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EMISSION FACTORS FOR DOMESTIC SOLID FUELS PROJECT - WORK PACKAGE 1 REPORT

Report for: Defra

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Date:
5/1/2024

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We would like to dedicate this report to our dear friend and colleague, Prof Alan Williams, who passed away suddenly on 6th September 2023.

Alan was a lively and valued member of the research team on this project with nearly 70 years' experience in fuels, combustion and emissions. We will remember him as someone who was always sharp, always insightful, always prompting lively debate, and someone with a genuine thirst for enquiry in research. He is fondly remembered and sadly missed.

GLOSSARY

AMS	Aerosol Mass Spectrometer
AQEG	Defra Air Quality Expert Group
AQISG	Air Quality Inventory Steering Group
AVEC	Light Attenuation Versus Evolved Carbon
BC	Black Carbon
BS	British Standard
CAS	Centre for Atmospheric Sciences (University of Manchester)
CEMS	Continuous Emission Monitoring Systems
CEN/TS	CEN Technical Specification
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO	Carbon Monoxide
Defra	Department for Environment, Food and Rural Affairs
DP	Differential Pressure
EC	Elemental Carbon (Black Carbon)
ECL	Environmental Compliance Limited
EEA	European Environment Agency
EF	Emission Factor
EFDSF	Emission Factors for Domestic Solid Fuels (this project)
EIG	Emission Inventory Guidebook
EMEP	European Monitoring and Evaluation Programme (of the UN Convention on long-range Transboundary Air Pollution)
EN	European Standard
EPA	Environmental Protection Agency (US)
FID	Flame Ionisation Detector
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatography-Mass Spectrometry
GJ	Gigajoules
HEPA	High-Efficiency Particulate Air
HETAS	Heating Equipment Testing and Approval Scheme
ISO	International Organization for Standardization
I-TEQ	International Toxic Equivalent
IVOC	Intermediate Volatile Organic Compounds
LOD	Limit of Detection
MCERTS	Monitoring Certification Scheme
MCS	Microgeneration Certification Scheme
MJ	Megajoules
MSF	Manufactured Solid Fuels
MST	Manual Sampling Train

NAEI	National Atmospheric Emissions Inventory
NMVOC	Non-Methyl Volatile Organic Compounds
NO	Nitrogen Oxide
NO_X	Nitrogen Oxides
NPL	National Physical Laboratory
OC	Organic Carbon
PAH	Polycyclic Aromatic Hydrocarbon
PCDD/F	Polychlorinated Dibenzo-p-Dioxins and Polychlorinated Dibenzofurans (also referred to simply as 'Dioxins')
PM	Particulate Matter
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
QA/QC	Quality Assurance/ Quality Control
SCAPE	School of Chemical and Process Engineering (University of Leeds)
SG	Steering group
SOA	Secondary organic aerosol
SO_X	Sulfur Oxides
STP	Standard Temperature and Pressure
SVOC	Semi-volatile Organic Compounds
TB	Test Batch
TC	Total Carbon
TGA	Thermogravimetric Analysis
TOC	Total Organic Carbon
TPM	Total Particulate Matter
UKCA	UK Conformity Assessment
VOC	Volatile Organic Carbon
WP	Work Package

1. EXECUTIVE SUMMARY

1.1 Introduction

This is the Work Package 1 Report for the project “Emission Factors for Domestic Solid Fuels”. The project is being undertaken by Ricardo Energy and Environment (Ricardo), Kiwa Gastec (Kiwa), Environmental Compliance Ltd (ECL), University of Manchester and University of Leeds for the United Kingdom Department for Environment, Food and Rural Affairs (Defra).

Work Package 1 concerns the development of emission factors for the combustion of wood at different moisture contents in a range of appliances that can be commonly found in domestic residences in the UK, at the time of writing.

This report contains background information about the project team, scope of work and methodology. It includes detailed information about the fuels and appliances, and results of the test programme which have been used to develop the emission factors. Within the report, the authors outline the challenges and uncertainties associated with the final emission factors.

The emission factors developed through this project will be used directly in the UK National Atmospheric Emissions Inventory, which fulfils reporting requirements under the National Emissions Ceiling Directive (NECD) (transposed into UK law as the National Emissions Ceiling Regulations (NECR); the United Nations Economic Commission for Europe (UNECE)’s Convention on Long Range Transboundary Air Pollution (CLRTAP).

In addition to fulfilling the national and international reporting requirements, the NAEI provides emissions data for a wide range of other uses including providing policy makers and the public with an understanding of the key polluting sources, how these sources have varied over time and how they are likely to contribute to pollution in the future.

1.2 Governance

A Steering Group has been set up by Defra to provide expert advice around domestic solid combustion, emissions measurements, and emissions factors calculations; to review progress and outcomes from the emissions factors project. The Steering Group are required to review and approve results, reports, model(s), calculations and other project outputs and challenge assumptions. The Steering Group has convened several times during this study and has given approval to proceed at key stages of the project:

1. Approval of the Test Protocol
2. Approval to proceed to the main test programme following review of results from the Round Robin testing
3. Approval of the outputs of the WP1 test programme and emission factors (with some exceptions).

Selected outputs of this study have since been presented to the UK’s Air Quality Inventory Steering Group (AQISG), a separate group with remit to govern the scientific development of the NAEI and, approved by them for use in the NAEI 2021 (which was published spring 2023).

1.3 Test protocol and round robin

An early deliverable of this programme was the test protocol, in February 2022. The test protocol sets out the details of the project team’s proposed testing methodology and was informed by a round robin testing programme and feedback from the project Steering Group. It addresses several considerations including:

- How to measure ‘real-world’ emission performance.
- Consistent appliance operation.
- Pollutant Measurements.
- Methodology development for Black Carbon measurements and condensables characterisation.
- Performance characterisation - assessments of uncertainty, variability, and accuracy of measurements through repeatability testing.
- Uncertainty and accuracy of results.
- Method for the creation of final emissions factors and co-operation with the NAEI agency.

Some measurement and consistency issues were evident in the round robin exercise used to assess the test protocol. Burn rate reproducibility during operation phases was poorer than a previous Defra study and these issues were exacerbated by challenges in stove performance, which led to modifications to test procedures. However, three independent laboratories testing emissions of several pollutants using the same appliance and test protocol produced consistent results, within the uncertainty of the measurement and, particularly, noting the natural variability in the fuel used. Measurements were made over a test period of several hours duration comprising ignition (from cold), three refuels and the shutdown period.

1.4 Fuel

Using the growing stock and laboratory test fuel information beech was chosen for the test programme as it is used widely across the UK and its use in this test programme can be linked to existing data on appliance testing, allowing comparisons to be made. Three moisture content levels were selected to represent the various conditions of the wood commonly burnt in domestic settings. These were:

1. Dry wood (commonly available 'kiln dried' wood supplied in sealed plastic bags), 6% moisture content.
2. Seasoned wood (seasoned in-house), 15% moisture content targeted.
3. Wet wood (represents wood stored in outdoor/wet conditions), 25% moisture content targeted.

Fuel samples were independently analysed, and results are presented in the appendices.

1.5 Test cycle/burn cycle

The project test cycle considered emissions during ignition, steady operation including three refuels, and shutdown. This is summarised below.

Ignition

- The typical batch mass of the wood for WP1 refuels was 1.2 kg split between two logs.
- Wood logs were typically 35-38cm in length with a diameter of 5-10cm. Bark was not removed; logs were placed with the bark face pressed into the fire bed.
- For ignition the total mass of kindling material was limited at 50% of the total batch mass (0.6 kg kindling).
- The total mass of starting aids (firelighter) was limited at 3% of the total batch mass. Firelighters were placed in the centre of the kindling. A kerosene-based firelighter was used for all ignition batches.

Steady operation

The operation step is the phase where the appliance is hot and will most closely align with standard test methods for domestic solid fuel heating appliances. In this step the appliance was allowed to run and burn down fuel in the fuel bed. The fuel bed was refuelled twice more during this period of operation (three fuel batches in total), refuelling when the flames had gone out. A standardised refuel procedure is described in the test protocol.

Shutdown

The shutdown step in the test cycle is the period where the final batch is allowed to burn out completely. The start of shutdown was defined as when the flames go out.

Typical durations for each phase are:

- Start-up ¾ to 1 hour.
- Normal operation 3x~45minutes = 2½ to 3 hours.
- Shutdown 1 to 1½ hours.

1.6 Measurements

Measurements for the main test programme were taken by Kiwa and ECL at the Kiwa laboratory. A custom-made test rig was used to house the appliances, sampling equipment and analysers.

The test programme is based on measurements on **three** test cycles for each fuel and appliance combination. Note that some measurements may be taken over all phases of a test cycle and others may be collected separately during start-up, shutdown and a single operating step.

Repeat testing allowed the uncertainty in the measurements to be reported and the interval and confidence level to be expressed. For this work a normal distribution will be used to assess the uncertainty and the result expressed to a 95% confidence interval. Three tests are the minimum required to complete this assessment.

The following pollutants were measured:

Table 1-1 Pollutants measured in Work Package 1

Measurement	Measurement location	Comments
CO	Appliance outlet	Continuous measurement, unweighted CO and O_2 used to standardise integrated samples. Weighted data used to standardise continuous measurements. NOx data used in preference to dilution tunnel data.
CO_2		
TOC/HC		
NOx		
NOx	Dilution tunnel	Continuous measurements, unweighted CO data used to establish dilution ratio for integrated samples. Weighted CO data used to establish dilution ratio for continuous measurements. NOx and SO_2 not used (close to LoD and/or variable).
CO		
CO_2		
SO_2		
TOC/HC		
PM	Appliance outlet	Heated filter measurement, integrated samples for alternate phases of burn cycle.
PM	Dilution tunnel	Heated filter measurement, integrated samples for alternate phases of burn cycle.
Dioxins & Furans	Dilution tunnel	Integrated sample collected over entire burn cycle (combined sample).
PAH		
SO_2	Dilution tunnel	Integrated sample collected over entire burn cycle.
PM	Dilution tunnel	Impactor measurement, integrated samples for alternate phases of burn cycle.
PM_{10},		
$PM_{2.5}$,		
PM_1		
Black carbon	Dilution tunnel	Integrated samples collected over short periods in alternate phases of burn cycle. Analysed for EC and OC. Single sample for each fuel.
Condensable PM I	By calculation	Difference between heated filter measurements at dilution tunnel and appliance outlet.
Condensable PM II	By calculation	Difference between particle size impactor and heated filter measurements at dilution tunnel and appliance outlet respectively.

1.7 Appliances

Three stoves and an open fire have been tested during this study, to represent the installed base in the UK and to capture the significant developments in stove performance over the years. The categories and appliances tested were:

1. Open fire - **Parkray Paragon inset open fire**
2. Pre-2000 closed stove - **Hunter Oakwood**
3. 2000-2009 closed stove - **Stovax / Dovre Model Dovre 500MRF**
4. Very efficient modern stove (clearSkies level 2 or above) - **Charnwood Model: C4**

1.8 Quality and Uncertainty

An independent audit has been carried out during WP1 to assess compliance with the agreed test protocol and measurement methods. This has provided assurance that the test protocol and measurement methods have been followed and has identified improvements which have since been implemented.

The uncertainty in the final emission factors comprises a range of contributing elements including:

- Representativeness of the appliances
- Variation in fuels
- Variation in operation
- Measurement – include measurement method, sampling protocol, analysis LoD (Limit of Detection), calibration/reference materials
- Data handling – data acquisition, storage and handling – the processes to work up the measured data into the final emission factors.

These are discussed in Chapter 7.

1.9 Emission Factor Development

The measurement programme provided:

- continuously monitored emission concentration data throughout the different phases of the burning cycle for some gaseous measurements (CO, CO_2, O_2, NOx, TOC),
- an integrated concentration measurement for (PCDD/F, PAH and SOx) over the whole burn cycle,
- integrated PM-related concentration measurements for alternate phases of the burning cycle (ignition, 2^{nd} operation/refuel and burnout phases).

The calculation of emission factors for each appliance and fuel combination from the emission concentration data reported by the test houses required several calculation stages, discussed in Chapter 8.

Emission factors have been developed and agreed for use in the NAEI for dry, seasoned and wet wood for the four appliance types for NOx, SO_2, CO, NMVOC, PAH, PCDD/F. In general, although substantial changes can be seen for estimates from wood-burning, the impact of changes on UK national emissions is generally small. However, the new emission factors for PAH including Benzo(a)pyrene contribute to a significant reduction in national emissions.

Further emission factors have been developed for dry, seasoned and wet wood for the four appliance types for PM, PM_{10}, $PM_{2.5}$, PM_1. In a deviation from the intended approach, these emission factors were developed solely from the particle size measurements data due to some measurement issues. This has been proposed as a pragmatic and conservative approach. Further work is proposed to validate these emission factors using additional data in the project’s third and final work package (WP3), before incorporating them into the NAEI. WP3 includes the burning of wood fuels in a number of additional stoves of the same type/category as tested as part of WP1. Although we do not expect the new test results to be dramatically different from the previous ones, the PM emission factors presented here are subject to minor changes once the final part of the project’s test programme is completed.

In addition, condensable PM emission factors are being determined and represent the difference between PM determined at the dilution tunnel (using the particle size measurements) and PM determined at the appliance outlet. Note that condensable PM emission factors are not currently applied in the NAEI as total filterable + condensable emissions are reported.

The project team considers that the proposed country-specific emission factors:

- Better represent UK operating practise with respect to burn duration, number of refuels, fuel load, draught and wood species.
- Are based on three replicate test cycles – this is equivalent to or better than most studies referenced in the EIG.
- Better represents appliances used in the UK.
- Are based on tests for the same appliance and the same test cycles for measured pollutants.
- Provide data measured by accredited test houses using test approaches that are consistent with EN and CEN/TS approaches for emission measurement.
- Allow application of emission factors for different moisture levels.

Black Carbon emission factors have also been developed in the WP1 measurement programme but are for a more limited dataset, with only one measurement taken for each appliance-fuel combination in each phase of the burn cycle (rather than three repeat measurements). In Work Package 3, three repeat measurements will be made for black carbon, which will allow verification of the data collected so far, and the WP1 data will be combined with the WP3 data to produce a black carbon emission factor for each category of appliance, for dry, seasoned and wet wood. The black carbon data produced by WP1 has not been used to update the black carbon emission factors in the NAEI 2021 (published Spring 2023) and these factors will be reconsidered when testing in WP3 is concluded.

1.10 Recommendations

The following recommendations are made:

1. To include the emissions factors for dioxins and furans, PAHs, SO_2, CO, NO_x and NMVOCs in the NAEI21.
2. To use PM data from the dilution tunnel particle size measurement data (Dekati) for WP1 – these emission factors are generally higher and represent a more conservative approach than the comparative measurements. Where the particulate emission factors determined using the particle size equipment at the dilution tunnel are lower than at the appliance outlet (a situation for one set of tests at the open fire), the project team propose to apply the dilution tunnel data to the appliance outlet. This approach will be reviewed prior to the incorporation of new emission factors into the NAEI, when more data are available from the wider range of appliances being tested in WP3.
3. To delay incorporation of the PM emission factors into the NAEI until 2025, when more data are available from WP3, subject to review and approval by the AQISG.
4. Review black carbon (elemental carbon) measurements in WP3.

2. INTRODUCTION

2.1 BACKGROUND, AIMS AND OBJECTIVES

This is the Work Package 1 Report for the project “Emission Factors for Domestic Solid Fuels”. The project is being undertaken by Ricardo Energy and Environment, Kiwa Gastec, Environmental Compliance Ltd, University of Manchester and University of Leeds for the United Kingdom Department for Environment, Food and Rural Affairs (Defra).

The project is to provide data for the National Atmospheric Emissions Inventory (NAEI) which is a business-critical model used by Defra for policy development and to report emissions of air pollutants under international statutory obligations. The NAEI estimates emissions across a range of sectors and sources including domestic (residential) fuel use for heating, cooking and leisure.

The overall aim of the project is to reduce the uncertainty in the NAEI emission estimates for domestic combustion through the development of UK-specific pollutant emission factors for solid fuels (wood, mineral fuels and manufactured briquettes). Residential burning is a ‘key category’ in the UK emission inventory for many pollutants; this means that it is a source that makes an important contribution to the emissions totals and trends. Key categories are those which, when summed up in descending order of magnitude, cumulatively add up to 80 % of the total level. The main contributions are from solid fuel use – for some pollutants solid fuel is the largest source.

The aim of the project is to develop emission factors for a range of pollutants emitted from burning the following solid fuels in selected domestic appliances:

- wood (for a range of moisture contents)
- house coal
- anthracite
- manufactured solid fuels (MSFs)
- coffee logs.

Work Package 1 concerns the development of emission factors for the combustion of wood at different moisture contents in a range of appliances that can be commonly found in domestic residences in the UK, at the time of writing.

This report contains background information about the project team, scope of work and methodology. It includes detailed information about the fuels and appliances, and results of the test programme which have been used to develop the emission factors. Within the report, the authors outline the challenges, uncertainties associated with the final emission factors, and recommendations for further work.

2.2 SCOPE OF WORK

This project includes three technical work packages (WP1, WP2 and WP3) and a project management work package (WP4). WP1 is the “Measurement of emission factors for wood fuels” and ran from September 2021 to May 2022. WP2 is the “Measurement of emissions factors for other domestic solid fuels - house coal, anthracite, Manufactured Solid Fuels (MSFs) and coffee logs”, but is not covered in this report. Testing for WP2 is ongoing at the time of writing, and the results will be presented in a separate report later in 2022. WP3 will be an extension of WP1 and WP2, measuring emissions of the fuels in additional appliances.

Work Package 1 - Measurement of emission factors for wood fuels included the following tasks and this report draws together the deliverables outlined below:

- Development of the test protocol (Deliverable 1.1). This has included work to determine the final test protocol, black carbon method development, procurement of equipment, fuel, stoves and construction of the open fire. As part of the development of the methodology testing in three different laboratories was carried out to review repeatability and ensure that the test protocol was fully validated, tested and is robust enough for use in the test programme. This Round Robin was conducted by the University of Leeds, the University of Manchester and Kiwa, between November 2021 and January 2022.
- The main test programme for pollutants’ emissions measurements (Deliverable 1.2) ran between February and April 2022.

- Emitted pollutants speciation and categorisation (Deliverable 1.3). The full suite of species measured is given below, and the measurement results have been used to develop aggregated emission factors for each category of pollutant. This is commensurate with the aggregated emission factors used in the NAEI.
- Particulates
    - Total filterable particulate matter (including condensable fraction)
    - Particulate fractions PM_{10} / $PM_{2.5}$ / PM_1 (including condensable fraction)
    - Condensable PM fraction.

- Polynuclear aromatic hydrocarbons (PAHs)
    - *Anthanthrene*
    - *Benzo(a)anthracene*
    - ***Benzo(a)pyrene***
    - ***Benzo(b)fluoranthene***
    - *Benzo(b)napth(2,1-d)thiophene*
    - *Benzo(c)phenanthrene*
    - *Benzo(ghi)perylene*
    - ***Benzo(k)fluoranthene***
    - *Cholantherene*
    - *Chrysene*
    - *Cyclopenta (c,d)pyrene*
    - *Dibenzo(a,i)pyrene*
    - *Dibenzo(ah)anthracene*
    - *Fluoranthene*
    - ***Indeno (1,2,3-cd)pyrene***
    - *Napthalene*

    *Note the compounds in **bold** are required for international reporting.*

- Polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs)

  We monitored the following tetra, penta, hexa and hepta chlorinated dibenzo dioxin and furan congeners which have toxic equivalence factors:
    - *2378-TCDD*
    - *12378-PCDD*
    - *123478-HxCDD*
    - *123678-HxCDD*
    - *123789-HxCDD*
    - *1234678-HpCDD*
    - *2378-TCDF*
    - *12378-PCDF*
    - *23478-PCDF*
    - *123478-HxCDF*
    - *123678-HxCDF*
    - *234678-HxCDF*
    - *123789-HxCDF*
    - *1234678-HpCDF*
    - *1234789-HpCD*

    *Note the **total** (expressed as a toxic equivalence) is required for international reporting.*

    - Black carbon refers to only condensed phase species, and will include the IVOC and SVOC that is condensable on the filter media taken from the cooled dilution tunnel sampling point.
    - IVOC and SVOC speciation will not be measured within the scope of the full test program, but limited speciation was performed within development of the test protocol phase at Manchester.
    - SO_2 **,** NOx, CO, TOC
- Emissions Factors development (Deliverable 1.4)
- Co-operation with NAEI compilation agency (Deliverable 1.5).

The WP1 scope of work is summarised in Table 2-1, below.

Table 2-1 : Summary of Technical Work Package 1 specification

WP	Item	Requirement		
1	***Measurement of emission factors for wood fuels***			
1.1	Test protocol	As real-world and repeatable as possible		
1.2	Measurements	Fuel	Appliance	Pollutant
		Three wood moisture ranges 0-10% (very dry wood); 11-20% (seasoned wood); 21-30% (wet wood).	3-4 appliances (open fire and stoves)	$PM_{2.5}$ filterable and condensable Polycyclic aromatic hydrocarbons (PAHs)/ Benzo[a]pyrene (B[a]P) Polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) SO_2 Black Carbon
1.3	Speciation and categorisation of particulate and condensable pollutants	Definition of $PM_{2.5}$, range of condensables (e.g.: intermediate/semivolatile/volatile Volatile Organic Compounds (VOCs)), volatility range of VOCs/intermediate-volatility organic compounds (IVOCs)/semivolatile organic compounds (SVOCs)/organic aerosol covered		
1.4	Develop Emission factors	For pollutants of interest		
1.5	Liaise with NAEI	To ensure that emission factors can be used seamlessly in the Inventory		
Other	-	Identify species, type(s), shape and size of wood fuels – to reflect domestic burning activity in UK. Agree a moisture test procedure and wood storage management.		

2.3 PROJECT INCEPTION PLAN

A full description of the scope of work and approach was set out in the project Inception Plan, which was presented to the Steering Group and Defra and agreed at the project outset. Elements covered in the Inception Plan included the following:

- The aims and objectives
- The scope of work including pollutant measurements undertaken
- Development of the Test Protocol
- Pollutant measurement methods
- Round Robin testing
- Development of black carbon test protocol
- Elaboration of emission factors from measured concentration data
- Establishing collaboration with NAEI compilation agency
- Appliance choice and procurement
- Fuel choice and analysis
- Project plan

These elements have also been addressed in the WP1 report because elements of the work programme (for example the test protocol and the black carbon sampling procedure) were informed by development work within the project.

2.4 TEAM

The project team includes the current National Atmospheric Emissions Inventory (NAEI) Agency (Ricardo), and the project team fully understand the existing model and the needs of the Inventory Agency for incorporating new information. Several members of the Ricardo team are also part of the NAEI project team and have a detailed understanding of the NAEI, residential combustion models and international best practise for emission inventories.

Ricardo is an energy and environmental consultancy, providing overall management and technical leadership of the programme of work.

Kiwa Gastec have led the procurement, set up and testing of emissions from the range of appliances covered by this work. Kiwa holds accreditations for laboratory testing of solid fuels and appliances and measurement of smoke emissions, for product certification under the Microgeneration Certification Scheme (MCS) of biomass appliances and for UK Conformity Assessment (UKCA) Approved Body activities under the Construction Product Regulation for solid fuel heating appliances.

