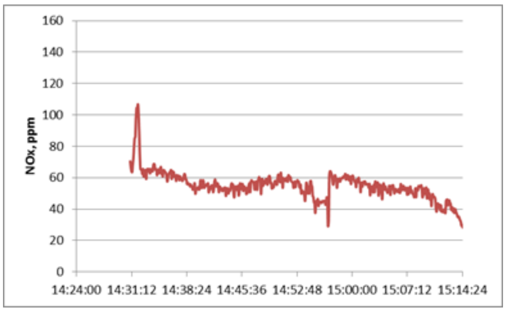


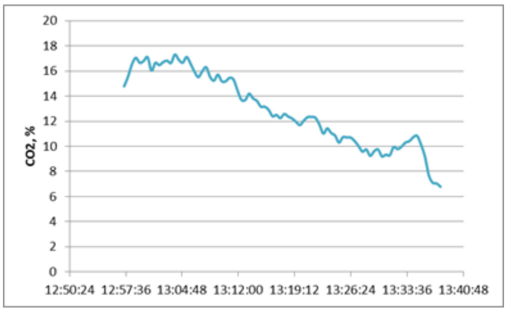












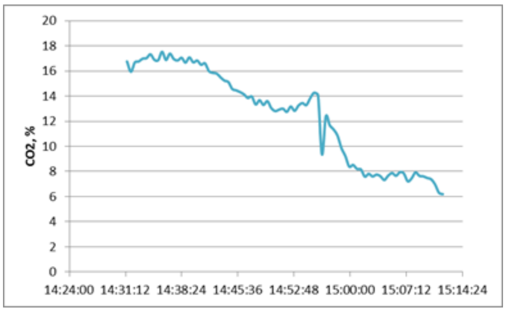


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Figure A3.1j Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance B, Low Output

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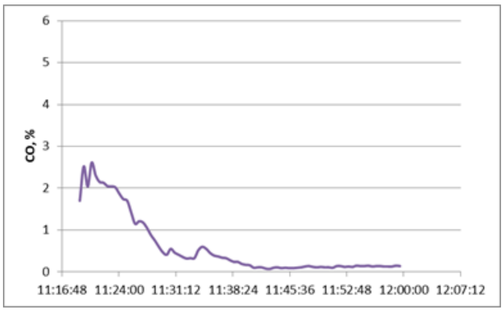
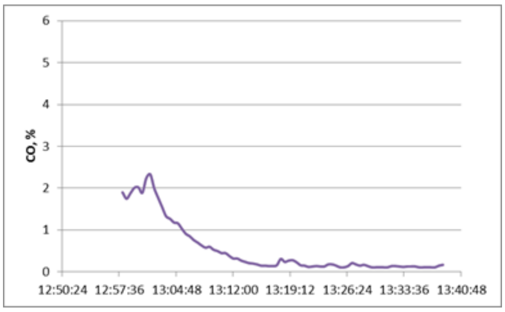
<tr><td>
</td><td>
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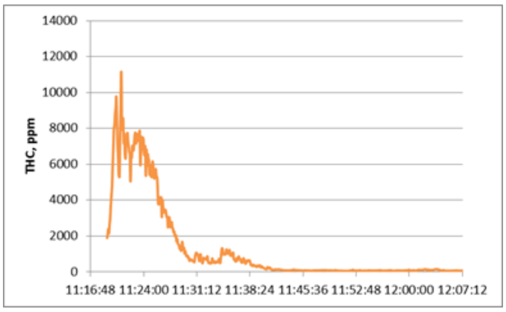
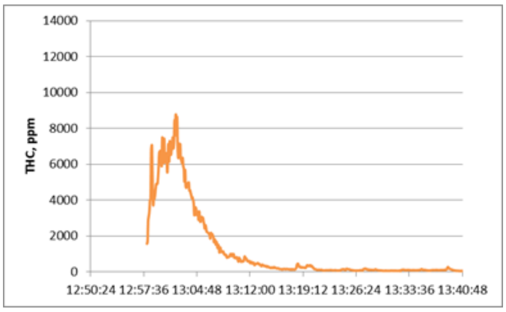
<tr><td>
</td><td>
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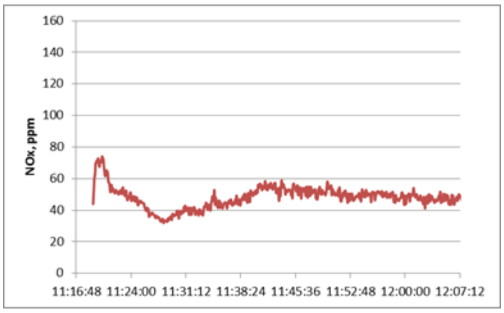
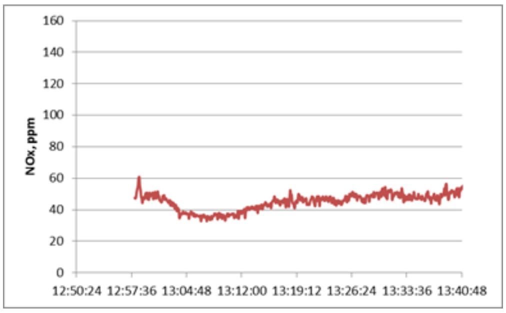
<tr><td>
</td><td>
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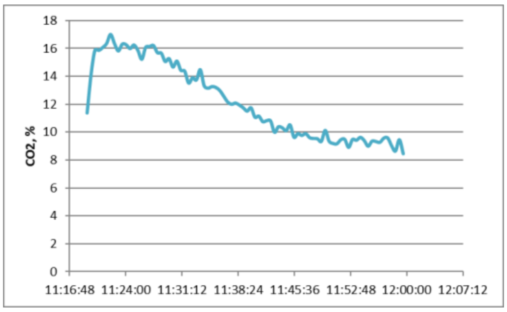
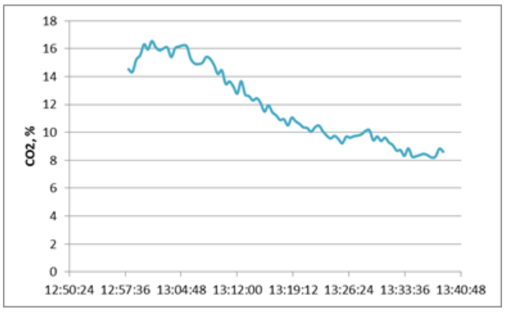
<tr><td>
</td><td>
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Figure A3.1k Flue gas measurement traces of OD, CO and CO2 for Appliance C, High Output

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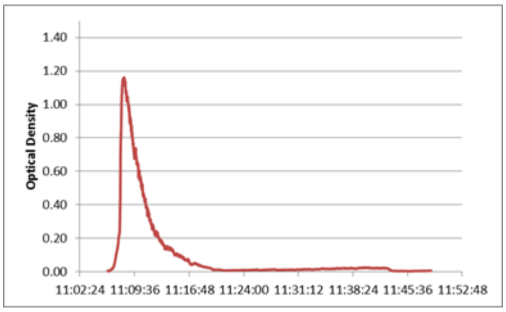
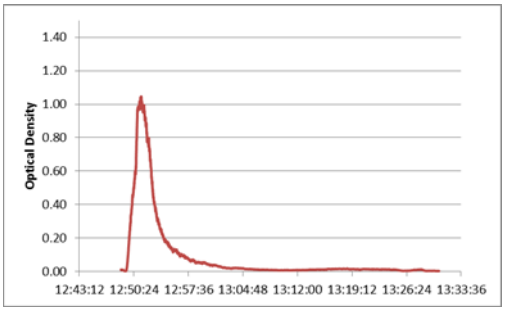
<tr><td>
</td><td>
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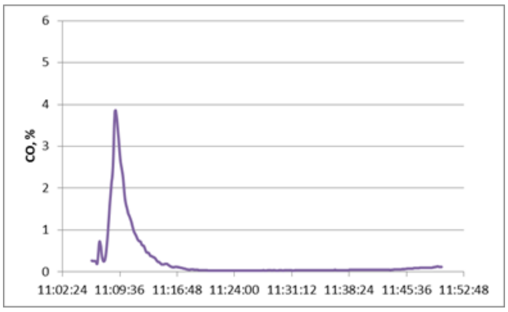
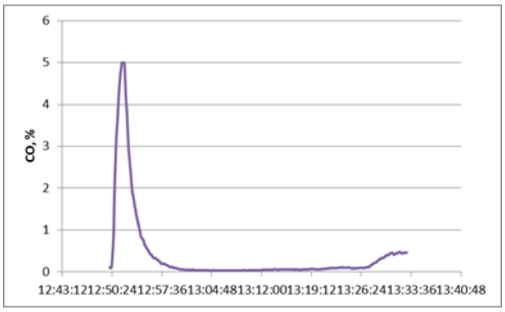
<tr><td>
</td><td>
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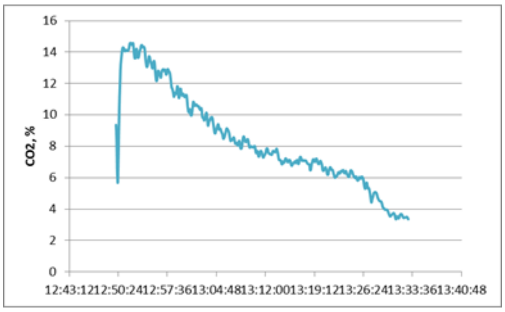
</td><td>
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Figure A3.1l Flue gas measurement traces of OD, CO and CO2 for Appliance C, High Output

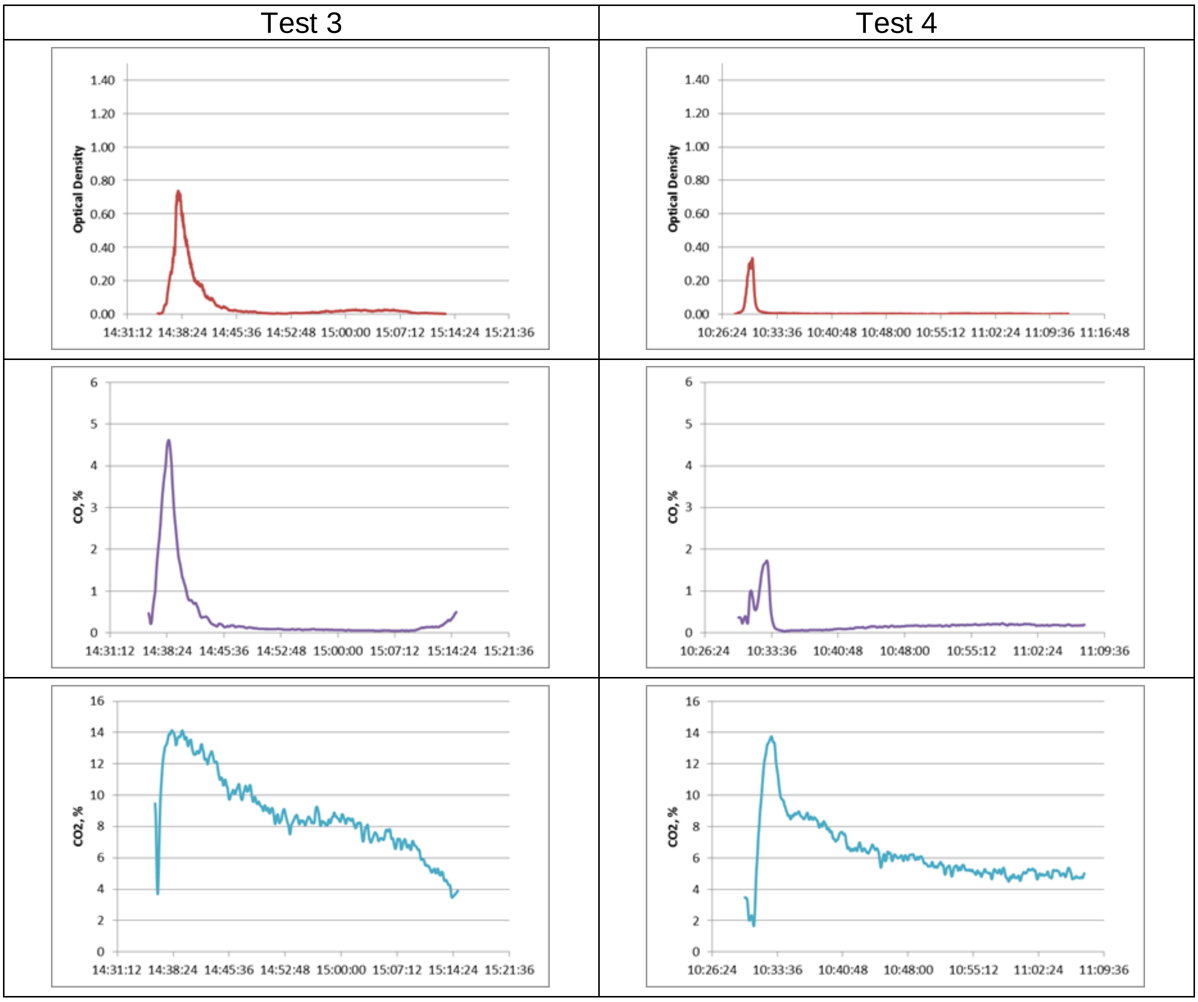

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Figure A3.1m Flue gas measurement traces of OD, CO and CO_2 for Appliance C

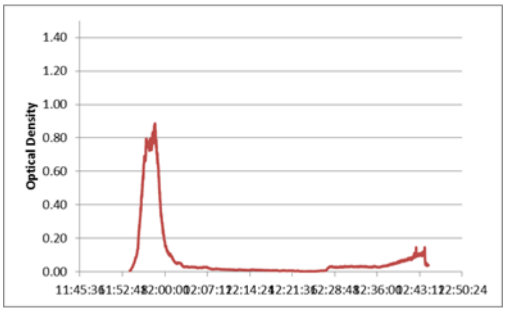
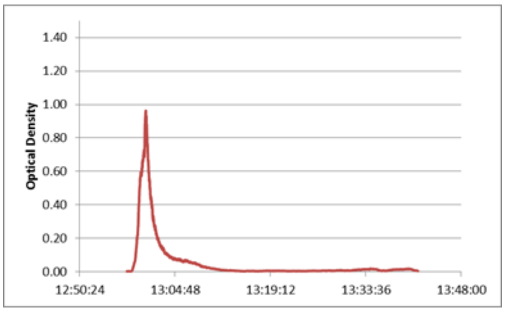
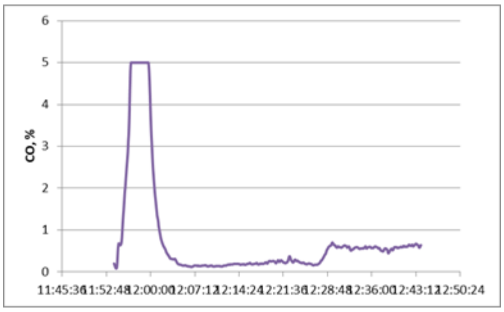
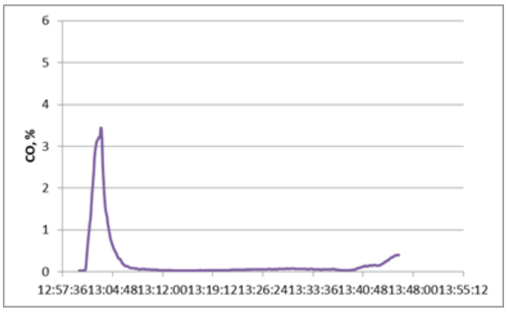
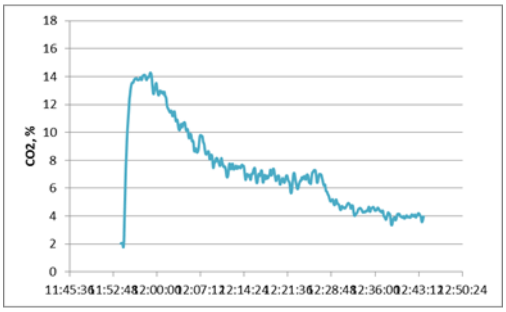
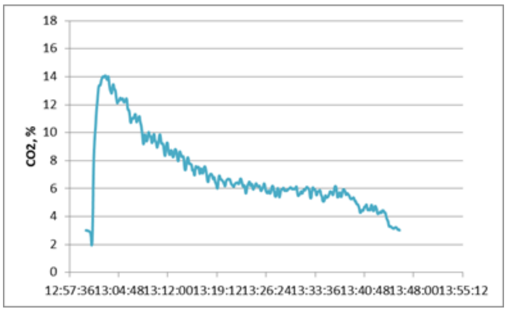
High output Test 5	Low output Test 1
	
	
	

Figure A3.1n Flue gas measurement traces of OD, CO and CO2 for Appliance C, Low Output

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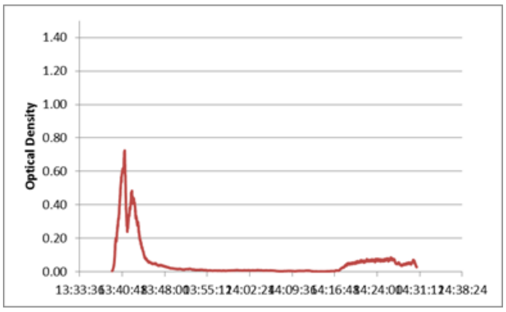
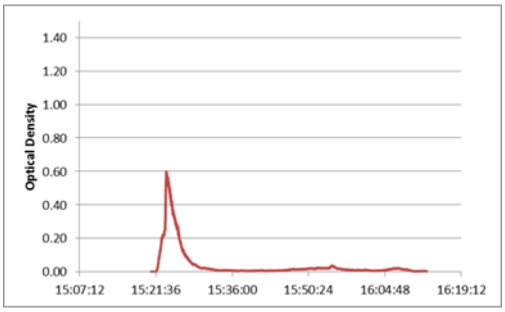
<tr><td>
</td><td>
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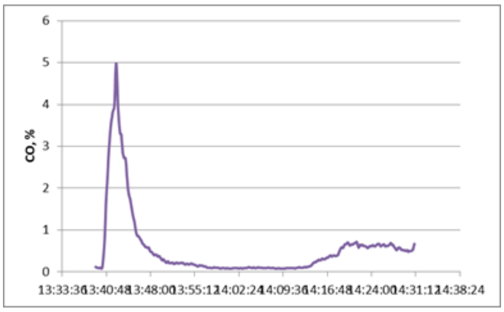
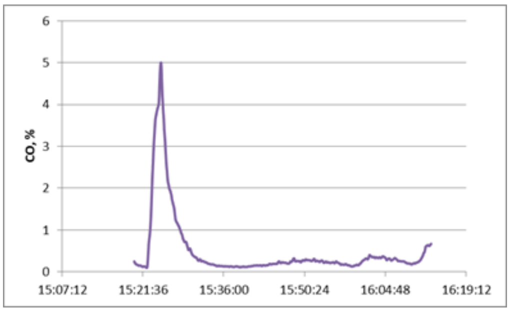
<tr><td>
</td><td>
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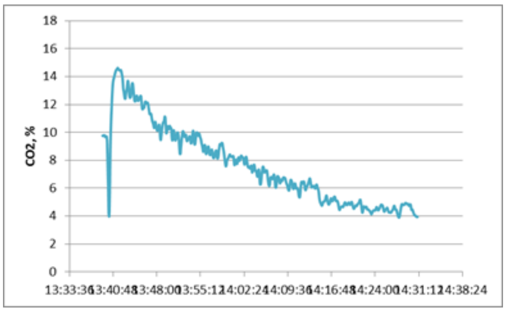
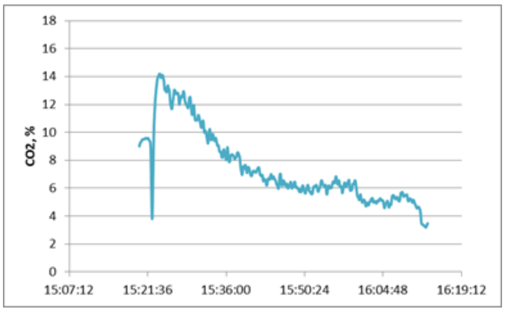
<tr><td>
</td><td>
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Figure A3.1o Flue gas measurement traces of OD, CO and CO2 for Appliance C, Low Output

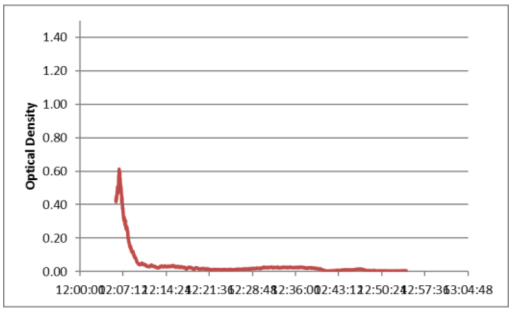
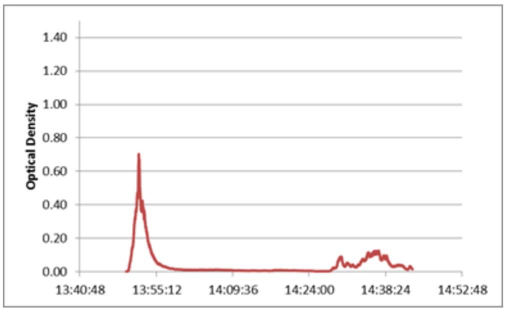
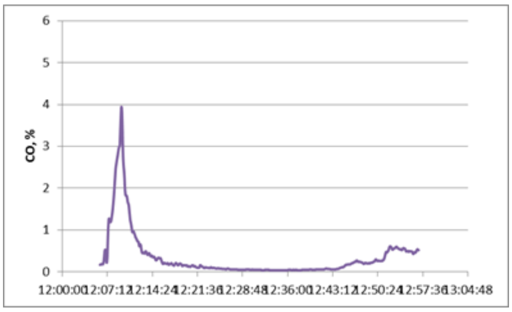
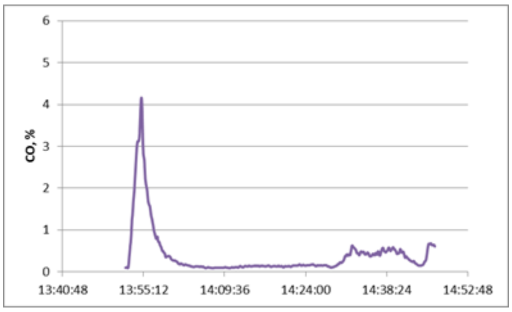
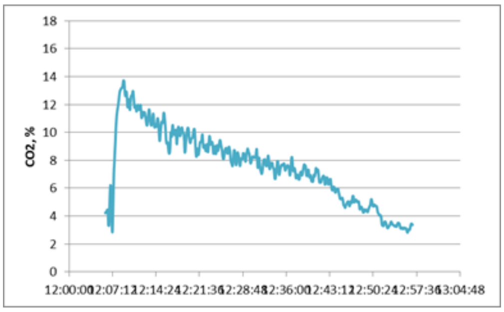
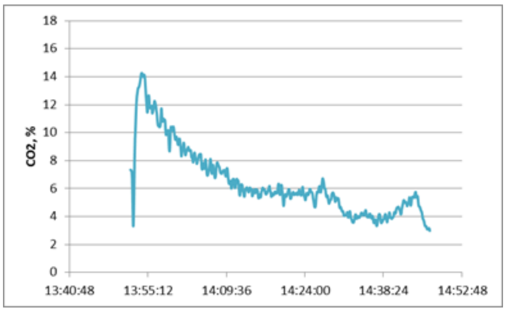
Test 4	Test 5
	
	
	

Figure A3.1p Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, High Output

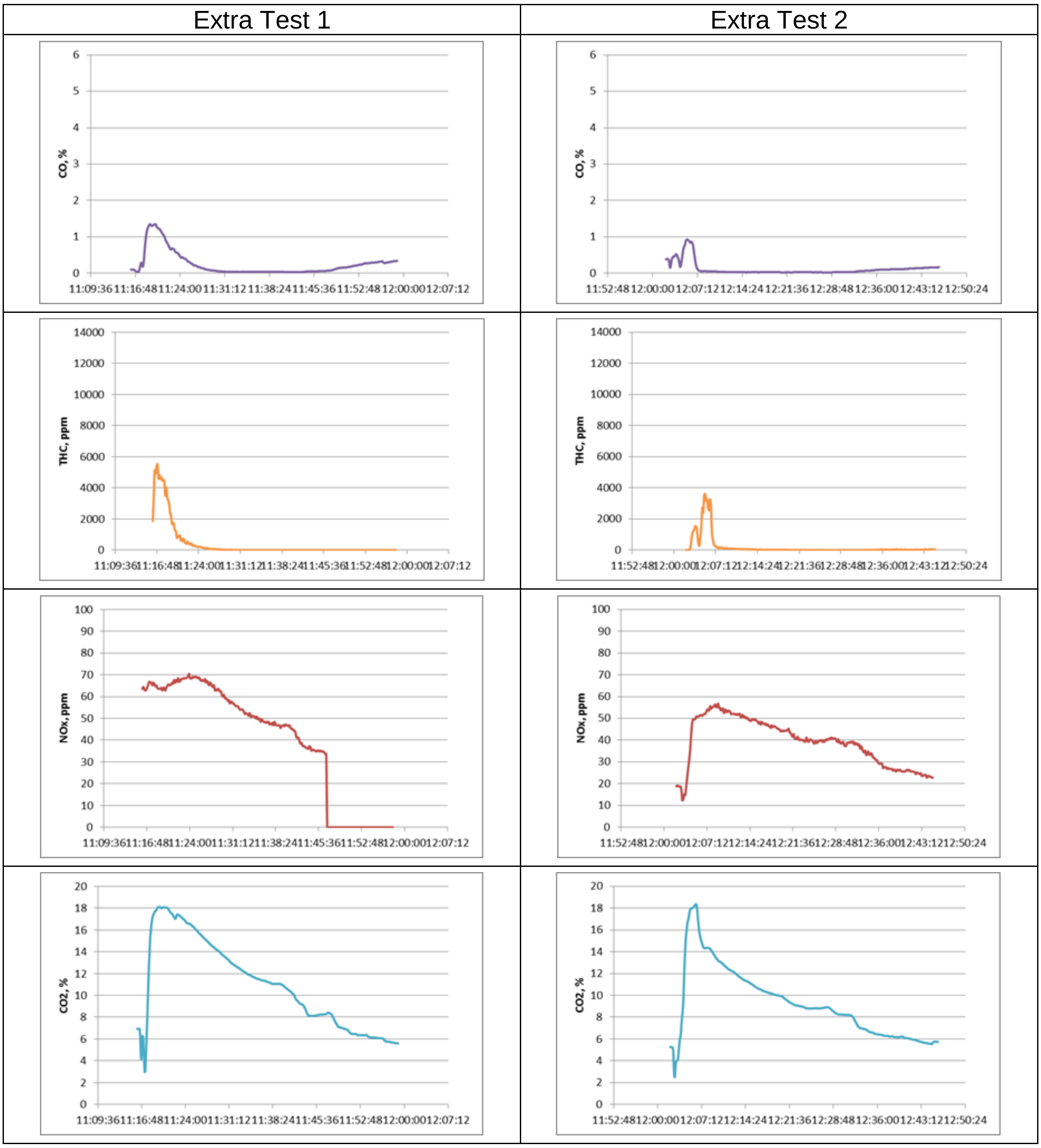


Figure A3.1q Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, High Output

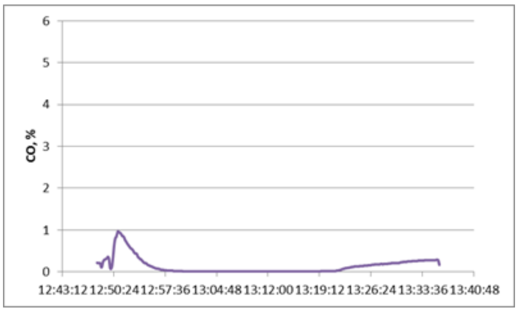
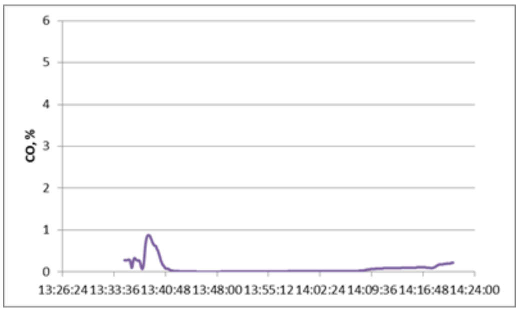
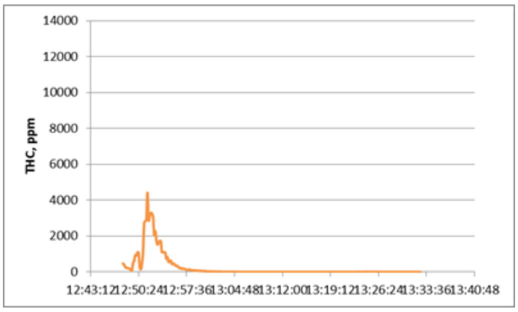
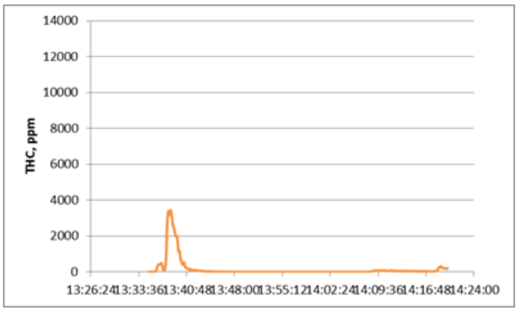
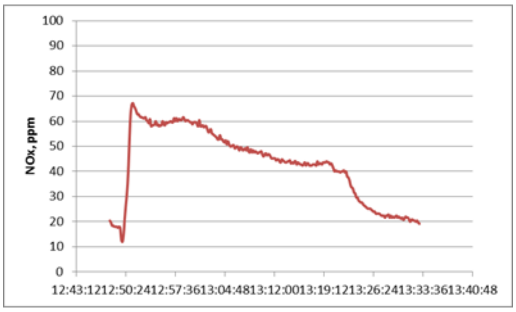
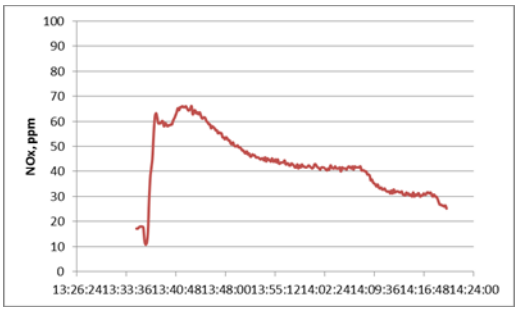
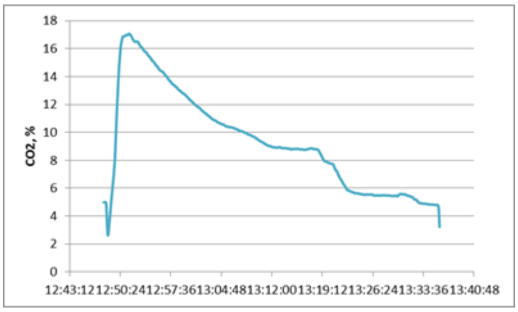
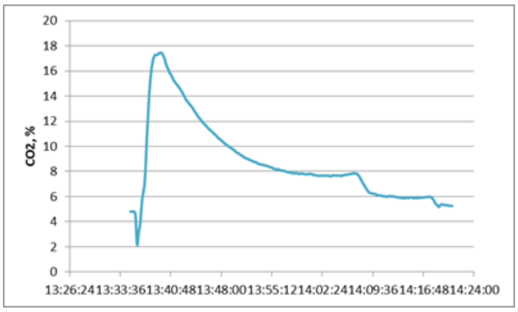
Extra Test 3	Extra Test 4
	
	
	
	

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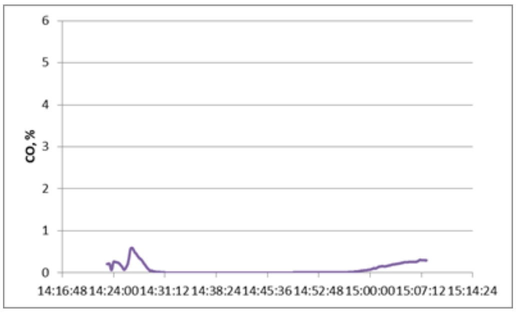
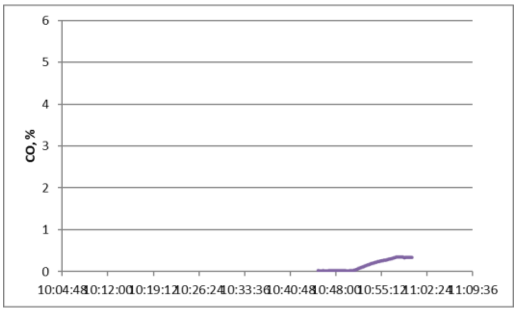
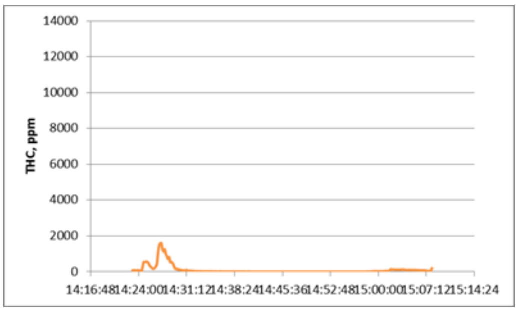
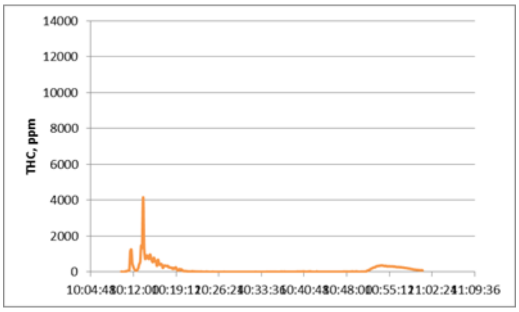
Figure A3.1r Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C,

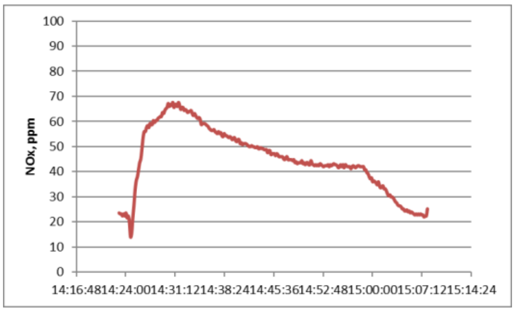
High Output, Extra Test 5	Low Output, Extra Test 1

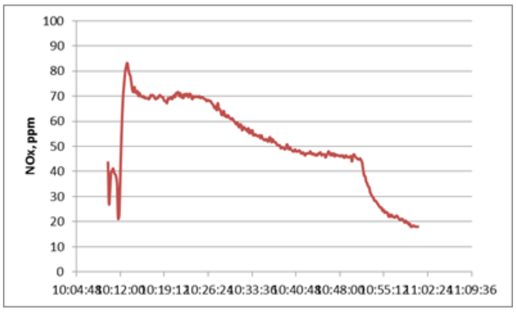


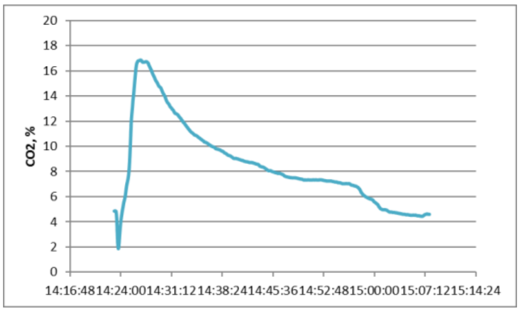












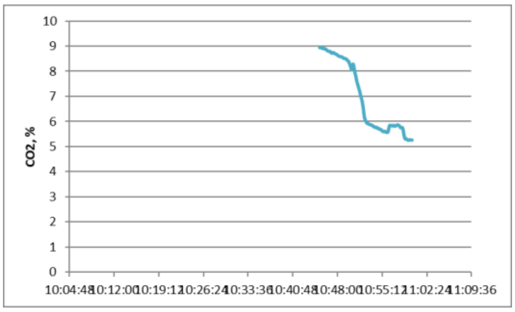


Figure A3.1s Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, Low Output

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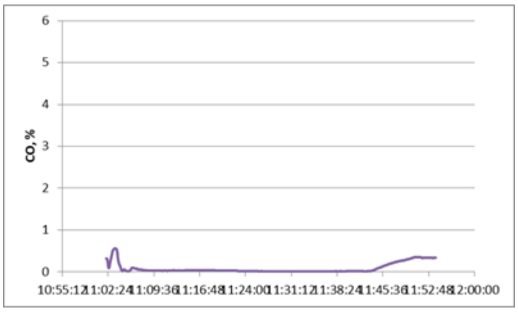
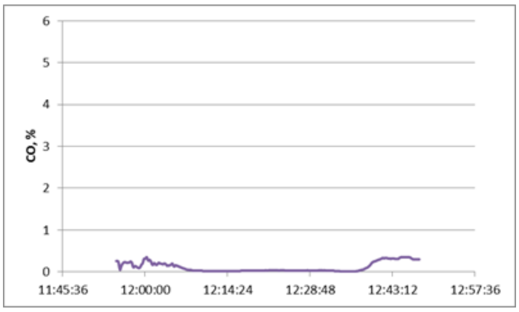
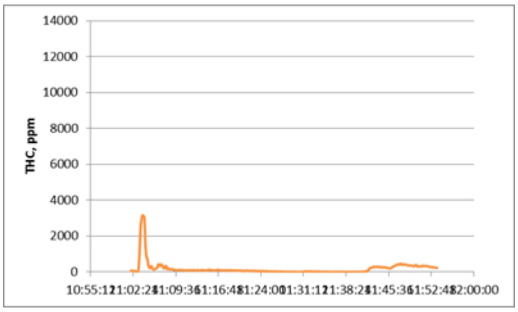
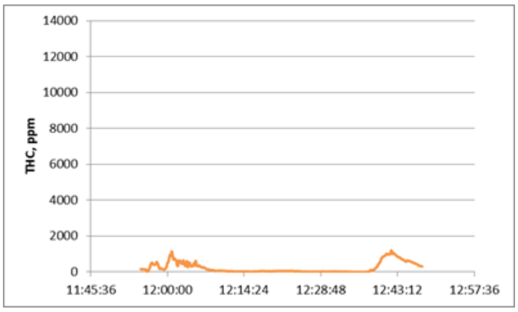
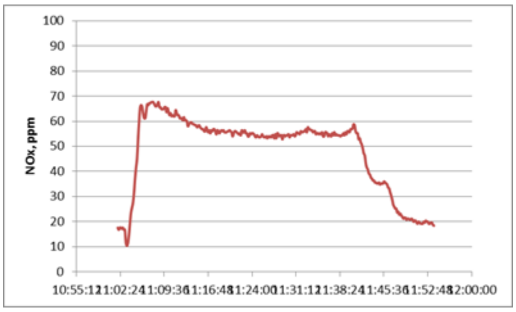
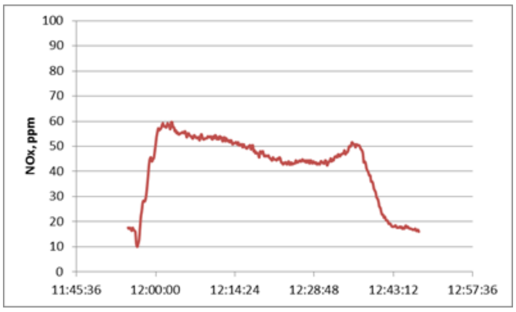
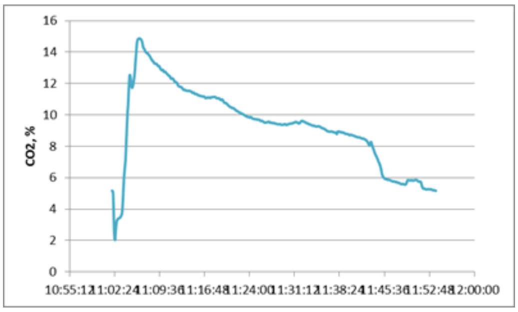
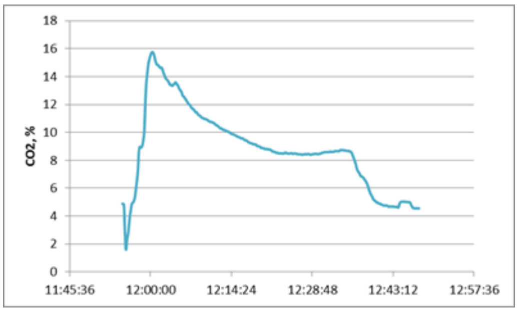
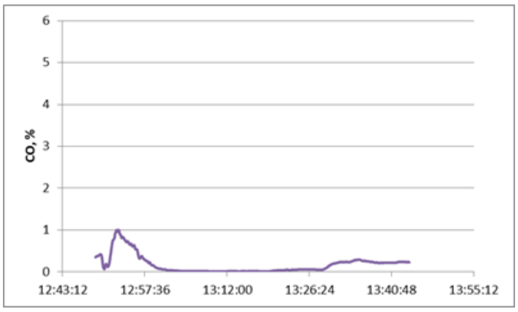
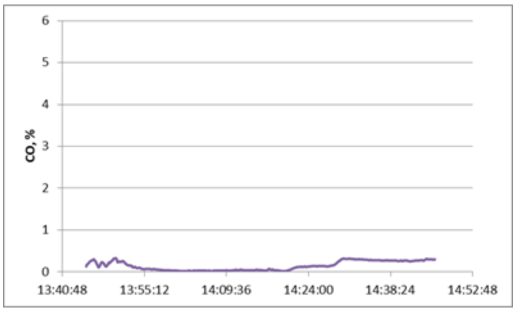
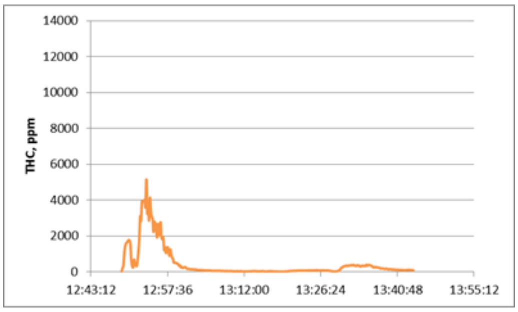
	
	
	
	

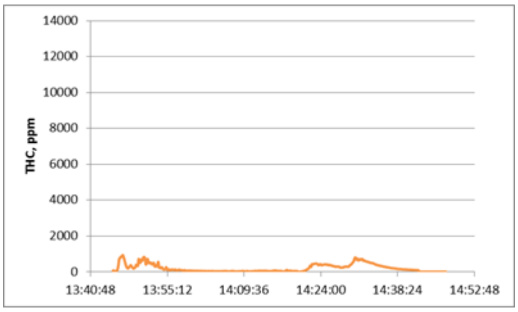
Figure A3.1t Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, Low Output

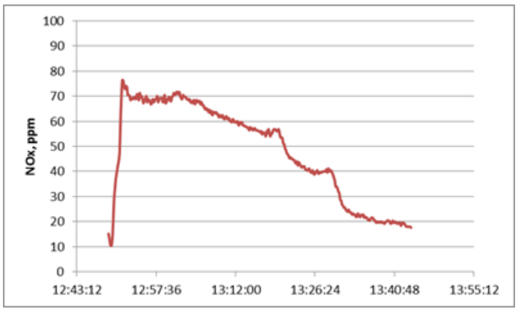
Extra Test 4	Extra Test 5

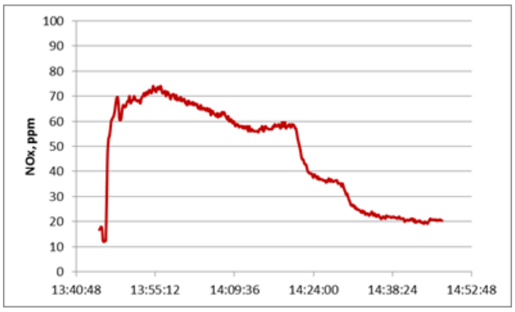


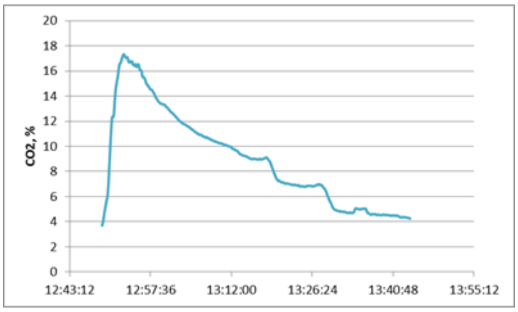


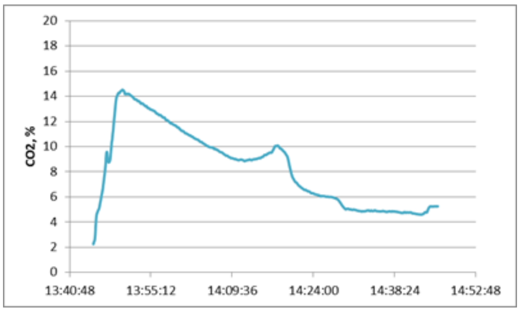












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60097-2

Figure A3.1u Flue gas measurement traces of OD, CO and CO_2 for Appliance D, High Output

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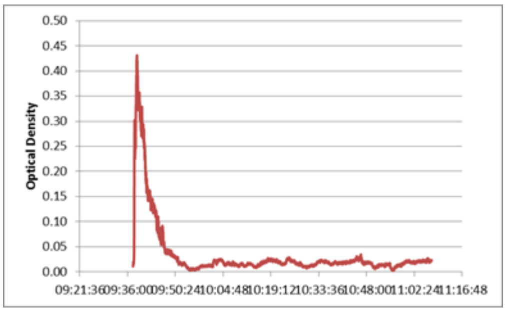
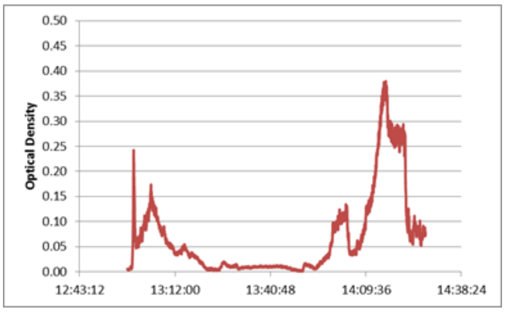
<tr><td>
</td><td>
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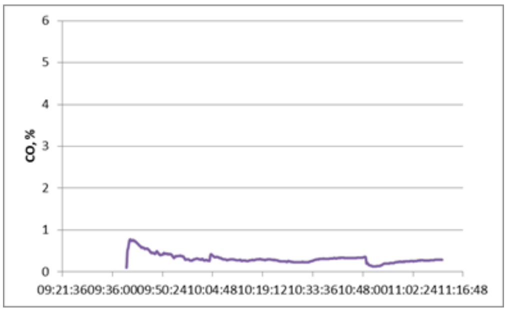
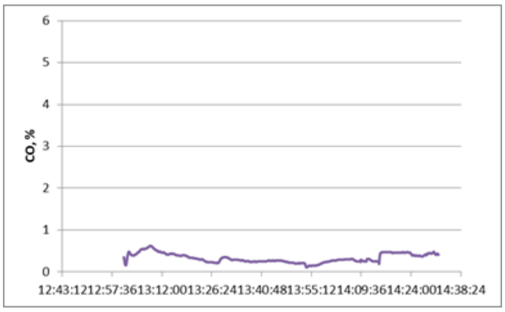
<tr><td>
</td><td>
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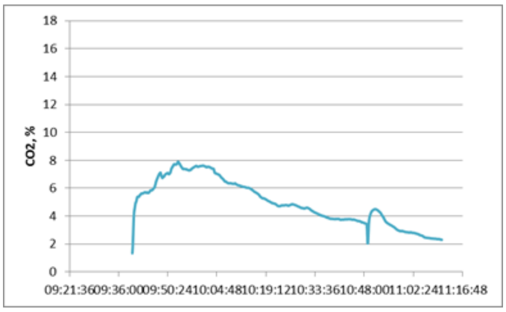
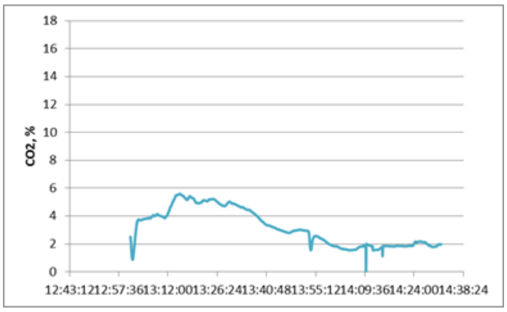
<tr><td>
</td><td>
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Figure A3.1v Flue gas measurement traces of OD, CO and CO2 for Appliance D, High Output

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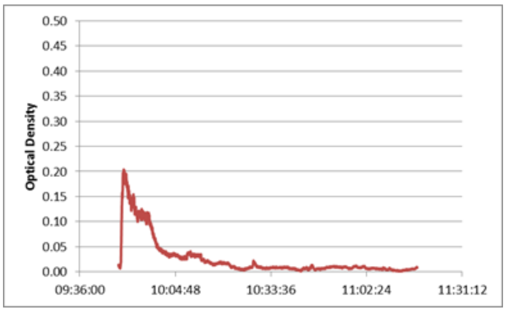
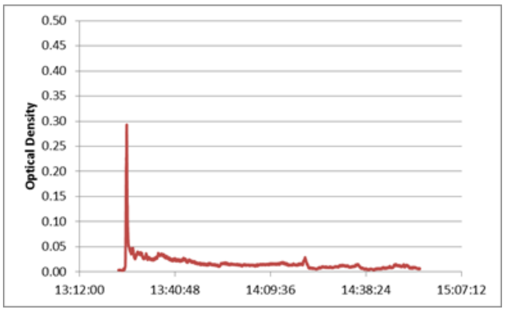
<tr><td>
</td><td>
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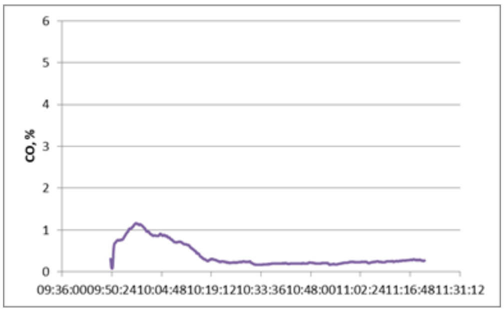
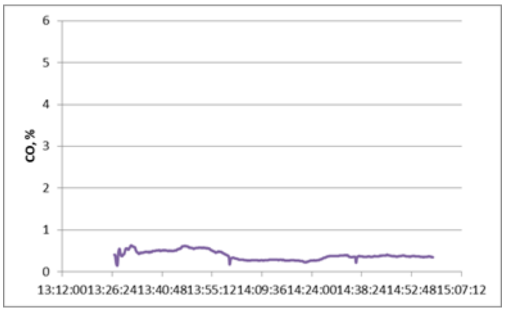
<tr><td>
</td><td>
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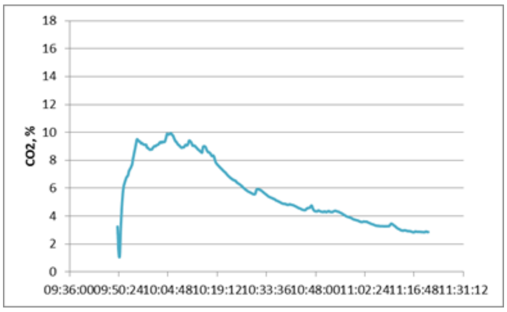
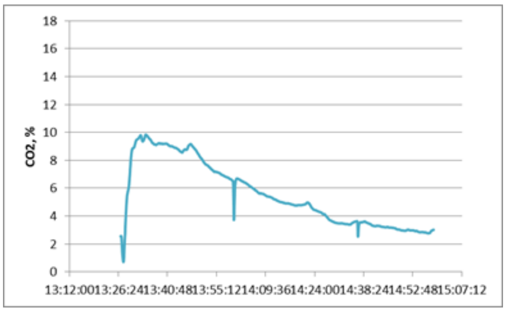
<tr><td>
</td><td>
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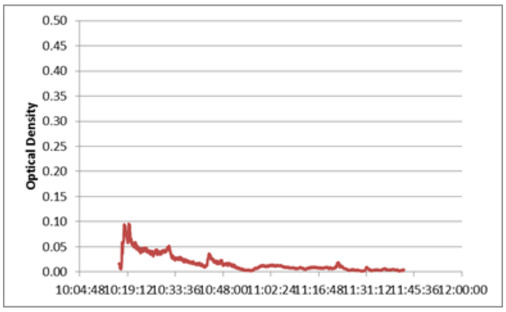
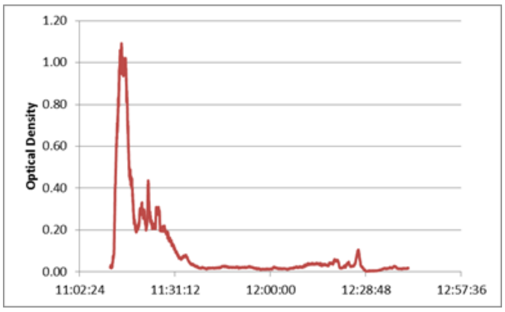
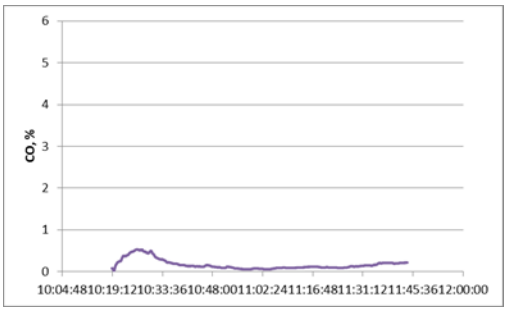
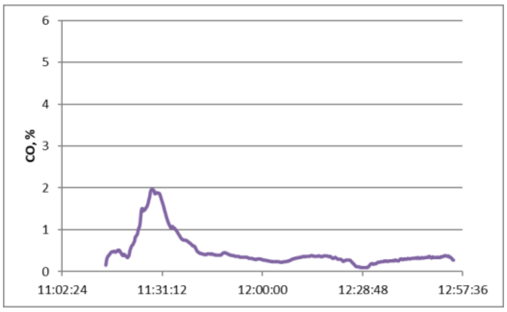
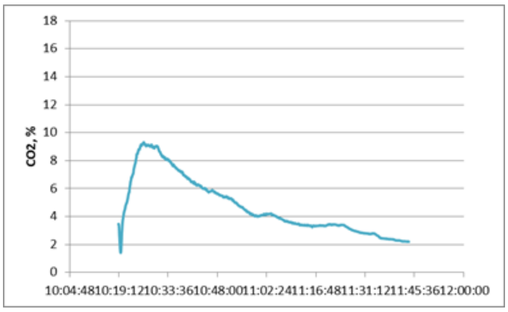
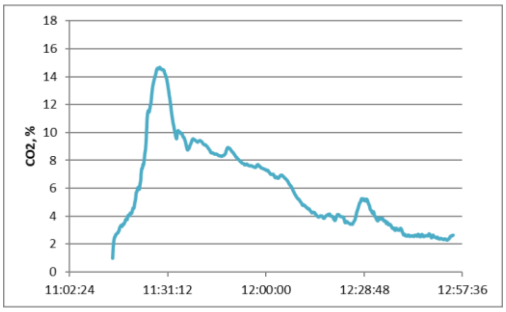
Figure A3.1w Flue gas measurement traces of OD, CO, THC, NOx and CO2 for Appliance D

High Output, Test 5	Low Output, Test 1
	
	
	

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60097-2

Figure A3.1x Flue gas measurement traces of OD, CO and CO2 for Appliance D, Low Output

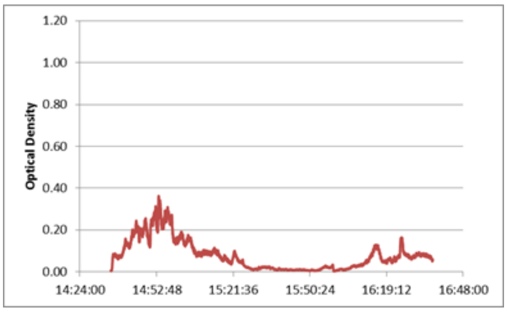
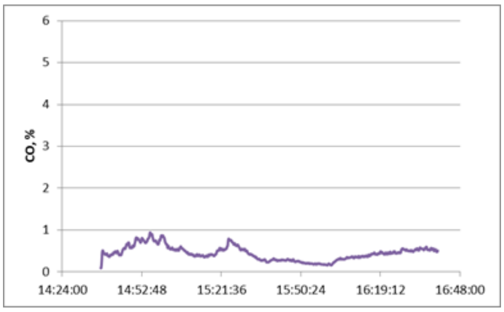
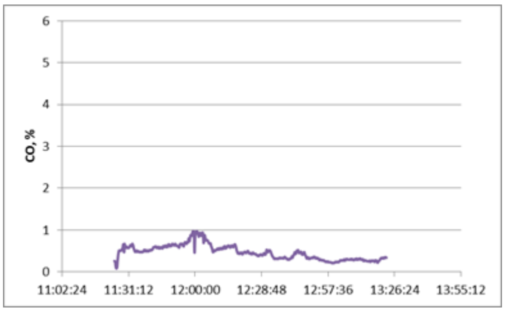
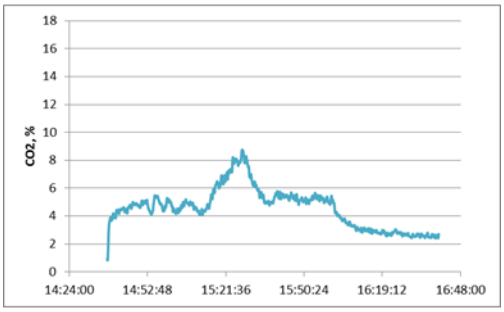
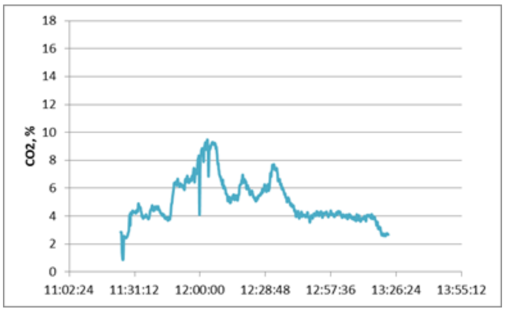
Test 2	Test 3
	
	
	

Figure A3.1y Flue gas measurement traces of OD, CO and CO2 for Appliance D, Low Output

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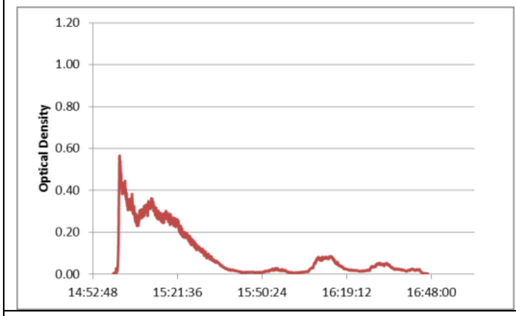
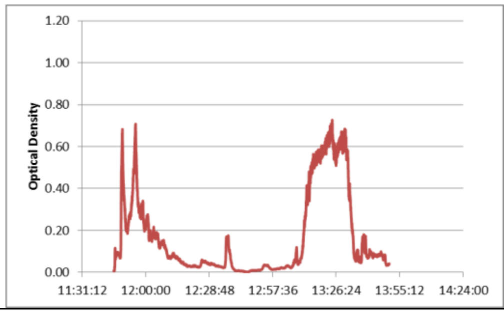
<tr><td>
</td><td>
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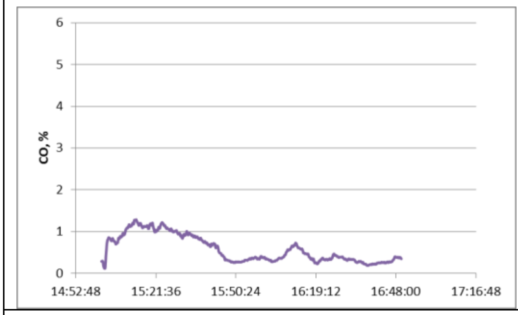
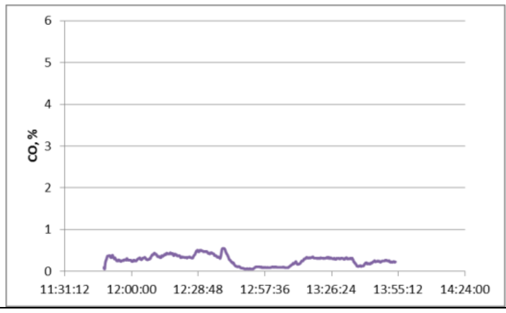
<tr><td>
</td><td>
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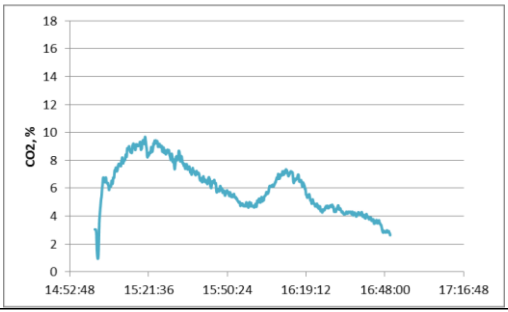
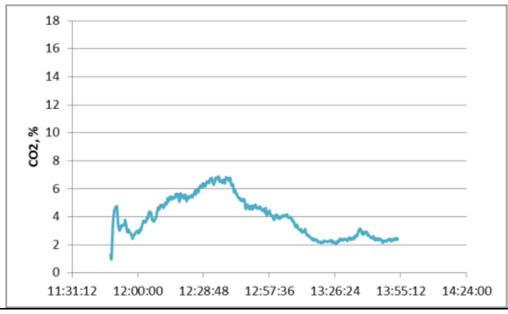
<tr><td>
</td><td>
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Figure A3.1z Flue gas measurement traces of CO and CO2 for Appliance E, High Output

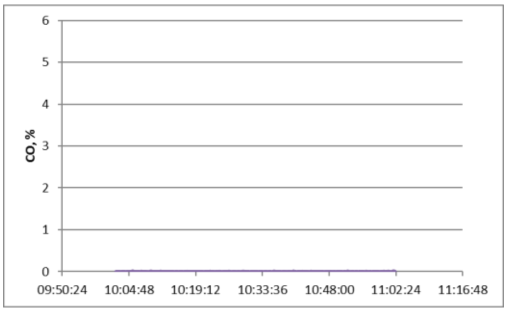
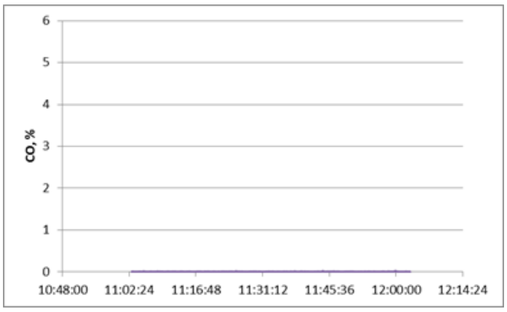
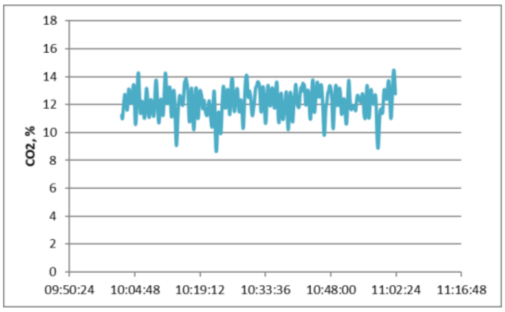
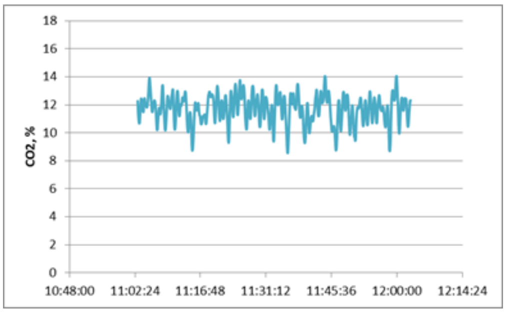
Test 1	Test 2
	
	

Figure A3.1aa Flue gas measurement traces of CO and CO2 for Appliance E, High Output

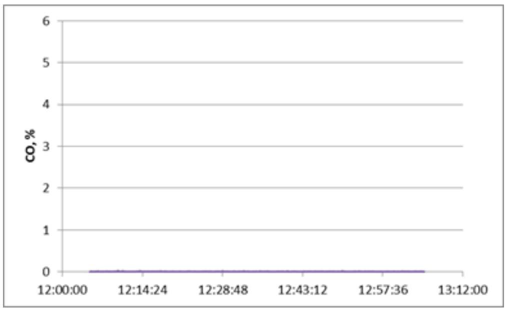
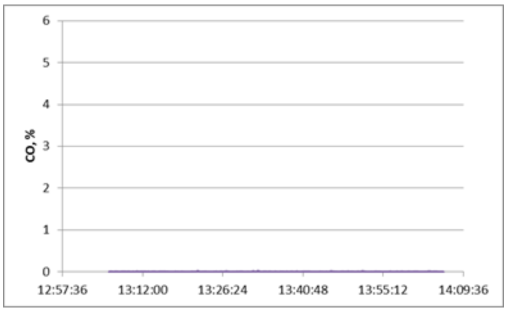
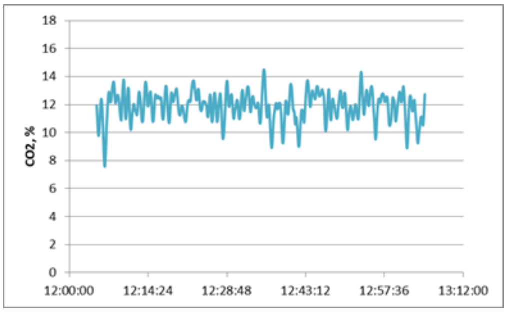
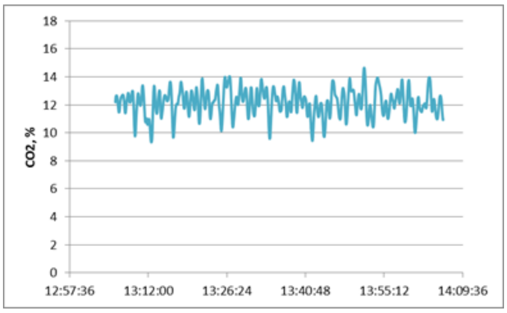
Test 3	Test 4
	
	

Figure A3.1ab Flue gas measurement traces of CO and CO2 for Appliance E

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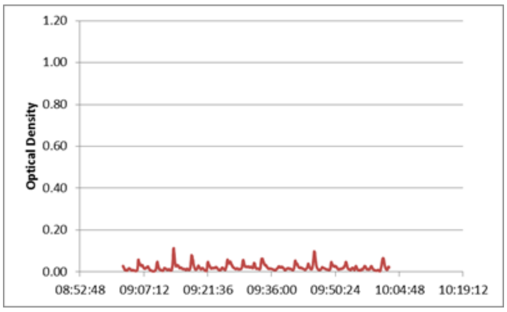
<tr><td></td><td>
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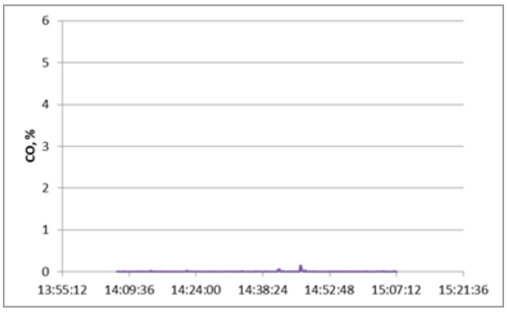
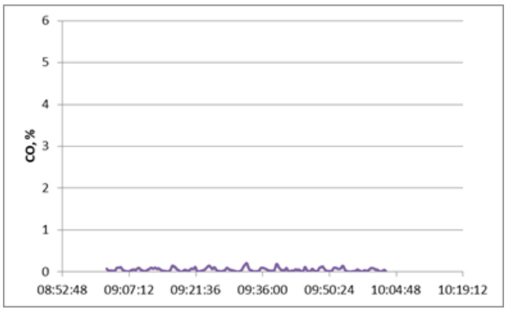
<tr><td>
</td><td>
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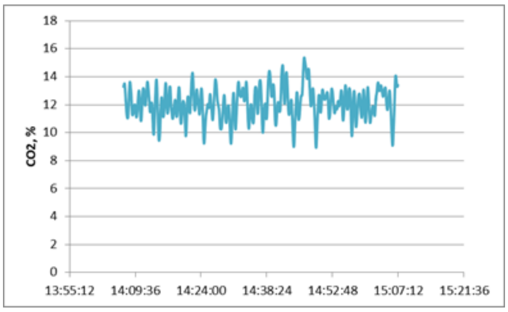
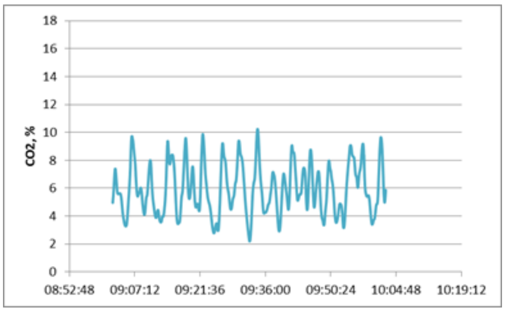
<tr><td>
</td><td>
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Figure A3.1ac Flue gas measurement traces of OD, CO and CO2 for Appliance E, High Output

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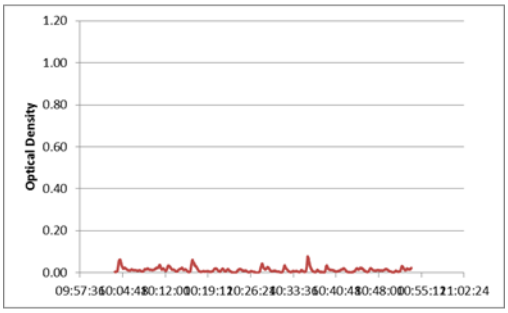

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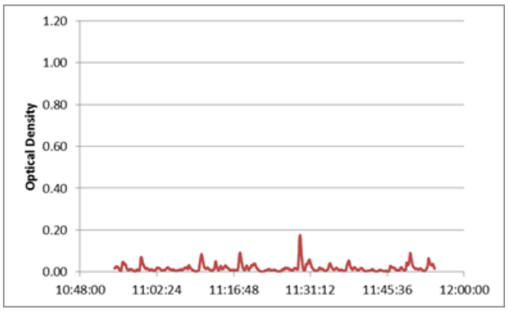

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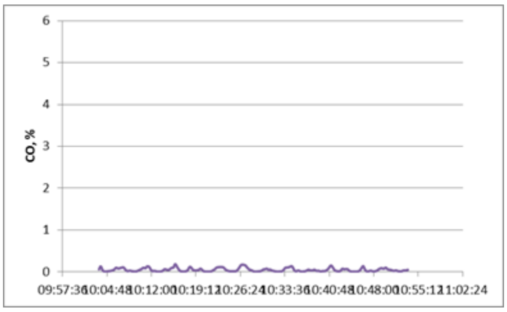

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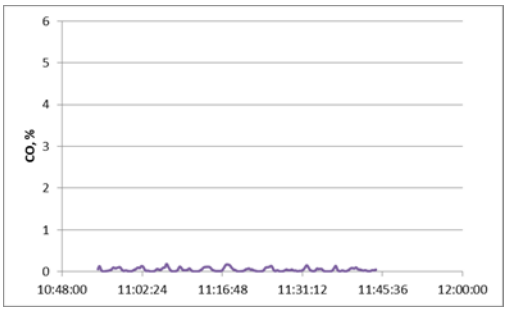

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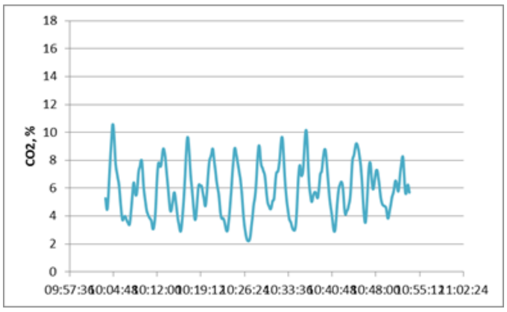

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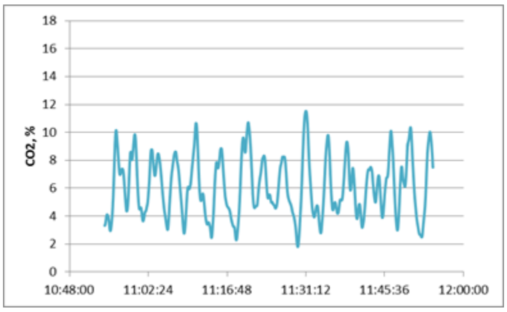

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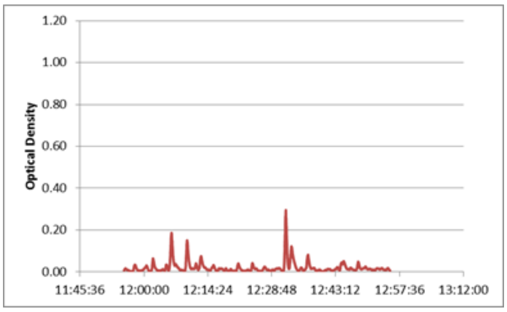
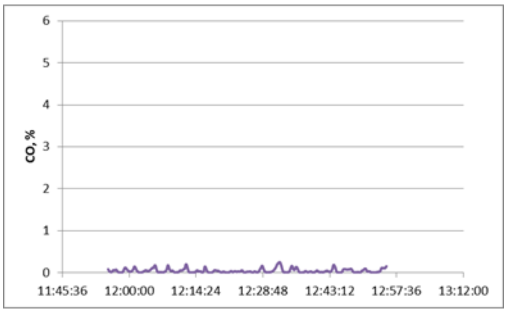
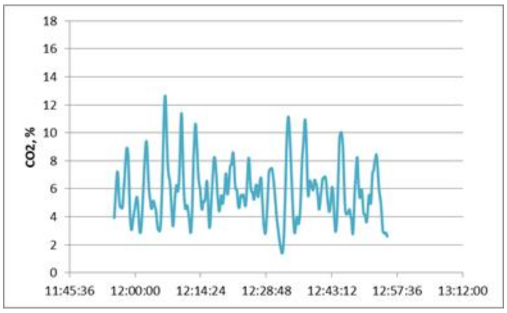
Figure A3.1ad Flue gas measurement traces of OD, CO and CO2 for Appliance E, High Output

Test 4







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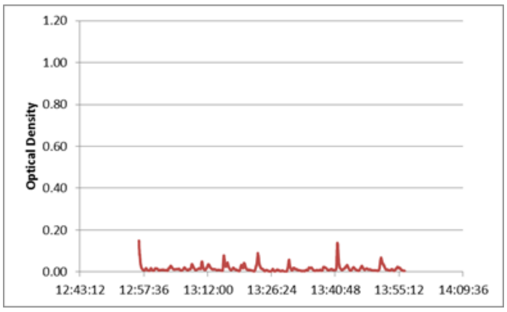

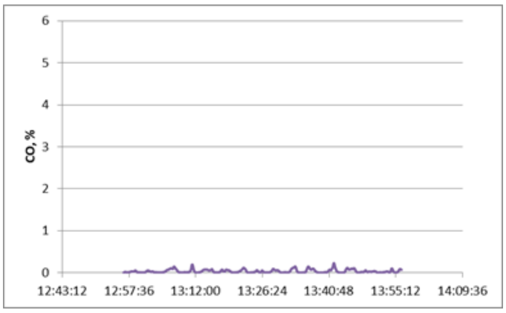

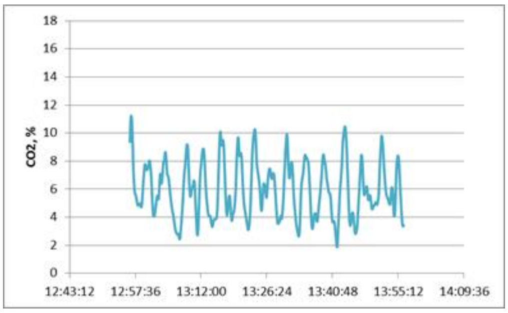

Figure A3.1ae Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, High Output

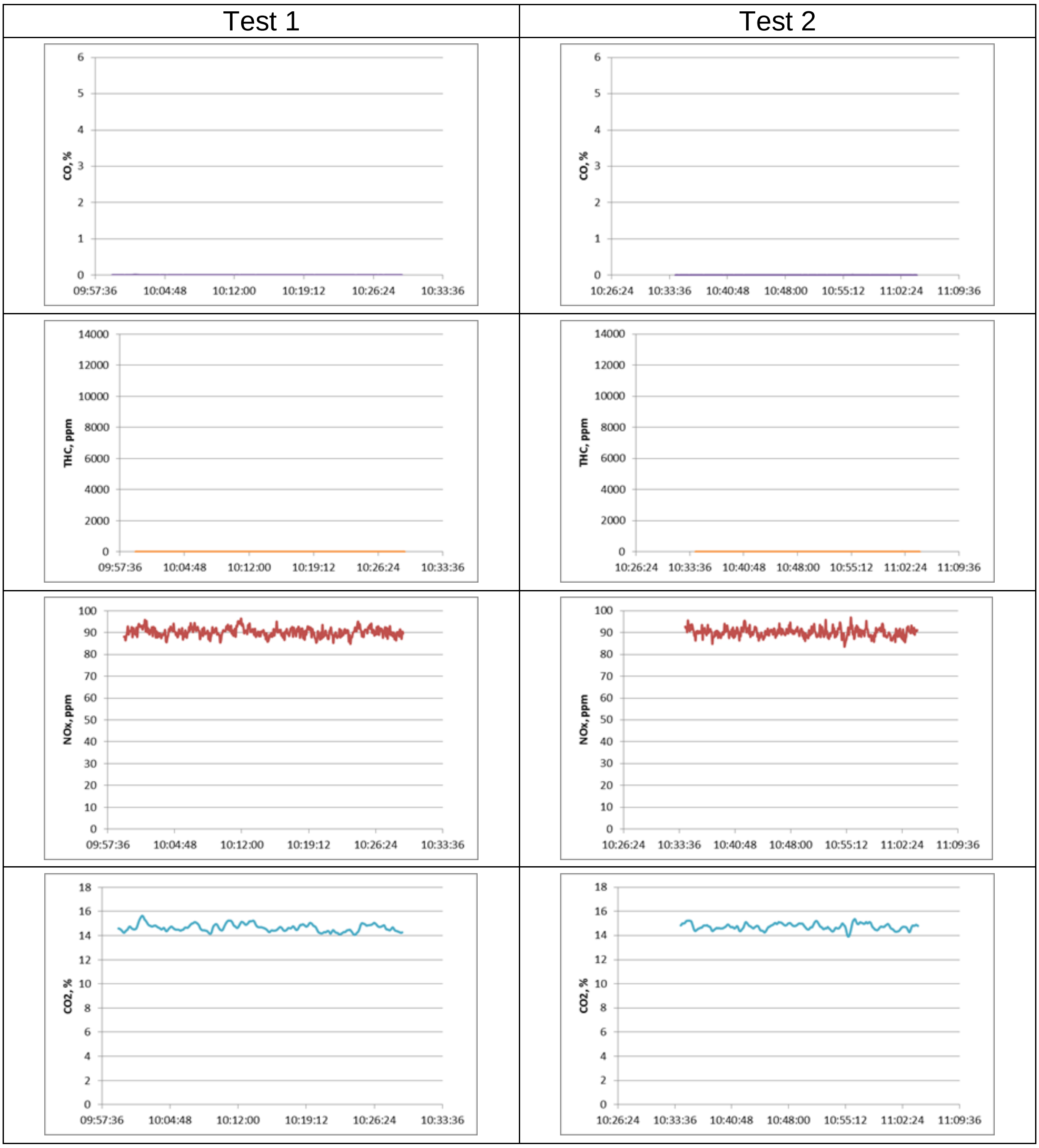

Figure A3.1af Flue gas measurement traces of CO, NOx, THC and CO2 for Appliance F, High Output, Test 3 (left) and Test 4 (right)