Environmental Compliance Limited (ECL) is an accredited emissions monitoring test house that have carried out testing of PCDDs/PCDFs/PAHs/PCBs, Acid Gases, Volatile Organic Compounds and combustion gases in Work Package 1.

The **University of Leeds** School of Chemical and Process Engineering (SCAPE) have provided expert advice to the project team through the project Steering Group and verification of the test protocol through participation in Round Robin testing. It has world-class facilities for the characterisation of solid fuels, including a fully instrumented, biomass heating stove test facility (gas analysis, temperature measurements, burning rates, flow rates, total particulate, particle size, VOC all in situ; PAH ex situ).

The Centre for Atmospheric Sciences (CAS) at the **University of Manchester** have also provided expert advice and test protocol verification through participation in Round Robin testing. Their state-of-the-art laboratories have been used to provide further detailed analysis of the black carbon and condensable fractions of the emitted pollutants.

2.5 STEERING GROUP

2.5.1 Role and composition

A Steering Group has been set up by Defra to provide expert advice around domestic solid combustion, emissions measurements, emissions factors calculations; and to review progress and outcomes from the emissions factors project. The Steering Group are required to review and approve results, reports, model(s), calculations and other project outputs and challenge assumptions. At the end of the project, the Steering Group will advise the NAEI Air Quality Inventory Steering Group (AQISG) on whether to adopt the new emission factors into the NAEI.

Defra's Emission Factors for Domestic Solid Fuels Steering Group includes representatives from the following organisations:

- Defra Air Quality and Industrial Emissions team
- Department for Energy Security and Net Zero (formerly Department for Business, Energy and Industrial Strategy)
- Defra Air Quality Expert Group (AQEG)
- Team representatives from the Supplier (Ricardo)
- Supplier's sub-contractors (University of Manchester, University of Leeds, Kiwa Gastec, Environmental Compliance Limited)
- Experts in domestic combustion, appliance testing and air quality science, including HETAS, National Physical Laboratory and Aarhus University.

2.5.2 Terms of Reference

The Emissions Factors for Domestic Solid Fuels Steering Group (EFDSF SG) has been established to:

- Provide expert advice around domestic solid combustion, emission measurements and emission factors calculations
- Review progress and outcomes from the emission factors for domestic solid fuels project
- Fulfil a role in steering and/or advising on the delivery of the project relevant to members' expertise - review and approve results, reports, model(s), calculations and other project outputs and challenge assumptions

- Recommend the incorporation of these factors into the NAEI by working with the Air Quality Inventory Steering Group (AQISG) (run separately to this project). The final decision on whether to adopt these factors into the NAEI will be made by the AQISG.

2.5.3 Steering Group Meetings

The first Steering Group meeting and Technical Workshop was held on the 2nd September 2021 to present the project Inception Plan, Gantt chart and technical approach.

A second Steering Group meeting was held on 25th November 2021, at which the draft test protocol was discussed and views from the expert members sought. These were incorporated into the test protocol, which was approved by the Steering Group, along with the appliances and fuels to be included in testing, in December 2021.

The third Steering Group meeting was held on the 16th February 2022 to present and discuss the results of an initial Round Robin test programme. Following the circulation of the test results, approval was given for the project to proceed to the main programme of testing.

A fourth Steering Group meeting took place on 7th July 2022 to discuss potential issues in the setup of the filter holder in the heated filter sampler which could potentially cause a bypass of particulate matter, see section 6.9 for more detail.

A fifth meeting was held on 12th September 2022, to examine the results of the main test programme and the developed emission factors. Following this meeting, the Steering Group approved the outputs of the WP1 test programme and emission factors (with some exceptions), and these have since been presented to the UK's Air Quality Inventory Steering Group (AQISG), a separate group with remit to govern the scientific development of the NAEI. In November 2022 the AQISG approved the use of the new emission factors in the next annual NAEI compilation cycle 'NAEI 21', which includes annual emissions datasets up to 2021 and were published in Spring 2023 at https://naei.beis.gov.uk/. This report is provided as evidence, and contains further detail and explanation of methods, analysis of data and a review of the newly developed emission factors.

New emission factors have been approved and have been included in the NAEI 21 dataset, for dioxins and furans, PAHs, SO_2, CO, NO_x and NMVOCs. Emission factors have also been approved by the project steering group and AQISG for Total PM, PM_{10}, $PM_{2.5}$, PM_1 and condensable PM; however, the emissions factors will not be included in the NAEI until they are reviewed again when more data are available from WP3.

2.6 RELATED REPORTS

An inception report and test protocol were produced as part of the project, but key information has been included in this report. In addition, further reports will be produced for WP2 and WP3 after test work is completed, and emission data finalised. More details can be obtained by contacting the NAEI helpline[1].

2.7 PURPOSE

In previous work by Kiwa and Ricardo for Defra, the repeatability of particulate measurement results from solid fuel appliances was shown to be a significant challenge[2]. This was particularly apparent when testing log burning appliances, as the construction of the fire bed (with only a few pieces of fuel) can have a large impact on the burning rate and pollutant emissions. For this reason, great care must be taken in fuel preparation in terms of size, moisture content and tree species to ensure that variability of the fuel does not greatly influence results. A Test Protocol was developed and used in Work Package 1 to reduce the variability of the results as much as possible whilst keeping the requirement to reflect real world stove use. However, even with detailed testing protocols for the different fuels and appliances there was a need to validate the Test Protocol and a series of Round Robin tests were conducted for this purpose.

The main test programme in WP1 was based on the use of three repeat tests. To ensure this could provide acceptable uncertainty the Round Robin tests undertook further repeats on selected measurements to enable

[1] The helpline can be accessed via the NAEI website - https://naei.beis.gov.uk or air.emissions@ricardo.com

[2] Assessment of particulate emissions from wood log and wood pellet heating appliances, report here https://uk-air.defra.gov.uk/library/reports?report_id=952

a better understanding of the uncertainty and variation. Testing in different laboratories to review repeatability ensured that the Test Protocol was fully validated, tested and was robust enough for use in the test programme.

The Round Robin tests did not focus on all measurements (it did not include the PAH, Dioxins and Furans or heavy metals). The repeatability and precision of the test work was explored by:

- Using the same appliance at Kiwa, University of Leeds, University of Manchester.
- Carrying out multiple repeat tests to assess measurement and test uncertainty.
- Using the testing to highlight any practical issues in the test protocol (and revision).
- Comparing test results across laboratories.

The Round Robin included mandatory measurements of burn rate, appliance outlet temperature, carbon monoxide (CO), oxides of nitrogen (NO_x) and particulate matter (>PM_{10}, PM_{10}, $PM_{2.5}$ and Total PM). The results of these measurements are shown in Appendix A.2.

Some of the laboratories carried out additional measurements and analysis, which are described in Appendix A.1 for completeness.

Table 2-2 Test schedule (note that only seasoned wood was tested with the Dovre stove)

Laboratory	Test dates
Leeds University	22nd November 2021 - 12th December 2021
Kiwa	13th December 2021 - 9th January 2022
Manchester University	10th January 2022 – 28th January 2022

2.8 PROGRAMME OF WORK

2.8.1 University of Leeds

The Leeds team consists of Professors Jenny Jones, Alan Williams, and Research Fellow, Andrew Price-Allison. This group made the first set of Round Robin measurements for the project and followed a Round Robin procedure, which was developed to ensure consistency in set-up and operation of the stove. These tests took place over a three-week period and commenced on 22 November 2021.

The stove selected for the Round Robin was a Dovre 500MRF multi-fuel stove, which is rated at about 5-7 kW with a recommended a minimum flue pressure of 14.9 Pa. It was delivered to Leeds by Kiwa on 17 November, 2021.

The stove was equipped with primary and secondary air controls; the former was an air control wheel and the latter a slider control.

The stove was mounted on a balance to give burning rates and the stove chimney was monitored to measure the temperature, and the concentrations of O_2, CO_2, CO and, NO. The measurement instrumentation also allowed measurement of CH_4 and total aromatic hydrocarbons which were undertaken for information. The gases from the stove chimney entered a dilution tunnel where they were mixed with unfiltered laboratory air; by adjusting the distance between the chimney and the dilution tunnel. In this way the dilution ratio could be changed between 5 and 16; this varied both the dilution tunnel temperature and the concentration of the particles. The particle sizes were measured using a Dekati Impactor (Model PM_{10}) which was situated 8m along the dilution tunnel and could measure the size ranges <1 µm, 1-2.5 µm, 2.5-10 µm, >10 µm and the total particulate mass/volume of diluted gas. More details are given in Appendix A.1.

Figure 2-1 The Test Rig showing the Stove and Measurement Equipment

On arrival at the University of Leeds, the stove was tested by the Leeds and Kiwa teams, as required by the Test Protocol, and it was found that there was a very large air leak around the door. This was repaired at Leeds though there remained a slight residual leak, not unusual for a stove of this age. Further testing was undertaken and it was found that the concentrations of the combustion produced gases were lower than expected. This was due to an additional air leak around the secondary air control which allowed large amounts of air to enter the combustion chamber even when the slide was closed. The consequence of this is that the secondary air control had to be set in a fixed open position throughout the experiments and this set up was used by all three test sites.

Kiwa supplied the fuel for all round robin tests, it was debarked beech wood, seasoned in-house with around 11% moisture content. The initial load consisted of two 600g logs, 560g kindling and approximately 50g of firelighter (Zip, High Performance) placed in the centre. Some difficulties were experienced with ignition being too slow and some slight modifications were later made to the Test Protocol. The Steering Group raised concerns that debarking the wood does not reflect real world behaviour. For the purpose of the Round Robin, consistency in fuel is essential and the team proceeded with the debarked wood, however for the main test programme the logs were not debarked.

The test period, measurements and sampling began at the point of ignition. This was followed by three refuels before the stove entered the burnout phase. The end of the burnout phase and the test was set at 30 minutes from the end of the third refuel phase. Gaseous measurements were made throughout the test run but the Dekati Impactor measurements were limited to during the ignition batch, the second refuelling batch and the final burnout phase due to the time taken to change filters inbetween phases.

2.8.2 Kiwa

The Kiwa team consisted of Senior Consultant: Sam Cottrill, Consultant: Kamil Tarnawski, Test Engineers: Jason Powys, Technical Reviewer: Mark Lewitt. This group made the intermediate set of Round Robin measurements for the project and followed the Round Robin procedure as defined during the Leeds Round Robin tests.

Kiwa were the second lab to undertake round robin testing on the Dovre 500MRF multi-fuel stove. The stove arrived from Leeds on the week begining 13th December 2021. Kiwa undertook 5 tests with the final test happening on the 7th January 2022.

As per the test proceadure the stove was mounted on a balance to give burning rates and the stove chimney was monitored to measure the temperature, concentrations of O_2, CO_2, CO, NOx, CH_4. Kiwa had a vertical dilution tunnel which diluted gasses to provide dilution tunnel temperatures around 30°C. The particle sizes were measured using a Dekati Impactor (Model PM_{10}).

During testing the leaks which were witnessed in the Leeds laboratory were confirmed due to the age of the stove. Kiwa used the secondary air controls which had been set in a fixed open position.

2.8.3 University of Manchester

The Manchester team consists of Academics; Amanda Lea-Langton, James Allan, Gordon McFiggans, Research Fellows; Dawei Hu, Abdullah Alhelali and Senior Technician Dan Wilson. Additional support was provided by Arthur Garforth and Eddi Asuquo for sample analysis. This group made the final set of Round Robin measurements for the project and followed the final version of the Round Robin procedure as defined during the Kiwa and Leeds Round Robin tests.

The Dovre 500MRF test stove was delivered to Manchester on the 10th January 2022, and the Round Robin tests were conducted from 13th January to 19th January. There was sufficient fuel for one additional test on the 20th Jan for collection of resin trap samples for VOC speciation.

The condition of the stove was poor, with an air leak around the door that would have led to more entrainment than a newer stove. In order to minimise changes between the 3 test sites, no remedial work was conducted, and the stove was tested as received. All wood was prepared and delivered by Kiwa as part of the same test batch used by others, and the same Round Robin test procedure was followed by all laboratories.

2.9 ROUND ROBIN RESULTS

The focus of the round robin tests was to look at repeatability between the three testing sites and to gauge the uncertainties associated with stove testing. The graphs below show the variability between testing sites, where the same stove and wood type are used. Following experience from the testing work at Leeds, the test programme was slightly changed for the other two test sites to optimise the protocol so results may not be so consistent with Leeds. Full results are available in Appendix A.2.

Burn rates between test runs and sites could be quite variable especially in ignition and shutdown phases. The general trend is the same between test runs, high burn rate for ignition and the three refuels then a much lower burn rate at the shutdown stage, Figure 2-2. Variability in the temperature of the appliance outlet, Figure 2-3, is much less across the tests than for burn rate and a general increase in the temperature is seen from the ignition phase to the third refuel and as expected, the shutdown phase had a much lower appliance outlet temperature. Both the burn rate and the appliance temperature are very dependent on how the fuel catches and burns.

Figure 2-2 Average Burn Rates for each phase of the burn cycle

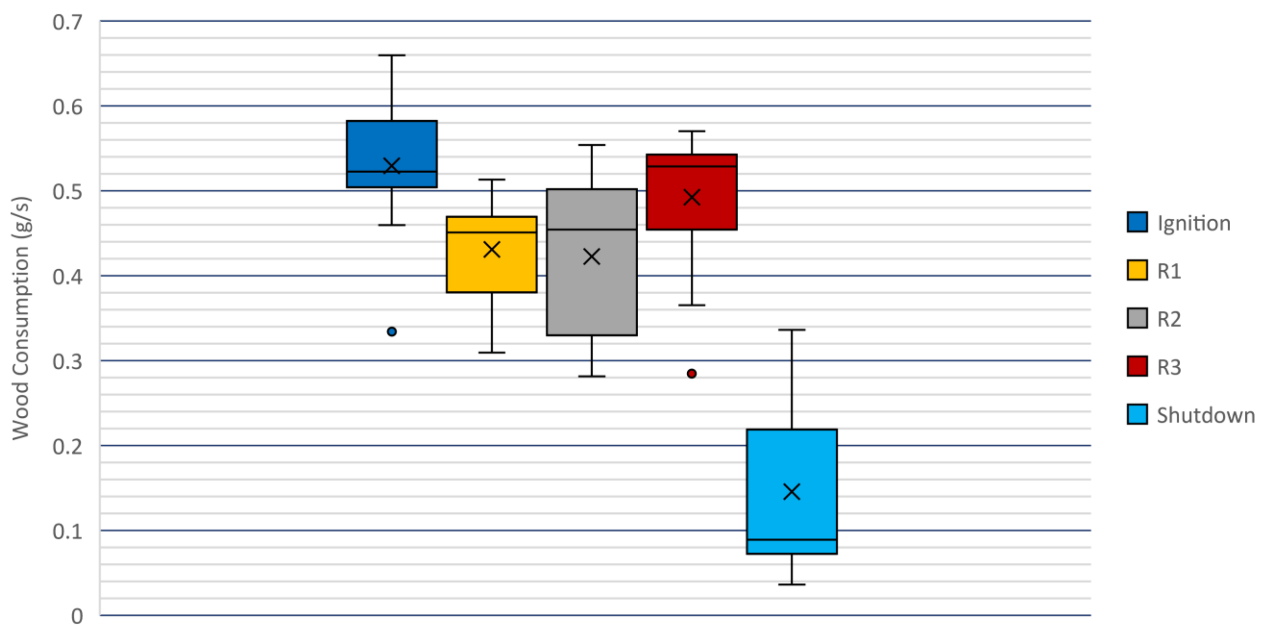
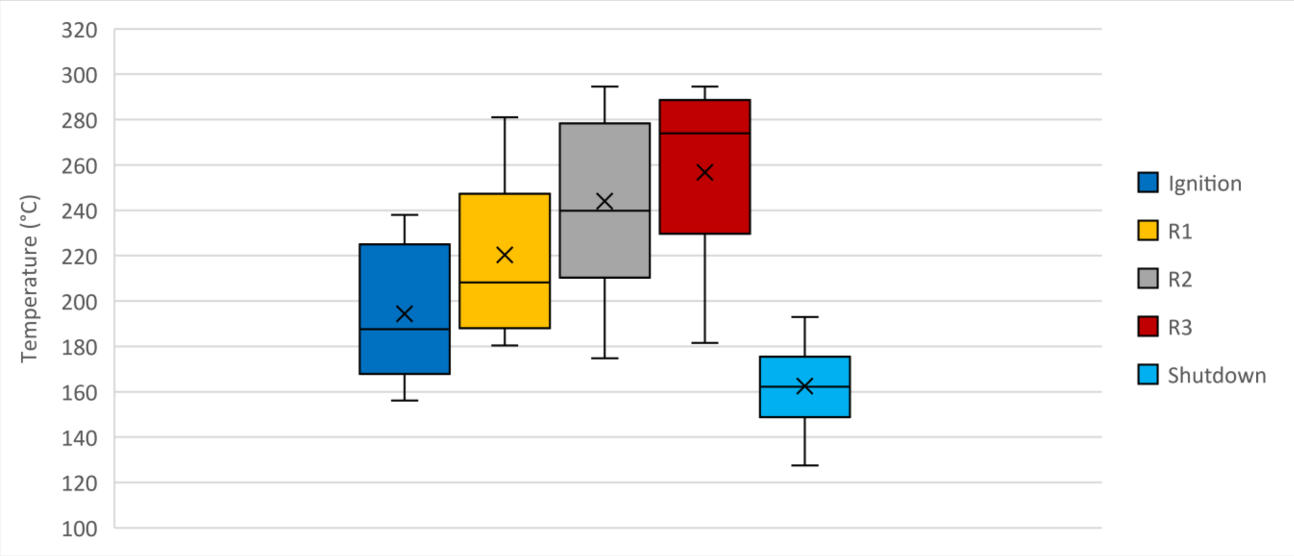
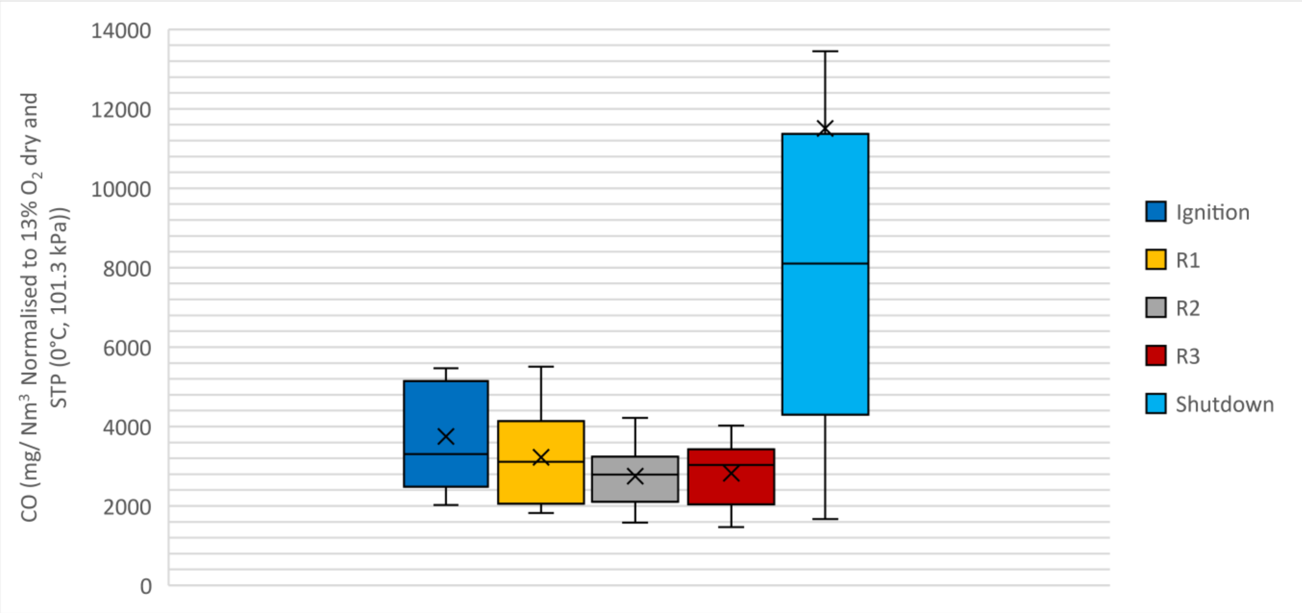


Figure 2-3 Average Appliance Outlet Temperatures for each phase of the burn cycle



The carbon monoxide concentrations are fairly stable across the ignition and three refuels but are higher during the burn out phase, Figure 2-4. The broad standard deviations seen for the gas concentrations is thought to primarily be due to the leak in the stove.

Figure 2-4 Average Carbon Monoxide Concentration at the Appliance Outlet



Excluding value of 63011 mg/Nm^3 recorded in Leeds test 1 for the Shutdown phase

Figure 2-5 Average Oxides of Nitrogen Concentration at the Appliance Outlet

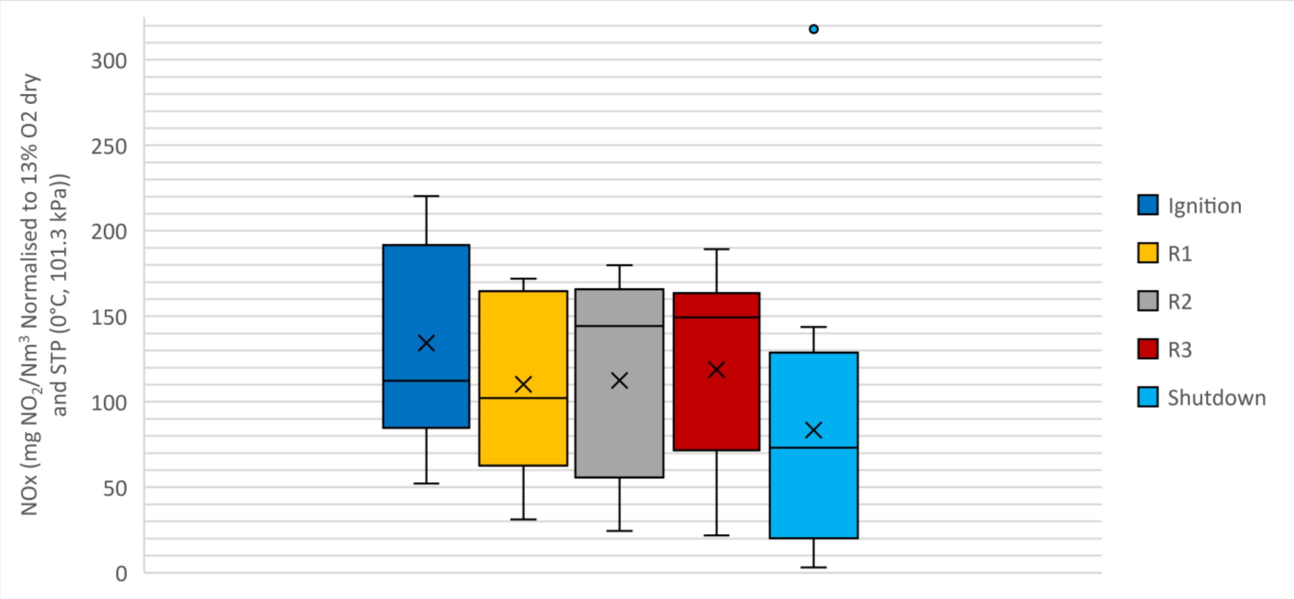
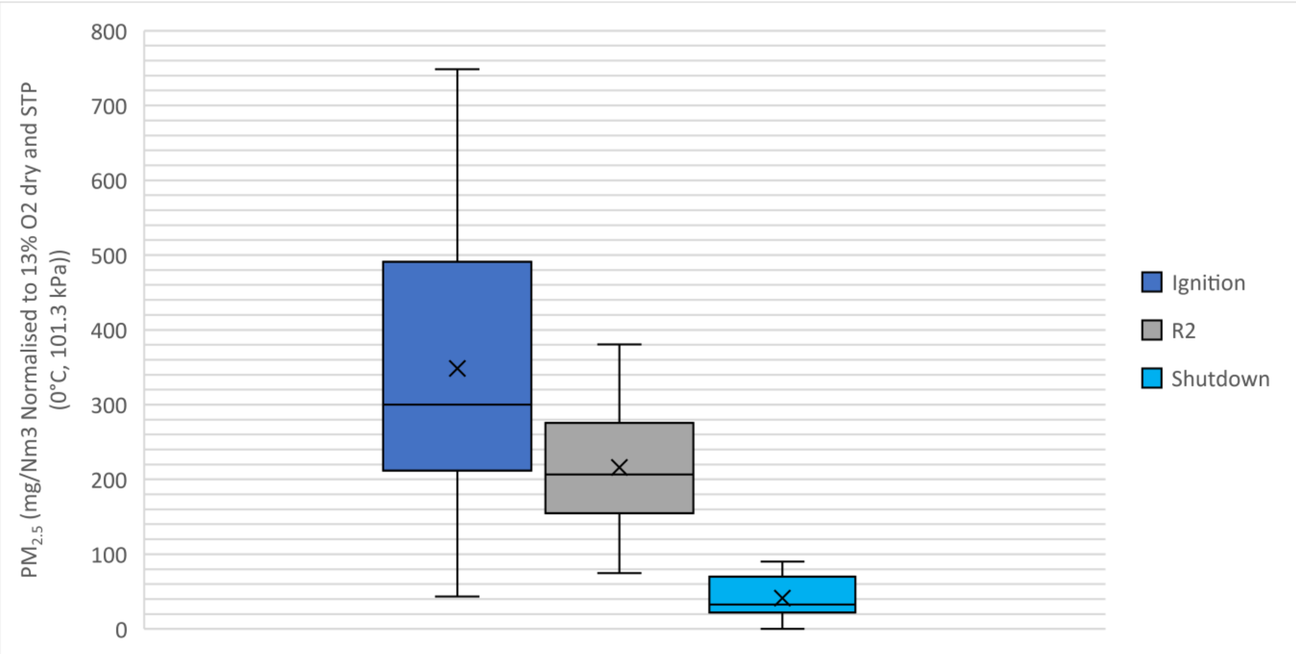


Figure 2-6 Average $PM_{2.5}$ Concentration in the Dilution Tunnel



Measurements of PM_1 were also made and these results are given in Appendix A1.

2.10 ROUND ROBIN CONCLUSIONS

2.10.1 Challenges

A number of challenges were encountered in the Round Robin trial including:

- The Dovre 500MRF stove is an old unit which, although functional, had some issues including a warped door (leaking air) and a relatively primitive air wash design implementation – much of the air going into the appliance was bypassing the combustion zone.
- The stove is relatively large and the intended kindling load and refuel procedure was amended to increase the fuel/energy availability to assure logs would ignite at refuel.
- Determining an appropriate refuelling point using CO_2 level was not practical on this appliance.

- Fuel orientation impacted quality of burn and refuel ignition.

Some of these issues may not have been evident if the modern stove or another appliance had been used for the Round Robin. However, the Round Robin was a useful experience for honing the main test programme including identifying the need to factor in time to assess operation of all the appliances and, where appropriate, allowing further investigation and repair of older devices in the test programme.

2.10.2 Repeatability of measurements

The Round Robin looked at a limited set of parameters:

- **Fuel burn rate** – the Kiwa burn rates were generally more consistent than others but operation phase relative standard deviation (13-22%) was generally higher than achieved in the previous Defra study – potentially impacted by stove issues.
- **Appliance outlet temperature** – the average appliance temperatures had a relative standard deviation of about (15%) with consistent trends for all three test facilities.
- **Carbon monoxide** – relative standard deviation values were about 35-50% which indicates the variability measured.
- **Oxides of nitrogen** – relative standard deviation during ignition and operation (refuel) was 14-27% but was 55% during shutdown phase. However, some datasets were discarded due to measurement issues and some of the variability may be due to different measurements.
- **$PM_{2.5}$** – Other measurements were continuous and direct measurement whereas $PM_{2.5}$ is an integrated measurement on diluted flue gas. The Relative Standard Deviation was higher than for other measurements but consistent.

2.10.3 Outcomes

The Round Robin interlaboratory process provided some important learning outcomes:

- Some measurement and consistency issues were evident. Burn rate reproducibility during operation phases was poorer than the previous Defra study. These issues were exacerbated by challenges in stove performance which has led to modifications to test procedures for the main test programme.
- The revised test protocol for the main test programme adopted a more practical indication of refuelling point – transferable to testing on the other stoves and open fire.
- The round robin measurement results broadly validate the proposed test protocol but indicate a need for some basic checks in the main programme that test runs are consistent.
- Three independent laboratories testing emissions of several pollutants using the same appliance and test protocol produced consistent results, within the uncertainty of the measurement and, particularly, noting the natural variability in the fuel used.

On the basis of these results, presented to the Steering Group on 16th February 2022, the test protocol was approved, and authorisation given to proceed to the main test programme. The test protocol addresses several considerations including:

- How to measure ‘real-world’ emission performance.
- Consistent appliance operation
- Pollutant Measurements.
- Methodology development for Black Carbon measurements and condensables characterisation.
- Performance characterisation - assessments of uncertainty, variability, and accuracy of measurements through repeatability testing
- Uncertainty and accuracy of results
- Method for the creation of final emissions factors and co-operation with the NAEI agency.

3. BLACK CARBON CATEGORISATION

3.1 EC/OC ANALYSIS

3.1.1 Initial design of the test protocol

The Inception Plan identified that further work was needed on the proposed method for BC and condensable measurements using the thermal-optical technique. This included: (i) identifying optimised time and volume for sampling of the filters to be sent to Sunset labs for BC analysis and (ii) determining the most appropriate choice of thermal optical protocol from those available. The details of this work are summarised in this section and Appendix 3.

The samples for the main test programme were taken using quartz fibre filters in the dilution tunnel position and were sent to Sunset labs for thermo-optical analysis. The filter loading is critical for the analysis to give good results and overloaded samples could not be analysed. To avoid this Manchester University conducted preliminary tests to inform the precise protocol in terms of optimised time and volume for sampling.

As this research work was required ahead of the test stove procurement phase, Manchester University used their existing test stove and fuels for this preliminary work. The stove was an Ecodesign compliant ESSE Bakeheart wood burning stove supplied by ESSE Engineering, UK[3]. The wood tested was dry beech wood (<5% moisture) and wet beech wood (>25% moisture).

This research involved use of advanced analysers to characterise the particulate emissions from the dilution tunnel throughout a typical combustion cycle, and includes ignition, operation and shutdown. The analysers include:

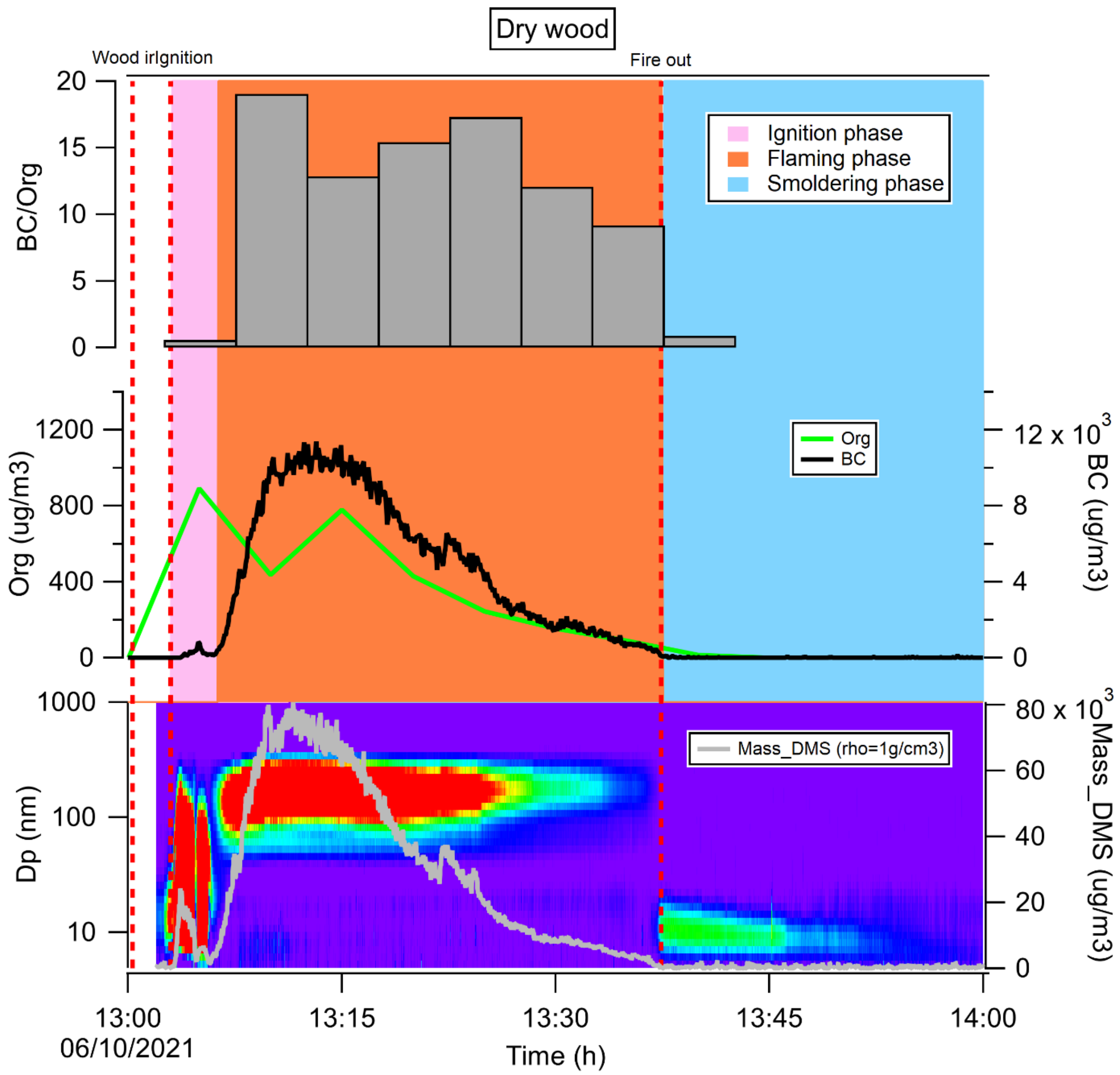
- SP2: Single particle soot photometer which directly quantifies the black carbon in individual aerosol particles
- AMS: Aerosol mass spectrometer that gives real time mass analysis of the organic fraction
- DMS500: Differential mass spectrometer which gives real time measurement of particle size distribution, number and mass

In accordance with standard procedures such as BS EN 13240, the flue draft was maintained at ~12Pa on the appliance throughout the testing. Measurements of burning rate, gas analysis (flue and dilution tunnel) and temperatures were also taken for future reference but are not presented here.

It should be noted that variation in results will occur according to the use of different fuels (e.g. moisture content) and different appliances. The stove used at Manchester University is known to have good emissions performance compared to older technology designs and further data from the Round Robin tests was needed to give an estimate of expected variation. Typical test result using dry wood is shown below in Figure 3-1 and wet wood in Figure 3-2, which illustrates the period of the burn cycle in which the black and organic carbon emissions occur. It should be noted that the black carbon is mainly emitted after the fire has become established, whereas the PM is more dominated by organic matter during the ignition phase.

[3] https://www.esse.com/wood-fired-cook-stoves/bakeheart/#

Figure 3-1 Examples of Data Collected for Dry Wood Runs



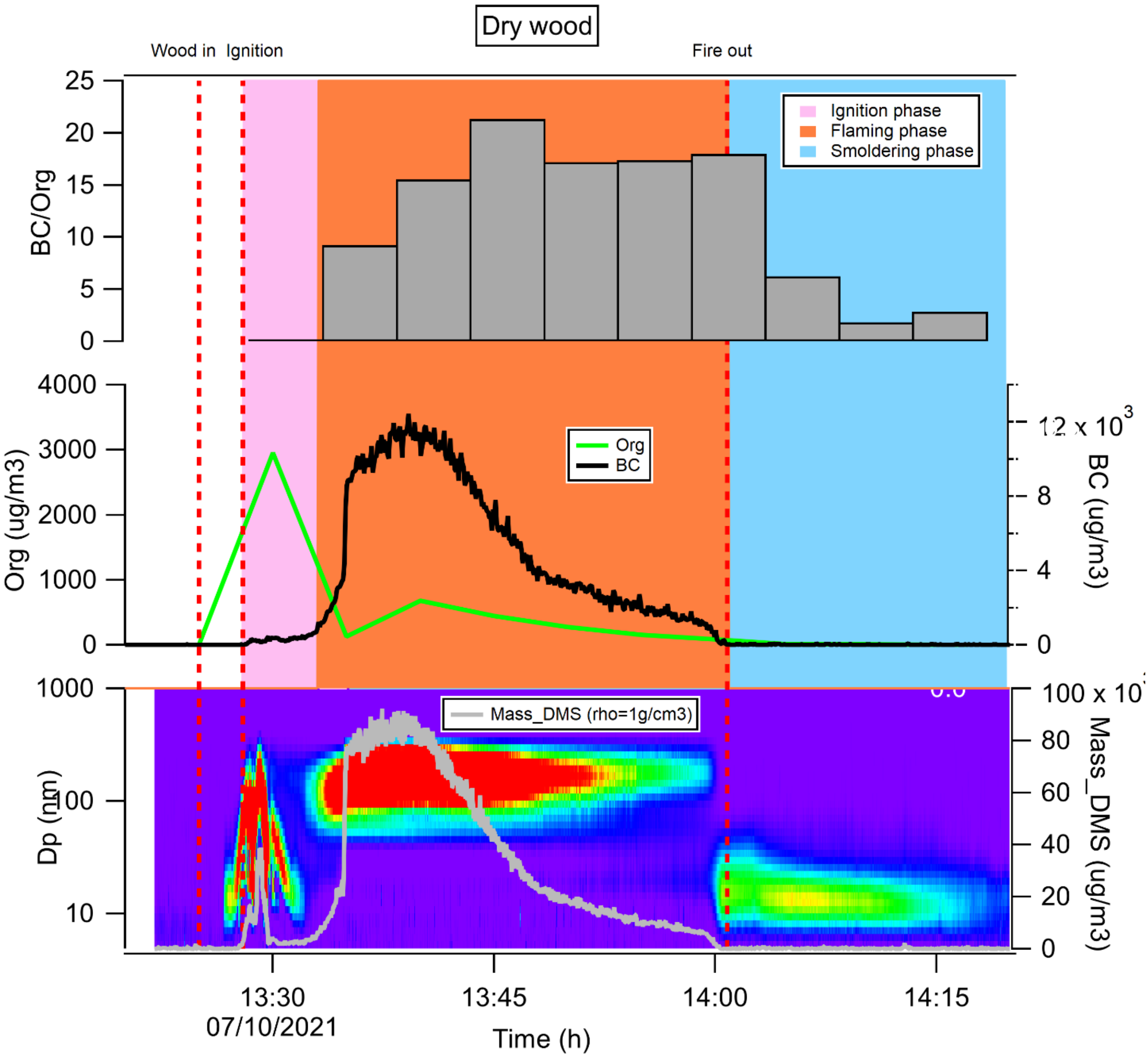
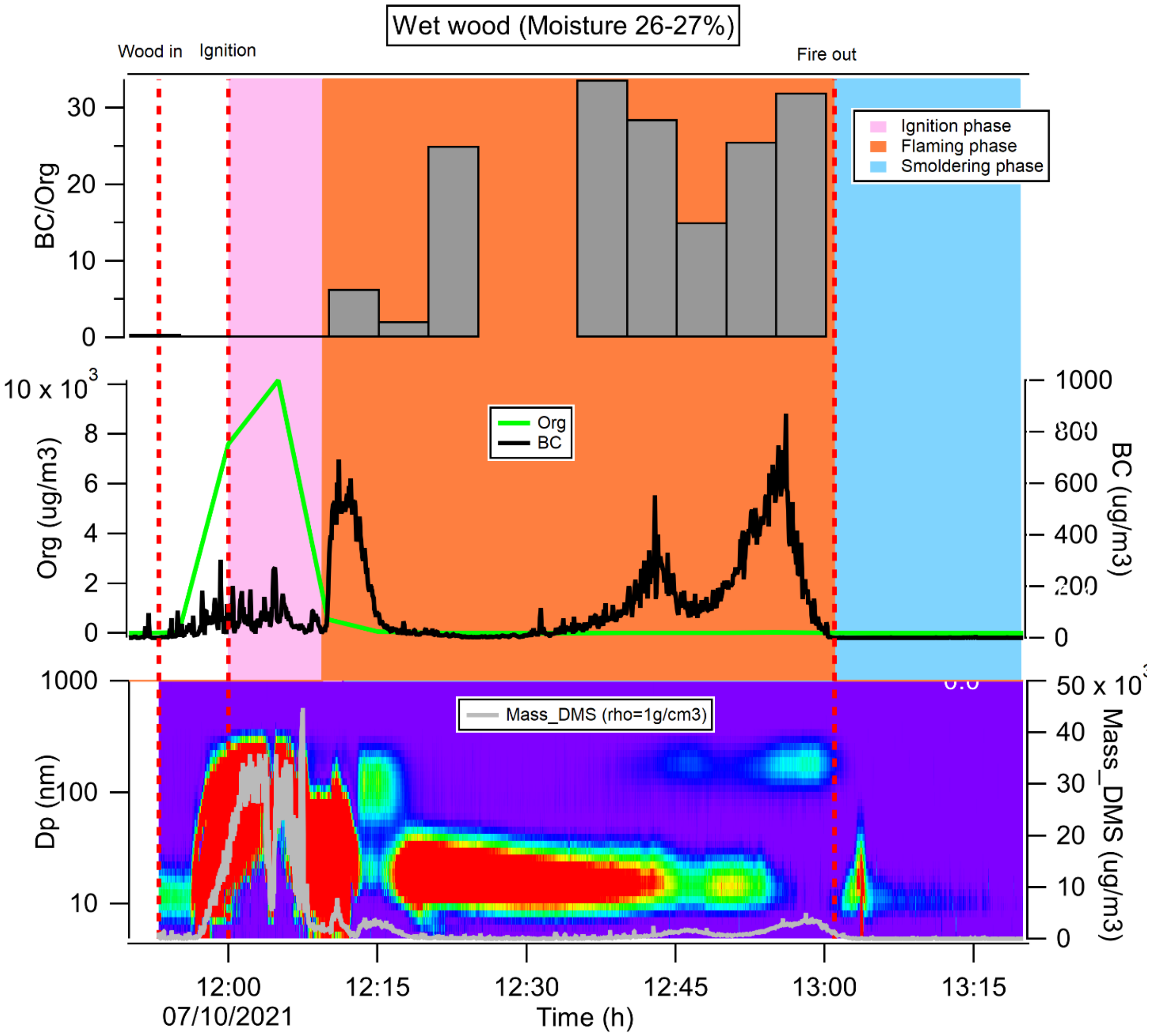
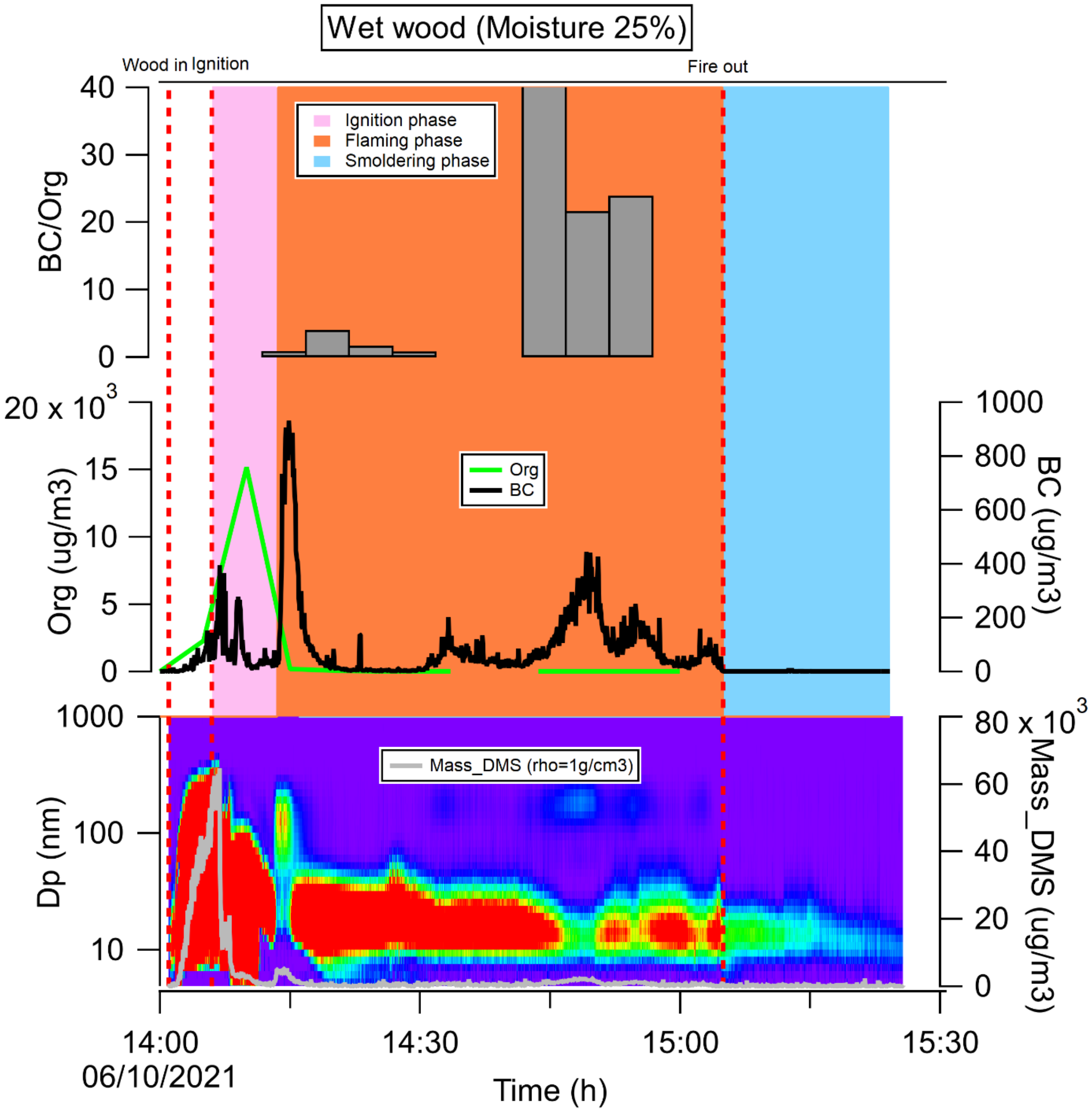

Dry wood
Wood in
Ignition
Fire out
BC/Org
Ignition phase
Flaming phase
Smoldering phase
Org (ug/m3)
Org
BC
BC (ug/m3)
12 x 10^3
Dp (nm)
Mass_DMS (rho=1g/cm3)
Mass_DMS (ug/m3)
13:30
07/10/2021
13:45
14:00
14:15
Time (h)

Figure 3-2 Examples of Data Collected for Wet Wood Runs





The preliminary results were used to inform the appropriate collection of samples for EC/OC analysis and to verify that the $PM_{2.5}$ collection strategy for the Dekati sampler was appropriate, as well as for the determination of flaming and smouldering zones.