Test 3	Test 4

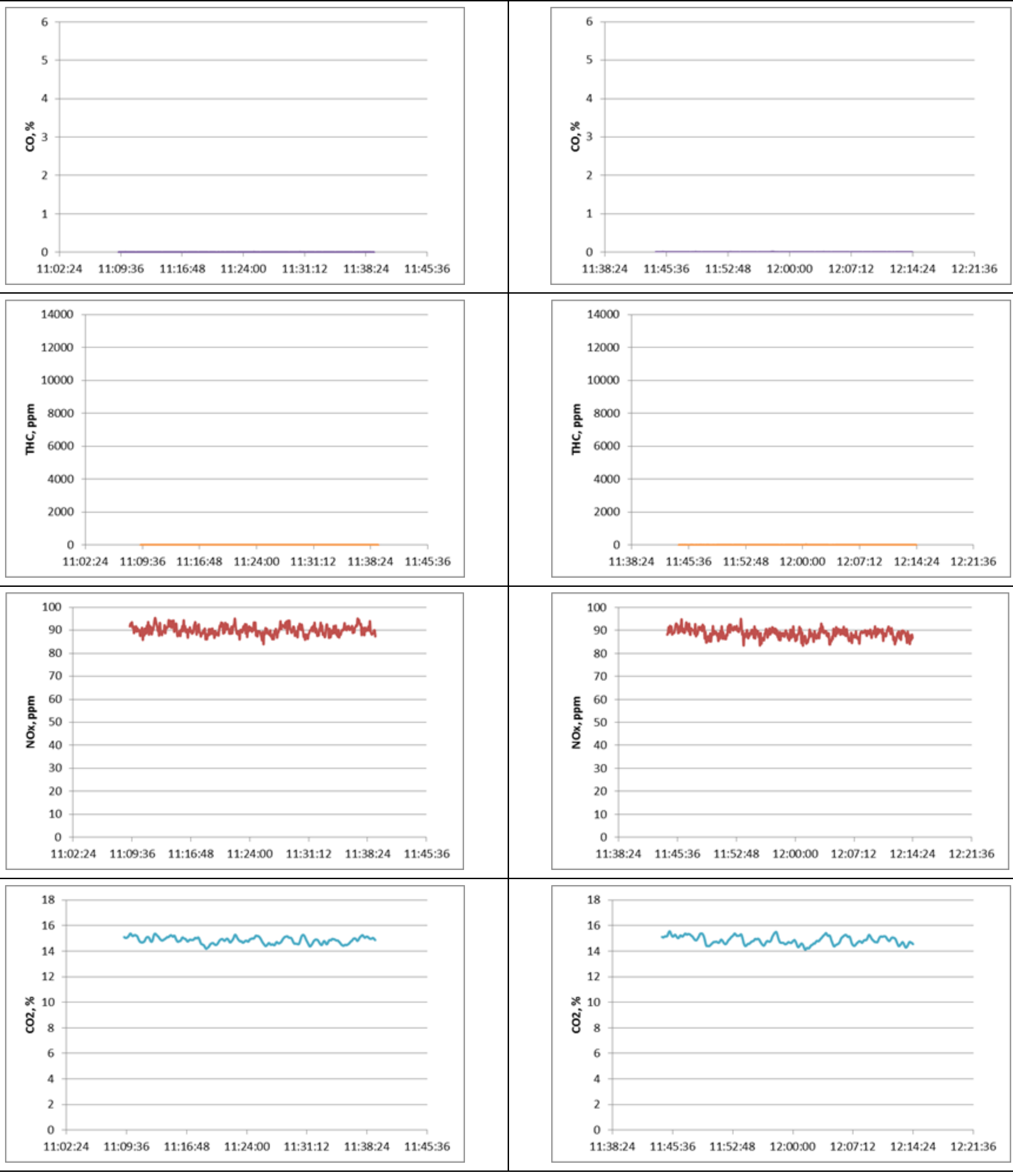

Figure A3.1ag Flue gas measurement traces of CO, NOx, THC and CO2 for Appliance F

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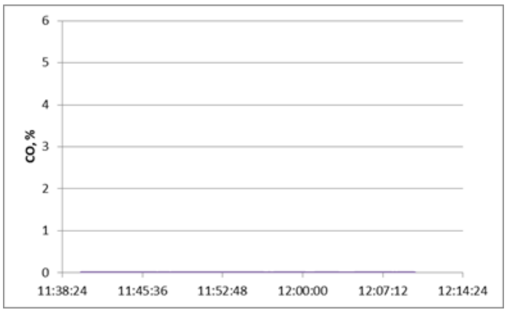
</td><td>
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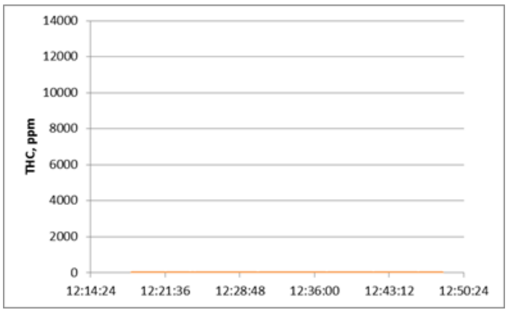
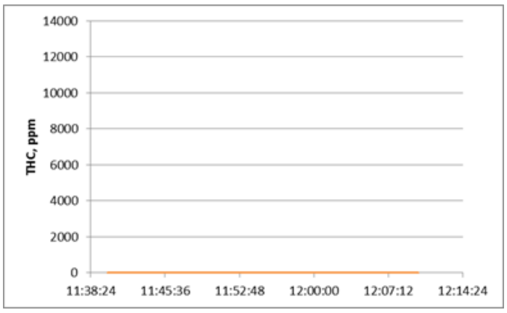
<tr><td>
</td><td>
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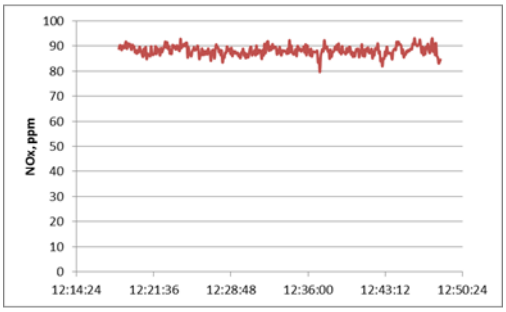
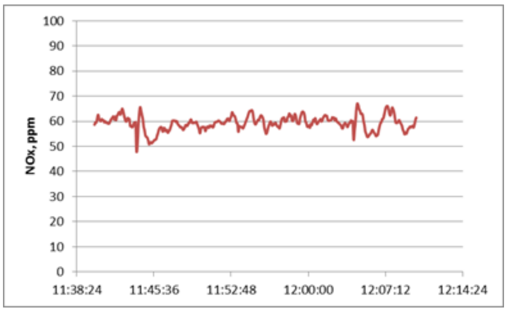
<tr><td>
</td><td>
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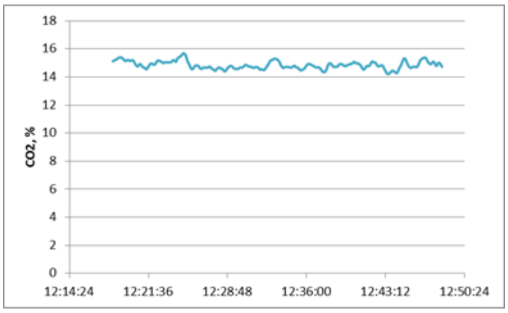
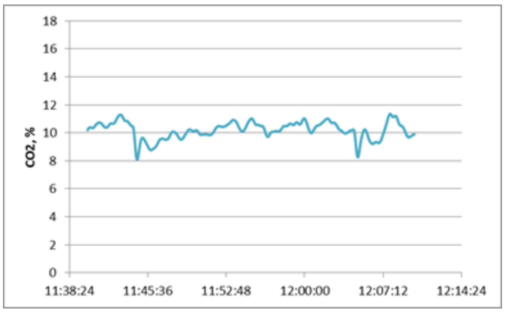
<tr><td>
</td><td>
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Figure A3.1ah Flue gas measurement traces of CO, NOx, THC and CO2 for Appliance F, Low Output

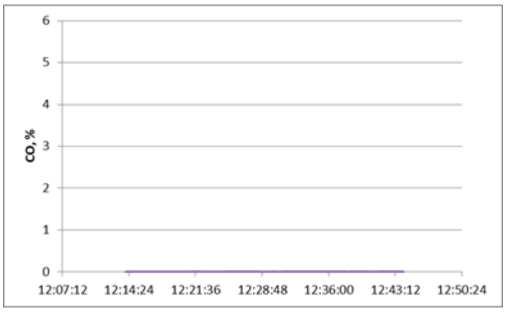
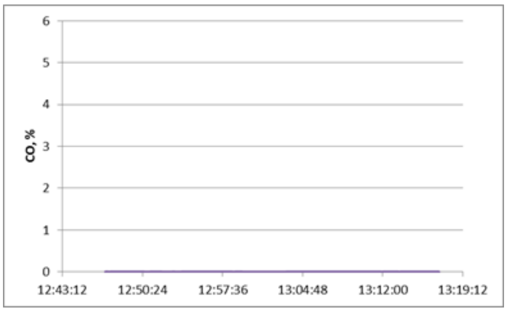
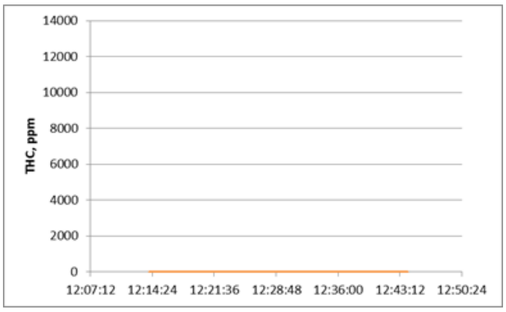
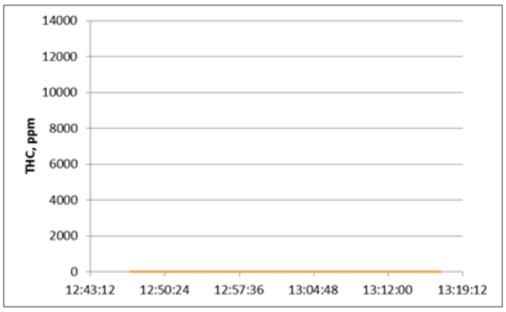
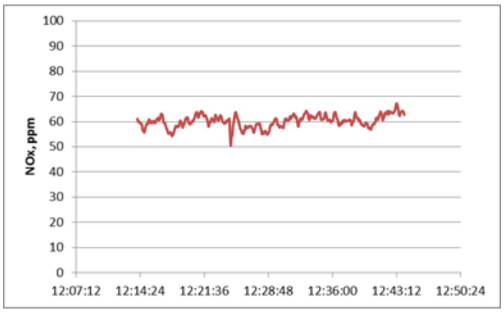
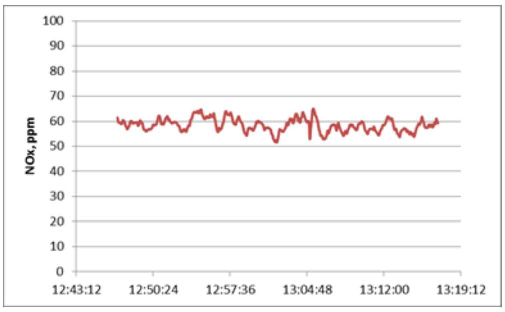
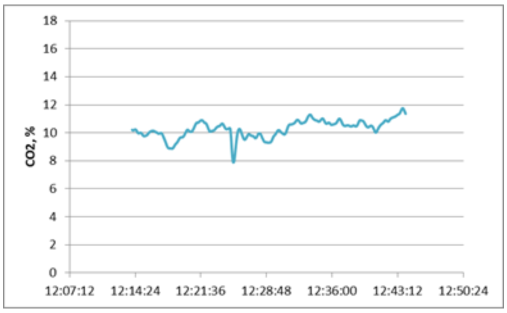
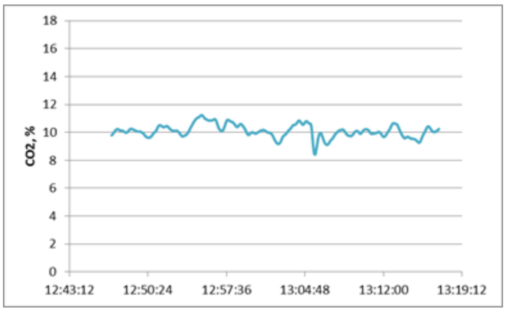
Test 2	Test 3
	
	
	
	

Figure A3.1ai Flue gas measurement traces of CO, NOx, THC and CO2 for Appliance F, Low Output

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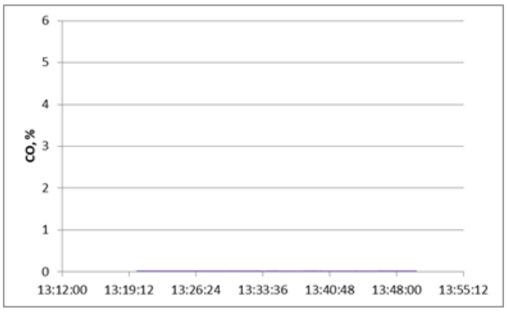

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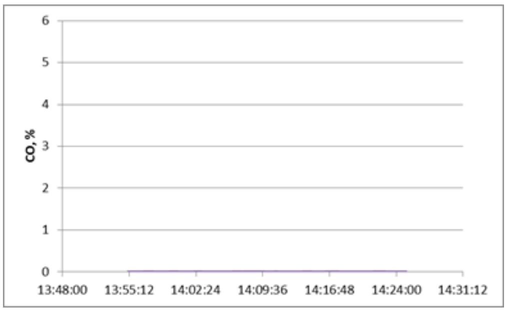

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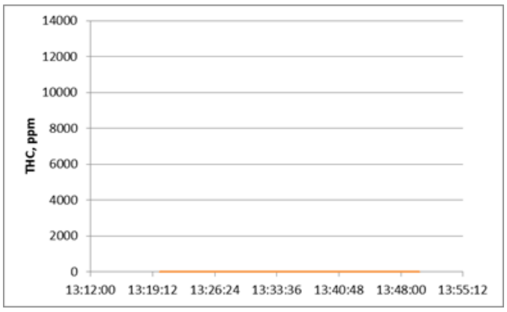

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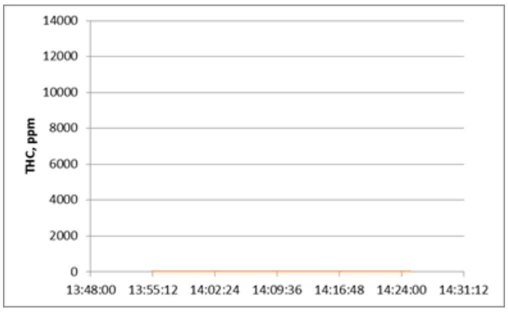

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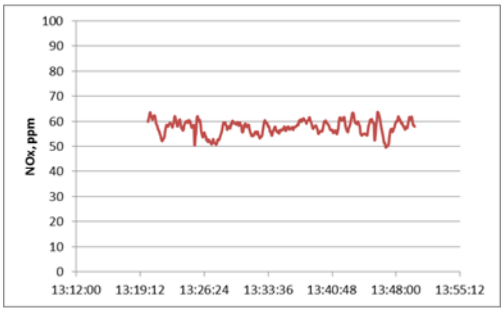

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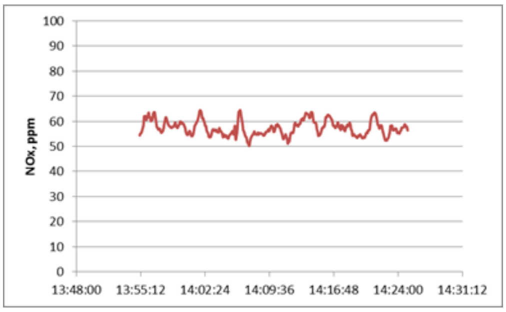

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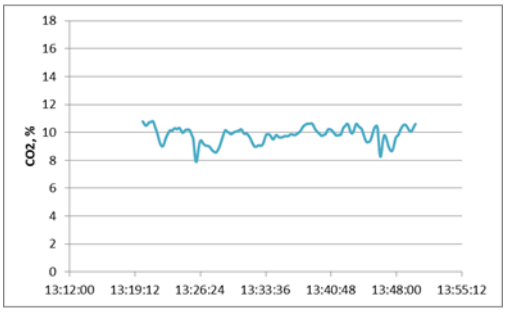

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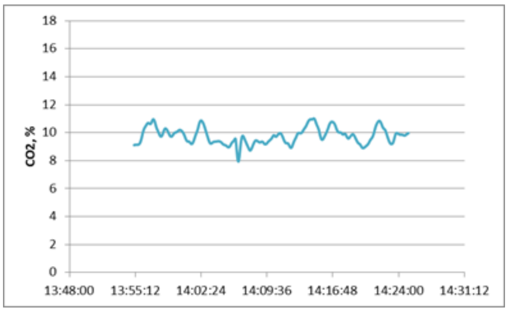

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Figure A3.2a Smoke measurements for each test on each appliance and averages

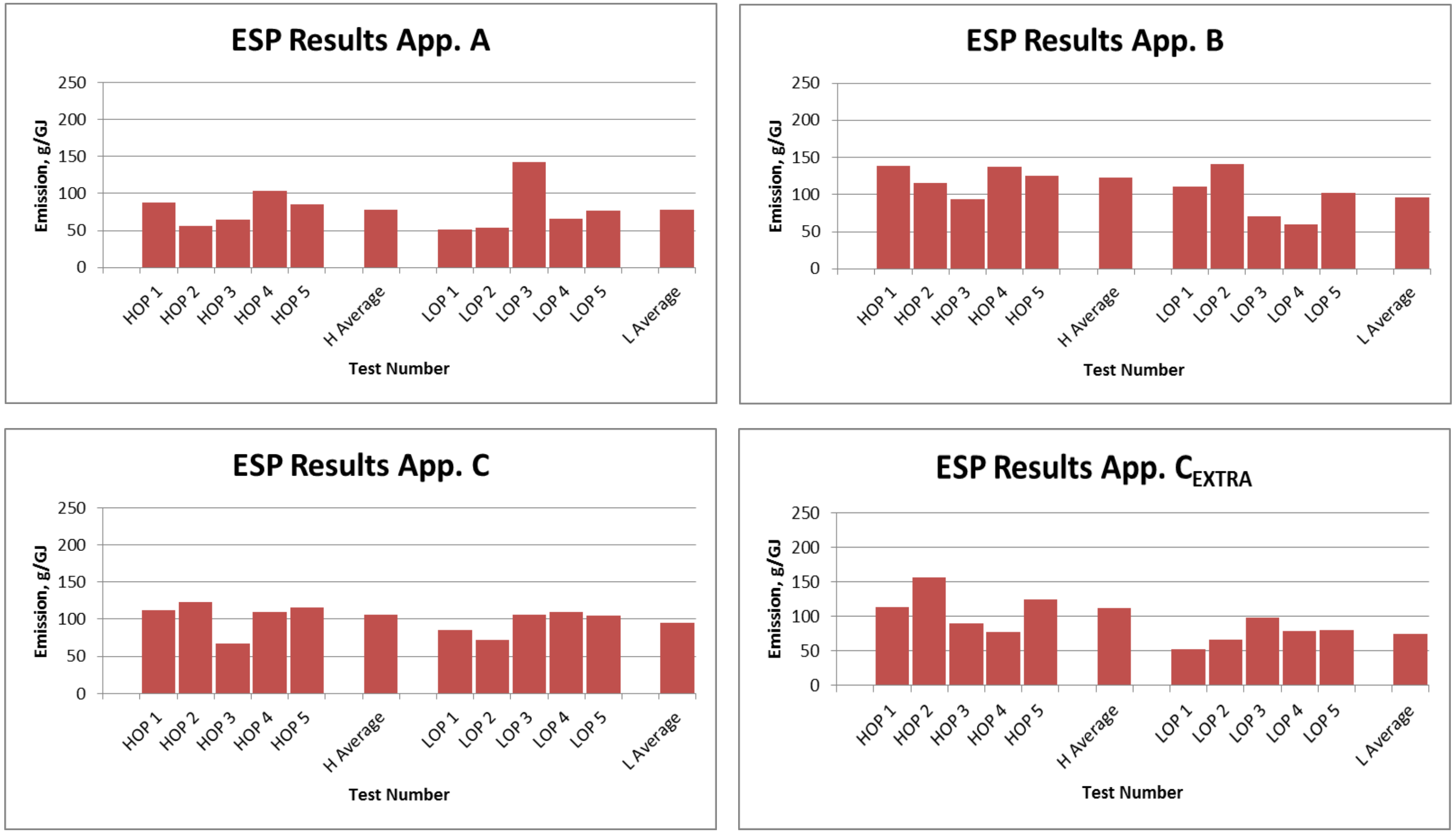
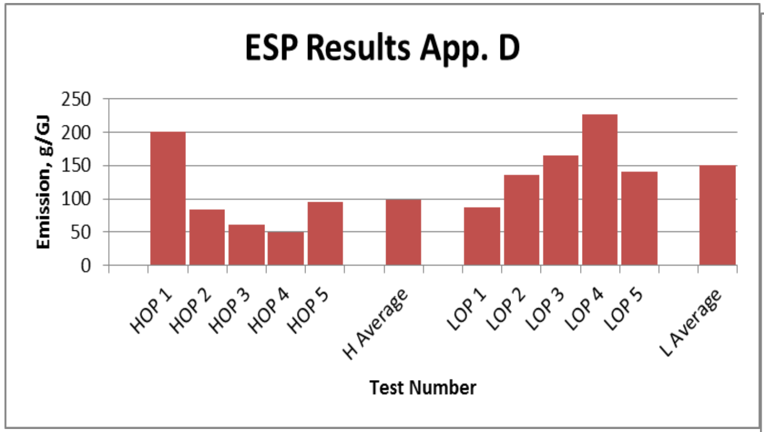
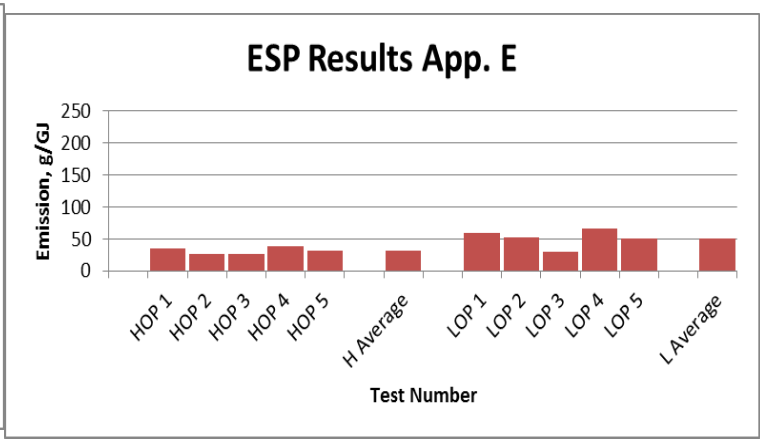


Figure A3.2b Smoke measurements for each test on each appliance and averages





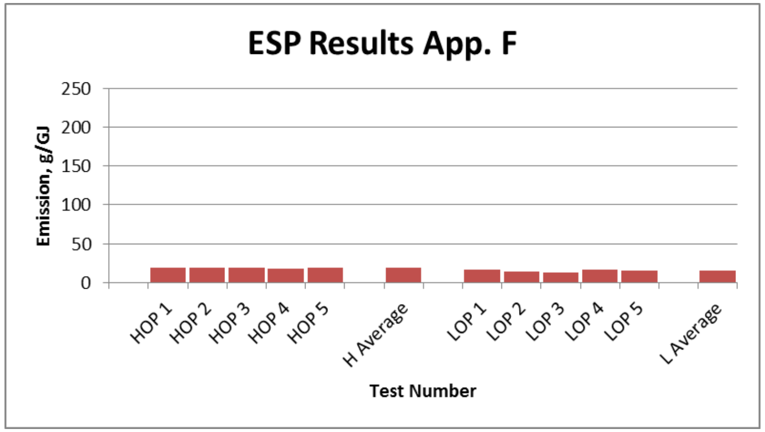
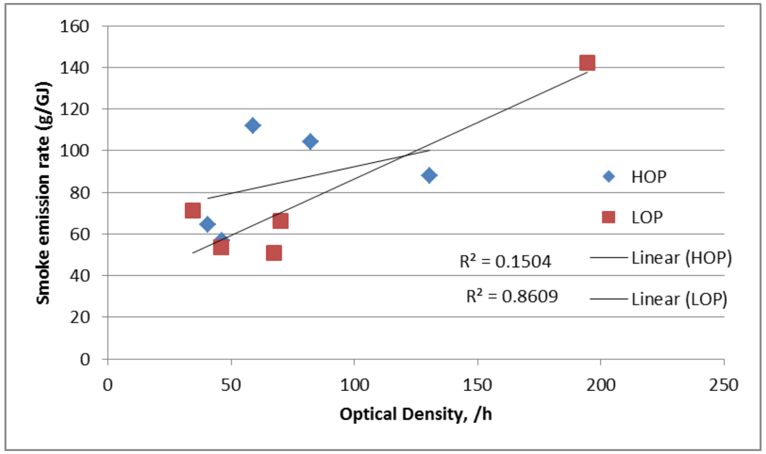


Figure A3.3a Appliance A correlation tests



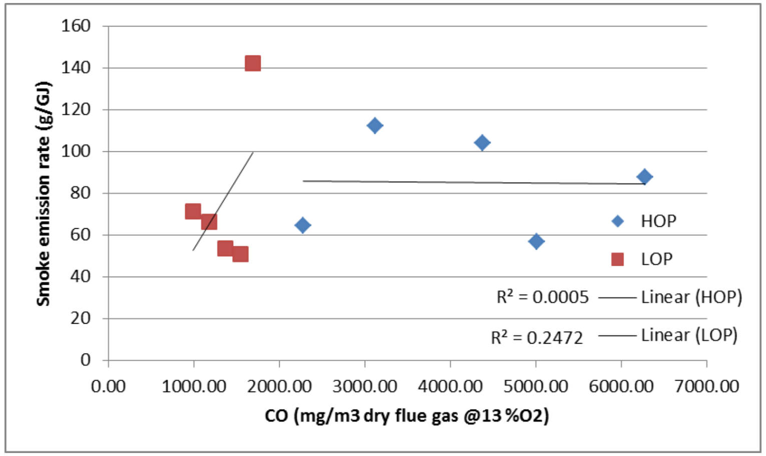


Figure A3.3b Appliance B correlation tests

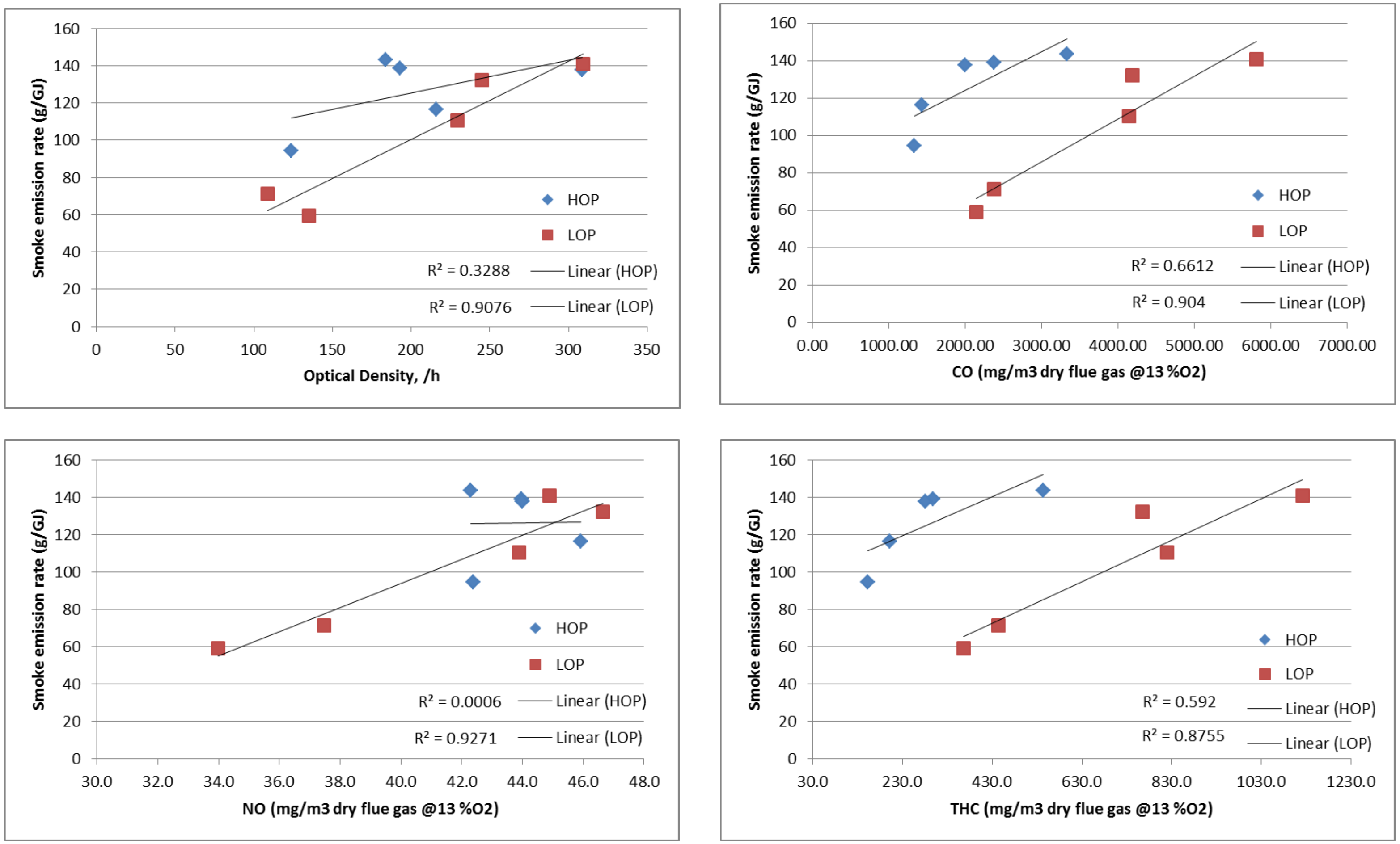
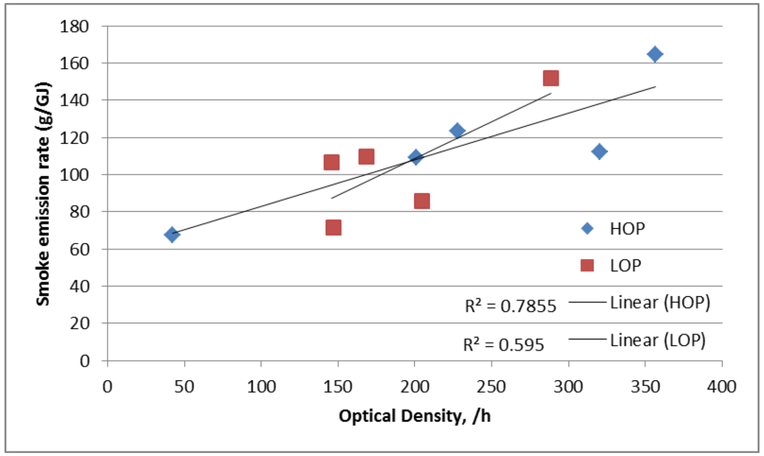
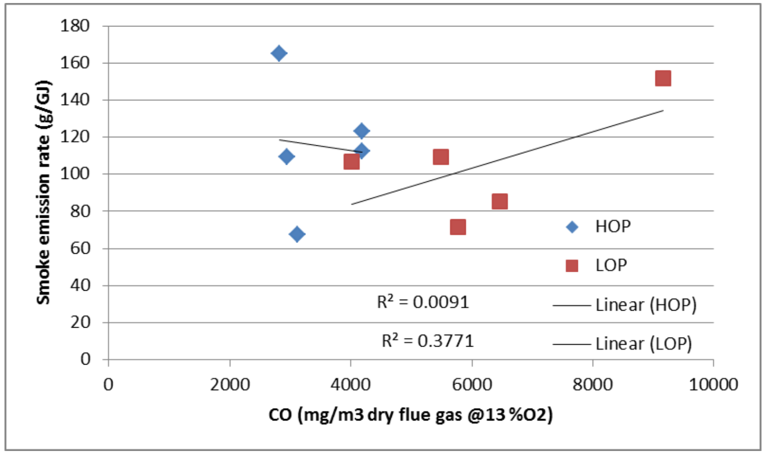
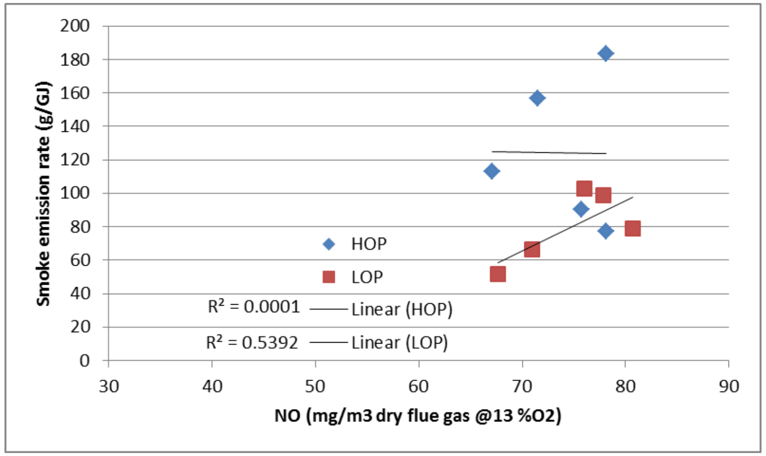


Figure A3.3c Appliance C correlation tests





Charts below are from Appliance C extra tests



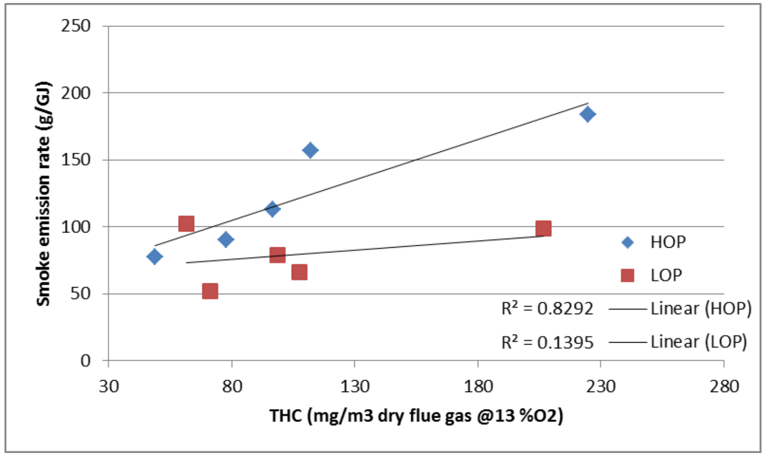
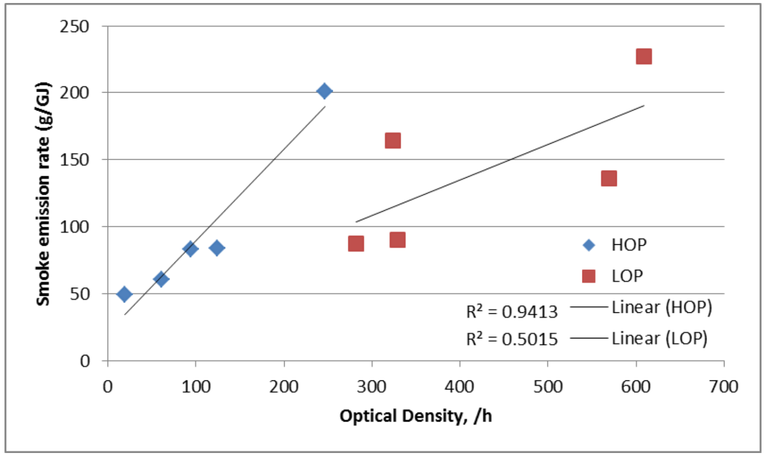


Figure A3.3d Appliance D correlation tests



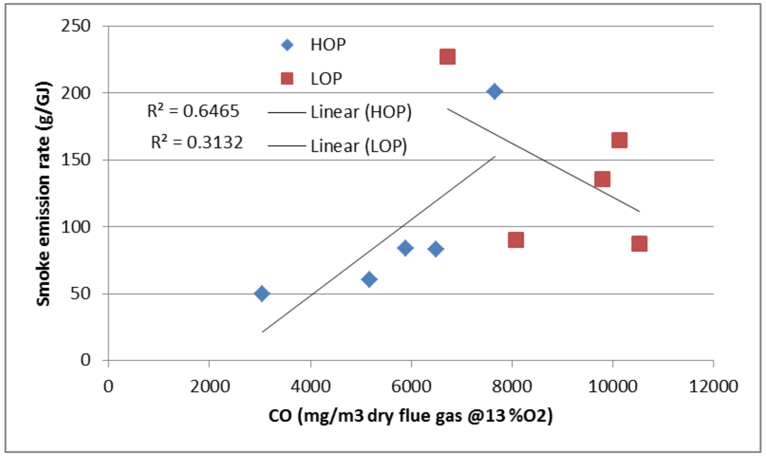
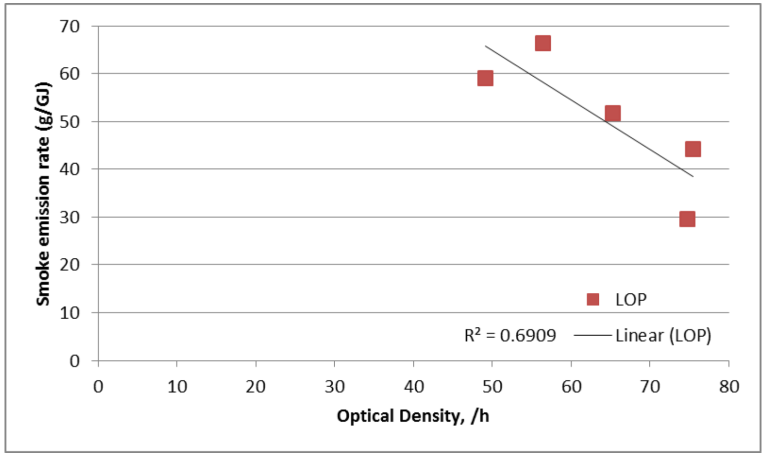
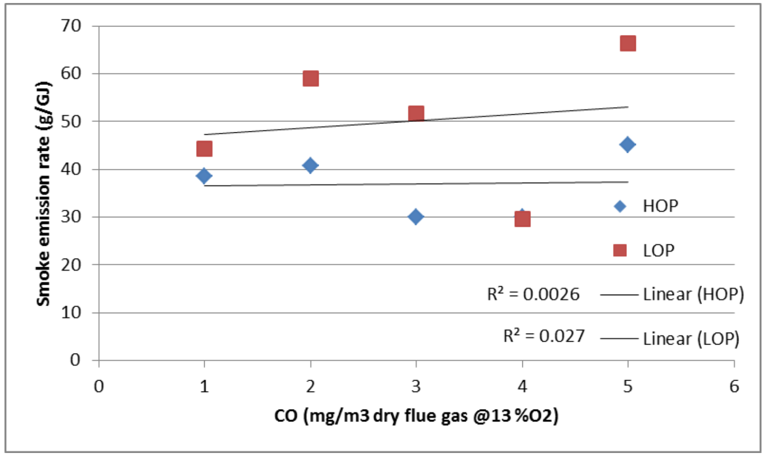


Figure A3.3e Appliance E correlation tests





Appendix 4 Optical smoke measurement

Particles absorb, reflect, refract or transmit light depending on their properties. In general smoke particles do not allow perfect transmission. So, when measurements are made they are all likely to contribute to the overall reduction in light transmitted through the flue gas stream and hence to the degree of obscuration.

Theory indicates $\ln I_o/I = K_c.3.c.s/4.x.d$

Where I_o and I are initial and final light intensities, K_c is an extinction area coefficient, c is the mass concentration of the aerosol, s is the length of the light path, x is $2\pi a/\lambda$ (where a is the radius of a spherical particle and λ is the wavelength of the light) and d is the density of the individual aerosol particles.

Gravimetric measurement techniques (ESP, DIN+, FFDT) all collect either nominally all or a sub sample (with greater or lesser degrees of representativeness of the total) of these particles. The mass of particles collected in each case is used to determine the amount of smoke emitted during the test period.

In accordance with the above (assuming all wood smoke particles are broadly similar), some degree of relationship between gravimetric measurement and integrations of optical density profiles during measurement period might be expected.

Obscuration has historically been used on industrial plant as an indicator of particulate emissions and for 30 years engineers in the UK have used smoke obscuration data (especially time in excess of an obscuration of 0.2) as a reliable indicator of gravimetric emissions.

As a result of this the potential applicability of optical obscuration as a proxy for gravimetric emissions has been investigated using the results from this test programme. The results for individual appliances at high and low output rates are presented in Appendix 3, Figure A3.3a to e. These plots suggest that some form of relationship may be present for an individual appliance at one operating setting. However, to be a useful proxy for smoke measurement it would be necessary for the relationship to be generalizable for at least specific categories of appliance and preferably for all wood fired appliances.

The results for Appliances A, B, C, D and E at different outputs are summarised in Figure A4.1 below.

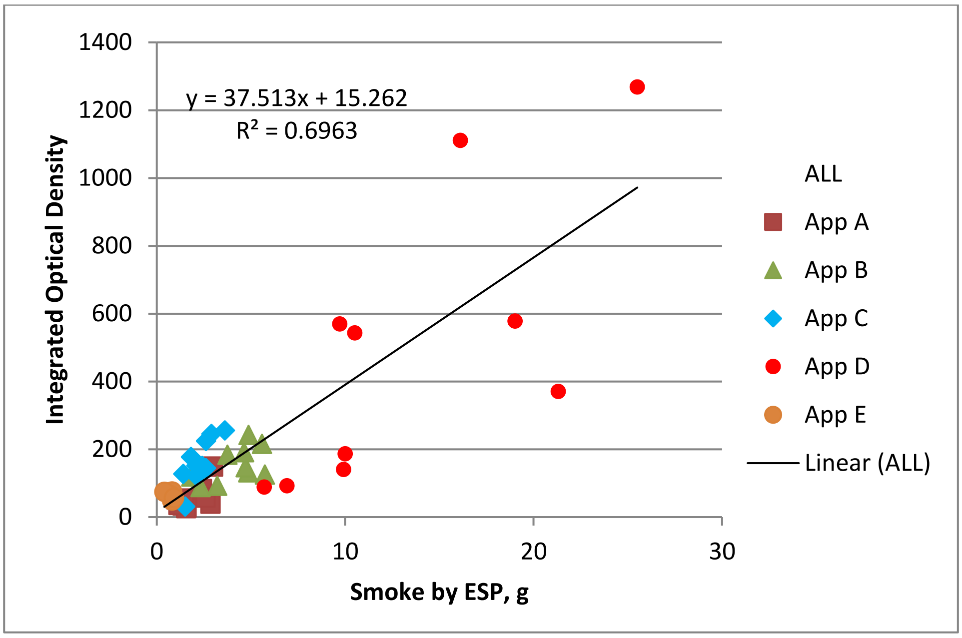


Figure A4.1 Comparison of gravimetric (ESP) and optical measurements of smoke

This figure shows that a wide selection of wood burning appliances do follow simple theory. Especially encouraging are the proximity of a linear best fit to the origin and the R^2 value of 0.7.

There are several factors that affect measurements of optical density and which may help to account for the observed spread. Foster[ix] carried out studies which considered several including:

- characteristics of smoke particles,
- dispersion of the smoke particles in the flue gas stream
- concentration of smoke particles in the flue gas stream

Foster found that a defined relationship exists, provided that the particle suspension is sufficiently dilute and dispersed, between the initial and final light intensity and particle radius, particle density and mass concentration. For this work a fluidised bed smoke source was used that produced consistent particles forming a well dispersed smoke.

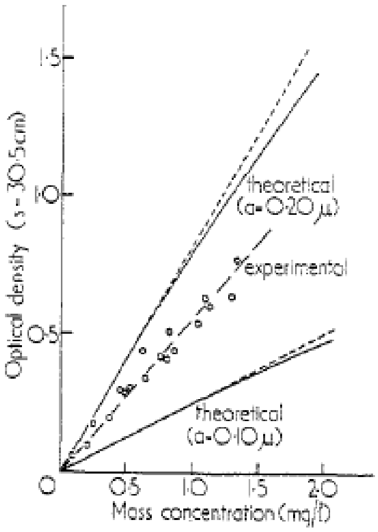


Fig. 2. Relationship between optical density and mass concentration of the particle phase of wood smoke
- - - - - extrapolation of linear portion of theoretical curve.

Figure 4.2 From Foster[ix]

It is not possible for the appliances used in this current study to achieve this. In particular the output from log fired, manually fuelled, appliances, varies significantly across the course of an operational cycle. Pellet fired appliances are more consistent and the points for Appliance E in **Error! Reference source not found.** are closely grouped.

Foster characterised the smoke particles from his test work and noted that they were “spherical tarry droplets that all have the same density irrespective of their size”. This is contrary to a more detailed examination of the composition of smoke particles by Rau[x] which showed a mixture of char (which he described as elemental carbon) and organic carbon (present as the tarry material observed by Foster[ix]) The ratio of char to tar appears to vary substantial depending upon whether the appliance is operating fuel lean (i.e. with the air damper open) or fuel rich (i.e. with the air damper nearly closed)

This condensation based particle development mechanism means that the local flue gas conditions and temperature in particular will have a significant effect on the amount of particulate matter detected. So the fact that ESP and FFDT sample at flue exit temperatures or lower as opposed to the fixed temperature of the DIN+ filter (70°C for the standard tests) is likely to contribute to the inconsistencies between the results for these methods. In almost all cases DIN+ reports a very low level (~200g/GJ or less apart from the low output condition for Appliance D) which may in part be accounted for by the escape of volatile matter through the filter.

It is possible that in some cases the amounts of smoke exceeded the concentration at which, "multiple re-scattering" could occur causing the relationship between OD levels and smoke concentrations to break down, although at the low smoke levels produced by these appliances and the low obscurations this seems unlikely

The flue gas velocities from natural draft appliances, particularly in low output modes of operation are low and not turbulent. The only disturbances that may be present are due to direction changes. This is unlikely to generate a 'well mixed' situation in the gas. Thus it cannot be guaranteed that the OD meter is measuring a representative 'slice' of flue gas. However, this is possibly a more difficult issue for measurements based on extraction of sub-samples as for the DIN+ method because at least the obscuration crosses the whole chimney rather than taking the sample from a single point. It may be less of an issue for FFDT measurements because the method provides for multi-point traverses to be used to gain representative samples. It is not an issue for the ESP method as the total flue flow is used.

A useful anecdote supporting further possible development of this technique is that several technicians can reliably predict quantitative emissions (as determined by ESP) from visual examination of an obscuration trace and it is fundamentally simple and low cost.

References

[ix] Foster W W, Attenuation of light by wood smoke. British Journal of Applied Physics, vol. 10, September 1959, pp416 – 420.
[x] Rau J A, Composition and Size Distribution of Residential Wood Smoke Particles. Aerosol Science and Technology, 10:1, pp181-192

Appendix 4 – Test report 2 (Comparative trials and inter-laboratory comparison)

Assessment of particulate and NO_x emissions from a range of log and pellet appliances and boilers by a range of measurement techniques

Report on inter-method and inter-laboratory comparisons

Prepared by: Kiwa GASTEC
Prepared for: Ricardo AEA for Defra
Report Number: 60097-3
Date: October 2016

Defra
60097-3

Assessment of particulate and NO_x emissions from a range of log and pellet appliances and boilers by a range of measurement techniques

Report on inter-method and inter-laboratory comparisons

Prepared by

Name Mark Lewitt

Position Principal Consultant

Approved by

Name Iain Summerfield

Position Principal Consultant

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Table of Contents

Glossary

A number of terms are used in this report which have a range of accepted meanings, their use in this report is defined below:

Volatile matter	Refers to a component of solid fuel. The components (other than moisture) of a solid fuel that are attached to or held within the structure of a solid fuel under ambient conditions which are released by application of heat
Condensable material	Refers to a component of the emission to atmosphere. Components of volatile matter and products of incomplete combustion that can condense within the temperature range between the combustion chamber exit and ambient conditions
Measurement methods or techniques	The principles and steps required to make a measurement of a substance, parameter or property
Test protocols	The principles and steps required to deliver the substance at the required conditions for measurement and the specific manner of executing a measurement method
Particulate	Solid/liquid matter suspended in flue gas streams and emitted to atmosphere. The terms 'dust' and 'smoke' are sometimes used synonymously.

1 Introduction

Particulate air pollution has been a recognised problem in urban centres and many of the countries in the EU have passed a wide variety of local legislation. This has resulted in a number of different approaches to measuring particulate emissions for residential solid fuel appliances, both qualitative and quantitative. Unfortunately, these approaches can report very different values. This is further complicated as the different methods traditionally report results in different units.

Such differences were not of great consequence when local legislation was written around the local measurement technique, but with the advent of the EU single market and the rise in interest in biomass, the situation is now changing. There is considerable evidence to indicate that the different national measurement techniques can collect and report widely varying quantities of particulates and NO_x.

This work programme carried out a series of comparative and round robin tests to investigate this issue to provide Defra with robust evidence to inform the choice of measurement technique to be used to demonstrate compliance with emission limits. Tests of particulate, total hydrocarbon (THC) and NO_x measurements from representative biomass appliances were carried out.

This report shows the results of tests carried out by Kiwa Gastec in the UK (Lab 1), Danish Technical Institute (Lab 2) and TÜV SÜD in Germany (Lab 3) using six, biomass fired, appliances although only two were sent to Lab 2 and Lab 3. Overall three particulate measurement methods were used; Electrostatic Precipitator (ESP), Heated Filter (DIN+) and Full Flow Dilution Tunnel (FFDT).

It examines the ranges of results obtained for multiple measurements of particulate emission for individual appliances operated under two generic conditions, i.e. at full and at reduced firing rates.

On this basis the **reproducibility** of the results from each method and the relationships between the measurements using the different methods are assessed.

2 Appliances and test conditions for the Study

Six appliances were used in the study and their general characteristics are summarised in Section 2.1. To provide context for the interpretation of the results presented in this report, the effects of appliance design including both function and fuel type are discussed in general terms in Section 2.2.

2.1 Appliances

Table 1 presents a summary of the features of the appliances used for this study.

Table 1 Comparison of Appliance Features

Appliance	A	B	C	D	E	F
Type	Stove room-heater	Insert room-heater	Stove room-heater	Room-heater boiler	Room-heater boiler	Boiler
Fuel	logs	logs	logs	logs	pellet	pellet
Output, kW	4.5	8	6	16	15	200
UK Clean Air Act Exempt?*	no	yes	yes	no	no	no
BImSchV 2?	no	no	yes	no	yes	no
RHI Certificate?*	na	na	na	no	yes	no
MCS Compliant?	na	na	na	no	yes	na
Nordic Swan Ecolabel?**	yes	no	no	no	no	no
Likely to burn clean / dirty?	Clean	Clean	Clean	Dirty	Clean	Clean

* Exemption and Certification has not been applied for or completed in some cases.

** An ecolabel, application not submitted for some appliances

na not applicable

2.2 Appliance operating characteristics

Combustion behaviour in a solid fuel appliance depends on several factors including:

- Fuel with respect to the individual pieces:
    - Dimensions
    - Mass
    - Shape
    - Composition including moisture which is known to be significant
    - Structural characteristics
- Appliance:
    - Combustion chamber characteristics (size, surfaces, fuel/ash bed)
    - Air supplies (primary, secondary, tertiary, wash air)
    - Air flow controls (manual dampers vs automatic valves, naturally vs mechanically ventilated)
    - Flue arrangement (diameter, position of exit from appliance)
    - Ratio of fuel size to firebed size.
- Installation (particularly important for appliances reliant on natural draft to provide combustion air):
    - Characteristics of the chimney to which the appliance flue is connected.
    - Air availability in the space where the appliance is installed
- Operation:
    - Fuelling and de-ashing practices (for log fired appliances number and positioning of logs, timing of refuelling)
    - Ambient conditions such as air temperature, pressure and humidity. This is expected to be modest.

2.2.1 Effects of fuel characteristics on combustion

Here we consider the two fuel types used in this investigation. These are both woody biomass based, being wood logs and wood pellets.

Logs

For test work logs are sourced in batches from a supplier. As delivered they will have a range of compositions and structures and each log will be different in terms of:

- The proportions of; heart wood, sap wood and bark present
- The number of knots present

- The surface condition: relatively smooth or with varying sizes and numbers of splinters and splits present

These properties can affect ignition, release of volatile matter and the rate of burnout of the individual logs.

As described in the report on ESP[ii] measurements care was exercised in log selection to minimise the variation between logs used in the test work however, every log is unique.

The presentation of the logs in the combustion chamber also affects their behaviour under combustion conditions

- The number of logs used to make up the charge of a particular mass.
- Positioning of the logs. The compactness of the fuel bed affects the escape and ignition of volatiles. When logs are closely packed they can act as radiation shields hindering heat transfer and the ignition of the hydrocarbons released in the space between them. Once they have reached a sufficient temperature the logs may act as an ignition source. This is to a significant extent outside the control of the person refuelling the appliance. The firebed is very hot and it is considered inappropriate to spend significant time attempting to arrange the logs in precise geometric patterns. Once ignition has taken hold they inevitably collapse in a random fashion.

During this work every effort was made to use a consistent number of logs (typically three) arranged similarly for each test on a particular appliance to minimise variations that these effects might cause. However, wood logs are inherently relatively large (compared both to pellet or chip fuels and to the combustion chambers of domestic appliances), manually/mechanically cut/split pieces of tree and can have significant variation in physical dimensions which is likely to impact combustion behaviour.

Pellets

Woody biomass pellets whilst heterogeneous compared to fuels such as oil and gas still have relatively narrow ranges for such properties as:

- Size (diameter (6 or 8 mm) and length (3 to 40 mm) being controlled in manufacturing process) which provides consistent combustion behaviour in appliance firebeds of many pellets (several tens to hundreds depending on its rating)
- Surface (generally quite similar from pellet to pellet and without features that could affect ignition significantly)
- Composition (due to the homogenisation that occurs during manufacture)
- Bulk density – allowing consistent fuel feed rates during operation

Combustion of such fuels and thus also emission of gases and particulates is expected to be consistent during a period of firing.

2.2.2 Effects of appliance features on combustion

Structural characteristics

The rate and location of heat removal/loss from the combustion chamber influences the combustion behaviour in the fuel bed.

Roomheaters typically incorporate refractory-lined combustion chambers. Once this refractory has reached a sufficient temperature it can act as an ongoing radiative source assisting ignition and helping to improve stability and evenness of combustion.

Boilers generally have significant areas of relatively cool metal heat transfer surface and ignition of fresh fuel relies on maintaining a sufficient temperature in the fuel bed. This presents a challenge for maintenance and control of combustion in batch fed log appliances of this type.

In addition, the refuelling process for manually-fed log combustion appliances involves opening the appliance door which allows ingress of additional cooler air from the environment. This temporarily disrupts the flow conditions in the appliance and leads to some cooling.

Input characteristics

For pellet fired appliances the effect of the heat transfer surface is less of an issue as the small size fuel pieces are more readily ignited by the heat from the fuel bed. Also there are no refuelling related issues in continuously fed appliances.

Repeatability of operating conditions for manual feed log fired appliances is inherently lower than for automatically fed pellet fired appliances. This is because:

- The control of the fuel and air supplies to pellet fired appliances is much more consistent during operation, by virtue of mechanical fuel delivery and mechanically-assisted ventilation
- The high quality of modern automatic control systems means that the same settings can easily be applied in separate periods of operation
- Pellet fuels are potentially much more homogenous than logs although non-standard pellets can perform very poorly. Similarly, pellets which have been mishandled in delivery and/or storage can be abraded and will have higher fines content which will lead to poor combustion performance
- Appliances with combustion beds that are large relative to the size of the individual pieces of fuel generally can achieve more stable operation.

The problem of repeatability of appliance operation even with consecutive periods of operation has been noted previously by other workers investigating emissions from small wood fired appliances[i]. It has proved a significant challenge for interpretation of the results of the test programme reported here which includes inter-laboratory comparisons.

2.3 Appliance operating conditions

To facilitate the assessment of the repeatability of the test conditions for the various appliances, measurements of various parameters were made during the individual particulate measurement periods (which for the log fired appliances coincided with burn cycles):

- Burning rate (as charged), kg h^{-1}
- Heat output, kW
- Efficiency, % net
- Flue draught, Pa
- Flue temperature, °C
- Ambient temperature, °C
- CO_2, %
- CO, %
- O_2, %
- NOx, ppm
- THC, ppm

These data are presented for individual test periods in Table A1.1 to Table A1.10. Averages of parameters for individual tests and averages for individual appliances are presented.

Direct measurements of the conditions within the combustion chamber of appliances such as those included in this test programme were not undertaken (and would require modification of appliances). For the purposes of this study, the concentrations of key species in the flue gas are used as proxies to indicate the overall behaviour in the combustion chambers and to provide potential links to particulate emission.

As discussed in the ESP results report [ii] the **average** emissions of NOx, THC and CO taken individually were not found to provide good correlations with **average** particulate emission rates. However, their concentrations in the flue gas together with that of CO_2, provide information about the progress of the combustion process.

Traces for each of these parameters for individual tests are presented in Appendix 1:

- Appliance A, ESP measurements: Figures A1.1a to A1.1e,
- Appliance A, DIN+/FFDT measurements: Figures A1.1f to A1.1j
- Appliance B, ESP measurements: Figures A1.2a to A1.2e

- Appliance B, DIN+/FFDT measurements: Figures A1.2f to A1.2j
- Appliance C, ESP measurements: Figures A1.3a to A1.3e
- Appliance C, DIN+/FFDT measurements: Figures A1.3f to A1.3j
- Appliance D, ESP measurements: Figures A1.4a to A1.4e
- Appliance D, DIN+/FFDT measurements: Figures A1.4f to A1.4j
- Appliance E, ESP measurements: Figures A1.5a to A1.5e
- Appliance E, DIN+/FFDT measurements: Figures A1.5f to A1.5j
- Appliance F, ESP measurements: Figures A1.6a to 1.6e
- Appliance F, DIN+ measurements Figures A1.6f to 1.6j

3 Particulate Emission Measurement

3.1 Test protocol

The overall testing protocols for particle emissions measurements include; the manner of appliance installation, method of appliance operation and the measurement technique (method of sampling and measurement).

The different measurement techniques and test protocols have been developed to meet national requirements and are described in 3.2). The test protocols have differences in the number of replicate measurements, burn rates/output and other factors to address practical issues in testing or regulatory requirements. Appendix 2 presents a summary of different test protocols, and associated measurement techniques, in use for residential solid fuel roomheater appliances.

For this study, the following common requirements were incorporated and represent deviations from the 'normal' test protocols:

- 5 replicate measurements at each output
- Measurements at a reduced output (as well as at rated output).
- For log fired appliances - Natural firebed
- Dilution tunnel measurements at fixed draught (to allow simultaneous 'DIN+' sampling of undiluted flue gases)

Normal practise for each measurement technique with regard to test start, finish and duration were maintained. The fuel was from a common source (prepared in accordance with local practise) and a test engineer from Lab 1 supervised setup of the stoves and advised control/damper settings to achieve equivalent operation for the inter-laboratory comparison.

3.2 Measurement Techniques

3.2.1 Overview

There are three principle techniques for particulate emission measurement in flue gases from biomass and solid fuelled appliances (stoves, inset fireplaces and boilers) of less than 50kW.

a) In-situ collection from **total flue gas flow** using an Electrostatic Precipitator (ESP) – UK BS3841-2.

b) Extraction **of a proportion** of the undiluted flue gas and collection of the filterable material from this sample, one example of this heated filter approach is the 'DIN+' method which shares some features of the EN and ISO reference methods for particulate matter in ducts (EN 13284-1, ISO 9096). The EN and ISO methods are commonly applied to larger appliances and industrial plant.

c) Using a full flow dilution tunnel to dilute the total flue gas flow coupled with isokinetic extraction of a **proportion of the diluted flue gas** and collection of the filterable material from this sample. The NS3058 and BS3841-2 standards include definitions of the dilution methods. The EN reference method for sampling particulate matter in ducts (EN 13284-1) can be adopted.

Note that these **techniques** are typically applied within the testing **protocols** with different requirements with regard to fuel (specification and fuelling method), operation (burn rate/output, numbers of replicate tests, sampling periods) and reporting.

3.2.2 Total Flue Gas Flow Technique - ESP

The BS 3841 ESP is expected to collect almost all of the particulates present at the flue conditions where it is applied. Slippage tests reported in the ESP report[ii], supported this view. Typically, measurements are made at a point in the stack where the flue gas temperatures are below 100°C. At such temperatures a significant amount if not all condensable material from the flue gas will have condensed if sufficient flue gas mixing has occurred to facilitate contact with nucleation particles (i.e. ash and unburned carbon). It could also be used for continuous collection across the whole refuel cycle for batch fired appliances (although this is not part of the UK testing protocol).

3.2.3 Extractive Sampling by DIN+

The DIN CERTCO DIN+ certification scheme defines a test protocol based around the harmonised EN appliance standards but also incorporating a particulate measurement method generally referred to as the DIN+ method. The DIN+ method uses fixed flow rate, anisokinetic sampling of the flue gas for fixed durations and collects the particulates using a filter sleeve.

CEN/TS 15883:2009 (for residential appliances that provide some direct space heating) Annex A1 Austrian and German particle test methods, requires that the temperature "in the sleeve area" be maintained at 70°C. The sampling point is not constrained except that it must be possible to maintain the filter at the required temperature which may include application of cooling.
Furthermore, in CEN/TS 15883:2009 A.1.1:

- It is indicated that the measurement be during a "nominal heat output" test as specified in EN 13240:2001 A.4.7, EN 13229:2001 A.4.7 or EN 12815:2001 A.4.9. This may be an issue for this method when applied to reduced output operation which generally involves a reduced flue gas flowrate at the stack.
- The sampling period starts 3 minutes after the fuel load is added the duration of measurement is 30 minutes.

3.2.4 Extractive Sampling from Full Flow Dilution Tunnel

The dilution tunnel samples the particulates at gas temperatures below 100°C. In this study the temperatures were typically in the range 30 to 40°C. At such temperatures a significant amount if not all condensable material from the flue gas will have condensed if sufficient flue gas mixing has occurred to facilitate contact with nucleation particles (I.e. ash and unburned carbon).

Note that there are at least four dilution tunnel-based test protocols in use across the world (the Norwegian standard - NS3058, based on the US Environmental Protection Agency methodology, included in CEN/TS 15883:2009, the alternative method in UK Standard BS3841:1994 included in CEN/TS 15883:2009 and, the Australian/New Zealand Standard) – whilst the measurement approach is broadly similar there are differences in both the dilution tunnel designs and test protocols.

BS 3841 Part2:1994 Annex A (Informative) demonstrates good correlation between results from the ESP and dilution tunnel methods for mineral fuels. The existence of a similar correlation for particulate emissions from wood combustion was investigated in this study.

3.2.5 Extractive Sampling via Isokinetic Stack Sampling

This method was not used in this study because most of the appliances were small and used natural draft flue arrangements. The flue gas velocities in such flues are low, often below the limit of detection using conventional reference measurement techniques (usually by pitot tube). This means that it is not possible to match the sampling velocity with the flue gas velocity. This can result in anisokinetic sampling which may lead to over or under sampling of different particle size fractions.

The reference isokinetic particulate measurement Standards are BS EN 13284-1 and BS ISO 9096. EN 303-5 (the standard for solid fuel central heating hot water boilers that do not heat the space in which they are installed) permits sampling at flue gas temperature, or 110°C. It also requires sampling rate to be pseudo isokinetic.

The use of these methods is typically limited to large scale boilers usually fitted with forced draft and induced draft fans. The approach is mentioned for completeness and because it can provide the basis for particulate sampling using FFDT systems.

3.3 Comparison of Measurement Techniques

The strengths and weaknesses of the measurement techniques are compared in Table 2 below:

Table 2 Comparison of Measurement Techniques

Measurement Method	Features	Strengths	Weaknesses
ESP [Generally used for appliances with output <50kW]	• Collects emissions from total flow at stack temperature • Usually carried out with appliance under the draft condition for normal operation i.e. if natural draft appliance then with natural draft only • Can be carried out over several refuelling cycles i.e. extended testing	• Sampling errors eliminated • Most condensable material captured • Limited number of associated measurements	• Impractical except in a laboratory • Bespoke equipment • Depends critically on measurement of weight gains that are small relative to the weight of the collection device i.e. 2g in 7000g.

Measurement Method	Features	Strengths	Weaknesses
Dilution Tunnel [Generally used for appliances with output <50kW]	• Samples extracted isokinetically, at low temperature from diluted full flow	• Most of condensable material captured • Relatively high tunnel velocity enables isokinetic sampling	• Impractical except in a laboratory • Different methods apply different dilution criteria • Requires many precise measurements with scope for introducing uncertainty • Requires precise procedures for drying and handling of filter papers
DIN+ [Generally used for appliances with output <50kW]	• Samples extracted at a predetermined rate from undiluted flue gas.	• Suitable for use in laboratory (in a standard measurement section e.g. as specified in EN 13240) or on site	• Some condensable material not captured • Filter can block – avoids sampling during initial period after refuelling
Isokinetic Stack Sampler to EN13284-1 or ISO 9096. [Generally used for appliances with output >50kW]	• Samples extracted isokinetically, at high temperature	• Suitable for use in laboratory or on site	• Difficult to measure low stack velocities, so difficult to demonstrate isokinetic sampling • Condensable material not captured

3.4 Reporting of Results and Measurement Units

The different test protocols report results in different units reflecting the regulatory requirements in different countries:

- Concentration units, i.e. mass of pollutant per volume of flue gas (usually related to dry gas at 0°C, 1 atmosphere pressure and a fixed oxygen concentration)

- Rate units i.e. mass of pollutant per unit time

- Emission factors, mass of pollutant per unit mass of fuel or, mass of pollutant per unit energy (input or output)

These bases have fundamentally different approaches and so it can be challenging to convert between them.

Although the emission reporting units are based on measured values, these are averages over a burn cycle and the conversions assume that excess air levels and/or burning rate are constant over the sampling period which is not the case for batch fed log appliances.

Measurements reported in rate units are readily converted to mass per energy input units. In fact the adoption of such units can provide opportunities to simplify measurements and calculations required. This is illustrated in Appendix 3 for the FFDT. Unless noted otherwise, for comparison purposes, the emission data for this study have been reported on the same basis:

g/GJ net thermal input.

3.4.1 ESP

The results of the ESP tests are usually quoted in terms of a rate of emission in g/h, i.e. the weight gain of the precipitator divided by the sampling time. As both numbers are from direct measurement the confidence in these values is high. Conversion to g/GJ (input) requires knowledge of fuel consumption and calorific value (energy content) of the fuel – which are normally determined as part of the test protocol. Conversion of the results to an average emission concentration (in mg/m^3) requires knowledge of the average specific flue gas volume (m^3 of flue gas per kg or GJ of fuel) and fuel consumption. As already mentioned, the flue gas velocity from a natural draft appliance is usually too low to measure.

3.4.2 DIN+

The results from DIN+ measurements are usually quoted as an average emission concentration i.e. the weight gain of the filter divided by the volume of gas sampled. As both values are measured (i.e. weight and volume) confidence is high. Additional corrections are applied to standardise to a reference oxygen concentration and to reference temperature and pressure.

Conversion of the results to an emission rate or emission factor requires knowledge of the specific flue gas volume (m^3 of flue gas per kg or GJ of fuel).

3.4.3 FFDT

The results from the FFDT can be quoted either as a rate, emission factor or a concentration. However, the dilution rate needs to be determined and this provides additional uncertainty in the reported measurements. In this work, Lab 1 initially estimated the dilution rate by two methods:

- CO_2 concentration of the gas flows before and after dilution;
- Temperatures of the flue gas, dilution air, and diluted flow.

There was some discrepancy between the 2 methods, and agreement was found only to be within ±10%. Because temperature measurements are generally considered to be simpler to perform and less uncertain than gas analysis, the temperature method was selected to estimate dilution rate. However, there is scope for significant uncertainty in the results it produced.

Further investigations were undertaken and alternative method for deriving emission results on a g/GJ basis was developed. Ultimately, it was concluded that this simplified calculation method (shown in the right hand image in Appendix 3) involved less sources of error and all the Lab 1 FFDT results presented in g/GJ were recalculated using this method. This approach also enabled account to be taken of background particulate levels in the dilution air which measurements had shown to be small but significant.

3.4.4 Isokinetic Sampling

The results from isokinetic sampling can be quoted either as a rate or a concentration as the sampling is isokinetic and the flue gas flowrate is measured as part of the procedure. Additional corrections are applied to standardise to a reference oxygen concentration and to reference temperature and pressure. Conversion of the concentration results to an emission factor requires knowledge of the specific flue gas volume (m^3 of flue gas per kg or GJ of fuel).

3.4.5 Summary - Results and Units

Table 3 summarises the appropriateness of different measurements methods to reporting in different unit types.

Table 3 Comparison of reporting of results to different unit types

Method	Usual units	Information required	Information required for reporting to:		
			mg/Nm³	**g/h**	**g/GJ**
ESP	g/h	Mass collected, sampling period.	Fuel consumption, Specific flue gas volume	-	Fuel consumption, Calorific value of fuel
DIN+	mg/Nm³	Mass collected, sampled volume (and temperature, pressure), O_2/CO_2 concentration	-	Fuel consumption, Specific flue gas volume, sampling period.	Specific flue gas volume
FFDT	g/kg	Mass collected, sampled volume (and temperature, pressure), dilution ratio (e.g. dilution flow/flue gas volume, CO_2 or temperature ratios), fuel consumption.	Specific flue gas volume.	Fuel consumption, sampling period.	Calorific value of fuel
Isokinetic stack sampling	mg/Nm³	Mass collected, sampled volume (and temperature, pressure). O_2/CO_2 concentration	-	Fuel consumption, Specific flue gas volume, sampling period.	Specific flue gas volume

4 Testwork

4.1 Test Matrix – Inter-method Comparisons

Table 4 below shows which methods were used by each laboratory and on which appliances they were used.

Table 4 Test Matrix for Inter-method comparison tests

Laboratory	Appliance	Output	Method	Replicates
Lab 2	B	High	DIN+ 70°C	5
			FFDT	5
		Low	DIN+ 70°C	5
			FFDT	5
	C	High	DIN+ 70°C	5
			FFDT	5
		Low	DIN+ 70°C	5
			FFDT	5
Lab 3	B	High	DIN+ 70°C	5
		Low	DIN+ 70°C	5
	C	High	DIN+ 70°C	5
		Low	DIN+ 70°C	5
Lab 1	A	High	DIN+ 70°C	5
			FFDT	5
			ESP	5
		Low	DIN+ 70°C	5
			FFDT	5
			ESP	5
	B	High	DIN+ 70°C	5
			FFDT	5
			ESP	5
		Low	DIN+ 70°C	5
			FFDT	5
			ESP	5
	C	High	DIN+ 70°C	5
			FFDT	5
			ESP	5
		Low	DIN+ 70°C	5
			FFDT	5
			ESP	5
	CEXTRA	High	ESP	5
		Low	ESP	5
	D	High	DIN+ 70°C	5
			FFDT	5
			ESP	5
		Low	DIN+ 70°C	5
			FFDT	5
			ESP	5
	E	High	DIN+ 70°C	5
			FFDT	5
			ESP	5
		Low	DIN+ 70°C	5
			FFDT	5
			ESP	5
	F	High	DIN+ 70°C	5
			ESP	5
		Low	DIN+ 70°C	5
			ESP	5

4.2 Test Matrix – Inter-laboratory Comparisons

Table 5 below summarises the methods and firing levels for the tests carried out at different laboratories and the number of replicate measurements carried out in each case.

Table 5 Test Matrix for Inter-laboratory comparison tests

Method	Appliance	Output	Laboratory	Replicates
DIN+ 70°C	B	High	Lab 2	5
			Lab 1	5
			Lab 3	5
		Low	Lab 2	5
			Lab 1	5
			Lab 3	5
	C	High	Lab 2	5
			Lab 1	5
			Lab 3	5
		Low	Lab 2	5
			Lab 1	5
			Lab 3	5
FFDT	B	High	Lab 2	5
			Lab 1	5
		Low	Lab 2	5
			Lab 1	5
	C	High	Lab 2	5
			Lab 1	5
		Low	Lab 2	5
			Lab 1	5

This has provided points of comparison between:

- two laboratories for the FFDT measurement method on two appliances
- three laboratories for the DIN+ measurement method on two appliances

4.3 Test Procedures

The appliance operation procedures were as described in the previous report presenting the results from the ESP measurements[ii]. A Lab 1 technician witnessed the procedures at Lab 2 and Lab 3 to confirm that where possible they were consistent with those applied at Lab 1.

4.4 Test Fuels

The test fuel used for the log boiler and stoves (appliances A, B, C, and D) was test wood logs conforming to the specification given in BS EN 13240:2001[iii] for thermal performance testwork on roomheaters burning wood logs.

For the two pellet boilers (appliances E and F), the fuel was wood pellets bearing the ENplus A1 mark. They were of 6mm diameter and conformed to BS EN 14961-2[iv].

Logs were procured by Lab 1 from their regular supplier for all the test work on log fuelled appliances. All the logs were beech and of uniform length. Logs for the tests carried out at Lab 2 and Lab 3 were provided to them by Lab 1.

4.5 Measurement Equipment and Methods

4.5.1 ESP Method

For the particulate emission measurement work the appliances were installed with their flues connected to a brick chimney fitted with an electrostatic precipitator housing.

Particulate emissions were measured using the electrostatic precipitator method described in BS 3841: Part 2:1994[v], chapter 3, together with PD6434:1969[vi]. In particular this latter requires the measurement of optical density. After refuel the appliance is allowed to recover by virtue of its own draft. No artificial draft is applied as in the case of the other techniques.

The procedures for appliance operation fuel selection and particulate measurements by ESP and Optical Density (OD) were presented in the ESP report[ii]. Background to the basis of OD measurements was also presented.

4.5.2 FFDT Method

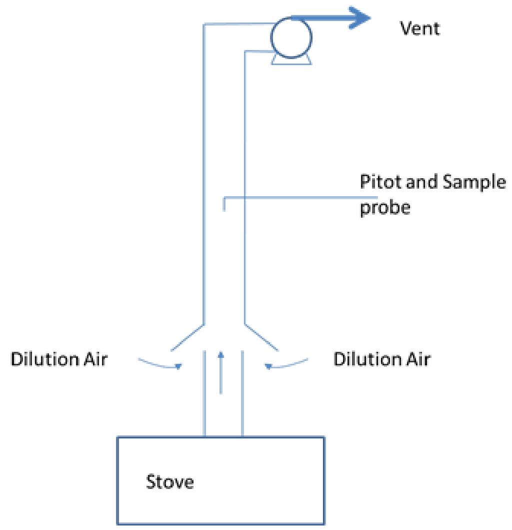

Figure 1 FFDT arrangement

Particulate emissions were measured using the FFDT method described in BS 3841: Part 2:1994[v] (Lab 1) and NS 3058 (Lab2).

Measurements of THC, NOx and CO/CO_2 were made at the same time as the particulate measurements (to CEN/TS 15883) so that the repeatability of the test conditions could be judged.

The arrangement is shown in **Error! Reference source not found.**. The dilution air is drawn from the environment and blank tests showed that it contained a small but significant background concentration of particulates. The calculation methodology was adjusted to account for this.

4.5.3 DIN+ Method

Particulate emissions were measured using the DIN+ method described in CEN/TS 15883[vii] by all laboratories. Where both DIN+ and FFDT methods were used they were carried out in parallel, during the same test period. In these cases, comparisons between these methods should give a good indication of the effect of method on the particulate emission measurements as there should be no contribution from variations in combustion conditions.

Selected method statements are provided in Appendix 4 and Appendix 5.

4.5.4 Flue gas sampling and analysis

The flue gas compositions were measured during each test and the general arrangement of the equipment at Lab 1 is illustrated in Figure 2.

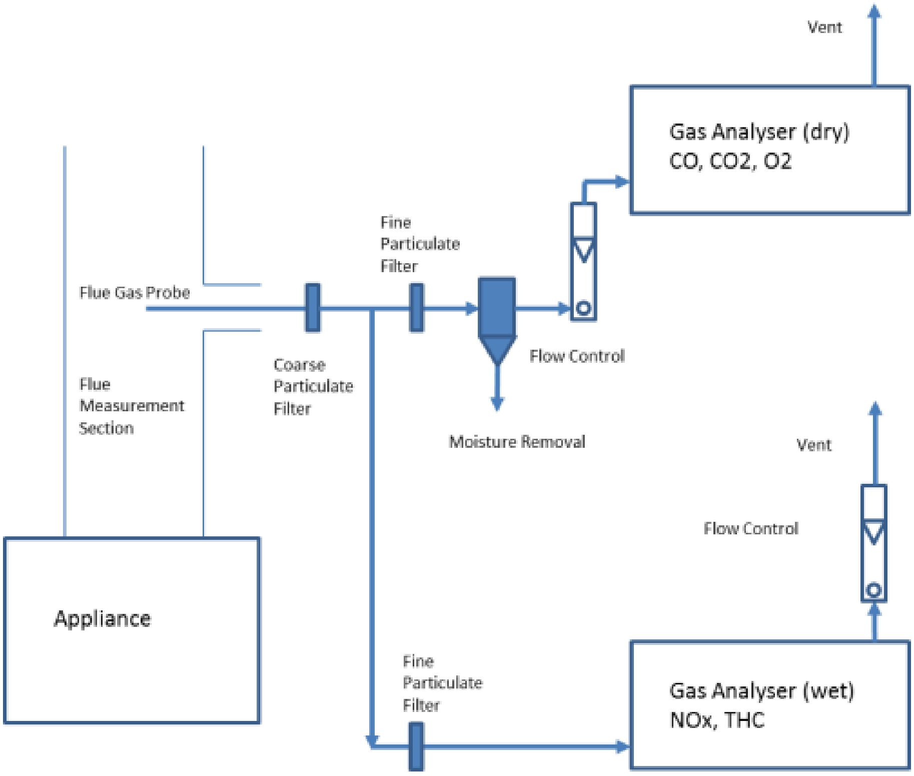

Figure 2 Flue gas sampling and analysis arrangement used by Lab 1

Unfortunately, sampling, instrumental and data logging failures prevented the collection of THC and NOx emissions measurements during some test periods. Oxygen concentrations can be readily estimated based on the concentrations of CO_2, and any other oxidised species present in significant concentrations (for example CO for some tests) and so they were not measured on every occasion. However, only measured oxygen and CO_2 concentrations are presented in this report.

5 Results and Discussion

Summary and exemplary tables and plots are included within the main text.

Individual results from particulate emission tests listed in the matrices in Table 4 and Table 5 above are presented in Appendix 1, Table A1.11 to Table A1.16. Also presented in Appendix 1 are the recorded operating parameters and results from CO_2, CO, THC, and NOx emission measurements.

The appendices also present various comparative plots used to visualise the data and to assist in efforts to identify any relationships present in the data between particulate measurements using different methods or of the same methods when applied in different laboratories.

An overview of the trends and patterns in the operating conditions as presented in the appendices indicates:

1. The overall patterns of emission of the flue gas components varies not only with appliance and output level but also between repeat tests at the same nominal condition
2. CO and THC traces for the same test generally show similar patterns of peaks in emission concentrations
3. In many cases for the log fired appliances there is an initial and predominant peak in CO, THC and CO_2 and this is usually within the first five minutes of recorded data from the test.
   NOTE: The CO/CO_2 profiles for the Low Output tests did not always follow this pattern – see in particular the profiles for Appliances A and D for Low output tests.
4. The pellet fired appliances showed frequent and regular small peaks in CO concentration. It is likely that these occur as fuel pellets drop regularly into the fuel bed. The average levels of CO and CO_2 are very consistent during operation and CO remained at low levels.
5. In the cases where NOx was measured, the traces show a different type of pattern when compared to the other measured parameters. In some cases, where elevated levels of CO and THC indicated that combustion was fuel-rich/oxygen lean, the NOx concentrations were lower. This is consistent with known NOx formation/destruction mechanisms in combustion systems.

All discussions of the performance of particulate measurements must be viewed in the context of the behaviour of the fuels and appliances during measurements.

For log fired appliances the measured emission profiles generally, though not exclusively show an initial peak within about the first five minutes after refuelling. The degree to which this peak is included in the particulate sampling period may have a significant effect on the amount captured and thus on the apparent total emission for a firing cycle for appliances of this type.

The variability in emission concentration trends of CO, THC and CO_2 at the same nominal condition may reflect variability in log fuels and the chaotic nature of the combustion of volatile matter.

The presence of relatively cool metal surfaces within boiler appliances and the batch operation of log fired roomheaters may account for some of the variability in the measured emissions from Appliance D.

5.1 Repeatability of particulate measurement methods

Repeatability of the combustion conditions is discussed in Section 2.2 **Error! Reference source not found.**. In summary, fuel and appliance characteristics strongly influence the repeatability of the emission of particulates and unburnt volatile matter from the combustion chamber. Log fired appliances incorporating a boiler are least likely to give reproducible burn cycles (from one refuel to the next). Pellet fired appliances receiving a continuous feed of fuel into the firebed are likely to give the most reproducible emissions behaviour.

Results of individual tests are given in Appendix 1, Tables A1.11 and A1.16. The results are summarised in Table 6 to Table 11 below. Results are presented as g of emission per net GJ of energy input in the fuel (g/GJ).

Table 6 to **Table 11** summarise the average, the standard deviation and the relative standard deviation[1] (the standard deviation expressed as a percentage of the average value) of the particulate measurements from the emission tests for each appliance at each output condition (for five individual measurements unless noted otherwise).

Table 6 Repeatability of Lab 1 ESP Results, g/GJ

Appliance		**A**	**B**	**C**	**C** Extra tests	**D**	**E**	**F**
Output level	Statistic							
High	Average	86	126	115	124	96	32	18
	SD	24.4	20.6	34.8	44.8	60.8	5.8	0.4
	RSD	**28%**	**16%**	**30%**	**36%**	**64%**	**18%**	**2%**
Low	Average	78	103	105	80	141	50	15
	SD	38.0	36.2	30.4	21.5	58.0	14.2	1.7
	RSD	**49%**	**35%**	**29%**	**27%**	**41%**	**28%**	**12%**

[1] The use of RSD is discussed in the previous report on the results from ESP measurements at Lab 1 indicating the caution that is required in their interpretation.

Table 7 Repeatability of Lab 1 FFDT Results, g/GJ

Appliance		A	B	C	D	E	F
Output level	Statistic						
High	Average	82	120	119	137	80	
	SD	22	48	59	26	8	
	RSD	**27%**	**40%**	**50%**	**19%**	**10%**	
Low	Average	168	77	97	402	79	
	SD	29	38	15	152	14	
	RSD	**17%**	**49%**	**15%**	**38%**	**18%**	

Table 8 Repeatability of Lab 2 FFDT Results, g/GJ

Appliance		A	B	C	D	E	F
Output level	Statistic						
High	Average		187	62			
	SD		58	1			
	RSD		**31%**	**1%**			
Low	Average		230	114			
	SD		45	13			
	RSD		**20%**	**11%**			

Table 9 Repeatability of Lab 1 DIN+ Results, g/GJ

Appliance		A	B	C	D	E	F
Output level	Statistic						
High	Average	21	64	25	88	19	16
	SD	6	30	17	42	7	2
	RSD	**27%**	**47%**	**68%**	**48%**	**35%**	**15%**
Low	Average	18	28	59	607	15	4
	SD	6	11	29	375	4	1
	RSD	**32%**	**39%**	**49%**	**62%**	**28%**	**13%**

Table 10 Repeatability of Lab 2 DIN+ Results, g/GJ

Appliance		A	B	C	D	E	F
Output level	Statistic						
High	Average		74	27			
	SD		13	5			
	RSD		**18%**	**20%**			
Low	Average		61	7			
	SD		21	2			
	RSD		**35%**	**27%**			

Table 11 Repeatability of Lab 3 DIN+ Results, g/GJ

Appliance		A	B	C	D	E	F
Output level	Statistic						
High	Average		91	32			
	SD		20	24			
	RSD		**22%**	**76%**			
Low	Average		115	22			
	SD		24	24			
	RSD		**21%**	**111%**			

NOTE: Measurements that Lab 3 excluded have not been included in these statistics.

Overall the repeatability of particulate measurements by the various methods in the different laboratories was found to be highly variable especially for the log burning appliances (the range of RSD across all appliances, measurement techniques and testhouses is from 1 to >100% but with a median of about 29%). The pellet stove results were generally less variable and the large pellet boiler offered the most consistent results (%RSD at high output 2% with ESP and 15% using DIN+). This is in accord with the expectation that the greater the ratio of fuel bed size to refuel size the more consistent and reproducible the combustion behaviour. Appliance C was tested using the ESP in the same laboratory several weeks apart (see Table 6), the average results differ, although almost within their respective standard deviations.

5.2 Inter-laboratory comparison results – FFDT method

FFDT measurements carried out at two laboratories (Lab 1 and Lab 2) are summarised in Table 12 below. These results are also presented graphically in Appendix 6, Figure A6.1.

Table 12 Particulate measurements by FFDT method made at two laboratories, g/GJ

Output	High				Low			
Appliance	B		C		B		C	
Laboratory	2	1	2	1	2	1	2	1
Test 1	134	161	62	223	284	60	108	82
Test 2	199	157	62	85	226	38	107	105
Test 3	276	142	63	77	261	123	131	116
Test 4	138	81	63	100	212	111	123	82
Test 5	189	57	61	112	168	52	100	98
Average	**187**	**120**	**62**	**119**	**230**	**77**	**114**	**97**
SD	**58**	**48**	**1**	**59**	**45**	**38**	**13**	**15**
Ratio average Lab 2/Lab 1	**1.56**		**0.52**		**3.00**		**1.18**	

There is significant variability in the results from this method from the different laboratories and no clearly discernible pattern was identified. The standard deviations are, in most cases, very large compared to the measured and average emission values and thus the 95% confidence intervals (± 2 x SD) show high levels of uncertainty for most of the measurements.

If Lab 1 and Lab 2 had a fundamental procedural or other difference in measurement technique then the Lab 1 or Lab 2 emission values might be expected to show the same ratio to each other. However, this has not occurred. The differences between the two laboratories also often exceed the standard deviations.

Note that these tests were not conducted on the same burn cycles so differences in emissions include differences arising from differences in measurement technique applied by the testhouses but, they will also reflect variability in emissions from differences in operation at each testhouse or a combination of both factors.

5.3 Inter-laboratory comparison results – DIN+ method

DIN+ measurements carried out at the three laboratories are summarised in Table 13 below. These results are also presented graphically in Appendix 6, by the plots in Figure A6.2.

Table 13 Particulate measurements by DIN+ method made at three laboratories, g/GJ

Output	High						Low					
Appliance	B			C			B			C		
Laboratory	2	1	3	2	1	3	2	1	3	2	1	3
Test 1	82	30	93	7	11	*20***	90	36	*104**	24	56	*5****
Test 2	61	72	*115**	5	11	*2****	75	27	92	30	90	*25***
Test 3	69	75	102	8	16	56	78	10	*143**	35	77	32
Test 4	25	39	61	10	47	*56***	54	30	95	21	14	10
Test 5	67	106	*82**	6	39	*24***	71	38	*138**	26	59	36
Average	**74**	**64**	**91**	**7**	**25**	**39**	**74**	**28**	**115**	**27**	**59**	**26**
SD	**13**	**30**	**20**	**2**	**17**	**20**	**13**	**11**	**24**	**5**	**29**	**12**
Ratio average to Lab 1	**1.14**	**1.00**	**1.41**	**0.29**	**1.00**	**1.58**	**2.61**	**1.00**	**4.06**	**0.46**	**1.00**	**0.44**
Ratio highest average to lowest	**1.41**			**5.44**			**4.06**			**2.30**		

NOTES:
* Lab 3 reported that high particle loadings affected sample volume
** Lab 3 reported problems with fuel ignition /burnout
*** Lab 3 excluded these results because they considered them too low – and they have not been used in calculation of these statistics

The standard deviations are relatively large but again it must be noted that, as for the FFDT measurements discussed in Section 5.2, the repeatability of appliance operation is a key factor affecting these results. Confusingly some laboratories determined emissions falling on going from high fire to low fire whereas other laboratories determined an increase.

A Lab 1 technician witnessed the tests at Lab 2 and Lab 3 and noted some small differences in procedures. For example, Lab 2 notched the faces of their logs (with an axe) to give faster ignition; this might be expected to produce low emissions, but this is not clear from the results.

Lab 2 and Lab 3 used identical proprietary sampling equipment for DIN+ measurements.

Note that these tests were not conducted on the same burn cycles so may reflect differences in measurement technique applied by the testhouse, they may reflect variability in emissions from differences in operation at each testhouse or a combination of both factors.

5.4 Comparison of particulate measurement results from different methods

The approaches to assessing the data include simple statistical methods and regression analysis. Tables A1.3 and A1.4 present the summary statistics (average, standard deviation and relative standard deviation[2]) of the particulate results derived from the repeat measurements on each appliance using the different measurement methods at Lab 1 and Lab 2.

The data in these tables are also presented graphically in Figures A1.6 to A1.11. It must be noted that the FFDT and DIN+ results were carried out simultaneously on the same burn cycle (although with differences in sampling period start times and duration) – other comparisons are not based on the same burn cycle and consequently subject to additional uncertainty.

Table 14 presents the parameters from linear regression analyses comparing the particulate measurement methods.

Table 14 Results of least squares linear regression fitting to particulate measurements by different methods

Laboratory	Comparison	Basis	n	Fit Slope	Fit Offset	Fit Correlation, R"
Lab 1	FFDT vs ESP*	Averages	10	1.7	-25	0.34
Lab 1	DIN+ 70°C vs ESP*	Averages	10	3.1	-191	0.31
Lab 1	DIN+ 70°C vs FFDT	ALL Values	50	1.7	-129	0.77
Lab 1	DIN+ 70°C vs FFDT	Averages	10	1.8	-148	0.95
Lab 2	DIN+ 70°C vs FFDT	ALL Values	20	0.3	2	0.46
Lab 2	DIN+ 70°C vs FFDT**	Averages	4	0.3	-4	0.59
Lab 1 / Lab 2	DIN+ 70°C vs FFDT	ALL Values	70	1.4	-117	0.65

Notes:

* ESP measurements and DIN+/FFDT are made on separate burn cycles and so individual relationships between measurements will not be present and comparisons between the ESP and the DIN+/FFDT methods are of the average results of the repeat measurements on each appliance.

** On this basis the sample size is inadequate to provide statistically meaningful information and it is presented only for completeness.

The offset is the displacement from the origin of intercept of the best fit line. R^2 provides a crude measure of quality of the data fit to the model of the relationship. If all three of the

[2] The use of RSD is discussed in the previous report on the results from ESP measurements at Lab 1 indicating the caution that is required in their interpretation.

measurement techniques performed similarly then a linear relationship of slope +1 would be expected. The slopes of the linear fits to these data sets suggest that the relationships are not 1:1 indicating other variables are influencing the results. The closest to a 1:1 relationship was found where the whole data set for the Lab 1 and Lab 2 DIN+ 70°C and FFDT results are used. Scatter in the results appears significant in all cases.

5.5 Relationship between measurements of particulates and THC

CEN\TC295-WG5 commissioned a study comparing particle measurement for residential solid fuel fired appliances, which reported in April 2011[viii]. The study asserted that the three measurement methods (direct stack sampling, FFDT and ESP) are not comparable because the method principles differ. The study investigated the emissions from two wood fired appliances using three particulate sampling techniques (direct sampling through a heated filter[3] backed by either impingers or a dilution section and filter for collection of condensables and FFDT). In addition, continuous measurements of THC using an analyser with a flame ionisation detector (FID) were made[4]. Tests and measurements were undertaken for two appliances in two laboratories. The appliances were a pellet stove and a wood log insert appliance (Appliance B in the current study), It was concluded that for several reasons comparison between the results of the different laboratories was not possible.

The CEN study presents a correlation between THC measurement and condensable emissions. In spite of a clear statement that “A comparison between the FFDT results and the combination HF + FID shows no correlation” these relationships were subsequently presented as the basis of a proposal for treatment of measurements by different methods:

1. FFDT: [pm] * 1
2. HF + impingers: [pm] * 1
3. HF + FID: [pm (HF)] * 1 + [THC] * 0.42

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[3] The sampling arrangement used in the DIN+ method is a heated filter arrangement. In the CEN study the method used is identified as “an adaption of US EPA method 5h”.

[4] FID instruments measures the carbon present and an assumption of the average molecular weight associated with each C atom must be made to estimate the amount of hydrocarbon present. The instrument used in the CEN study was calibrated using methane which is a common approach, as is the use of propane. Neither of these calibrants reflect the range of species that make up the volatile matter released from wood which includes many oxygenated species and aromatic species.

In the study reported here parallel measurements of particulate by FFDT and DIN+ methods were used. THC was also measured continuously during these tests. The applicability of the proposed model 3 above has been tested using the data collected.

The CEN study dealt with concentrations of particulates and THC on a mgm^{-3} at $13\%O_2$ basis and the data for the present study has also investigated the correlation for both emission concentrations and emission factors.

As far as understood from the CEN report the measurements and calculations used by Lab 1 and Lab 2 were similar in the current study.

Comparisons between measured FFDT emissions and predicted FFDT emissions by the proposed CEN relationship are made using emission data expressed in mg/m^3 and g/GJ.

All the measurements of THC in this study were made using analysers calibrated with methane.

The data were collected by Lab 1 and Lab 2. All three measurements were carried out in parallel for each test on appliances B and C.

For each complete set of data (matched FFDT, DIN+ and THC determinations) the predicted FFDT result was determined by applying the proposed CEN formula:

$$FFDT_{(Predicted)} = DIN+ + (0.4 \times THC)$$

The results for all the individual tests included are presented in Table A7.1, Table A7.2 in Appendix 7 and Table A8.1 in Appendix 8.

The relationships using the mg/m^3 based data are plotted in Appendix 7, Figure A7.1a to Figure A7.2b for each Appliance included in the investigation of this model. The relationships based on the g/GJ data are plotted in Appendix 8, Figure A8.1a to e.

The data from the linear regression analysis of the data sets are presented in Table 15 and Table 16 below.

Table 15 Statistics from investigation of validity of proposed model for prediction of particulates measured by FFDT from particulates measured by DIN+ and THC by FID type analyser using data in

mg/m³

Laboratory	Appliance	Output	Slope of fitted line	Intercept of fitted line with $FFDT_{Predicted}$ axis	R^2 of fitted line	Number of data points included, n
Lab 1	A	ALL	0.40	32	0.231	10
		HIGH	1.14	-26	0.590	5
		LOW	1.12	-91	0.925	5
	B	ALL	0.52	182	0.106	10
		HIGH	0.80	96	0.751	5
		LOW	2.42	46	0.528	5
	C	ALL	-0.09	142	0.006	10
		HIGH	-0.73	188	0.354	5
		LOW	-0.19	183	0.029	5
	D	ALL	1.99	-84	0.971	7
		HIGH	2.66	-227	0.889	3
		LOW	2.14	-219	0.953	4
	E	ALL	0.97	-46	0.572	10
		HIGH	-0.07	38	0.002	5
		LOW	0.06	-1	0.787	5
Lab 2	B	ALL	0.65	89	0.484	9
		HIGH	0.26	163	0.246	5
		LOW	0.50	192	0.663	4
	C	ALL	-0.94	228	0.666	10
		HIGH	-22.31	2236	0.330	5
		LOW	-1.25	281	0.653	5
Lab 1 + Lab 2	ALL	ALL	1.76	-100	0.839	66

Table 16 Statistics from investigation of validity of proposed model for prediction of particulates measured by FFDT from particulates measured by DIN+ and THC by FID type analyser using data in

g/GJ

Laboratory	Appliance	Output	Slope of fitted line	Intercept of fitted line with $FFDT_{Predicted}$ axis	R^2 of fitted line	Number of data points included, n
Lab 1	A	ALL	0.24	29	0.199	10
		HIGH	0.82	-10	0.548	5
		LOW	0.68	-43	0.857	5
	B	ALL	0.83	103	0.389	10
		HIGH	0.75	85	0.734	5
		LOW	1.98	43	0.853	5
	C	ALL	-0.13	115	0.010	10
		HIGH	-0.26	113	0.159	5
		LOW	4.13	-280	0.833	5
	D	ALL	2.79	-39	0.928	7
		HIGH	3.47	-130	0.985	3
		LOW	2.76	-26	0.849	4
	E	ALL	0.02	17	0.002	10
		HIGH	-0.24	40	0.071	5
		LOW	0.09	10	0.073	5
	All	All	2.85	-172	0.823	47

Note: The Lab 2 data were not included in this analysis because it was not possible to re-calculate their FFDT results on the same basis as used for the Lab 1 results.

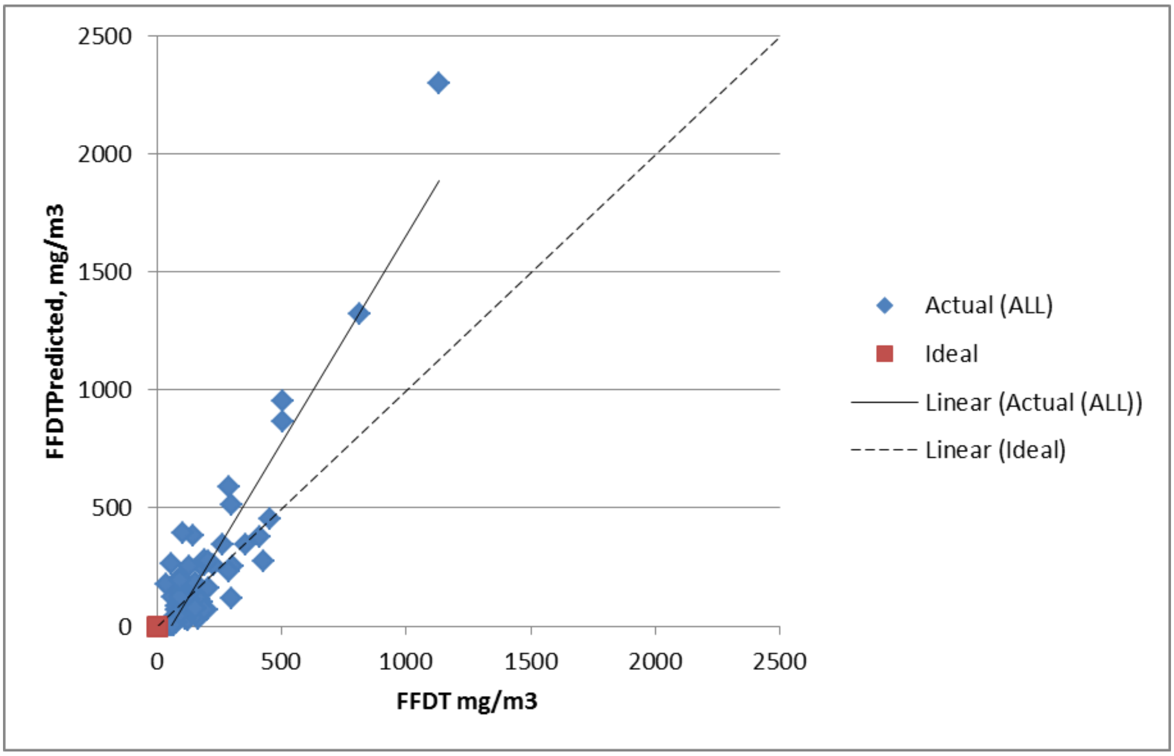
The observed relationships between the modelled and the actual FFDT results vary considerably between individual appliances and operating outputs.

When the complete concentration data set is used the parameters in the bottom line of Table 15 result. The values are plotted in Figure 3, below. The values exerting control over the fitted trend line are all from one appliance (D) at one output (High).

The proposed CEN model was postulated on an empirical basis using a small number of data points for two appliances (one log fired and the other pellet fired). The findings from the current study suggest that the proposed model is not valid when applied to measurements covering a wider range of appliances. These findings also illustrate the risk of selecting specific groups of data. For example, selecting only the High Output results for Appliance A or only the Low Output results from Appliance B suggests reasonable agreement with the proposed CEN model.

Development of a widely applicable model for relating particulate measurements using different methods would need sound theoretical basis, validated using extensive sets of measurements.

Note that following input from this study and other concerns, the CEN proposal was not taken forward.



5.6 Comparison of pellet appliance results

Comparisons of particulate measurement methods require consistent particle generation sources for analysis of the measurements using the different techniques to give a clear picture of their relationships.

In these studies, the appliances expected to consistent sources were E (the pellet room heater/boiler) and F (the large pellet fired boiler). These appliances can be operated reproducibly and are expected to generate similar amounts of particulate each time that they are operated under the same conditions. The operating parameters and emission measurements for the ESP tests are given in individually Table A1.1, Table A1.2a and Table A1.2b and in summary in Table A1.3 and Table A1.4. The operating parameters and emission measurements for the DIN+/FFDT tests are given in individually Table A1.5, Table A1.6, Table 1.8a and Table A1.8b individually and in summary in Table A1.9 and Table A1.10.

Figure 3 Actual against predicted FFDT particulate measurements, LAB 1 and Lab 2 results for all Appliances at High and Low Outputs

Pellet fired appliances have continuous fuel feed and ash removal so that once combustion is established the ash/fuel bed varies only to a limited extent. In contrast with manually fed log appliances over a series of burn cycles the ash/fuel bed can develop substantially. So, for the fifth test in a sequence the logs may be in a significantly different level in the combustion chamber. Depending on the appliance this can lead to large changes in the way that the air from various inlets interacts with the fuel.

Measured flue gas temperatures are a key indicator of the results of the fuel/air interactions. These showed that the conditions in Appliances E and F during operation were reproducible on different occasions. The average flue gas temperatures for the ESP tests and for the DIN+ tests differed by less than 10°C. In contrast, between different sets of tests, the log fired appliances recorded differences in average flue temperatures of about 60°C to 130°C.The particulate measurement results for Appliance E are shown in Table 17.

Table 17 Measurements of particulate emission from Appliance E by three methods

Output level	Statistic	ESP	FFDT	DIN+
High	Average	37	80	19
	SD	6.7	8	7
	RSD	**18%**	**10%**	**35%**
Low	Average	58	79	15
	SD	16.4	14.5	4
	RSD	**28%**	**18%**	**28%**

It can be seen that for Appliance E there is a general ranking in the results:

DIN+ < ESP < FFDT

The variability of the pellet stove emission concentrations from the different measurement techniques is relatively high but generally better than found for wood log roomheaters. The variation in particulate emission concentrations is perhaps surprising given the very low THC emission concentrations determined at Appliance E but provides a further indication that the use of a THC correlation to determine PM emissions may be unsound. High combustion efficiency (as indicated by the low average CO and THC emission concentrations determined at Appliance E) may not be sufficient justification for direct filter measurement of particulate on small pellet appliances.

The results for Appliance F are shown in Table 18.

Table 18 Measurements of particulate emission from Appliance F by two methods

Output level	Statistic	ESP	FFDT	DIN+
High	Average	18		16
	SD	0.4		2
	RSD	**2%**		**15%**
Low	Average	15		4
	SD	1.7		1
	RSD	**12%**		**14%**

For Appliance F, both measurement methods have relatively good repeatability and, at high output, good comparability.

The reason why the variability of the pellet stove particulate emission concentrations is higher than found for the pellet boiler is not known but may reflect a more stable combustion environment in the larger appliance F.

6 Conclusions

There are two aspects to the testing of particulate and THC emission from biomass fired appliances which affect the individual results obtained:

- Appliance characteristics and operation
- Particulate emission measurement method and execution

This report covers inter-method comparisons and inter-laboratory comparisons.

6.1 Consistency of results (Intra-laboratory comparisons)

The large, continuously fed and very clean burning pellet boiler (Appliance F) gave good reproducibility between the DIN+ and ESP techniques.

The semi-continuously fed pellet stove (Appliance E) gave a significant divergence between techniques with the FFDT giving a mean of 75, the ESP 48 and the DIN+ method 17g/GJ. The SDs for each technique are larger than found for the larger Appliance F but generally smaller than for wood log roomheaters.

The variation in particulate emission concentrations between measurement techniques is perhaps surprising given the very low THC emission concentrations determined at Appliance E.

The wood log roomheaters generally showed very large variations in emissions from run to run, the %RSD for all labs and for all measurement techniques ranged from 1 to >100%, typically >20% and with a median %RSD's around 29%.

The use of any of the particulate measurement techniques as the basis for determining regulatory compliance for log fired roomheater appliances appears to have limitations.

6.2 Inter-laboratory comparisons

The high variability noted between different measurement runs at individual test laboratories makes inter-laboratory comparisons of measurement techniques difficult. It is not possible to be definitive regarding inter-laboratory comparisons for the same measurement techniques other than that, even when the appliance and measurement apparatus was identical (as in the DIN+ tests at Lab 2 and Lab 3), the particulate emission results can be substantially different.

6.3 Inter-method comparisons

Statistically there is some indication that the ESP and FFDT techniques report broadly similar and higher values than DIN+ but even this is not without individual exception.

The high variability noted between different measurement runs at individual test laboratories makes comparisons of measurement techniques difficult for wood log appliances.

For Appliance E (the pellet stove boiler) there is a general ranking in the particulate emission concentration results:

DIN+ < ESP < FFDT

However, this was on a single appliance (and at a single test laboratory) and there was significant variability in particulate emission concentrations. The difference in particulate emissions determined by the different measurement techniques is perhaps surprising given the very low THC emission concentrations determined for this appliance.

For Appliance F (the 200 kW output pellet boiler), the ESP and DIN+ measurement techniques methods have relatively good repeatability and, at high output, good comparability.

6.4 Proposed CEN relationship

The emission data from the current study indicate that the model proposed by CEN in prEN 16510 for calculating particulate emissions from DIN+ and THC data is not valid when applied to the wider range of appliances.

Development of a widely applicable model for relating particulate measurements using different methods would need sound theoretical basis, validated using extensive sets of measurements.

6.5 Particulate measurement and market surveillance

The emission data indicate that use of any of the particulate test protocols and measurement techniques as the basis for determining regulatory compliance for batch fed log fired appliances appears to have limitations.

The measurement of particulate emissions from biomass appliances is much less consistent than measurement of efficiency or heat output. Standard deviations of five consecutive tests using the measurement techniques assessed in this study are often >20% of the average value reported. Comparison of emission data between different test laboratories also shows variability.

This may not be an issue when determining compliance with a national or regional pass or fail criteria at a specific point in time. However, this variability presents a greater challenge to manufacturers considering declaration of emission data for potential compliance verification by market surveillance authorities in the context of the proposed Ecodesign verification tolerances.

7 Possible ways forward

The test work here has shown that within the scope of this survey none of the measurement techniques applied under the test protocols used here has the level of reproducibility that might be hoped from an emission measurement technique. The results of this study suggest that this is mainly an issue for residential appliances and, in particular, the batch-fired wood log appliances.

Further work is needed to establish:

- the extent to which variability is due to the appliance and fuel characteristics and how this could be mitigated to develop a robust, consistent emission test protocol

- the extent to which variability is due to different sampling periods, test durations and sampling techniques and how the test protocol and sampling techniques can be improved to reduce uncertainty in emission test results

In defining an emissions measurement test protocol/measurement technique suitable for application to log burning roomheaters the variability of the combustion, (shown by the levels of Optical Density, THC and CO measured throughout sequential tests on individual appliances) should be considered. In some cases, the plots of these measurements for the duration of tests indicate that the bulk of emissions may occur in a narrow time frame close to the refuel time so the exact timing of a particulate measurement could have a significant impact on the apparent level of particulate emission.

8 References

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[iii] BS EN 13240:2001 Roomheaters fired by solid fuel - Requirements and test methods.
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[v] BS 3841-2 1994 Determination of smoke emission from manufactured solid fuels for domestic use – Part 2: Methods for measuring the smoke emission rate
[vi] PD 6434:1969 Recommendations for The design and testing of smoke reducing solid fuel burning domestic appliances
[vii] CEN/TS 15883:2009 Residential solid fuel burning appliances - Emission test methods
[viii] E Smit PM measurement for residential solid fuel fired appliances An experimental comparison of measurement methods, Draft report, CEN/TC 295/ WG 5 N 053/2011, April 2011

Appendix 1 Detailed test data and results

Table A1.1 Fuel and energy information for individual tests at Lab 1 for ESP measurements

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
A	HIGH	1	1.124	0.67	1.68	5.54	78.0
A	HIGH	2	1.132	0.63	1.80	5.94	78.0
A	HIGH	3	1.170	0.73	1.60	5.30	78.0
A	HIGH	4	1.128	0.70	1.61	5.33	78.0
A	HIGH	5	1.146	0.70	1.64	5.41	78.0
A	LOW	1	1.118	0.77	1.45	1.45	78.0
A	LOW	2	1.124	0.77	1.36	1.36	78.0
A	LOW	3	1.115	0.78	1.43	1.43	78.0
A	LOW	4	1.107	0.77	1.39	1.39	78.0
A	LOW	5	1.098	0.78	1.41	1.41	78.0
B	HIGH	1	1.801	0.68	2.65	8.87	80.0
B	HIGH	2	1.822	0.68	2.68	8.97	80.0
B	HIGH	3	1.820	0.68	2.68	8.96	80.0
B	HIGH	4	1.824	0.75	2.43	8.14	80.0
B	HIGH	5	1.827	0.70	2.61	8.74	80.0
B	LOW	1	1.804	0.78	2.31	7.74	80.0
B	LOW	2	1.798	0.80	2.25	7.53	80.0
B	LOW	3	1.786	0.78	2.29	7.67	80.0
B	LOW	4	1.766	0.82	2.15	7.21	80.0
B	LOW	5	1.789	0.88	2.03	6.81	80.0
C	HIGH	1	1.446	0.72	2.01	6.98	83.0
C	HIGH	2	1.458	0.70	2.08	7.24	83.0
C	HIGH	3	1.396	0.63	2.22	7.70	83.0
C	HIGH	4	1.472	0.73	2.02	7.01	83.0
C	HIGH	5	1.456	0.75	1.94	6.74	83.0
C	LOW	1	1.264	0.82	1.54	5.36	83.0
C	LOW	2	1.393	0.85	1.64	5.69	83.0
C	LOW	3	1.292	0.87	1.49	5.16	83.0
C	LOW	4	1.304	0.83	1.57	5.46	83.0
C	LOW	5	1.269	0.90	1.41	4.90	83.0
C_{EXTRA}	HIGH	1	1.443	0.70	2.06	6.24	72.5
C_{EXTRA}	HIGH	2	1.438	0.75	2.04	6.11	72.3
C_{EXTRA}	HIGH	3	1.455	0.73	1.92	5.79	70.7
C_{EXTRA}	HIGH	4	1.410	0.85	1.96	5.84	76.3

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
C_{EXTRA}	HIGH	5	1.410	0.90	1.99	5.88	75.6
C_{EXTRA}	LOW	1	1.466	0.72	1.79	5.77	71.9
C_{EXTRA}	LOW	2	1.468	0.75	1.66	5.28	71.5
C_{EXTRA}	LOW	3	1.485	0.83	1.61	5.08	77.3
C_{EXTRA}	LOW	4	1.399	0.87	1.57	4.95	75.7
C_{EXTRA}	LOW	5	1.425	0.97	1.47	4.61	75.1
D	HIGH	1	7.922	1.50	5.28	16.61	75.0
D	HIGH	2	7.582	1.50	5.05	15.89	75.0
D	HIGH	3	7.869	1.50	5.25	16.50	75.0
D	HIGH	4	7.540	1.52	4.96	15.60	75.0
D	HIGH	5	7.653	1.43	5.35	16.83	75.0
D	LOW	1	7.720	1.65	4.68	14.71	75.0
D	LOW	2	7.390	2.02	3.66	11.50	75.0
D	LOW	3	7.492	1.95	3.84	12.08	75.0
D	LOW	4	7.661	1.78	4.30	13.53	75.0
D	LOW	5	7.440	2.08	3.58	11.25	75.0
E	HIGH	1	2.280	0.75	3.09	12.50	83.6
E	HIGH	2	2.240	0.75	3.09	12.50	83.6
E	HIGH	3	2.300	0.75	3.09	12.50	83.6
E	HIGH	4	2.300	0.75	3.09	12.50	83.6
E	HIGH	5	2.240	0.75	3.09	12.50	83.6
E	LOW	1	0.740	1.00	0.78	3.10	81.3
E	LOW	2	0.760	1.00	0.78	3.10	81.3
E	LOW	3	0.780	1.00	0.78	3.10	81.3
E	LOW	4	0.800	1.00	0.78	3.10	81.3
E	LOW	5	0.780	1.00	0.78	3.10	81.3
F	HIGH	1	23.247	0.50	46.49	203.94	88.8
F	HIGH	2	23.247	0.50	46.49	203.94	88.8
F	HIGH	3	23.247	0.50	46.49	203.94	88.8
F	HIGH	4	23.247	0.50	46.49	203.94	88.8
F	HIGH	5	23.247	0.50	46.49	203.94	88.8
F	LOW	1	6.574	0.50	13.15	56.93	90.0
F	LOW	2	6.574	0.50	13.15	56.93	90.0
F	LOW	3	6.574	0.50	13.15	56.93	90.0
F	LOW	4	6.574	0.50	13.15	56.93	90.0
F	LOW	5	6.574	0.50	13.15	56.93	90.0

NOTE: For Appliance E and F the efficiency is heat to water determined using the direct method. The efficiencies of the other appliances were calculated using the losses method.

Table A1.2a Conditions recorded for individual tests at Lab 1 for ESP measurements - temperatures

Appliance	Output	Test #	Flue draught		Flue temp bottom		Flue temp top		Ambient temp	
			Average	SD	Average	SD	Average	SD	Average	SD
A	HIGH	1	9.52	0.76	122.15	11.33	ND	ND	ND	ND
A	HIGH	2	10.77	0.82	228.05	21.64	ND	ND	ND	ND
A	HIGH	3	10.29	1.03	202.31	20.75	ND	ND	ND	ND
A	HIGH	4	9.72	1.02	205.94	19.46	ND	ND	ND	ND
A	HIGH	5	10.15	0.87	208.10	17.19	ND	ND	ND	ND
A	LOW	1	9.70	0.76	116.01	15.32	ND	ND	ND	ND
A	LOW	2	10.00	0.78	202.78	21.40	ND	ND	ND	ND
A	LOW	3	10.47	0.86	191.91	20.12	ND	ND	ND	ND
A	LOW	4	9.56	0.98	193.39	23.74	ND	ND	ND	ND
A	LOW	5	10.22	0.73	210.92	27.75	69.26	5.74	22.70	0.19
B	HIGH	1	13.93	1.15	276.13	21.48	93.52	6.84	24.11	0.55
B	HIGH	2	13.72	0.98	266.64	20.81	94.42	5.18	26.32	0.59
B	HIGH	3	13.47	0.84	258.27	18.55	94.13	4.54	28.12	0.26
B	HIGH	4	12.38	0.75	238.02	17.09	79.73	4.71	21.69	0.10
B	HIGH	5	13.08	0.87	248.72	18.65	86.48	4.82	22.36	0.09
B	LOW	1	10.97	1.17	221.73	24.40	76.17	6.74	25.15	0.37
B	LOW	2	10.82	1.19	214.99	24.27	77.91	6.13	27.78	0.29
B	LOW	3	11.22	1.42	215.10	30.15	81.33	7.59	27.78	0.24
B	LOW	4	10.58	1.23	191.70	24.71	67.44	6.84	22.21	0.23
B	LOW	5	10.59	1.07	190.31	21.47	69.26	5.74	22.70	0.19
C	HIGH	1	9.06	1.38	211.08	29.62	64.81	8.92	23.30	0.86
C	HIGH	2	9.26	1.59	212.22	37.93	68.91	12.79	25.85	0.94
C	HIGH	3	9.29	1.57	202.71	37.79	68.26	11.95	27.58	0.45
C	HIGH	4	8.74	1.35	187.29	33.00	65.42	9.73	25.28	0.26
C	HIGH	5	9.50	1.67	208.03	37.30	71.84	16.83	26.74	0.40
C	LOW	1	7.70	2.57	166.44	62.32	58.18	19.04	24.63	0.69
C	LOW	2	7.71	1.94	159.53	49.16	57.79	15.31	26.89	0.69
C	LOW	3	8.18	2.18	169.28	54.05	62.00	16.76	28.25	0.44
C	LOW	4	7.47	1.62	159.29	40.13	57.76	10.77	25.98	0.39
C	LOW	5	7.41	1.84	146.33	48.51	57.39	14.14	27.30	0.62
C_{EXTTRA}	HIGH	1	16.93	1.16	368.70	29.05	ND	ND	20.38	0.49
C_{EXTTRA}	HIGH	2	16.14	1.32	333.45	19.49	ND	ND	19.80	0.06
C_{EXTTRA}	HIGH	3	16.59	1.53	329.74	23.50	ND	ND	19.99	0.15
C_{EXTTRA}	HIGH	4	16.83	1.59	325.43	18.26	ND	ND	20.62	0.22
C_{EXTTRA}	HIGH	5	16.64	1.34	328.67	20.01	ND	ND	21.57	0.24
C_{EXTTRA}	LOW	1	13.92	1.47	286.84	14.83	ND	ND	20.11	0.14

Appliance	Output	Test #	Flue draught		Flue temp bottom		Flue temp top		Ambient temp	
			Average	SD	Average	SD	Average	SD	Average	SD
C_{EXTTRA}	LOW	2	13.92	1.47	286.84	14.83	ND	ND	20.11	0.14
C_{EXTTRA}	LOW	3	14.04	1.45	280.83	15.26	ND	ND	20.61	0.21
C_{EXTTRA}	LOW	4	13.03	1.22	283.06	19.99	ND	ND	21.39	0.24
C_{EXTTRA}	LOW	5	13.95	1.54	273.15	18.48	ND	ND	21.87	0.12
D	HIGH	1	15.58	2.25	224.93	46.45	ND	ND	ND	ND
D	HIGH	2	15.82	3.46	226.68	72.80	ND	ND	ND	ND
D	HIGH	3	17.92	2.90	279.76	68.44	ND	ND	ND	ND
D	HIGH	4	17.42	2.96	262.86	70.11	ND	ND	ND	ND
D	HIGH	5	18.33	2.99	285.80	75.11	ND	ND	ND	ND
D	LOW	1	14.67	3.12	224.61	77.00	ND	ND	ND	ND
D	LOW	2	12.76	1.86	170.40	41.02	ND	ND	ND	ND
D	LOW	3	12.77	3.09	173.54	39.92	ND	ND	ND	ND
D	LOW	4	14.84	1.59	201.19	33.96	ND	ND	ND	ND
D	LOW	5	13.03	2.49	171.77	50.75	ND	ND	ND	ND
E	HIGH	1	*	*	119.76	1.50	ND	ND	20.26	0.23
E	HIGH	2	*	*	119.83	0.91	ND	ND	20.87	0.18
E	HIGH	3	*	*	122.32	1.36	ND	ND	21.37	0.20
E	HIGH	4	*	*	124.18	0.89	ND	ND	21.79	0.16
E	HIGH	5	*	*	125.68	1.40	ND	ND	22.15	0.20
E	LOW	1	*	*	49.00	1.18	ND	ND	20.34	0.16
E	LOW	2	*	*	49.21	1.15	ND	ND	20.60	0.14
E	LOW	3	*	*	49.32	1.30	ND	ND	20.80	0.15
E	LOW	4	*	*	49.14	1.20	ND	ND	21.12	0.16
E	LOW	5	*	*	50.28	1.27	ND	ND	21.42	0.17
F	HIGH	1	*	*	175.12	1.32	ND	ND	20.33	0.29
F	HIGH	2	*	*	177.29	1.00	ND	ND	20.99	0.19
F	HIGH	3	*	*	178.29	1.13	ND	ND	21.20	0.16
F	HIGH	4	*	*	180.47	0.80	ND	ND	21.47	0.20
F	HIGH	5	*	*	182.00	1.39	ND	ND	21.61	0.15
F	LOW	1	*	*	93.22	2.61	ND	ND	20.21	0.12
F	LOW	2	*	*	97.35	2.49	ND	ND	20.35	0.15
F	LOW	3	*	*	100.63	2.16	ND	ND	20.85	0.16
F	LOW	4	*	*	100.12	0.23	ND	ND	21.01	0.13
F	LOW	5	*	*	101.35	2.14	ND	ND	21.51	0.13

NOTE: * Appliances E and F are forced draft appliances

Table A1.2b Conditions recorded for individual tests at Lab 1 for ESP measurements – flue gas

Appliance	Output	Test #	CO_2, %		CO, %		O_2, %		NOx ppm		THC ppm	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
A	HIGH	1	3.39	0.91	0.13	0.19	ND	ND	ND	ND	ND	ND
A	HIGH	2	8.44	2.47	0.62	0.94	ND	ND	ND	ND	ND	ND
A	HIGH	3	7.52	1.75	0.44	0.42	ND	ND	ND	ND	ND	ND
A	HIGH	4	6.25	1.63	0.16	0.22	ND	ND	ND	ND	ND	ND
A	HIGH	5	6.05	1.77	0.31	0.61	ND	ND	ND	ND	ND	ND
A	LOW	1	5.10	1.84	0.06	0.07	ND	ND	ND	ND	ND	ND
A	LOW	2	7.03	2.27	0.14	0.12	ND	ND	ND	ND	ND	ND
A	LOW	3	6.57	2.32	0.12	0.11	ND	ND	ND	ND	ND	ND
A	LOW	4	6.65	2.71	0.13	0.13	ND	ND	ND	ND	ND	ND
A	LOW	5	5.67	1.65	0.08	0.07	ND	ND	ND	ND	ND	ND
B	HIGH	1	11.38	3.15	0.70	0.98	ND	ND	ND	ND	ND	ND
B	HIGH	2	10.71	3.37	0.50	0.57	ND	ND	ND	ND	ND	ND
B	HIGH	3	10.59	3.32	0.30	0.35	ND	ND	ND	ND	ND	ND
B	HIGH	4	10.16	2.62	0.28	0.34	ND	ND	ND	ND	ND	ND
B	HIGH	5	11.46	3.46	0.42	0.51	ND	ND	ND	ND	ND	ND
B	LOW	1	11.70	3.88	0.88	1.02	ND	ND	ND	ND	ND	ND
B	LOW	2	11.74	3.66	0.87	0.94	ND	ND	ND	ND	ND	ND
B	LOW	3	11.40	4.34	1.22	0.96	ND	ND	ND	ND	ND	ND
B	LOW	4	11.31	2.94	0.50	0.65	ND	ND	ND	ND	ND	ND
B	LOW	5	10.84	3.04	0.45	0.57	ND	ND	ND	ND	ND	ND
C	HIGH	1	8.57	2.70	0.26	0.61	11.77	2.83	ND	ND	ND	ND
C	HIGH	2	8.41	3.04	0.39	0.92	11.67	3.27	ND	ND	ND	ND
C	HIGH	3	8.86	2.57	0.41	0.86	11.19	2.86	ND	ND	ND	ND
C	HIGH	4	6.09	1.98	0.21	0.24	14.28	2.16	ND	ND	ND	ND
C	HIGH	5	7.13	2.69	0.24	0.58	12.86	2.91	ND	ND	ND	ND
C	LOW	1	7.34	3.06	0.76	1.22	12.71	3.65	ND	ND	ND	ND
C	LOW	2	7.63	2.80	0.55	0.82	12.48	3.08	ND	ND	ND	ND
C	LOW	3	7.51	2.65	0.49	0.81	12.51	3.08	ND	ND	ND	ND
C	LOW	4	7.60	2.63	0.34	0.57	12.52	2.66	ND	ND	ND	ND
C	LOW	5	6.48	2.49	0.41	0.61	13.53	2.76	ND	ND	ND	ND
C_{EXTTRA}	HIGH	1	10.96	4.06	0.24	0.32	9.44	4.05	55.0	11.3	546.8	1283.0
C_{EXTTRA}	HIGH	2	9.25	3.23	0.11	0.18	11.44	2.91	39.1	10.7	197.8	617.3
C_{EXTTRA}	HIGH	3	9.32	3.63	0.14	0.19	11.14	3.33	43.0	14.5	236.1	655.0
C_{EXTTRA}	HIGH	4	8.76	3.29	0.09	0.15	11.60	3.03	43.3	12.2	156.8	531.3
C_{EXTTRA}	HIGH	5	8.56	3.35	0.08	0.12	11.53	3.08	45.1	13.0	99.2	249.2
C_{EXTTRA}	LOW	1	9.30	2.60	0.08	0.12	10.82	2.40	51.6	11.3	546.8	1283.0

Appliance	Output	Test #	CO_2, %		CO, %		O_2, %		NOx ppm		THC ppm	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
C_{EXTTRA}	LOW	2	9.30	2.60	0.08	0.12	10.82	2.40	48.3	15.2	178.1	387.8
C_{EXTTRA}	LOW	3	8.83	2.94	0.11	0.11	11.22	2.72	42.3	13.1	225.8	292.4
C_{EXTTRA}	LOW	4	8.99	3.81	0.17	0.21	10.83	3.62	48.3	19.1	449.7	866.4
C_{EXTTRA}	LOW	5	8.34	3.11	0.14	0.11	11.39	2.90	47.3	19.5	204.0	213.6
D	HIGH	1	4.96	1.63	0.32	0.11	ND	ND	ND	ND	ND	ND
D	HIGH	2	3.17	1.33	0.33	0.11	ND	ND	ND	ND	ND	ND
D	HIGH	3	5.78	2.31	0.39	0.28	ND	ND	ND	ND	ND	ND
D	HIGH	4	5.57	2.32	0.39	0.10	ND	ND	ND	ND	ND	ND
D	HIGH	5	4.74	2.04	0.17	0.12	ND	ND	ND	ND	ND	ND
D	LOW	1	6.07	3.15	0.48	0.40	ND	ND	ND	ND	ND	ND
D	LOW	2	4.56	1.43	0.44	0.17	ND	ND	ND	ND	ND	ND
D	LOW	3	5.07	1.59	0.46	0.18	ND	ND	ND	ND	ND	ND
D	LOW	4	6.07	1.79	0.58	0.32	ND	ND	ND	ND	ND	ND
D	LOW	5	3.97	1.45	0.27	0.12	ND	ND	ND	ND	ND	ND
E	HIGH	1	12.18	0.98	0.002	0.002	ND	ND	ND	ND	ND	ND
E	HIGH	2	11.69	0.98	0.002	0.002	ND	ND	ND	ND	ND	ND
E	HIGH	3	11.87	1.04	0.002	0.002	ND	ND	ND	ND	ND	ND
E	HIGH	4	12.15	0.96	0.002	0.002	ND	ND	ND	ND	ND	ND
E	HIGH	5	12.09	1.13	0.004	0.010	ND	ND	ND	ND	ND	ND
E	LOW	1	5.95	1.80	0.054	0.039	ND	ND	ND	ND	ND	ND
E	LOW	2	5.93	1.83	0.051	0.040	ND	ND	ND	ND	ND	ND
E	LOW	3	6.12	2.14	0.048	0.045	ND	ND	ND	ND	ND	ND
E	LOW	4	5.82	2.03	0.049	0.048	ND	ND	ND	ND	ND	ND
E	LOW	5	5.96	1.97	0.039	0.038	ND	ND	ND	ND	ND	ND
F	HIGH	1	14.96	0.29	0.002	0.001	ND	ND	92.50	2.28	10.13	1.76
F	HIGH	2	14.68	0.28	0.002	0.001	ND	ND	90.74	2.25	6.65	0.49
F	HIGH	3	14.79	0.26	0.002	0.001	ND	ND	90.16	1.98	5.49	0.67
F	HIGH	4	14.83	0.29	0.002	0.001	ND	ND	88.49	2.03	4.27	1.07
F	HIGH	5	14.95	0.38	0.003	0.002	ND	ND	87.88	1.93	3.46	0.40
F	LOW	1	10.12	0.68	0.002	0.001	ND	ND	59.29	3.23	1.72	0.27
F	LOW	2	10.24	0.56	0.001	0.001	ND	ND	59.49	2.70	1.12	0.21
F	LOW	3	9.78	0.57	0.001	0.001	ND	ND	57.35	2.89	0.69	0.14
F	LOW	4	9.96	0.36	0.001	0.000	ND	ND	58.36	2.15	0.55	0.06
F	LOW	5	9.80	0.52	0.001	0.001	ND	ND	57.58	3.08	0.33	0.13

Table A1.3 Repeatability of test conditions - flue gas compositions for ESP measurements at Lab 1

Appliance	Output level	% CO2			% CO			% O2			NOx ppm			THC ppm		
		Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD
A	High	6.32	2.44	0.39	0.326	0.570	1.75	13.63	2.74	0.20	ND	ND	ND	ND	ND	ND
A	Low	6.20	2.30	0.37	0.106	0.108	1.02	13.75	2.41	0.18	ND	ND	ND	ND	ND	ND
B	High	10.85	3.23	0.30	0.436	0.611	1.40	ND	ND	ND	47.69	19.08	0.40	873.87	1886.23	2.16
B	Low	11.39	3.60	0.32	0.773	0.884	1.14	ND	ND	ND	50.89	11.89	0.23	1551.62	2801.83	1.81
C	High	7.77	2.82	0.36	0.300	0.681	2.27	12.40	3.03	0.24	ND	ND	ND	ND	ND	ND
C	Low	7.30	2.76	0.38	0.509	0.848	1.67	12.76	3.09	0.24	ND	ND	ND	ND	ND	ND
C_{EXTRA}	High	9.34	3.62	0.39	0.13	0.21	1.61	11.05	3.39	0.31	44.5	13.4	0.30	227.6	711.7	3.13
C_{EXTRA}	Low	8.93	3.08	0.35	0.12	0.14	1.20	11.04	2.87	0.26	47.5	17.3	0.36	124.1	595.1	4.80
D	High	4.85	2.17	0.45	0.323	0.181	0.56	15.69	2.49	0.16	ND	ND	ND	ND	ND	ND
D	Low	5.08	2.11	0.41	0.441	0.271	0.61	15.26	2.34	0.15	ND	ND	ND	ND	ND	ND
E	High	12.00	1.05	0.09	0.002	0.005	2.07	ND	ND	ND	ND	ND	ND	ND	ND	ND
E	Low	5.95	1.95	0.33	0.048	0.042	0.89	ND	ND	ND	ND	ND	ND	ND	ND	ND
F	High	14.84	0.32	0.02	0.002	0.001	0.66	ND	ND	ND	89.96	2.70	0.03	6.05	2.66	0.44
F	Low	9.95	0.60	0.06	0.001	0.001	0.61	ND	ND	ND	58.31	3.08	0.05	0.85	0.54	0.64

Note: These statistics are calculated from whole data set recorded for the multiple tests of each appliance at each output level.

Table A1.4 Repeatability of test conditions – draft and temperatures for ESP measurements at Lab 1

Appliance	Output level	Flue draught, Pa			Flue temp bottom / Flue temp, °C			Flue temp top, °C			Ambient, °C		
		Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD
A	High	10.08	1.01	0.10	193.00	40.80	0.21	ND	ND	ND	ND	ND	ND
A	Low	9.99	0.89	0.09	183.15	40.62	0.22	ND	ND	ND	ND	ND	ND
B	High	13.29	1.08	0.08	257.07	23.53	0.09	89.44	7.88	0.09	24.46	2.45	0.10
B	Low	10.83	1.24	0.11	206.17	28.33	0.14	74.20	8.47	0.11	25.03	2.41	0.10
C	High	9.17	1.54	0.17	204.22	36.41	0.18	67.86	12.67	0.19	25.72	1.57	0.06
C	Low	7.69	2.07	0.27	160.00	51.90	0.32	58.63	15.52	0.26	26.64	1.35	0.05
C_{EXTRA}	High	16.62	1.43	0.09	336.70	27.36	0.08	ND	ND	ND	20.47	0.68	0.03
C_{EXTRA}	Low	13.77	1.48	0.11	281.78	17.74	0.06	ND	ND	ND	20.86	0.73	0.04
D	High	17.00	3.14	0.18	255.64	72.02	0.28	ND	ND	ND	ND	ND	ND
D	Low	13.55	2.66	0.20	186.58	54.14	0.29	ND	ND	ND	ND	ND	ND
E	High	ND	ND	ND	122.43	2.75	0.02	ND	ND	ND	21.30	0.71	0.03
E	Low	ND	ND	ND	49.41	1.31	0.03	ND	ND	ND	20.87	0.42	0.02
F	High	ND	ND	ND	178.62	2.75	0.02	ND	ND	ND	21.12	0.50	0.02
F	Low	ND	ND	ND	98.72	3.82	0.04	ND	ND	ND	20.84	0.54	0.03

Note: These statistics are calculated from whole data set recorded for the multiple tests of each appliance at each output level.

Table A1.5 Fuel and energy information for individual tests at Lab 1 for FFDT and DIN+ measurements

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
A	HIGH	1	1.198	0.67	1.80	5.40	72.3
A	HIGH	2	1.210	0.68	1.77	5.20	70.0
A	HIGH	3	1.196	0.75	1.59	5.00	75.4
A	HIGH	4	1.198	0.73	1.63	5.20	76.5
A	HIGH	5	1.198	0.67	1.48	4.70	72.3
A	LOW	1	1.201	0.78	1.53	4.80	75.4
A	LOW	2	1.209	0.77	1.58	5.00	76.6
A	LOW	3	1.198	0.88	1.36	4.20	74.4
A	LOW	4	1.194	0.87	1.38	4.30	75.9
A	LOW	5	1.201	0.78	1.59	5.20	75.4
B	HIGH	1	1.782	0.70	3.34	6.80	63.7
B	HIGH	2	1.815	0.70	2.59	6.70	61.5
B	HIGH	3	1.821	0.67	2.73	7.40	64.9
B	HIGH	4	1.807	0.80	2.26	6.10	63.8
B	HIGH	5	1.782	0.70	2.17	6.10	63.7
B	LOW	1	1.791	0.98	1.82	5.60	73.0
B	LOW	2	1.800	0.97	1.86	5.80	74.4
B	LOW	3	1.833	0.87	2.12	6.60	74.6
B	LOW	4	1.834	0.83	2.20	6.90	76.1
B	LOW	5	1.791	0.98	2.00	6.40	73.0
C	HIGH	1	1.483	0.75	1.98	5.90	71.9
C	HIGH	2	1.446	0.70	2.07	6.00	69.2
C	HIGH	3	1.460	0.75	1.95	5.60	69.4
C	HIGH	4	1.484	0.73	2.02	6.00	70.3
C	HIGH	5	1.483	0.75	2.01	5.90	71.9
C	LOW	1	1.485	0.78	1.90	6.10	77.4
C	LOW	2	1.483	0.85	1.74	5.60	77.2
C	LOW	3	1.495	0.85	1.76	6.10	77.8
C	LOW	4	1.488	0.80	1.86	6.00	77.5
C	LOW	5	1.485	0.78	1.66	5.10	77.4
D	HIGH	1	8.044	1.50	6.03	13.80	61.5
D	HIGH	2	8.000	1.63	4.90	12.60	61.1
D	HIGH	3	8.096	1.57	5.17	12.70	58.9
D	HIGH	4	7.968	1.53	5.20	13.30	60.9
D	HIGH	5	8.044	1.50	5.31	13.40	61.5
D	LOW	1	7.977	2.07	3.86	12.80	78.3
D	LOW	2	7.979	2.02	3.96	12.90	77.7

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
D	LOW	3	7.924	2.07	3.83	12.30	76.6
D	LOW	4	8.003	2.08	3.84	12.00	74.1
D	LOW	5	7.977	2.07	3.81	12.10	78.3
E	HIGH	1	2.280	0.75	3.04	13.80	94.3
E	HIGH	2	2.240	0.75	3.00	13.60	94.2
E	HIGH	3	2.300	0.75	3.07	13.90	94.2
E	HIGH	4	2.300	0.75	3.07	13.90	94.2
E	HIGH	5	2.280	0.75	3.00	13.50	94.3
E	LOW	1	0.740	1.00	0.74	3.40	96.2
E	LOW	2	0.760	1.00	0.76	3.50	96.3
E	LOW	3	0.780	1.00	0.78	3.60	96.2
E	LOW	4	0.800	1.00	0.80	3.70	96.2
E	LOW	5	0.740	1.00	0.78	3.60	96.2
F	HIGH	1	23.245	0.50	22.58	203.90	90.0
F	HIGH	2	23.245	0.50	32.65	203.90	90.0
F	HIGH	3	23.245	0.50	33.82	203.90	90.0
F	HIGH	4	23.245	0.50	31.09	203.90	90.0
F	HIGH	5	23.245	0.50	31.22	203.90	90.0
F	LOW	1	23.245	0.50	9.66	56.90	90.0
F	LOW	2	23.245	0.50	9.37	56.90	90.0
F	LOW	3	23.245	0.50	9.63	56.90	90.0
F	LOW	4	23.245	0.50	12.42	56.90	90.0
F	LOW	5	23.245	0.50	11.50	56.90	90.0

NOTE: For appliance F fuel charge, heat output and efficiency results were determined as an average over the period of testing and not individually for each particulate measurement period. For Appliance F the efficiency is heat to water determined using the direct method. The efficiencies of the other appliances were calculated using the losses method.

Table A1.6 Fuel and energy information for individual tests at Lab 2 for FFDT and DIN+ measurements

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
B	HIGH	1	1.710	0.70	2.45	8.40	79.0
B	HIGH	2	1.710	0.65	2.62	9.10	80.0
B	HIGH	3	1.710	0.65	2.62	8.80	77.0
B	HIGH	4	1.730	0.76	2.27	7.70	78.0
B	HIGH	5	1.720	0.70	2.44	8.40	79.0
B	LOW	1	1.690	0.78	2.18	7.10	75.0
B	LOW	2	1.680	0.79	2.12	7.00	78.0
B	LOW	3	1.670	0.80	2.09	7.20	79.0
B	LOW	4	1.680	0.73	2.30	8.10	81.0
B	LOW	5	1.690	0.77	2.21	7.80	81.0
C	HIGH	1	1.450	0.79	1.85	6.20	78.0
C	HIGH	2	1.490	0.81	1.84	6.20	78.0
C	HIGH	3	1.460	0.80	1.82	6.20	78.0
C	HIGH	4	1.460	0.80	1.83	6.10	78.0
C	HIGH	5	1.420	0.76	1.87	6.30	78.0
C	LOW	1	1.450	0.92	1.58	5.40	78.0
C	LOW	2	1.420	0.81	1.74	6.20	81.0
C	LOW	3	1.440	0.88	1.65	5.70	80.0
C	LOW	4	1.440	0.83	1.73	6.10	80.0
C	LOW	5	1.460	0.89	1.64	5.70	79.0

Table A1.7 Fuel and energy information for individual tests at Lab 3 for DIN+ measurements

Appliance	Output	Test #	Fuel charge, kg	Duration of test, h	Burning rate (as charged), kg h^{-1}	Heat output, kW	Efficiency, % net
B	HIGH	1	1.73	0.77	2.30	7.30	75.5
B	HIGH	2	1.73	0.78	2.20	7.30	77.2
B	HIGH	3	1.75	0.73	2.40	7.80	76.0
B	HIGH	4	1.73	0.72	2.40	7.90	76.4
B	HIGH	5	1.71	0.83	2.00	6.50	74.6
B	LOW	1	1.73	0.72	2.40	8.10	78.5
B	LOW	2	1.69	0.80	2.10	6.90	76.1
B	LOW	3	1.63	0.72	2.30	7.60	78.5
B	LOW	4	1.8	0.82	2.20	7.30	77.2
B	LOW	5	1.66	0.72	2.30	7.50	75.6
C	HIGH	1	1.48	0.88	1.70	5.50	78.7
C	HIGH	2	1.45	0.85	1.70	5.50	76.6
C	HIGH	3	1.45	0.73	2.00	6.80	81.4
C	HIGH	4	1.48	0.93	1.60	5.30	79.5
C	HIGH	5	1.49	0.80	1.90	6.40	81.4
C	LOW	1	1.45	1.05	1.40	4.90	81.9
C	LOW	2	1.46	1.27	1.20	4.10	82.4
C	LOW	3	1.45	1.22	1.20	4.20	82.4
C	LOW	4	1.45	0.97	1.50	5.50	84.9
C	LOW	5	1.45	1.02	1.40	5.10	82.8

Table A1.8a Conditions recorded for individual tests at Lab 1 for FFDT and DIN+ measurements - temperatures

Appliance	Output	Test #	Flue draught, Pa		Flue temp bottom, °C		Flue temp top, °C		Ambient temp, °C	
			Average	SD	Average	SD	Average	SD	Average	SD
A	HIGH	1	11.95	1.40	304.78	23.90	36.51	8.49	21.65	0.20
A	HIGH	2	10.46	1.01	313.92	24.05	37.36	3.93	21.91	0.19
A	HIGH	3	9.60	0.47	275.04	9.09	33.72	10.11	23.14	0.19
A	HIGH	4	9.46	0.47	270.66	13.39	33.75	9.25	23.43	0.12
A	HIGH	5	9.48	0.45	264.55	16.80	33.78	8.46	23.98	0.14
A	LOW	1	6.25	0.26	256.71	7.10	35.41	4.42	24.02	0.43
A	LOW	2	12.04	0.62	255.07	13.45	35.48	5.12	24.39	0.20
A	LOW	3	6.38	0.37	235.43	13.98	34.53	4.91	24.36	0.23
A	LOW	4	6.42	0.39	234.93	15.05	33.49	9.63	24.53	0.30
A	LOW	5	6.48	0.43	233.82	21.26	36.03	5.96	25.89	0.36
B	HIGH	1	11.41	0.28	424.14	17.60	39.25	1.72	19.01	0.32
B	HIGH	2	11.50	0.30	418.25	21.83	38.62	2.31	19.07	0.35
B	HIGH	3	11.25	0.20	401.81	17.98	38.39	1.51	20.43	0.21
B	HIGH	4	11.27	0.26	377.47	18.81	37.45	1.64	21.40	0.24
B	HIGH	5	11.56	0.35	361.16	12.15	35.20	1.53	22.33	0.30
B	LOW	1	7.38	0.25	333.29	18.12	29.91	1.78	20.70	0.28
B	LOW	2	7.43	0.20	335.57	18.73	30.17	1.67	20.95	0.21
B	LOW	3	7.36	0.19	349.17	13.71	32.50	1.09	21.56	0.31
B	LOW	4	7.44	0.18	348.97	12.80	35.14	1.52	22.19	0.25
B	LOW	5	7.27	0.16	323.39	11.48	34.12	1.35	22.59	0.30
C	HIGH	1	13.36	0.50	283.17	15.63	31.48	9.87	19.85	0.28
C	HIGH	2	13.59	0.54	351.99	28.31	34.03	1.11	20.44	0.27
C	HIGH	3	12.98	0.54	330.24	20.89	36.02	7.71	23.22	0.40
C	HIGH	4	13.28	0.46	344.62	25.11	38.08	6.22	24.07	0.22
C	HIGH	5	13.52	0.37	329.68	21.74	37.40	5.57	24.71	0.19
C	LOW	1	6.15	0.19	279.55	18.80	28.80	9.69	19.46	0.39
C	LOW	2	6.26	0.16	258.85	17.39	29.13	8.40	20.63	0.28
C	LOW	3	6.36	0.22	266.38	19.86	29.67	5.68	21.37	0.19
C	LOW	4	5.96	0.29	268.59	18.19	47.23	8.19	21.86	0.20
C	LOW	5	6.58	0.20	262.10	20.45	29.03	6.18	21.90	0.17
D	HIGH	1	11.91	0.35	388.28	91.18	52.65	10.90	20.08	0.27
D	HIGH	2	12.77	0.76	349.98	86.17	46.28	8.44	20.01	0.56
D	HIGH	3	12.89	0.30	356.29	106.92	49.59	12.18	21.40	0.37
D	HIGH	4	14.07	0.70	335.50	50.39	42.23	5.15	17.08	0.21
D	HIGH	5	13.57	0.48	351.11	62.50	44.12	6.03	18.29	0.24
D	LOW	1	6.77	1.25	266.81	32.47	27.39	1.54	18.65	0.35

Appliance	Output	Test #	Flue draught, Pa		Flue temp bottom, °C		Flue temp top, °C		Ambient temp, °C	
			Average	SD	Average	SD	Average	SD	Average	SD
D	LOW	2	6.52	0.33	277.55	42.87	28.97	2.26	19.32	0.42
D	LOW	3	6.06	0.35	235.14	53.47	28.00	3.35	18.41	0.47
D	LOW	4	6.05	0.29	288.62	48.19	29.65	2.26	19.62	0.13
D	LOW	5	6.21	0.32	287.05	30.79	30.65	1.79	21.23	0.42
E	HIGH	1	0.78	0.05	119.49	1.03	31.38	5.96	26.02	0.15
E	HIGH	2	0.85	0.05	121.99	0.45	32.13	1.57	26.77	0.16
E	HIGH	3	0.90	0.05	123.12	0.42	32.49	5.54	27.45	0.08
E	HIGH	4	0.98	0.05	124.14	0.68	32.72	3.26	27.73	0.07
E	HIGH	5	1.00	0.05	127.03	1.24	33.20	4.31	27.87	0.09
E	LOW	1	0.10	0.00	49.32	0.78	24.21	9.14	22.87	0.18
E	LOW	2	0.10	0.00	49.89	0.64	24.93	7.84	23.56	0.24
E	LOW	3	0.10	0.01	50.95	0.52	25.96	7.80	24.44	0.21
E	LOW	4	0.20	0.05	52.50	0.71	26.77	8.08	25.16	0.14
E	LOW	5	0.28	0.04	53.79	0.65	27.17	8.05	25.69	0.13
F	HIGH	1	ND	ND	186.01	0.53	ND	ND	18.85	0.13
F	HIGH	2	ND	ND	186.08	0.59	ND	ND	18.79	0.11
F	HIGH	3	ND	ND	186.78	0.55	ND	ND	19.01	0.13
F	HIGH	4	ND	ND	188.76	0.71	ND	ND	19.14	0.14
F	HIGH	5	ND	ND	189.04	0.49	ND	ND	19.30	0.11
F	LOW	1	ND	ND	96.68	1.25	ND	ND	18.36	0.15
F	LOW	2	ND	ND	96.92	0.99	ND	ND	18.42	0.17
F	LOW	3	ND	ND	97.23	1.14	ND	ND	18.88	0.13
F	LOW	4	ND	ND	97.21	1.16	ND	ND	19.00	0.12
F	LOW	5	ND	ND	97.36	0.98	ND	ND	19.27	0.17

Table A1.8b Conditions recorded for individual tests at Lab 1 for FFDT and DIN+ measurements – flue gas

Appliance	Output	Test #	CO_2, %		CO, %		O_2, %		NOx ppm		THC ppm	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
A	HIGH	1	8.35	2.65	0.24	0.44	ND	ND	44.20	10.68	317.01	716.26
A	HIGH	2	7.64	2.19	0.09	0.16	ND	ND	41.10	11.86	36.49	76.06
A	HIGH	3	8.37	1.63	0.21	0.09	ND	ND	42.40	5.60	221.58	162.84
A	HIGH	4	8.73	2.09	0.24	0.23	ND	ND	46.11	7.14	249.39	298.31
A	HIGH	5	8.43	2.99	0.33	0.30	ND	ND	49.76	13.74	404.51	509.96
A	LOW	1	7.48	1.80	0.10	0.12	ND	ND	46.98	12.58	217.83	413.08
A	LOW	2	7.81	2.10	0.08	0.09	ND	ND	40.31	10.76	71.93	175.73
A	LOW	3	6.47	2.09	0.13	0.10	ND	ND	33.24	15.15	272.35	286.86
A	LOW	4	6.85	2.06	0.11	0.11	ND	ND	44.78	13.30	191.86	297.65
A	LOW	5	7.77	2.39	0.13	0.14	ND	ND	41.34	10.37	321.33	432.63
B	HIGH	1	9.26	3.91	0.30	0.59	9.63	4.58	99.15	21.79	1282.52	3336.49
B	HIGH	2	8.47	3.47	0.27	0.46	10.53	4.06	79.20	18.23	892.65	2321.56
B	HIGH	3	8.95	3.48	0.28	0.38	9.82	4.05	84.95	11.27	938.07	1908.96
B	HIGH	4	7.90	2.62	0.18	0.16	10.98	3.02	79.47	17.19	465.16	653.72
B	HIGH	5	8.11	1.98	0.14	0.08	10.64	2.25	89.65	17.83	290.20	252.22
B	LOW	1	9.85	2.89	0.32	0.33	10.16	2.88	58.88	9.64	857.58	1354.75
B	LOW	2	10.39	3.23	0.24	0.20	9.56	3.12	72.52	12.52	498.91	751.99
B	LOW	3	11.86	3.89	0.65	0.72	7.67	4.01	79.88	13.39	2431.49	3838.72
B	LOW	4	12.88	3.32	0.71	0.60	6.42	3.41	72.12	10.40	2549.67	3257.38
B	LOW	5	11.36	3.09	0.50	0.45	8.14	3.16	68.47	10.69	1385.41	1940.30
C	HIGH	1	7.49	2.46	0.15	0.23	12.85	2.55	47.539	14.716	186.014	465.455
C	HIGH	2	8.82	3.02	0.19	0.58	11.46	3.20	51.420	16.001	470.058	1872.771
C	HIGH	3	8.05	2.47	0.13	0.35	11.94	2.67	45.558	8.289	200.199	815.213
C	HIGH	4	8.94	3.58	0.26	0.73	10.77	4.02	47.744	11.998	625.815	2200.207
C	HIGH	5	8.54	3.26	0.26	0.63	11.11	3.62	54.893	16.482	457.593	1728.666
C	LOW	1	9.62	2.82	0.20	0.42	9.40	3.21	105.575	19.532	284.796	1060.788
C	LOW	2	8.57	2.30	0.16	0.30	10.51	2.66	97.269	21.392	333.388	1021.885
C	LOW	3	9.44	3.31	0.30	0.47	9.29	3.86	81.965	24.297	938.779	2029.532
C	LOW	4	9.26	3.36	0.25	0.37	9.49	3.92	63.390	23.645	48.769	53.826
C	LOW	5	8.87	3.36	0.25	0.36	9.94	3.91	75.398	25.472	597.154	1442.090
D	HIGH	1	8.23	3.01	0.69	0.44	11.58	3.25	40.78	11.33	2537.06	2017.36
D	HIGH	2	6.99	2.69	0.44	0.24	13.18	2.70	37.72	14.19	1527.22	1185.56
D	HIGH	3	6.71	2.86	0.51	0.28	13.18	3.17	34.73	13.12	960.96	852.65
D	HIGH	4	6.60	1.64	0.34	0.11	13.60	1.61	49.96	11.49	ND*	ND*
D	HIGH	5	6.97	2.12	0.57	0.30	12.99	2.17	33.98	13.93	ND*	ND*
D	LOW	1	13.08	2.87	1.51	0.55	6.34	2.76	36.08	8.91	ND*	ND*

Appliance	Output	Test #	CO_2, %		CO, %		O_2, %		NOx ppm		THC ppm	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
D	LOW	2	12.64	2.25	1.32	0.30	6.88	2.10	41.92	8.03	4632.77	1700.83
D	LOW	3	9.25	2.24	0.90	0.24	10.58	2.35	37.32	7.96	3870.61	1547.99
D	LOW	4	9.76	1.97	0.77	0.12	9.59	2.06	56.15	7.96	2354.95	621.27
D	LOW	5	10.88	1.58	0.94	0.23	8.23	1.73	56.73	6.29	2829.25	1059.00
E	HIGH	1	13.72	0.98	0.01	0.02	ND	ND	81.28	3.61	8.45	11.85
E	HIGH	2	13.90	1.12	0.02	0.04	ND	ND	79.64	3.66	6.80	17.41
E	HIGH	3	14.16	1.10	0.03	0.05	ND	ND	79.21	2.91	9.85	35.96
E	HIGH	4	14.41	1.13	0.05	0.08	ND	ND	76.89	3.06	12.62	50.93
E	HIGH	5	14.25	1.40	0.06	0.11	ND	ND	73.29	3.39	24.23	103.08
E	LOW	1	6.30	1.89	0.04	0.04	ND	ND	40.87	16.53	49.27	177.77
E	LOW	2	6.13	1.49	0.02	0.03	ND	ND	39.80	13.28	16.35	46.98
E	LOW	3	5.92	1.29	0.02	0.02	ND	ND	38.01	12.19	10.94	46.44
E	LOW	4	6.15	1.55	0.02	0.04	ND	ND	41.13	12.92	25.23	166.44
E	LOW	5	6.08	1.44	0.02	0.03	ND	ND	41.47	12.31	8.11	26.24
F	HIGH	1	14.03	0.22	0.0013	0.0002	ND	ND	ND*	ND*	ND*	ND*
F	HIGH	2	13.92	0.22	0.0012	0.0002	ND	ND	ND*	ND*	ND*	ND*
F	HIGH	3	13.97	0.25	0.0011	0.0002	ND	ND	ND*	ND*	ND*	ND*
F	HIGH	4	14.18	0.29	0.0012	0.0003	ND	ND	ND*	ND*	ND*	ND*
F	HIGH	5	14.03	0.25	0.0011	0.0002	ND	ND	ND*	ND*	ND*	ND*
F	LOW	1	8.93	0.42	0.0008	0.0008	ND	ND	ND*	ND*	ND*	ND*
F	LOW	2	8.94	0.36	0.0005	0.0005	ND	ND	ND*	ND*	ND*	ND*
F	LOW	3	9.09	0.45	0.0006	0.0006	ND	ND	ND*	ND*	ND*	ND*
F	LOW	4	8.99	0.48	0.0006	0.0007	ND	ND	ND*	ND*	ND*	ND*
F	LOW	5	9.36	0.49	0.0006	0.0005	ND	ND	ND*	ND*	ND*	ND*

NOTE: * instrument / logging fault

Table A1.9 Repeatability of test conditions - flue gas compositions for FFDT and DIN+ measurements at Lab 1

Appliance	Output level	% CO2			% CO			% O2			NOx ppm			THC ppm		
		Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD
A	High	8.32	2.37	28	0.22	0.28	126	ND	ND	ND	45	11	24	248	435	175
A	Low	7.24	2.15	30	0.11	0.11	100	ND	ND	ND	38	17	45	198	333	168
B	High	8.46	3.11	37	0.22	0.36	161	10.39	3.60	35	69	38	55	580	1740	300
B	Low	11.20	3.45	31	0.47	0.52	110	8.47	3.58	42	65	22	33	1395	2521	181
C	High	8.36	3.03	36	0.20	0.54	271	11.64	3.33	29	49	14	29	385	1563	405
C	Low	9.14	3.09	34	0.23	0.39	168	9.74	3.58	37	78	35	44	415	1294	312
D	High	7.07	2.57	36	0.50	0.31	62	12.95	2.72	21	32	20	62	976	1431	147
D	Low	11.11	2.69	24	1.08	0.43	39	8.33	2.74	33	39	19	49	2728	1959	72
E	High	14.09	1.17	8	0.03	0.07	208	ND	ND	ND	78	4	6	12	55	444
E	Low	6.12	1.54	25	0.02	0.03	150	ND	ND	ND	40	14	34	22	114	520
F	High	14.0	0.9	6	0.0012	0.0003	28	ND	ND	ND	ND	ND	ND	ND	ND	ND
F	Low	7.2	3.7	52	0.0010	0.0107	1026	ND	ND	ND	ND	ND	ND	ND	ND	ND

Note: These statistics are calculated from whole data set recorded for the multiple tests of each appliance at each output level. All gas analyses are as measured.

Table A1.10 Repeatability of test conditions – draft and temperatures for FFDT and DIN+ measurements at Lab 1

Appliance	Output level	Flue draught, Pa			Flue temp bottom / Flue temp, °C			Flue temp top, °C			Ambient, °C		
		Average	SD	RSD	Average	SD	RSD	Average	SD	RSD	Average	SD	RSD
A	High	10.2	1.3	12	285	27	9	23	1	4	35	3	7
A	Low	7.5	2.3	30	242	18	7	25	1	3	35	2	6
B	High	11.4	0.3	3	393	30	8	21	1	6	38	2	6
B	Low	7.4	0.2	3	338	18	5	22	1	4	32	3	8
C	High	13.3	0.5	4	328	33	10	22	2	9	35	3	10
C	Low	6.3	0.3	5	267	20	8	21	1	4	33	8	25
D	High	13.1	0.9	7	355	84	24	61	11	18	15	1	5
D	Low	6.3	0.7	11	271	47	17	57	9	15	16	1	3
E	High	0.9	0.1	11	123	3	2	27	1	3	32	1	2
E	Low	0.2	0.1	51	51	2	3	24	1	4	26	1	4
F	High	ND	ND	ND	186	3	1	ND	ND	ND	19	0.4	2
F	Low	ND	ND	ND	101	20	20	ND	ND	ND	19	0.5	2

Note: These statistics are calculated from whole data set recorded for the multiple tests of each appliance at each output level.

Table A1.11 Results for the standard methods applied by Lab 1 – Particulate emission over five repeats, g/GJ

Output	High			Low		
Appliance	DIN+ 70°C	ESP	FFDT	DIN+ 70°C	ESP	FFDT
A	28	113	113	17	72	143
A	16	89	69	10	51	107
A	15	57	66	19	54	173
A	21	65	64	16	144	119
A	26	105	98	26	67	168
B	30	143	161	36	132	60
B	72	139	157	27	110	38
B	75	116	142	10	141	123
B	94	94	81	30	71	111
B	138	138	57	38	59	52
C	11	165	223	56	152	82
C	11	112	85	90	86	105
C	16	123	77	77	72	116
C	47	67	100	14	107	82
C	39	109	112	59	110	98
D	53	84	155	458	90	472
D	113	201	150	526	87	465
D	32	83	96	1271	136	584
D	128	61	125	370	164	234
D	112	49	156	410	227	253
E	22	34	71	20	44	98
E	7	35	86	19	59	65
E	22	26	80	12	52	66
E	22	26	73	15	30	79
E	24	39	90	10	66	88
F	12	18	ND	3	15	ND
F	17	19	ND	3	16	ND
F	17	19	ND	3	14	ND
F	16	18	ND	4	12	ND
F	16	18	ND	4	16	ND

Table A1.12 Results for the standard methods applied by Lab 2 – Particulate emission over five repeats, g/GJ

Output	High			Low		
Appliance	DIN+ 70°C	ESP	FFDT	DIN+ 70°C	ESP	FFDT
B	90	ND	134	82	ND	284
B	75	ND	199	61	ND	226
B	78	ND	276	69	ND	261
B	54	ND	138	25	ND	212
B	71	ND	189	67	ND	168
C	24	ND	62	7	ND	108
C	30	ND	62	5	ND	107
C	35	ND	63	8	ND	131
C	21	ND	63	10	ND	123
C	26	ND	61	6	ND	100

Table A1.13 Results for the standard methods applied by Lab 3 – Particulate emission over five repeats, g/GJ

Output	High			Low		
Appliance	DIN+ 70°C	ESP	FFDT	DIN+ 70°C	ESP	FFDT
B	93	ND	ND	*104**	ND	ND
B	*115**	ND	ND	92	ND	ND
B	102	ND	ND	*143**	ND	ND
B	61	ND	ND	95	ND	ND
B	*82**	ND	ND	*138**	ND	ND
C	*20***	ND	ND	*5****	ND	ND
C	*2****	ND	ND	*25***	ND	ND
C	56	ND	ND	32	ND	ND
C	*56***	ND	ND	10	ND	ND
C	*24***	ND	ND	36	ND	ND

NOTES:
* Lab 3 reported that high particle loadings affected sample volume
** Lab 3 reported problems with fuel ignition /burnout
*** Lab 3 excluded these results because they considered them too low

Table A1.14 Results for the standard methods applied by Lab 1 – Particulate emission statistics, g/GJ

Method	Output	Appliance	Max	Min	Average	SD	RSD, %
DIN+ 70°C	High	A	28	15	21	6	27
		B	106	30	64	30	47
		C	47	11	25	17	68
		D	128	32	88	42	48
		E	24	7	19	7	35
		F	17	12	16	2	15
	Low	A	26	10	18	6	32
		B	38	10	28	11	39
		C	90	14	59	29	49
		D	1271	370	607	375	62
		E	20	10	15	4	28
		F	4	3	4	0	13
ESP	High	A	113	57	86	24	28
		B	143	94	126	21	16
		C	165	67	115	35	30
		D	201	49	96	61	64
		E	39	26	32	6	18
		F	19	18	18	0	2
	Low	A	144	51	78	38	49
		B	141	59	103	36	35
		C	152	72	105	30	29
		D	227	87	141	58	41
		E	66	30	50	14	28
		F	16	12	15	2	12
FFDT	High	A	113	64	82	22	27
		B	161	57	120	48	40
		C	223	77	119	59	50
		D	156	96	137	26	19
		E	90	71	80	8	10
	Low	A	173	107	142	29	21
		B	123	38	77	38	49
		C	116	82	97	15	15
		D	584	234	402	152	38
		E	98	65	79	14	18

Table A1.15 Results for the standard methods applied by Lab 2 – Particulate emission statistics, g/GJ

Method	Output	Appliance	Max	Min	Average	SD	RSD, %
DIN+ 70°C	High	B	90	54	74	13	18
		C	35	21	27	5	20
	Low	B	82	25	61	21	35
		C	10	5	7	2	27
FFDT	High	B	276	134	187	58	31
		C	63	61	62	1	1
	Low	B	284	168	230	45	20
		C	131	100	114	13	11

Table A1.16 Results for the standard methods applied by Lab 3 – Particulate emission statistics, g/GJ

Method	Output	Appliance	Max	Min	Average	SD	RSD, %
DIN+ 70°C	High	B	115	61	91	20	22
		C	56	20	39	20	50
	Low	B	143	92	115	24	21
		C	36	10	26	12	45

NOTE: Measurements that Lab 3 excluded have not been included in these statistics.