Figure 3-3 and Figure 3-4 show the cumulative mass of BC (Figure 3-3) and OC (Figure 3-4) for four separate tests using dry wood, performed at Manchester during the method development phase. This was done to determine the most optimum time and duration for sampling for offline analysis and demonstrate repeatability. For the BC, results were in reasonable agreement however there was one outlier result as shown in green. The reason for this different result is not known but is expected to be related to the fuel properties, highlighting the degree of variability that can occur with stove testing. The amounts of OC measured were proportionately far lower than for BC, and hence an even greater degree of variability was observed, Figure 3-4.

Figure 3-3 Cumulative Mass of Black Carbon Across Flaming Phase, Dry Wood

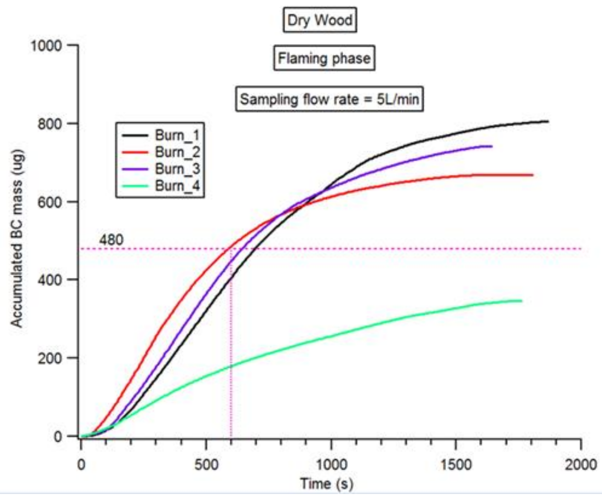
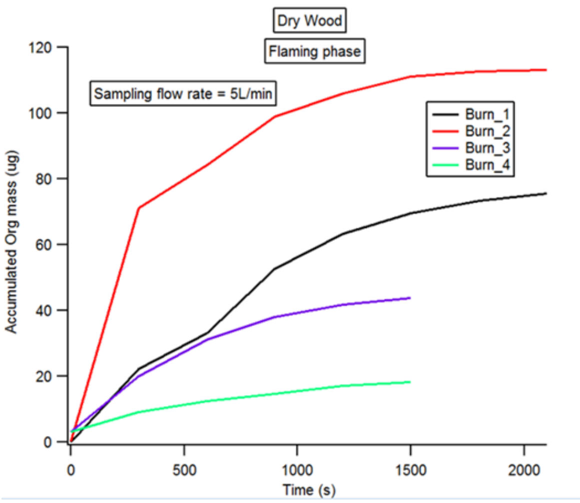


Figure 3-4 Cumulative Mass of Organic Carbon Across Flaming Phase, Dry Wood



3.1.2 Determination of EC/OC test protocol

3.1.2.1 Quantification of BC

The black carbon (BC) was quantified by equating this to the elemental carbon (EC) determined using thermal-optical analysis. Thermal-optical analysis is an analytical procedure where material on a filter is heated, and the evolved carbon is measured as a gas. An optical correction is performed to correct for any charring artefacts (Birch and Cary, 1996[4]). This is used to quantify EC, organic carbon (OC) and total carbon (TC).

The accuracy of the thermal optical technique depends strongly on the precise protocol used for the thermal cycle, and a number of different established protocols exist. Three commonly-used protocols were tested using the samples produced during the WP1 experiments at Manchester University; IMPROVE-A, NIOSH870 and EUSAAR-2 (Cavalli et al., 2010[5]; Brown et al., 2017[6]). The analysis was performed at Sunset Labs BV in The Netherlands. Of these, IMPROVE-A was judged to be unsuitable and NIOSH870 and EUSAAR-2 produced very similar results. Out of the two remaining protocols, NIOSH870 was judged to produce the most reliable

[4] Birch, M. E., and Cary, R. A.: Elemental carbon-based method for monitoring occupational exposures to particulate diesel exhaust, Aerosol Sci. Technol., 25, 221-241, 10.1080/02786829608965393, 1996

[5] Cavalli, F., Viana, M., Yttri, K. E., Genberg, J., and Putaud, J. P.: Toward a standardised thermal-optical protocol for measuring atmospheric organic and elemental carbon: the EUSAAR protocol, Atmos. Meas. Tech., 3, 79-89, 10.5194/amt-3-79-2010, 2010

[6] Brown, R. J. C., Beccaceci, S., Butterfield, David M., Quincey, P. G., Harris, P. M., Maggos, T., Panteliadis, P., John, A., Jedynska, A., Kuhlbusch, T. A. J., Putaud, J.-P., and Karanasiou, A.: Standardisation of a European measurement method for organic carbon and elemental carbon in ambient air: results of the field trial campaign and the determination of a measurement uncertainty and working range, Environmental Science: Processes & Impacts, 19, 1249-1259, 10.1039/C7EM00261K, 2017.

data for EC, as EUSAAR-2 appeared to be erroneously characterising some refractory OC as EC (Appendix A.3). The NIOSH870 protocol was used to test all BC samples in the test programme. As recommended by the Steering Group, some of the samples have been retained for future analysis using EUSAAR-2 or any other protocols in use by the community, to investigate comparability. In particular, EUSAAR-2 is the protocol used for ambient measurements across Europe, but is not currently the standard in the UK.

3.2 CONDENSABLES SPECIATION

As detailed in the inception plan, further work was anticipated in order to better define the quantification method of 'condensable' PM and work was performed at Manchester to investigate this. The summary of the condensable PM work is given here, further details including test results of thermal optical analysis of particulates and VOCs captured on sorbent tubes are shown in Appendix A.4.

ISO 25597:2013 (for PM_{10} and $PM_{2.5}$ determination in emission samples)[7] defines condensable particulate matter (PM) as "particulate matter formed at temperatures below 30 °C due to physical and/or chemical processes". In the case of organic matter derived from domestic solid fuel burning emissions, this is contributed to through two distinct mechanisms:

1. Semi-volatile organic compounds that condense onto the particulates as the fire plume cools and dilutes, either in the flue or after emission into the atmosphere.
2. Secondary organic aerosol (SOA) formed from emitted VOCs, through atmospheric oxidation processes.

As part of this work, it was deemed that the type 1 condensable PM, defined as condensable primary organic aerosol or CPOA in Simpson et al. (2020[8]), could be measured through a comparison of samples obtained using a heated 'DIN+' sampler on the flue, with filters obtained from the dilution tunnel at 30 °C. This can either be quantified as a gravimetric mass or as organic carbon determined using thermal-optical analysis. However, WP1 data produced by the heated filter method (both at appliance outlet and dilution tunnel) was compromised due to reasons outlined in 7.5 and A.8. Therefore, type 1 condensable PM were quantified using Dekati data from the dilution tunnel.

The type 2 condensable matter (SOA) is thought to be a potentially significant emission from domestic solid fuels (e.g. Tiitta et al., 2016[9]), but is harder to quantify at the point of emission. Quantifying this requires predicting the SOA formation through a simulation of atmospheric oxidation on the emissions, either by subjecting them to chemical processes in a reactor or predicting the evolution using a numerical model. While the scientific community's understanding of these processes has improved dramatically in recent decades, the manner in which this can be quantified for reporting purposes is currently the subject of much debate within the EMEP community (Simpson et al., 2020). Key to this is the 'yield' of the emitted VOCs, which is the percentage of emitted organic carbon that ultimately condenses, as opposed to being converted to more volatile compounds such as carbon dioxide. This 'yield' is known to depend on a number of factors, in particular the specific mixture of VOCs emitted and the chemical and meteorological conditions they experience in the atmosphere. Until such a definition is agreed on, it would be inappropriate to include an estimate of type 2 condensable PM measurements.

In lieu of this, speciated data on VOCs was collected during the Manchester method development experiments using sorbent tubes and GC-MS analysis. The OC data produced can be subsequently inspected to determine the approximate volatility of the organic matter sampled in the dilution tunnels, by quantifying the OC evolved as a function of temperature. Once a yield formulation is agreed internationally, these data products can be

[7] ISO 25597 : Stationary source emissions — Test method for determining PM2,5 and PM10 mass in stack gases using cyclone samplers and sample dilution.

[8] Simpson, D., Fagerli, H., Colette, A., Gon, H. D. v. d., Dore, C., Hallquist, M., Hansson, H. C., Maas, R., Rouil, L., Allemand, N., Bergström, R., Bessagnet, B., Couvidat, F., Haddad, I. E., Safont, J. G., Goile, F., Grieshop, A., Fraboulet, I., Åsa Hallquist, Hamilton, J., Juhrich, K., Zbigniew Klimont, Kregar, Z., Mawdsely, I., Megaritis, A., Ntziachristos, L., Pandis, S., Prévôt, A. S. H., Schindlbacher, S., Seljeskog, M., Sirina-Leboine, N., Sommers, J., and Åström, S.: How should condensables be included in PM emission inventories reported to EMEP/CLRTAP?, EMEP Technical Report MSC-W 4/2020, 2020

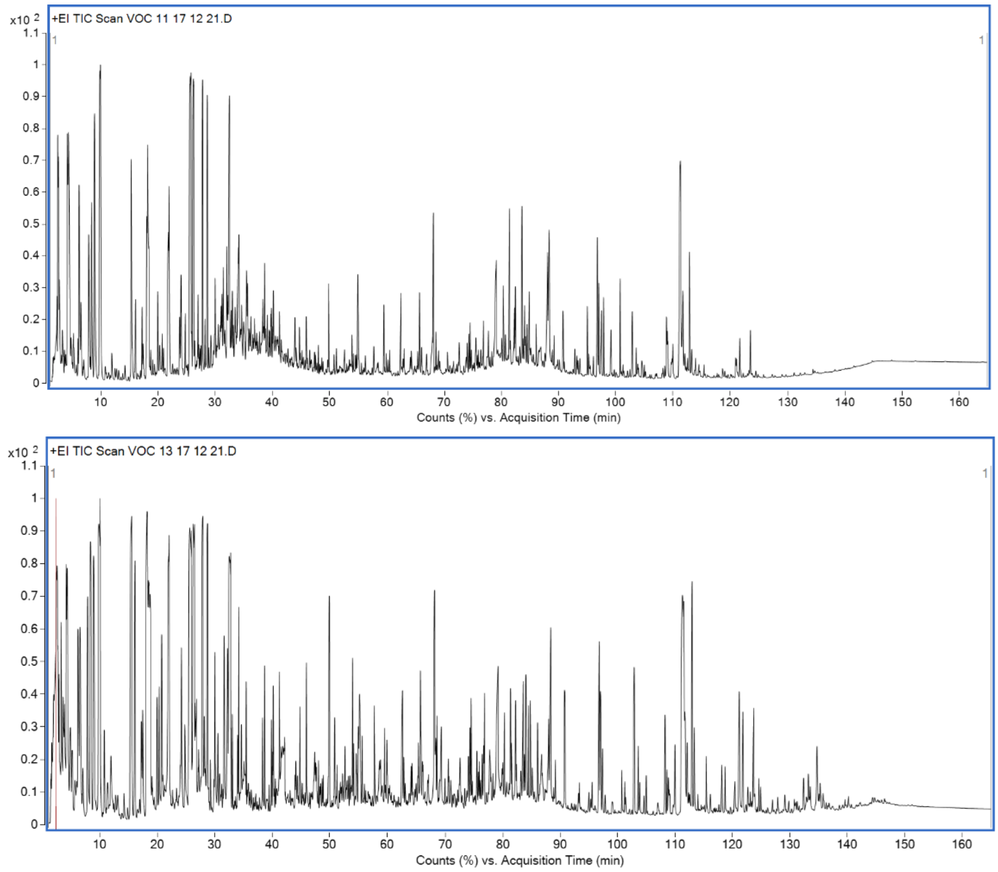
[9] Tiitta, P., Leskinen, A., Hao, L., Yli-Pirilä, P., Kortelainen, M., Grigonyte, J., Tissari, J., Lamberg, H., Hartikainen, A., Kuuspalo, K., Kortelainen, A. M., Virtanen, A., Lehtinen, K. E. J., Komppula, M., Pieber, S., Prévôt, A. S. H., Onasch, T. B., Worsnop, D. R., Czech, H., Zimmermann, R., Jokiniemi, J., and Sippula, O.: Transformation of logwood combustion emissions in a smog chamber: formation of secondary organic aerosol and changes in the primary organic aerosol upon daytime and nighttime aging, Atmos. Chem. Phys., 16, 13251-13269, 10.5194/acp-16-13251-2016, 2016

reviewed to derive a proxy metric for the intermediate volatile organic compounds (IVOCs) that are known to generally have the higher SOA yields (Robinson et al., 2007[10]; Stewart et al., 2021[11]).

The condensables speciation is achieved by taking a sample of the organic carbon on a resin trap in the heated line behind the Din+ filter sample. The tube is subsequently thermally desorbed directly into a gas chromatography-mass spectrometry (GC-MS) instrument. Manchester University analysed a range of samples obtained from the in-house ESSE Bakeheart stove during the method development phase and this gave an indication of the species present as shown below, however a more extensive study using a range of fuels and the Dovre Round Robin stove was not possible due tight project time constraints.

The initial challenge was optimising the amount of sample to be collected for GC-MS analysis, as discussed in section 3.1. For the material collected, it was found that there is less OC sample mass and more variation between samples compared to the BC mass fraction which is reasonably consistent between tests. Two example chromatograms are shown in Figure 3-5, which are based on initial work at Manchester University before the Round Robin phase.

Figure 3-5 Chromatograms with a Wide Range of Peaks Demonstrating a Complex Mixture of Species, (ESSE Bakeheart stove, flaming operation phase top: Dry beechwood 6-10%, bottom: Wet beechwood 30-32%)



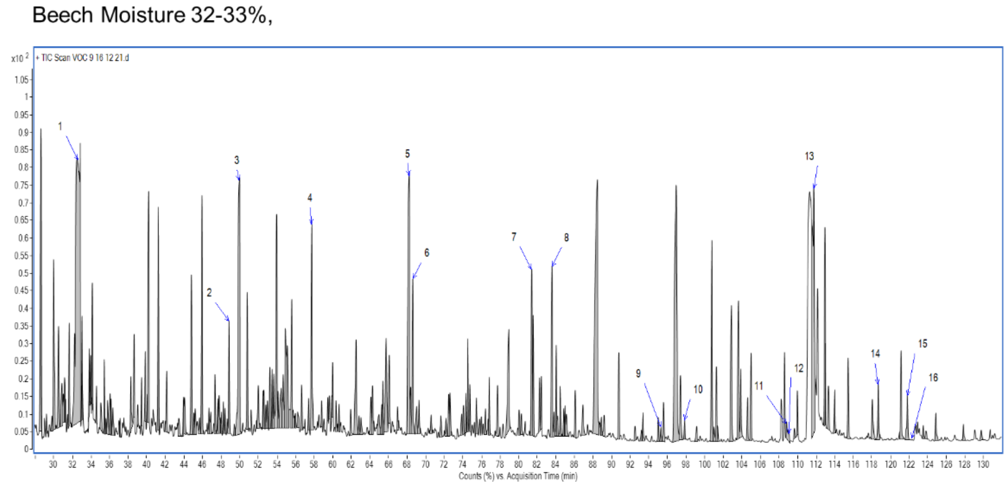
A complex range of species are seen, which include typical products of wood pyrolysis such as methyl-phenols and other oxygenates. A portion of the organic component includes Polycyclic Aromatic Hydrocarbons (PAH), some of which are condensable at room temperature, and some of which are also associated with adverse health impacts. The 16 US-EPA priority PAH species were identified in the samples as shown in Figure 3-6. The scope of full speciation would not be included into the main test program at Kiwa and it was important not to interfere with the round robin tests by introducing too many non-core measurements. However, further

[10] Robinson, A. L., Donahue, N. M., Shrivastava, M. K., Weitkamp, E. A., Sage, A. M., Grieshop, A. P., Lane, T. E., Pierce, J. R., and Pandis, S. N.: Rethinking organic aerosols: semivolatile emissions and photochemical aging, Science, 315, 1259-1262, 10.1126/science.1133061, 2007.

[11] Stewart, G. J., Nelson, B. S., Acton, W. J. F., Vaughan, A. R., Hopkins, J. R., Yunus, S. S. M., Hewitt, C. N., Nemitz, E., Mandal, T. K., Gadi, R., Sahu, L. K., Rickard, A. R., Lee, J. D., and Hamilton, J. F.: Comprehensive organic emission profiles, secondary organic aerosol production potential, and OH reactivity of domestic fuel combustion in Delhi, India, Environ Sci: Atmos, 1, 104-117, 10.1039/D0EA00009D, 2021.

extensive analysis of PAH content of the emissions will be conducted by ECL as part of the main sampling regime conducted at Kiwa.

Figure 3-6 Chromatogram with PAH Identification (ESSE Bakeheart stove, flaming operation phase, Wet beechwood 30-32%)



(1)Naphthalene, (2)Acenaphthene, (3)Acenaphthylene, (4)Fluorene, (5)Phenanthrene, (6)Anthracene (7)Fluoranthene, (8)Pyrene, (9)benzo[a]anthracene, (10)Chrysene, (11)benzo[b]fluoranthene, (12)Benzo[k]fluoranthene, (13)benzo[a]pyrene, (14)benzo[g,h,i]perylene, (15)indeno[1,2,3-c,d]pyrene, (16)dibenz[a,h]anthracene

Typical species identified in this work are given in the appendix (Table A10). It can be seen that the carbon number of the species present has a wide range. The smallest species representing the most volatile and the larger species being more condensable. The importance of consistent sampling temperature is noted for particulate collection for comparative measurement of filter paper samples. The smallest and hence most volatile species will not condense at the standard collection temperature but could subsequently condense onto a cooler backup filter, this is expected and should not be confused with breakthrough of solid black carbon. The results highlight ambiguity in what is “condensable”, as the terminology adopted is operational with a defined methodology for sampling. The issue of accounting for the behaviour of Intermediate Volatile Organic Compounds (IVOC) and Semi-Volatile Organic Compounds (SVOC) is under discussion at a European level in terms of the Gothenburg protocol review.

The results indicate that a much more extensive study is required that could not be included within the tight project timescale. Manchester University will continue this analysis using samples from their own test stove as a parallel project. To date, samples from wet wood suggest a greater abundance of species compared to dry wood, however there is much variation between results. Conclusive trends in terms of combustion phase and moisture are not yet available due to limited samples. Future detailed data, along with results from this Defra project, will be used further to inform the interpretation of the thermal-optical analysis, allowing for an estimate of the condensable mass based on the thermally-resolved organic carbon data. This will allow for further interrogation of the data as the definition of ‘condensable’ is clarified on a scientific level, and will guide further experiments should they be necessary.

4. WOOD FUEL

4.1 MOISTURE LEVELS, PROCUREMENT, STORAGE, SPECIFICATION

It is essential that an acceptable level of consistency be achieved in the fuels used for this study otherwise there will be greater variation and uncertainty in the results. For mineral fuels and manufactured fuels variability in composition, moisture content and dimensions tend to be quite low (although much more variable than for refined liquid and gaseous fuels) and therefore whilst fuel choice is important the variability of the fuel itself is more easily managed. The situation for log wood fuel is different. Characteristics such as moisture content can change much more quickly than for mineral fuels. The project team recognise the importance of a clear specification to assure consistency in all the fuels used. The following section describes the fuel selection for the work programme.

The wood used for the test programme was sourced from a local supplier, Mark Hannis Firewood. They delivered firewood which is locally sourced from within 5 miles of the sawmill. This wood is delivered partially seasoned to around 20% - 25% moisture content prior to delivery. For laboratory use, this wood is then stored and processed as appropriate for the tests. Further detail of how the moisture content was managed can be found in the sections below on Wet, Seasoned and Dry wood

For testing log wood fired appliances to the relevant standard (BS EN 13240 or BS EN 16510-1) the test fuel specification prescribes the species to be beech, birch or hornbeam. Information from wood suppliers suggests that beech or ash are the main species of log fuels used in the UK. This does vary geographically as suppliers will source material close to where they are established.

To represent the real world, we can examine the UK supply of wood fuel. The 2020 Forest Resource Assessment[12] shows the composition of the UK Growing Stock (using the metric: million m^3 over bark) to be Oak 11% (not a fuel wood), Spruces 35% (not a fuel wood), Scots Pine 9% (not a fuel wood), Ash 7%, beech 5% and Birches 5%.

Using the growing stock and laboratory appliance test fuel information, beech was chosen for the test programme as it is used widely across the UK and its use in this test programme could also be linked to existing data on appliance testing allowing comparisons to be made.

The wood was supplied in 25cm tall wedges of varying size and weight. This was then divided into seasoned, wet and dry wood and stored or seasoned accordingly. This can be seen in Figure 4-2. To keep the fuel mass constant between tests, each wood piece was cut down to size using a hand axe and weighed. Each log was cut into rough pentagon shapes with some bark left on the log, representative of the fuels burned in a domestic setting. This size was able to fit into all appliances tested. Prepared logs can be seen in Figure 4-1.

[12] Forest Research, Forest Resources Assessment 2020, available here : https://www.forestresearch.gov.uk/tools-and-resources/statistics/statistics-by-topic/international-returns/forest-resources-assessment/

Figure 4-1 Wood logs cut to size

The moisture content of wood is from 'inherent' moisture contained within the cells of the plant and 'free' moisture on exposed surfaces (both external and internal surfaces of the porous structure) i.e., not bound within the wood structure. When wood is harvested, changes in moisture content start to occur to align with prevailing humidity levels. Three moisture content levels were selected to represent the various conditions of the wood commonly burnt in domestic settings. This included dry wood, seasoned wood, and wet wood.

The approach to determination of moisture using current standards involves:

- Sampling from supply: BS EN ISO 18135:2017 Solid Biofuels – Sampling
- Preparing the sample: BS EN ISO 14780:2017 Solid biofuels — Sample preparation
- Determination of moisture content: BS EN ISO 18134-1:2015 Solid biofuels - Oven dry method Parts 1-3

The uncertainties relating to the measurement of moisture contents in wood logs are expected to be significant. The key question for this project relates to how characteristics can be determined for material 'as used' and, how these relate to any measurements made in an analytical laboratory. For this project a range of measurement approaches were used.