FIGURES

Figure A1.1a Flue gas measurement traces of OD, CO and CO_2 for Appliance A, ESP, High Output, Test1 (left) and Test 2 (right)

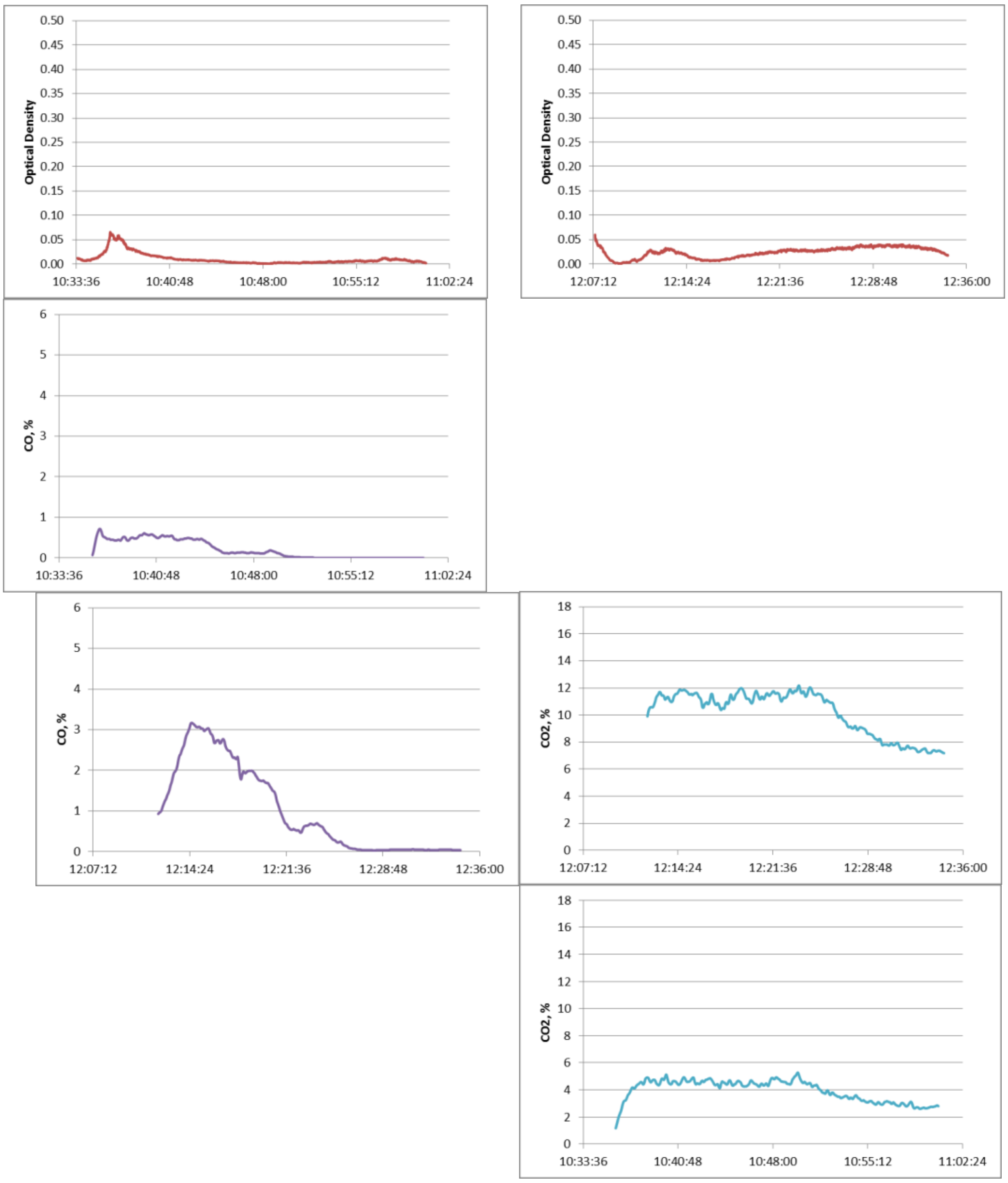


Figure A1.1b Flue gas measurement traces of OD, CO and CO_2 for Appliance A, ESP, High Output, Test 3 (left) and Test 4 (right)

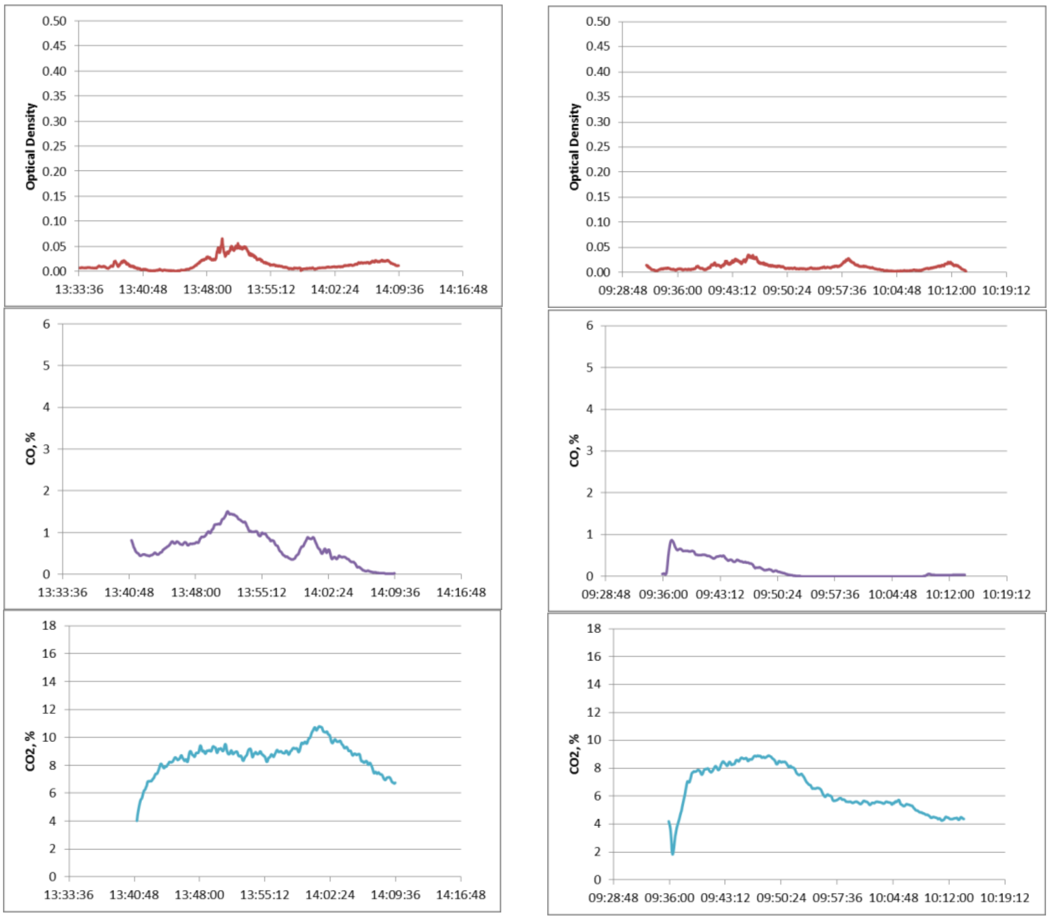


Figure A1.1c Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance A, ESP, High Output, Test5 (left), Low Output, Test 1 (right)

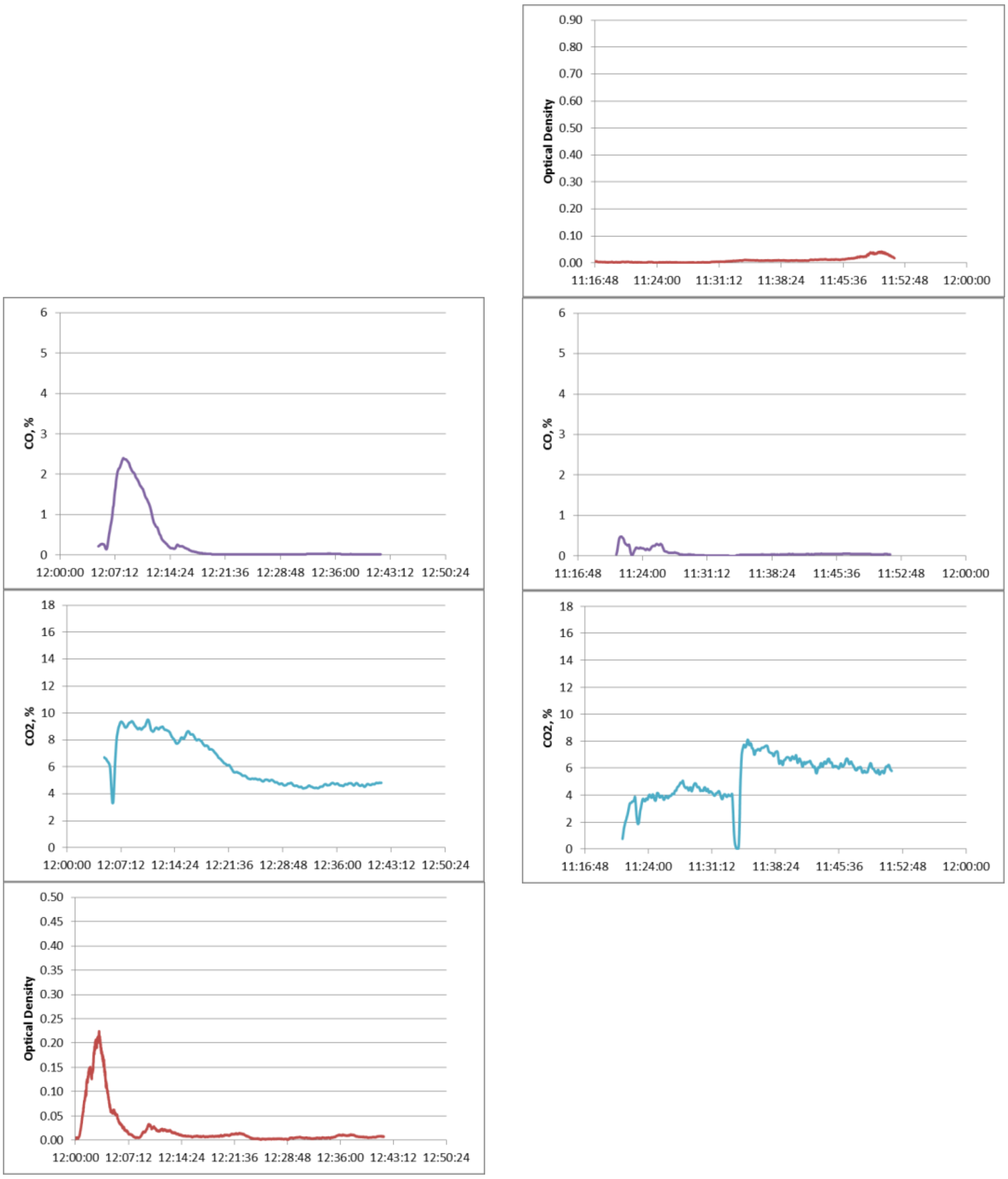


Figure A1.1d Flue gas measurement traces of OD, CO and CO_2 for Appliance A, ESP, Low Output, Test 2 (left) and Test 3 (right)

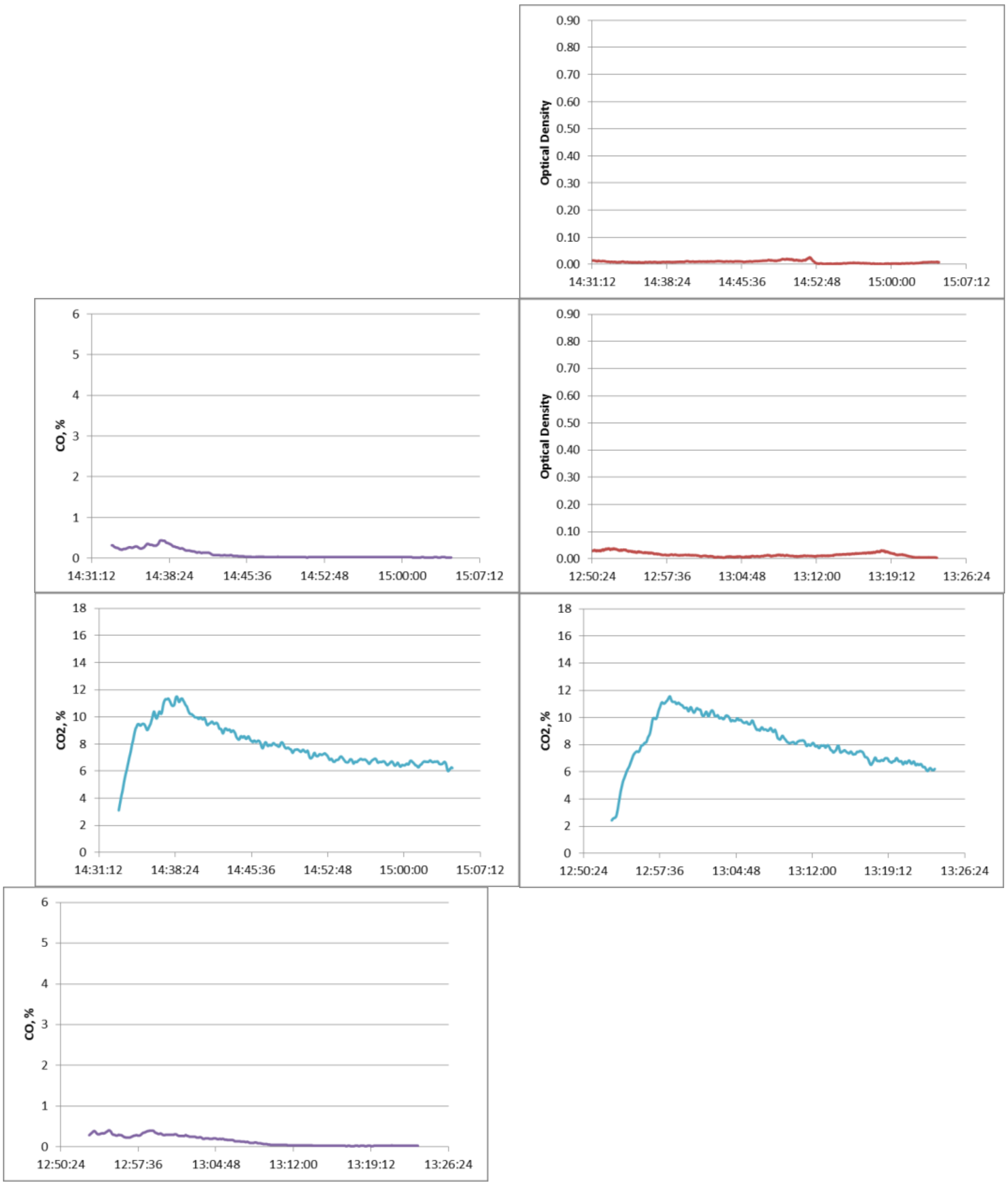


Figure A1.1e Flue gas measurement traces of OD, CO and CO_2 for Appliance A, ESP, Low Output, Test 4 (left) and Test 5 (right)

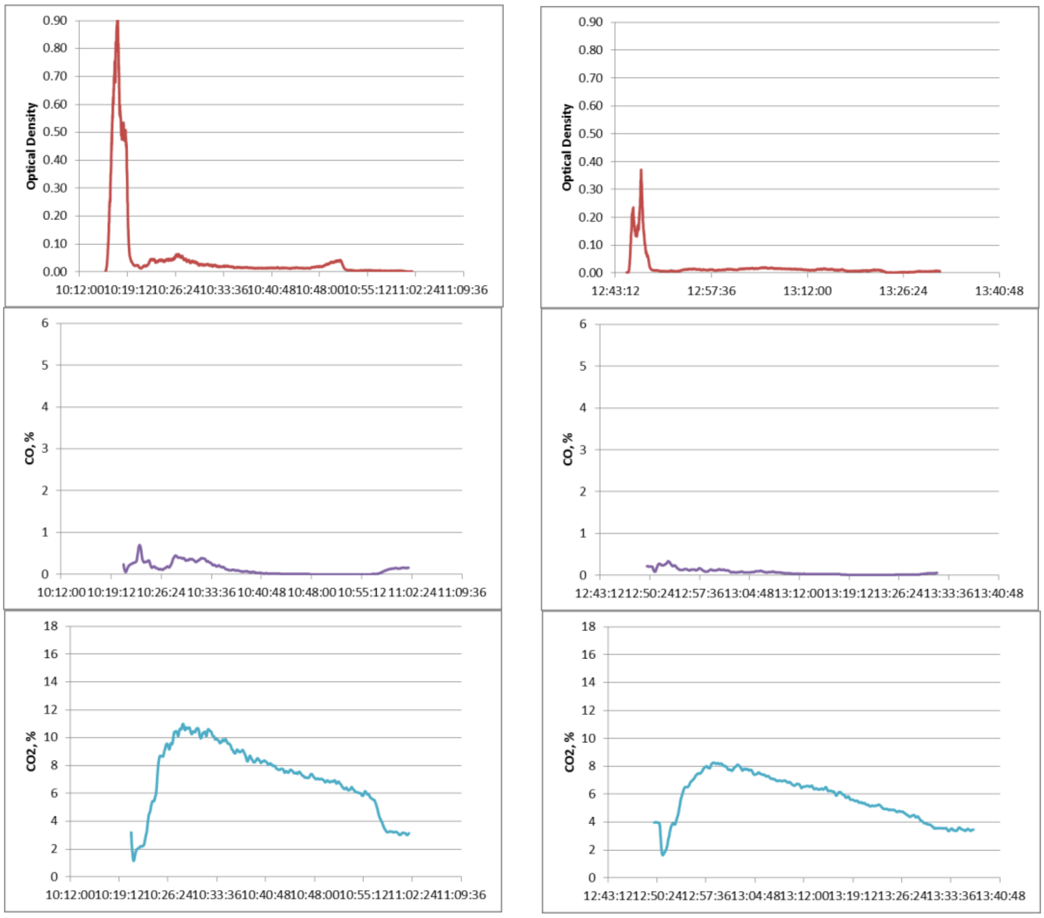


Figure A1.1f Flue gas measurement traces of OD, CO and CO_2 for Appliance A, FFDT/DIN+, High Output, Test1 (left) and Test 2 (right)

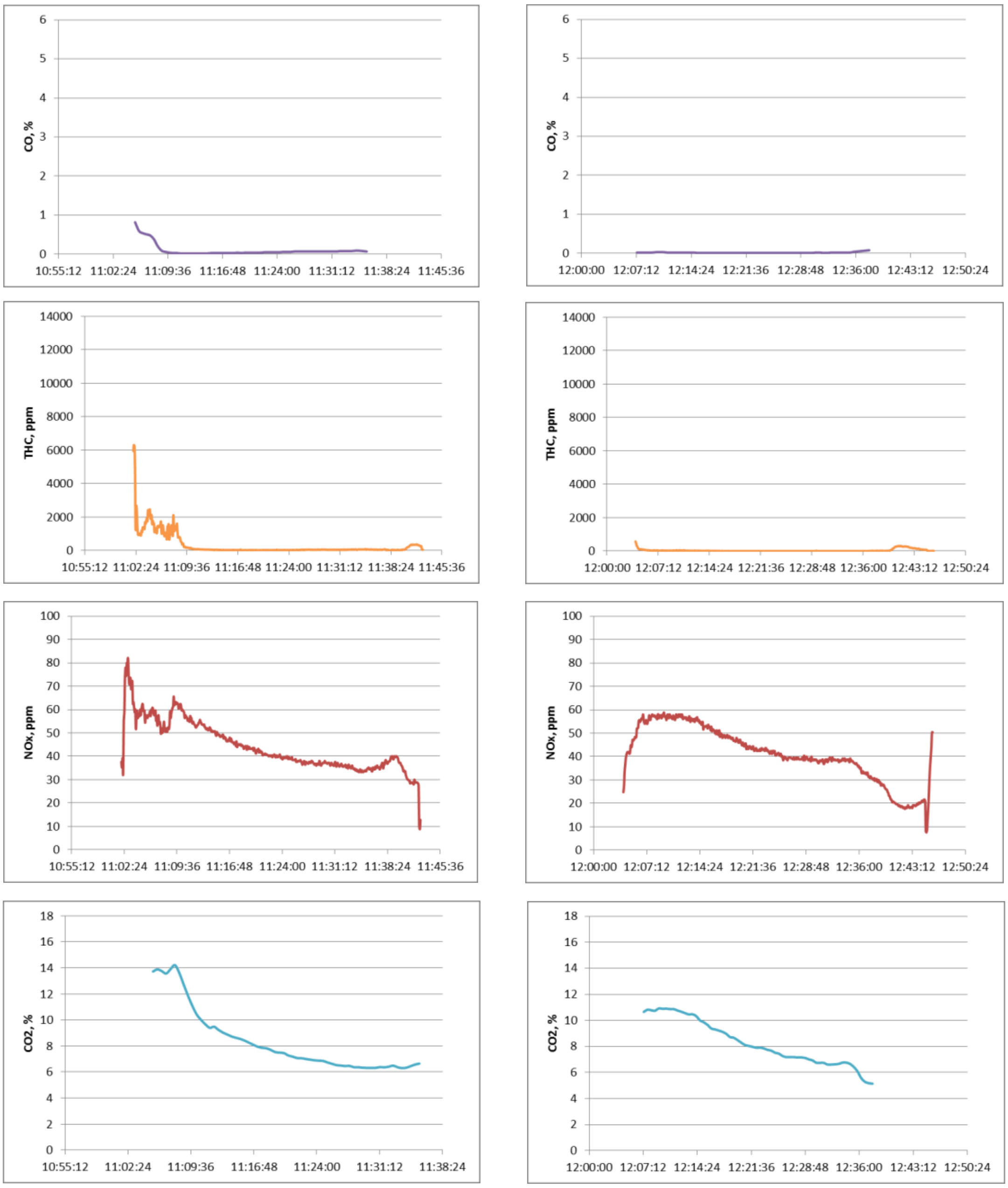


Figure A1.1g Flue gas measurement traces of OD, CO and CO_2 for Appliance A, FFDT/DIN+, High Output, Test3 (left) and Test 4 (right)

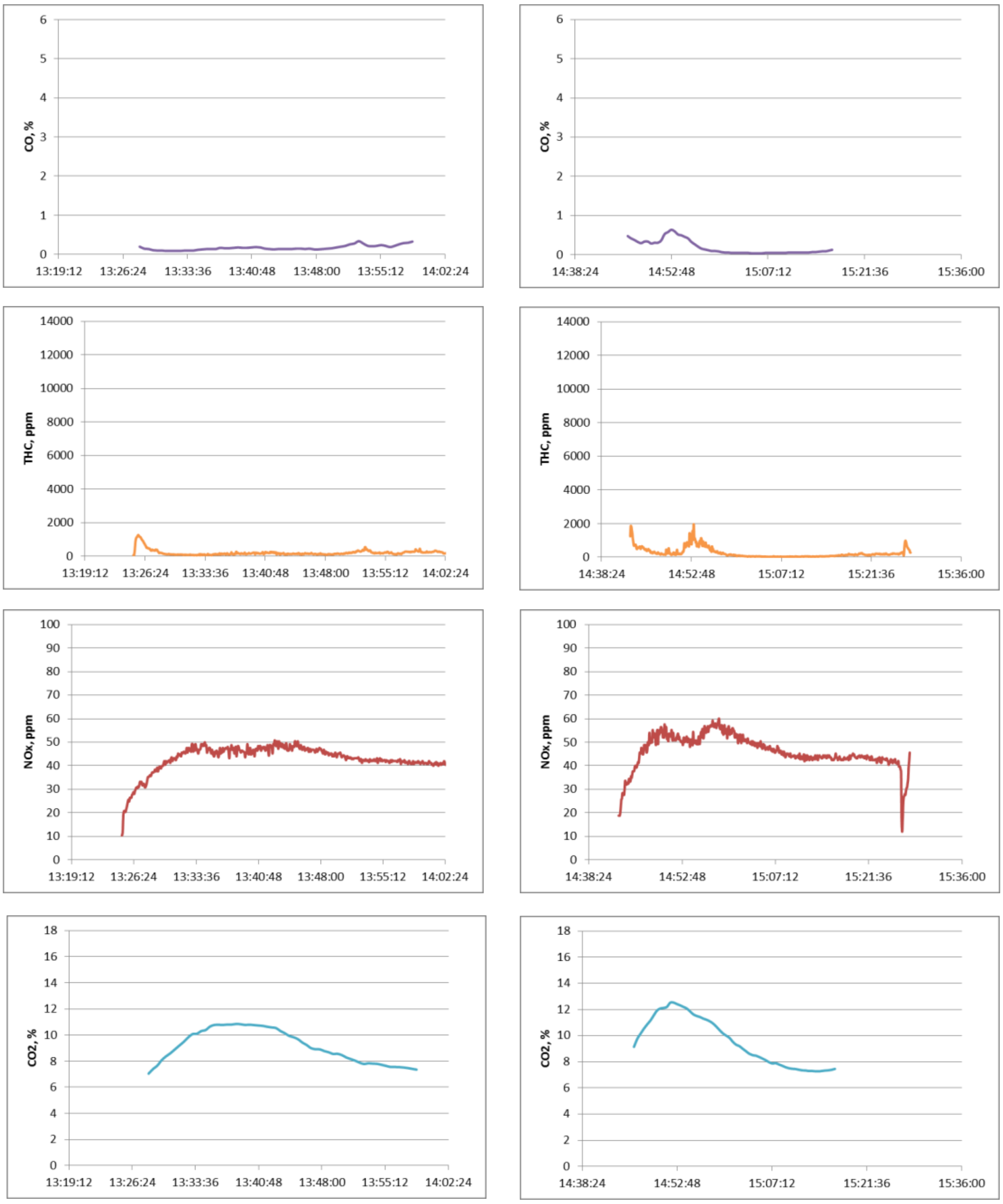


Figure A1.1h Flue gas measurement traces of OD, CO and CO_2 for Appliance A, FFDT/DIN+, High Output, Test 5 (left) and Low Output Test 1 (right)

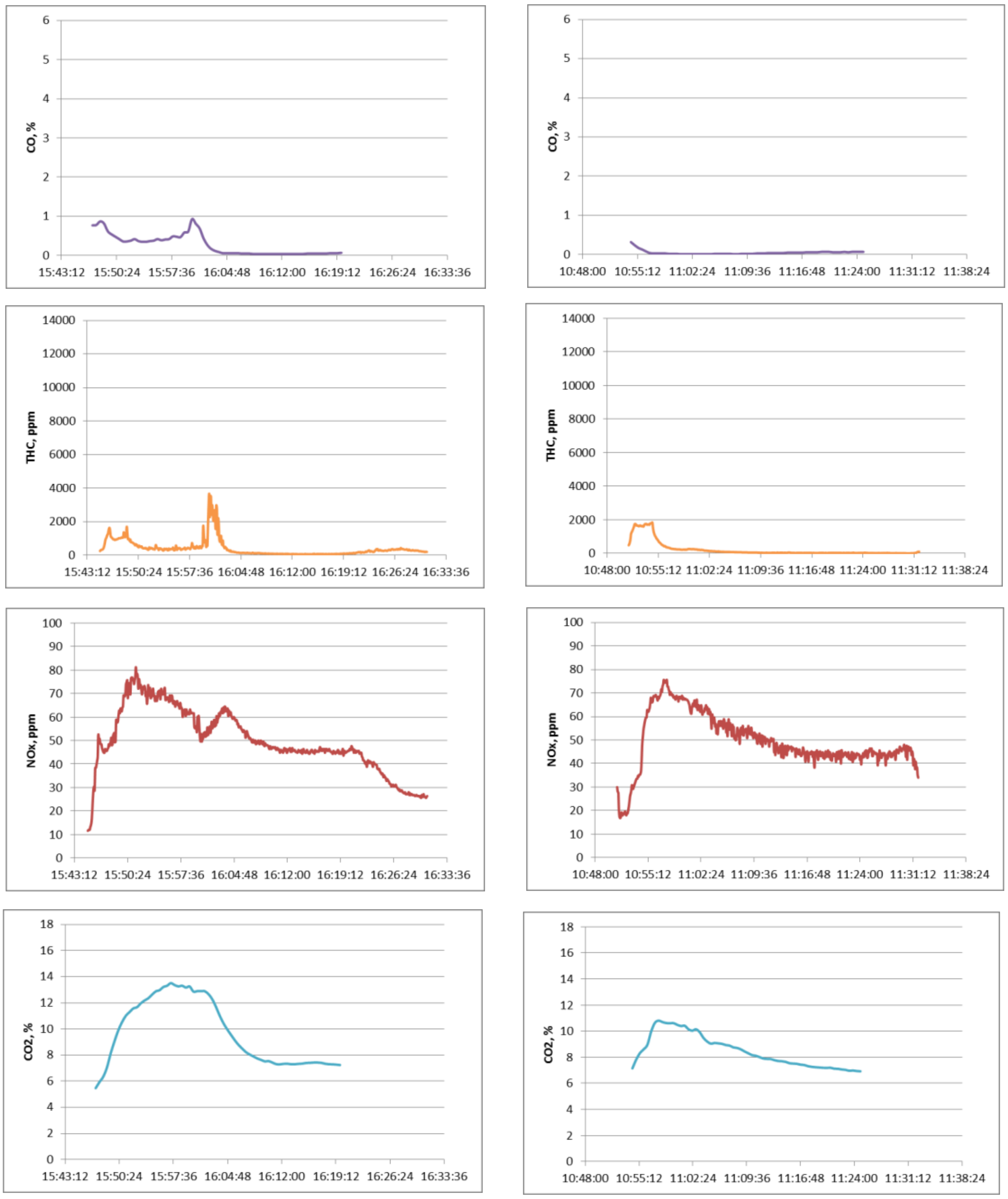


Figure A1.1i Flue gas measurement traces of OD, CO and CO_2 for Appliance A, FFDT/DIN+, Low Output, Test 2 (left) and Test 3 (right)

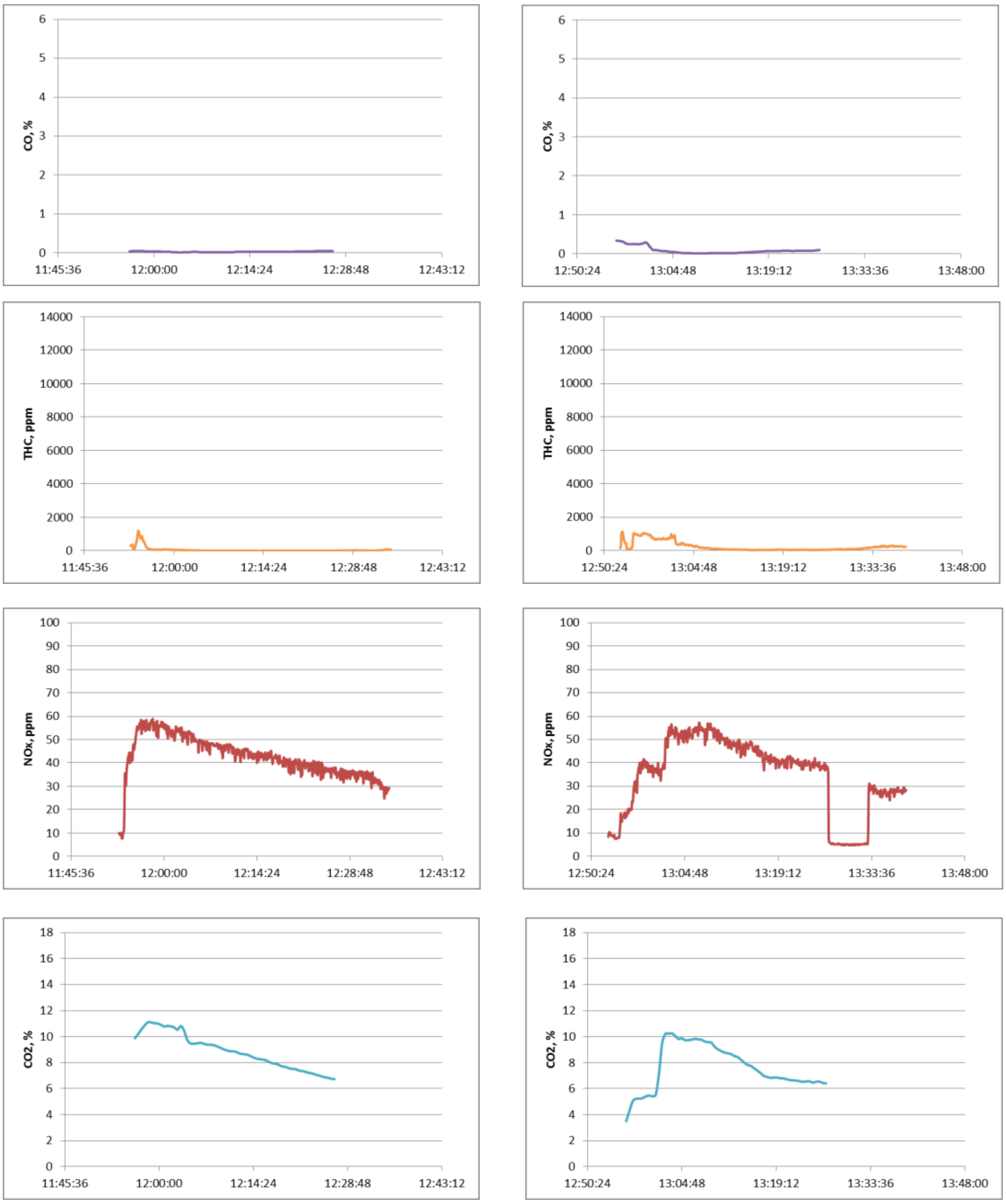


Figure A1.1j Flue gas measurement traces of OD, CO and CO_2 for Appliance A, FFDT/DIN+, Low Output, Test 4 (left) and Test 5 (right)

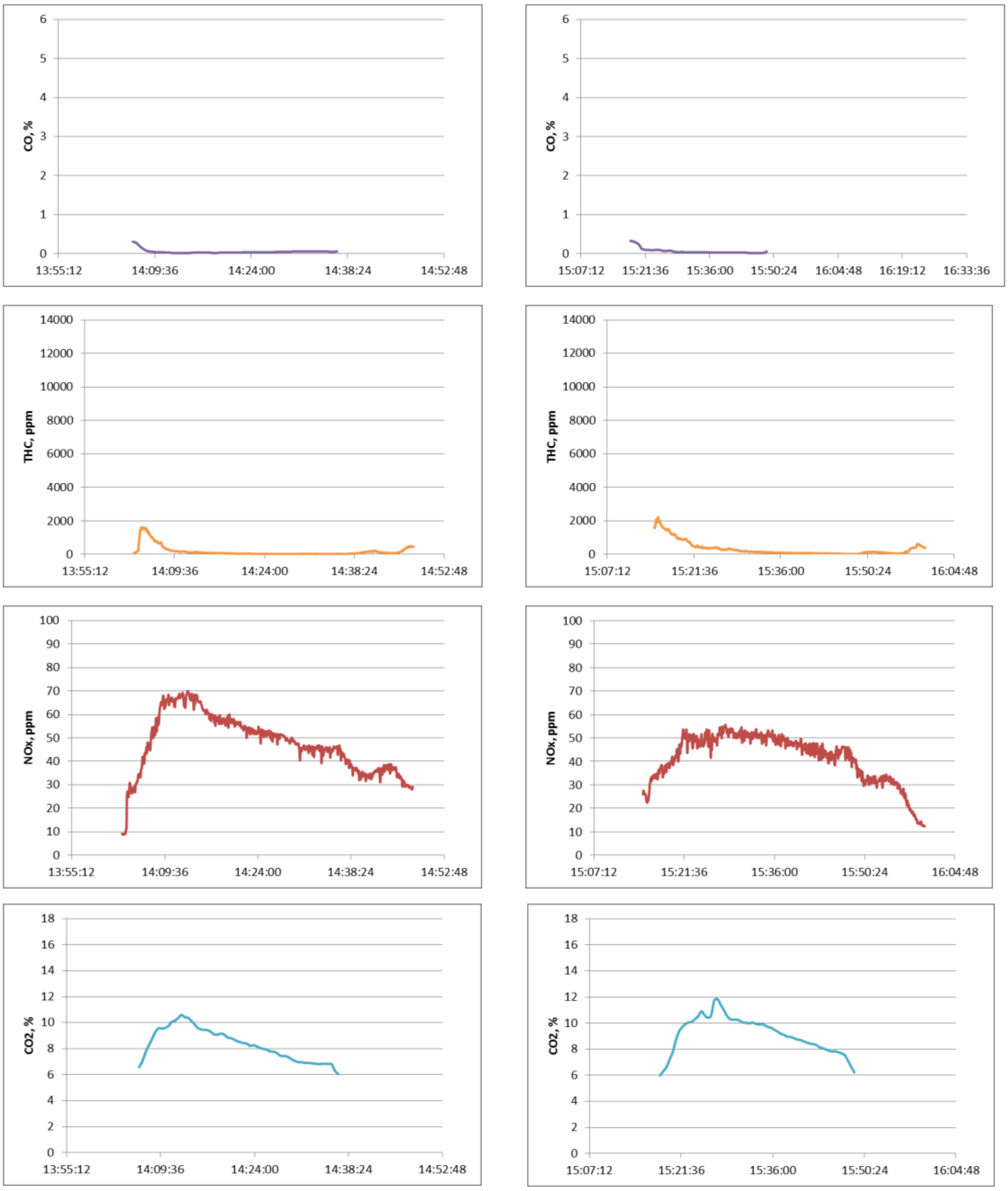
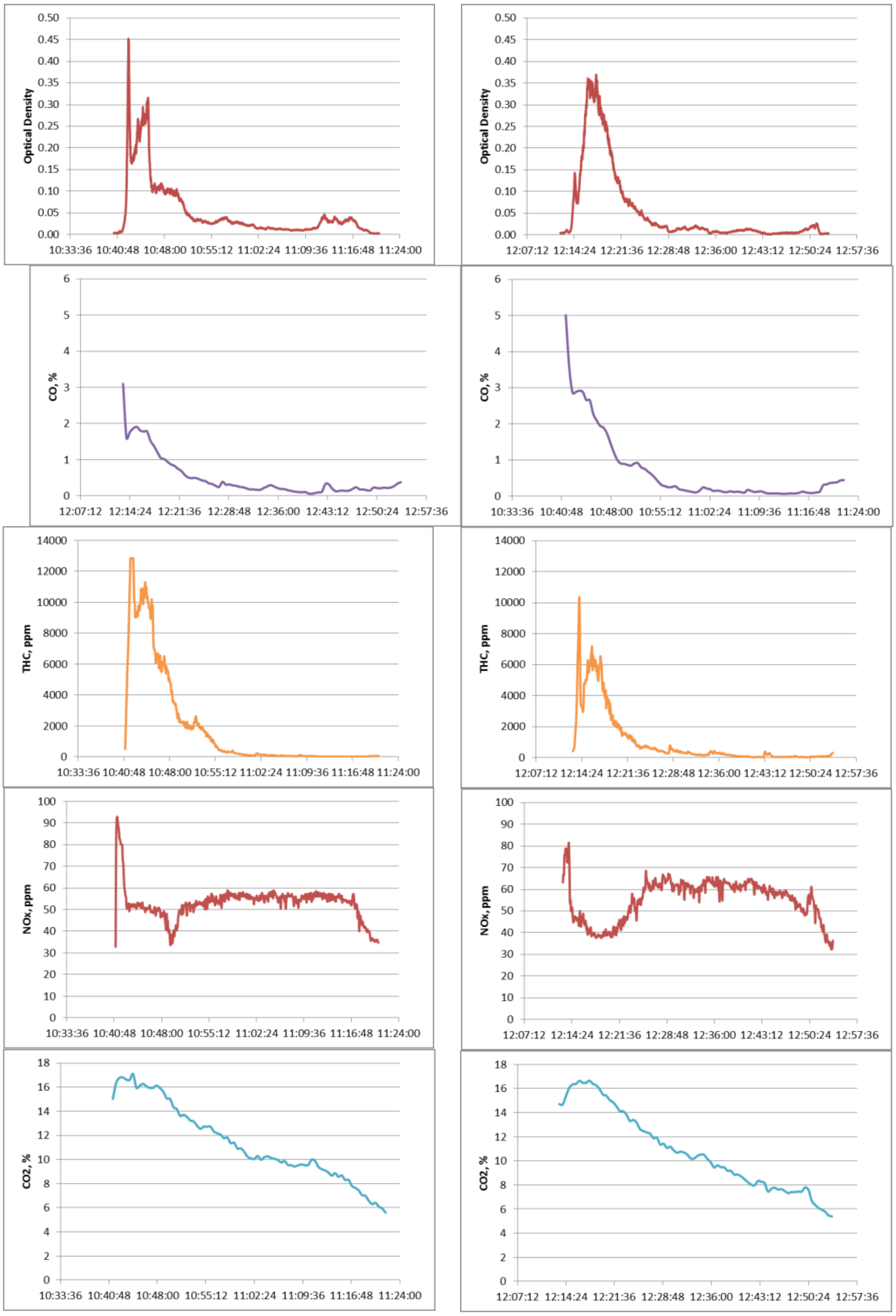


Figure A1.2a Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance B,



ESP, High Output, Test1 (left) and Test 2 (right)

Figure A1.2b Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance B, ESP, High Output, Test3 (left) and Test 4 (right)

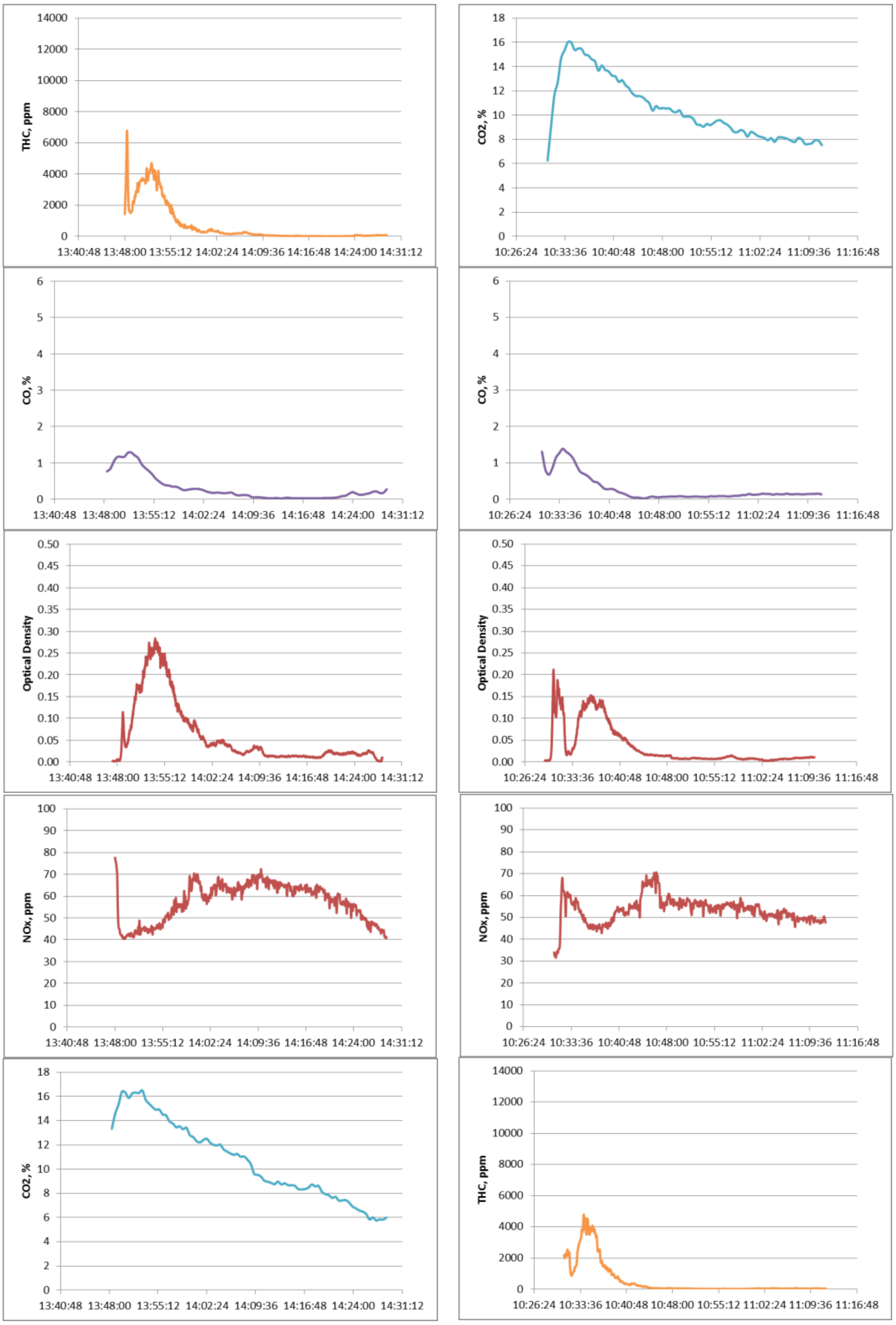


Figure A1.2c Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance B, ESP, High Output, Test5 (left), Low Output, Test 1 (right)

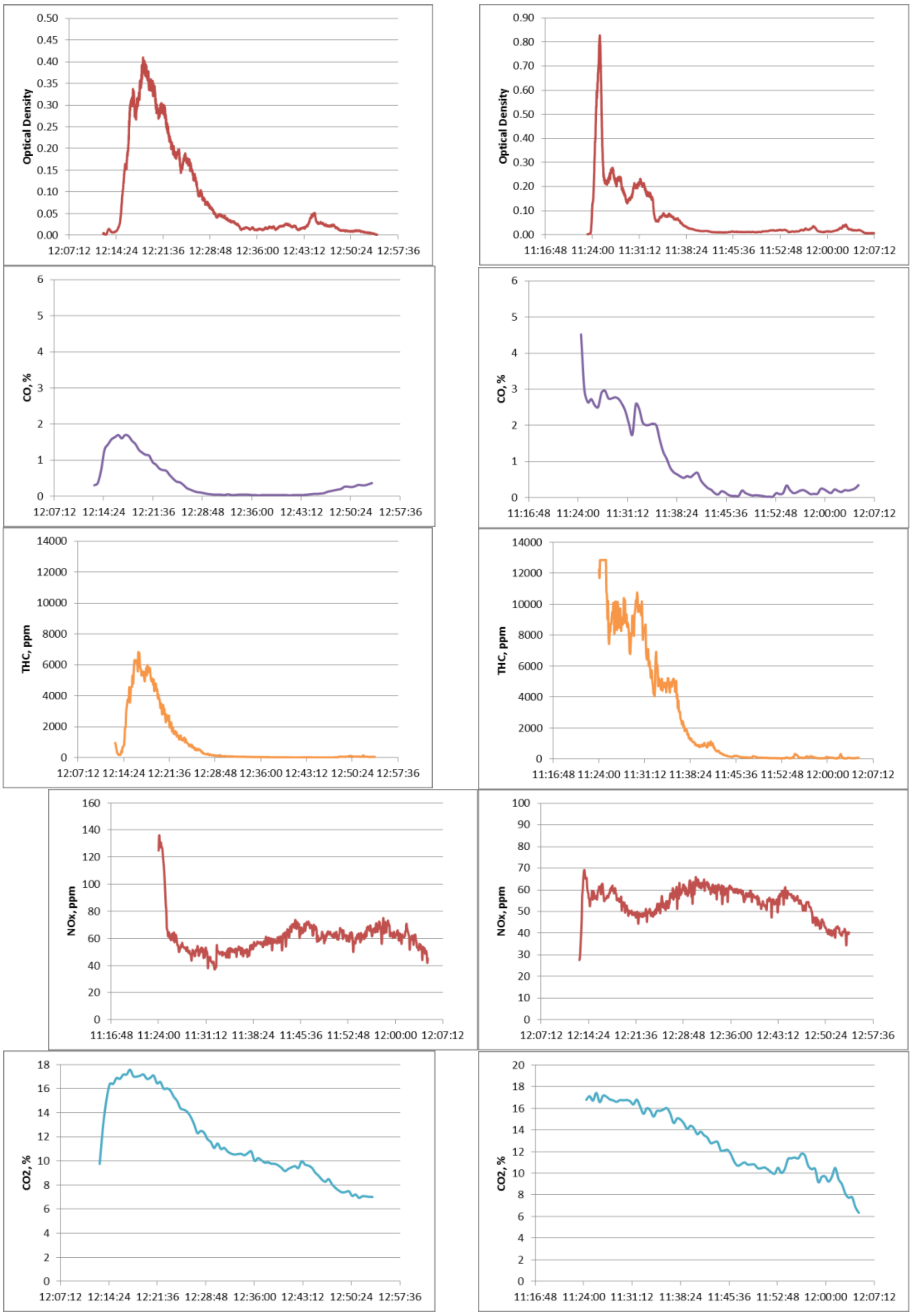


Figure A1.2d Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance B, ESP, Low Output, Test 2 (left), Test 3 (right)

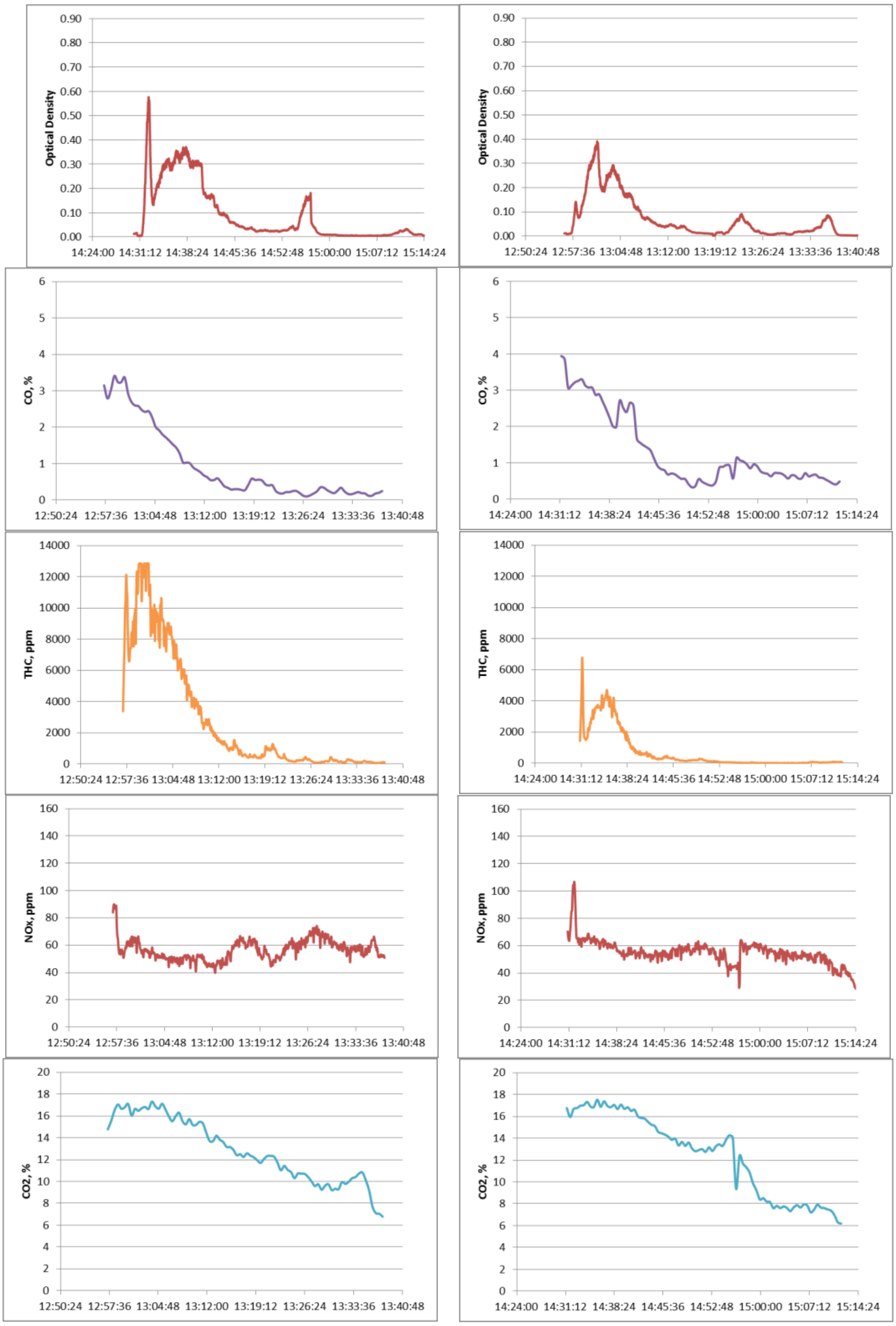


Figure A1.2e Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance B, ESP, Low Output, Test 4 (left), Test 5 (right)

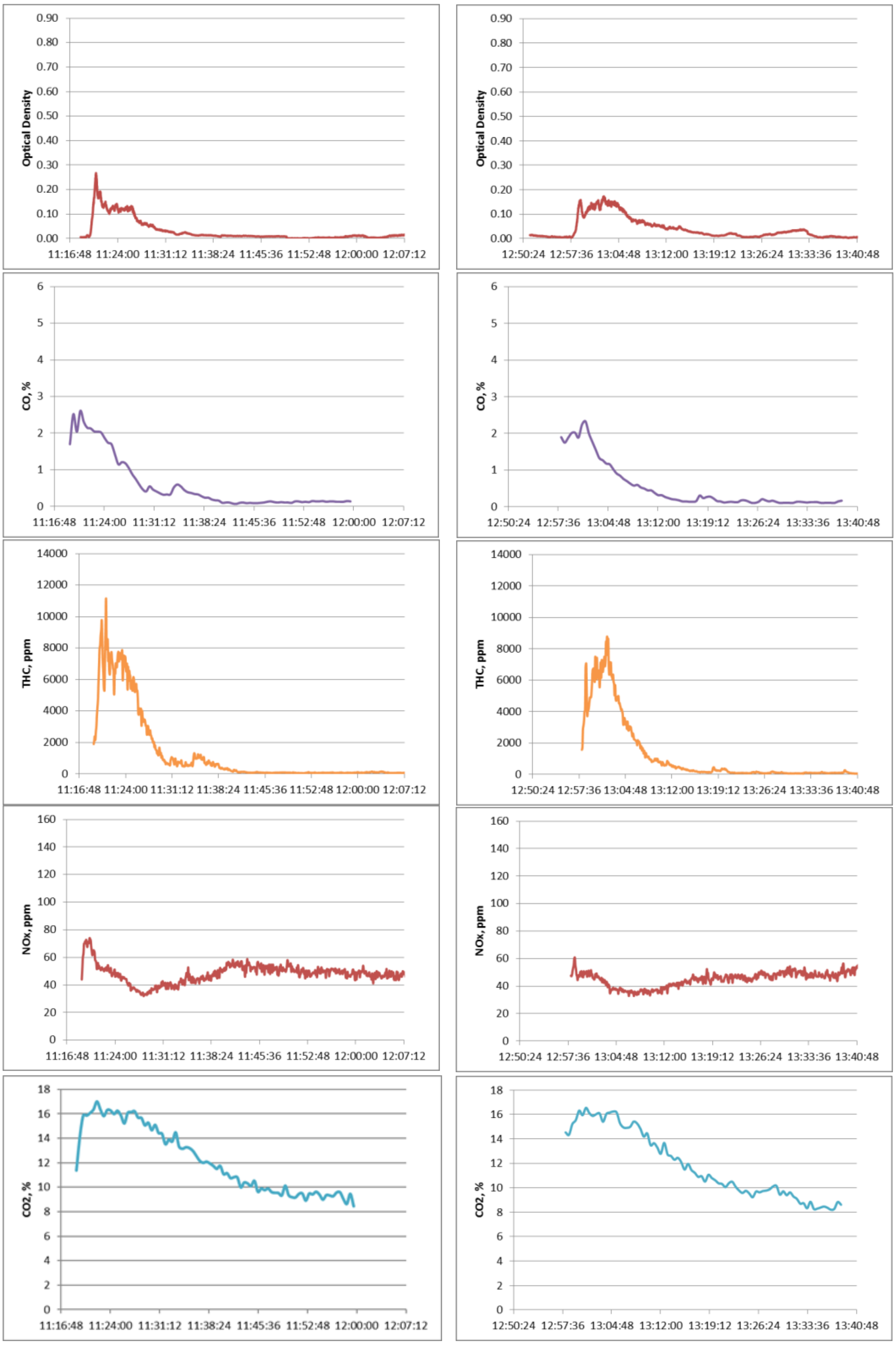


Figure A1.2f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, DIN+, High Output, Test1 (left) and Test 2 (right)

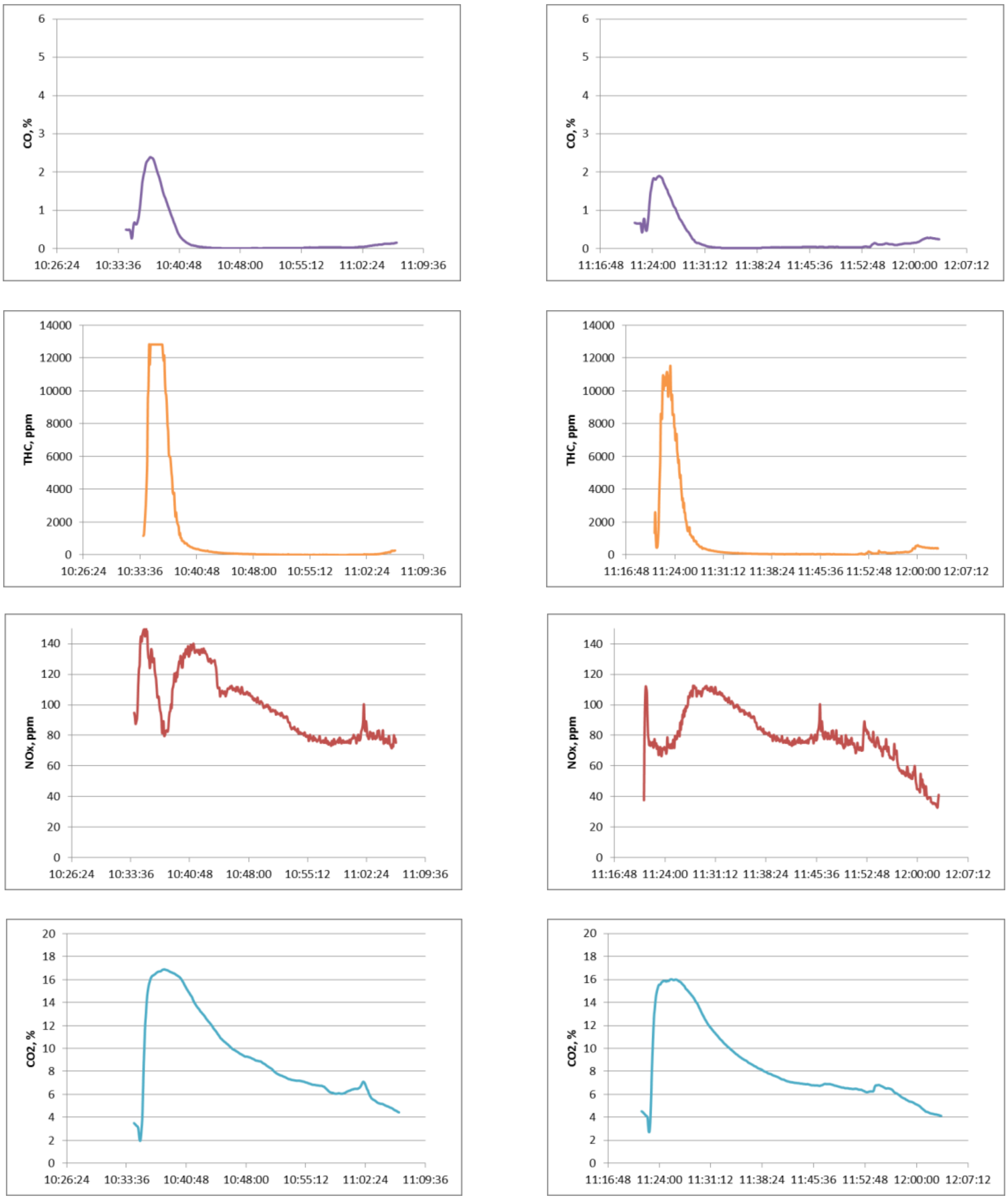


Figure A1.2g Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, DIN+, High Output, Test 3 (left) and Test 4 (right)

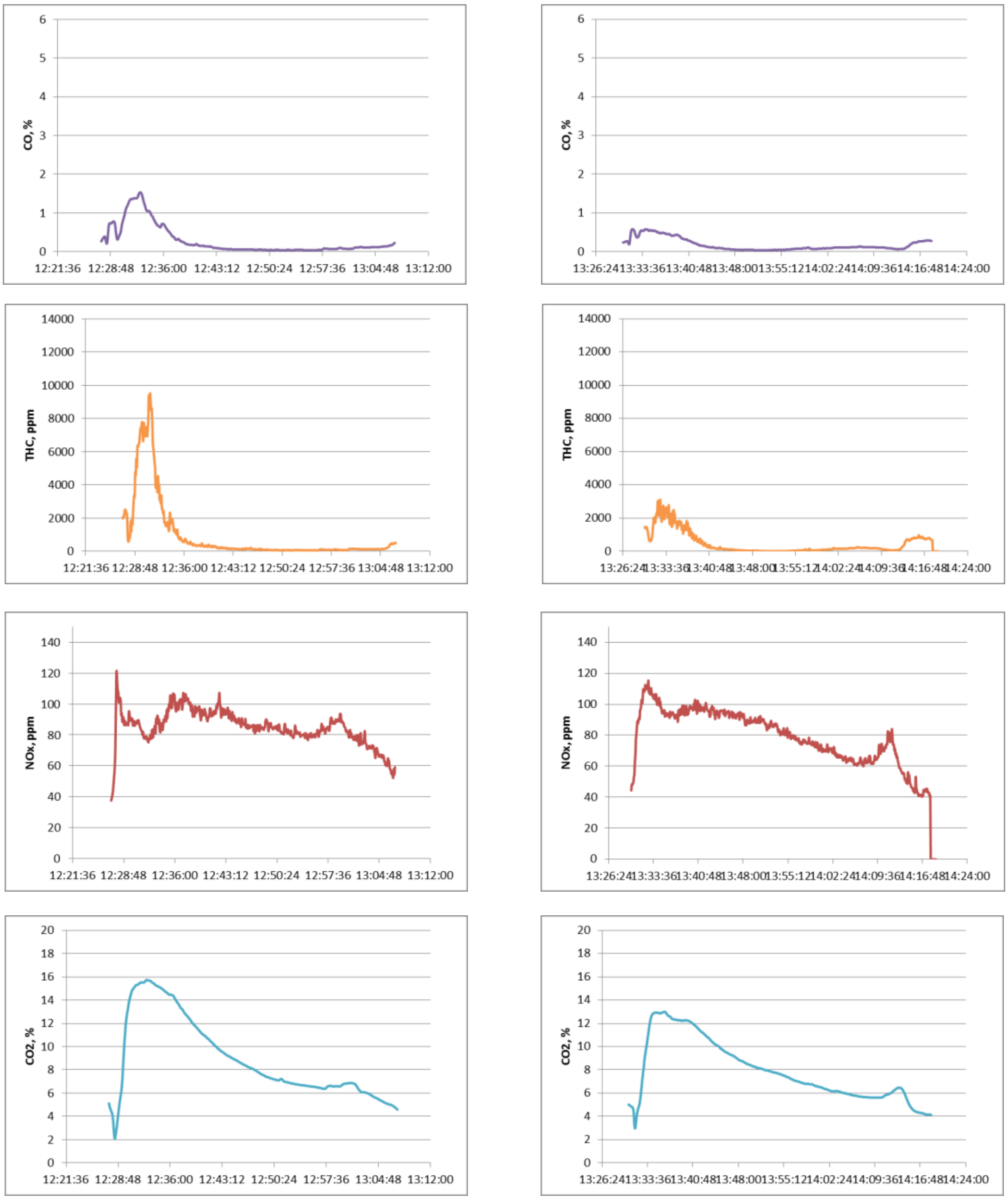


Figure A1.2h Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, DIN+, High Output, Test 5 (left) and Low Output Test 1 (right)

Figure A1.2i Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, DIN+, Low Output, Test 2 (left) and Test 3 (right)

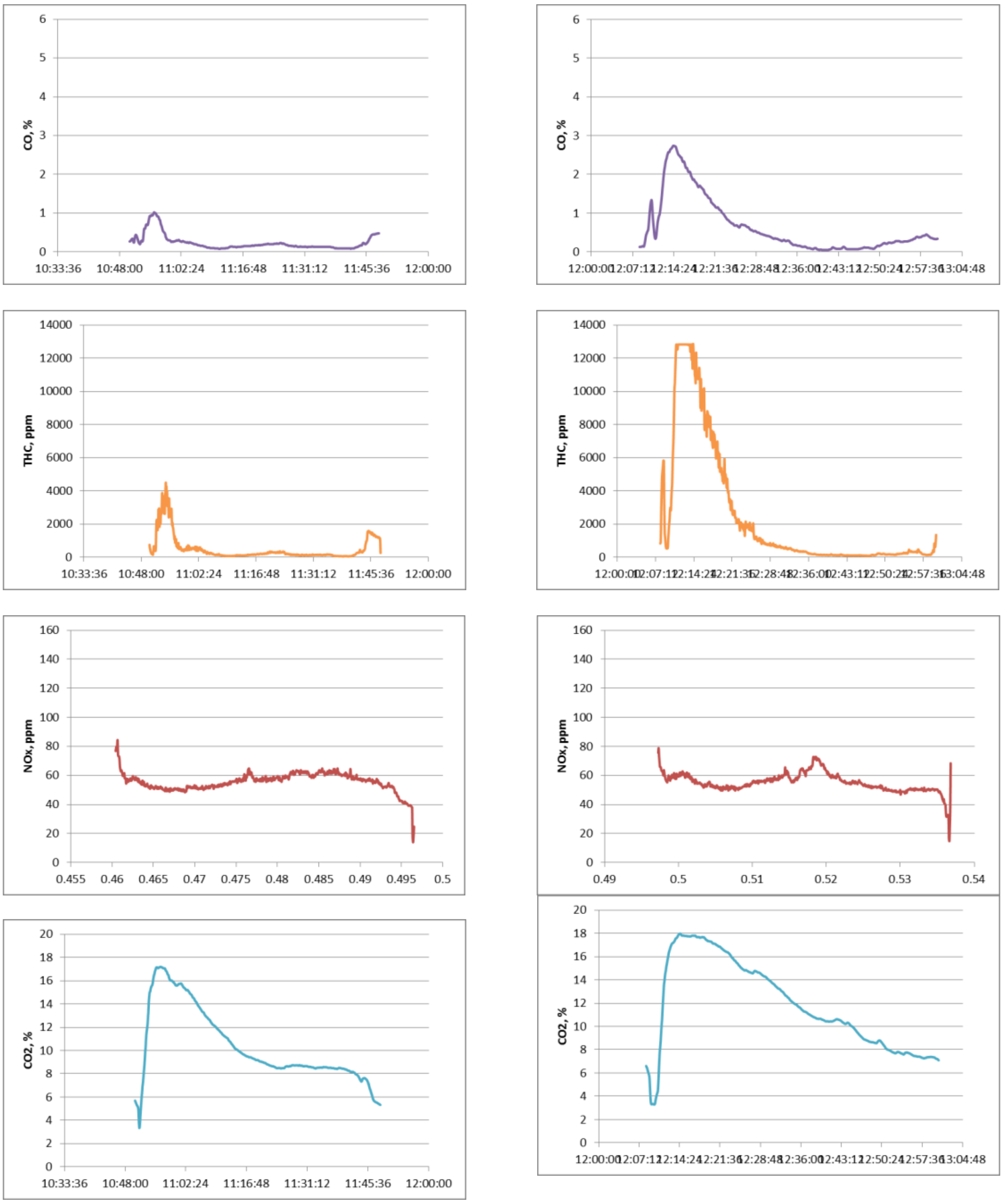


Figure A1.2j Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, DIN+, Low Output, Test 4 (left) and Test 5 (right)

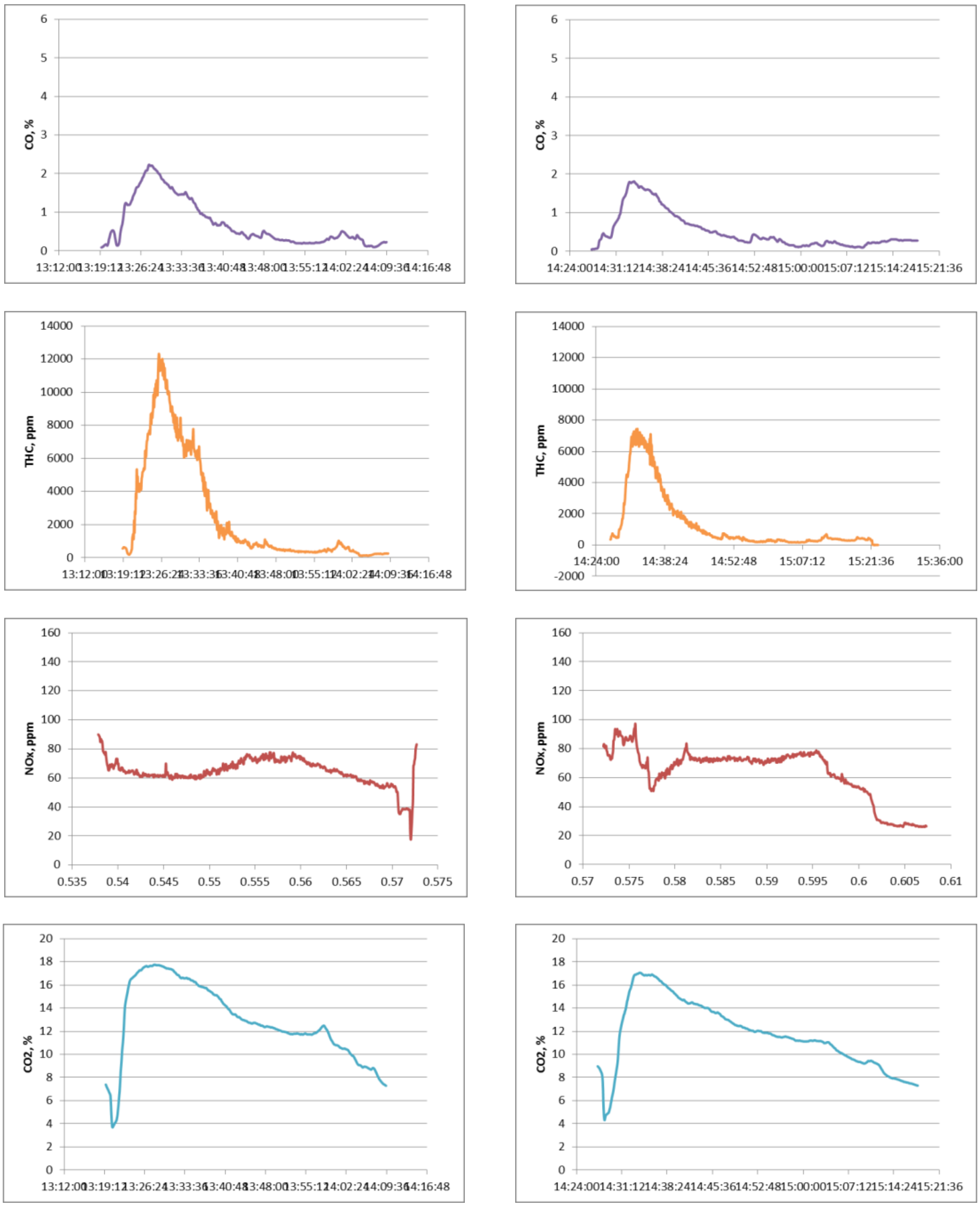


Figure A1.3a Flue gas measurement traces of OD, CO and CO_2 for Appliance C, ESP, High Output, Test1 (left) and Test 2 (right)

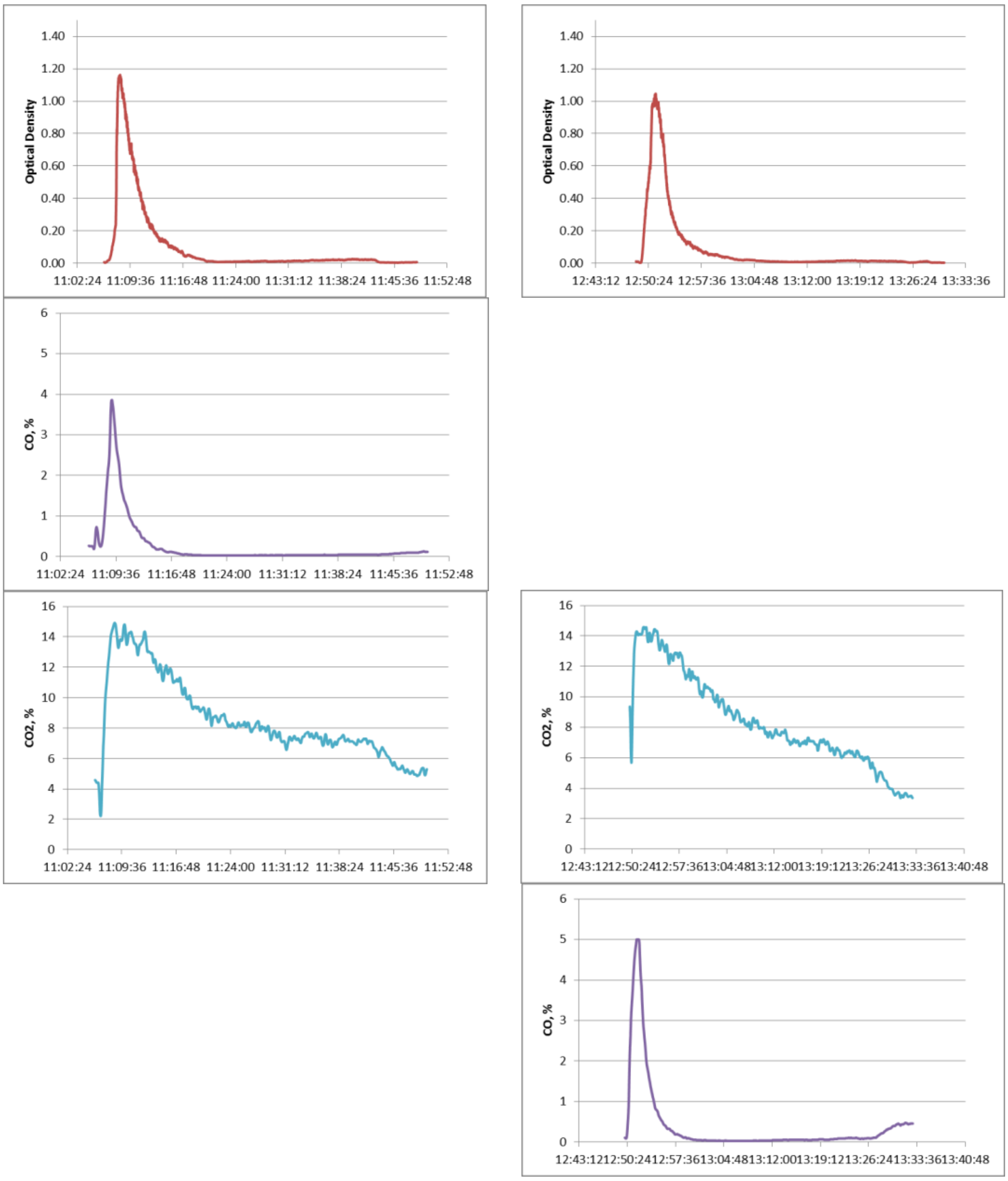


Figure A1.3b Flue gas measurement traces of OD, CO and CO_2 for Appliance C, ESP, High Output, Test 3 (left) and Test 4 (right)

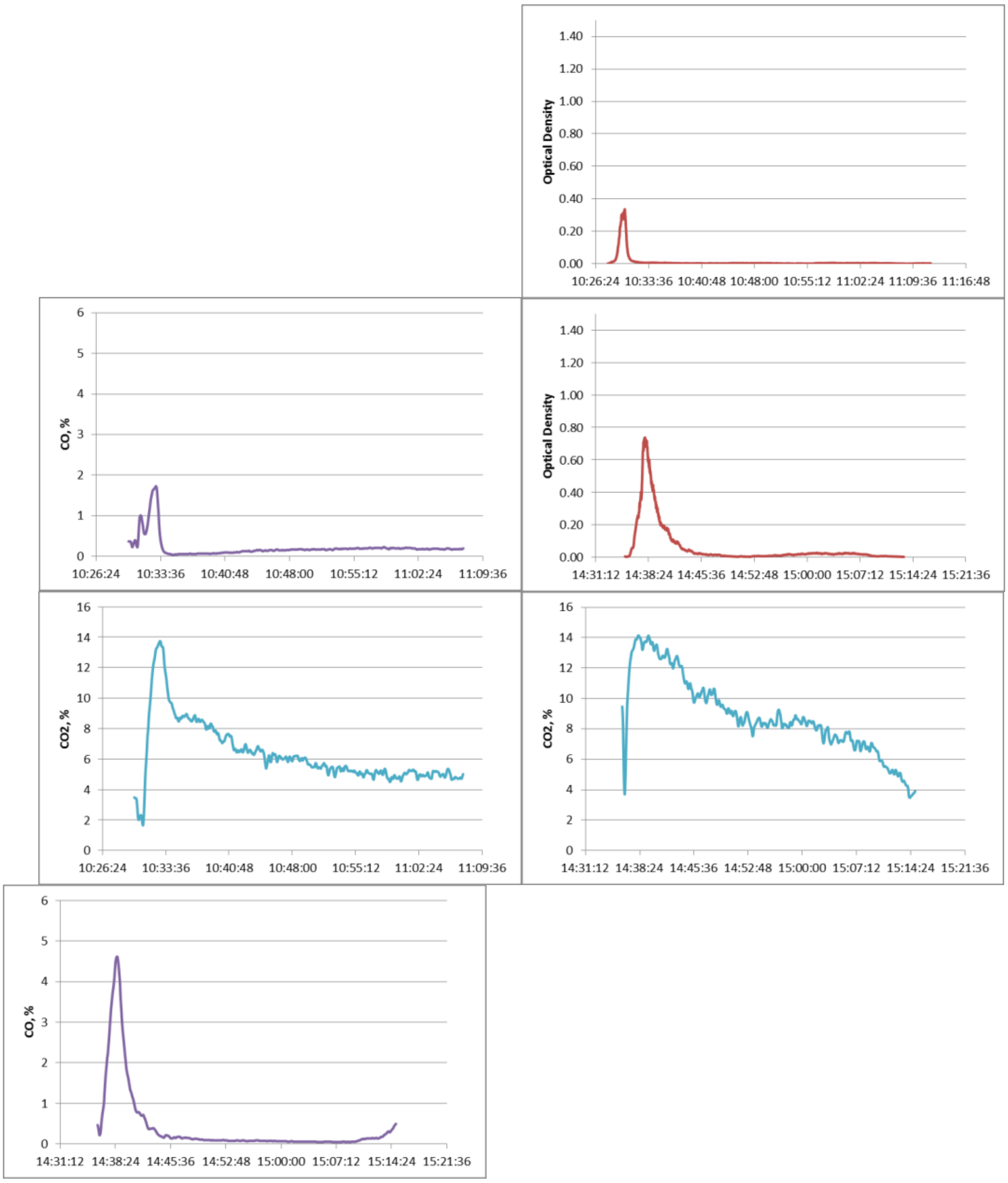


Figure A1.3c Flue gas measurement traces of OD, CO and CO_2 for Appliance C, ESP, High Output, Test5 (left), Low Output, Test 1 (right)

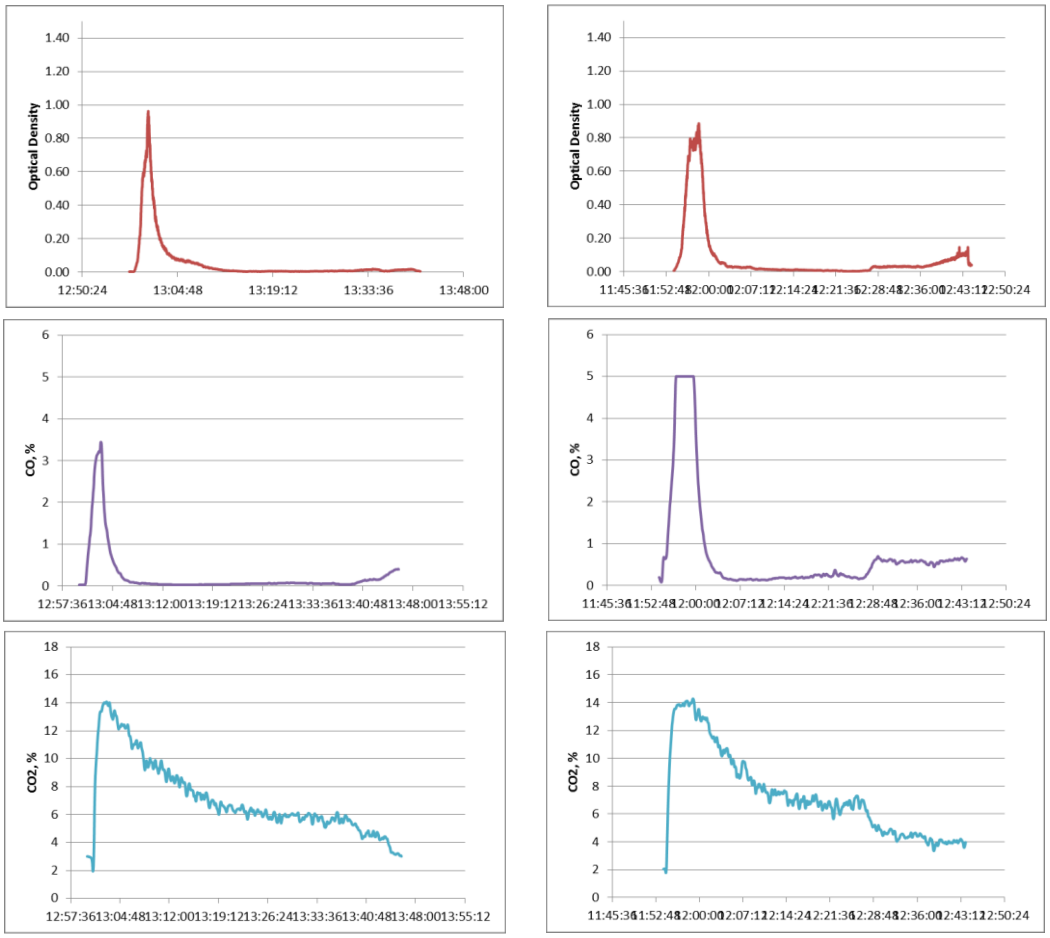


Figure A1.3d Flue gas measurement traces of OD, CO and CO_2 for Appliance C, ESP, Low Output, Test 2 (left) and Test 3 (right)

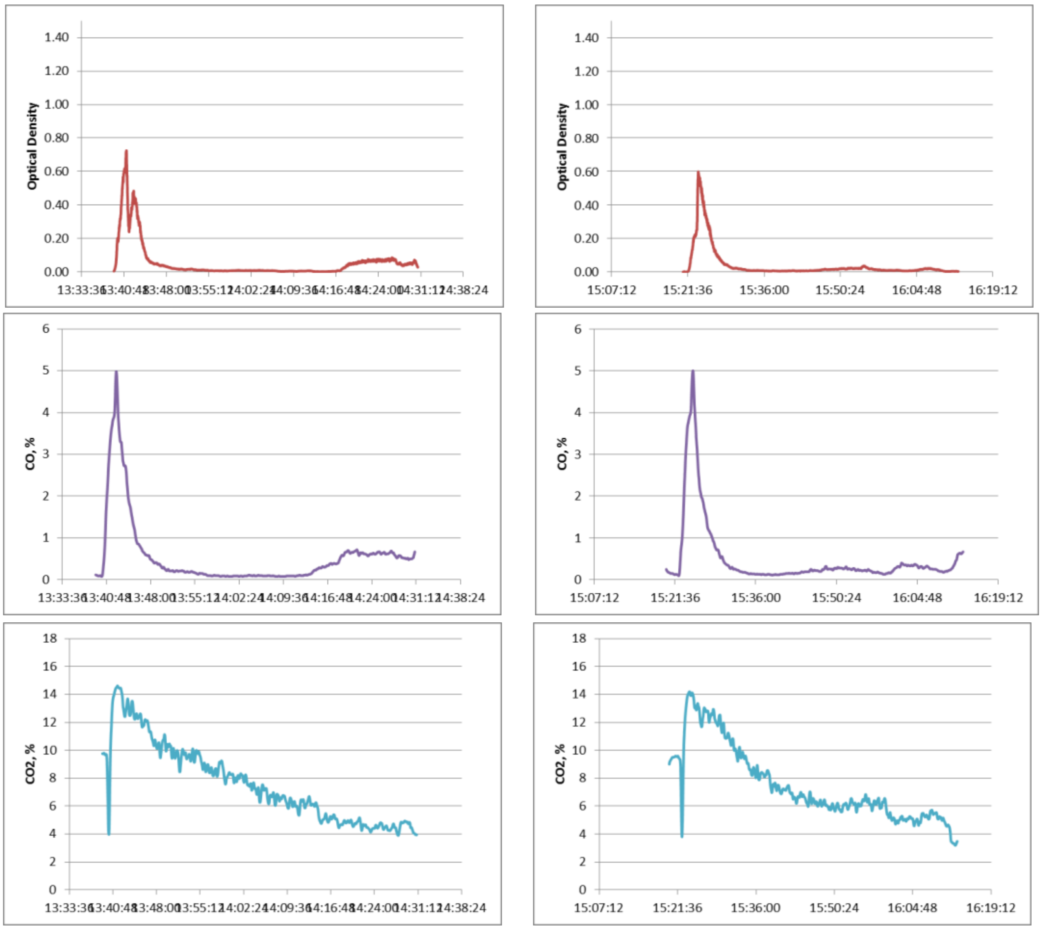


Figure A1.3e Flue gas measurement traces of OD, CO and CO_2 for Appliance C, ESP, Low Output, Test 4 (left) and Test 5 (right)

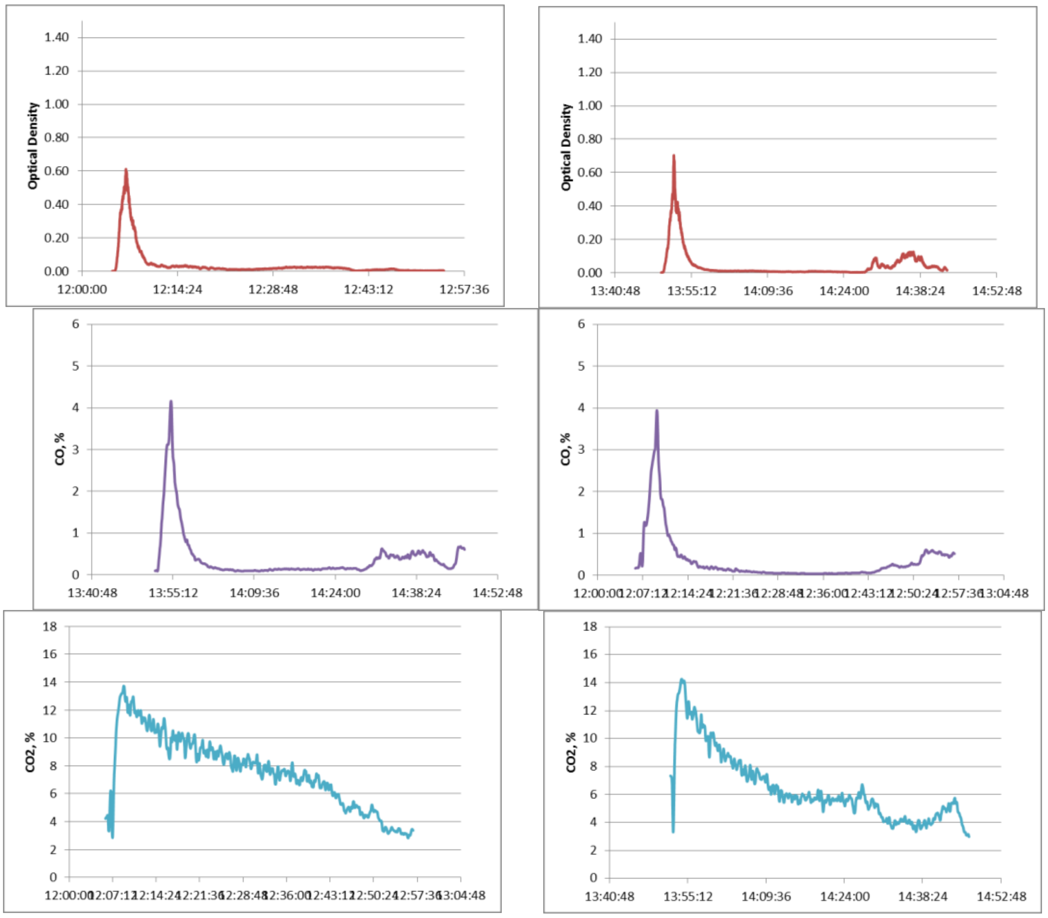


Figure A1.3f Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, ESP, High Output, Extra Test1 (left) and Extra Test 2 (right)

Figure A1.3g Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, ESP, High Output, Extra Test 3 (left) and Extra Test 4 (right)

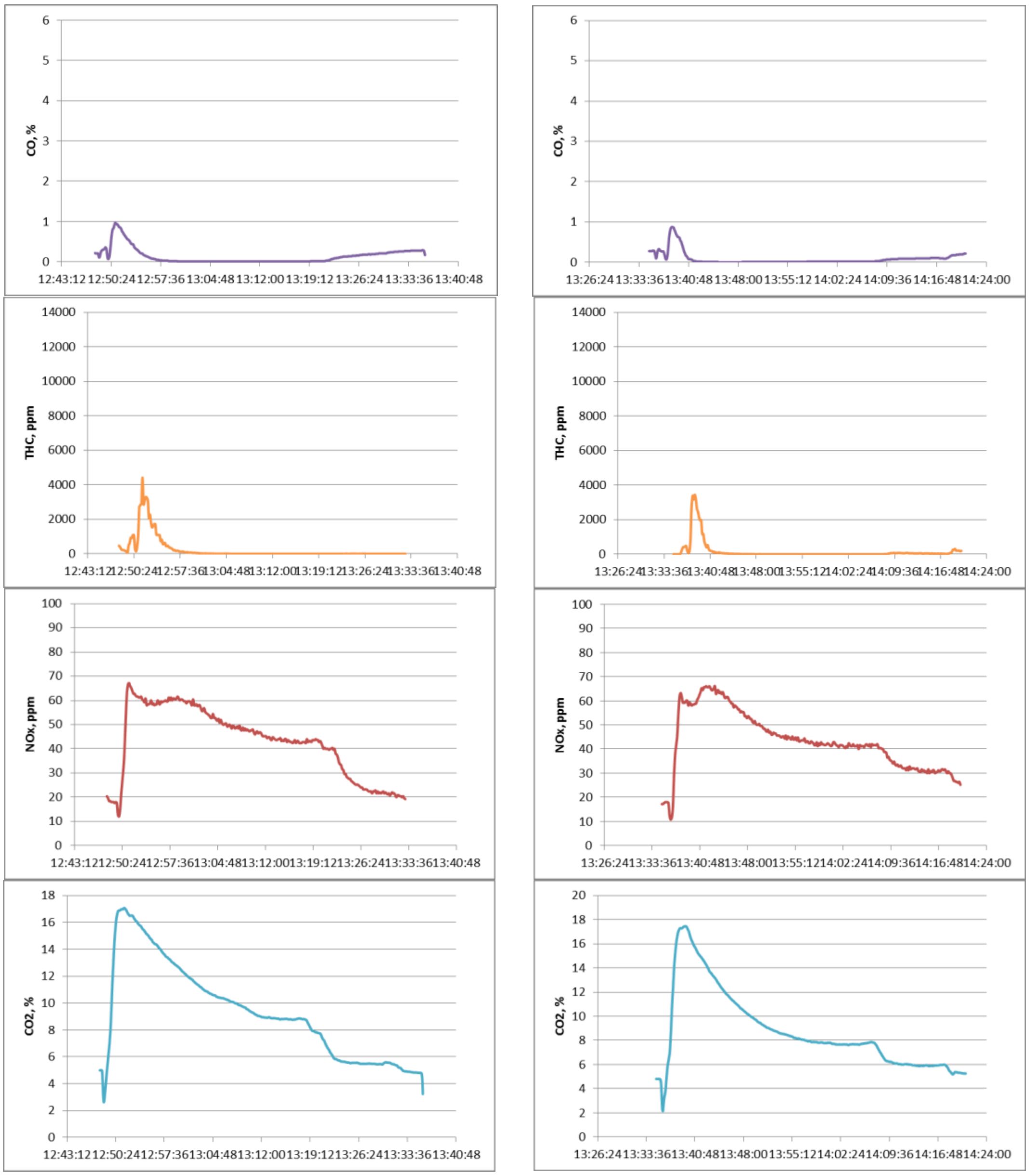


Figure A1.3h Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, ESP, High Output, Extra Test 5 (left) and Low Output, Extra Test 1 (right)

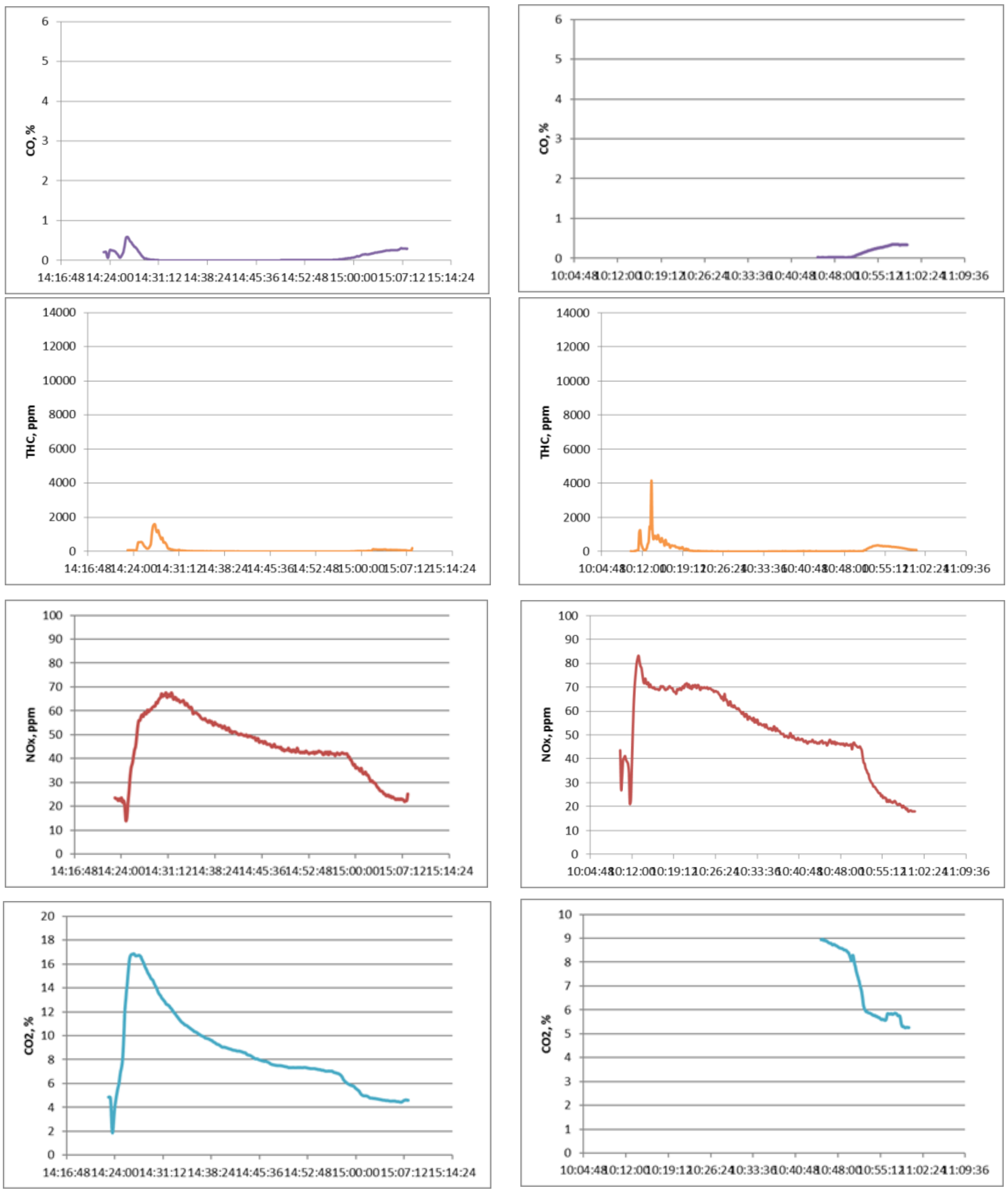


Figure A1.3i Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, ESP, Low Output, Extra Test 2 (left) and Extra Test 3 (right)

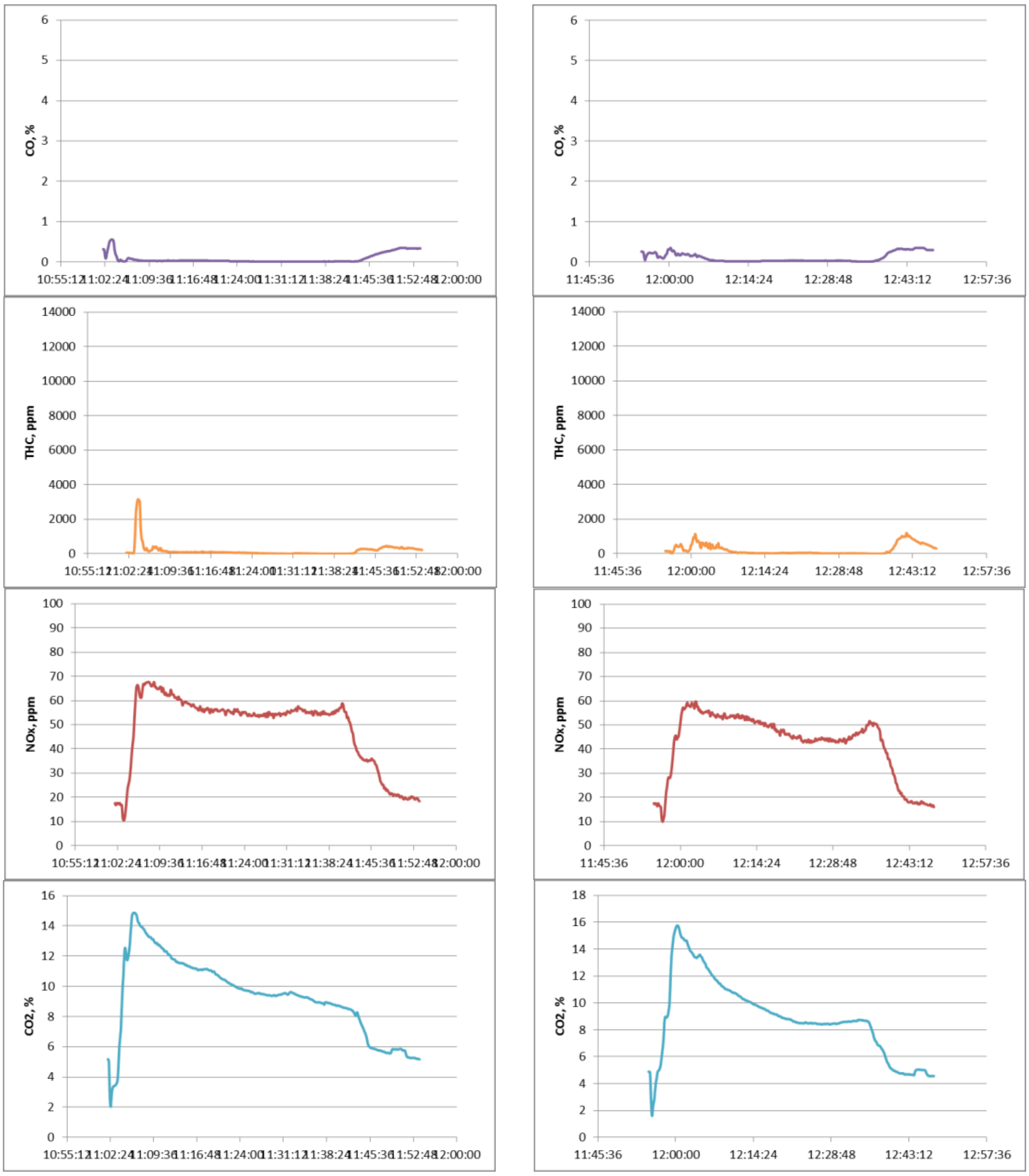


Figure A1.3j Flue gas measurement traces of CO, THC, NOx and CO2 for Appliance C, ESP, Low Output, Extra Test 4 (left) and Extra Test 5 (right)

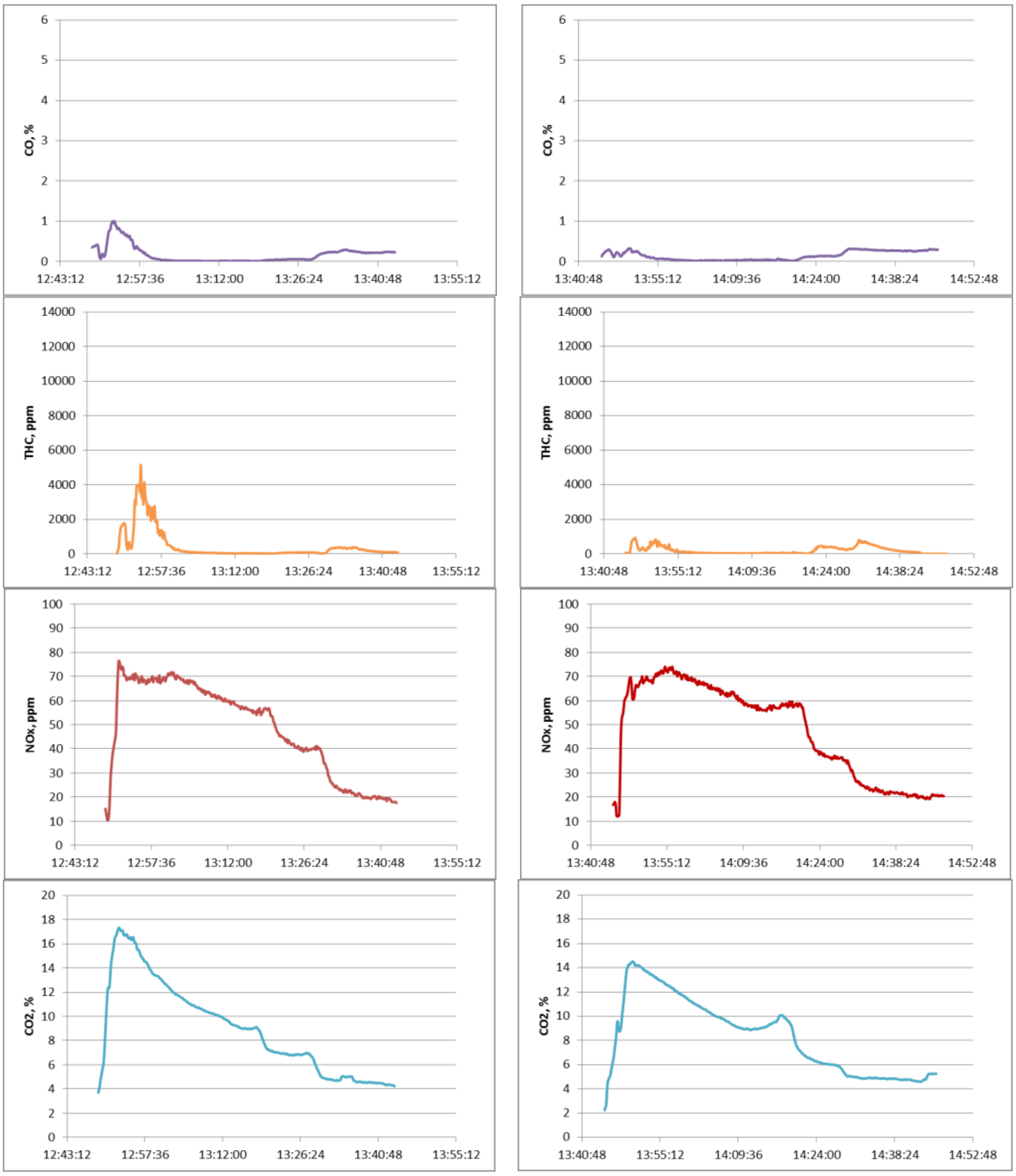


Figure A1.3k Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance C, DIN+, High Output, Test1 (left) and Test 2 (right)

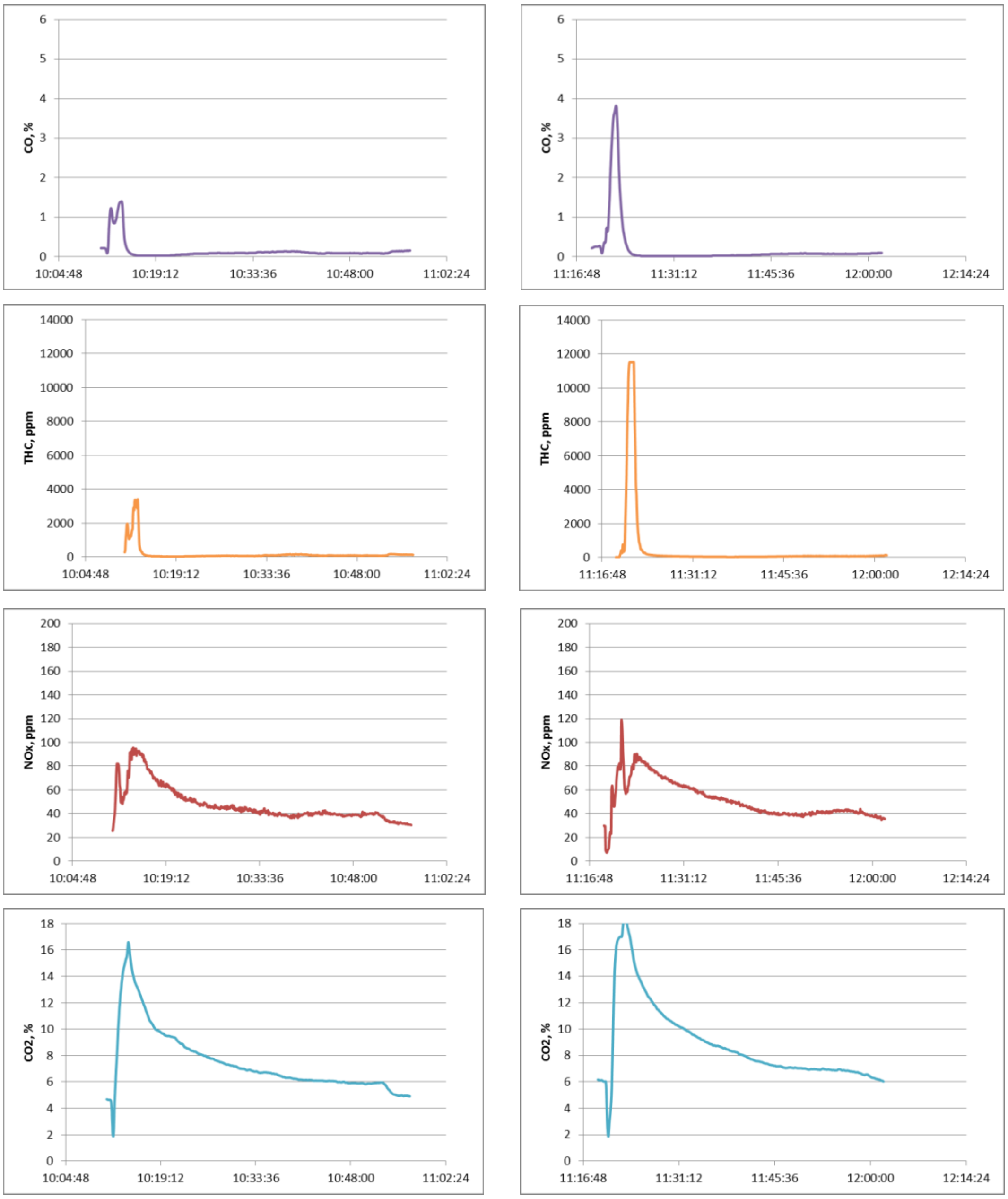


Figure A1.3k Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance C, DIN+, High Output, Test 3 (left) and Test 4 (right)

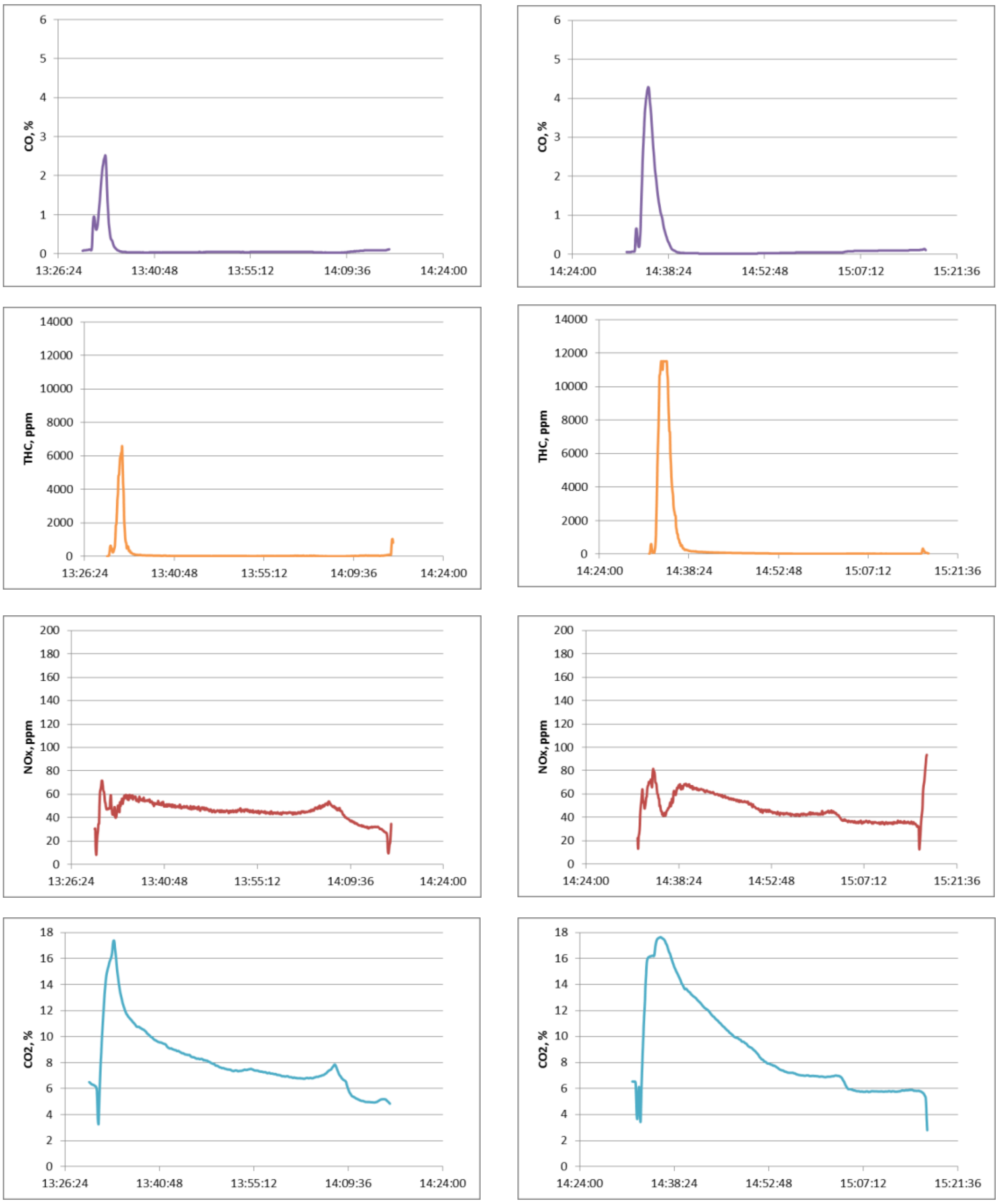


Figure A1.3k Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance C, DIN+, High Output, Test 5 (left) and Low Output Test 1 (right)

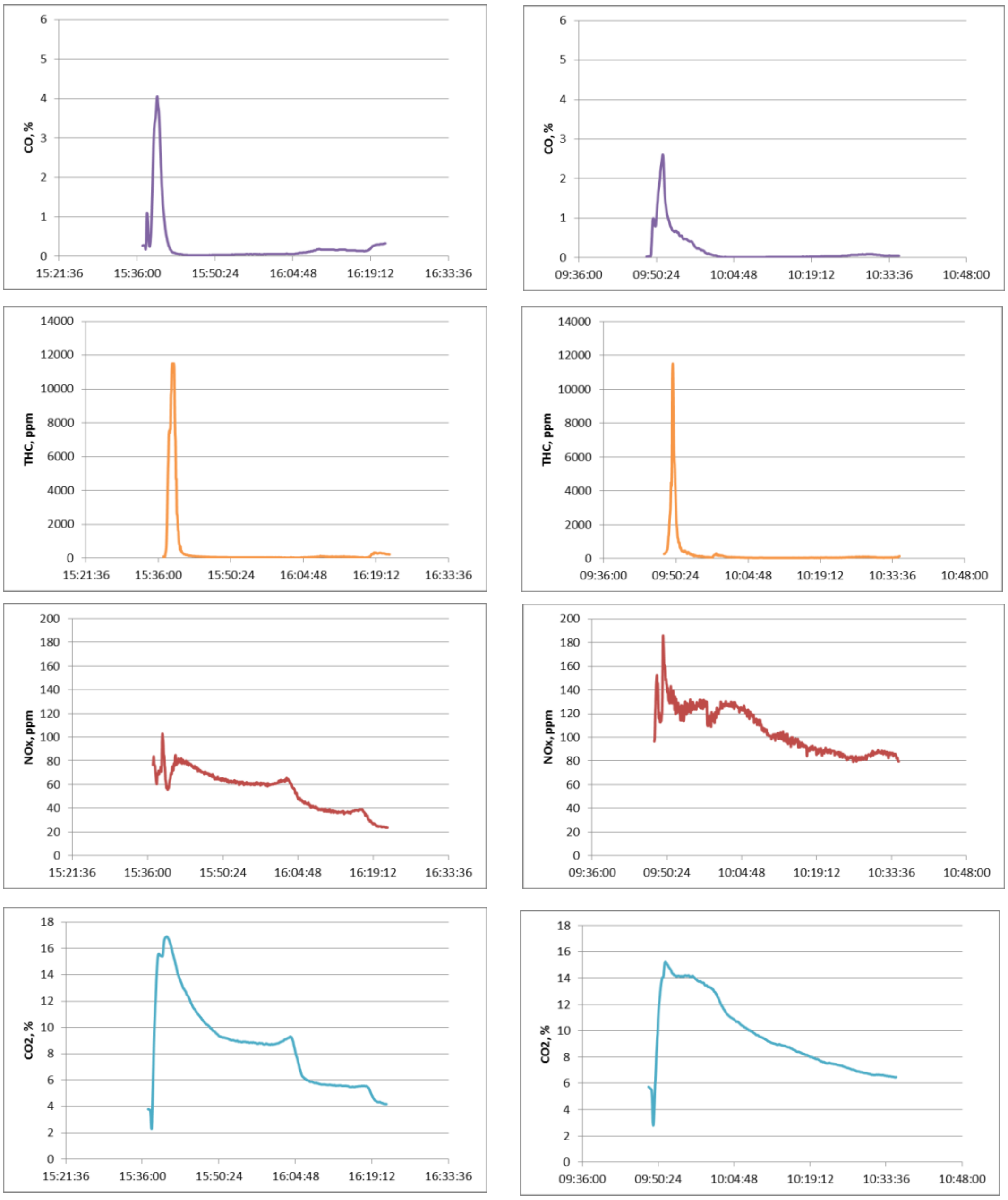


Figure A1.3l Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance C, DIN+, Low Output, Test 2 (left) and Low Output Test 3 (right)

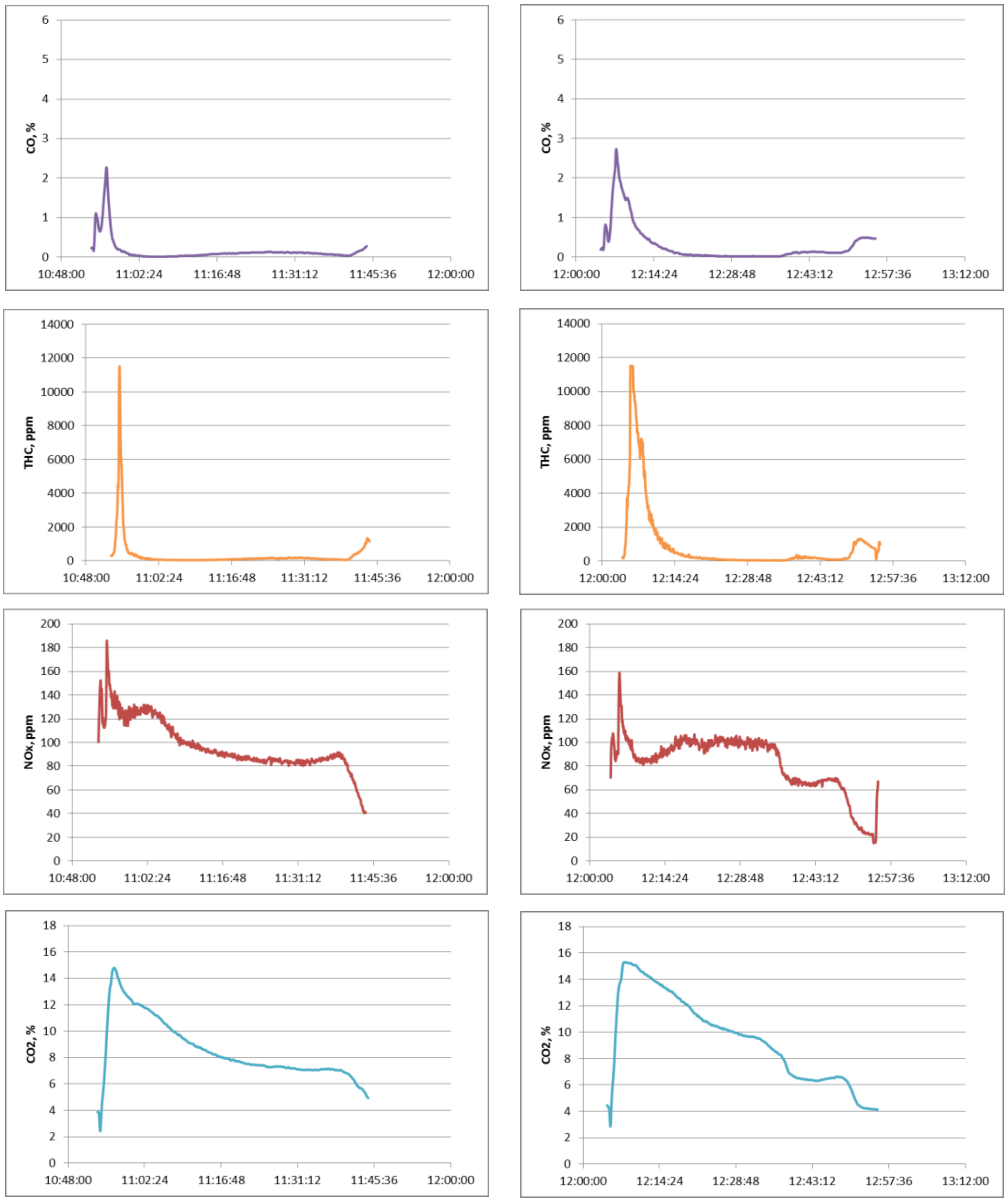


Figure A1.3l Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance C, DIN+, Low Output, Test 4 (left) and Low Output Test 5 (right)

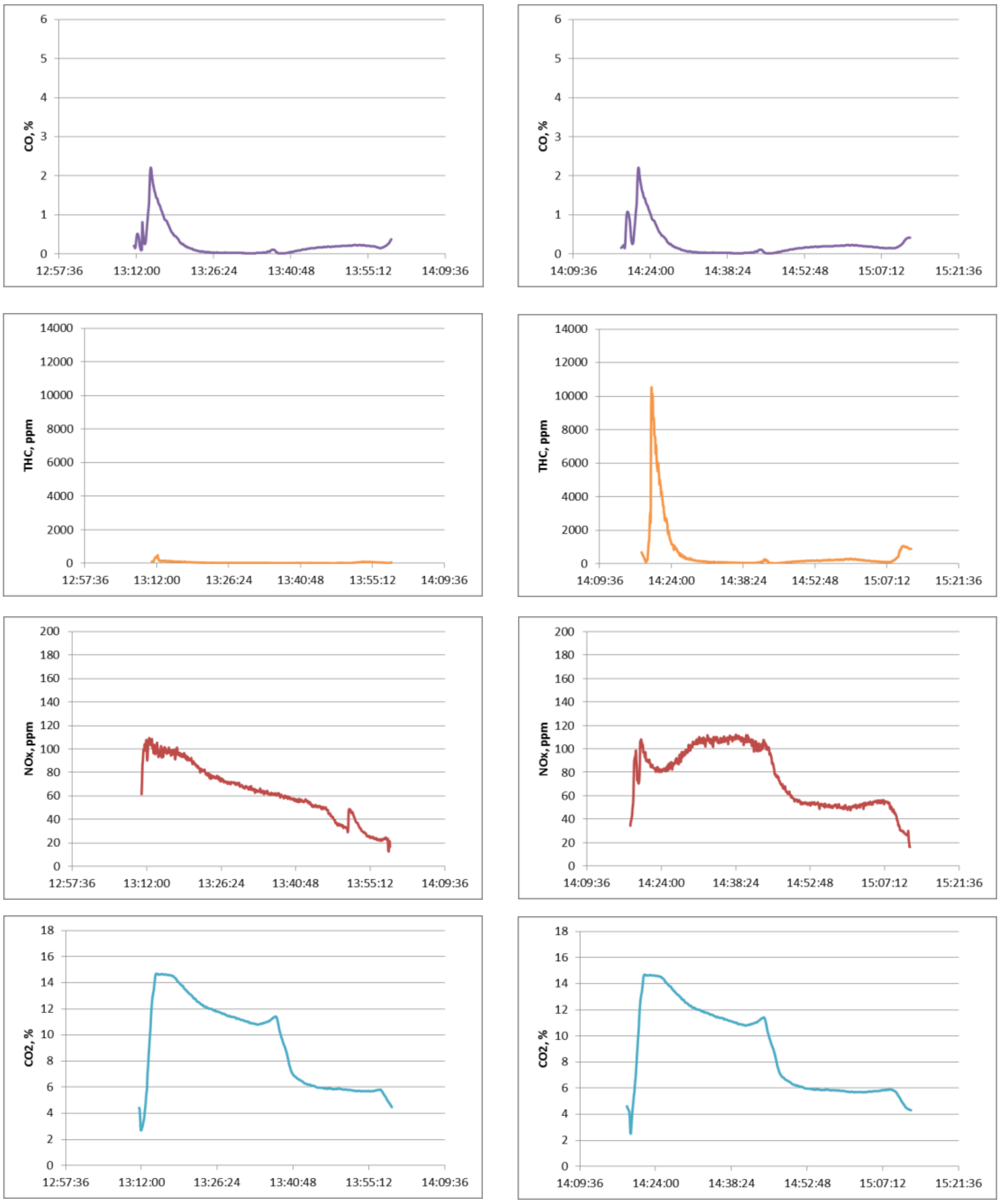


Figure A1.4a Flue gas measurement traces of OD, CO and CO_2 for Appliance D, ESP, High Output, Test1 (left) and Test 2 (right)

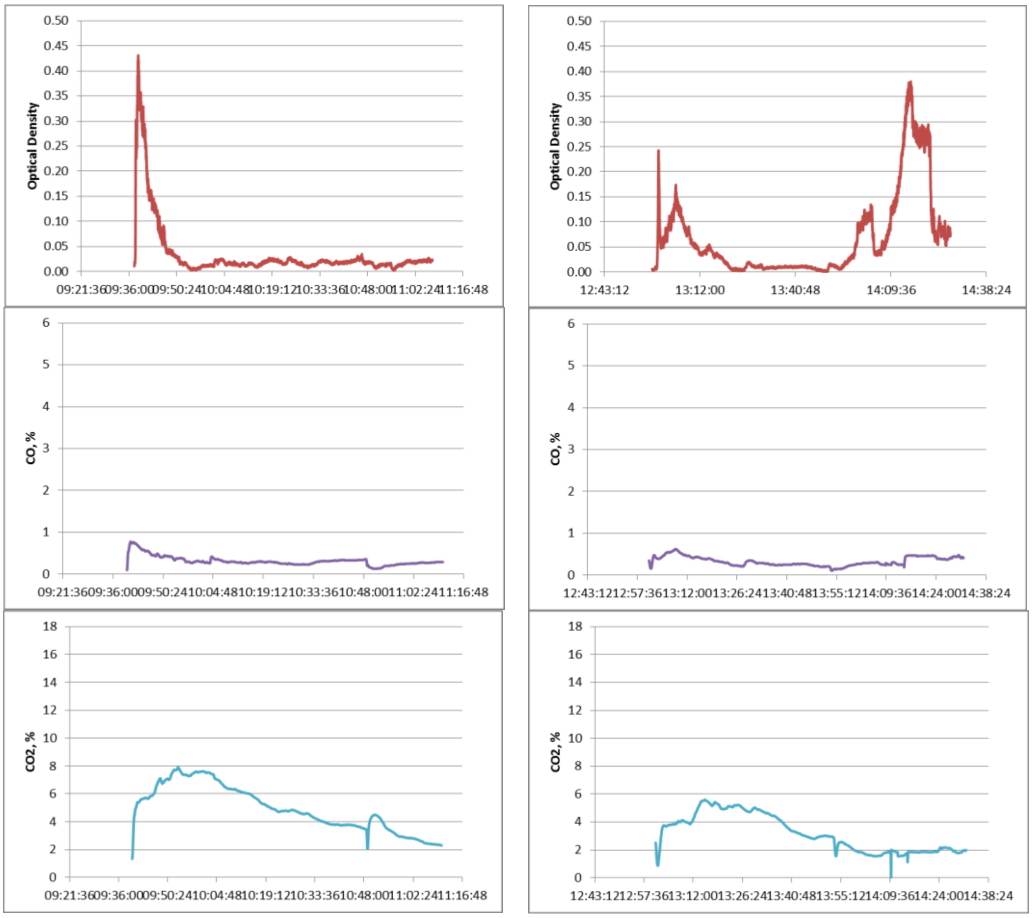


Figure A1.4b Flue gas measurement traces of OD, CO and CO_2 for Appliance D, ESP, High Output, Test 3 (left) and Test 4 (right)

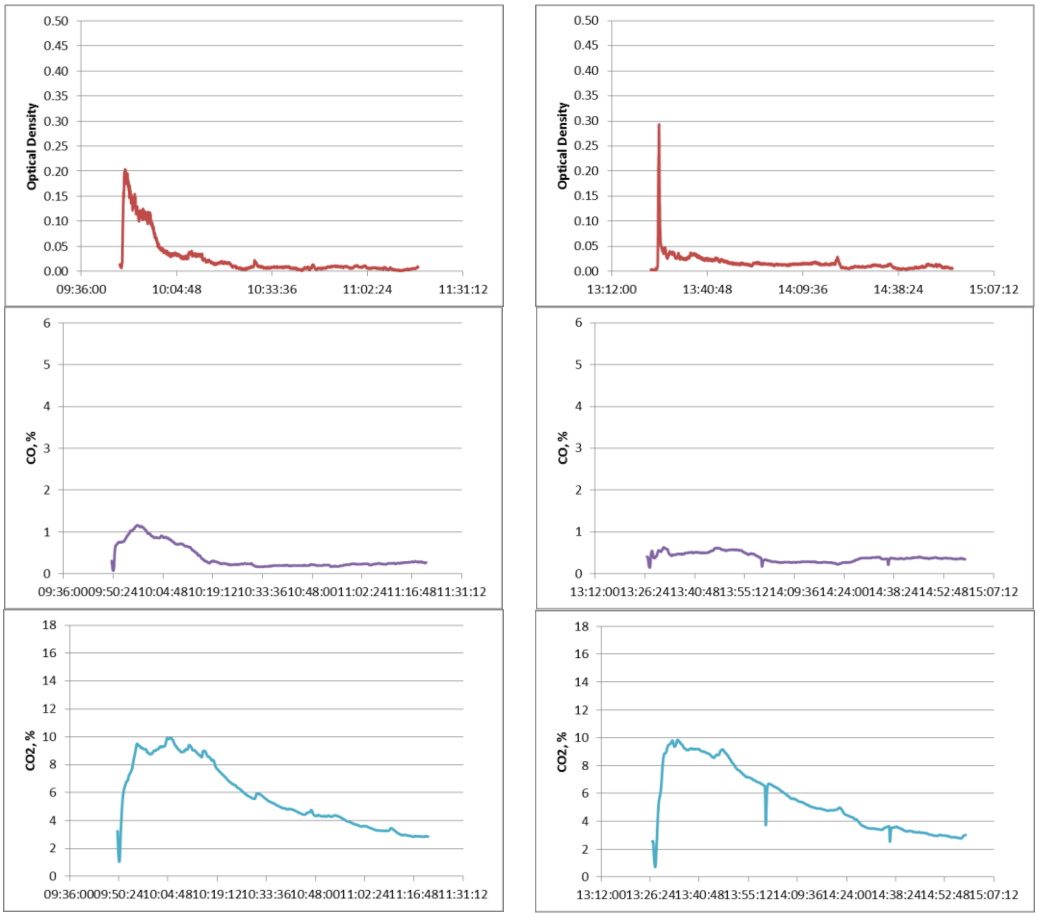


Figure A1.4c Flue gas measurement traces of OD, CO, THC, NOx and CO_2 for Appliance D, ESP, High Output, Test5 (left), Low Output, Test 1 (right)

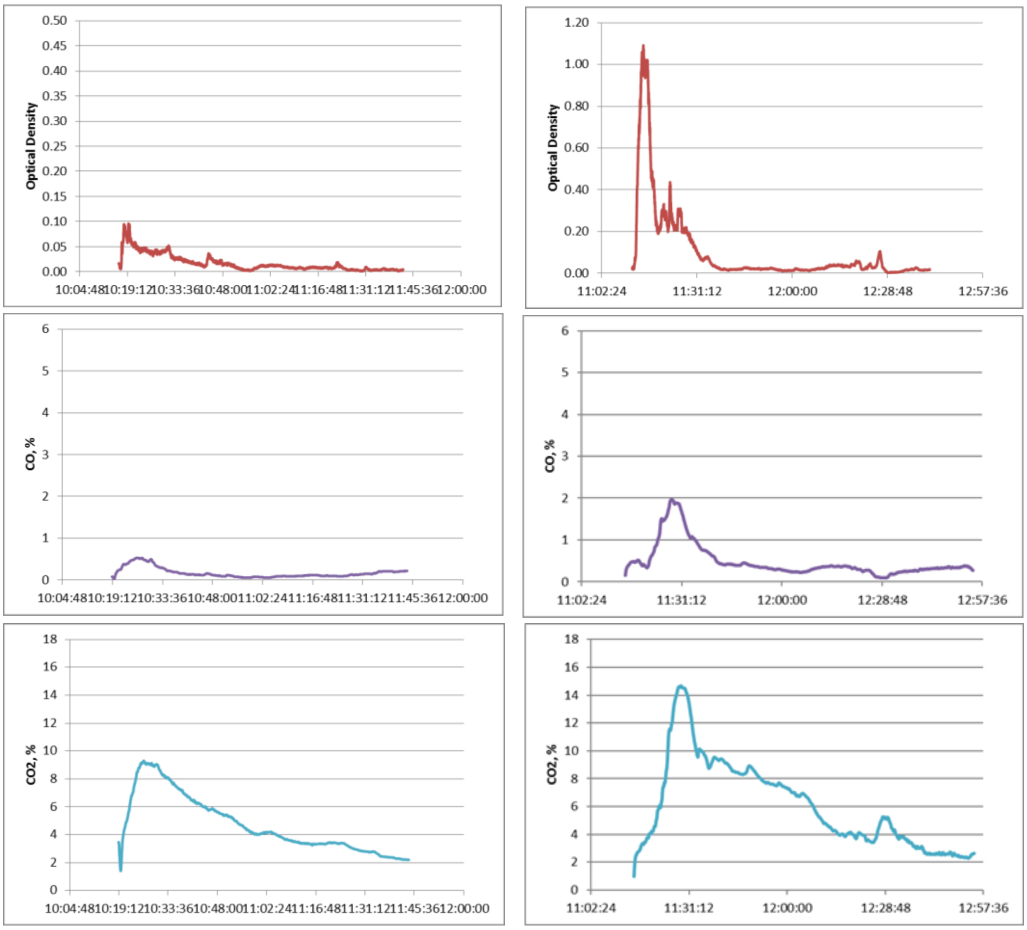


Figure A1.4d Flue gas measurement traces of OD, CO and CO_2 for Appliance D, ESP, Low Output, Test 2 (left) and Test 3 (right)

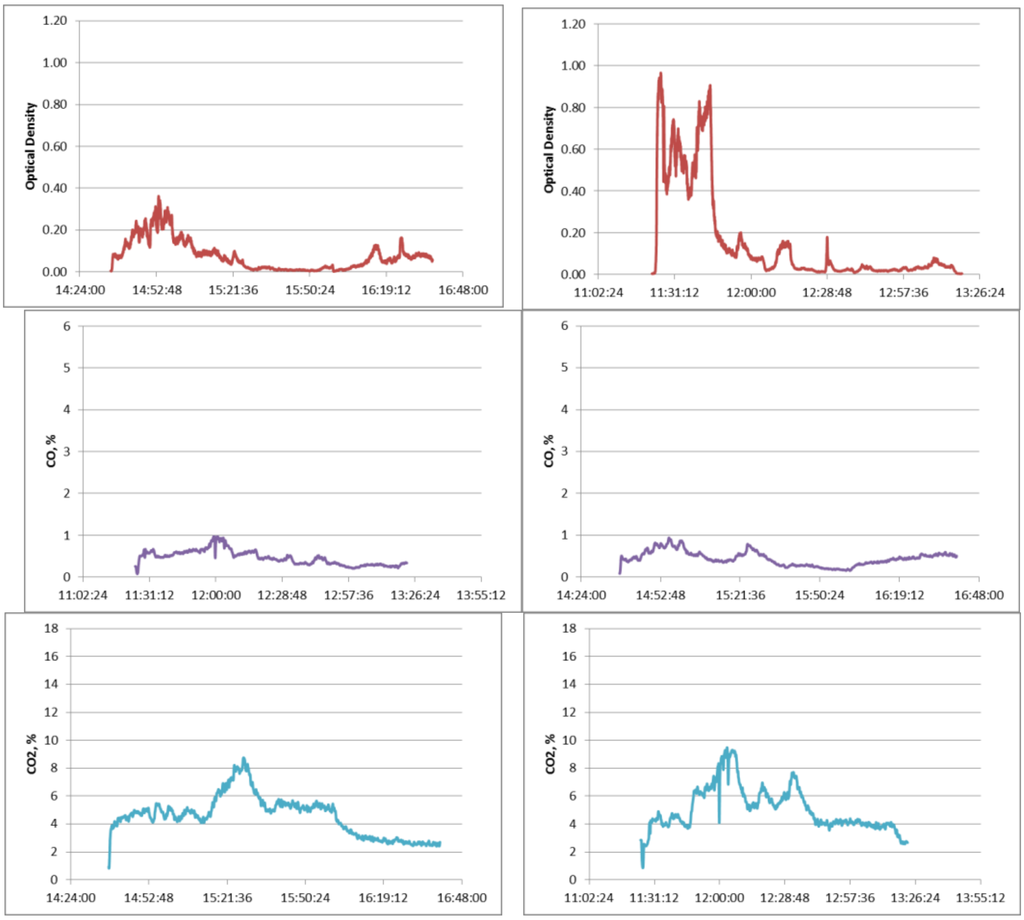


Figure A1.4e Flue gas measurement traces of OD, CO and CO_2 for Appliance D, ESP, Low Output, Test 4 (left) and Test 5 (right)

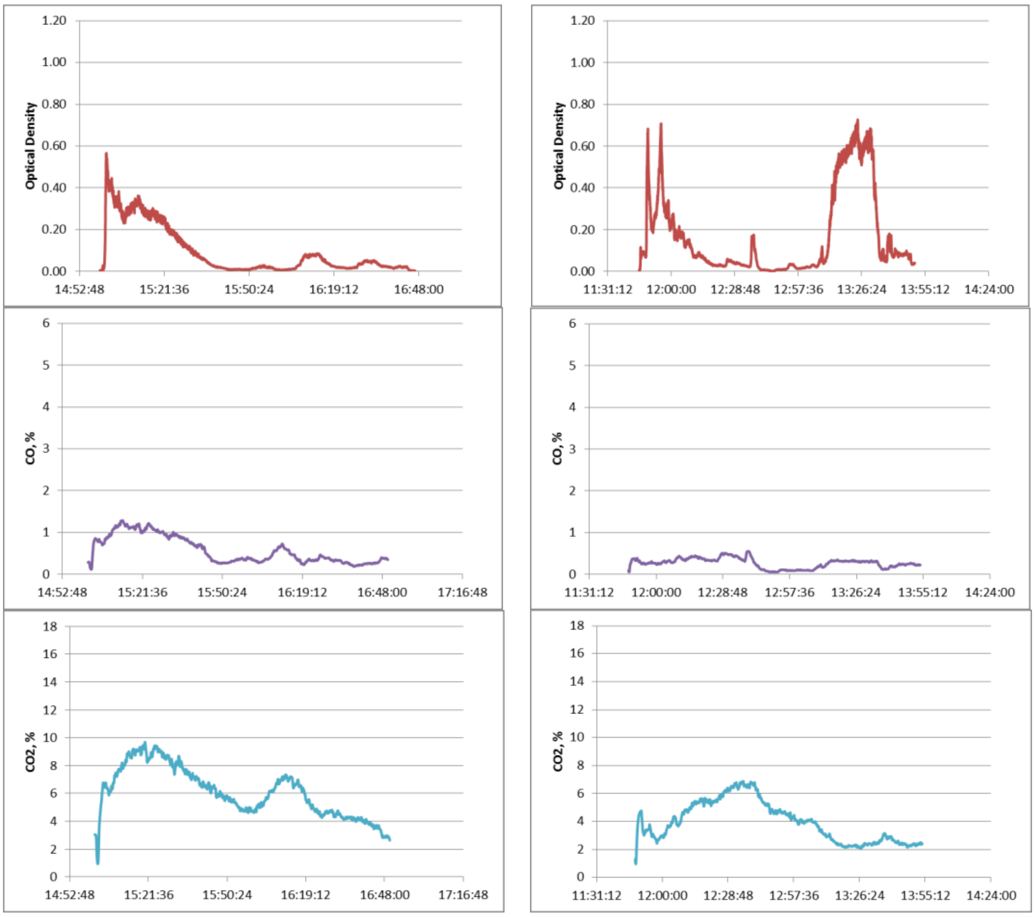


Figure A1.4f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance D, DIN+, High Output, Test 1 (left) and Test 2 (right)

Figure A1.4f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance D, DIN+, High Output, Test 3 (left) and Test 4 (right)

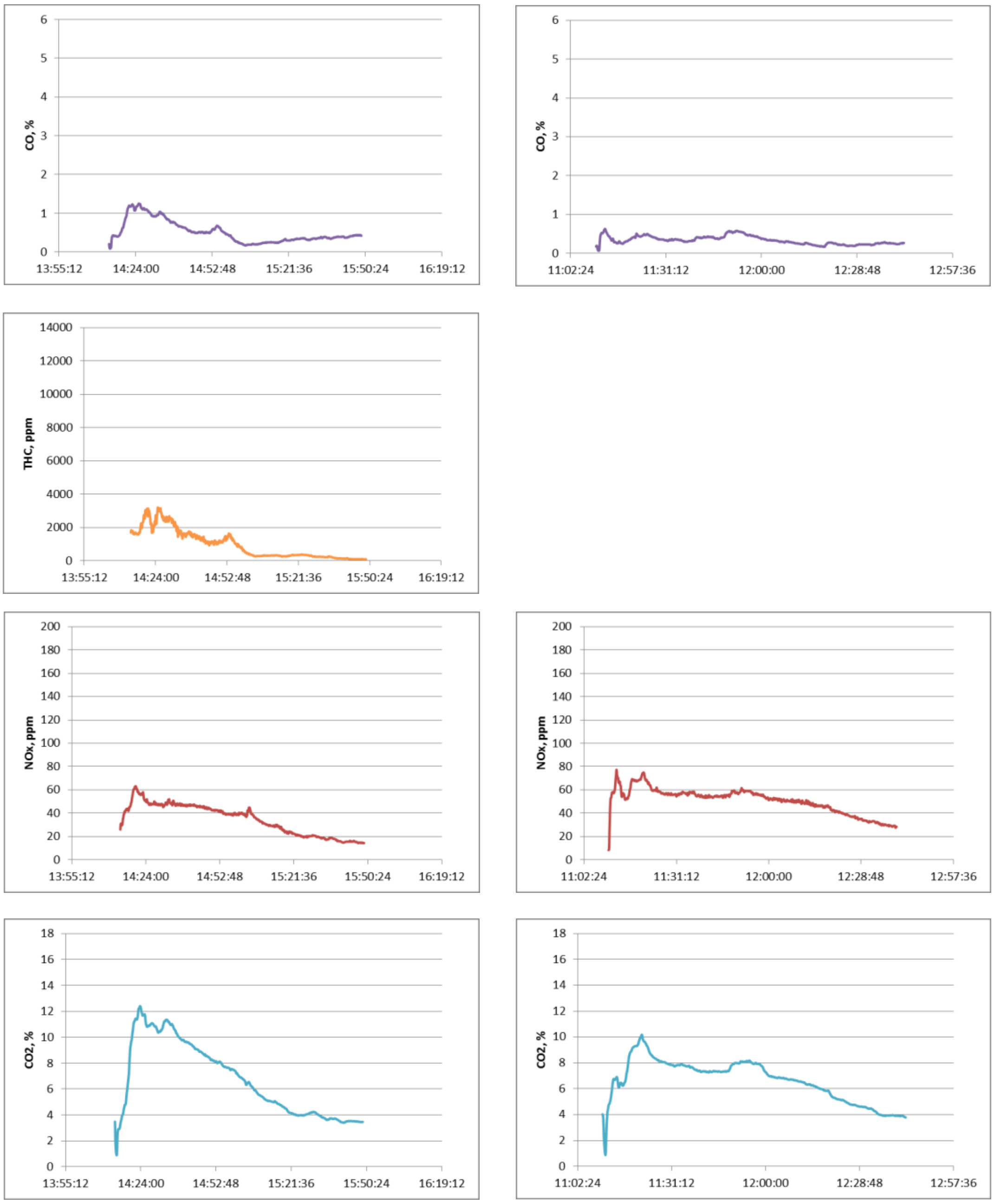


Figure A1.4f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance D, DIN+, High Output, Test 5 (left) and Low Output Test 1 (right)

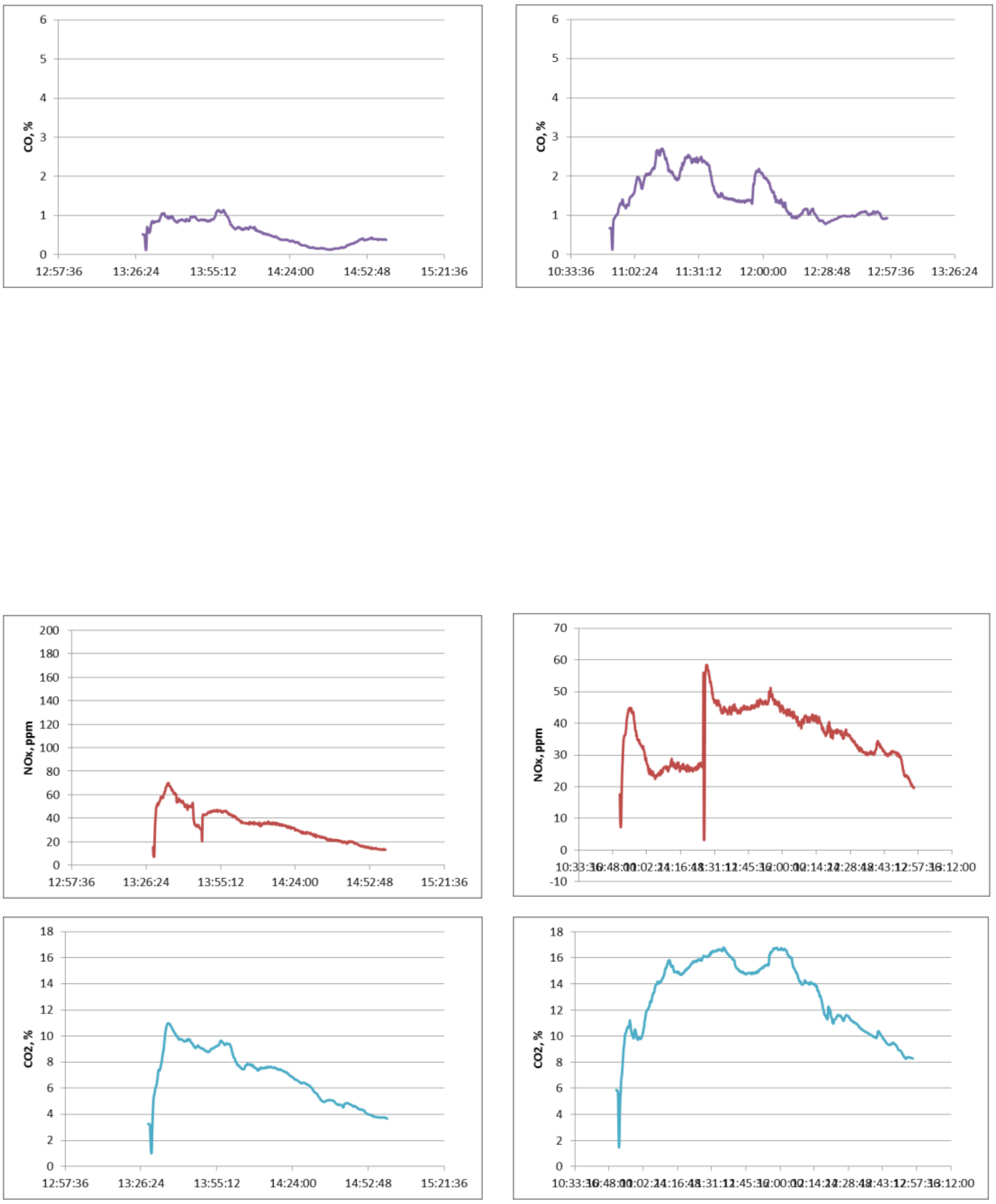


Figure A1.4f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance D, DIN+, Low Output, Test 2 (left) and Test 3 (right)

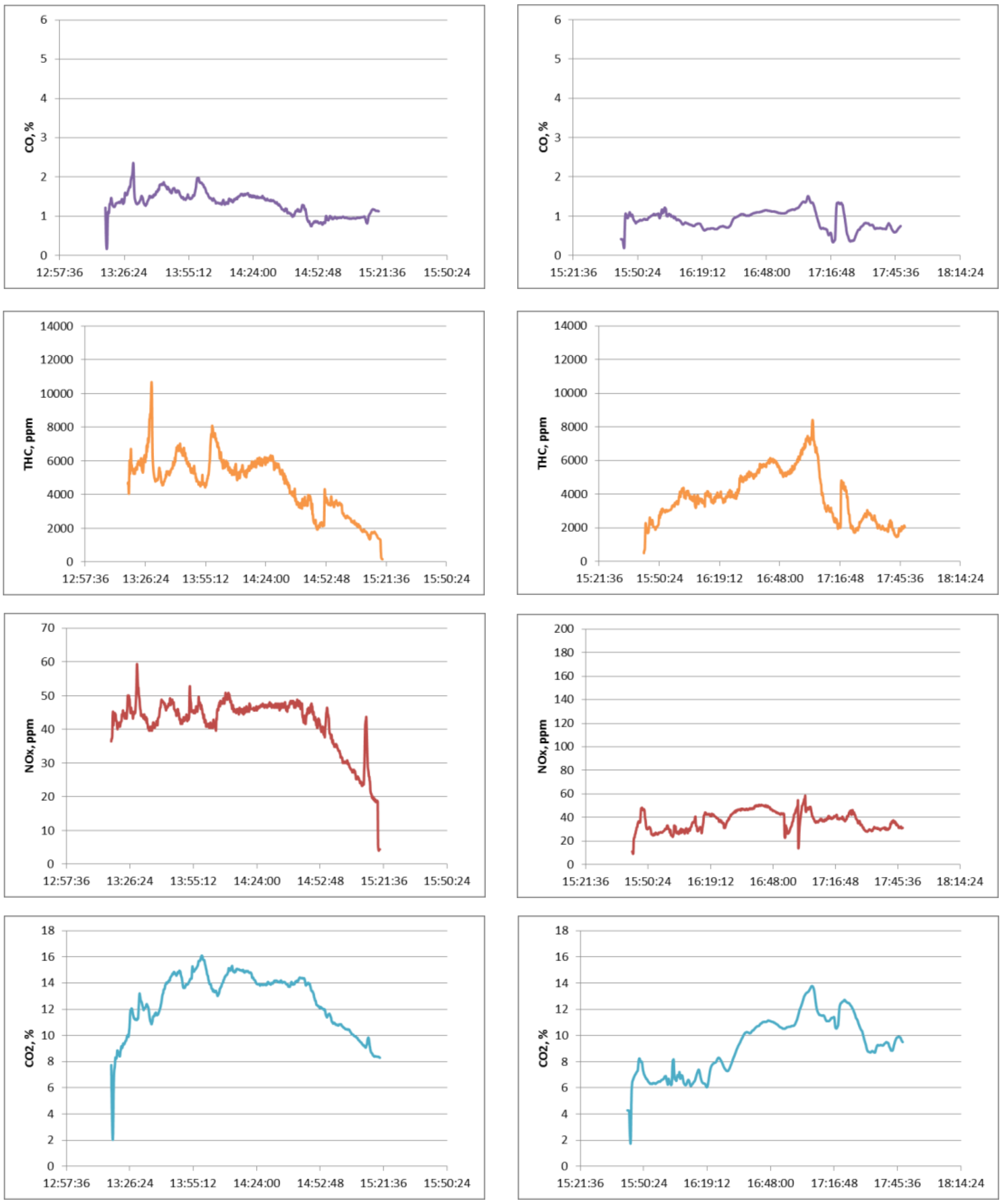


Figure A1.4f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance D, DIN+, Low Output, Test 4 (left) and Test 5 (right)

Figure A1.5a Flue gas measurement traces of CO and CO2 for Appliance E, ESP, High Output, Test 1 (left) and Test 2 (right)

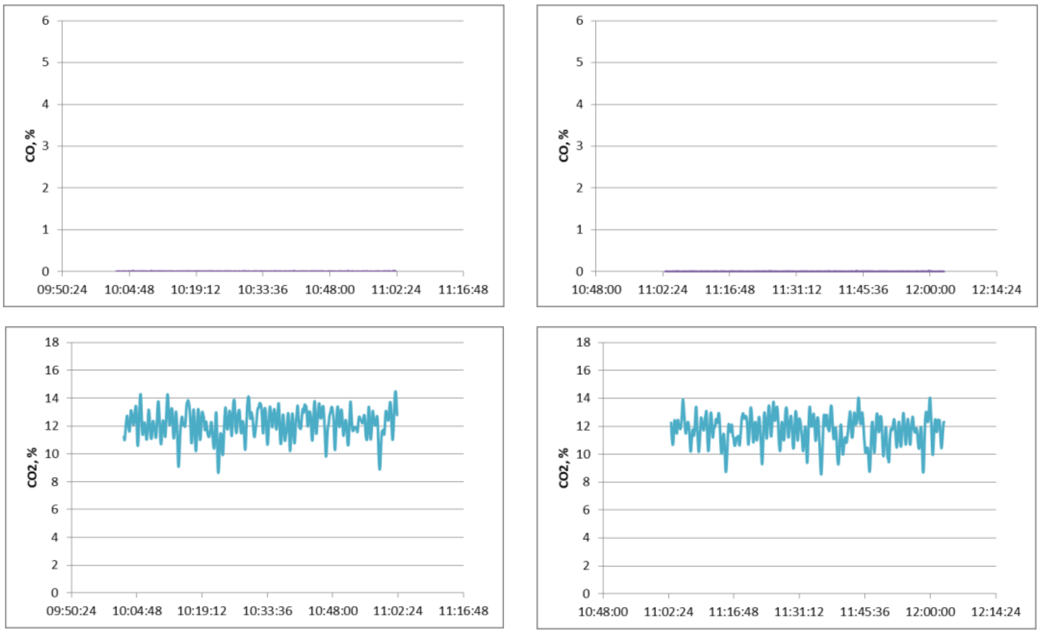


Figure A1.5b Flue gas measurement traces of CO and CO2 for Appliance E, ESP, High Output, Test 3 (left) and Test 4 (right)

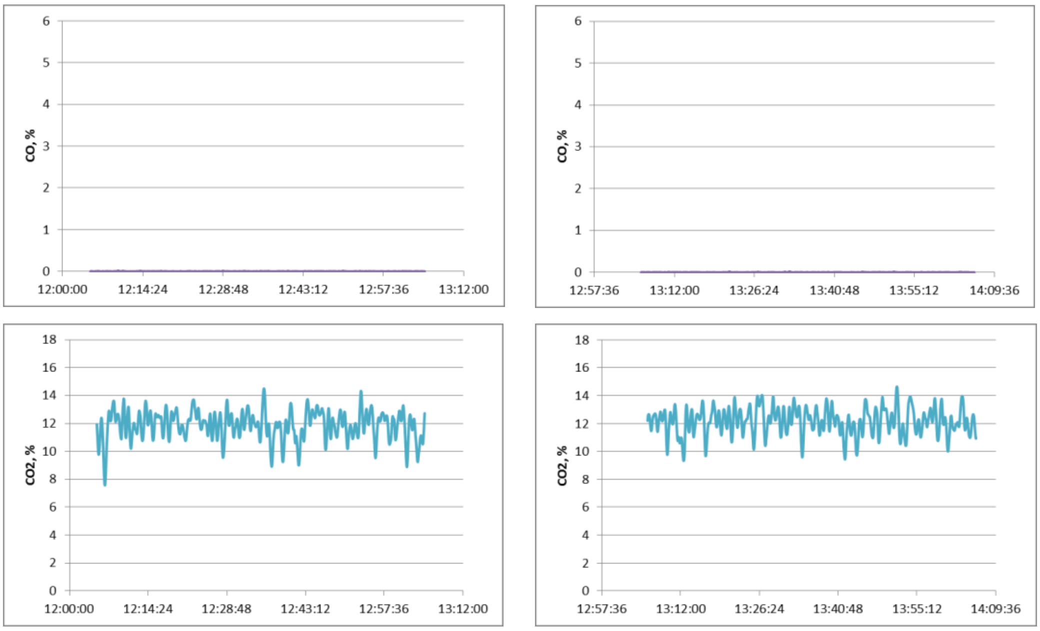


Figure A1.5c Flue gas measurement traces of CO and CO2 for Appliance E, ESP, High Output, Test 5 (left) and Low Output Test 1 (right)

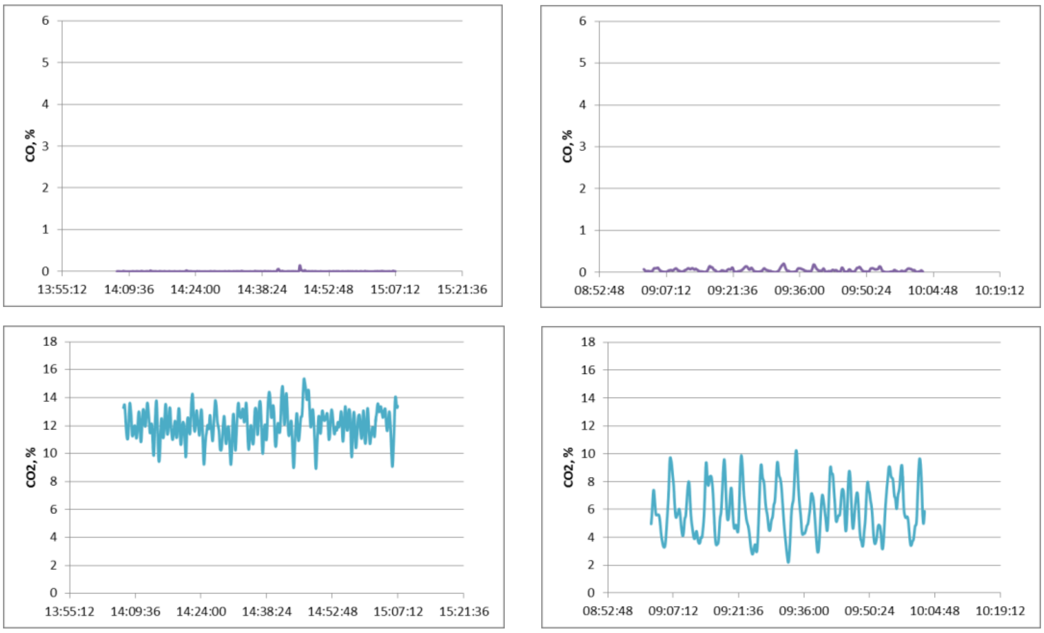


Figure A1.5d Flue gas measurement traces of CO and CO2 for Appliance E, ESP, Low Output, Test 2 (left) and Test 3 (right)

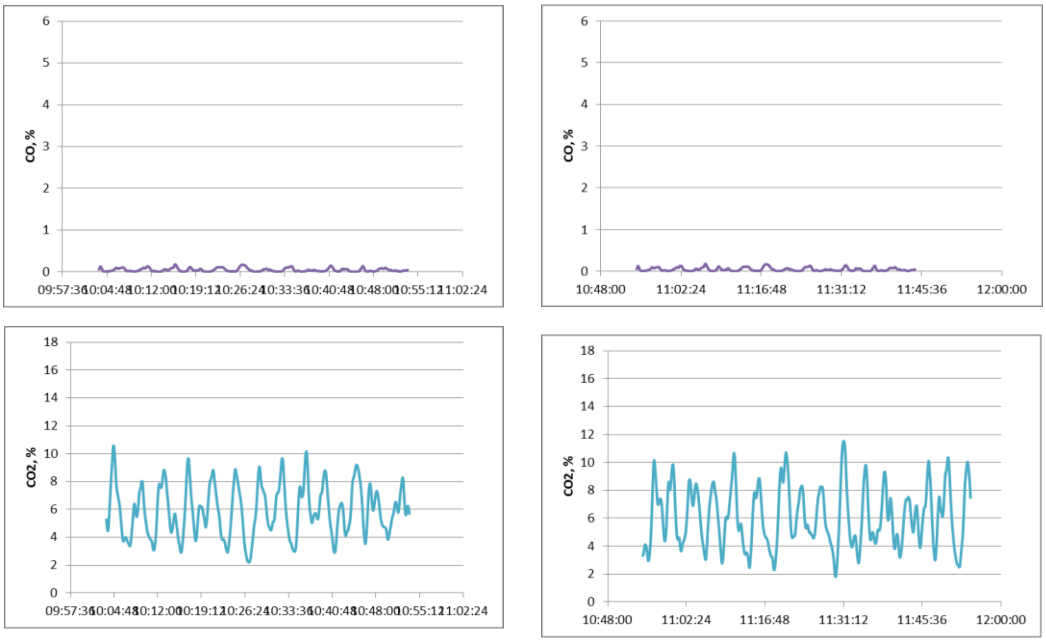


Figure A1.5e Flue gas measurement traces of CO and CO2 for Appliance E, ESP, Low Output, Test 4 (left) and Test 5 (right)