- Accredited laboratory testing as part of the fuel analysis (On delivery)
- Oven drying based measurements of a representative samples (Weekly).
- Moisture probe measurements at point of use (Daily)

The management of the three moisture levels for the test fuels differed slightly and is detailed below:

Dry wood (moisture content 0% - 10%) – 6% target moisture selected

Dry wood is the commonly available as 'kiln dried' wood and typically supplied in the UK in sealed plastic bags to maintain moisture levels. Kiwa used its own kilns to dry wood to the targeted 6% moisture levels. By preparing wood logs at 15% moisture to 666g and placing in a kiln over for 48 hours dried the wood to the required levels. This resulted in wood logs of 600g with a moisture content of 5%. These logs were then stored in sealed plastic bags until the test date to prevent exchange of moisture with the atmosphere with a sealed sample sent away for accredited laboratory testing. The storage and testing protocol were designed to limit the potential exposure period.

Seasoned wood (moisture content 11% - 20%) – 15% target moisture selected

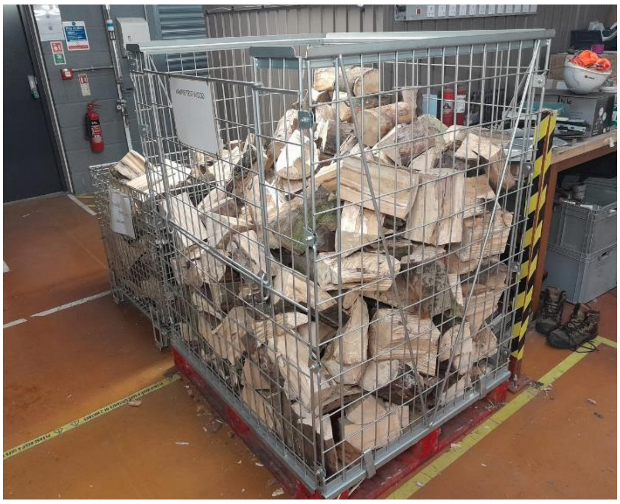
This wood was stored inside of the building in controlled conditions until the desired moisture content is achieved. Kiwa has developed methods and expertise in ensuring 15% moisture contents in its current procedures for its solid fuel testing laboratory. There is a constant cycle of deliveries and drying of wood to ensure that there is always wood fuel available for testing. Any fuel that is out of spec i.e. below 15% moisture this is returned to the supplier. The experience and expertise at Kiwa resulted in wood moisture content being close to that specified in the standard (BS EN 16510-1:2018 Table B.1 — Test fuel specifications) i.e. (15±3)%. This is controlled through weekly tests on fuel moisture using Kiwa's in house procedures undertaken on a weekly basis. This procedure can be found in A.6. Hand-held moisture probes provide a final check before the logs were used for testing.

Wet wood (moisture content 21% - 30%) - 25% target moisture selected

This represents unseasoned wood or wood stored in outdoor/wet conditions. Achieving consistent levels of moisture significantly above the equilibrium levels for seasoned wood is a challenge. To manage the fuel for the test programme logs were sourced in a wet state with moisture levels of around 30%. These were then stored in humid conditions to maintain the elevated moisture level. Once the 25% level required for testing has been achieved the wood logs were sealed in bags until the test date. This was managed so that testing was completed within a few weeks of being stored to ensure that the wood fuel did not deteriorate in the wet bagged condition.

Actual moisture content of the wood used for trials based on accredited laboratory analysis and daily/weekly analysis can be found in Table 4-1.

Figure 4-2 Storage of wood fuels



*Seasoned wood pictured on the left, wet wood on the right.

4.2 FUEL ANALYSIS

Samples of the three types of wood (dry, seasoned and wet) were analysed by Alfred H Knight Energy Services Ltd which is accredited for solid fuel analysis. The full data sets from this analysis can be found in Appendix 0. Table 4-1 shows the ranges of moisture content set out to differentiate the wood types in this test programme as well as the moisture content reported in the wood analysis.

Table 4-1 Measured Moisture Content of Wood

Wood Type	Moisture Content Range	Actual Moisture Content
Dry Wood	0 - 10 %	5.8 %
Seasoned Wood	11 - 20 %	15 %*
Wet Wood	21 - 30 %	25.9 %

*Seasoned in house, moisture content measured in house at time of use.

5. APPLIANCES

5.1 DRIVERS FOR SOLID FUEL APPLIANCE DEVELOPMENT

The procurement of stoves and open fires was an important part of the project as the appliance choice had an impact on the emissions factors. Defra required the selection of stoves to represent the installed base in the UK and to capture the significant developments in stove performance at breakpoints of years 2000, 2010, current (Ecodesign and better – ClearSkies Mark 2 or above). The drivers for stove development over time which has driven improved performance have been:

Introduction of the Construction Products Directive[13]: For closed stoves the standard harmonised under this Directive was EN13240:2001. This was amended in 2004 and the threshold for efficiency was added of equal to or exceeding 50% net.

Publication of the 2010: Domestic Building Services Compliance Guide[14] (DBSCG): This sets a minimum efficiency threshold for 'Solid fuel dry room heater - 65% gross' and for 'Simple open fire 37% gross'. The project teams' experience is that there were appliances in the market which significantly exceeded this minimum level of performance prior to this guidance being published.

Ecodesign regulation for solid fuel space heaters[15] which came into force 2022: This sets the minimum threshold for seasonal space heating energy efficiency to not be less than 65 % net, and sets emission limits for NOx, OGC, particulate, and CO. In the regulation seasonal efficiency is efficiency measured at rated output -10% for appliances without controls or electrical supplementary heating. So, a measured efficiency of not less than 75 % net must be achieved in standard type tests. The Ecodesign benchmark is seasonal efficiency of 86% net.

clearSkies[16] - Since early 2020 the clearSkies Mark certification scheme has been operating and shows that a significant number of products are available in the market that exceed the requirements of the Ecodesign regulation. Prior to the clearSkies mark an 'Ecodesign-ready' listing was available and numerous stoves were included in this for two or more years prior to clearSkies.

The developments have impacted the performance of stoves and therefore impacted the installed base of appliances. As the appliance inventory has been built up over decades, it is not possible for a single appliance to give a statistically robust representation of the products installed over timeframes of 10 or more years. The selection of appliances solely on the basis of age, but will not necessarily result in an appropriate representation of the performance of these segments of the installed population. This is highlighted by the publication of the 2010: DBSCG which set minimum efficiency thresholds which many appliances were already meeting. Appliance choice should not be based just on age but also its relative performance to the installed inventory.

5.2 CATEGORIES

One appliance was selected from the following criteria with the aim to use multifuel stoves in all work packages where possible:

i. open fire
ii. pre-2000 closed stove
iii. 2000-2009 closed stove
iv. modern stove (Ecodesign-compliant, clearSkies level 2 or above)

5.3 SELECTED STOVES AND JUSTIFICATIONS

The specification of each stove can be found in Appendix A.6.

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[13] Construction Products Directive (Council Directive 89/106/EEC) (CPD) is a now repealed European Union Directive which aimed to remove technical barriers to trade in construction products between Member States in the European Union. The directive is now replaced by Regulation (EU) No 305/2011

[14] https://www.gov.uk/government/publications/amended-approved-document-l1b-and-domestic-building-services-compliance-guide

[15] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2015.193.01.0001.01.ENG

[16] www.clearskiesmark.org

5.3.1 Open fire

The choice of open fire was a standard grate setting (Parkray Paragon inset open fire of 400 mm nominal width). This setting is used for the routine testing of manufactured smokeless fuels. It is a standard setting and is wholly appropriate for this test programme.

Parkray Paragon inset open fire no data on installations available

5.3.2 Pre-2000 closed stove

The pre-2000 closed stove proved difficult to source. Several options were found but their size was not appropriate for the test program. A suitable stove released circa. 1997 was sourced, however due to the age, there is little detail from the manufacturer as they no longer have records of their discontinued models. The 'turbo baffle' system which was part of the air system has been blocked for the test program according to the manufacturer's recommendation.

Hunter Oakwood no data on installations available

5.3.3 2000-2009 closed stove

The HETAS installation dataset starts from 2006. We have used data collected between 2006 to 2009, where there was a total of 114,636 notifications across these 4 years (HETAS commented that there are fewer manufacturers during this period and a lot less models). Three stoves stood out as models appropriate for this period, the following was considered as most appropriate:

Stovax / Dovre Model Dovre 500MRF (2.9%) installations across 4 years

5.3.4 Very efficient modern stove (Clear Skies level 2 or above)

HETAS guidance for choosing the final stove was from cross-checking the Clear Skies website with the installed inventory. Their selection from the period, 1st July 2020 to 30th June 2021 was selected from approximately 112,400 notifications. The model chosen is not the most popular installed but, is the most popular Clearskies model when including all the model derivatives.

Charnwood Model: C4 (0.95%) 1st July 2020 to 30th June 2021.

6. WP1 POLLUTANT MEASUREMENTS

6.1 TEST PROTOCOL

Initial testing and discussions with the Steering Group informed the development of a Test Protocol, which defined how the measurement programme in WP1 should be undertaken to develop the emissions factors for all the specified fuels and appliances. The Test Protocol was largely developed before the Round Robin began and was subsequently updated based on the challenges and findings from the Round Robin tests. The Test Protocol was presented to the Steering Group on 25th November 2021 and was approved for use and applied in the WP1 test programme.

The test protocol addresses several considerations including:

- How to measure 'real-world' emission performance
- Consistent appliance operation
- Pollutant Measurements
- Methodology development for Black Carbon measurements and condensables characterisation
- Performance characterisation - assessments of uncertainty, variability, and accuracy of measurements through repeatability testing
- Uncertainty and accuracy of results
- Method for the creation of final emissions factors and co-operation with NAEI agency

The Test Protocol describes the equipment set up, methodology, appliance operation and operating parameters in detail and these are summarised in this report.

6.2 REAL WORLD EMISSIONS

6.2.1 Overview

The requirement for real world conditions to be replicated in the laboratory is a challenge. Current appliance type-test and emission test methods[17] exclude transitional phases such as start-up and shutdown. Excluding these phases ensures that different laboratories can use the standards when assessing appliance performance with acceptable uncertainty and repeatability. However, this approach is not suitable to produce representative emission factors as key parts of the operational cycle of the stoves are not assessed. These transitional phases as well as end-user behaviour, appliance refuelling and burn length will contribute to real-world emissions.

The operating cycle of a fireplace or stove includes four modes of operation (Figure 6-1) – Off / Start-up / Steady Operation / Shutdown. The testing method will include Start-up, 'Steady' operation (that is pseudo-steady operation including refuelling) and Shutdown (combustion and heat output decline until there is no combustion in the off phase).

The European beReal[18] project looked at test methodologies for measuring the performance of an appliance including start-ups, refuelling and shutdowns. The beReal test methodology was developed using a survey of the real-life operation behaviour of biomass room heating appliance users in Europe. The "beReal-Firewood" test method is characterized by a test cycle starting with an ignition phase followed by batches of refuelling with a period of cooling down between each batch as the material burns down. The appliance is run to simulate real-life operation where fires are manually refuelled over a period of cycles until a final shutdown period.

[17] For example the harmonised appliance performance Standard BS EN 13240:2001 +A2:2004 - Roomheaters fired by solid fuel - Requirements and test methods and the successor Standard BS EN 16510 Pt 1.

[18] beReal: Advanced Testing Methods for Better Real Life Performance of Biomass Room Heating Appliances - http://www.bereal-project.eu/

Figure 6-1: Four stages of operation for stoves and open fires

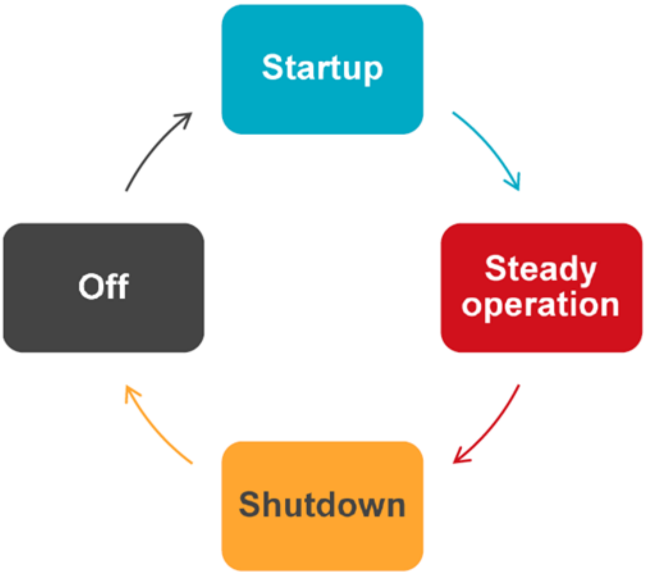

Figure 6-2: Test profile for real-world testing of stoves and open fires

For developing emission factors for the UK some parts of the beReal test method are considered appropriate to UK appliance operation but other aspects are not applicable to UK practise. For example, the beReal test cycle includes eight cycles of refuelling including three partial loads. This number of cycles represents behaviour in European countries (informed by a user survey) which typically experience colder weather than the UK and, where appliances may provide more heating requirements in a property.

The recent Defra study on domestic burning[19] looked at UK burn profiles and found that indoor burners in winter did not necessarily burn every week. The report highlighted that UK solid fuel appliances are mainly used for supplementary heating rather than as the main source of heat. The report also shows that the average burn hours and user segmentation points are limited to daily burn hours, for example in the evening. The survey found that 8% of UK users for which solid fuels are the primary source of heat typically, only burnt for 5 hours – much lower than beReal.

Seasonal average hours burned by UK users are provided in Figure 6-3 for days of the week and it can be seen that the mean hours burned per day ranges from about 1 hour (summer) to 4.5 hours (winter). The daily operating hours are limited and unlikely to represent multiple operating periods in the day on the appliances, that is the operating hours are for a single operation of the appliance (for example afternoon or evening). Recent UK research into indoor air pollution from use of solid fuel appliances indicates a similar average duration of use of about four hours[20].

Figure 6-4 provides a summary of the weekly operating hours of open fires and stoves from the Defra burning survey which, in general, suggests that stoves are used for longer periods than open fires.

[19] Defra Burning in UK Homes and Gardens - Research Report December 2020 available here : http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20159&FromSearch=Y&Publisher=1&SearchText=burning&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

[20] Indoor Air Pollution from Residential Stoves: Examining the Flooding of Particulate Matter into Homes during Real-World Use by Rohit Chakraborty et al Atmosphere 2020, 11(12), 1326 available here https://www.mdpi.com/2073-4433/11/12/1326/htm

Figure 6-3 : Mean daily and weekly hours burned across seasons and percentage of indoor burners (from Defra domestic burning survey, 2020 Table 2.12)

Day	Spring		Summer		Autumn		Winter	
	Mean	%	Mean	%	Mean	%	Mean	%
Monday	2.1	12%	0.9	2%	2.7	21%	3.7	42%
Tuesday	1.6	10%	0.8	2%	2.7	20%	3.7	43%
Wednesday	1.7	11%	0.8	2%	2.6	20%	3.6	41%
Thursday	1.5	10%	0.7	1%	2.7	20%	3.7	42%
Friday	1.5	9%	1.1	3%	2.8	20%	3.9	43%
Saturday	1.5	9%	1.1	3%	3.3	24%	4.5	50%
Sunday	1.7	10%	0.9	2%	3.3	23%	4.5	49%
Total	**15.1**	**19%**	**8.7**	**7%**	**20.8**	**33%**	**27.9**	**61%**

Figure 6-4 : Weekly seasonal burning hours for open fires and stoves (from Defra domestic burning survey, 2020 Table 3.10)

	Number of hours burning in the last 7 days							
	Open fire				Closed stove			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Unwtd base	*47**	*25**	*96*	*137*	*59**	*18**	*155*	*343*
Mean	15	8	22	21	18	5	19	29
Median	10	3	15	14	6	2	14	21

* These sample bases are small so the results should be treated with some caution.

Note that wood logs and mineral fuels have different qualities including energy content/density and physical size which influence the burn rates. Consequently, a wood stove will usually require more frequent refuelling than a solid mineral fuel. Wood stoves typically operate with a refuelling period of 40-60 minutes whereas a mineral fuel stove may require refuelling every 90-120 minutes or higher.

6.2.2 Proposed test cycle

The project test cycle considered emissions during ignition, shutdown and three consecutive batches (3 refuels in the operation step) for wood fuels – this is based on the experience within the project team and the Defra burning survey data.

Appliance output is dependent on the appliance instructions on fuel load and air settings or, the capacity of the firebed (open fireplace). The project aimed to achieve the appliance's declared nominal output during steady operation, but priority was given to achieving repeatable outputs rather than the appliances' declared output. This approach is justified because (particularly for older appliances) real-world output may differ from the declared output – the declared output can be based on market requirements rather than capacity of the appliance. Also, for the older appliances, the appliance condition may not be consistent with the 'as built' condition – for example, there may be small leaks in gaskets and seals from the normal wear and aging of the appliance.

Partial load operation was not proposed for inclusion in the test programme. A range of operation is considered in the beReal protocol (and in most national appliance **emission** test procedures) but was not included in this project for the following reasons:

- Stoves are not commonly declared to operate at different outputs (the project team recognises declaration of stove output does not always reflect capacity and that regulation of air controls can allow some degree of load control).

- Including partial loads introduces additional variation into the test protocol reducing repeatability of results and/or potentially requiring an increase in the amount of testing.
- High outputs are excluded for similar reasons as partial outputs. In addition, although very high outputs are part of several emission measurement standards and appliance standards, they may represent abuse/misuse of the appliance.
- As fires develop and burn down, output will vary during the burn cycles.
- Although there is anecdotal evidence that the operation of appliances can vary significantly and include partial load, the project team had not identified UK-specific information that could be used to develop a representative test cycle that would incorporate variation in load/operation (the beReal data on operating hours are not consistent with UK practise so it was not reasonable to expect that beReal output variation would apply to UK).

The test programme included wood fuels of different moisture content but the impact of other fuel properties on emissions was not assessed.

Other real-world aspects such as user behaviour (for example misuse, maintenance) were not addressed in the test programme. Such issues have been reported as having significant impact on emissions but robust, detailed information on how appliances are operated in the UK are not available to allow elaboration in the test programme.

6.3 CONSISTENT APPLIANCE OPERATION

The operation of each appliance was set out in a testing guide to provide key information for the test engineers.

6.3.1 Appliance familiarisation

On installation, the test engineer reviewed the appliance manual (where available) and familiarised themselves with operation of the air controls. The manual was used to check operation of controls and recommended control settings. A small number of trial burns were undertaken to check operation, interaction with the dilution tunnel and determine air control settings and fuel quantities to achieve either the nominal output or another output condition. The trial burns were used to adjust the quantity of fuel and kindling for the individual appliances. Placement and orientation of the fuel on the grate was also assessed to optimise ignition after refuelling (to minimise user-intervention after refuelling)[21]. Appliance control settings were recorded and, for convenient reference later, marked on the appliance with chalk.

6.3.2 Test cycle steps

The following test cycle steps were undertaken, note that fuel quantities were adjusted to reflect findings during the trial burns:

Ignition/Start-up

To measure the performance of appliances during start-up, a consistent method for setting up the fuel bed and defining test length is required. The beReal study set out a methodology for start-up:

- The mass of the first fuel batch for ignition to be at least 100% of the fuel mass representing the required output (nominal load).
- Kindling material - hardwood can be used.
- The total mass of kindling material will be limited to ≤25% of the total batch mass.
- Kindling will be placed under the logs for startup
- Two small firelighting starting aids will be used with the total mass of starting aids limited to ≤3% of the total batch mass.

For start-up from cold some manufacturers indicate that the door should be left ajar for up to 10 minutes. This period is considered too long from Kiwa and university experience. Typically, manufacturers' instructions require the air control(s) to be in the fully open position and to leave the stove door ajar for a period of 2 – 3 minutes in order to establish flames on a new fuel charge. If the door is closed after 2 minutes the likelihood is that the logs will not catch sufficiently, unless the stove has a powerful air wash control (these vary between appliances and older appliances have basic or no air wash).

[21] Note that some appliances have large grates and placement of the logs can influence how easily fuel ignites and hence emissions, most users will understand from experience where to place the fuel to minimise intervention to 'encourage' ignition but for the test programme we will use the trial burns (and engineer experience) to determine placement of fuel.

Figure 6-5 : Ignition fuel load and kindling crib arrangement

For the WP1 test programme the beReal study ignition procedure was adapted to reflect the Round Robin testing experience and also incorporated input from the project Steering Group regarding bark on logs:

- The typical batch mass of the wood for WP1 refuels was 1.2 kg (for seasoned wood - dry and wet wood quantities were adjusted) and consisted of two logs.
- Wood logs were typically 35-38cm in length with a diameter of 5-10cm. Bark was **not** removed; logs were placed with the bark face pressed into the firebed.
- For ignition the total mass of kindling material was limited at 50% of the total batch mass (0.6 kg kindling).
- Kindling comprised 0.6 kg of wood and provided from the same wood material as the fuel logs.
- Kindling was placed under the logs for startup.
- The total mass of starting aids (firelighter) was limited at 3% of the total batch mass. Firelighters were placed in the centre of the kindling. A kerosene based firelighter[22] was used for all ignition batches.
- The ignition batch was carefully constructed so as to ensure repeatable conditions. An appropriate mass of firelighter was placed in the centre of the grate. A square crib of kindling was constructed around the firelighter leaving a space at the front of the pile allowing for airflow. Two logs were placed horizontally on top of the crib.

A larger quantity of kindling was used than for the beReal project following experience with the appliance used in the round robin testing and from anecdotal commentary that UK users prefer to set a larger fire initially.

For the stoves, the primary air control was placed in the fully open position and the secondary air control at 75% open. The door was left open for 3 minutes (1-2cms from the fully closed position) until the fire was blazing brightly, then the door was fully closed. The primary air was closed about 10 minutes after the door was closed. The secondary air control remained in the 75% open position and was unadjusted throughout the experiment. All appliance settings (and any changes) will be noted during the test procedure.

Note that these are the control settings determined for the appliance used in the round robin testing. Other appliances and the open fireplace required different operation which was determined from initial trial burns. Similarly, burning dry and wet wood required different settings.

The test period began when ignition of the fire bed started. Following the experience from the round robin testing, the start-up period was deemed complete when the flames were extinguished, this is considered more consistent with user-behaviour than a fixed fuel weight or flue gas composition. In the event that the flames go out with a substantial mass of fuel remaining on the grate, for example for the wet wood test programme, the fuel particles were manually broken apart to promote flaming combustion. Once start-up period ends, the appliance was refuelled and the test entered the next stage of the operating test cycle.

(Steady) Operation

The operation step is the phase where the appliance is hot and will most closely align with standard test methods for domestic solid fuel heating appliances. In this step the appliance is allowed to run and burn down

[22] 'Zip', High performance firelighter

fuel in the fuel bed. The fuel bed was refuelled twice more during this period of operation in WP1 (three fuel batches in total). The time for adding a new fuel batch was when the flames went out.

A standardised refuelling approach was used for each appliance to reduce the variability of results and ensure fires were built in a similar manner. The times of opening the appliance door, raking fire bed, adding fuel, closing door and opening/closing the air control were recorded. Settings used for air controls were determined during trial burns and recorded during the test, particularly for any deviations.