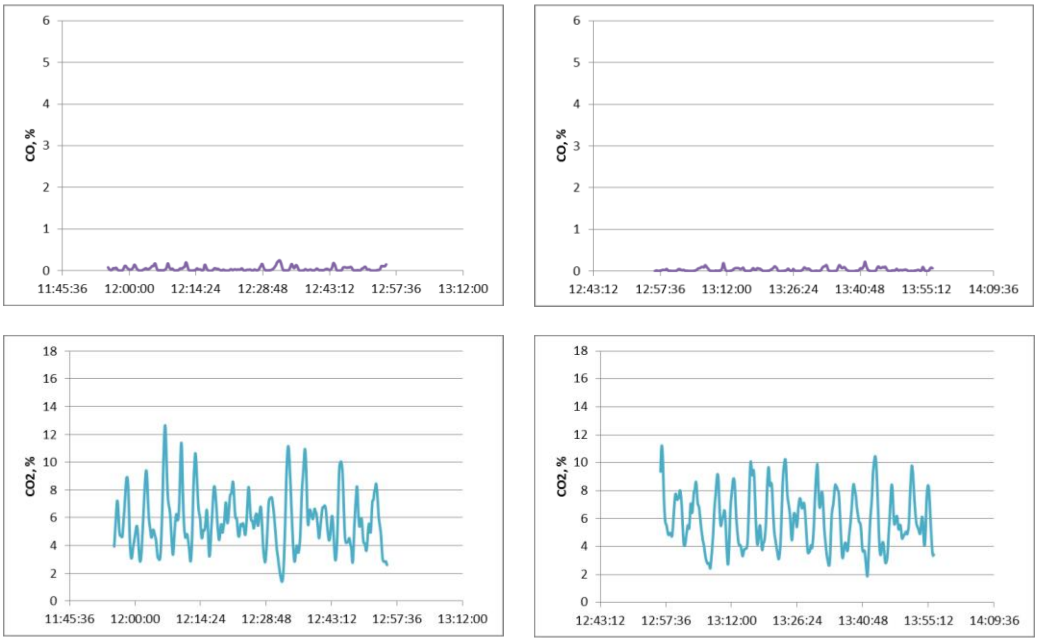


Figure A1.5f Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance E, DIN+, High Output, Test 1 (left) and Test 2 (right)

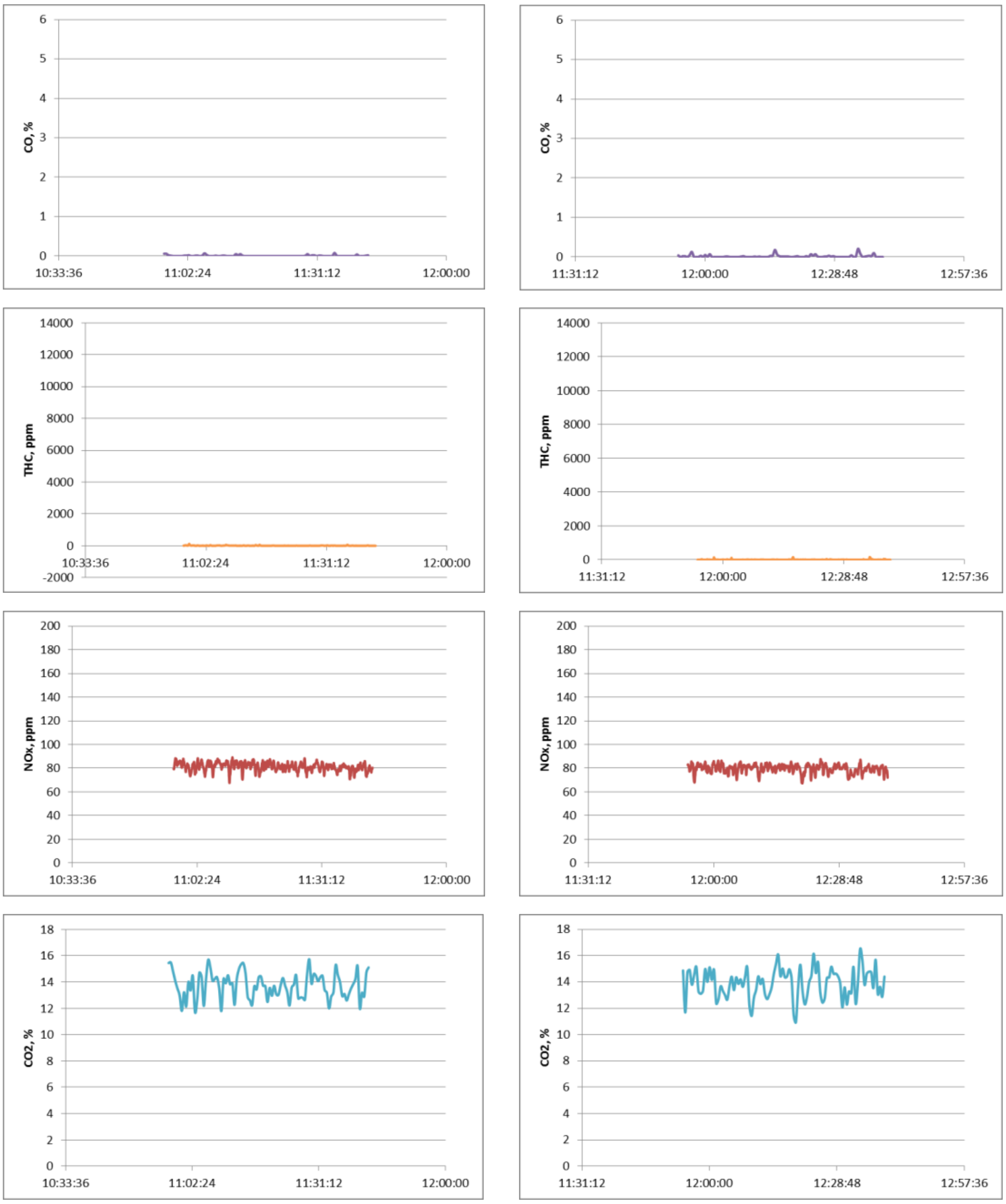


Figure A1.5g Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance E, DIN+, High Output, Test 3 (left) and Test 4 (right)

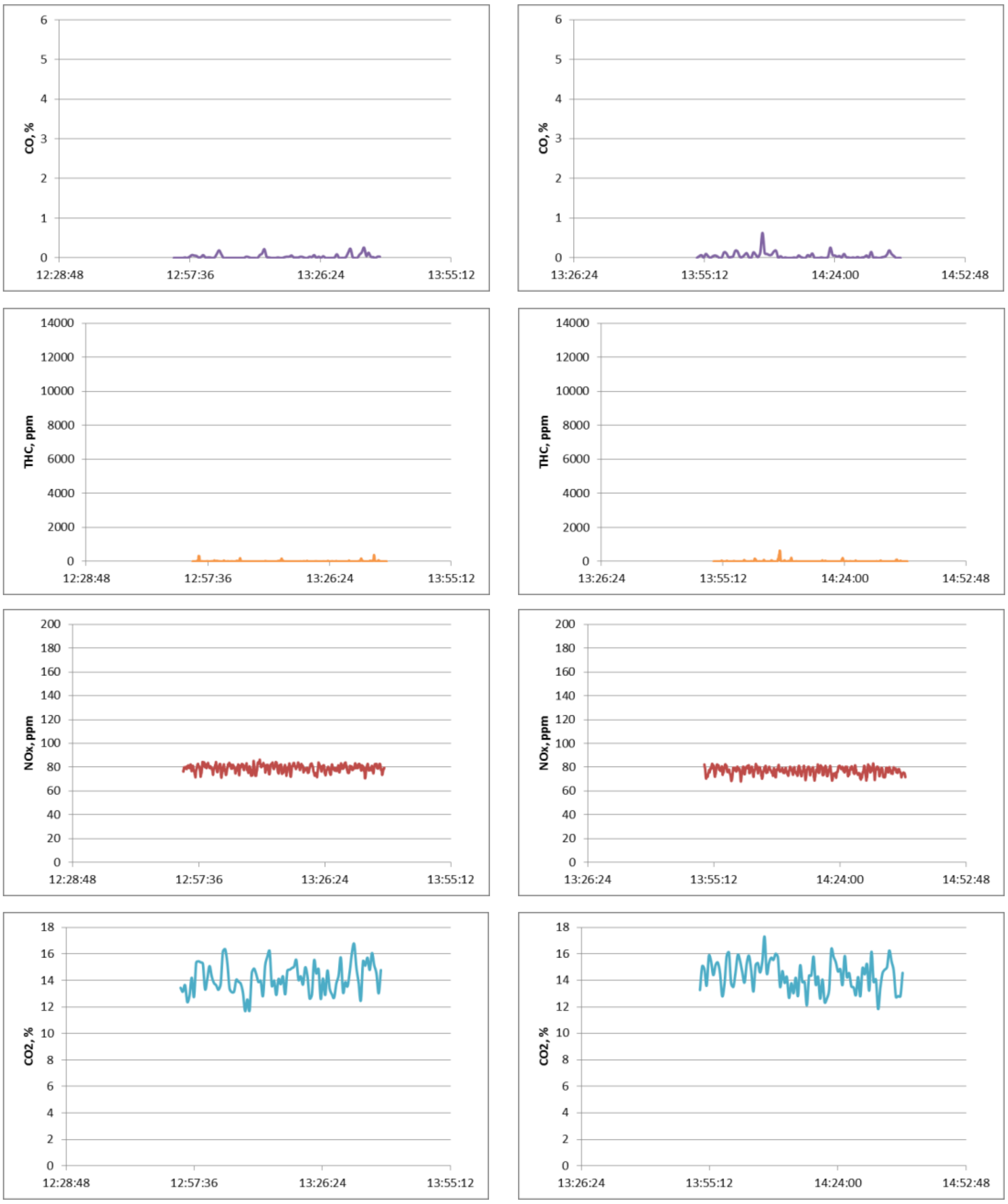


Figure A1.5h Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance E, DIN+, High Output, Test 5 (left) and Low Output Test 1 (right)

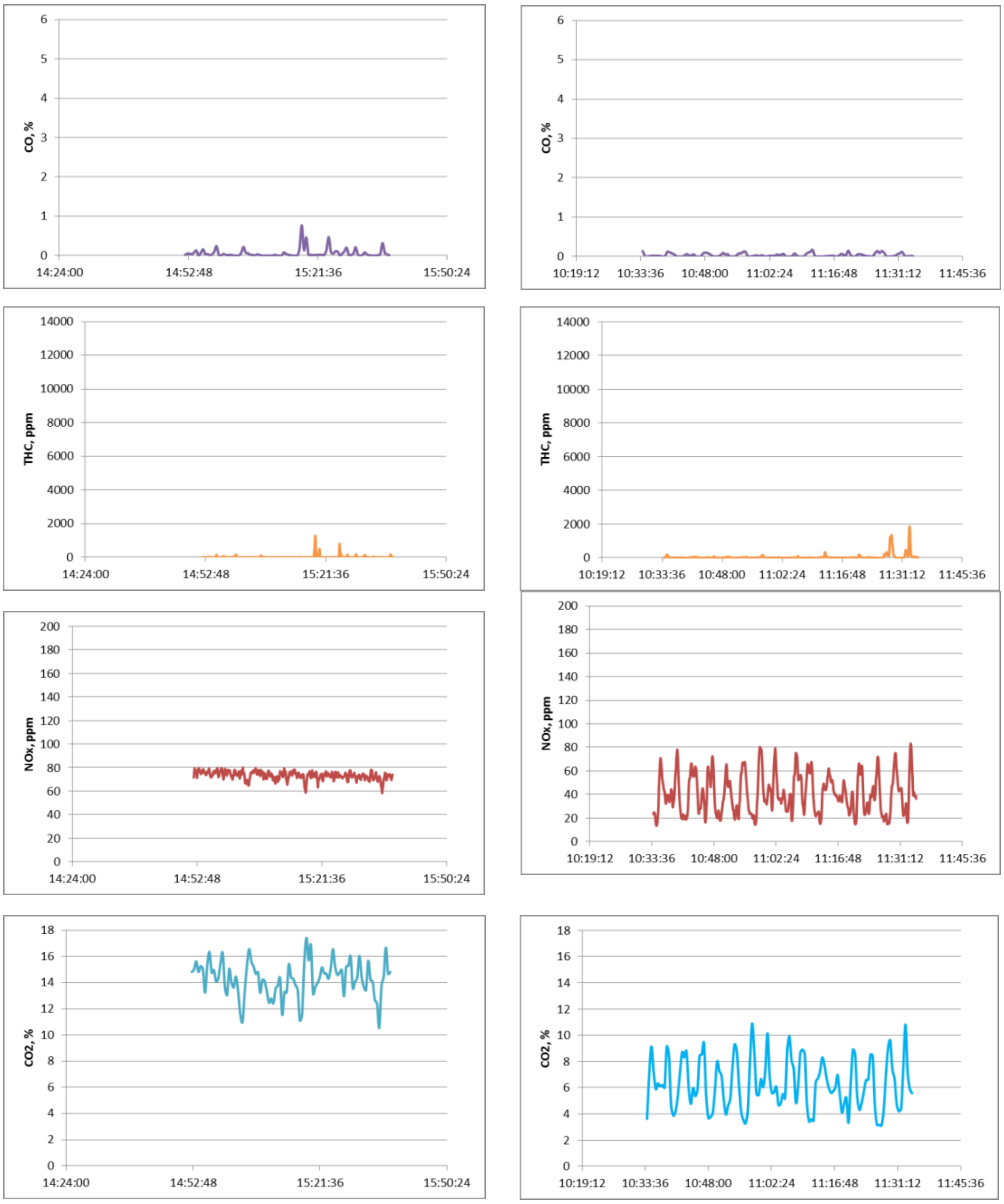


Figure A1.5i Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance E, DIN+, Low Output, Test 2 (left) and Test 3 (right)

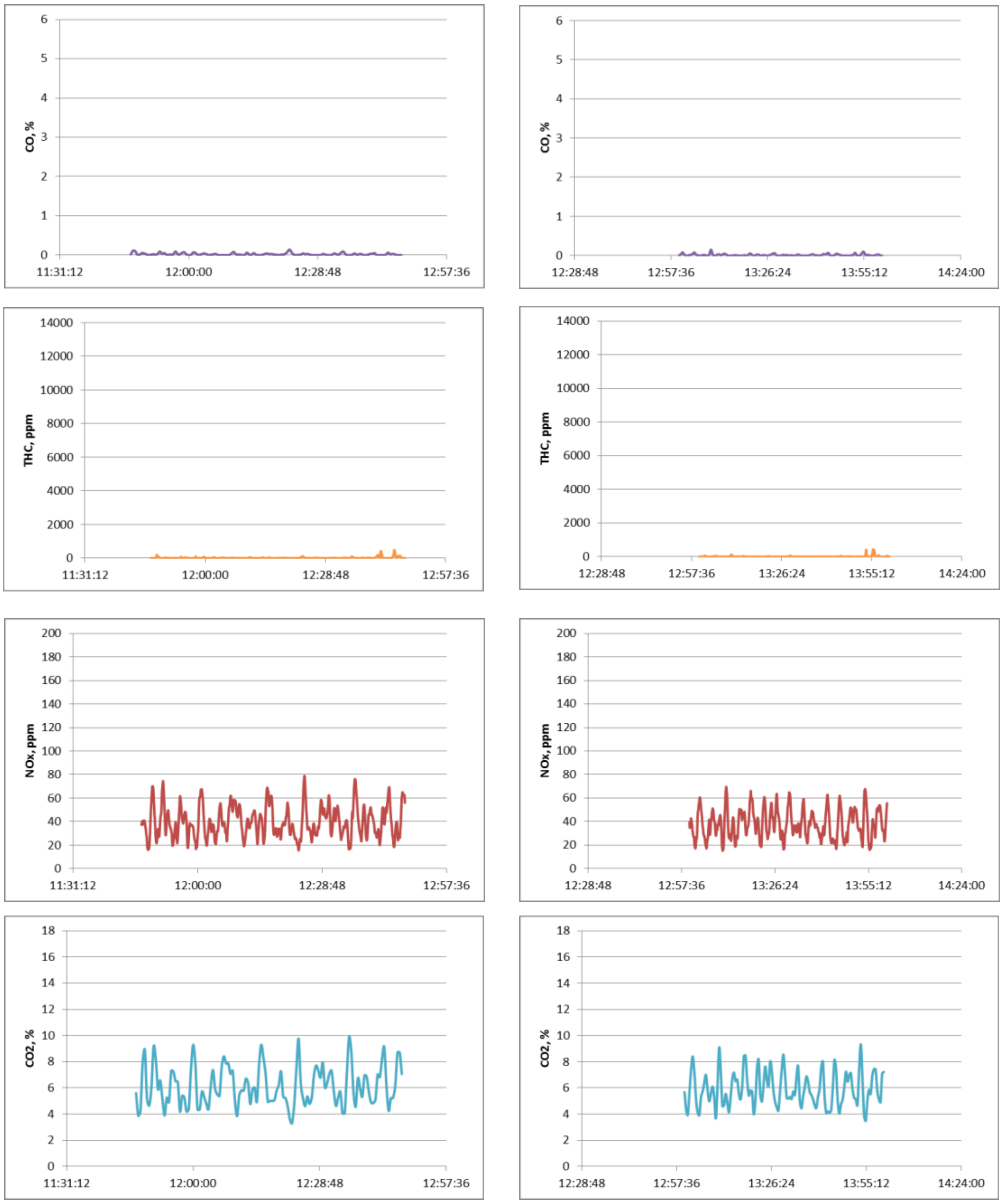


Figure A1.5j Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance E, DIN+, Low Output, Test 4 (left) and Test 5 (right)

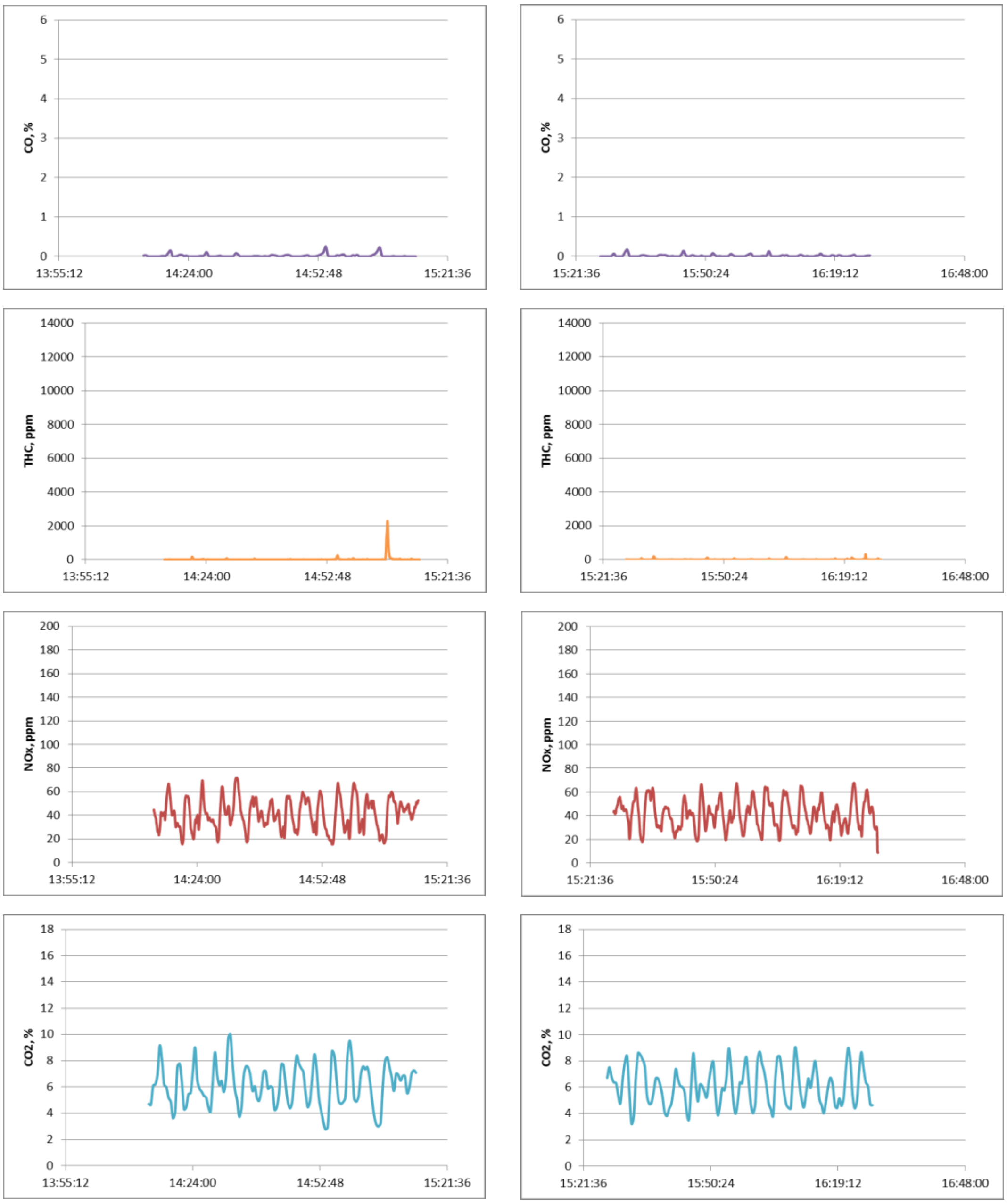


Figure A1.6a Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, ESP, High Output, Test 1 (left) and Test 2 (right)

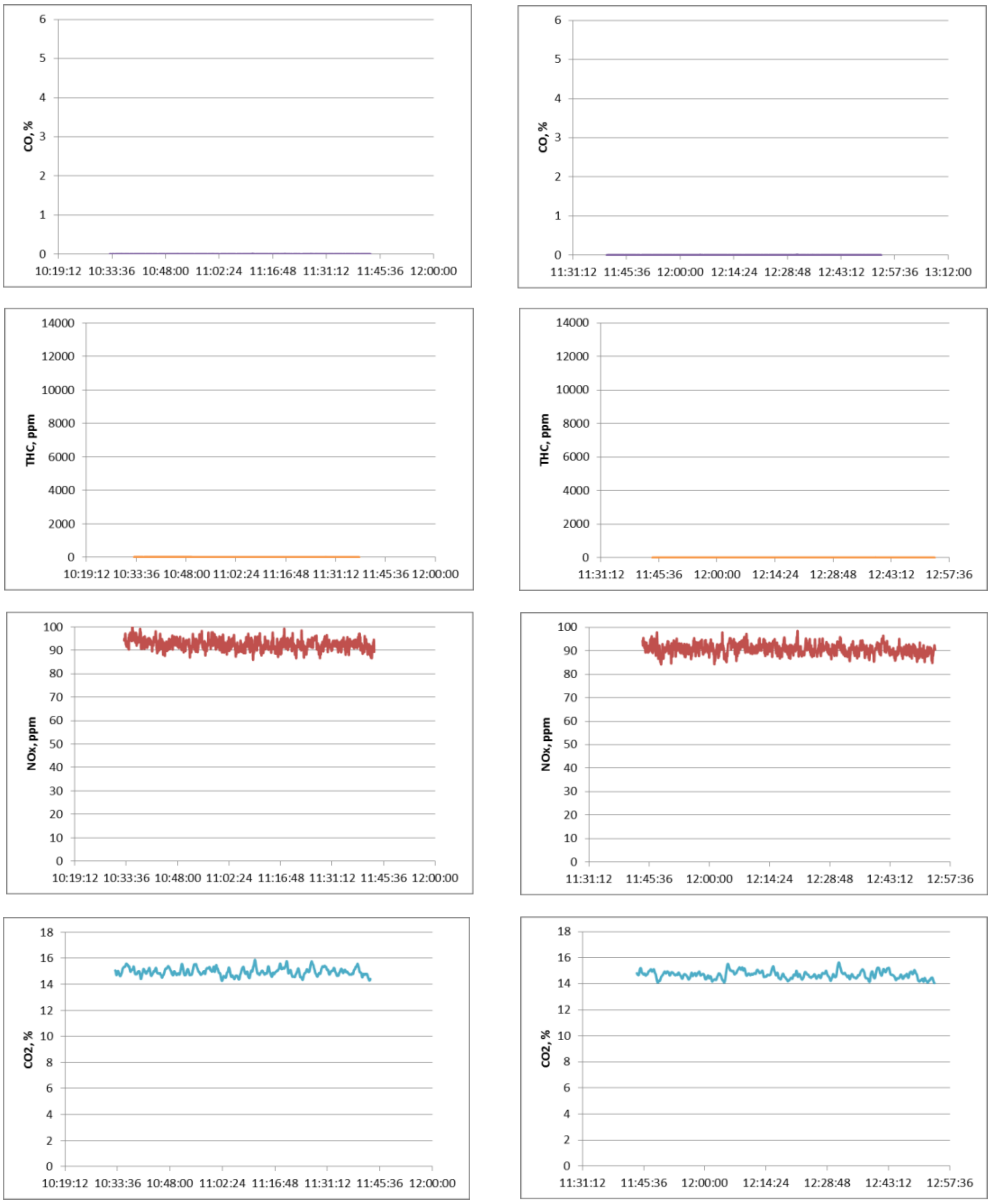


Figure A1.16b Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, ESP, High Output, Test 3 (left) and Test 4 (right)

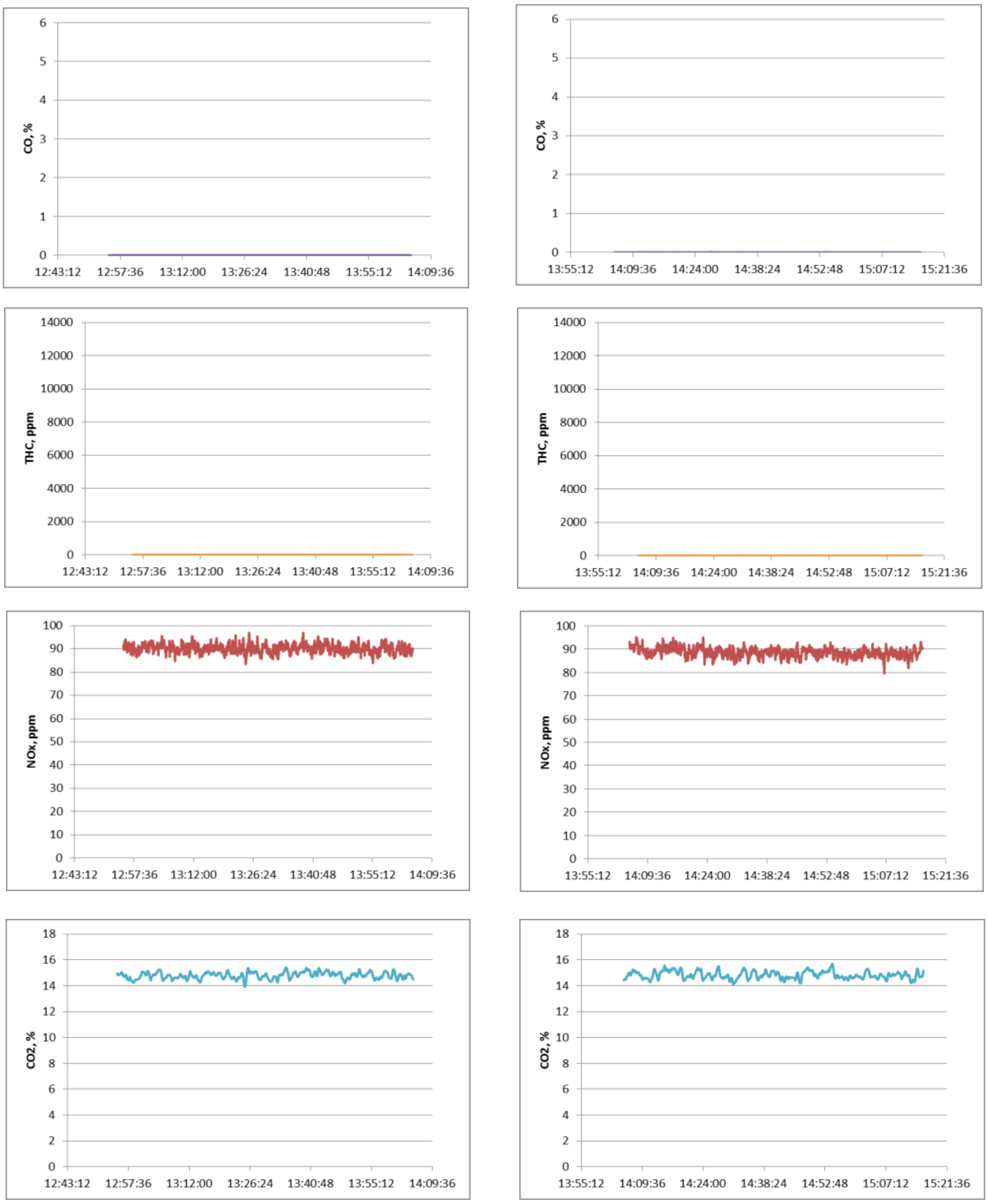


Figure A1.6c Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, ESP, High Output, Test 5 (left) and Low Output, Test 1 (right)

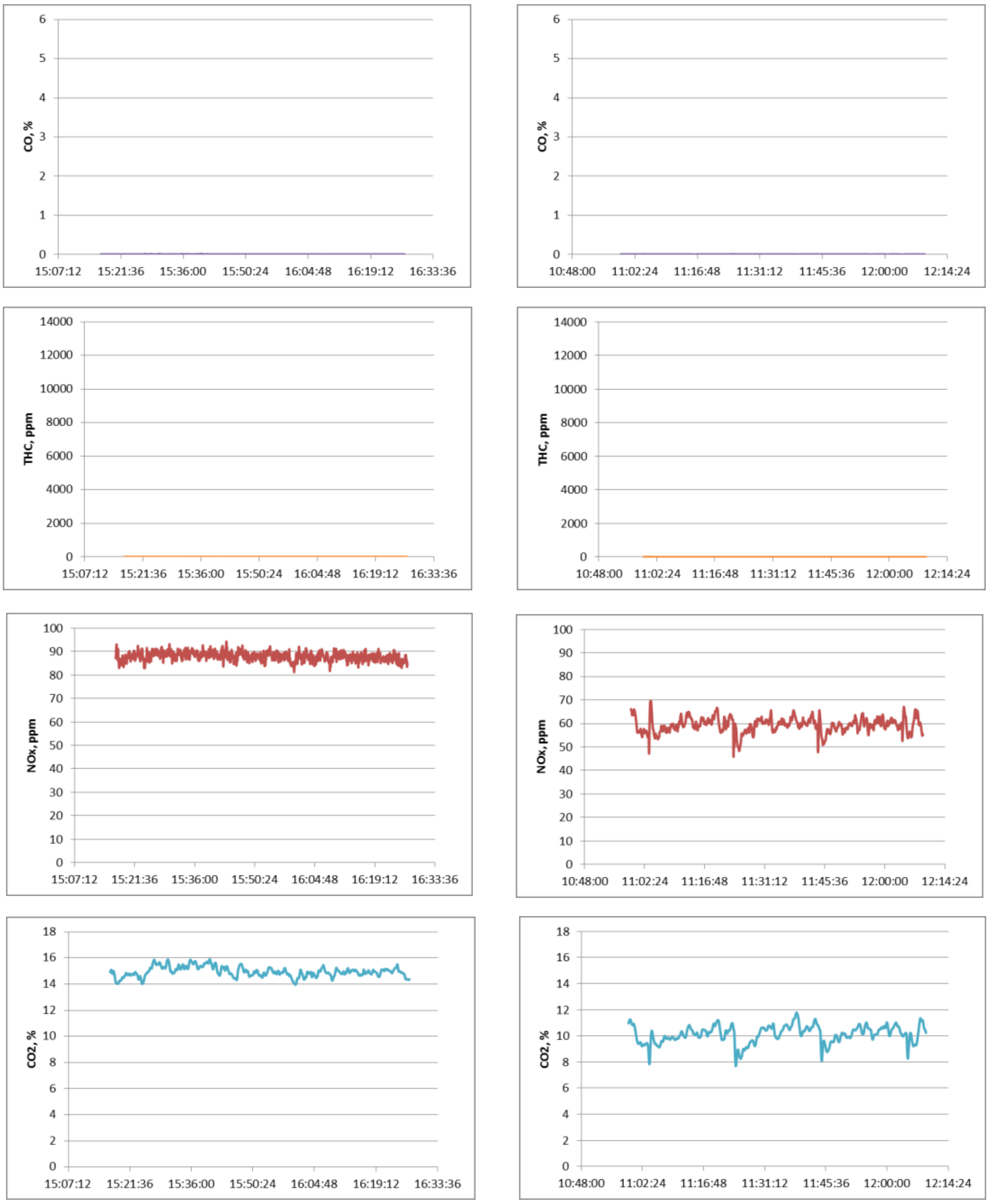


Figure A1.6d Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, ESP, Low Output, Test 2 (left) and Test 3 (right)

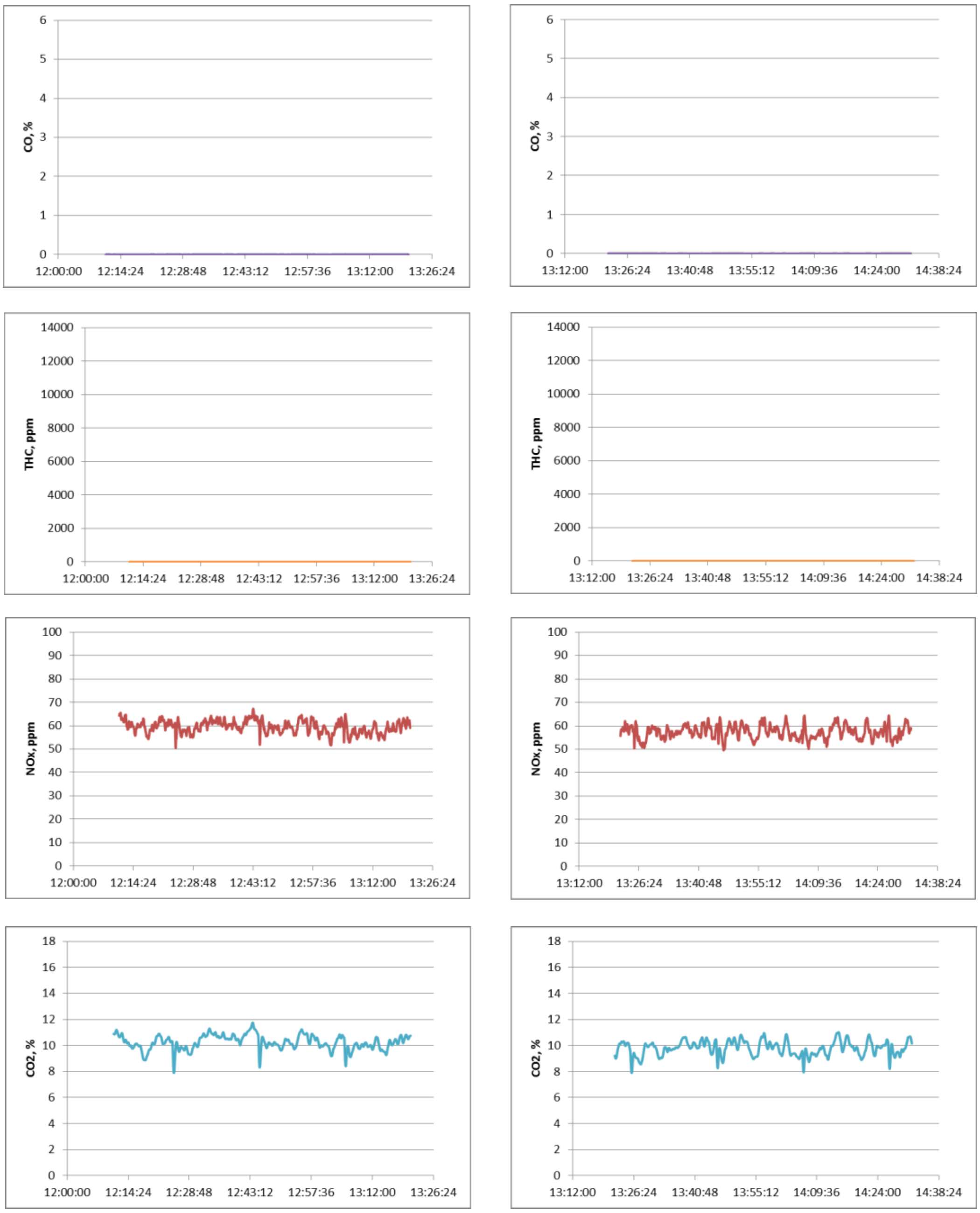


Figure A1.6e Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, ESP, Low Output, Test 4 (left) and Test 5 (right)

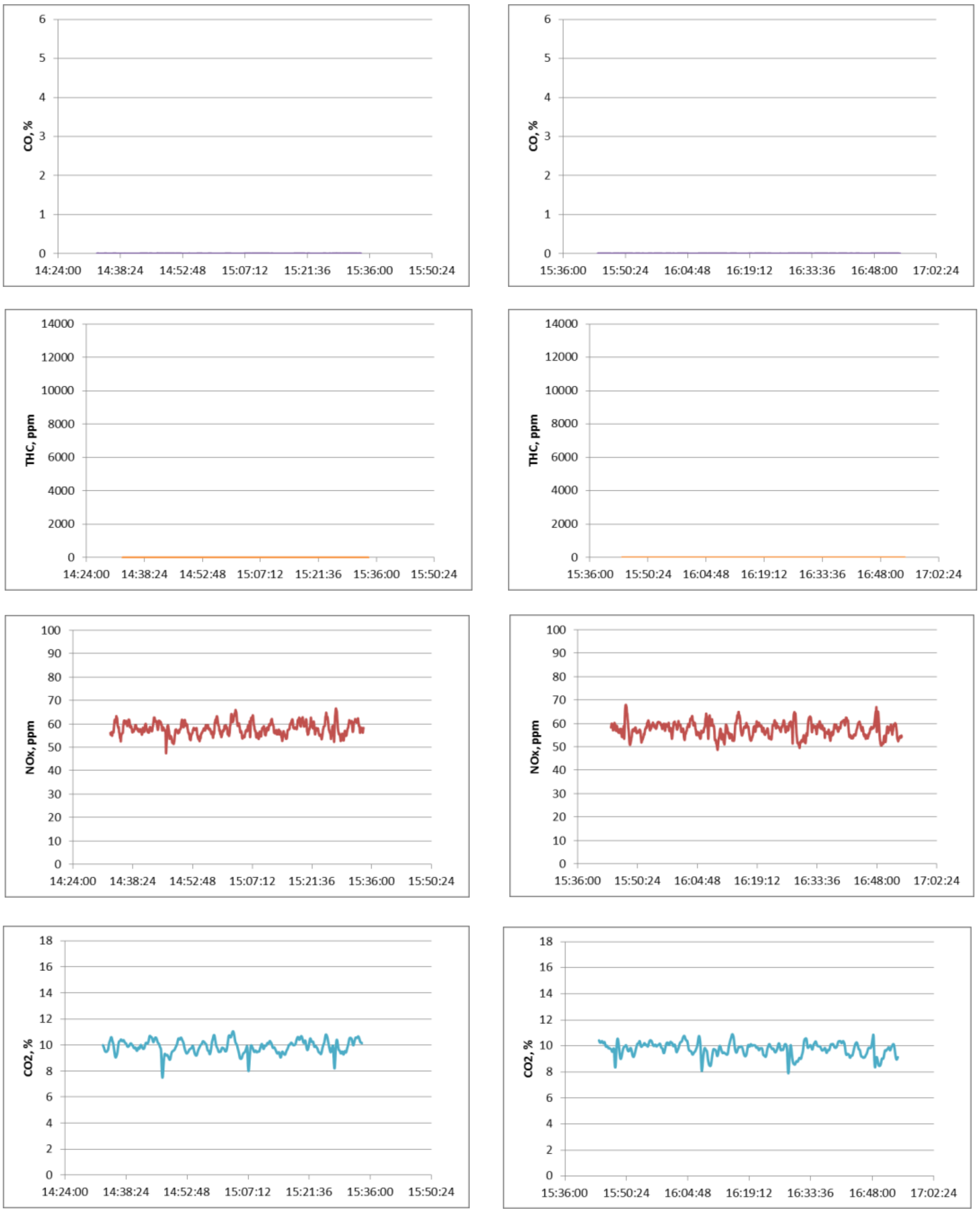


Figure A1.6f Flue gas measurement traces of CO, and CO_2 for Appliance F, DIN+, High Output, Test 1 (left) and Test 2 (right) Note: Equipment problem prevented collection of NOx and THC.

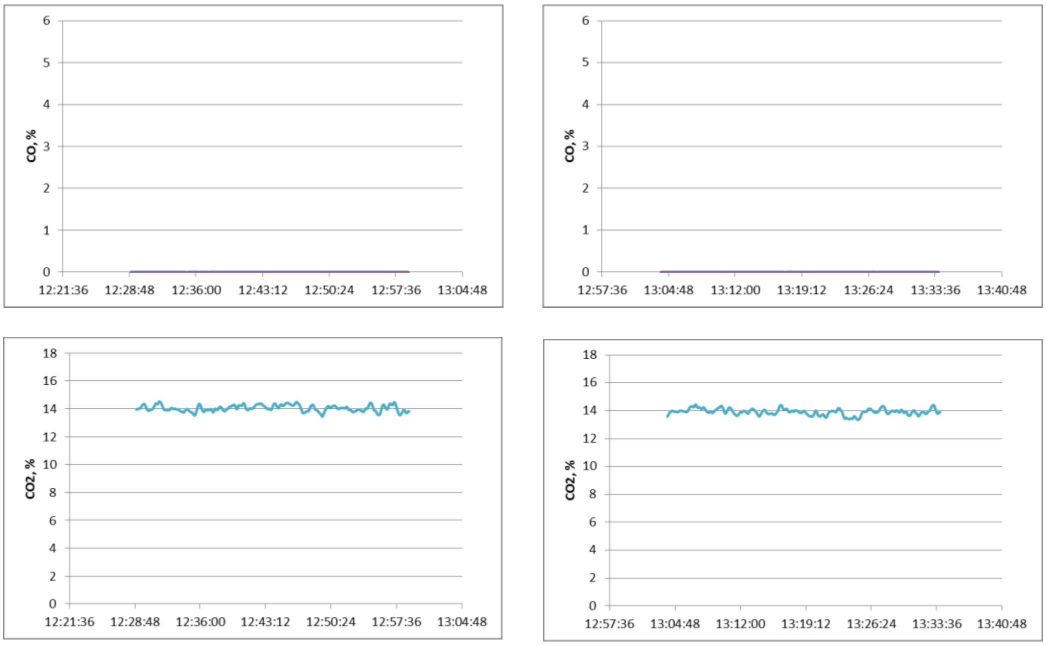


Figure A1.6g Flue gas measurement traces of CO and CO_2 for Appliance F, DIN+, High Output, Test 3 (left) and Test 4 (right) Note: Equipment problem prevented collection of NOx and THC.

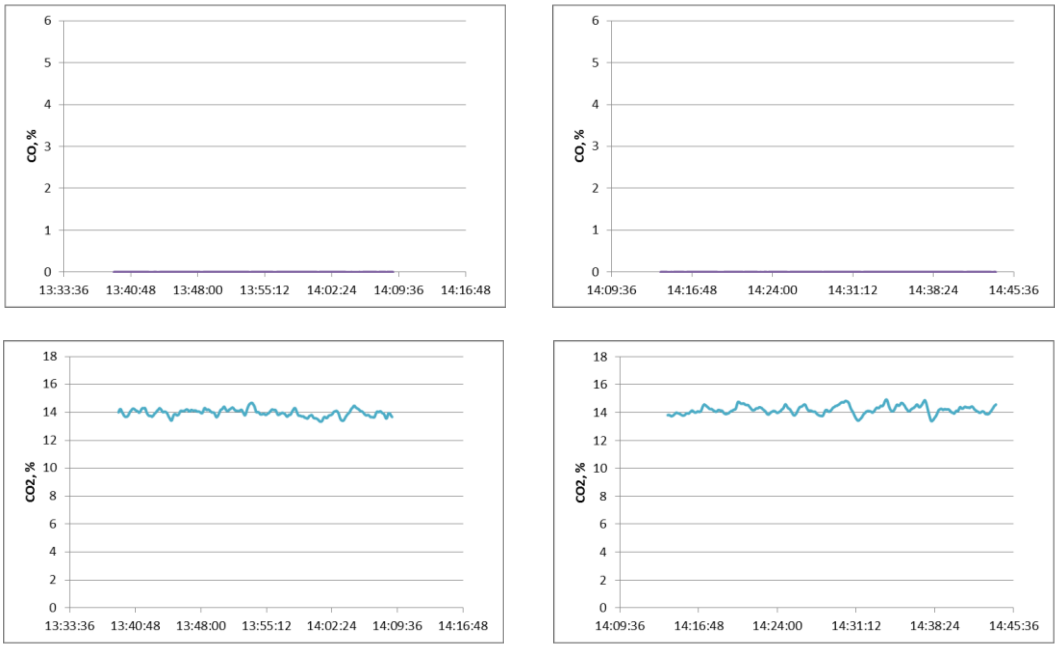


Figure A1.6h Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, DIN+, High Output, Test 5 (left) and Low Output, Test 1 (right)

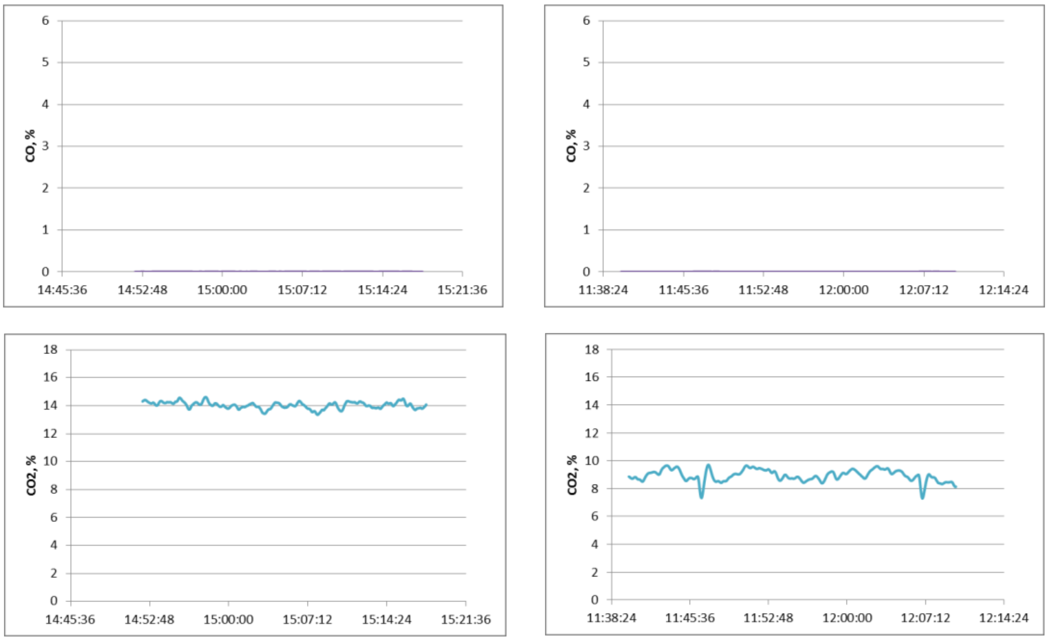


Figure A1.6i Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, DIN+, Low Output, Test 2 (left) and Test 3 (right)

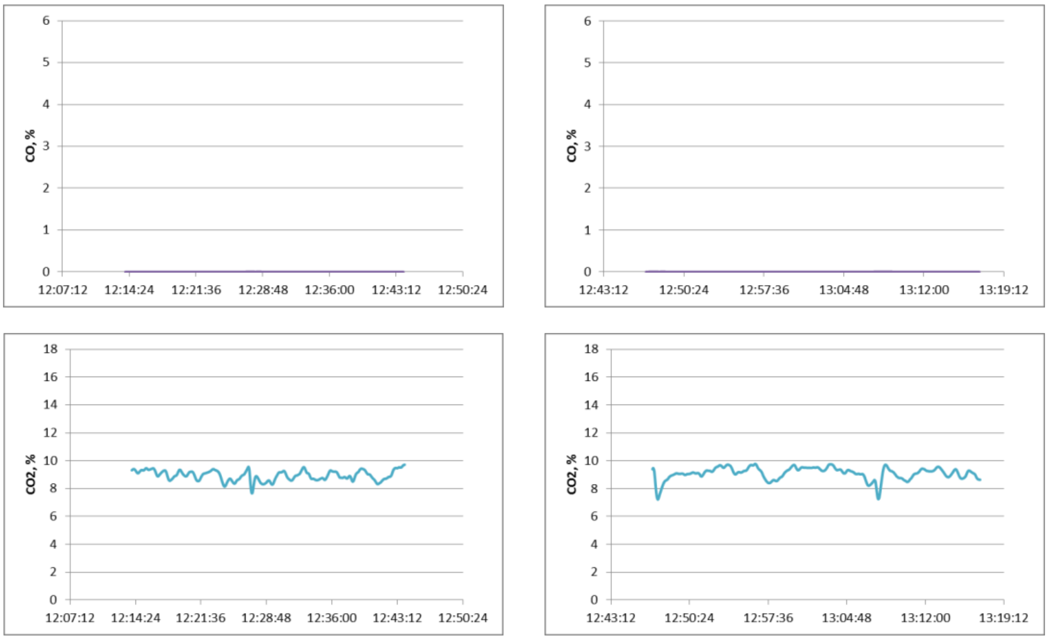


Figure A1.6j Flue gas measurement traces of CO, NOx, THC and CO_2 for Appliance F, DIN+, Low Output, Test 4 (left) and Test 5 (right)

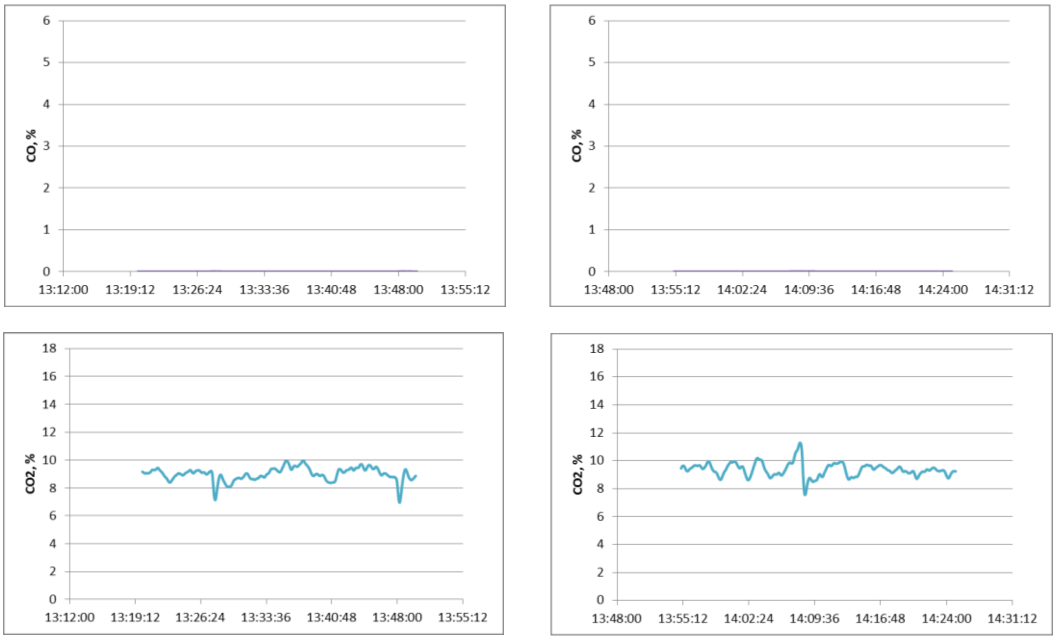


Figure A1.7 Comparison of Particulate emission measurements by Lab 1 from DIN+ 70°C and from FFDT including five repeats each of high and low output conditions, g/GJ

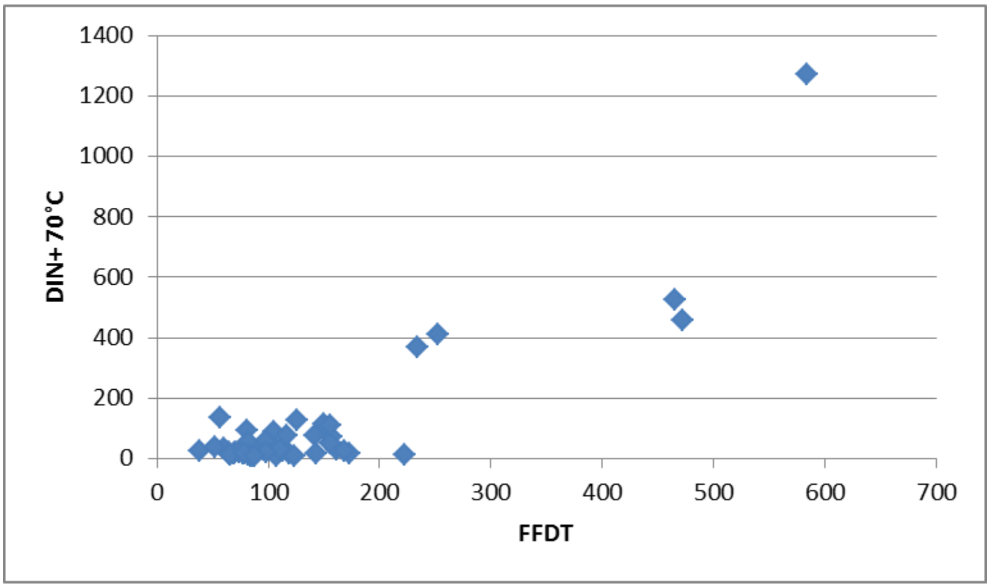


Figure A1.8a Comparison of particulate emission measurements by Lab 2 from DIN+ 70°C and from FFDT including five repeats each of high and low output conditions, g/GJ

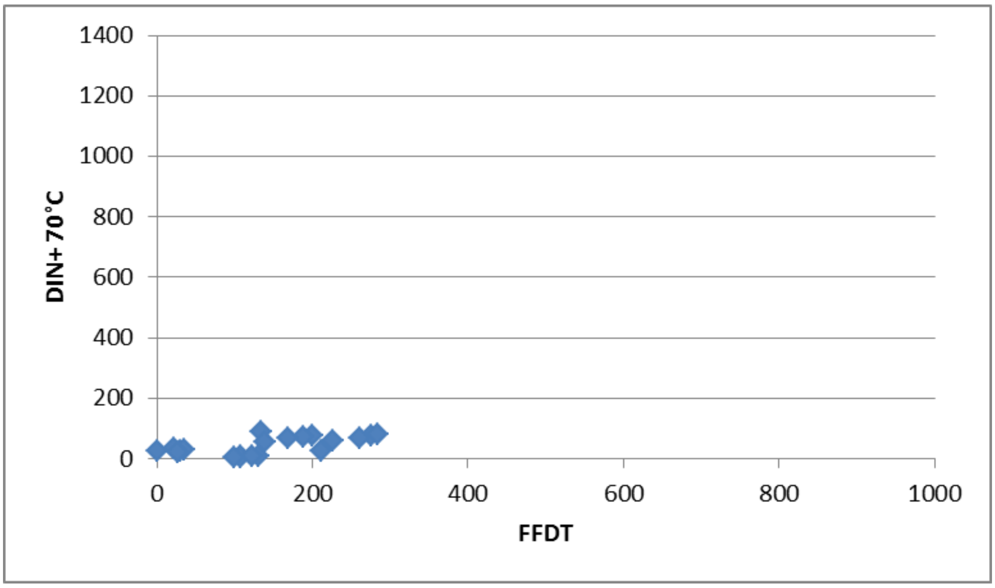
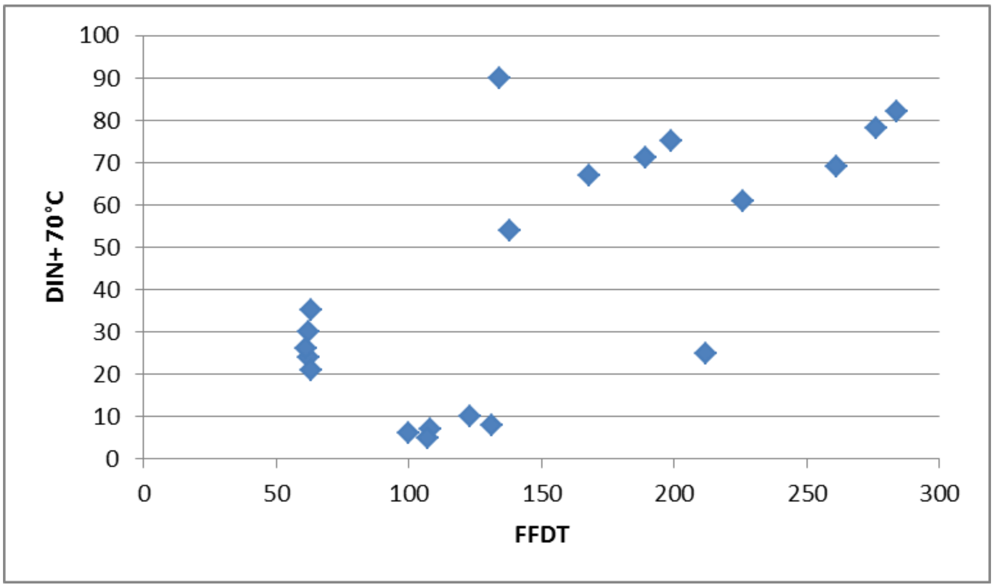


Figure A1.8b Comparison of particulate emission measurements by Lab 2 from DIN+ 70°C and from FFDT including five repeats each of high and low output conditions, g/GJ (contracted scales)



Key for Figures 1.9 to 1.12	Appliance
	A
	B
	C
	D
	E
	F

Figure A1.9 Comparison of particulate emission measurements by Lab 1 from DIN+ 70°C and from ESP including the averages of five repeats each of high and low output conditions, g/GJ

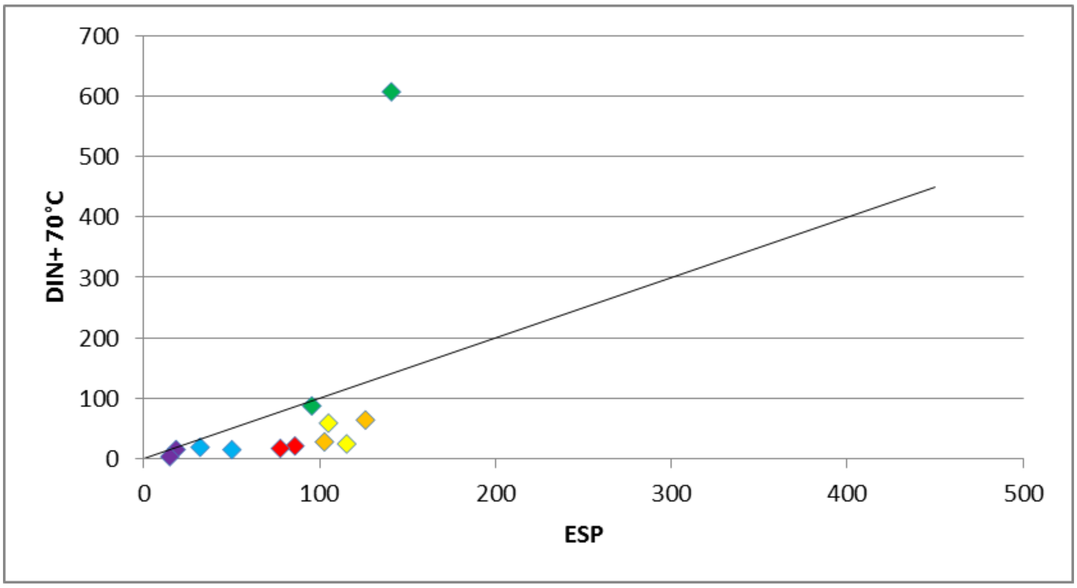
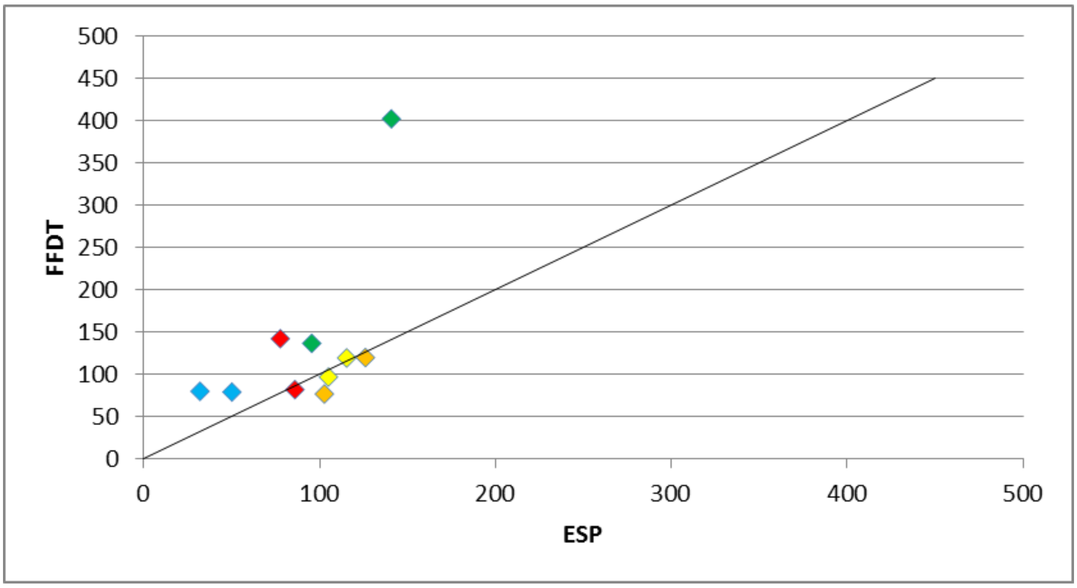
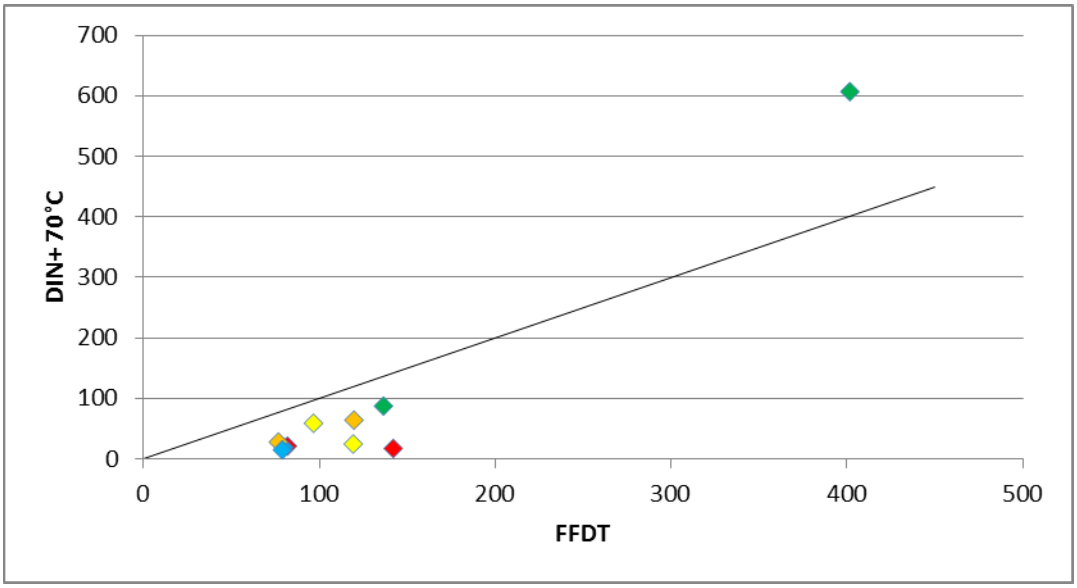


Figure A1.10 Comparison of particulate emission measurements by Lab 1 from FFDT and from ESP including the averages of five repeats each of high and low output conditions, g/GJ



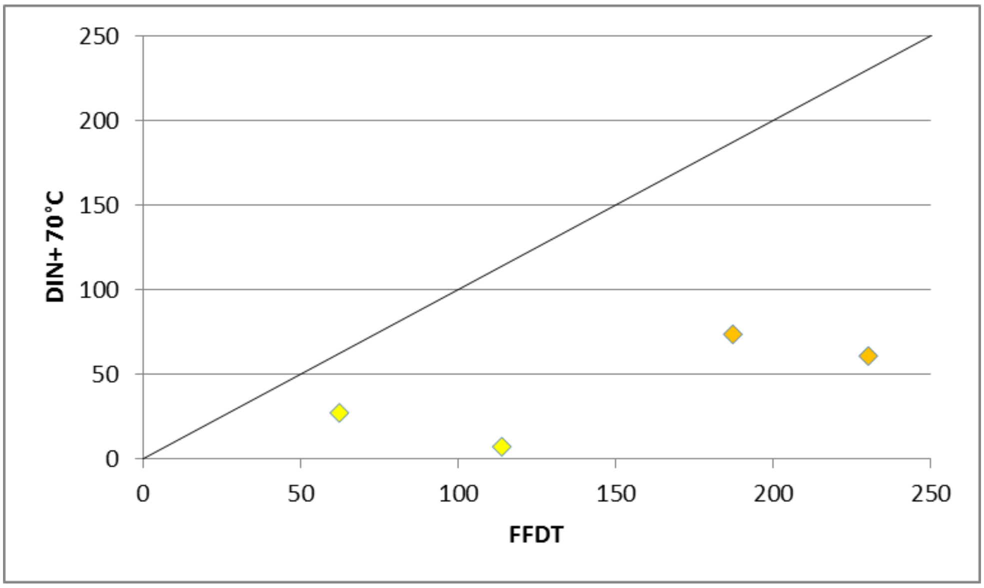
NOTE: Line shows the expected relationship if both techniques accurately measured the same particulate material.

Figure A1.11 Comparison of particulate emission measurements by Lab 1 from DIN+ 70°C and from FFDT including the averages of five repeats each of high and low output conditions, g/GJ



NOTE: Line shows the expected relationship if both techniques accurately measured the same particulate material.

Figure A1.12 Comparison of particulate emission measurements by Lab 2 from DIN+ 70°C and from FFDT including the averages of five repeats each of high and low output conditions, g/GJ

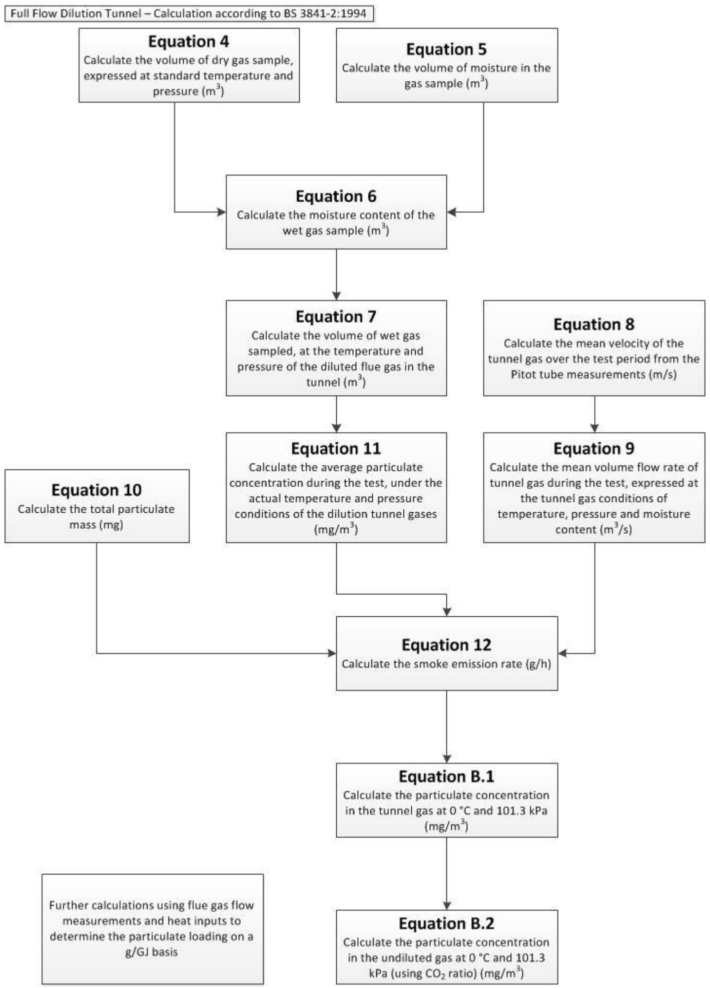


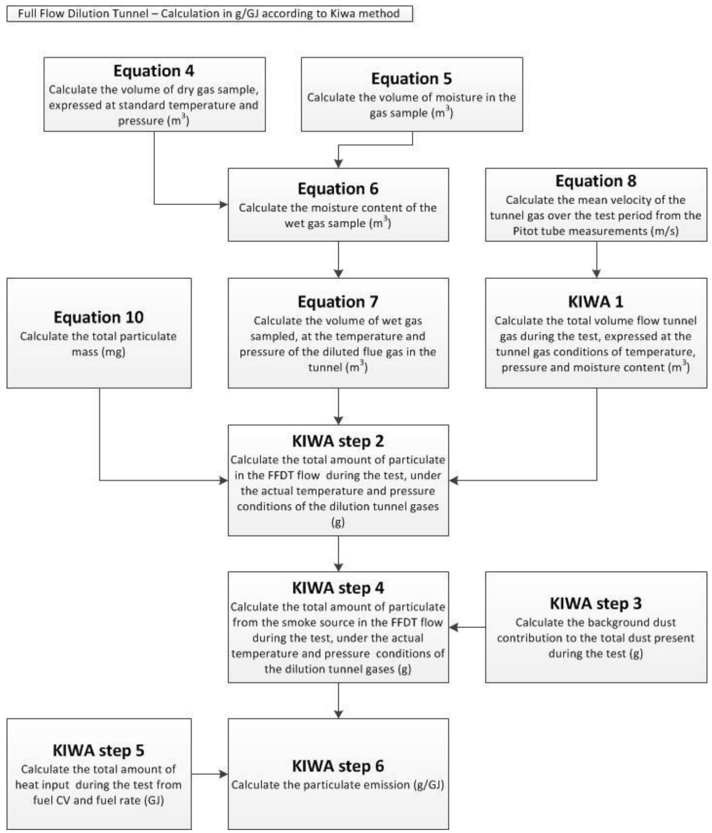
NOTE: Line shows the expected relationship if both techniques accurately measured the same particulate material.

Appendix 2 Summary of particulate measurement Test protocols

Country	Standard	Test outputs & tests					Fuel bed	Draught	Duration	Sampling technique	Expression of emission	Comment
		>Rated	Rated	Medium	Low	Other						
UK	BS3841-2, PD BS 6434	-	5	(5)	5	misuse	Natural	Natural	From refuel to basic firebed.	Electrostatic precipitator or Dilution tunnel	g/hr	Requires output of appliance for assessment against limits. Also continuous indicative monitoring of opacity to assess peaks. Ele precipitator is unique to UK but allows dilution tunnel. Dilution tu approach not as defined as USEPA, Norwegian or Australian me
Germany	VDI, DINplus	-	3	-	-	-	Natural	Fixed	30 minutes starting 3 minutes after refuel	Stack	mg/Nm3	Requires output of appliance for assessment against limits. Out filter with no filter specification and, no collection of material colle probe , Near-isokinetic sampling, fixed volume of exhaust gas
Norway	NS3058/ 3059	1	1	1	1	-	Test crib	Natural	From refuel to basic firebed	Dilution tunnel	g/kg	Very similar to USEPA procedure and test facility. Up to 4 burn r (defined by appliance output/size) aggregated into a single emiss Dual high efficiency filters held at constant temperature to captur Nordic Swan criteria are at low and high output and can be asses individual burn rates.
USA Canada	USEPA Method 5G, Method 28	1	1	1	1	-	Test crib	Natural	From refuel to basic firebed	Dilution tunnel	g/hr	Up to 4 burn rates aggregated into a single emission rate. Dual h efficiency filters held at constant temperature to capture PM.
	USEPA Method 5H, Method 28	1	1	1	1		Test crib	Natural	From refuel to basic firebed	Stack	g/hr	Method uses high efficiency filter at fixed temperature external to backed up by chilled condensable sampling train and final low te high efficiency filter. Material in probe also recovered.
Australia New Zealand	AS/NZS 4013, 4012	-	3	3	3	-	Natural	Natural	From refuel to basic firebed	Dilution tunnel	g/kg	Multiple tests at 3 burn rates. Dual high efficiency filters held at c temperature to capture PM.

Appendix 3 FFDT calculation comparison





Appendix 4 Lab 1 DIN+ method statement

TEST EQUIPMENT USED	Equipment Number	Calibration Status	
Test Rig	FAT		
Data logger (PC)	FAT		
Squirrel logger	FAT		
Flue gas analyser (NO_2)	FAT	Span before test	
Flue gas analyser (C_xH_y)	FAT		
Heated filter box (set to 70°C)	FAT		
Pumped gas flow temp	FAT		
Heated filter box temp	FAT		
Gas meter	FAT		
Stop watch	FAT		
Scales for filters	FAT		

Note: Ensure that equipment has valid calibration status before starting test.

1. <u>METHOD</u>

1 The DINplus testing for particulates, NOx and hydrocarbons is carried out concurrent to the efficiency and nominal heat output test conducted as described in BS EN12809, 12815,13229, 13240, 14785 and 303-5. The DINplus methodology follows that outlined in DD CEN/TS 15883:2009 and a DIN CERTCO document available from TÜV Rheinland, dated June 2008. (There will be an accompanying test sheet – with the same test number – for the efficiency and nominal heat output test).

2 Span the NOx and hydrocarbon analysers and connect NOx and hydrocarbon to the Channels 11 and 12, respectively, of the Squirrel logger. Ensure that the ranges for the analysers are set to 10000 ppm for hydrocarbons and 400 ppm for NOx, and that the Squirrel ranges are set to 20 volts.

3 On lighting the appliance, ensure that the heaters for the line and filter housing are switched on.

4 Ensure that the thermocouple measuring the suction flow temperature is connected to a channel of the Pico logger

5 Prior to conducting first test in the series, take reading of gas meter, turn on suction pump and operate for 15 minutes exactly. Record gas meter reading at the end of this pre-test period and determine total gas volume used. Check if volume is between 0.140 and 0.150 m^3 (as measured). If readings are outside range, then pump speed should be adjusted as necessary and the procedure repeated for as many times as necessary. Use table below to record information.

Gas meter reading – end m^3						
Gas meter reading – start m^3						
Total gas volume m^3						

6 Weigh at least three filters (having been dried at 105°C for at least an hour and then stored in a desiccator for at least 4 hous).

7 Check that the filter housing is 70°C and heated line is 150°C. Then insert first filter.

8 Immediately prior to the first test in the series, insert dust sample probe (ensuring that it is correctly positioned) and connect heated line.

9 Three minutes after refuelling from the start of the test, switch on pump and simultaneously record the reading on the gas meter.

10 After 30 minutes, immediately turn off pump and record the reading on the gas meter. Determine total volume flow and approximate temperature of the suction gas. Calculate total flow corrected to NTP. If total flow is 270 +/- 5% litres , ie 256.5 – 283.5 litres, then test is valid.

11 Carefully remove filter and place in labelled petri dish. Put in drying oven at 105°C for at least one hour and store for at least 4 hours in a desiccator.

12 Weigh filter and dish

13 Repeat steps 9 – 12 for each test.

14 During a test make note of a spot sample of the analyser and Squrrel readings

	Analyser (ppm)	Squirrel (V)
NOx Channel 11		
HCs Channel 12		

15 At the end of the series of tests, remove/disconnect the dust sample probe and heated line. Rinse with acetone, collecting the washings in a tared aluminium tray. Allow the washings to evaporate at ambient temperature and record the weight of the tray and residue.

5. **<u>TEST PERIOD</u> Ensure logger is on before starting the test.**

			Test 1	Test 2	Test 3	Test 4
Filter number						
Mass filter, with support (before test)		g				
Mass filter, with support (after test)		g				
Mass gain **(A)**		g				
Washings	Mass tray + washings	g				
	Mass tray	g				
	Mass washings	g				
	Mass washings per test **(B)**	g				
Total mass gain (A + B)		g				
Clock time - Start						
Clock time - End						
Gas meter reading – end		m^3				
Gas meter reading – start		m^3				
Total gas volume		m^3				
Temperature flow gas (approx.)		°C				
Total flow (to 0°C) (approx.)#		litres				
Valid test? (Between 256.5 & 283.5 litres)						
Actual temp of flow gas*		°C				
Av.**CO_2 or O_2** in flow gas (during sampling period)* Delete as appropriate		%				

\# Corrected total flow = Total flow x (273)/(273+Temp flow)

***** from prn files

6. TEST RESULTS

The NOx, and CxHy logger data for each refuelling / efficiency period shall be copied to the Excel spreadsheet at N/SFAP/DINplusdatacollate.xls. For the purposes of reporting the NOx and CxHy and emissions, the final test results must also be processed using the spreadsheet at N/SFAP/DINplusdatacollate.xls.

For the purposes of reporting the particulate emissions, the final test results must be processed using the spreadsheet at N/SFAP/DINplus.xls. Note that the average oxygen or CO_2 contents used in the calculations are obtained from the separate spreadsheet used to determine the output and efficiency. A separate spreadsheet also applies for the temperature of the flow gas for the particulates.

For the particulate measurements, the thirty minute period of each particulate test should be highlighted in the oxygen (or CO_2) and flow gas temperature columns and the average values noted (from the bottom right of the screen)

Obtain printouts of test results. All printouts must be retained and filed with this document.

7. SUMMARISED TEST RESULTS

Parameter		**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Mean**
Mean CxHy emission	ppm					
Mean NOx emission	ppm					
Particulate emission	mg/Nm^3					

COMMENTS

Appendix 5 Lab 3 DIN+ method statement

Particulate Measurement

The particle test method applied in the tests corresponds to the method as described in CEN TS 15883:2009, Annex A.1 "Austrian and German particle test methods"

The test apparatus used for the measurement works with a filter made of ceramic fibre. The filter intake is heated to 70°C, the sampling line gives possibility to adjust the flue gas temperature in the limits as described in CEN TS 15883, Annex A1.2. The dimensions of the sampling probe are in line with the description in CEN TS 15883, Annex A1.2.