For WP1 the stove door was opened and the firebed raked flat and two wood logs of similar dimensions and weight were placed on top of the basic firebed, parallel to the appliance door. The initial burn tests were used to determine where on the grate the logs would be placed to optimise ignition. The stove door was closed immediately and air control(s) opened for a short period to reflect the manufacturers' instructions and experience from the initial trial burn. No changes were made to air settings when burning wood.

Shutdown

The shutdown step in the test cycle is the period where the final batch is allowed to burn out completely. The start of shutdown was not defined in the beReal project however, in WP1 the same flame-out approach was adopted as for refuelling during the operation phase.

The beReal project determined the testing to be completed when the appliance flue gas temperature has cooled down to 50°C or at a point where the appliance and fuel mass does not change significantly. For practical purposes, the proposed end point was at least 60 minutes from the start of the shutdown step and completion when activity (as indicated by weight change) was no longer recorded but subject to a maximum duration of 90 minutes. The maximum time is a practical constraint to allow completion of testing and end-of-test checks within a reasonable period.

The project test cycle considered emissions during ignition, three consecutive fuel batches (operation step) and shutdown for wood. The phase durations for WP1 were:

- Start-up ¾ to 1 hour.
- Normal operation 3x~45minutes = 2½ to 3 hours.
- Shutdown 1 to 1½ hours.

6.3.3 Adjustments to test cycle applied for wet wood

Due to the varying moisture content of the wood fuel, and the resulting burn characteristics, the testing protocol had to be adjusted to allow for variations in test time frames. Higher moisture contents of the wood fuels resulted in longer burn times for each phase with low moisture resulting shorter burn times for each phase. Appliance type also impact test time frames, but moisture is the largest factor in determining test length. Table 6-1 shows the average test time for each of the fuels.

Table 6-1 Average test times for different moisture contents

Dry Wood (6%)	Seasoned Wood (15%)	Wet Wood (25%)
3:00 hours	4:10 hours	5:00 hours

In addition, the test protocol was changed for wet wood due to the difficulty of igniting during refuels, one square of additional firelighters (approximately 15g) were added on each refuel. The embers left over from the ignition stage did not have sufficient heat to ignite fresh fuel. This is due to the heat required to evaporate the additional moisture present in wet wood.

6.3.4 Repeat measurements

The test programme was based on measurements on **three** test cycles for each fuel and appliance combination. Note that some measurements were taken over all phases of a test cycle and others were collected separately during start-up, shutdown and a single operating step.

The measurements taken are variable under standard laboratory tests and standards used for assessing solid fuel appliances for national particulate emission limits adopt a range of replicates and operating conditions. These range from single measurements at up to four operating outputs to three or five measurements at one or more outputs.

6.4 MONITORING OF OPERATING PARAMETERS

Key appliance operating parameters were monitored continuously and (where feasible) controlled during the test cycle. These included:

- Appliance draught – following comment and information from the Steering Group a draught of about 16 Pa was used throughout all stages of appliance operation which is higher than used for appliance testing under EN standards, but which is believed to be more typical of UK operation. It is the median value of example draughts provided to the project team by the Steering Group.
- Burn rate – appliances were installed on a balance and the weight was continuously recording during test.
- Appliance outlet temperature.
- Oxygen, CO, CO_2, OGC
- Ambient temperature, pressure and relative humidity were observed at intervals during the testing process.

6.5 POLLUTANT MEASUREMENTS

6.5.1 Overview

The main test programme was carried out at Kiwa's solid fuel testing laboratory near Cheltenham. Kiwa operates a UKAS accredited laboratory to carry out type-testing of solid fuel burning appliances. The laboratory can test the performance of solid fuel appliances in accordance with BS EN 13240: 2001 +A2:2004[23] and is also the centre for annual testing of manufactured smokeless fuels to demonstrate their continued compliance with HETAS registration. Development test work has also been undertaken by Manchester and Leeds universities to explore the condensable particulate fraction, validate the test protocol and comparative 'round robin' test work.

6.5.2 Measurement facilities

The test facility is based on the requirements in the BS EN 13240 standard for measuring the performance of residential room heaters fired by solid fuel. In addition to the requirements of the appliance performance test standard a dilution tunnel as specified in BS 3841 Part 2 (and in CEN/TS 15883)[24] was applied for some measurements.

Figure 6-6 shows how the appliance and measuring equipment were arranged. The dilution tunnel section sits directly above the stack testing section (shown to the side in Figure 6-6). Platform scales were used to monitor fuel burn rate. The test set up shown was used for all appliances in the test programme including the open fireplace. A number of techniques and instruments were used to measure the range of pollutants in the stack testing and dilution tunnel sections which are detailed below. Figure 6-7 shows the appliance test rig and selected instrumentation.

[23] BS EN 13240: 2001 +A2:200423 - Room heaters fired by solid fuel-requirements and test methods. Also BS EN 16510-1

[24] BS 3841: Part 2:1994 Determination of smoke emission from manufactured solid fuels for domestic use. Part 2: Methods for measuring the smoke emission rate and CEN/TS 15883 -Residential solid fuel burning appliances — Emission test methods

Figure 6-6: Test equipment set up for the test programme. (Not all sample ports are included for clarity)

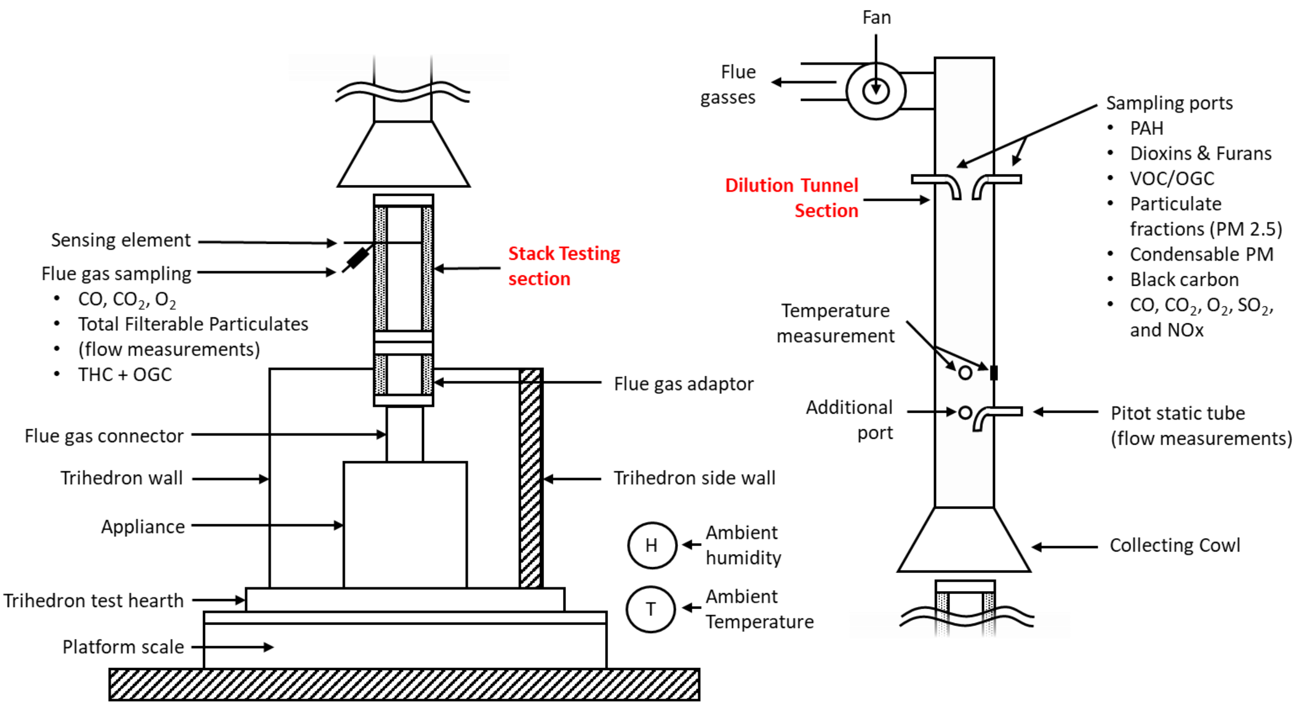

Figure 6-7: Appliance test rig

Table 6-2 : Summary of emission measurements

			Appliance outlet		Dilution tunnel						
Test phase	Appliance	Fuel	O_2/CO/CO_2+ OGC/VOC	TPM(filterable)	PCDD/F+PAH	O_2/CO/CO_2/ +OGC/VOC +NOx	SOx	TPM(filterable+ condensable)	PMx(filterable +condensable)	EC/OC (Black Carbon)	Metals
WP1	St1	W1	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W2	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W3	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
	St2	W1	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W2	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W3	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
	St3	W1	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W2	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W3	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
	Open	W1	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W2	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA
		W3	Cont. (3)	3x3	3x1	Cont. (3)	3x1	2x3	3x3	1x3	NA

Notes :
Appliances – ST=Stove
Fuel – W1/2/3 – Wood fuels at different moistures
Emission measurements – Cont.(3) – continuous measurement, 3 tests. N x n denotes replicates and individual phase measurements. For example, 3 x 3 denotes three sets of periodic measurement, three measurements per set (one each in ignition, operation and shutdown phases). Note that EC/OC samples are collected over only part of each phase. SOx and PCDD/f+PAH (3x1) collected over entire test.
NA – Not applicable.

6.5.2.1 Emission measurements in the stack testing section

The stack testing section is directly connected to the appliance outlet flue. This sampling section is as used in the EN Standards for appliance testing. Several pollutants are measured here:

Total filterable particulate
The PM concentration and mass flowrate will also be measured using an extractive sample system with a quartz filter using 'DIN+' sampling equipment. The quartz filter is conditioned and weighed before sampling. Flue gas is withdrawn via a heated sample line and passed through the filter which is heated to 70 °C. After exposure of the filter for a predetermined time and gas flowrate, the filter is conditioned and reweighed. The increased mass of the filter is used as the total amount of filterable particulate. Weighing of the filter follows a defined period of conditioning at a fixed temperature and humidity. Samples were collected over the course of the test cycle at different steps: Cold start, operation (a single refuel batch) and Shutdown. A pre-filter rinse was used to recover PM deposited upstream of the filter however, a combined rinse was collected for each test (covering measurements in the different phases).

Combustion gases - CO, CO_2, O_2
Combustion gases including carbon monoxide, carbon dioxide and oxygen (CO, CO_2, O_2) were measured using continuous gas analysis equipment, and analysis methods in accordance with BS EN 13240 and CEN/TS 15883.

Total Hydrocarbons (THC) / Organic Gaseous Carbon (OGC)
The performance measurements of residential solid fuel burning appliances also include the requirement to report the total hydrocarbon content in the flue gases from appliances burning solid fuels. The result obtained is expressed as propane equivalents. This measurement does not give information on speciation of organic constituents. It has been included as it is part of the requirements under the DIN+ standard method and was based on the sampling and analysis methods in accordance with CEN/TS 15883:2009[24].

6.5.2.2 Measurements in the dilution tunnel section

The following emission measurements were undertaken at the dilution tunnel above the stack testing section.

Combustion gases- CO, CO_2, O_2, SO_2, VOC and NOx
Continuous emissions monitoring for CO, CO_2, O_2, sulphur dioxide (SO_2) and oxides of nitrogen (NO_x as NO_2) were carried out by ECL, a UKAS accredited testing laboratory, number 2499 using an MCERTs-certified Horiba PG 250 in accordance with BS EN 15058:2017, ISO 12039:2001[25], BS EN 14789:2017, PD CEN/TS 17021:2017 and BS EN 14792:2017, and in-house technical procedure ECL/TPD/033c. In this method the stack gas is withdrawn and passed through the analyser where the gas stream is analysed by chemiluminescence (NOx), non-dispersive infrared (CO, SO_2, CO_2) and zirconium (O_2) techniques to determine the pollutant concentrations. Continuous monitoring for total volatile organic carbon (VOC)[26] was undertaken using an MCERTS certified Signal 3030PM or Sick F3006 flame ionisation detection (FID) analyser and heated (180°C) gas transport system to BS EN 12619:2013 and in-house technical procedure ECL/TPD/032A or 32B. Calibration of the continuous measurement systems was direct to the analyser and then via the probe through the entire gas transport system.

Sampling for SO_2 in WP1 was carried out in accordance with BS EN 14791:2017 and In-house technical procedure ECL/TPD/039 which is better suited to low SO_2 emission concentrations expected from wood and the application of a dilution tunnel than continuous systems. The stack gas was extracted, filtered and passed through a series of impingers containing Hydrogen Peroxide solution, with subsequent analysis by ion chromatography. In accordance with the standard, appropriate field blanks were submitted for analysis.

Black Carbon
Particulate matter was collected for offline analysis of Black Carbon (BC). Black carbon will be measured in particulate matter on a filter heated to 40°C and subjecting to thermal-optical analysis using the EUSAAR-2 protocol, which compared to other in-use protocols (for example NIOSHH, QUARTZ, IMPROVE) is known to suffer less charring artefacts when analysing wood smoke emissions. This analysis will give the amount of elemental carbon (equivalent to black carbon) on the filter. Samples will be taken for each test step, representative of flaming and smouldering. These samples will be collected separately from the filter samples for gravimetric analysis, as the optimum amount of material to collect will be different (too much material will

[25] Note that the method for CO_2 (ISO 12039:2001) may change as the testhouse will transition to PD CEN-TS 17405:2020 in 2021.
[26] Note that the VOC measurement at the dilution tunnel and the OGC measurement at the appliance outlet are essentially the same measurement approach – the measurement standards have different terminology for the same measurement.

prevent reliable thermal-optical analysis). The following test protocol has been informed by pilot experiment work undertaken at the University of Manchester (Section 3).

Sampling media – a 47mm binderless, sodium-free and heat-treated quartz fibre filters (Pall Tissuquartz 2500 QAT-UP). Unlike the samples taken for gravimetric analysis, only a limited amount of material must be collected in order to obtain a reliable elemental carbon (EC) measurement using thermal-optical analysis.

Handling - At all stages, the samples were handled using gloves and clean metal or plastic tweezers. The filters were handled by the edges and the filter holders and tweezers were cleaned using an appropriate solvent (2-propanol) before use.

Sampling - the samples were collected from the dilution tunnel using a particulate sampling system using a standard flowrate of 5 l min^{-1}. The filter holder was operated at 40 °C. The samples were collected concurrent with the gravimetric particulate samples being taken on the flue:

- Ignition – at the start of the ignition phase
- Operation – about ten minutes after refuelling during flaming phase
- Shutdown – no specific time period

The total volume of air sampled was about 20 litres (sample period of 4 minutes at 5 l min^{-1}).

Storage - After collection, the filters were stored in self-sealing petri dishes and then stored in a freezer at -18 °C.

Shipping - The samples were shipped to the analyst with cold packs to maintain a cold temperature.

Total filterable particulate

The PM concentration and mass flowrate were measured using an extractive sample system as applied at the stack section – the difference between the total filterable particulate at the dilution and stack testing sections provides the condensable PM. Three samples were collected over the course of the test cycle at different steps : Cold start, operation (a single refuel batch) and Shutdown. A pre-filter rinse was used to recover PM deposited upstream of the filter.

Condensable particulate fraction and semi-volatile organic carbon

Condensable PM currently lacks a consistent definition. The current EMEP recommendations[27] that ultimately may form the basis of CLRTAP reporting requirements involve the quantification of carbonaceous matter emissions binned according to a so-called ‘volatility basis set’ from Robinson et al[28]. This is particularly challenging for the ‘semi-volatile’ and ‘intermediate volatility’ organic compounds (SVOCs and IVOCs), which can exist in the vapour phase at the point of emission but partially recondense into the particle phase during atmospheric processing. Quantifying this requires a highly detailed analysis using a combination of different mass spectrometric techniques (e.g. Lu et al., 2018[29]) and is not deemed feasible to perform systematically in this work.

To quantify the condensable fraction, total filterable PM measurements in the dilution tunnel section will be compared to the measurements of total filterable PM measurement taken from the stack testing section – the difference providing an estimate of the condensable PM. The particulates measured from the stack testing section are from high temperature flue gasses and are passed through a heated filter and will not filter condensable particulates. Whereas, the dilution tunnel samples are taken at lower temperatures and the filter is unheated and will include part of the condensable particulate fraction.

Particulate Matter size fraction – (PM_{10}, $PM_{2.5}$, PM_1)

In addition to the total filterable PM taken from the Stack Testing Section and dilution tunnel, separate measurements to determine particle size were made at the dilution tunnel. The particulate size measurements were made using a Dekati PM_{10} Impactor which is a three-stage cascade impactor allowing for the collection of particles based upon the following mass size distributions: ≥10 µm, 2.5-10 µm and 1.0-2.5 µm. A final stage back-up filter is used for the collection of PM_1 (0.3-1 µm). This allows the $PM_{2.5}$ particulate fractions to be measured. The impactor operates at 30°C to prevent moisture condensation. A series of greased aluminum foils (25mm) are used at the upper stages of the impactor to collect the larger size fractions (≥10 µm, 2.5-10 µm and 1.0-2.5 µm). The mass of each fraction is measured which allows the quantification of each fraction.

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[27] EMEP Technical Report MSC-W 4/2020

[28] Robinson et al. (2007, doi: 10.1126/science.1133061).

[29] Lu et al., 2018, 10.5194/acp-18-17637-2018

Round robin measurements indicated sampling during the entire ignition period is likely to be a challenge due to clogging of the final filter. In these circumstances sample was collected until the required flowrate could no longer be maintained (reducing the flowrate will affect the particle sizes collected by the sampling system).

Samples were collected at alternate steps in the test cycle (as for total filterable particulate). A pre-filter rinse was used to recover PM deposited upstream of the filter (but, as for PM, the rinse was collected over the whole burn cycle).

Prior to sampling, foils and glass fibre filters were prepared in order to remove moisture; foils and filters were placed in a desiccator for a **minimum** of 12h prior to weighing.

At each weighing process, an unused filter, foil and a test weight were weighed to provide control weights. Both foils and filters need to be weighed before and after sampling. Before weighing the foil/filter were stored in a desiccator for a minimum of 12h to remove moisture. Filter papers were weighed for 3 min following the stabilisation of the balance output. Foils were weighed until the balance output is stabilised.

Quantitative cleaning and recovery of particulate material deposited in the sampling nozzle, probe and upstream of the impaction plates was undertaken. This was done at the end of the day to recover any particulate material that had been deposited over the test cycle. This was undertaken using acetone to rinse surfaces into a sample container for subsequent gravimetric analysis. The procedure followed here is the same as used when undertaking PM measurements on solid fuel stoves where the sample lines are washed at the end of the tests.

Dekati Sample Probe Flush Out

- Once the final burnout test has been completed the Dekati sampler was disconnected from the sample probe.
- The sample probe was disconnected and removed from the dilution tunnel.
- The sample probe was rinsed with acetone at least three times, rotating the sample probe when rinsing to ensure that all particulates and condensed residues are in contact with the solvent.
- The washings were transferred in a pre-weighed aluminium tray (weight recorded three times to four decimal places).
- Washings were evaporated overnight at ambient temperature.
- The aluminium tray was oven-dried at 105°C for at least one hour and stored for at least 4 hours in a desiccator.
- The weight of the tray and residue were recorded three times to four decimal places.
- The washing residue was distributed equally across each Dekati sampling period and reported as part of the >10µm fraction.

Any exterior combustion debris and debris generated during the cleaning process were removed before reuse.

Sampling was undertaken across the duration of a complete batch cycle thereby including the start-up, flaming phase and smouldering phase. Impactor sampling started following the ignition of the firelighter material (Ignition Batch), following reloading (Test Batch 2) and burn-out test.

Impactor sampling was aligned with the batch duration and stopped at the end of the designated test batch. During the **Burn-Out Phase batch**, the Impactor sampling was stopped when the end of test was reached. During the **Ignition Batch** higher PM loading may have required shorter test periods. Increased particulate loading during start-up will progressively block the filter and sampling must stop when the required flowrate (10 l/min) cannot be achieved. This process did not affect sampling during the operation phase.

Prior to ignition a pre-test sampling phase (field blank) test was undertaken, using an additional set of foils/filter will be undertaken to ensure that all sampling equipment and the Dilution Tunnel were clear of debris and sources of contamination. A sampling rate of 10 l/min and a sampling period of 20 min was used. These foils/filter underwent the same preparation, recovery and gravimetric analysis.

Table 6-3 : Particle fraction and total particulate sampling guidelines (WP1)

Ignition Batch	Test Batch #1	Test Batch #2	Test Batch #3	Burn-Out Phase
✔	X	✔	X	✔
Sampling at 10l/min	No sampling Recovery of impactor and reloading	Sampling at 10l/min	No sampling Recovery of impactor and reloading	Sampling at 10l/min
Sample until end of batch or until a flowrate of 10 L/min is no longer achievable	X	Sample until end of batch	X	Sample until end of test (60-90 minutes)

Polycyclic aromatic hydrocarbons (PAH) + Dioxins & Furans
PAH, Dioxins and furans were measured by ECL, a UKAS accredited testing laboratory, number 2499. Sample analysis was carried out by a UKAS accredited laboratory using gas chromatography and mass spectrometry. All sampling and analysis was completed to the relevant EN and ISO standards but there were deviations to combine the sampling into a single sampling train (to reduce sampling probes and equipment at the sampling position).

Dioxin and Furans emission sampling was carried out in accordance with BS EN 1948-1:2006 & MID and In-house technical procedure ECL/TPD/031. In this method a minimum of 3.5 cubic metres of stack gas was withdrawn isokinetically over the entire test cycle (note that this will be shorter than the typical minimum period of 6 hours), filtered at ≤125°C and then passed through a XAD resin trap and a series of impingers to remove all condensables. This sample went through subsequent analysis by GC-MS. In accordance with the standard, appropriate field blanks were submitted for analysis.

PAH emission sampling was carried out in accordance with BS ISO 11338:2003 and in-house technical procedure ECL/TPD/037. In this method stack gas was withdrawn isokinetically using the same sampling train as for the dioxins and furans – that is, a sample is filtered then passed through a XAD resin trap, and a series of impingers to remove all condensables, with subsequent analysis by GC-MS. In accordance with the standard, appropriate field blanks were submitted for analysis.

The procedure adopted used a **single** sampling train for both PAH and dioxins with combined solvent extraction with the bulk of the extracted sample being prepared and analysed for dioxins and a subsample prepared and analysed for PAH. Note that this modified procedure allows considerable efficiencies in equipment and time but does mean that sampling and analysis was **not within the scope of the UKAS/MCERTs accreditation**.

The emission measurements undertaken in the project for WP1 are summarised in Table 6-4.

6.5.3 Integrated measurements and sample analysis

Various metrics including PM, BC, condensables, dioxins, PAH, and SOx required integrated samples to be collected for offline analysis at the stack sampling section and/or the dilution tunnel. At both locations, measurements were accompanied with CO, O_2 and CO_2 measurements so that the amount of material collected can be referenced to fuel burned. For measurements at the dilution tunnel, we used the simultaneous measurement of CO at the appliance outlet and dilution tunnel to determine dilution ratio. Particulate samples were conditioned and weighed in-house with other samples sent away to accredited laboratories.

Samples were stored in accordance with the requirements of the measurement standards and a documented sample storage procedure.

Table 6-4 Components measured in WP1

Measurement	Measurement location	Comments
CO CO_2 TOC/HC NOx	Appliance outlet	Continuous measurement, unweighted CO and O_2 used to standardise integrated samples. Weighted data used to standardise continuous measurements. NOx data used in preference to dilution tunnel data.
NOx CO CO_2 SO_2 TOC/HC	Dilution tunnel	Continuous measurements, unweighted CO data used to establish dilution ratio for integrated samples. Weighted CO data used to establish dilution ratio for continuous measurements. NOx and SO_2 not used (close to LoD and/or variable).
PM	Appliance outlet	Heated filter measurement, integrated samples for alternate phases of burn cycle.
PM	Dilution tunnel	Heated filter measurement, integrated samples for alternate phases of burn cycle.
Dioxins & Furans PAH	Dilution tunnel	Integrated sample collected over entire burn cycle (combined sample).
SO_2	Dilution tunnel	Integrated sample collected over entire burn cycle.
PM PM_{10} $PM_{2.5}$ PM_1	Dilution tunnel	Impactor measurement, integrated samples for alternate phases of burn cycle.
Black carbon	Dilution tunnel	Integrated samples collected over short periods in alternate phases of burn cycle. Analysed for EC and OC. Single sample for each fuel.
Condensable PM	By calculation	Difference between PM measurements at dilution tunnel and appliance outlet.

6.6 TEST SCHEDULE

Table 6-5 Emission test programme

Test Week	Date of Test	Stove	Fuel
1	02/02/2022	Modern Stove	Seasoned Wood
1	03/02/2022	Modern Stove	Seasoned Wood
1	04/02/2022	Modern Stove	Seasoned Wood
2	15/02/2022	Dovre Stove	Seasoned Wood
2	16/02/2022	Dovre Stove	Seasoned Wood
2	17/02/2022	Dovre Stove	Seasoned Wood
3	22/02/2022	Open Fire	Seasoned Wood
3	23/02/2022	Open Fire	Seasoned Wood
3	24/02/2022	Open Fire	Seasoned Wood
4	01/03/2022	Open Fire	Dry Wood
4	02/03/2022	Open Fire	Dry Wood
4	03/03/2022	Open Fire	Dry Wood
5	08/03/2022	Modern Stove	Dry Wood
5	09/03/2022	Modern Stove	Dry Wood
5	10/03/2022	Modern Stove	Dry Wood
6	15/03/2022	Dovre Stove	Dry Wood
6	16/03/2022	Dovre Stove	Dry Wood
6	17/03/2022	Dovre Stove	Dry Wood
7	22/03/2022	Old Stove	Seasoned Wood
7	23/03/2022	Old Stove	Seasoned Wood
7	24/03/2022	Old Stove	Seasoned Wood
8	29/03/2022	Old Stove	Dry Wood
8	30/03/2022	Old Stove	Dry Wood
8	31/03/2022	Old Stove	Dry Wood
9	05/04/2022	Old Stove	Wet Wood
9	06/04/2022	Old Stove	Wet Wood
9	07/04/2022	Old Stove	Wet Wood
10	11/04/2022	Modern Stove	Wet Wood
10	12/04/2022	Modern Stove	Wet Wood
10	13/04/2022	Modern Stove	Wet Wood
11	19/04/2022	Dovre Stove	Wet Wood
11	20/04/2022	Dovre Stove	Wet Wood
11	21/04/2022	Dovre Stove	Wet Wood
12	25/04/2022	Open Fire	Wet Wood
12	26/04/2022	Open Fire	Wet Wood
12	27/04/2022	Open Fire	Wet Wood

6.7 AUDIT

As part of the test programme an audit was undertaken by Ricardo at Kiwa's test facility to ensure that the methodology that had been proposed and agreed by the project steering committee had been correctly implemented. This audit was successfully completed with the Kiwa and ECL test equipment and methodology being approved by Ricardo. One question which was raised during the audit focussed on the heated filter 'DIN +' filter housing and whether there was a requirement for a filter clamp within the system. This was further investigated by the Kiwa team, and the additional analysis is described below in Appendix A8.

6.8 QUALITY ASSURANCE AND QUALITY CONTROL

6.8.1 Importance of QA/QC

The emission factors developed through this project will be used directly in the UK National Atmospheric Emissions Inventory, which fulfils reporting requirements under the National Emissions Ceiling Directive (NECD) (transposed into UK law as the National Emissions Ceiling Regulations (NECR); the United Nations Economic Commission for Europe (UNECE)'s Convention on Long Range Transboundary Air Pollution (CLRTAP).

In addition to fulfilling the national and international reporting requirements, the NAEI provides emissions data for a wide range of other uses including providing policy makers and the public with an understanding of the key polluting sources, how these sources have varied over time and how they are likely to contribute to pollution in the future. NAEI data are publicly available via https://naei.beis.gov.uk and their uses include:

- Annual National and Official Statistics reporting.
- Input into models used for academic research and policy making (including Pollution Climate Mapping and UK Integrated Assessment Model) and analysis by expert groups on air quality.
- Input into ambient air quality mapping for compliance assessments against the requirements of the Fourth Daughter Directive (2004/107/EC) and the Ambient Air Quality Directive (2008/50/EC) and assessment against Air Quality Strategy Objectives.
- Development and assessing progress of national air quality plans.
- Local and regional reporting including production of inventories for England, Scotland, Wales and Northern Ireland, Local Air Quality Management and Clean Air Zones.
- Responding to Freedom of Information Act and Environmental Information Regulation requests, Parliamentary Questions and general queries from the public.

It is therefore critical that the measurements and derived emission factors are of high quality, and subject to checks that give the users confidence in the reported data – particularly around uncertainty of the emission factors data and applicability to UK domestic burning. It is a key responsibility of the project Steering Group to guide the project team in this respect and communication with the Steering Group has been frequent and valuable.

6.8.2 QA/QC of measurements and outputs

The initial phase of the project included test protocol development, which was subsequently used to determine repeatability and reproducibility of the protocol, through round-robin testing within the laboratories at Kiwa, Leeds and Manchester. Analysis of the round robin data has provided an understanding of the uncertainties associated with the test protocol.

The main test programme has been undertaken in the Kiwa laboratory. Testing of solid fuel appliances undertaken under Kiwa's laboratory accreditation supported by the systems required by the testing laboratory standard (ISO 17025) and the relevant appliance standards (BS EN 16510-1, BS EN 13240 and BS EN 13229). For this work, the appliance operation protocol has sometimes been different to those defined in appliance testing standards, as described and explained in the Test Protocol, but the support systems of sensor calibration, data collection and checking for accredited work have been applied throughout WP1. Where changes to methods were required, these have been documented in this report and/or in the Test Protocol and have been validated during the development and round-robin activities.

Regular checks have been carried out to ensure equipment is calibrated and working within specification. For measurements of components at the dilution tunnel (gaseous pollutants, PCDD/PCDF and PAH) sampling has been undertaken in accordance with the ECL Procedures based on EN Standards but with some deviations to combine sampling (for example PAH and PCDD/F). Where possible, testing has been undertaken in accordance with ECL's organizational MCERTS accreditation, by MCERTS qualified personnel and with MCERTS approved monitoring equipment to ensure that the highest quality of data is obtained.

Analytical methodologies have been applied as described in the Test Protocol. Compositional analyses of fuel samples have been undertaken at accredited test laboratories. The accuracy and uncertainty of results from accredited laboratories are reported with the results of the measurements. Where measurements of wood moisture are carried out by the project partners clearly defined methods have been agreed and followed to ensure consistency.

An audit has been carried out during WP1 to assess compliance with the agreed test protocol and measurement methods. This has provided assurance that the test protocol and measurement methods have been followed and has identified improvements that have since been implemented.

Automatic logging of data has been used where possible, with additional manual quality checks to check completeness and accuracy. Other data and metadata have been recorded manually in a dated and signed laboratory book, or electronically with associated files allowing checks and corrections to be made if any data issues are found. Data processing of the data collected by Kiwa and ECL is completed using Python code to ensure consistency in data handling and to enable quality control checks on test data to be systematically made. Using code to process data enables audits of the code and the output files and summary sheets used for emission factor calculations.

6.9 PARTICULATE MEASUREMENTS

Residential combustion is a key category within the NAEI for many pollutants and consequently higher tier emission inventory methods are preferred, including the use of country-specific emission factors to minimise uncertainty in emission estimates.

The EFDSF project has measured a range of pollutant emission factors for wood-burning, but PM measurement data required further investigation.

Heated filter sampling equipment designed to be used for solid fuel appliance emission testing in accordance with EN16510-1:2018 and CEN/TS 15883 was deployed at the dilution tunnel and at the appliance outlet (the conventional application for a heated filter measurement). A measurement audit in WP1 identified that the heated filter PM sampling equipment did not use a filter clamp to prevent potential bypass of filter media (common practice in other PM emissions sampling). Initial exploration indicated that evasion of filterable PM was likely small. However, a modification has been implemented (during WP2) to include a filter clamp to prevent evasion of the filter media. Simultaneous measurements on the dilution tunnel to compare a modified and unmodified filter holder indicated that overall PM collection was unchanged but there was more material collected on the filter of the modified filter.

Measurement of total PM and particle size data at the dilution tunnel taken using a particle size Impactor has allowed checking of heated filter PM data against another measurement approach. It is not best practice to derive total particulate data from gravimetric particle size measurements but, in this project, the PM and particle size measurements were undertaken simultaneously, the sample collection points were located in close proximity at the dilution tunnel and, both systems were sampling at a constant (and similar) flowrate. In addition, most of the material collected is PM_1 so weighing uncertainty for the PM_1 fraction should be similar to the heated filter measurement.

In WP1 the PM concentrations derived from particle size measurements are generally higher than the PM concentrations indicated by the heated filter method. On average they are about 80% higher during ignition and refuel phases of the burn test cycle. Initial data for anthracite on the modern stove indicate that this may not be the case in WP2.

A range of potential reasons for different measurement results at the dilution tunnel were assessed. Both sampling systems are manual, extractive, gravimetric sampling techniques which were located at the same sampling position with the sample inlets in close proximity and samples were collected over the same period. The sampling rates are similar and were verified using a calibrated gas meter. Filter media used in the sampling trains are different, but both are considered appropriate for sampling (fine) particulate. Weighing uncertainty is a factor because the particle size sample comprises more fractions and, dilution tunnel concentrations are relatively low (particularly during shutdown phase).

A comparison of PM concentrations at the dilution tunnel from different sampling trains (including an alternative low temperature PM sampling train with an unheated filter) was undertaken during WP2 for the modern stove burning anthracite (see also Appendix A.8). These data indicate that the modified heated filter equipment (with an O-ring) in general provided higher PM concentrations than the particle size measurements with a smaller variation than in WP1 (but with some significant variation between the three test methods).

The data points to possible loss of particulate matter from the heated filter due to evasion and this gives reason to disregard the data produced by the heated filter method in WP1 (not the case for WP2 when the equipment had been modified to include a clamp). However, the derived particulate emission factors for WP1 can be based on the particle size measurements instead, this approach generally provides a more conservative (higher) set of emission factors than using the heated filter measurements. This is considered reasonable because a number of measurement issues can contribute to a low PM measurement but, there are relatively few circumstances that might result in an overestimate for a gravimetric test method.

Following extensive investigations (detailed in Appendix 8) and discussion with the Steering Group, this study uses PM data from the dilution tunnel particle size measurement data (Dekati) for WP1 – these emission factors are generally higher and represent a more conservative approach than the comparative measurements.

Although the inconsistency between the data from the two PM measurement systems means that these emission factors are considered to have a higher uncertainty, use in the NAEI provides a consistent suite of emission factors (from the same appliance type and fuel type) and provides a significant improvement on the existing emission factors sourced from the EMEP/EEA Guidebook 2019.

6.10 UNCERTAINTY ASSESSMENT

6.10.1 Factors influencing uncertainty

The EFDSF project team is investigating ways to extend the measurement uncertainty to account for the data manipulation/handling operations (including dilution correction, normalisation of concentrations and the conversion of concentrations to emission factor) as well as other approaches to assessing a confidence interval, however, there are a range of wider uncertainty factors where quantification is not straightforward and not within the scope of the EFDSF project.

The uncertainty in the final emission factors comprises a range of contributing elements including:

- Representativeness of the appliances
- Variation in fuels
- Variation in operation
- Measurement – include measurement method, sampling protocol, analysis LoD, calibration/reference materials
- Data handling – data acquisition, storage and handling – the processes to work up the measured data into the final emission factors.

Note that a comparison of the emission factors with the current NAEI emission factors is considered further at Section 7.

6.10.2 Appliance representativeness

The test programme in WP1 is on four appliances that were selected as representative of different types of solid fuel room heater technology used in the UK. The choice of type of appliance was based on the broad types of appliance categories (open/stove) and aligned the stove age classification used in the NAEI to a technology type (basic control/secondary air/secondary and tertiary air) as set out to the EFDSF steering group earlier in the project. The EFDSF steering group helped identify the most popular installed stoves in recent years (used to choose the modern stove) and also provided information on the older appliances. The choice of appliance has been endorsed by the EFDSF steering group. However, it is recognised that it is a small subset of the diverse range of appliances in use in UK.

6.10.3 Fuel type and quality

Fuel is beech, chosen as representative of UK fuel use following discussion with wood suppliers. Clearly, other species of wood (and waste woods) are used but beech was agreed as a representative fuel. The moisture levels of wood have been chosen to provide a range of moisture to align with central moisture levels for the moisture range associated with dry wood, seasoned wood and unseasoned wood – recognising that these terms are not explicitly defined in terms of moisture content. A study of various wood types on a fireplace and a pre-Ecodesign stove indicated a wide range of $PM_{2.5}$ emission factors for a range of southern European wood types (but not including beech)[30]; emission factors ranged from 5.62 to 25.8 g kg^{-1} (dry basis) (cold start) for the woodstove and 8.11 and 29.0 g kg^{-1} (dry basis) (cold start) for the fireplace suggesting that choice of fuel is potentially a major uncertainty. A further study[31] reported that *using a different wood type might cause a two- or three-fold increase in individual emission factors*.

6.10.4 Operation

The appliance test cycle for the measurement programme is based on the typical UK hours of use and, for wood, comprises an ignition phase, normal operation with three refuels and a burnout phase (based on the Defra burning survey and an indoor air quality survey). Aggregate emission factors have been constructed for this test cycle based on combining these five phases. Note that it is possible, for some pollutants, to calculate other aggregations for example as a sensitivity check or to reflect different durations of operation. Previous work[2] has indicated repeatability can be poor with significant variation between individual refuel phases for PM measurement and, operator behaviour is known to be a significant influence on emissions. A recent study[31] reported that *the use of inadequate burning conditions can cause an emission factor increase as high as six-fold*.

6.10.5 Measurement

The appliance test protocol includes test methods which draw on EN Standards and/or EN Technical Specifications for emission and appliance testing but with compromises to reflect the challenges of sampling emissions from a small, batch-fired combustion appliance and a bespoke test protocol. Where no EN Standard exists we have used literature and research to guide the test methodology. The main measurements have been undertaken by IEC/ISO 17025 accredited test houses – recognising that many of the measurements are outside the scope of accreditation (because of changes from the accredited test methods to accommodate the test protocol and constraints of the test facility). For example, measurement during ignition (appliance testing) and combined PAH and PCDD/F sampling (emission testing). However, the test protocol reflects the objectives of the project and incorporated suggestions from the steering group to align operation closer with real-world operating conditions (around draught, retention of bark).

Uncertainties provided by the test houses for the measured concentrations are shown in Table 7-3. Note that these represent measurement uncertainties – they do not include other contributions to uncertainty, for example, data adjustments and calculations to determine emission factors, the representativeness of the appliances, test protocol or fuel.

Some measurements have more uncertainty than others due to a range of factors including analytical uncertainty. The analysis of the individual PCDD/F congeners indicated that although some congeners in the tests were reported as below the Limit of Detection (LoD) there were relatively few (six out of 36) tests where the tetra and penta-chlorinated PCDD congeners and penta-chlorinated PCDF congeners with the highest toxic equivalent factors were below the LoD. In the PAH samples, the four compounds used for international reporting were found above the LoD in all tests. Some other PAH compounds were reported below the LoD in several samples (Benzo(b)naptho(2,1,d)thiophene, Cholanthene, Dibenzo (ai)pyrene) however contribution to totals (assuming present at LoD) was <<1%.

6.10.6 Data handling

For some pollutants periodic integrated samples were collected over the entire test cycle (PCDD/F, PAH, SOx), some were measured continuously over the entire test cycle and data have also been gathered for each phase of operation (CO, NOx, TOC). For some pollutants, integrated samples were collected in selected phases of operation – ignition, 2nd refuel and burn out (PM, PM size). These latter samples sampled one refuel phase (of three) so are likely to have higher uncertainty than measurement that sampled all phases of operation.

In addition to the measurement uncertainties all pollutants have required data manipulation to get from concentrations to emission factors:

[30] Goncalves et al, 2011, Organic compounds in PM2.5 emitted from fireplace and woodstove combustion of typical Portuguese wood species. Atmospheric Environment 45 (2011).

[31] Fachinger et al, 2017, How the user can influence particulate emissions from residential wood and pellet stoves: Emission factors for different fuels and burning conditions. Atmospheric Environment 158 (2017).

1. Application of a dilution ratio based on CO concentrations measured at appliance outlet and dilution tunnel
2. Standardisation of undiluted concentration to a reference oxygen content
3. Application of a conversion factor to calculate an emission factor
4. Aggregation of short-term emission factors to cover the entire burn cycle.

These operations contribute additional uncertainty to the measurement uncertainty. Three sets of measurements were undertaken for each fuel and appliance combination, and this has allowed calculation of standard deviation and other indicators of repeatability. The EMEP/EEA Guidebook confidence intervals for emission factors are generally (much) larger but are typically based on expert judgment to assign an indicative uncertainty range. This reflects the challenges in understanding the uncertainty from combining emission factors reported by a range of studies (or calculated from reported data) with differing objectives, different appliances and often different measurement approaches.

Table 6-6 Selected measurement uncertainties

Measurement	Lab	Maximum Allowed Uncertainty of Method (MCERTS), %	Range of recorded uncertainty
Concentrations			
PCDD/F	ECL	30%	15 – 25%
PAH	ECL	30%	15 – 25%
SO_X	ECL	20%	10 – 20%
TOC	ECL	15%*	15 – 25%
CO	ECL	6%*	5 – 15%
Method uncertainty			
CO	Kiwa		6%
NO_X	Kiwa		±1.2 ppm
CO_2	Kiwa		2%
O_2	Kiwa		2%
PM	Kiwa		0.29g/h
Other			
Appliance/Fuel weight	Kiwa		±20g
Fuel load	Kiwa		±5g
Flue gas Draught	Kiwa		±2Pa
Flue gas temp	Kiwa		±5°C

- MCERTS maximum allowed uncertainties are for application on industrial activities (specifically ‘Part A’ activities regulated under Schedule 1 of the Environmental Permitting Regulations (England & Wales) 2016 and equivalent in Scotland and Northern Ireland).
- MCERTS maximum allowed uncertainties are defined in terms of Emission Limit Values (ELVs) for TOC and CO but ELVs for stoves are not applicable for measurement on diluted exhaust gases.
- PM uncertainty is for DIN+ PM test method (at appliance outlet)

7. EMISSION FACTORS

7.1 METHODOLOGY

The measurement programme provided:

- continuously monitored emission concentration data throughout the different phases of the burning cycle for some gaseous measurements (CO, CO_2, O_2, NOx, TOC),
- an integrated concentration measurement for (PCDD/F, PAH and SOx) over the whole burn cycle,
- integrated PM-related concentrations measurements for alternate phases of the burning cycle (ignition, 2^{nd} operation and burnout phases).

Measurements were generally undertaken at the dilution tunnel with selected measurements also undertaken at the appliance outlet.

Emission measurements were generally provided as concentrations (a volume or mass in a known volume of sampled gas). Continuously monitored data has a weighting to adjust for different burn rate at each 1-minute average data point (not applied to integrated samples). Black carbon and particle size data were reported as weights or similar metric and were developed into concentrations based on sample duration and reported sampling rate.

The calculation of emission factors for each appliance and fuel combination from the emission concentration data reported by the test houses required several calculation stages:

- Initial data check to confirm concentration provided at STP (0°C, 101.3kPa) and dry gas for period sampled, identification of odd data for review.
- Conversion to a mass concentration at STP for a dry gas (where required).
- Correction to undiluted concentration applying ratio of CO determined at appliance outlet and dilution tunnel (where required).
- Standardising to a reference oxygen concentration (13% O_2).
- Converting to a g/GJ net heat input emission factor by applying a stoichiometric dry flue gas volume (253 Nm^3/GJ net heat input) adjusted to 13% O_2 for wood.
- Aggregating emission factors for each phase for full burn cycle (weighted for fuel burned in each phase).
- Averaging for each appliance/fuel combination (3 tests to single value).

The full dataset of aggregated emission factors is provided at Appendix A.9.

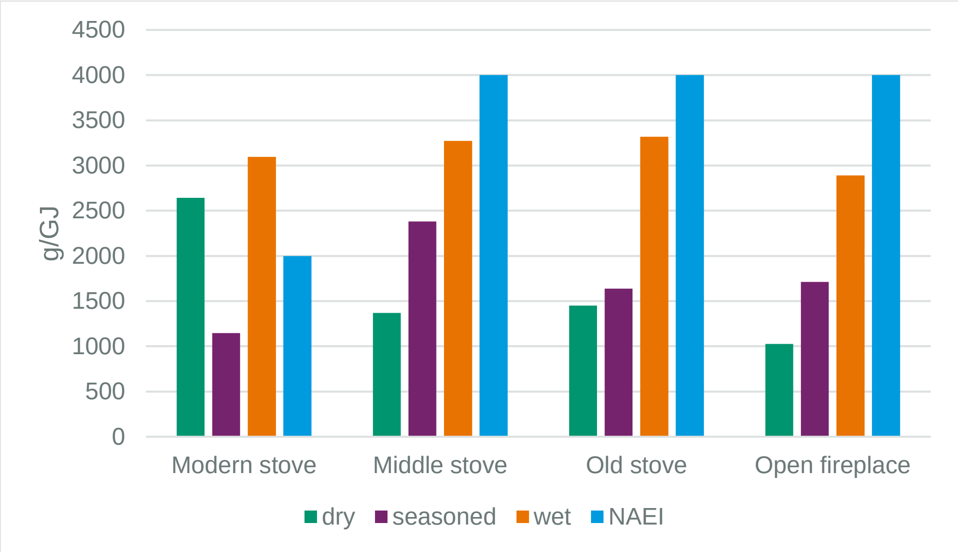
7.2 SUMMARY OF EMISSION FACTORS

7.2.1 Carbon monoxide (CO)

Emission factors generally increase as moisture increases on the open fireplace and older stoves. On the modern appliance, CO emissions are higher for both dry and wet fuels. A similar pattern is seen for PM (at the dilution tunnel). This indicates that on the more basic appliances, increasing moisture in the fuel increases emissions of CO and PM. This is consistent with higher fuel moisture decreasing combustion efficiency. The emissions observed for the modern appliance may indicate that the appliance design has been optimised for seasoned wood and drier fuels may also increase emissions compared to the seasoned moisture level.