Sequence of measurement

- drying of unloaded filter at 105°C, weighing with an accuracy of 0.2 mg
- installation of filter at probe intake and fixation
- start measurement 3 minutes after loading of fuel
- duration of measurement 30 minutes with a flow corresponding to an extraction volume of 270 l at 273 K and 1013 hPa
- removal of filter from intake and storage in filter container
- drying of loaded filter at 105°C weighing with an accuracy of 0.2 mg
- calculation of difference in weight and relation to the actual value for the extraction volume

Appendix 6 Inter-laboratory comparison test results

Figure A6.1 Comparison of the results for particulate emission measured by FFDT method at two laboratories

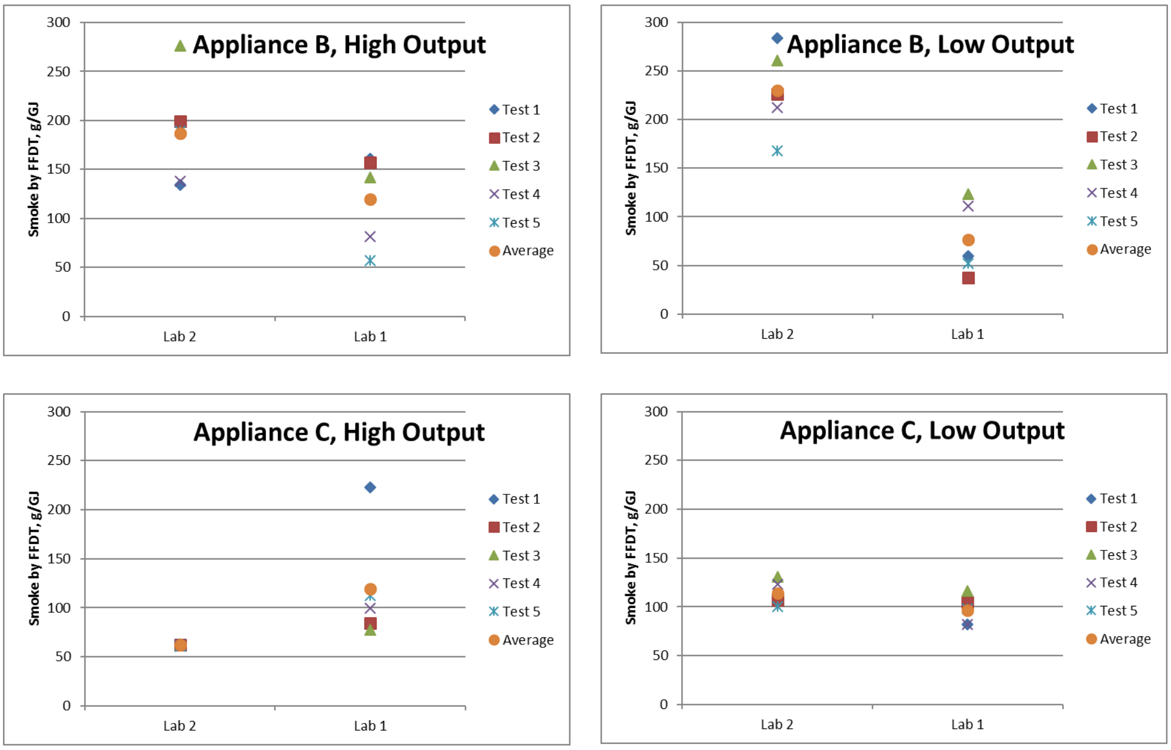
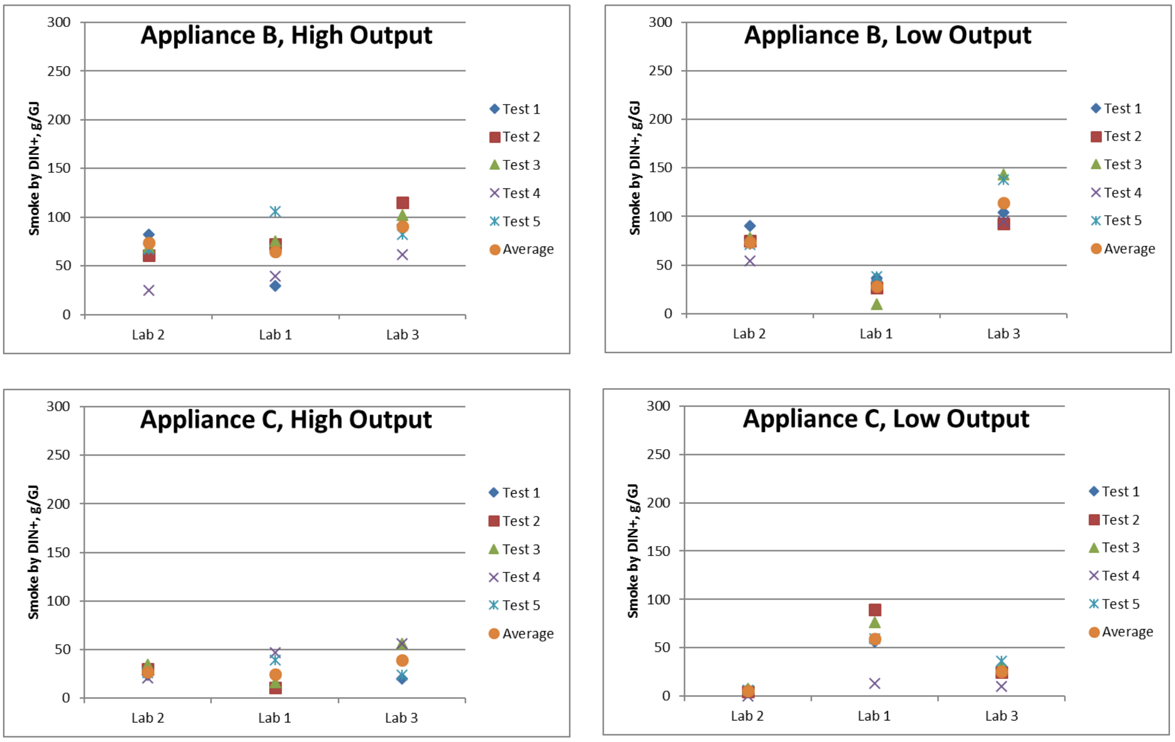


Figure A6.2 Comparison of the results for particulate emission measured by DIN+ method at three laboratories



Appendix 7 Application of proposed relationship between FFDT and DIN+/THC measurements (based on measurements in mg/m^3 @ 13%O_2)

Table A7.1 Lab 1 results in mg/m^3 13%O_2

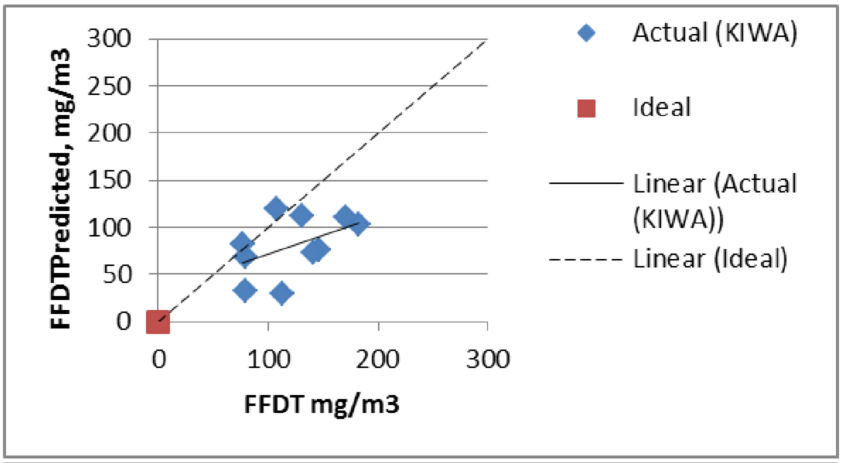
Appliance	Output	THC	FFDT	DIN+ 70	$FFDT_{Predicted}$
A	High	172	131	40	113
		22	80	24	33
		120	80	18	69
		131	77	27	82
		217	108	28	119
	Low	132	146	21	76
		42	114	12	30
		189	183	24	103
		126	141	19	72
		188	171	32	111
B	High	529	225	38	260
		397	191	91	257
		393	178	95	260
		215	105	49	140
		130	85	133	187
	Low	373	94	46	202
		207	64	34	121
		878	145	13	382
		850	106	38	395
		516	59	48	265
C	High	105	101	14	58
		230	128	13	110
		103	134	20	64
		286	36	59	179
		216	132	49	140
	Low	116	300	71	119
		148	124	113	175
		377	128	96	255
		19.9	125	17	25
		252	154	75	181
D	High	1253	286	65	592
		897	297	137	513
		574	193	40	281
	Low	1593	815	651	1320
		1745	1131	1566	2299
		974	504	457	866
		1057	503	507	951
E	High	2	66	33	34
		3	80	12	13
		4	80	35	37
		9	74	35	39
		5	85	38	40
	Low	7	67	30	33
		4	52	27	29
		3	45	18	19
		5	52	22	25
		5	61	15	17

Table A7.1 Lab 2 results in mg/m^3 13%O_2

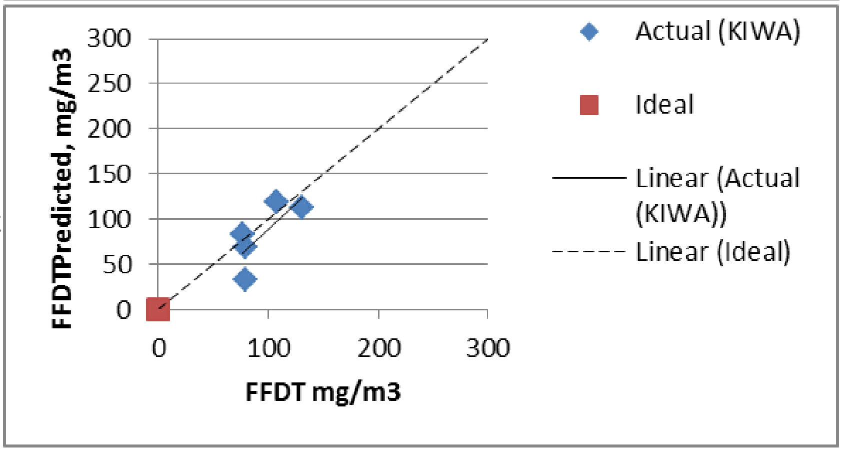
Appliance	Output	THC	FFDT	DIN+ 70	$FFDT_{Predicted}$
B	High	323	205	139	275
		334	304	114	254
		368	428	121	276
		183	209	82	159
		286	289	109	229
	Low	762	452	131	451
		587	358	97	344
		643	411	108	378
		569	262	104	343
C	High	279	93	35	152
		151	94	45	108
		209	95	52	140
		218	94	32	124
		368	93	39	194
	Low	47	166	11	31
		102	161	7	50
		137	199	12	70
		130	189	15	70
		157	154	10	76

Figure A7.1a Appliance A – Lab 1 tests

High and Low Output



High Output



Low Output

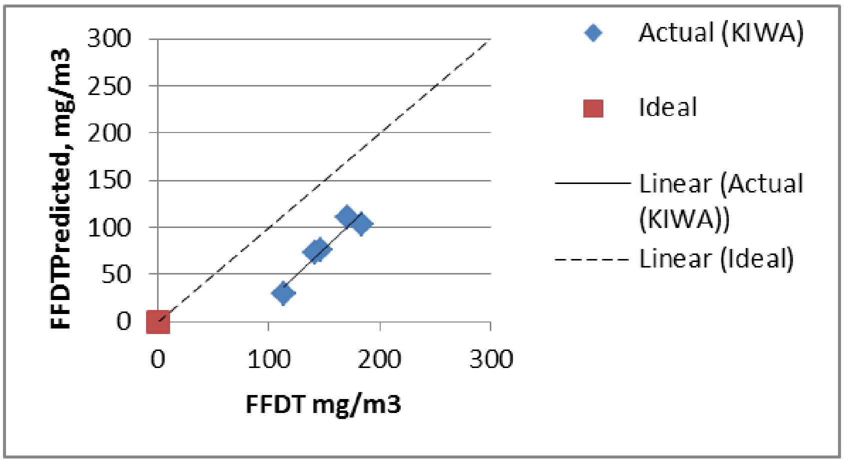
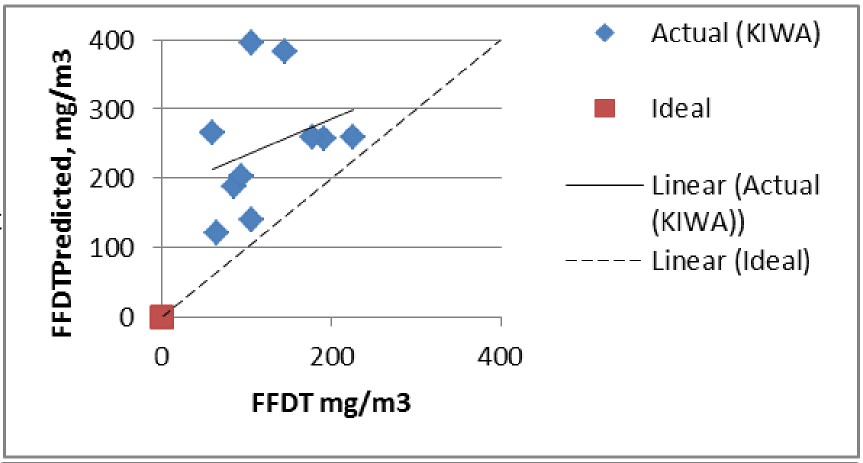
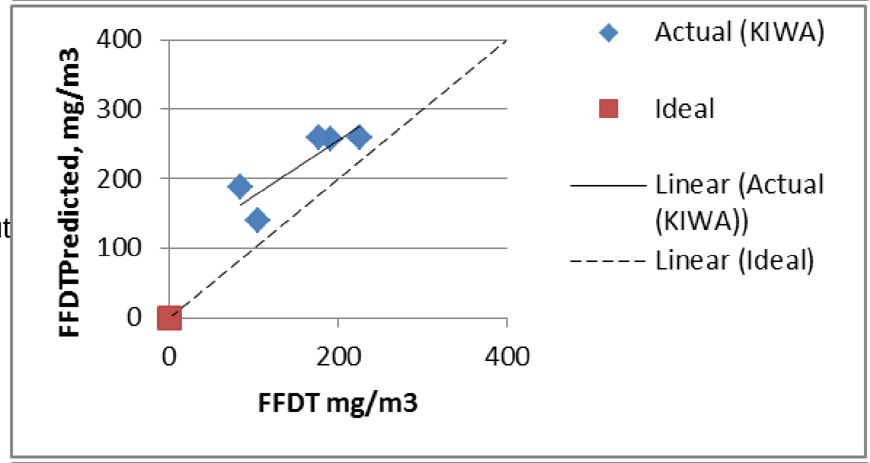


Figure A7.1b Appliance B

High and Low Output



High Output



Low Output

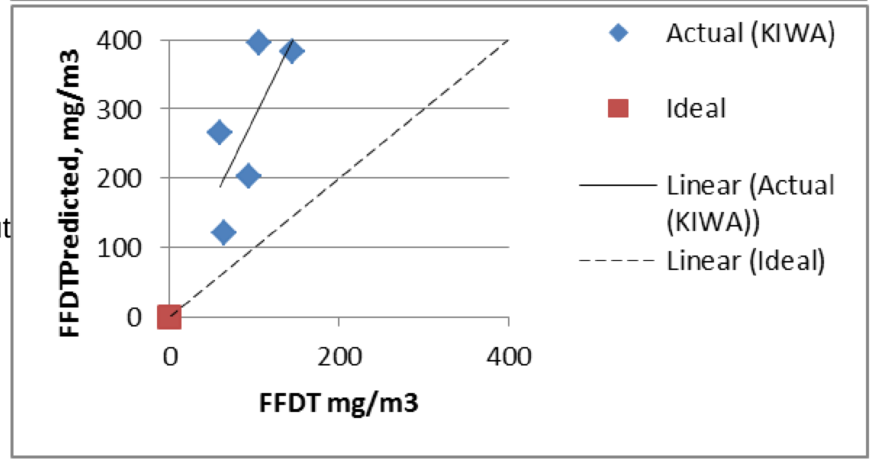
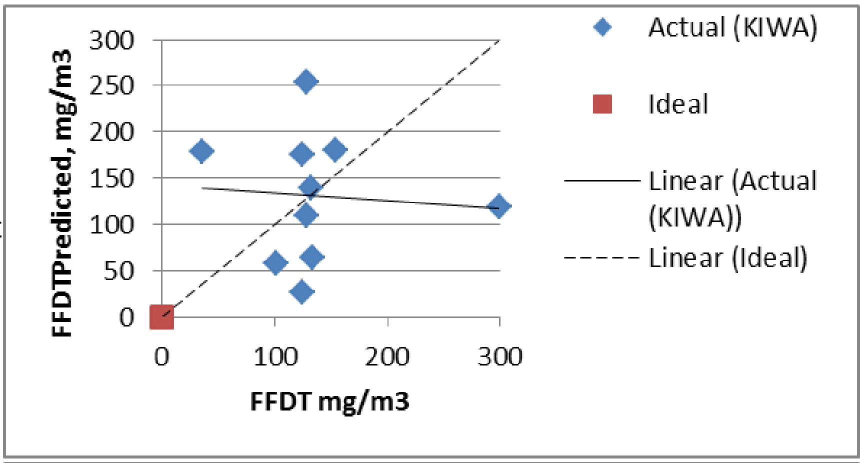
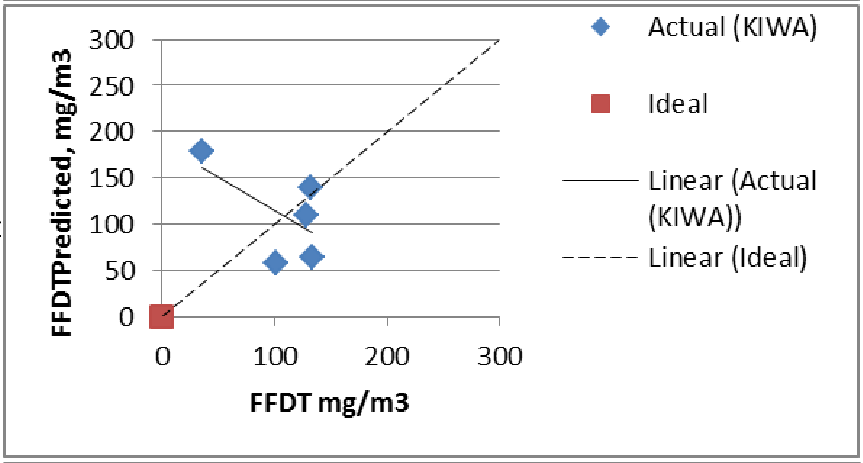


Figure A7.1c Appliance C – Lab 1 tests

High and Low Output



High Output



Low Output

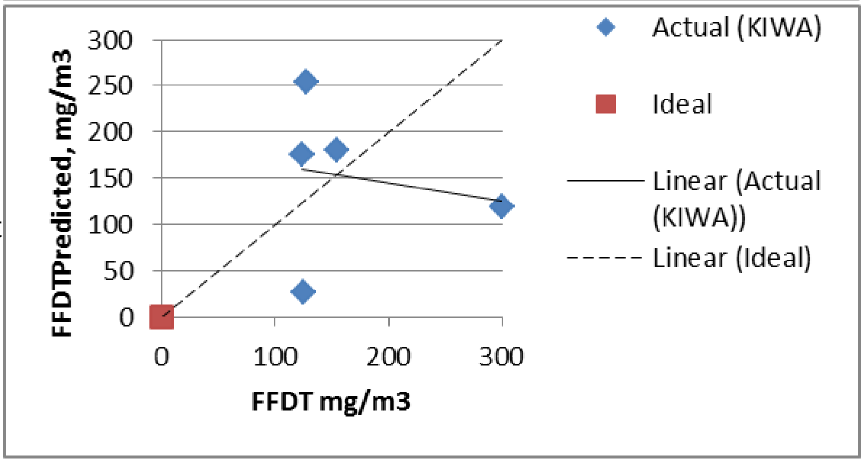
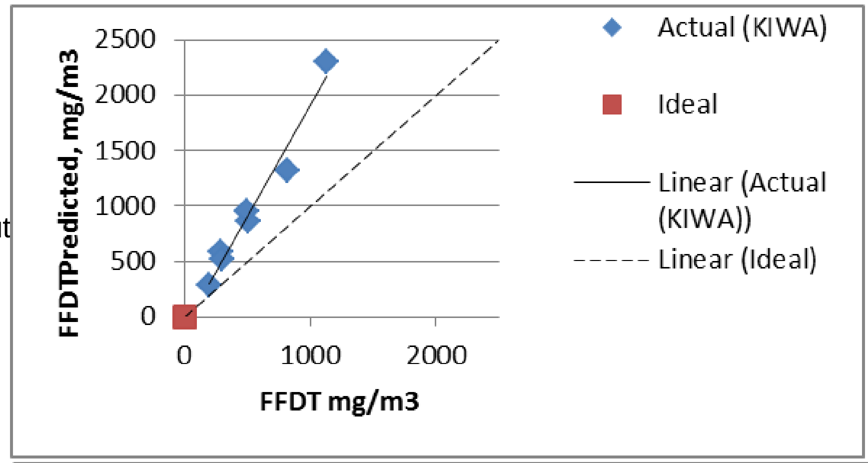
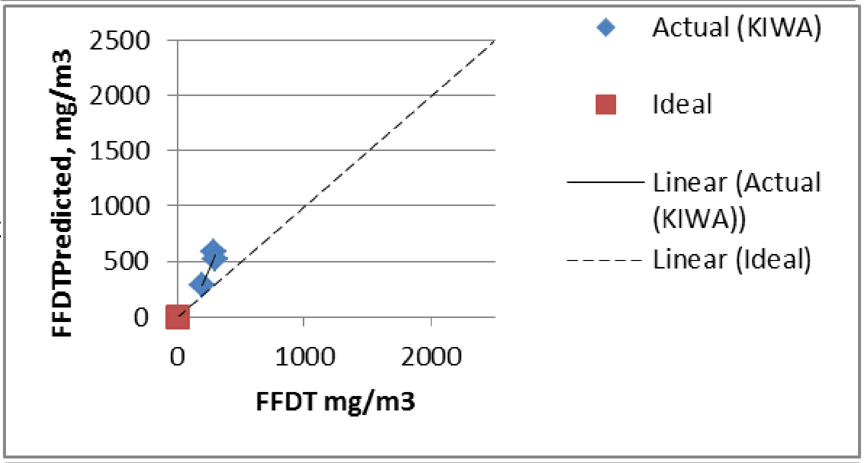


Figure A7.1d Appliance D – Lab 1 tests

High and Low Output



High Output



Low Output

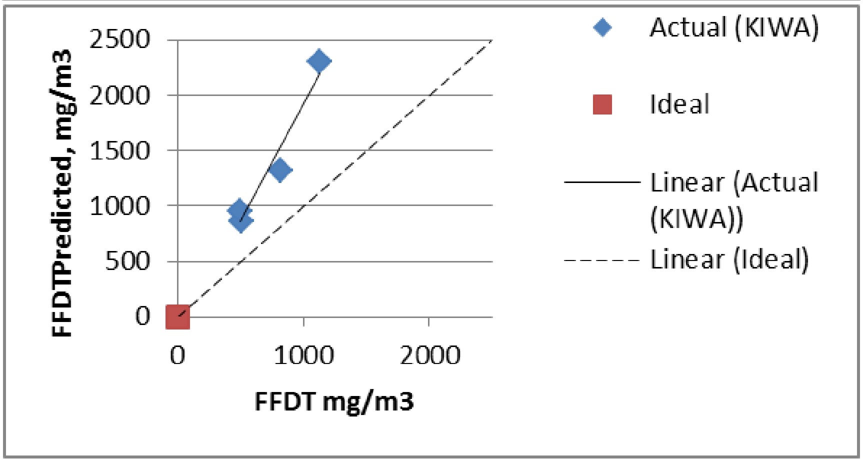
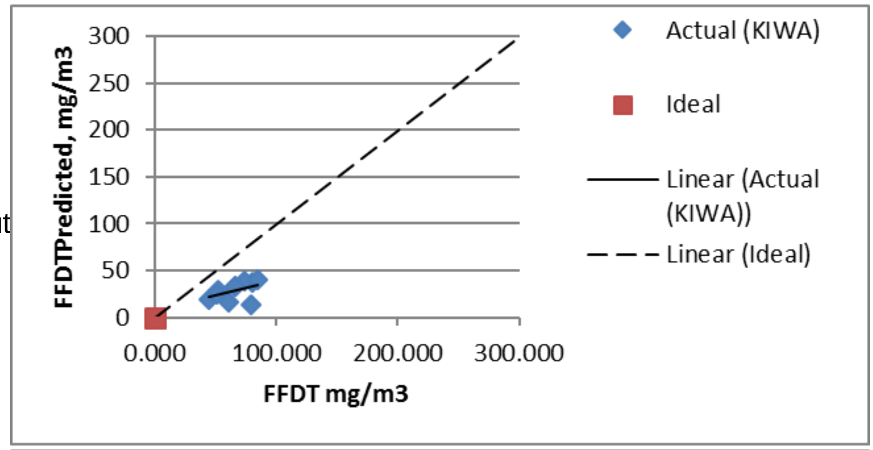
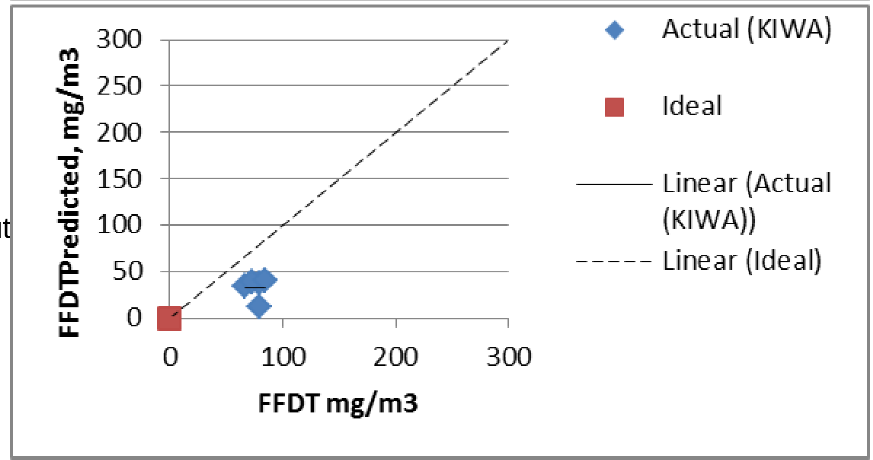


Figure A7.1e Appliance E – Lab 1 tests

High and Low Output



High Output



Low Output

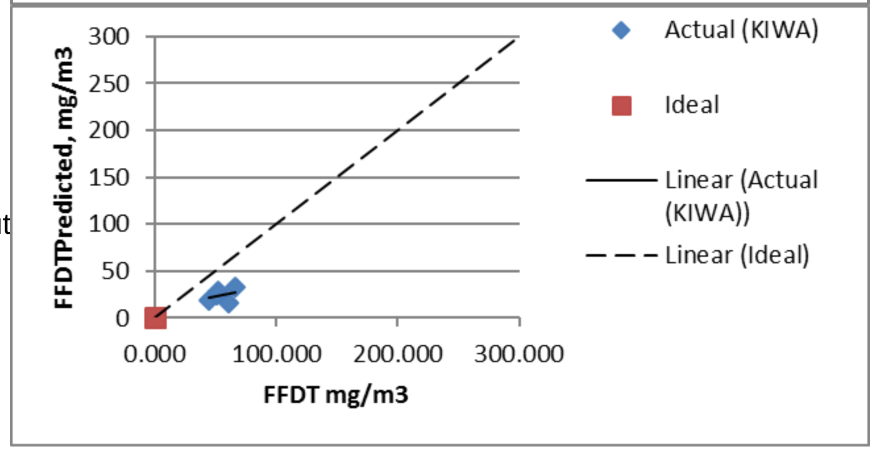
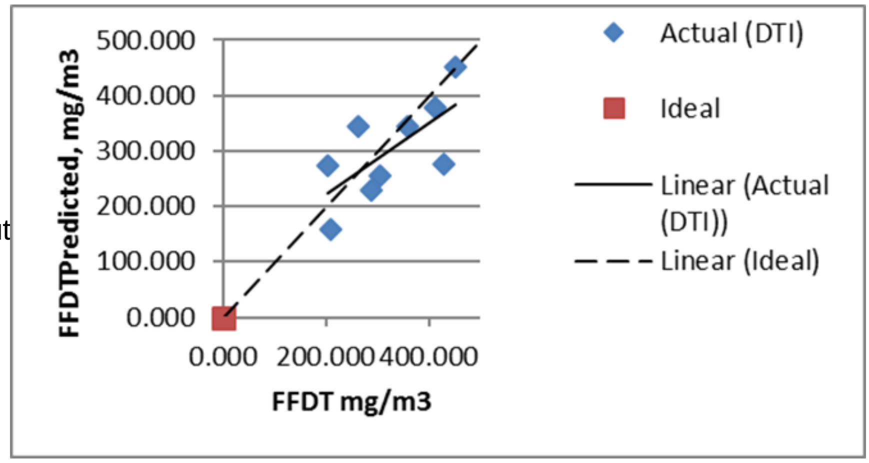
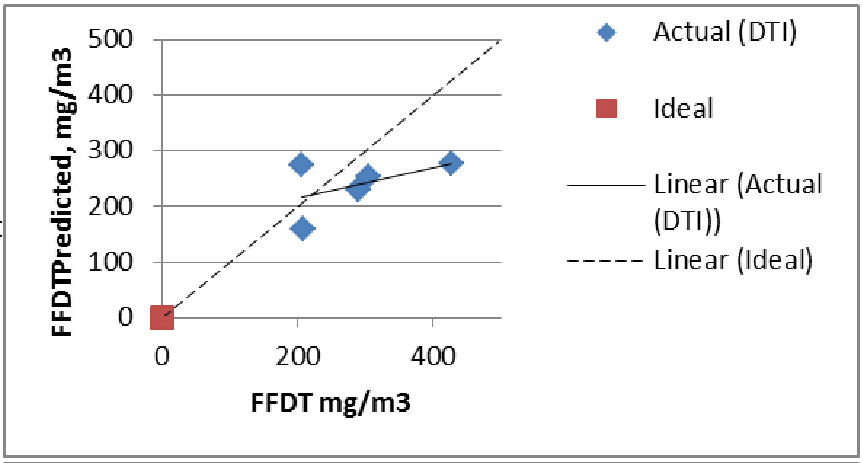


Figure A7.2a Appliance B – Lab 2 tests

High and Low Output



High Output



Low Output

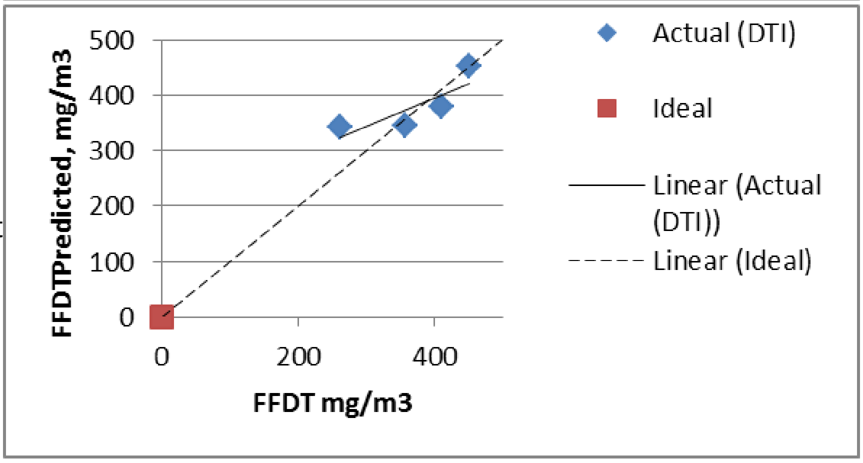
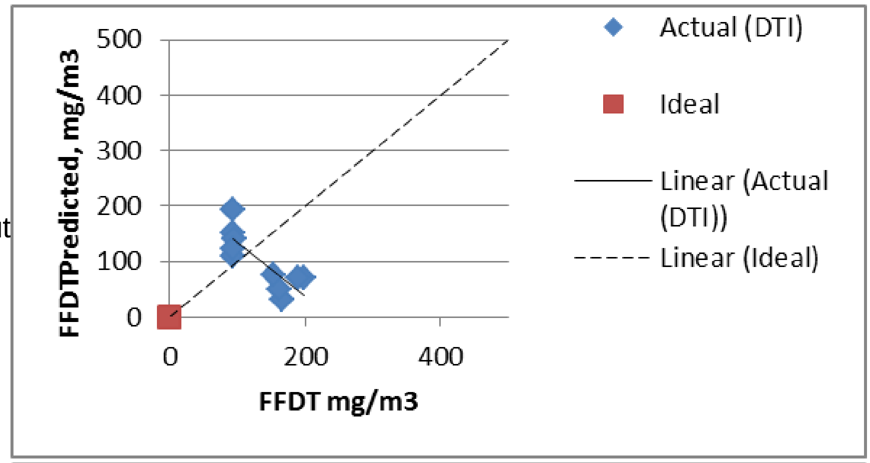
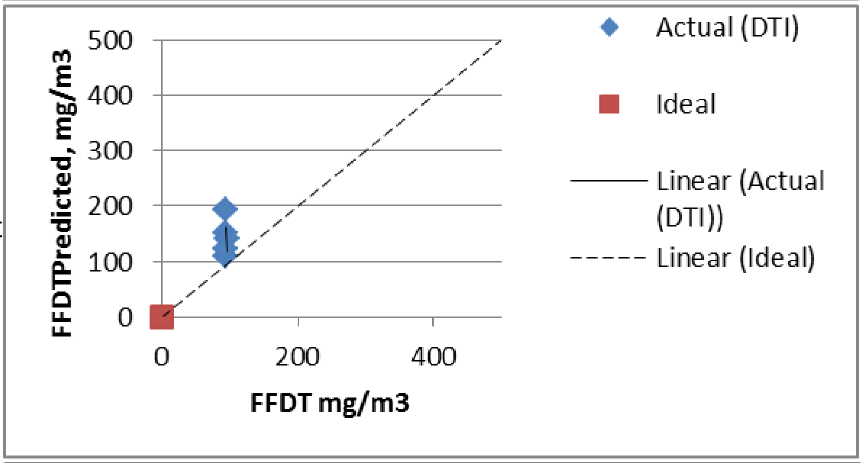


Figure A7.2b Appliance C – Lab 2 tests

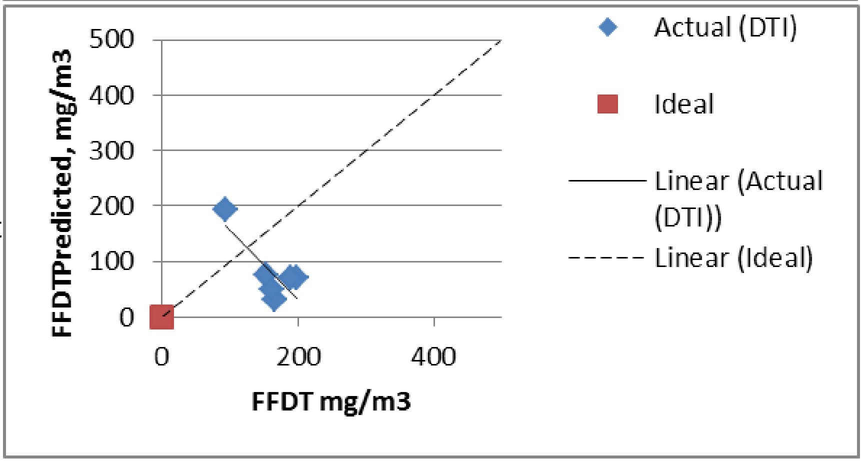
High and Low Output



High Output



Low Output



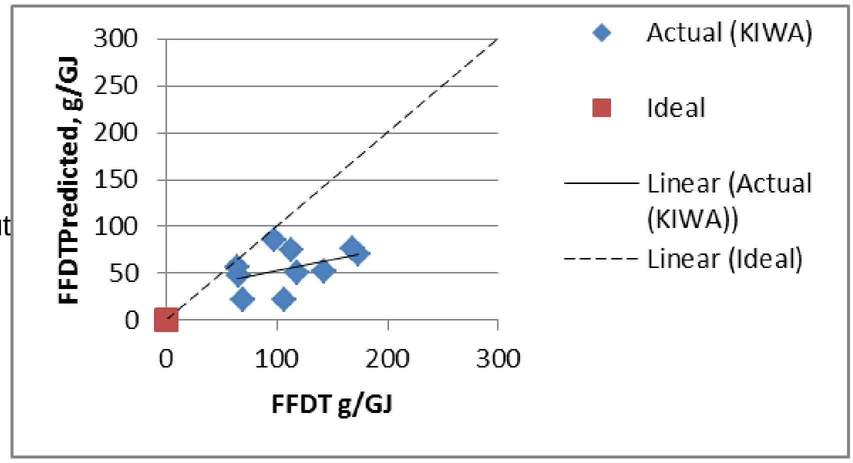
Appendix 8 Application of proposed relationship between FFDT and DIN+/THC measurements (based on measurements in g/GJ)

Table A8.1 Lab 1 results in g/GJ

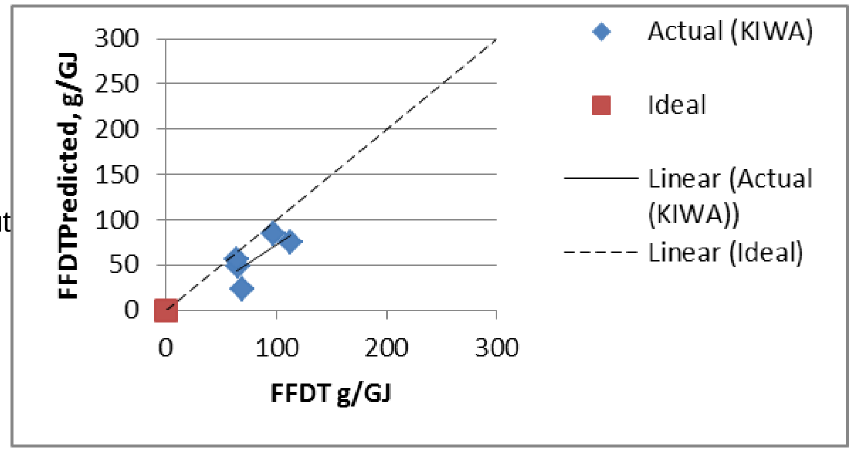
Appliance	Output	THC	FFDT	DIN+ 70	$FFDT_{Predicted}$
A	High	111	113	28	75
		14	69	16	22
		78	66	15	48
		84	64	21	57
		140	98	26	85
	Low	86	143	17	53
		27	107	10	22
		122	173	19	71
		82	119	16	50
		122	168	26	77
B	High	411	161	30	203
		311	157	72	203
		311	142	75	206
		174	81	39	112
		107	57	106	150
	Low	260	60	36	145
		145	38	27	88
		611	123	10	267
		596	111	30	280
		365	52	38	191
C	High	73	223	11	42
		159	85	11	78
		74	77	16	47
		208	100	47	134
		159	112	39	106
	Low	90	82	56	94
		117	105	90	139
		298	116	77	202
		16	82	14	20
		201	98	59	144
D	High	879	155	53	422
		627	150	113	376
		405	96	32	202
	Low	1076	465	526	978
		1191	584	1271	1771
		701	234	370	664
		758	253	410	729
E	High	2	71	22	23
		1	86	7	8
		2	80	22	23
		3	73	22	23
		5	90	24	26
	Low	7	98	20	23
		4	65	19	20
		2	66	12	13
		2	79	15	16
		3	88	10	11

Figure A8.1a Appliance A

High and Low Output



High Output



Low Output

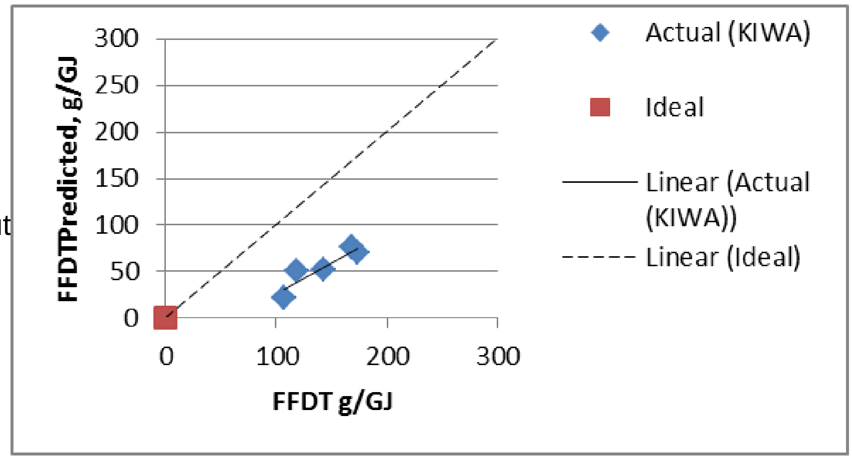
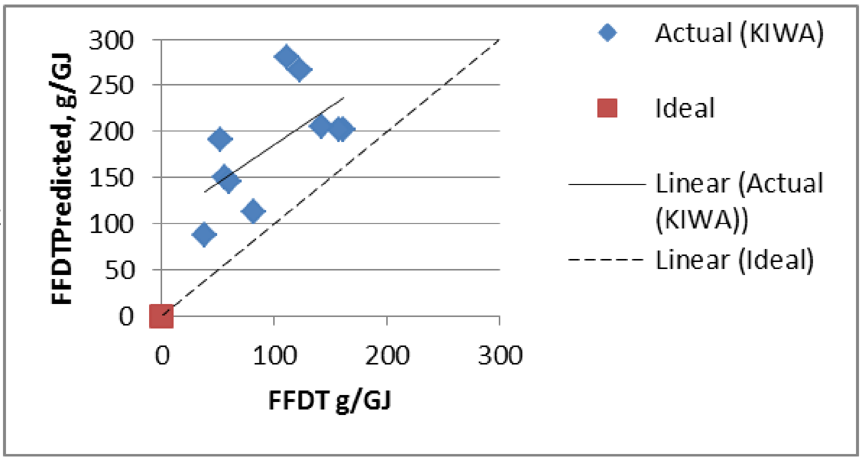
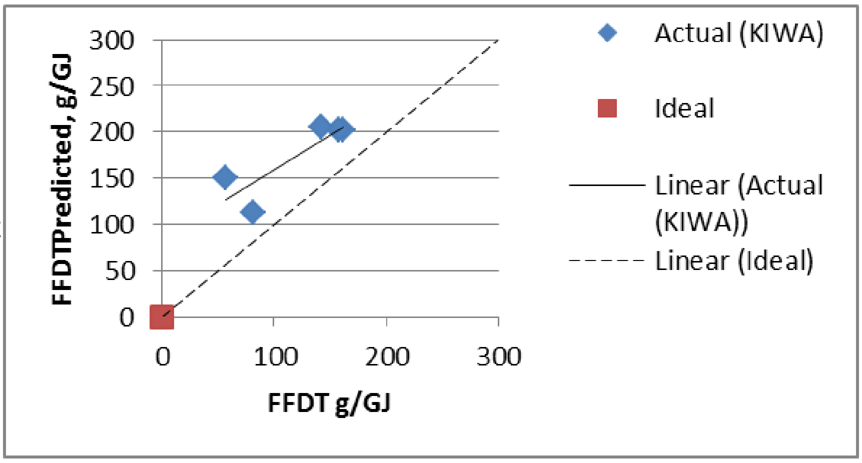


Figure A8.1b Appliance B

High and Low Output



High Output



Low Output

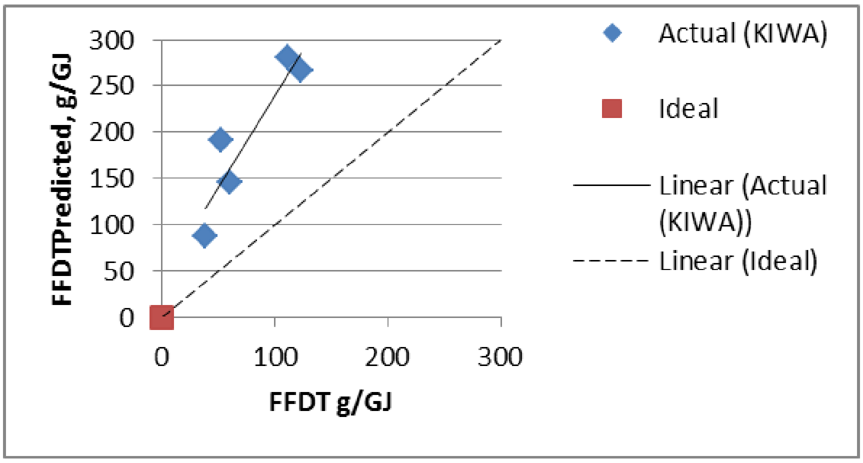
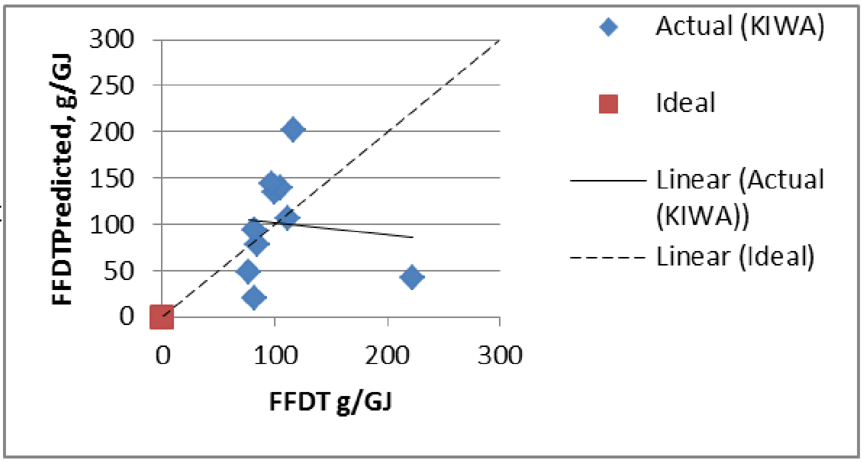
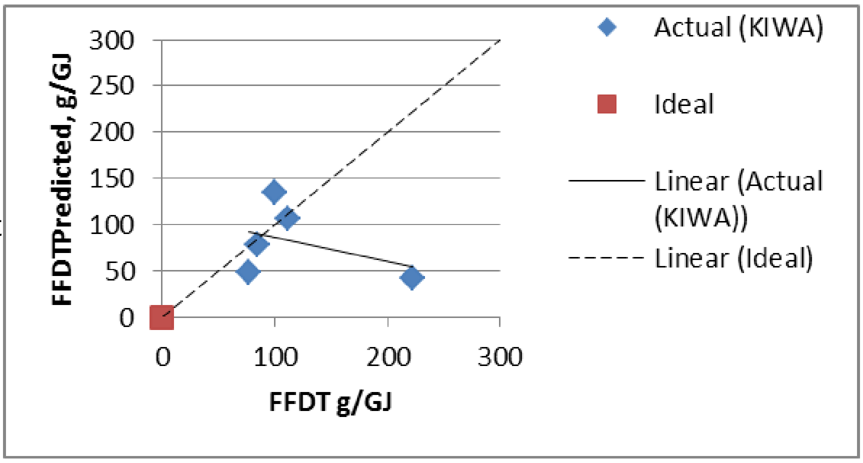


Figure A8.1c Appliance C

High and Low Output



High Output



Low Output

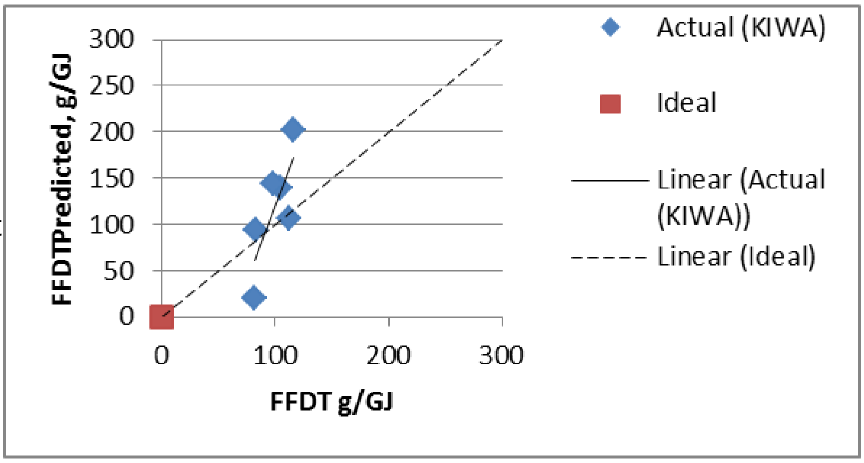
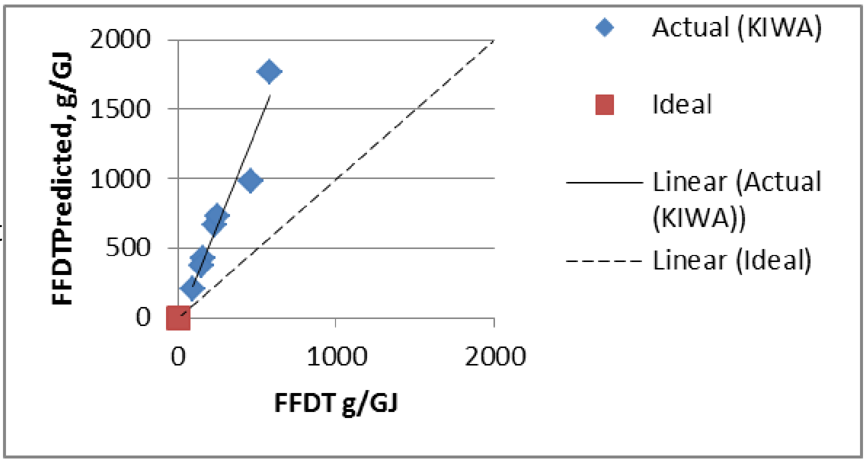
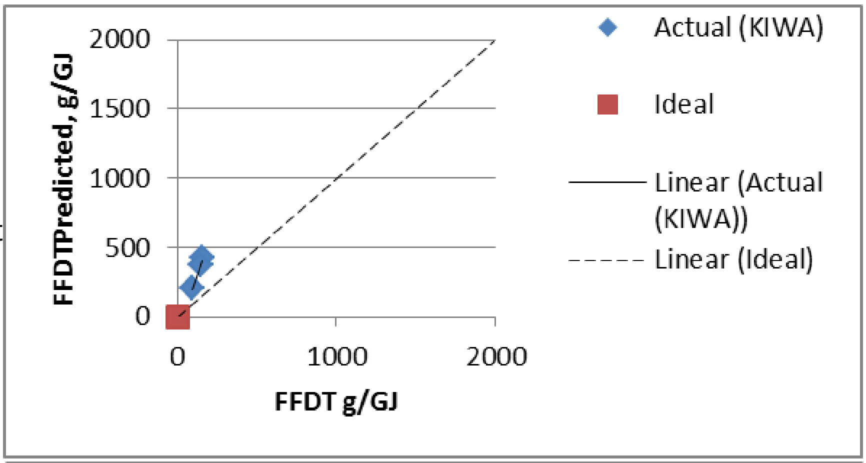


Figure A8.1d Appliance D

High and Low Output



High Output



Low Output

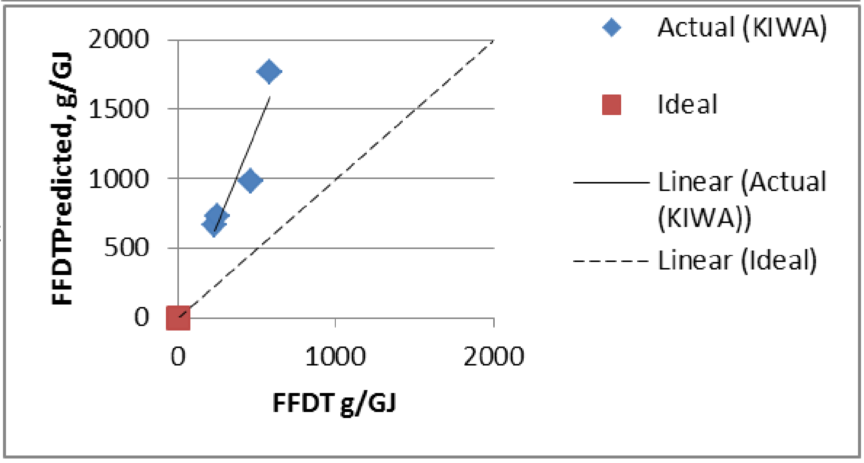
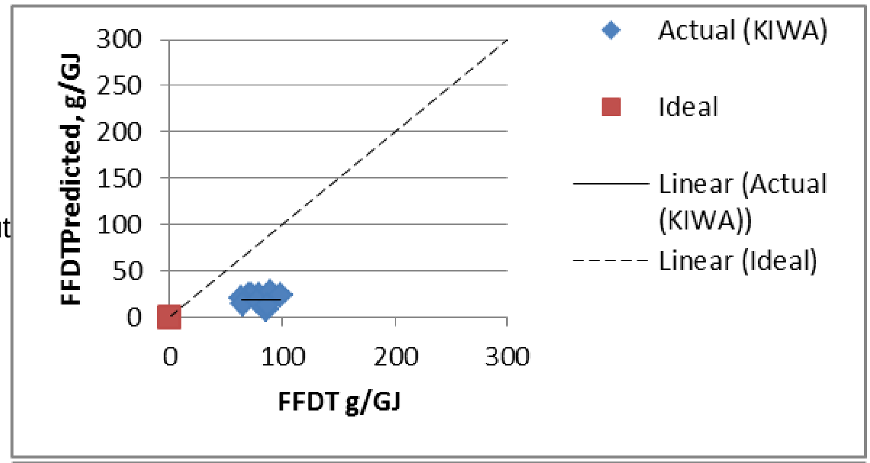
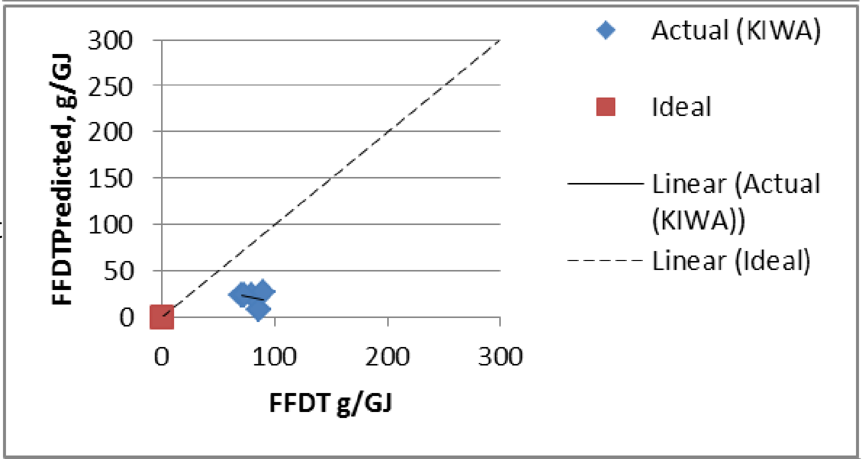


Figure A8.1e Appliance E

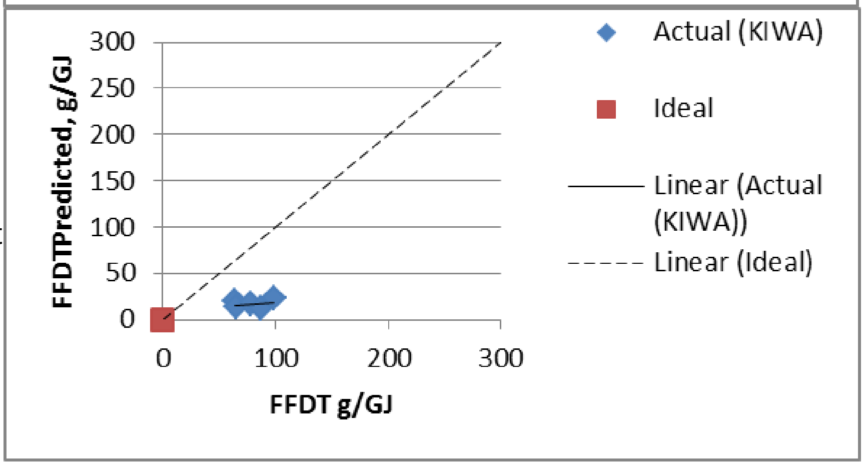
High and Low Output



High Output



Low Output



Appendix 5 – Test report 3 (Method adjustments)

Assessment of particulate and NO_x emissions from a range of log and pellet appliances and boilers by a range of measurement techniques

Report on the effect of method adjustments

Prepared by: Kiwa GASTEC
Prepared for: Ricardo AEA for Defra
Report Number: 60097-4
Date: October 2016

Defra
60097-4

Assessment of particulate and NO_x emissions from a range of log and pellet appliances and boilers by a range of measurement techniques

Report on the effects of method adjustments

Prepared by

Name Mark Lewitt

Position Principal Consultant

Approved by

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Table of Contents

Partner for progress

1 Introduction

Particulate air pollution has been a recognised problem in urban centres and many of the countries in the EU have passed a wide variety of local legislation. This has resulted in a number of different approaches to measuring particulate emissions, both qualitative and quantitative. Unfortunately, these approaches can report very different values. This is further complicated as the different methods traditionally report results in different units.

Such differences were not of great consequence when local legislation was written around the local measurement technique, but with the advent of the single market and the rise in interest in biomass, the situation is now changing. There is considerable evidence to indicate that the above measurement techniques can collect and report widely varying quantities of particulate matter and NO_x.

This work programme carried out a series of comparative and round-robin tests to investigate this issue to provide Defra with robust evidence to inform the choice of measurement technique to demonstrate compliance with emission limits. Tests of particulate, total hydrocarbon (THC) and NO_x measurements from representative biomass appliances were carried out.

This report shows the results of tests carried out by Kiwa Gastec in the UK (Kiwa) to assess the influence of modifying the emission test protocol on particulate emission measurement results using the heated filter ‘DIN+’ measurement technique.

It examines the ranges of results obtained for multiple measurements of particulate emission for individual appliances operated under two generic conditions, i.e. at full (rated output) and at reduced firing rates, which are referred to in this report as ‘High’ and ‘Low’ respectively.

On this basis the relationships between DIN+ and other measurement protocols derived from it are assessed and the scope to improve its **accuracy** and its **compatibility** with other particulate measurement protocols is investigated.

2 Description of Appliances

Table 1 presents a summary of the features of the appliance used for this study.

Table 1 Comparison of Appliance B Features

Appliance	**B**
Type	Insert room-heater
Fuel	logs
Output, kW	8
UK Clean Air Act Exempt?	yes
BImSchV 2?	no
RHI Certificate?	na
MCS Compliant?	na
Nordic Swan Ecolabel?	no
Likely to burn clean / dirty?	Clean

na not applicable

The effects of appliance characteristics and issues affecting the reproducibility of combustion conditions from test to test were discussed in the report on inter-method and inter-laboratory comparisons[i].

One area of uncertainty in measurements of particulate emissions from solid fuel roomheaters is the amount of condensable material in the flue gas and the extent to which such material is collected by different particulate sampling techniques.

The 'DIN+' sampling technique samples hot, undiluted flue gases and is thought to miss a significant amount of this condensable material but was chosen for this study as it does provide a more convenient and flexible/adaptable methodology for changes in the protocol.

This test programme aimed to investigate the effect of modifying the DIN+ sampling technique and measurement protocol to determine which elements have greatest impact on the measured levels of particulate emission.

3 Testwork

The test programme for this part of the study included carrying out measurements of particulate emissions from Appliance B using the DIN+ method but with small modifications to the technique and measurement protocol.

3.1 Test Matrix – Comparisons between standard and adjusted methods

Table 2 below shows tests carried out with each of the method adjustments. In addition to adjustments made to probe the question of loss of volatile matter, the variation in the particulates measurements with time during individual appliance operation cycles (i.e. a fuelling to burn out period) were also investigated.

Table 2 Test Matrix for DIN+ method adjustment comparison tests carried out on Appliance B

Output	Method	Replicates	Comment
High	DIN+ 70°C	5	Baseline DIN+ test.
	DIN+ 160°C	5	Filter temperature raised to match EN13284-1 (reference Standard for PM measurement).
	DIN+ +3min	5	Starting measurement when door closed after refuelling – DIN+ starts up to 3 minutes after refuelling.
	DIN+ full	5	Extending test period from 30 minutes to cover full (EN) burn cycle.
	DIN+ prefilt	3	Recovery of prefilter deposits (acetone and water rinse) to match EN 13284-1.
	DIN+ 10min	3 X 4	Short-term measurements to assess variability in PM emission over a burn cycle.
Low	DIN+ 70°C	5	Applying DIN+ test to a low output.
	DIN+ 160°C	5	Filter temperature raised to match EN13284-1.
	DIN+ prefilt	3	Recovery of prefilter deposits (acetone and water rinse) to match EN 13284-1.

Part of the test programme was to assess whether agreement between measurement techniques and protocols might be improved if they are based on comparable sampling periods.

3.2 Test Equipment

3.2.1 DIN+ method

Smoke emissions were measured using the DIN+ equipment, described in CEN/TS 15883[ii].

3.3 Test Fuel

The test fuel used was test wood logs conforming to the specification given in BS EN 13240:2001[iii] for thermal performance testwork on roomheaters burning wood logs. Fuel analyses are provided in **Table 3**.

The fuel selection method statement is reproduced in Appendix 1. In addition, for this work efforts were made to select similar logs for each test within the constraints of a batch of commercial logs. The logs used were all of a similar length as supplied.

Table 3 Test fuel analyses

Parameter	Units	Beech Wood Logs	
		ar	db
Total moisture	%	32.4	-
Free moisture	%	4.51(aa)	-
Ash content	%	0.1	0.2
Volatile matter	%	57.6	85.2
Fixed Carbon	%	9.9	14.6
Total Sulphur	%	<0.01	<0.01
Carbon	%	45.2	66.9
Hydrogen	%	6.06	8.96
Nitrogen	%	3.80	5.62
Oxygen by difference	%	12.4	18.3
Gross Calorific Value	MJ/kg	13.079	19.347
Net Calorific Value	MJ/kg	10.989	16.497

Notes:
ar as received
aa as analysed
db dry basis
nd not determined

3.4 Test Procedures and adjustments

Smoke emissions from the appliances were measured for two conditions, High Output and Low Output, which were attained through adjusting the air control settings

For High Output the primary and secondary air settings were those used for the nominal output tests. For Low Output a low setting for the secondary air that maintained clean combustion was determined and then used. The low setting used was not the minimum setting for the secondary air control.

The mass of fuel used as the refuel charge for each test was according to the appliance capacity. The standard method was to use four evenly sized logs, three laid side-by-side on the fuel bed and the fourth rested diagonally on top. However, this was adapted to meet the manufacturers' guidance for the appliance. The information provided in the appliance manual is summarised in Table 4 below.

Table 4 Appliance fuel specifications

Appliance	Manufacturer specified wood length, cm	Manufacturer specified wood diameter, cm	Standard fuelling	Maximum firing rate, kg/h
B	Up to 45	Not specified	Open stacking	2.6

The refuelling procedure adopted was to allow the newly charged fuel to burn with the primary and secondary air controls set at maximum for a maximum period of 2 minutes. After this period, with flames from the logs fully established, the primary air and secondary air supplies were adjusted to provide the required operating level i.e. High Output or Low Output. Setting the air flow accurately and repeatably was constrained by the appliance controls.

Following the ignition period a pre-test period was used to establish a suitable firebed.

The test durations were not predefined. The fire was allowed to burn back to the initial level of embers established at the start of the test.

Close attention was paid to the manufacturer's recommended operating procedures with regard to use of the appliance.

The appliance operation method for each of the replicate tests was in as far as possible identical including efforts to select similar logs for each test. However, other factors also may affect particle emission.

The progression of combustion will be different for every log, being affected by such factors as:

- The characteristics of the individual log including the presence of knots and the presence/thickness of bark.

- The preparation of the logs as the split surface of logs inevitably varies and can affect the way the logs lie in the appliance e.g. producing areas where one log shades another from the effect of full radiation, affecting the way that volatiles are released and ignited.

Individual log characteristics determine when events occur which are likely to cause short term fluctuations in particle pick up in the flue gas (such as the collapse of the partially burned logs).

3.4.1 Smoke measurements – DIN+ 70°C method

The smoke emission in all tests was measured using the DIN+ method described in CEN/TS 15883[IV]. The method statement is given in Appendix 2.

Ten tests were carried out, five each at high and low output. The operational profiles for the appliance for each test are presented in Appendix 3 (Figures A3.1a to A3.1e). Baseline measurements for DIN+ were also undertaken by two other test laboratories.

This base method is the one against which the results of variations upon it are considered in this report.

3.4.2 Smoke measurements – DIN+ 160°C method

This method mirrors the DIN+ technique and protocol except that the filter assembly is held at 160°C. The objective of this method adjustment was to investigate the impact of elevated temperature on the amount of material captured during sampling.

The particulate matter that comprises wood smoke is a combination of char and ash particles with varying amounts of condensed volatile matter. The char and ash provide nucleation points for condensation.

The temperature of the sample filter is likely to be an important controlling parameter which influences the amount of volatile matter condenses or remains condensed during sample collection and measurement.

Ten tests were carried out, five each at high and low output. The operational profiles for the appliance for each test are presented in Appendix 3 (Figures A3.2a to A3.2e).

3.4.3 Smoke measurements – DIN+ 70°C method including first 3 minutes

The standard DIN+ test commences sampling up to 3 minutes after refuelling. As demonstrated in the previous reports on the ESP method**Error! Bookmark not defined.**, and on method and laboratory comparisons[i] the trends for gaseous products of incomplete combustion and optical density indicate that the highest emission concentrations generally occur within five minutes of fuel addition.

For these measurements the sampling period was commenced at refuelling (this is the practise for the other particulate sampling techniques and protocols used for residential solid fuel heating appliances) and so the emissions during the initial 3 minutes were included in the samples.

Five tests were carried out at high output. The operational profiles for the appliance for each test are presented in Appendix 3 (Figures A3.3a to A3.3c).

3.4.4 Smoke measurements – DIN+ 70°C method full cycle

The DIN+ standard method specifies a 30minute sample extraction period commencing 3 minutes after fuel addition.

Measurements according to other particulate sampling techniques and protocols (including BS 3841[V], BS PD 6434 [VI], NS3058 and USEPA) use sampling periods based on the actual heat release cycle for an appliance from fuelling to burnout and are typically longer than 30 minutes.

These tests involved applying the DIN+ method to sampling periods comparable with those for the other methods used and reported previously[I,]**Error! Bookmark not defined.**.

Five tests were carried out at high output. The operational profiles for the appliance for each test are presented in Appendix 3 (Figures A3.4a to A3.4c).

3.4.5 Smoke measurements – DIN+ 70°C method – prefilter deposit recovery

For these tests the material deposited in the sampling train upstream of the filter was removed (and recovered) prior to each measurement. This is in contrast with the usual practice of cleaning the system after a set of measurements (in the case of this study typically 5 at on output condition) have been completed. The cleaning / recovery procedure described in the method statement in Appendix 2 was used.

Six tests were carried out, three each at high and low output. The operational profiles for the appliance for each test are presented in Appendix 3 (Figures A3.5a to A3.5c).

3.4.6 Particulate measurements – DIN+ 70°C method – 10 minute sub-sampling

Sequential sampling periods of 10 minutes each were carried out during individual appliance operation cycles.

Four periods were sampled across consecutive tests for timing reasons:

Period	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
0 to 10 minutes	X		X		X	
11 to 20 minutes		X		X		X
21 to 30 minutes	X		X		X	
31 to 40 minutes		X		X		X

Six tests were carried out, each at high output. The operational profiles for the appliance for each test are presented in Appendix 3 (Figures A3.6a to A3.6c).

4 Results and Discussion

Summary and exemplary tables and plots are included within the main text.

Individual results from particulate emission tests listed in the matrix in Table 2 above are shown in Appendix 3. Also presented in these appendices are results from CO_2, CO, hydrocarbon, and NOx emission measurements plotted as profiles (as identified in Section 3.4 above) and summarised in Tables A3.1a to A3.2d.

4.1 Inter-laboratory comparison results of 'baseline' DIN+ method

DIN+ measurements carried out on appliance B at the three laboratories were discussed in a previous report[i]. This current report does not consider inter-laboratory reproducibility and the results are reproduced here solely to provide context for the results of the DIN+ method adjustment studies reported here. For reference the results are summarised in Table 5 below.

Table 5 Particulate measurements by standard DIN+ method, on Appliance B, made at three laboratories, mg/m^3

Output	High				Low			
Laboratory	Lab2	Lab1		Lab3	Lab2	Lab1		Lab3
Sample system washings included?*	NO	NO	YES	NO	NO	NO	YES	NO
Test 1**	139	38	53	127	131	46	48	*173****
Test 2**	114	91	107	*164****	97	34	35	131
Test 3**	121	95	111	145	108	13	14	*197****
Test 4**	82	49	66	86	*39*****	38	39	160
Test 5**	109	133	150	*104****	104	48	49	*220****
Average	113	81	97	125	110	36	37	176
SD	20.7	38.3	38.9	31.2	14.7	13.9	14.0	34.2
RSD (%)	18	47	40	25	13	39	38	19
Ratio highest :lowest result	1.7	3.5	2.8	1.9	1.4	3.7	3.4	1.7
Ratio highest : lowest average result	1.5				5.0			

NOTES:
* The sample system washings are not included in the particulate measurement in the standard DIN+ method
** The results are presented in the sequence they were executed/reported. The Test number must not be taken to imply any relationship between tests of the same number.
*** The laboratory reported that high particle loadings affected sample volume
**** The laboratory reported that a sample timing error invalidated this result and it has not been used

For the two appliances tested (Appliance B and Appliance C) in the three laboratories, the differences in the results between laboratories were considered significant. The results from Appliance B from the three laboratories do not fit a simple relationship. For the High Output tests, the ranges of results from the three testhouses overlap but for the Low Output results there is no overlap in the ranges. The magnitude of the PM emission concentrations data reported for each laboratory for both outputs were Lab1<Lab2<Lab3.

For all laboratories, the variation in measured PM concentrations between tests appears high (as indicated by the standard deviations and the ratios between highest and lowest emission test results) and illustrates the difficulty in obtaining reproducible test conditions between tests for manually-controlled, wood log, appliances.

The DIN+ protocol adopted by Lab1 included a section of heated sample line to connect the sample probe to the heated sample filter holder. The other laboratories included a close-couple sampling probe and heated filter. The PM collected in the Lab1 heated sampling line were recovered quantitatively and the effect of their inclusion on the particulate measurements calculated. The results are included in Table 5. Around 17% (for High Output tests) and 5% (for Low Output tests) of particulate material extracted from the flue was deposited in the sampling line. However, the inclusion of a sample line between the probe and filter housing appears insufficient to account for the differences in average PM concentrations determined by Lab1 and those by Lab2 and Lab3.

4.2 Repeatability of all the variants of the DIN+ method

The relatively wide variation in PM emissions determined at the rated output baseline measurements may indicate the unpredictability of the combustion conditions from test to test, even for this single appliance (B) in the same laboratory and hence, limits the repeatability of PM measurement data that can be expected.

Results of individual tests are given in Appendix 3 (Tables A3.3 and A3.4). The results are summarised in **Table 6** below.

Table 6 Repeatability of Appliance B results when measured by DIN+ and DIN+ based methods, mg/m^3 @ 13% O_2

Method		**DIN+ 70°C**	**DIN+ 160°C**	**DIN+ 3 mins**	**DIN+ full cycle**	**DIN+ pre-filter**
Output level	Statistic					
High	**Average**	**81**	**77**	**94**	**62**	**59**
	SD	38	20	28	16	5
	RSD	47%	26%	30%	26%	9%
Low	**Average**	**36**	**105**			**12**
	SD	14	55			1
	RSD	39%	42%			10%

Although the repeatability of measurements (as indicated by the relative standard deviation) was generally better than for the baseline measurements, the variability in the measured particulate emission concentrations during the baseline tests limit the observations and conclusions regarding the method adjustment.

High filter temperature - The average particulate concentrations at ‘high’ filter temperature at rated output are essentially the same as found during the lower temperature baseline measurements. Higher particulate concentrations were found for the lower output test condition.

Measurement including period immediately after refuel - Although the inclusion of the initial 3 minutes after refuelling seems to show a significant increase in the amount of particulate collected on average over these tests which would be expected, the reported higher emissions are likely within the uncertainty of the baseline measurements.

Measurement over full test cycle - Although the average PM concentration was lower than the average concentration during the baseline and this might be expected if the full cycle included periods of lower PM emission, reported emissions are likely within the uncertainty of the baseline measurements. However, see Section 4.3 for more detailed analysis of PM emissions during different periods of the burn cycle.

Prefilter PM recovery – The average PM concentration was lower than during the baseline whereas this test should have included both material collected in the filter and material deposited upstream of the filter.

Overall the measurements by the different method variants gave fairly similar results on average to those from the baseline High Output conditions. The measurements at the Low Output conditions suggest a greater variability in the particulate emissions under these conditions.

4.3 Variation in particulate emission with time

Six tests carried out consecutively, with two 10 minute DIN+ 70°C samples collected at defined time intervals in each, provided limited time series of particulate concentrations. The results are presented in Table 7 and Figures A3.6a to A3.6c.

Table 7 Results for the standard and DIN+ method applied to a standard sample period and to multiple sample periods in a single test for Appliance B, High Output – Particulate emissions, mg/m³ at 13% O_2

Test	1	2	3	4	5	6	Average	Standard DIN+ method
0-10 mins	47		75		95		72	
11-20 mins		72		33		55	53	
21-30 mins	17		15		14		15	
31-40 mins		41		27		57	42	
Average	**46**							**81**
SD	26							38
RSD	57%							47%

As noted previously, the variability of emissions between burn cycles makes comparison difficult however, the following was found:

1. The highest measured particulate concentration was found during the initial ten minutes of a burn cycle, this period also had the highest average particulate concentration of the burn cycle.

2. The lowest particulate concentrations were found during the third interval (21-30 minutes into the burn cycle).

3. Measured particulate concentrations in the final interval sampled (31-40 minutes of the burn cycle) were higher than for the third interval.

4. The particulate concentration measured when CO / THC levels are elevated is higher than when these levels are low. Even when CO / THC levels have dropped to a relatively low level the levels of particulate measured remain significant.

5 Conclusions

The repeatability of the measurements, using the DIN+ method variants, reported here (as indicated by the relative standard deviation) was generally better than for the baseline DIN+ measurements. However, the variability in the measured particulate emission concentrations during the baseline tests limit comparisons with the baseline.

The average particulate concentrations at ‘high’ filter temperature at rated output are essentially the same as found during the lower filter temperature baseline measurements. However, higher particulate concentrations were found for the lower output test condition.

Although the inclusion of the initial 3 minutes after refuelling seems to show a significant increase in the amount of particulate collected on average over these tests, the reported higher emissions are likely within the uncertainty of the baseline measurements.

The highest measured particulate concentration was found during the initial ten minutes of a burn cycle, this period also had the highest average particulate concentration of the burn cycle.

The lowest particulate concentrations were found during the third interval (21-30 minutes into the burn cycle).

Measured particulate concentrations in the final interval sampled (31-40 minutes of the burn cycle) were higher than for the third interval.

The particulate concentration measured when CO / THC levels are elevated are higher than when these levels are low. However, even when CO / THC levels have dropped to a relatively low level the levels of particulate measured remained significant.

6 Recommendations for future testing

The results of the adjustments to testing have been difficult to assess because of the variability in the measured particulate emission concentrations during the baseline tests which has limited comparisons.

The information which was assessed in this test programme is relevant to development of an improved solid fuel appliance test procedures (and in particular the 'ideal' start and duration of testing).

It is recommended that further testing to investigate the relationship between testing measurement methods always undertakes **parallel** (simultaneous) measurements so that comparison is always with the same burn cycle – i.e. removing the uncertainties associated with the variability between burn cycles.

To assess whether the uncertainty due to the variability found between individual burn cycles may be reduced by extending emission tests to cover several burn cycles it is recommended that the impact of measuring particulate emissions from multiple refuels in a single test is investigated.

7 References

[I] Assessment of particulate and NOx emissions from a range of log and pellet appliances and boilers by a range of measurement techniques. Report on inter-method and inter-laboratory comparisons. Kiwa GASTEC at CRE, Report 60097-3, December 2013.
[II] CEN/TS 15883:2009 Residential solid fuel burning appliances - Emission test methods
[III] BS EN 13240:2001 Roomheaters fired by solid fuel - Requirements and test methods.
[IV] CEN/TS 15883:2009 Residential solid fuel burning appliances - Emission test methods
[V] BS 3841-2 1994 Determination of smoke emission from manufactured solid fuels for domestic use – Part 2: Methods for measuring the smoke emission rate
[VI] PD 6434:1969 Recommendations for The design and testing of smoke reducing solid fuel burning domestic appliances

Appendix 1 Log fuel selection method statement

Date: 08 May 2006	BS EN Standards 12815, 12809, 13229 & 13240,	GASTEC at CRE
	Tests with wood	Page: AII/02

Issue
SIZE OF WOOD LOGS

The test fuel specifications state that all fuels, including wood logs, should be "of commercial size in accordance with manufacturer's instructions". Potentially, this gives the manufacturer considerable leeway in describing the fuel size in its operating instructions.

Interpretation

The standards are not really ambiguous. Whilst they can be of the size in accordance with the manufacturer's instructions they also have to be "logs" and of "commercial size".

Thus the sizes allowable for wood logs are limited in range to the smallest (~300 mm) and largest (0.5 metre) available in the European market

Policy

Gastec at CRE will purchase logs on the commercial market. Whilst some selection can be made of these logs to suit the physical size of the appliance and the manufacturer's instructions no further size reduction of the logs will be permitted, eg to produce slivers, to generate wood pieces which could not sensibly be sold as "wood logs"

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Appendix 2 DIN+ method statement

TEST EQUIPMENT USED	Equipment Number	Calibration Status	
Test Rig	FAT		
Data logger (PC)	FAT		
Squirrel logger	FAT		
Flue gas analyser (NO_2)	FAT	Span before test	
Flue gas analyser (C_xH_y)	FAT		
Heated filter box (set to 70°C)	FAT		
Pumped gas flow temp	FAT		
Heated filter box temp	FAT		
Gas meter	FAT		
Stop watch	FAT		
Scales for filters	FAT		

Note: Ensure that equipment has valid calibration status before starting test.

1. <u>METHOD</u>

1 The DINplus testing for particulates, NOx and hydrocarbons is carried out concurrent to the efficiency and nominal heat output test conducted as described in BS EN12809, 12815,13229, 13240, 14785 and 303-5. The DINplus methodology follows that outlined in DD CEN/TS 15883:2009 and a DIN CERTCO document available from TÜV Rheinland, dated June 2008. (There will be an accompanying test sheet – with the same test number – for the efficiency and nominal heat output test).

2 Span the NOx and hydrocarbon analysers and connect NOx and hydrocarbon to the Channels 11 and 12, respectively, of the Squirrel logger. Ensure that the ranges for the analysers are set to 10000 ppm for hydrocarbons and 400 ppm for NOx, and that the Squirrel ranges are set to 20 volts.

3 On lighting the appliance, ensure that the heaters for the line and filter housing are switched on.

4 Ensure that the thermocouple measuring the suction flow temperature is connected to a channel of the Pico logger

5 Prior to conducting first test in the series, take reading of gas meter, turn on suction pump and operate for 15 minutes exactly. Record gas meter reading at the end of this pre-test period and determine total gas volume used. Check if volume is between 0.140 and 0.150 m^3 (as measured). If readings are outside range, then pump speed should be adjusted as necessary and the procedure repeated for as many times as necessary. Use table below to record information.

Gas meter reading – end m^3						
Gas meter reading – start m^3						
Total gas volume m^3						

6 Weigh at least three filters (having been dried at 105°C for at least an hour and then stored in a desiccator for at least 4 hous).

7 Check that the filter housing is 70°C and heated line is 150°C. Then insert first filter.

8 Immediately prior to the first test in the series, insert dust sample probe (ensuring that it is correctly positioned) and connect heated line.

9 Three minutes after refuelling from the start of the test, switch on pump and simultaneously record the reading on the gas meter.

10 After 30 minutes, immediately turn off pump and record the reading on the gas meter. Determine total volume flow and approximate temperature of the suction gas. Calculate total flow corrected to NTP. If total flow is 270 +/- 5% litres , ie 256.5 – 283.5 litres, then test is valid.

11 Carefully remove filter and place in labelled petri dish. Put in drying oven at 105°C for at least one hour and store for at least 4 hours in a desiccator.

12 Weigh filter and dish

13 Repeat steps 9 – 12 for each test.

14 During a test make note of a spot sample of the analyser and Squrrel readings

	Analyser (ppm)	Squirrel (V)
NOx Channel 11		
HCs Channel 12		

15 At the end of the series of tests, remove/disconnect the dust sample probe and heated line. Rinse with acetone, collecting the washings in a tared aluminium tray. Allow the washings to evaporate at ambient temperature and record the weight of the tray and residue.

5. TEST PERIOD Ensure logger is on before starting the test.

			Test 1	Test 2	Test 3	Test 4
Filter number						
Mass filter, with support (before test)		g				
Mass filter, with support (after test)		g				
Mass gain **(A)**		g				
Washings	Mass tray + washings	g				
	Mass tray	g				
	Mass washings	g				
	Mass washings per test **(B)**	g				
Total mass gain (A + B)		g				
Clock time - Start						
Clock time - End						
Gas meter reading – end		m^3				
Gas meter reading – start		m^3				
Total gas volume		m^3				
Temperature flow gas (approx.)		°C				
Total flow (to 0°C) (approx.)#		litres				
Valid test? (Between 256.5 & 283.5 litres)						
Actual temp of flow gas*		°C				
Av.CO_2 **or** O_2 in flow gas (during sampling period)* Delete as appropriate		%				

\# Corrected total flow = Total flow x (273)/(273+Temp flow)

* from prn files

6. TEST RESULTS

The NOx, and CxHy logger data for each refuelling / efficiency period shall be copied to the Excel spreadsheet at N/SFAP/DINplusdatacollate.xls. For the purposes of reporting the NOx and CxHy and emissions, the final test results must also be processed using the spreadsheet at N/SFAP/DINplusdatacollate.xls.

For the purposes of reporting the particulate emissions, the final test results must be processed using the spreadsheet at N/SFAP/DINplus.xls. Note that the average oxygen or CO_2 contents used in the calculations are obtained from the separate spreadsheet used to determine the output and efficiency. A separate spreadsheet also applies for the temperature of the flow gas for the particulates.

For the particulate measurements, the thirty minute period of each particulate test should be highlighted in the oxygen (or CO_2) and flow gas temperature columns and the average values noted (from the bottom right of the screen)

Obtain printouts of test results. All printouts must be retained and filed with this document.

7. SUMMARISED TEST RESULTS

Parameter		Test 1	Test 2	Test 3	Test 4	Mean
Mean CxHy emission	ppm					
Mean NOx emission	ppm					
Particulate emission	mg/Nm^3					

COMMENTS

Appendix 3 DIN+ method variants test results

TABLES

Table A3.1a Averages of operating parameters for each test - CO, %, as measured

Output	High					Low				
Method	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter
Test 1	0.30	0.42	0.20	0.22	0.19	0.32	0.48			0.42
Test 2	0.27	0.50	0.25	0.14	0.23	0.24	0.67			0.37
Test 3	0.28	0.27	0.33	0.22	0.22	0.65	0.95			0.29
Test 4	0.18	0.43	0.32	0.20		0.71	0.97			
Test 5	0.14	0.54	0.31	0.28		0.50	0.72			
Maximum	0.30	0.54	0.33	0.28	0.23	0.71	0.97			0.42
Minimum	0.14	0.27	0.20	0.14	0.19	0.24	0.48			0.29
Average	**0.23**	**0.43**	**0.28**	**0.21**	**0.21**	**0.48**	**0.76**			**0.36**
SD	**0.07**	**0.10**	**0.06**	**0.05**	**0.02**	**0.20**	**0.20**			**0.07**
RSD	**54%**	**39%**	**20%**	**23%**	**9%**	**42%**	**27%**			**18%**

Table A3.1b Averages of operating parameters for each test – NOx as NO_2 mg/m^3 @ 13% O_2

Output	High					Low				
Method	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter
Test 1	143	-	81	77	85	89	74			55
Test 2	124	-	69	99	92	104	64			51
Test 3	125	-	69	95	98	98	63			62
Test 4	130	120	41	84		81	74			
Test 5	142	115	69	68		87	82			
Maximum	143	120	81	99	98	104	82			62
Minimum	124	115	41	68	85	81	63			51
Average	**133**	**118**	**66**	**85**	**92**	**92**	**71**			**56**
SD	**9**	**4**	**15**	**13**	**6**	**9**	**8**			**6**
RSD	**7%**	**3%**	**22%**	**15%**	**7%**	**10%**	**11%**			**10%**

Table A3.1c Averages of operating parameters for each test – OGC mg C/m^3 @ 13% O_2

Output	High					Low				
Method	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter
Test 1	529		144	91	45	373	910			173
Test 2	397		128	35	89	207	1244			211
Test 3	393		173	88	69	878	1409			154
Test 4	215	528	190	81		850	1498			
Test 5	130	570	318	88		516	903			
Maximum	529	570	318	91	89	878	1498			211
Minimum	130	528	128	35	45	207	903			154
Average	**333**	**549**	**190**	**77**	**68**	**565**	**1193**			**179**
SD	**159**	**30**	**75**	**23**	**22**	**294**	**277**			**29**
RSD	**48%**	**5%**	**40%**	**31%**	**33%**	**52%**	**23%**			**16%**

Note: Organic Gaseous Carbon (OGC) is calculated from the Total Hydrocarbon (THC) according to the method in DD CEN/TS 15883:2009. This is the standard basis on which these emissions should be reported.

Table A3.1d Averages of operating parameters for each test – CO_2, %, as measured

Output	High					Low				
Method	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter
Test 1	9.6		12.0	8.6	8.7	10.2	9.2			5.7
Test 2	10.5		10.3	10.4	9.3	9.6	6.8			6.8
Test 3	9.8		9.4	9.7	9.6	7.7	6.7			8.3
Test 4	11.0	9.9	9.2	8.5		6.4	6.7			
Test 5	10.6	9.8	10.0	9.1		8.1	8.4			
Maximum	11.0	9.9	12.0	10.4	9.6	10.2	9.2			8.3
Minimum	9.6	9.8	9.2	8.5	8.7	6.4	6.7			5.7
Average	**10.3**	**9.9**	**10.2**	**9.3**	**9.2**	**8.4**	**7.5**			**6.9**
SD	**0.6**	**0.1**	**1.1**	**0.8**	**0.5**	**1.5**	**1.2**			**1.3**
RSD	**7%**	**8%**	**10%**	**7%**	**4%**	**11%**	**9%**			**9%**

Table A3.2a Average operating parameters for tests where 10 minute samples were collected using the standard DIN+ method – CO, % as measured

	Sample period from start of test				
	0 to 10	11 to 20	21 to 30	31 to 40	All
Test 1	0.75	0.34	0.06	0.08	0.30
Test 2	0.44	0.32	0.11	0.13	0.25
Test 3	0.32	0.08	0.07	0.14	0.17
Test 4	0.25	0.16	0.11	0.11	0.16
Test 5	0.75	0.22	0.03	0.12	0.29
Test 6	0.24	0.15	0.15	0.23	0.22

Table A3.2b Average operating parameters for tests where 10 minute samples were collected using the standard DIN+ method – OGC mg C/m^3 @ 13% O_2

	Sample period from start of test				
	0 to 10	11 to 20	21 to 30	31 to 40	All
Test 1	519	160	0	0	158
Test 2	176	77	10	0	58
Test 3	216	11	0	5	74
Test 4	87	42	5	0	31
Test 5	725	231	2	0	214
Test 6	144	42	14	31	96

Table A3.2c Average operating parameters for tests where 10 minute samples were collected using the standard DIN+ method – NOx, mg/m^3 @ 13% O_2

	Sample period from start of test				
	0 to 10	11 to 20	21 to 30	31 to 40	All
Test 1	75	79	76	79	73
Test 2	69	76	74	70	68
Test 3	83	97	86	72	76
Test 4	84	97	94	86	82
Test 5	85	83	83	79	73
Test 6	99	96	87	79	81

Table A3.2d Average operating parameters for tests where 10 minute samples were collected using the standard DIN+ method – CO_2, %, as measured

	Sample period from start of test				
	0 to 10	11 to 20	21 to 30	31 to 40	All
Test 1	17.0	13.6	11.2	9.5	12.9
Test 2	15.8	13.2	10.4	7.7	11.6
Test 3	14.4	11.1	8.8	7.6	10.2
Test 4	14.3	12.0	10.1	7.9	10.8
Test 5	15.5	12.1	9.9	6.5	11.4
Test 6	13.4	10.6	9.2	6.5	10.0

Table A3.3 Results for the standard and adjusted DIN+ methods applied for Appliance B – Particulate emissions over up to five repeats, mg/m^3 at 13% O_2

Output	High					Low				
Method	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter	70°C	160°C	Inc. init. 3 mins	Full cycle	Pre-filter
Test 1	38	107	105	83	64	46	97			11
Test 2	91	67	56	60	61	34	61			12
Test 3	95	52	83	58	54	13	84			13
Test 4	49	80	92	40		38	201			
Test 5	133	79	131	71		48	85			
Maximum	133	107	131	83	64	48	201			13
Minimum	38	52	56	40	54	13	61			11
Average	**81**	**77**	**94**	**62**	**59**	**36**	**105**			**12**
SD	**38**	**20**	**28**	**16**	**5**	**14**	**55**			**1**
RSD	**47%**	**26%**	**30%**	**26%**	**9%**	**39%**	**52%**			**10%**

FIGURES

Figure A3.1a DIN+ 70°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test1 (left) and Test 2 (right)

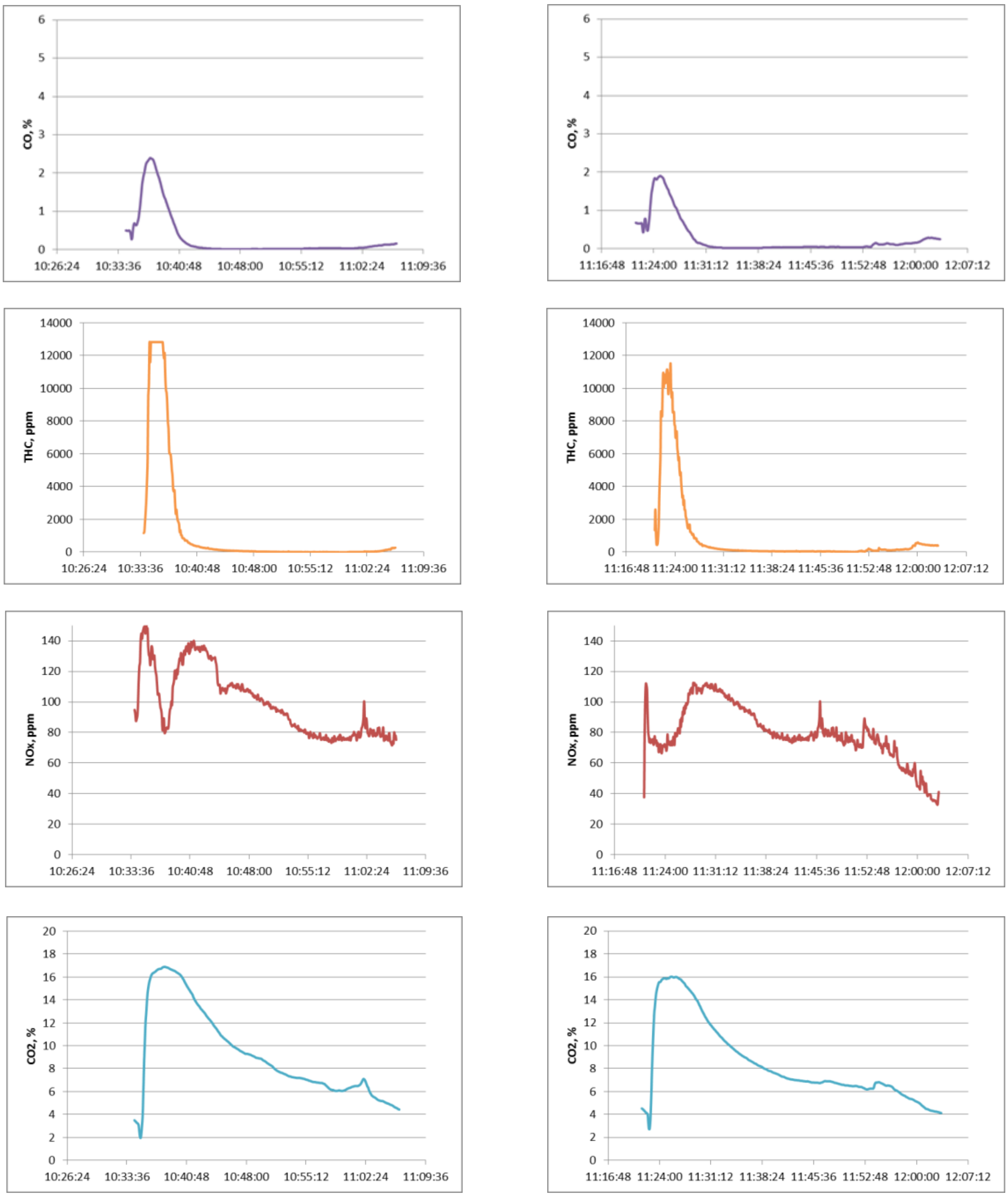


Figure A3.1b DIN+ 70°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 3 (left) and Test 4 (right)

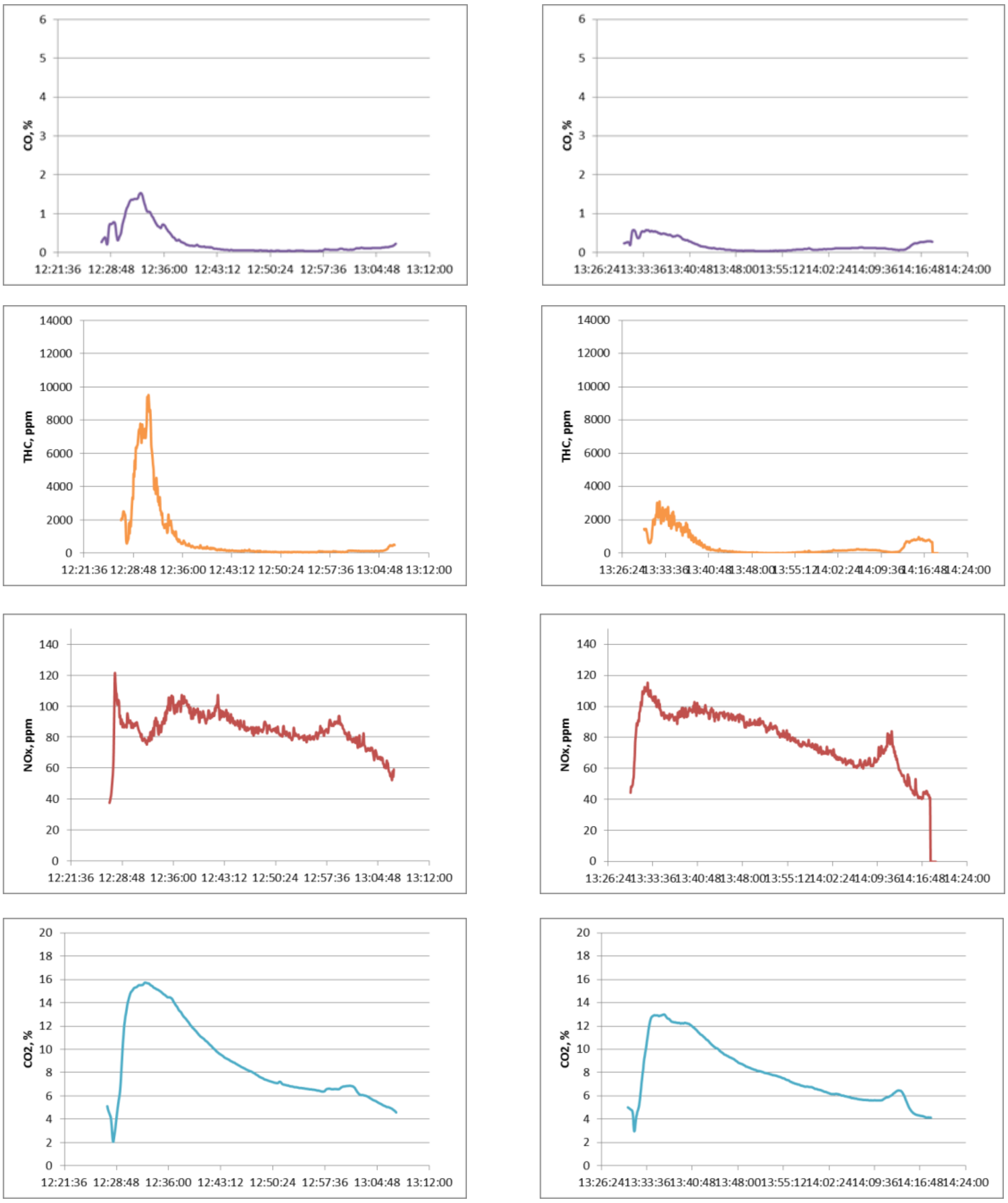


Figure A3.1c DIN+ 70°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 5 (left) and Low Output Test 1 (right)

Figure A3.1d DIN+ 70°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, Low Output, Test 2 (left) and Test 3 (right)

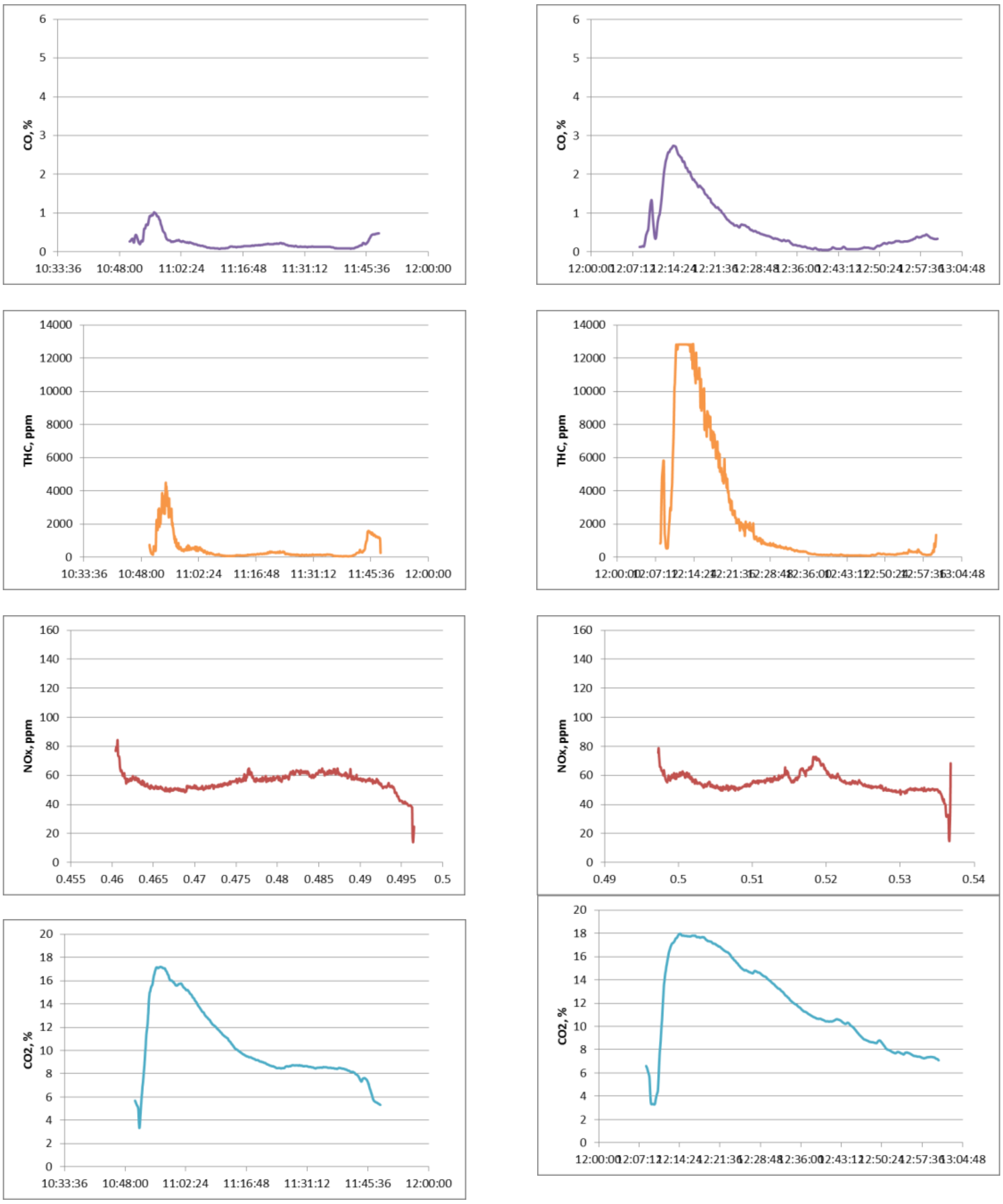


Figure A3.1e DIN+ 70°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, Low Output, Test 4 (left) and Test 5 (right)

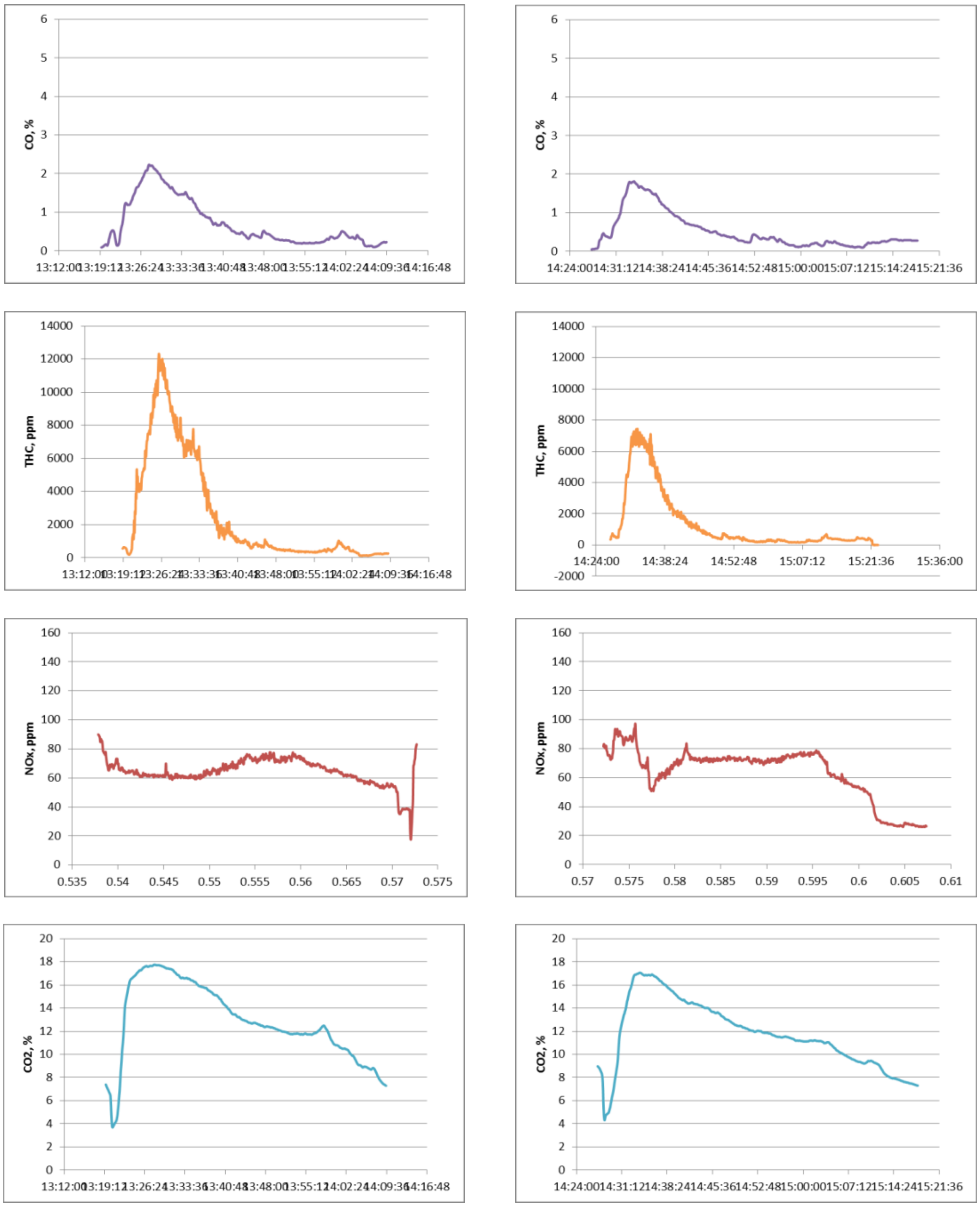
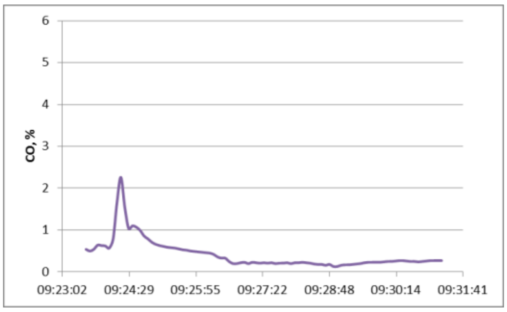
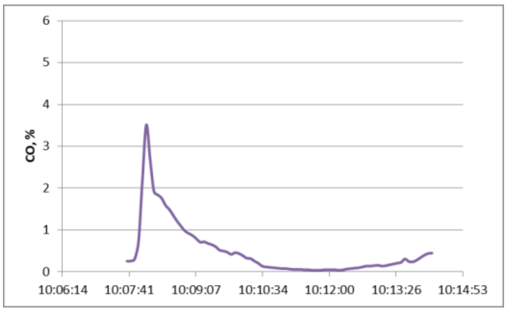
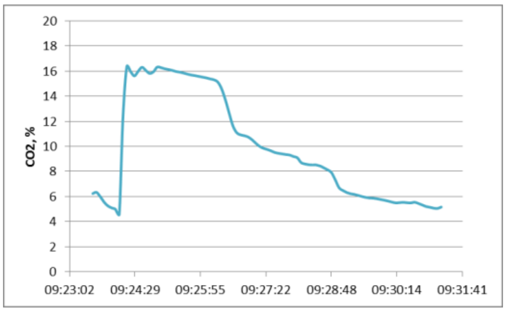


Figure A3.2a DIN+ 160°C method: Flue gas measurement traces of CO and CO_2 for Appliance B, High Output, Test1 (left) and Test 2 (right)







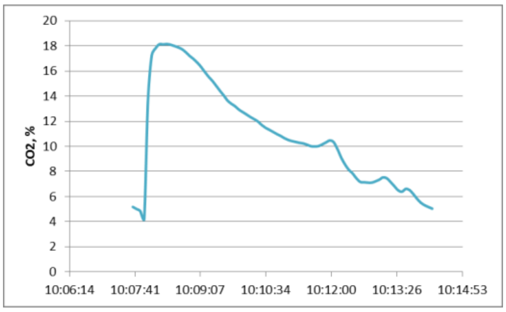


Figure A3.2b DIN+ 160°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 3 (left) and Test 4 (right)

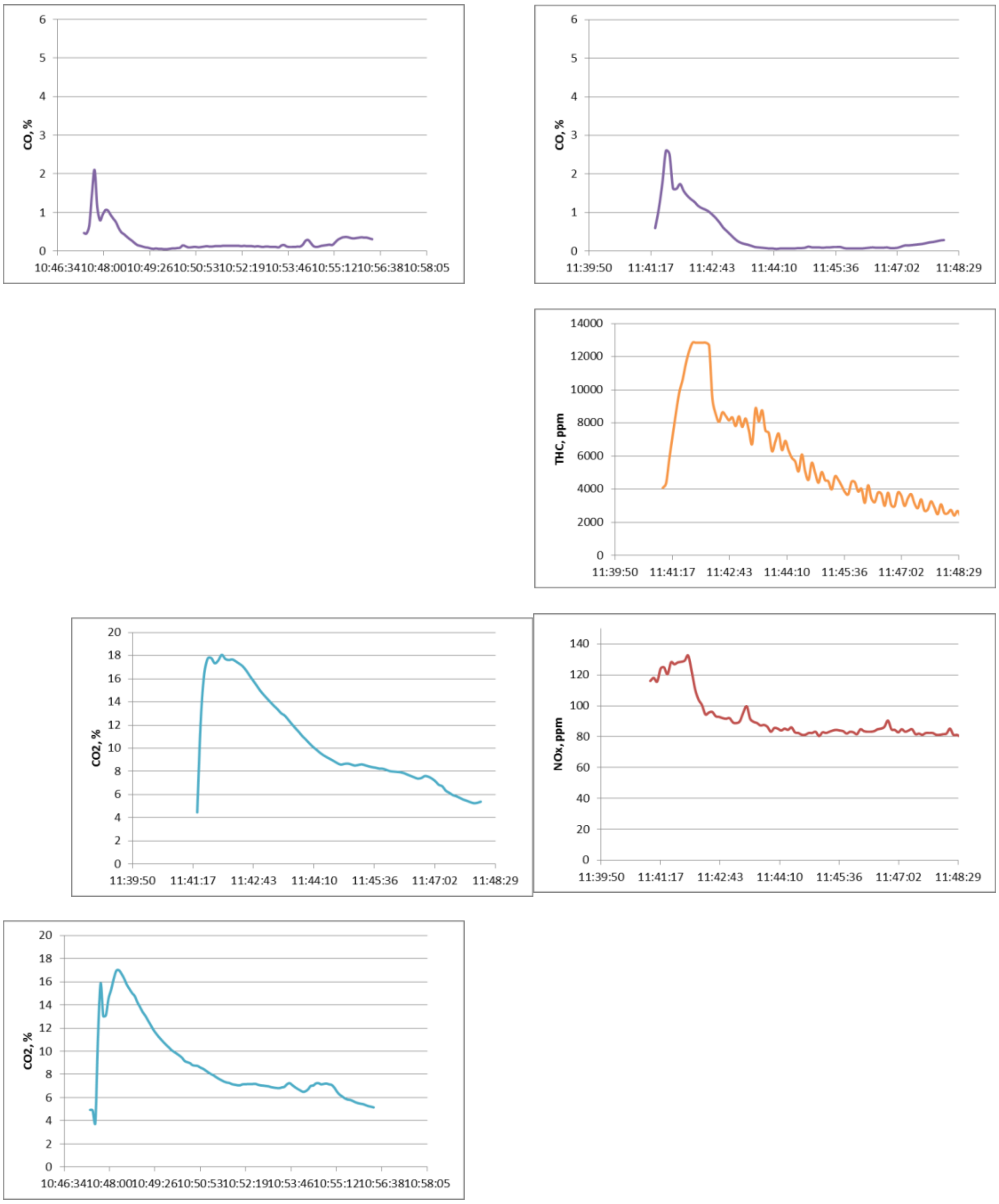


Figure A3.2c DIN+ 160°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 5 (left) and Low Output Test 1 (right)

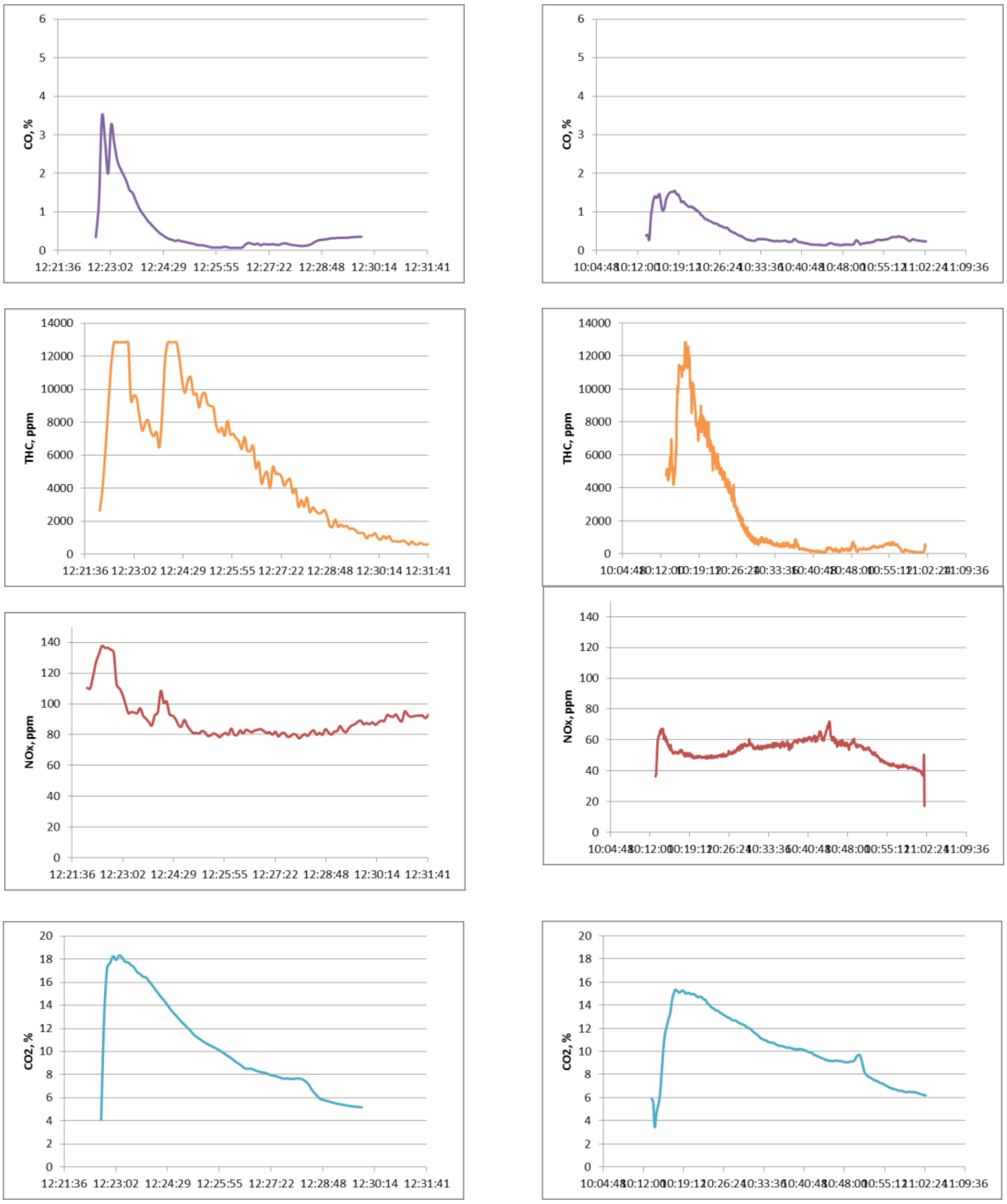


Figure A3.2d DIN+ 160°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, Low Output, Test 2 (left) and Test 3 (right)

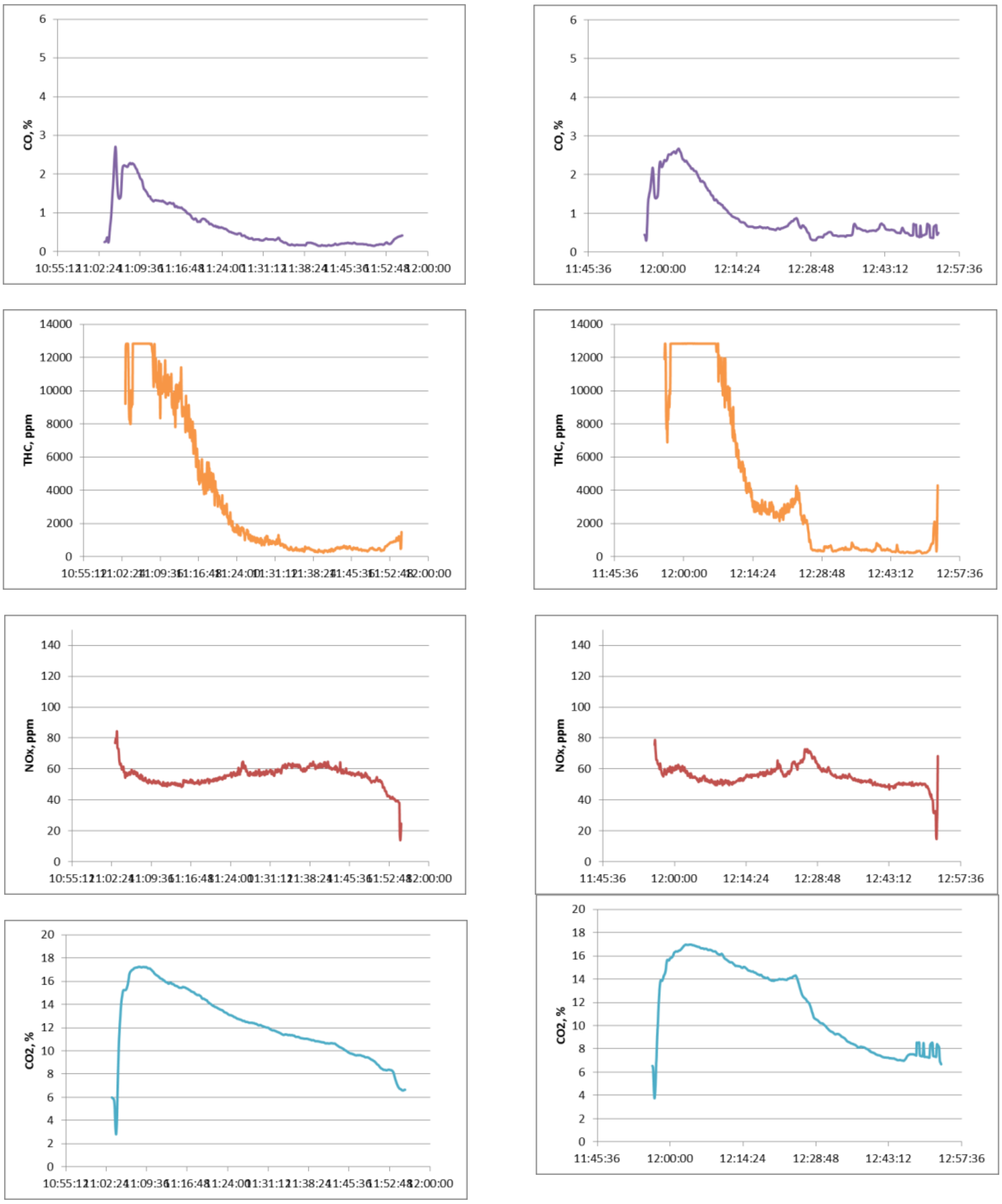


Figure A3.2e DIN+ 160°C method: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, Low Output, Test 4 (left) and Test 5 (right)

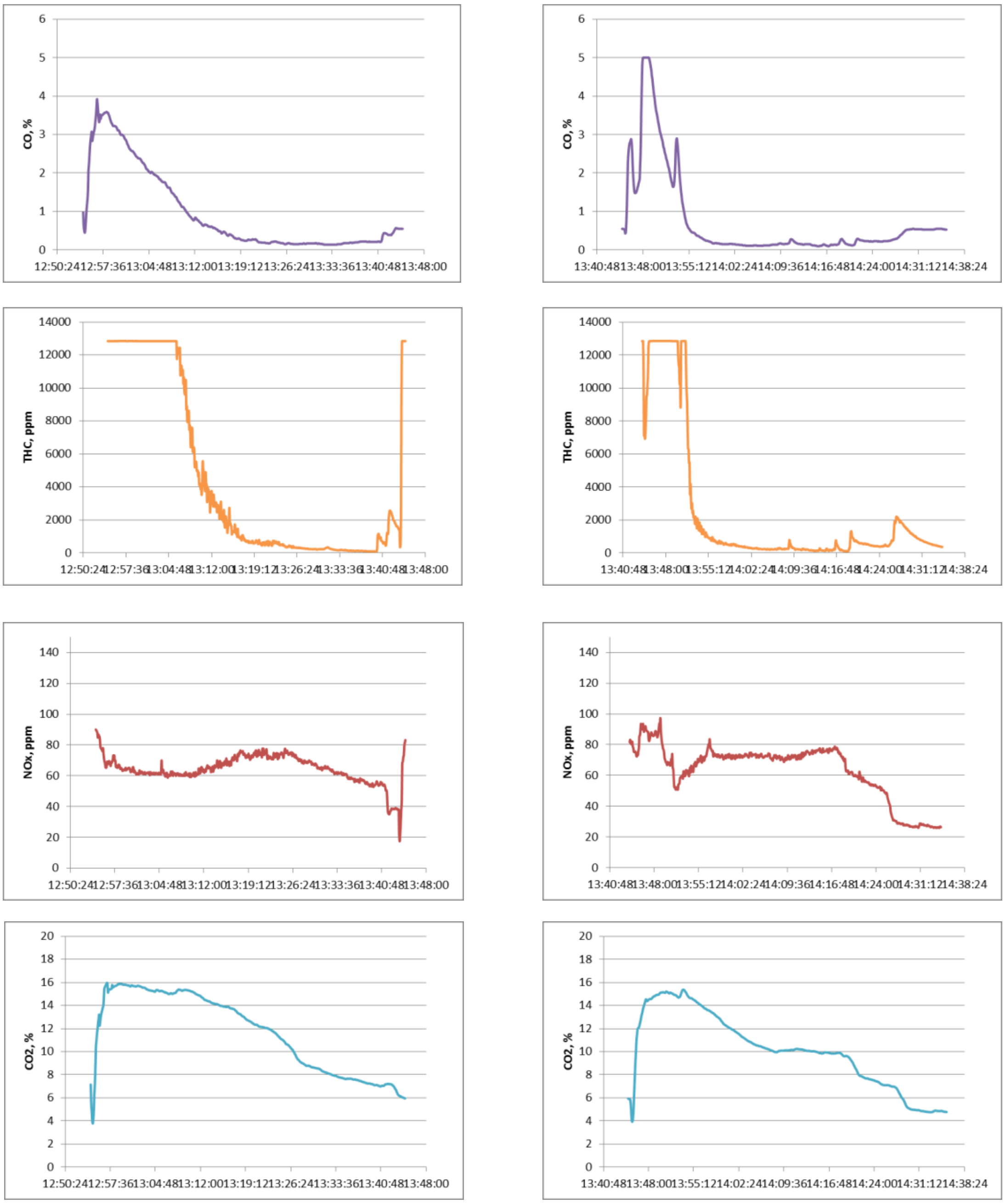


Figure A3.3a DIN+ 70°C method +3 mins at start: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test1 (left) and Test 2 (right)

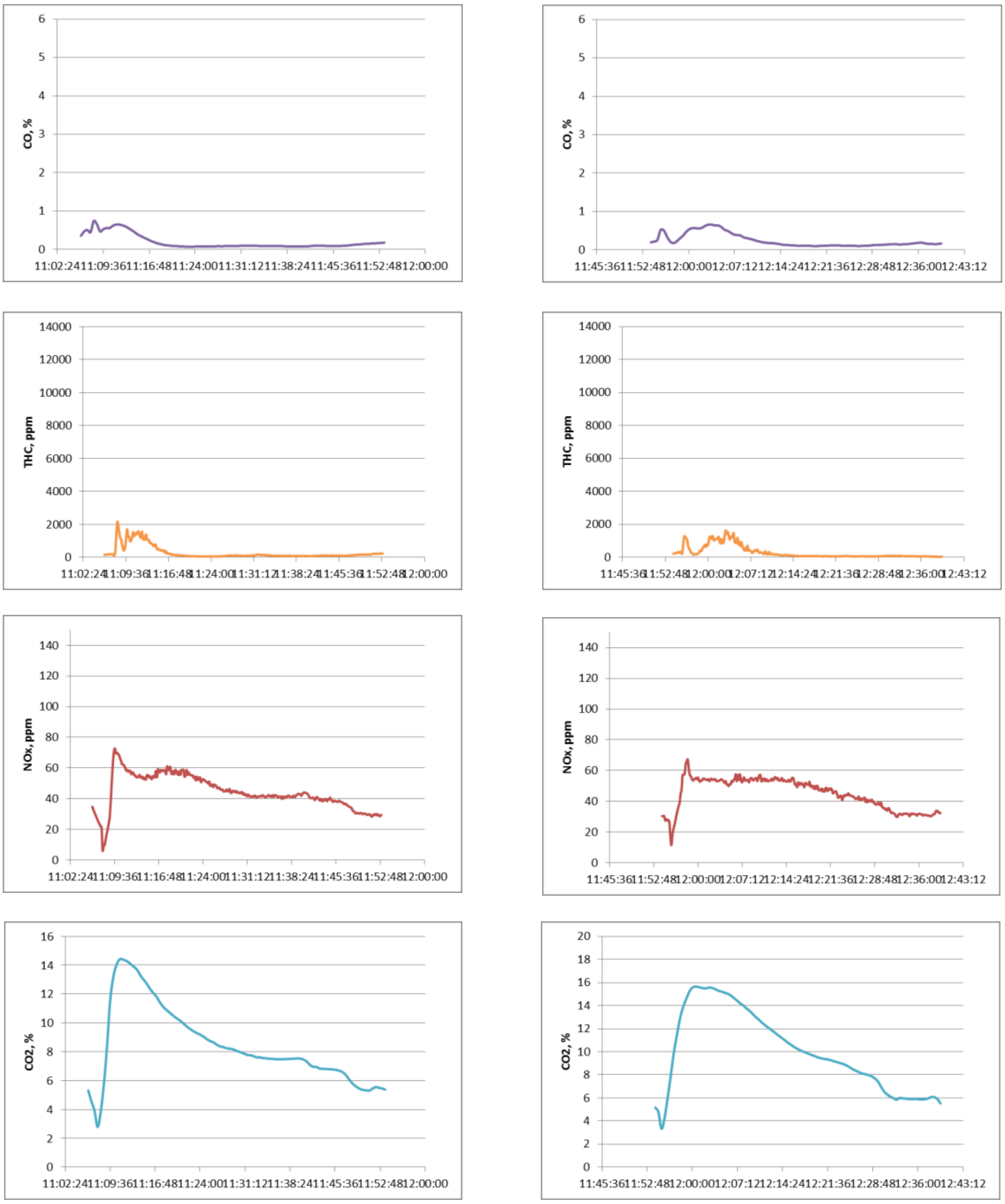


Figure A3.3b DIN+ 70°C method+3 mins at start: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 3 (left) and Test 4 (right)

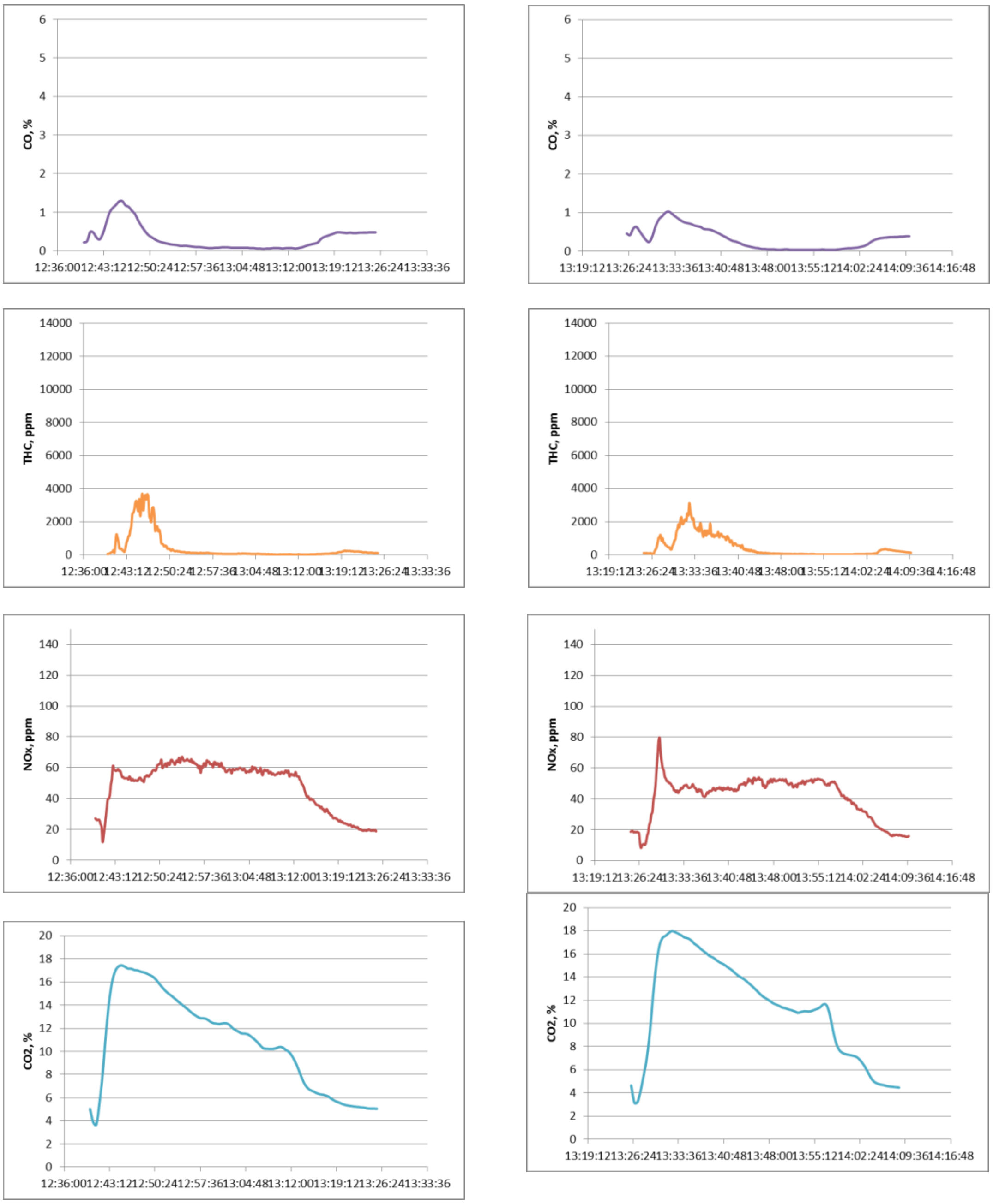


Figure A3.3c DIN+ 70°C method+3 mins at start: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 5

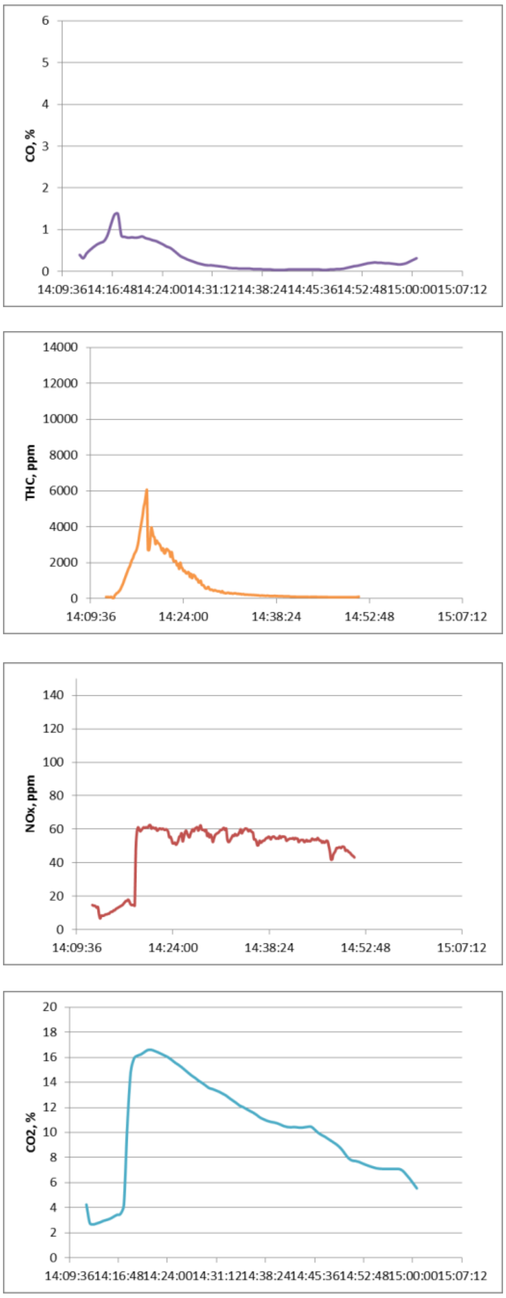


Figure A3.4a DIN+ 70°C method – full cycle: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test1 (left) and Test 2 (right)

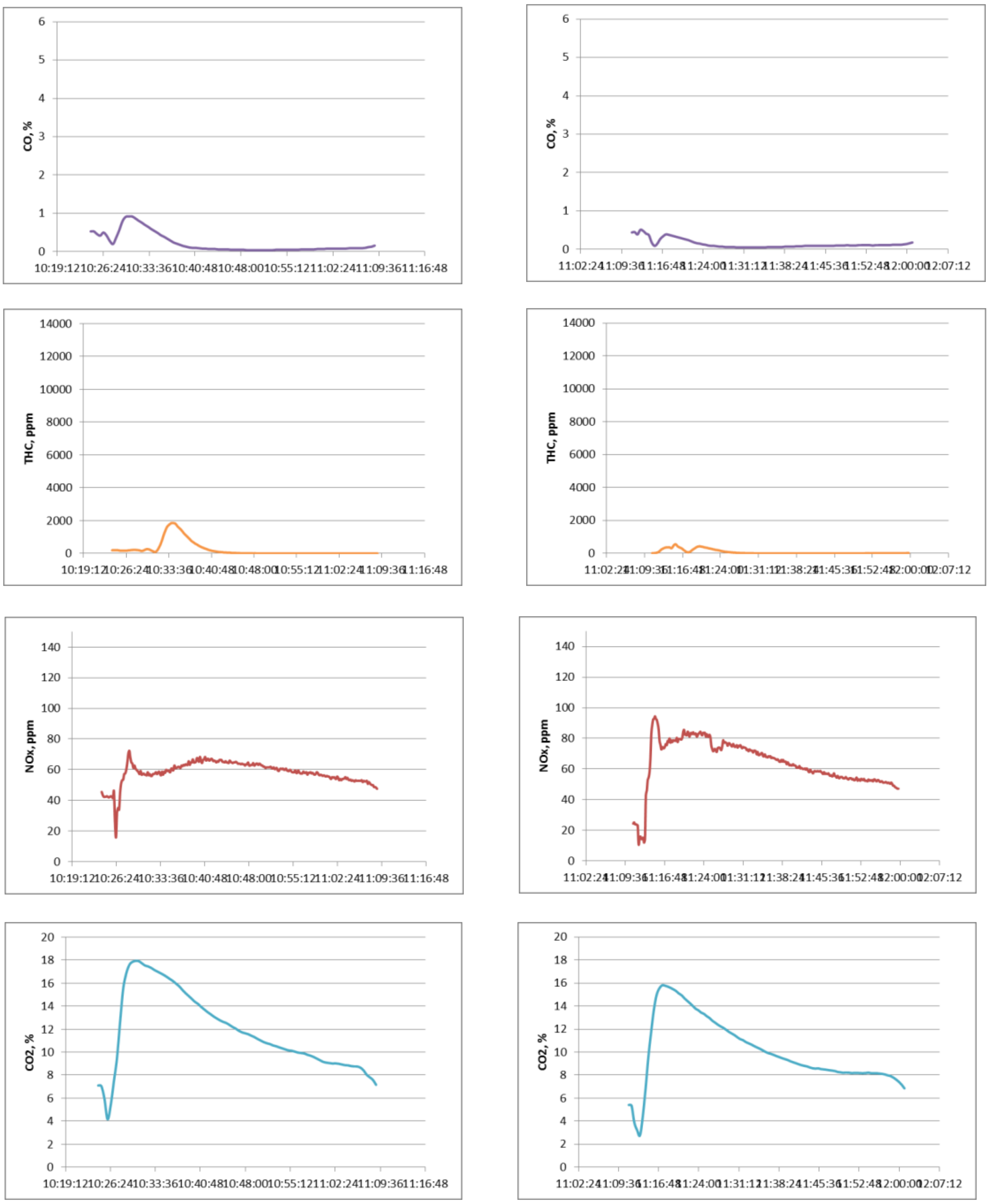


Figure A3.4b DIN+ 70°C method – full cycle: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 3 (left) and Test 4 (right)

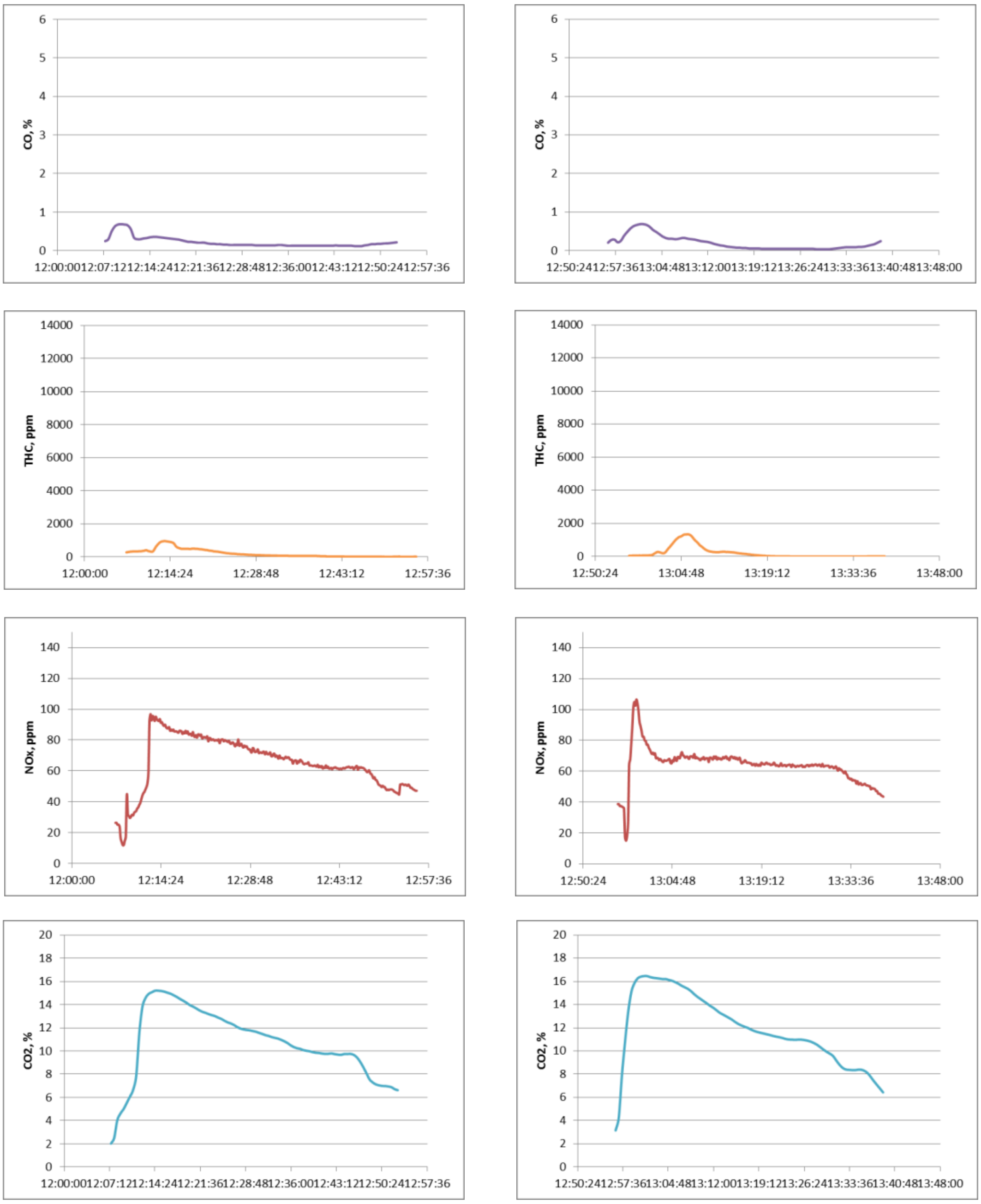


Figure A3.4c DIN+ 70°C method – full cycle: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 5

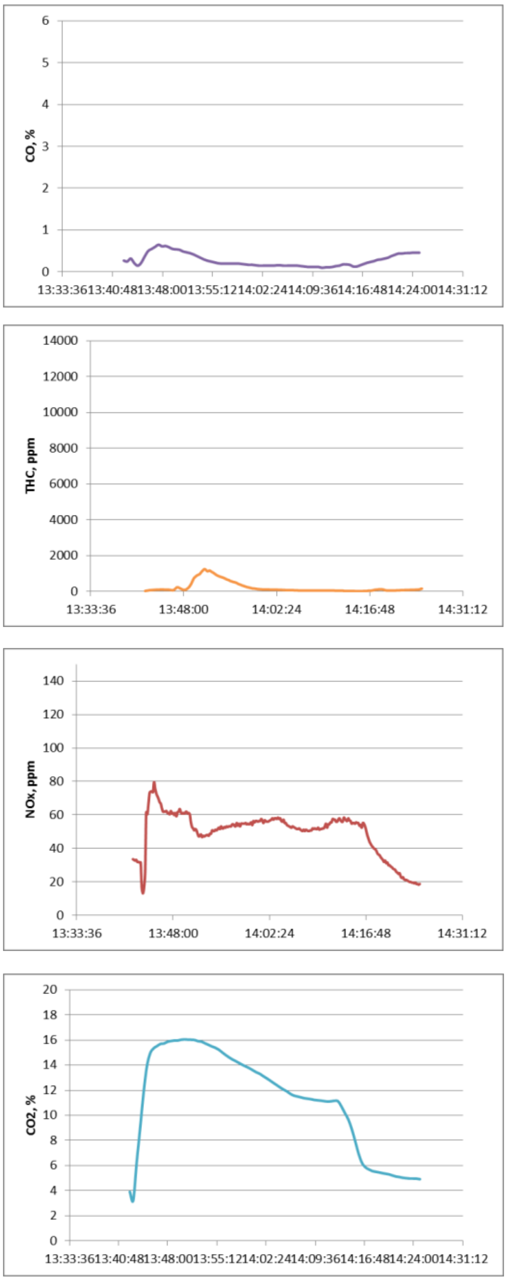


Figure A3.5a DIN+ 70°C method with individual pre-filter washings: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test1 (left) and Test 2 (right)

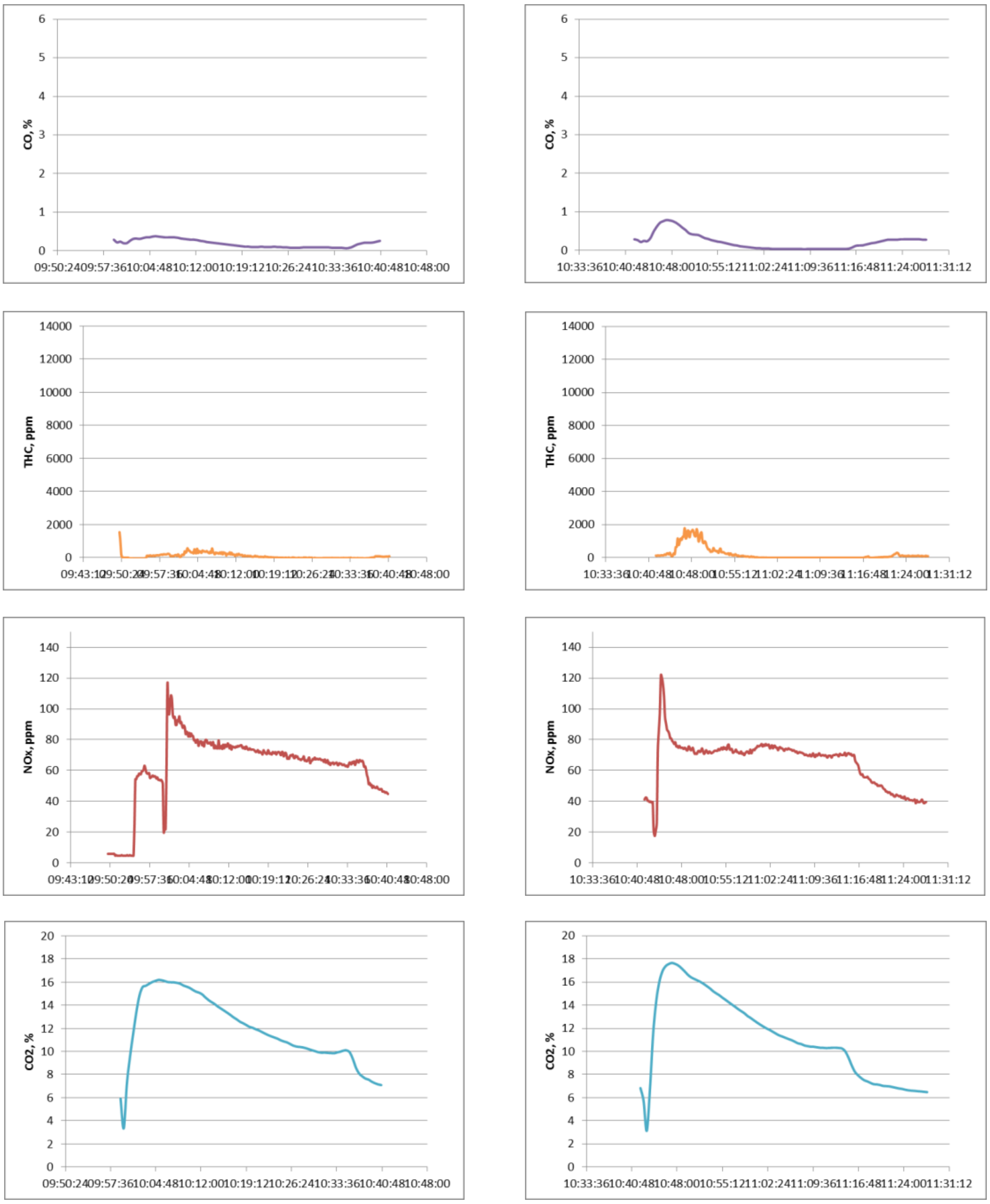


Figure A3.5b DIN+ 70°C method with individual pre-filter washings: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 3 (left) and Low Output Test 1 (right)

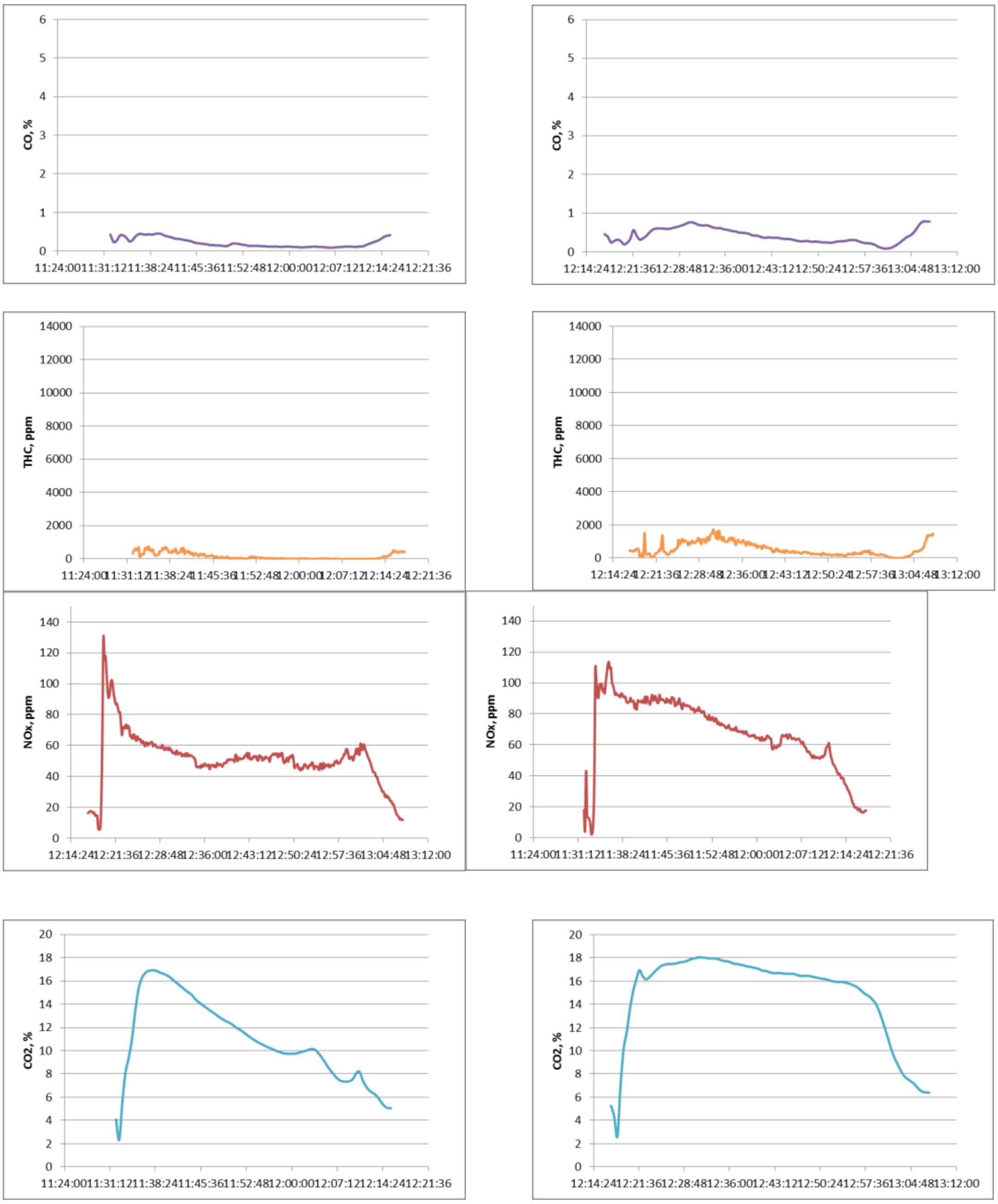


Figure A3.5c DIN+ 70°C method with individual pre-filter washings: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, Low Output, Test 2 (left) and Test 3 (right)

Figure A3.6a DIN+ 70°C method with 10minute samples: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 1 (left) and Test 2 (right) with particulate measurements for comparison

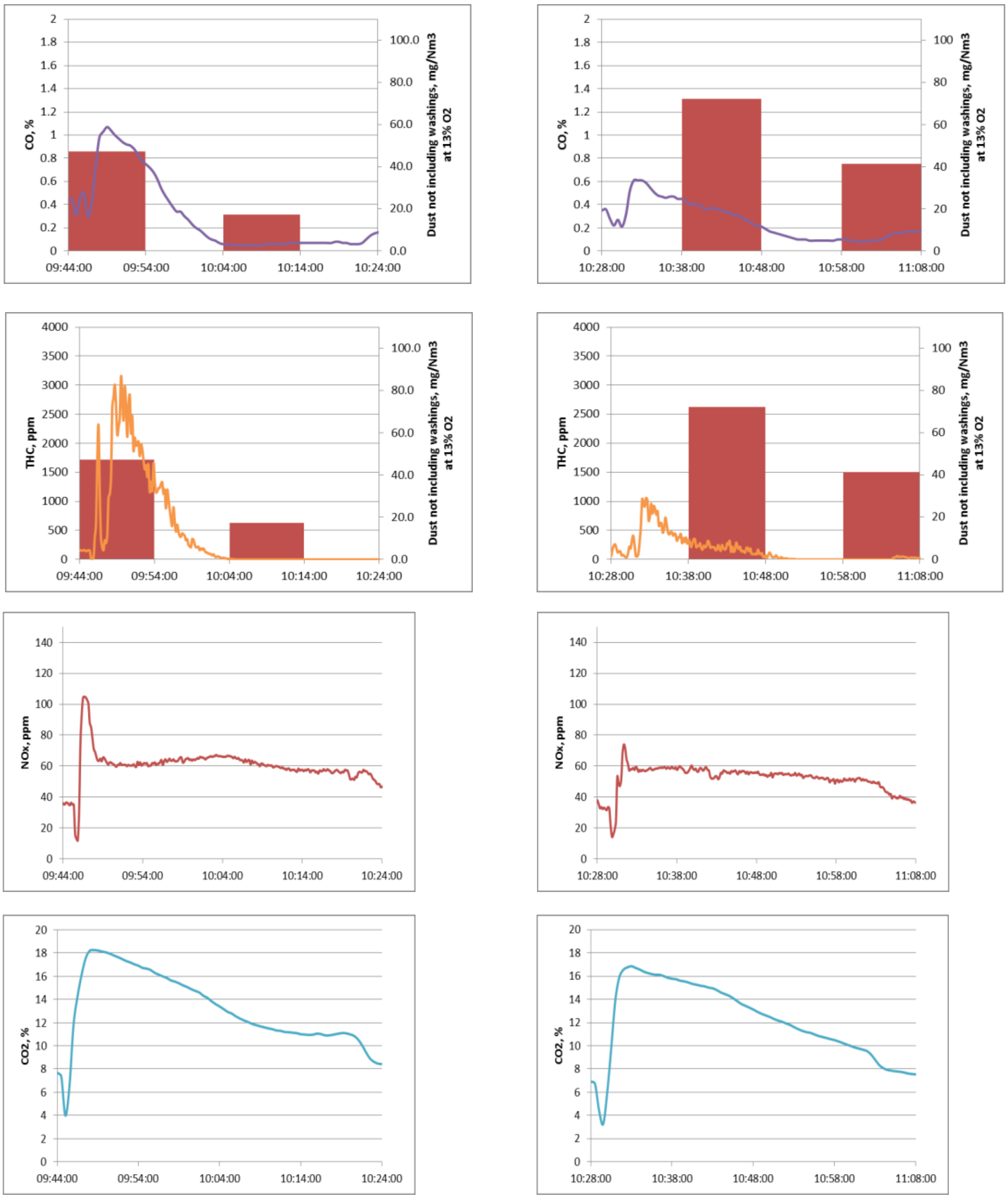


Figure A3.6b DIN+ 70°C method with 10minute samples: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 3 (left) and Test 4 (right) with particulate measurements for comparison

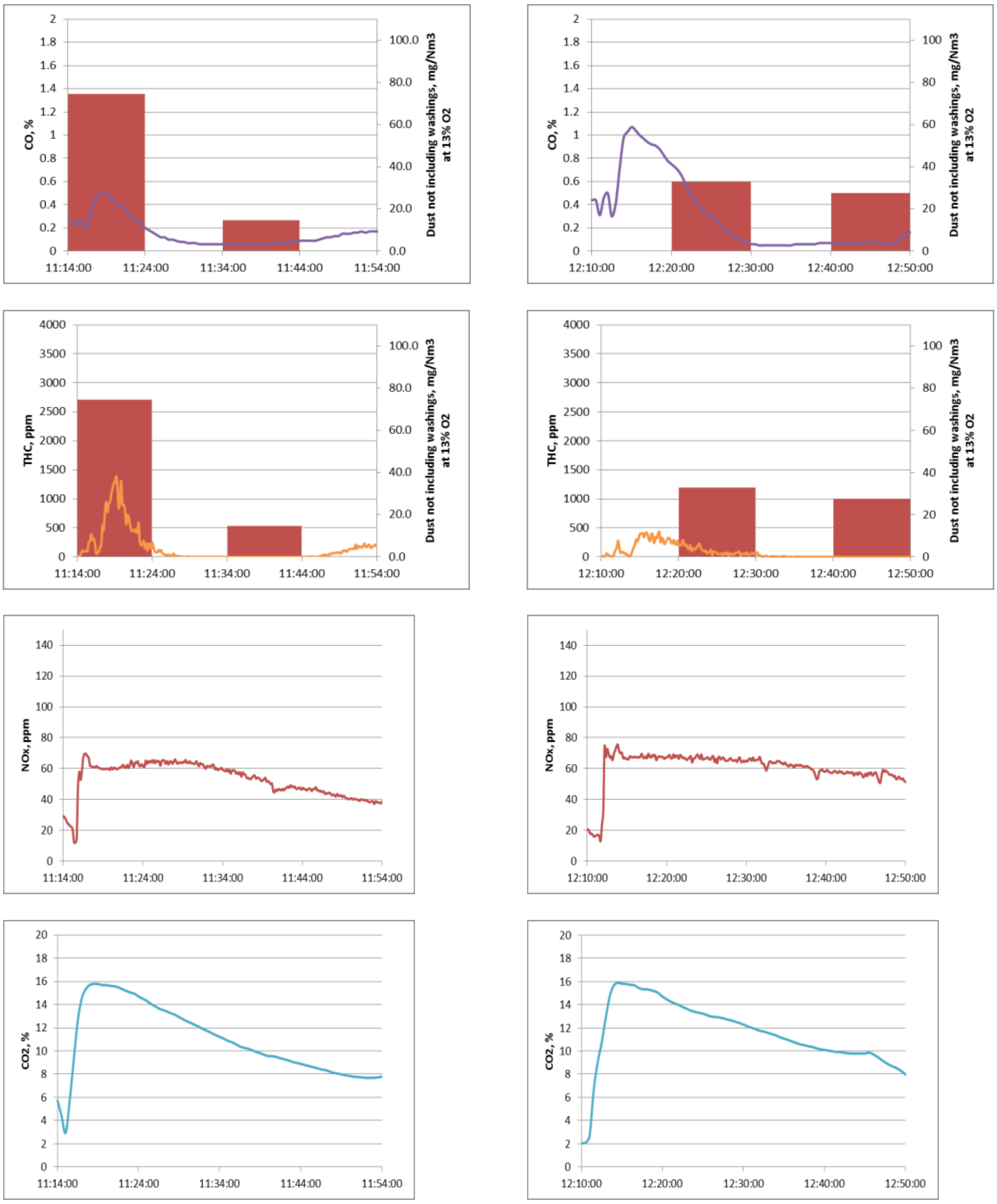
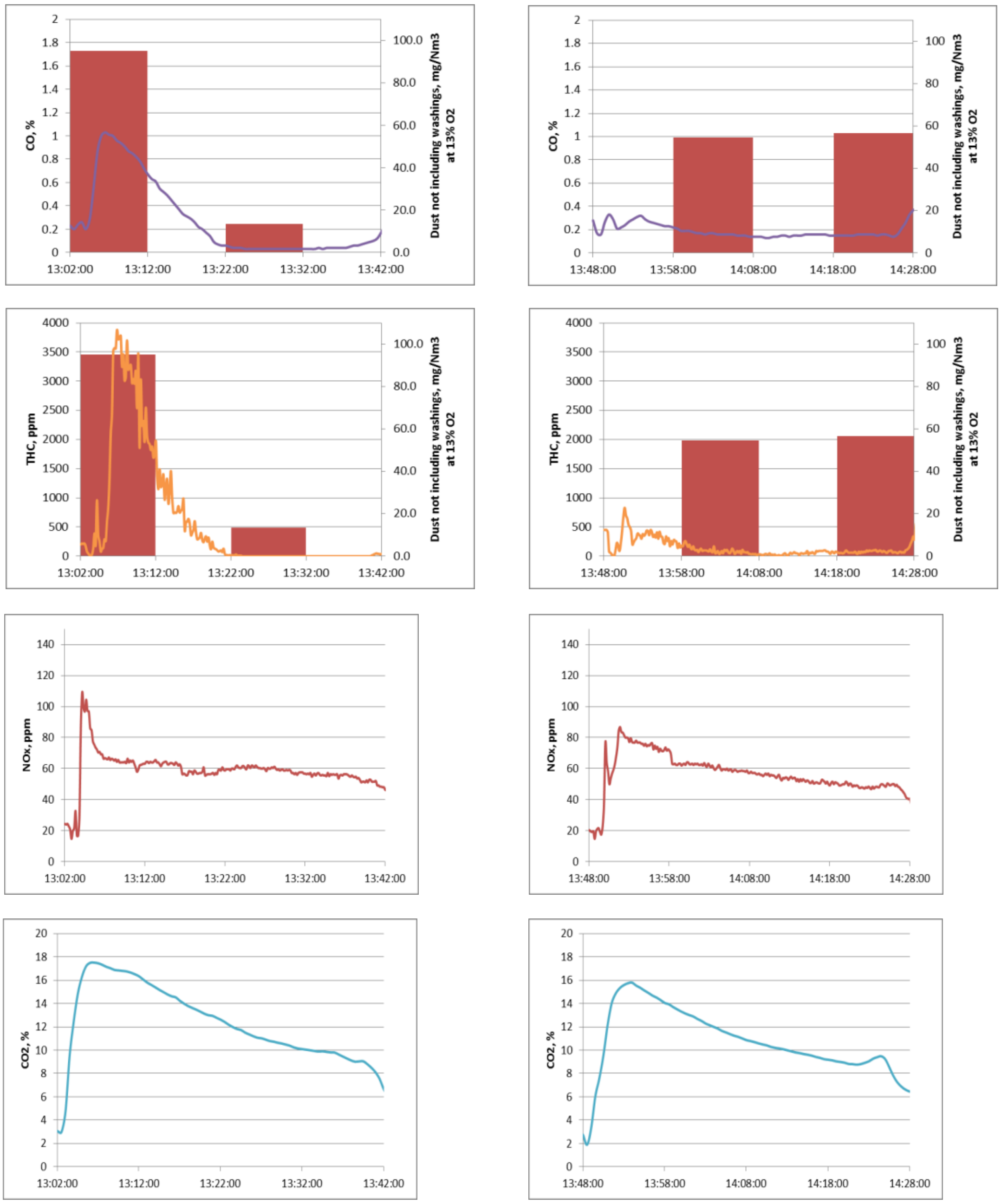


Figure A3.6c DIN+ 70°C method with 10minute samples: Flue gas measurement traces of CO, THC, NOx and CO_2 for Appliance B, High Output, Test 5 (left) and Test 6 (right) with particulate measurements for comparison



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