The CO (and particulate) emissions as shown in Figure 7-1, when using dry wood in the modern stove are unexpectedly high in comparison with the older technologies which would be expected to have poorer energy and combustion efficiency.

Figure 7-1 Carbon monoxide emission factors



7.2.2 Particulate matter

Total particulate matter, PM_{10} and $PM_{2.5}$ emission factors determined at the dilution tunnel are presented in Figure 7-2, Figure 7-3 and Figure 7-4 respectively. The highest emission factors for each appliance were for wet wood. Emission factors for seasoned wood are all lower than used in the current NAEI. At the modern stove, emission factors determined when burning wet and dry wood are higher than the current NAEI emission factor. Particle size distribution based on the aggregated emission factors are shown in Table 7-1 and are consistent with the NAEI for PM_{10} and $PM_{2.5}$ but the PM_1 fraction is higher than applied currently in the NAEI. The collected PM is predominantly PM_1 for all fuels and appliances but the PM_1 fraction is not as high as reported elsewhere in the literature for wood-burning stoves. Note that emission data reported for this study include sample probe washings (assigned to the $>PM_{10}$ size fraction) and the sampling system included a sample inlet aligned to the gas flow with near isokinetic sampling (it was not designed to exclude larger particle sizes).

In the PM datasets (and others including CO) the emission factors determined for the stoves might be expected to increase with the age of stove across each of the fuel types. However, this is not always evident in the measured data. In part this is likely due to how each appliance has been operated, variability between manufacturers, efficiency of the combustion chambers, and the condition of each individual appliance (particularly relevant for the older pre-owned stoves). All appliances were tested at 5kW and 16 Pa draught, but the manufacturer's rating of the 'middle stove' has a larger rated output and was in poor condition and although serviceable, may not have been in comparable condition to other appliances. Features of the test protocol, including retention of bark on the wood logs (more representative of real-life use of the stoves), result in more heterogenicity between fuel loadings which means that it is harder to assess trends. There are many variables to consider to fully characterise emissions and operation and these have not been tested in isolation within the test programme.

Figure 7-2 Total Particulate Matter emission factors

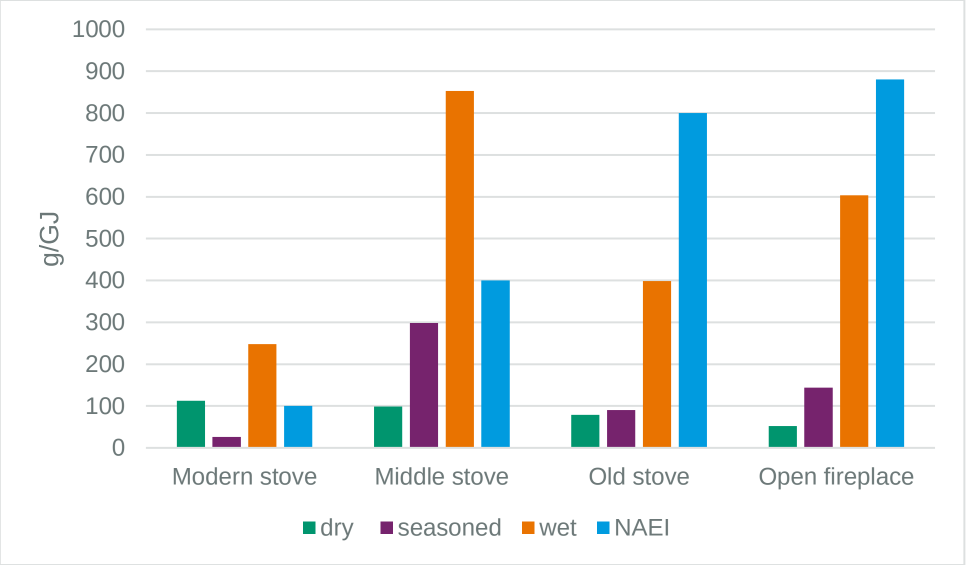


Figure 7-3 PM_{10} emission factors

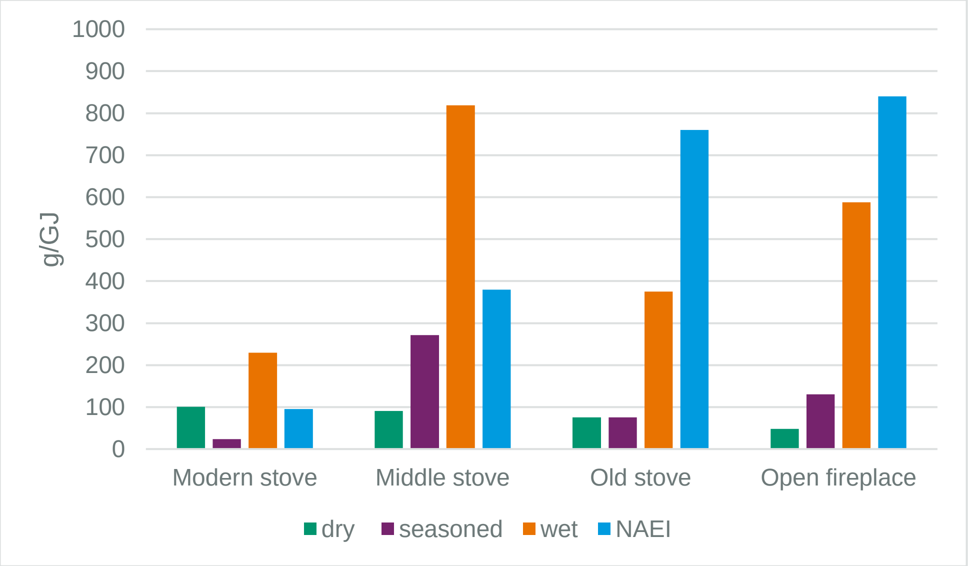


Figure 7-4 $PM_{2.5}$ emission factors

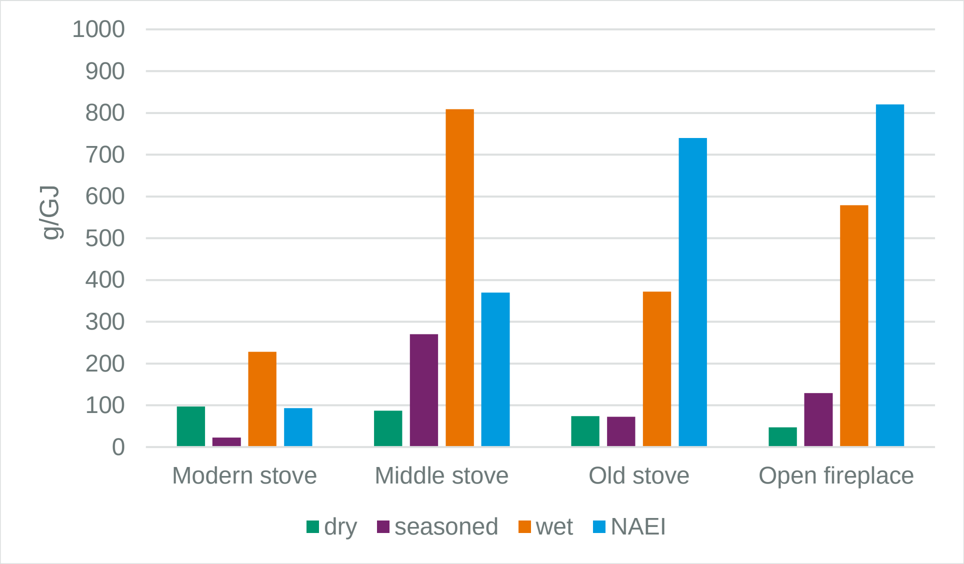
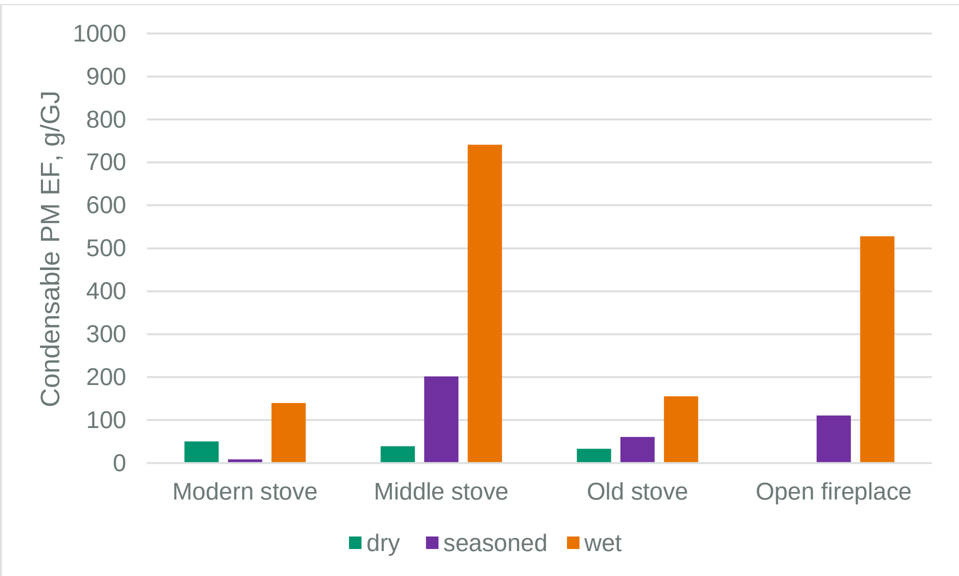


Figure 7-5 provides the condensable PM emission factors determined from the difference between total PM determined at the dilution tunnel (based on the particle size measurements) and the PM determined at the appliance outlet. Note that the NAEI reports total (filterable+condensable) PM for residential wood combustion and hence these emission factors are not proposed for use in the NAEI. The condensable PM emission factors are highest when burning wet wood for all types of appliance.

Table 7-1 Particle size fractions

Appliance	PM fraction	Composition, % TPM			NAEI, % TPM
		Dry wood	Seasoned wood	Wet wood	
Modern stove	PM_{10}	89	90	92	95
	$PM_{2.5}$	86	86	92	93
	PM_1	78	78	74	38
Middle stove	PM_{10}	92	91	96	95
	$PM_{2.5}$	88	91	95	93
	PM_1	78	89	82	38
Old stove	PM_{10}	95	83	94	95
	$PM_{2.5}$	93	80	93	93
	PM_1	85	76	84	38
Open fireplace	PM_{10}	92	91	97	95
	$PM_{2.5}$	90	90	96	93
	PM_1	81	79	79	38

Figure 7-5 Condensable PM



7.2.3 Total organic compounds and NMVOC

Higher fuel moisture increases TOC emissions (also referred to as HC and OGC) which is consistent with higher fuel moisture decreasing combustion efficiency. However, the older stove and the modern stove also had higher TOC emissions when burning drier wood (Figure 7-6). Note that measurements include methane and that emission factors used for international reporting are for non-methane volatile organic compounds (NMVOC). TOC emission factors have been modified for use in the NAEI by applying the NMVOC/methane ratio in the current NAEI (45%-67% depending on appliance type). Derived NMVOC emission factors are shown in Figure 7-7.

Figure 7-6 Total Organic Compounds emission factors

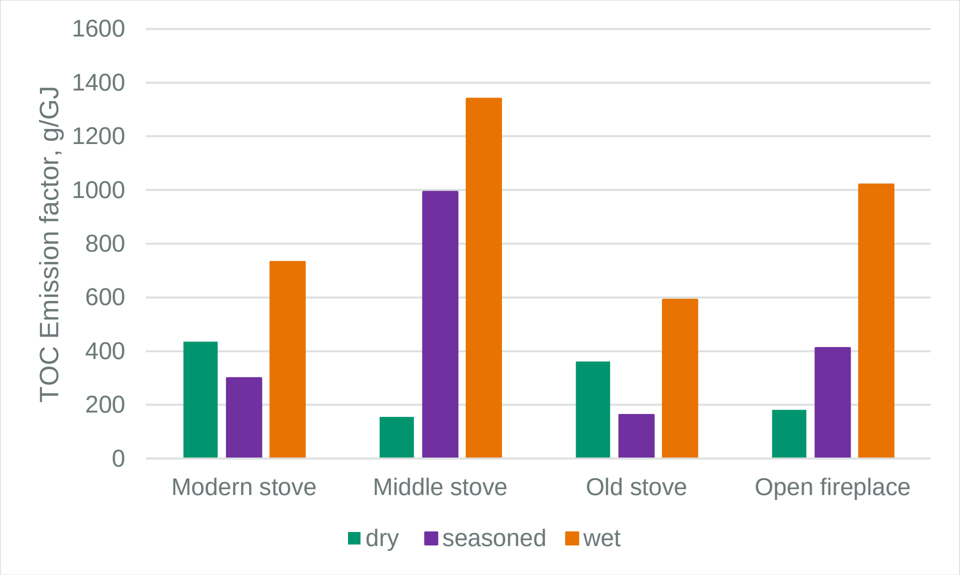
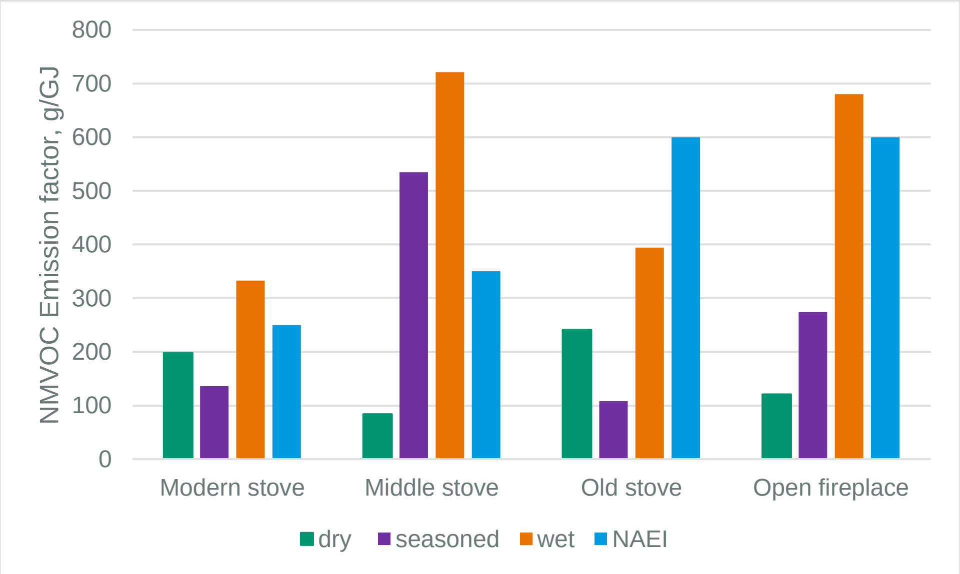


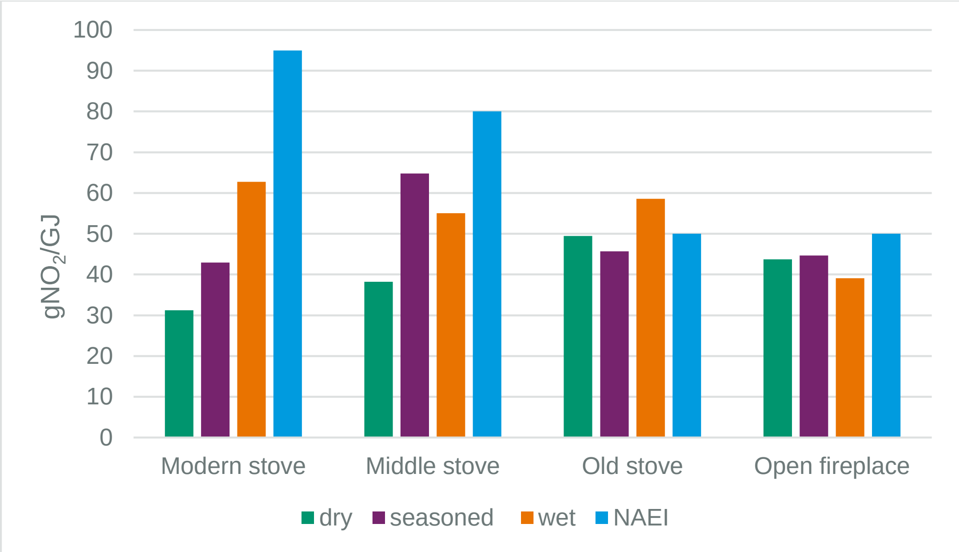
Figure 7-7 NMVOC emission factors



7.2.4 Nitrogen oxides (NO_X)

Emission factors for NO_X do not generally reflect fuel moisture content on the open fireplace or older stoves. Emission factors appear to increase with fuel moisture content at the modern appliance which is unexpected as moisture tends to suppress NO_X formation.

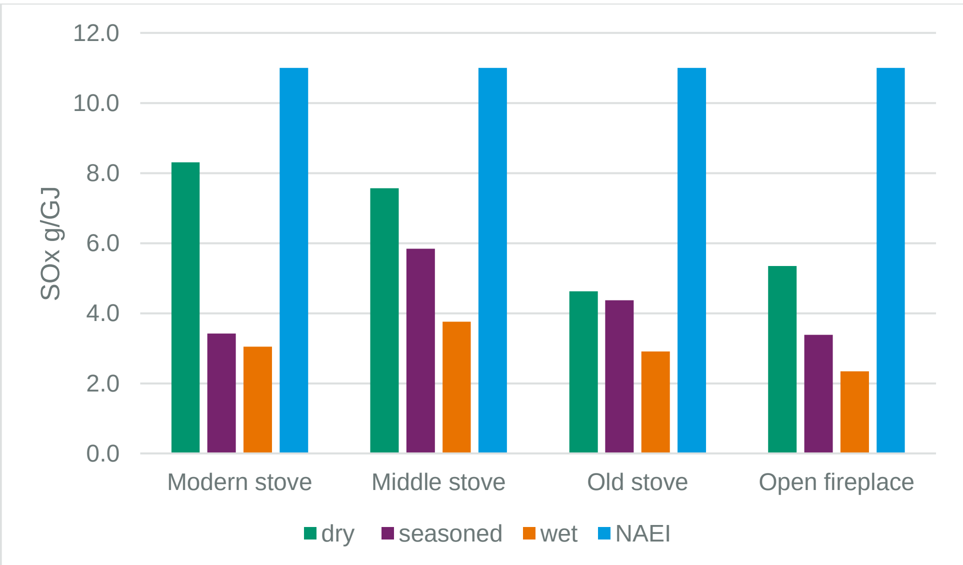
Figure 7-8 NO_X emission factors



7.2.5 Oxides of sulphur (SOx)

A periodic, integrated sampling methodology was applied as the anticipated concentrations after dilution were expected to be close to the limit of detection for continuous measurement techniques. The measured emission factors are low, as expected, and below the published emission factor (Figure 7-9).

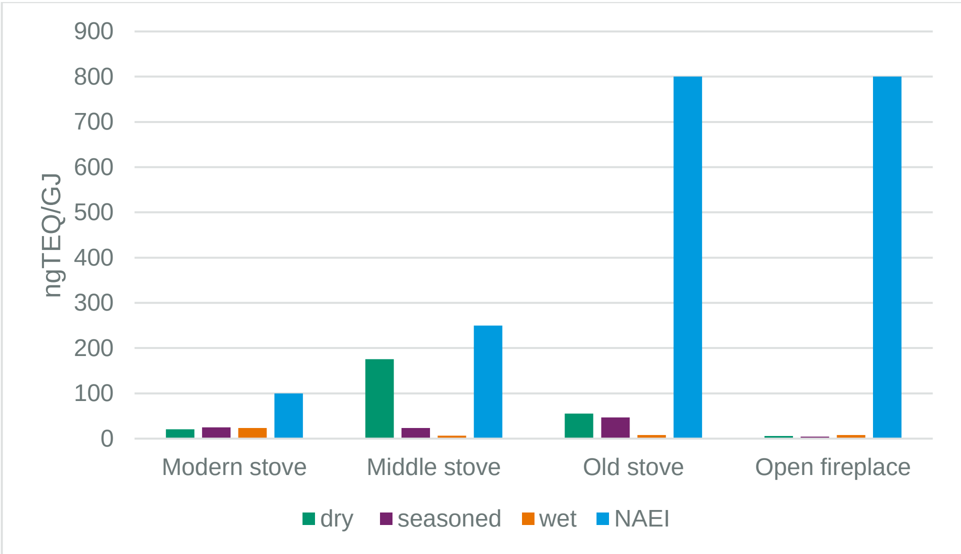
Figure 7-9 Oxides of sulphur emission factors



7.2.6 Dioxin and furans (PCDD/F)

The PCDD/F emission factors were lower than the NAEI default emission factors (Figure 7-10). The highest emissions were observed with the middle stove when burning dry fuel. Some of the higher PCDD/F emission factors in literature may be due to inclusion of wastes and non-wood fuels.

Figure 7-10 PCDD/F Emission factors



7.2.7 PAH

Sixteen PAH compounds (Figure 7-11) were determined however only four (Figure 7-12) are used for international reporting for emission inventories. These are Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(k)fluoranthene and Indeno(1,2,3-cd)pyrene. The B(a)P emission factors are provided as an example of the four PAH used for international reporting (see Figure 7-13) and were generally lower than the NAEI default factors for the two older stoves and the open fireplace. However, emission factors for the modern appliance are higher than NAEI default and the B(a)P emission factors when burning dry wood on the modern appliance are much higher than found when burning seasoned or wet wood.

Figure 7-11 Total PAH emission factors

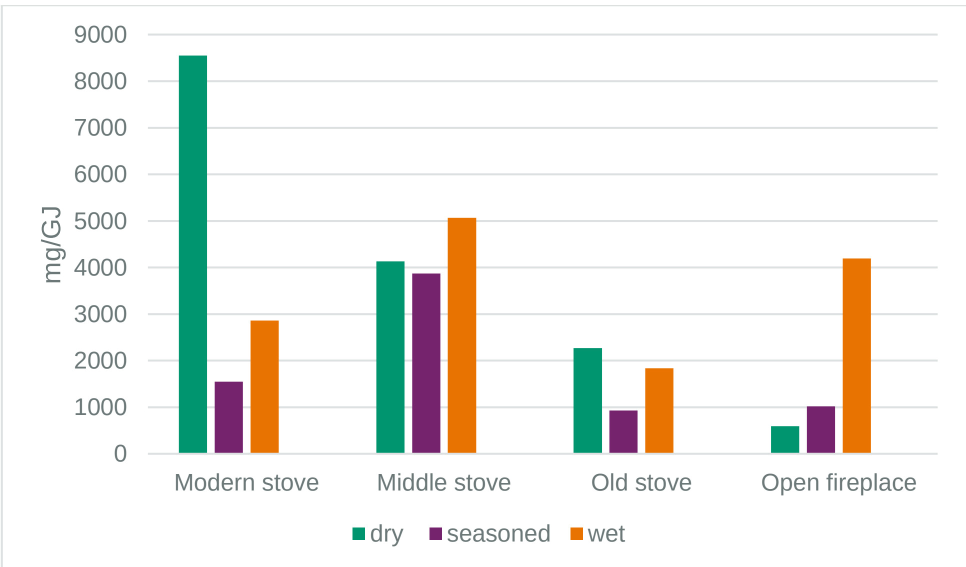


Figure 7-12 Total LRTAP PAH emission factors

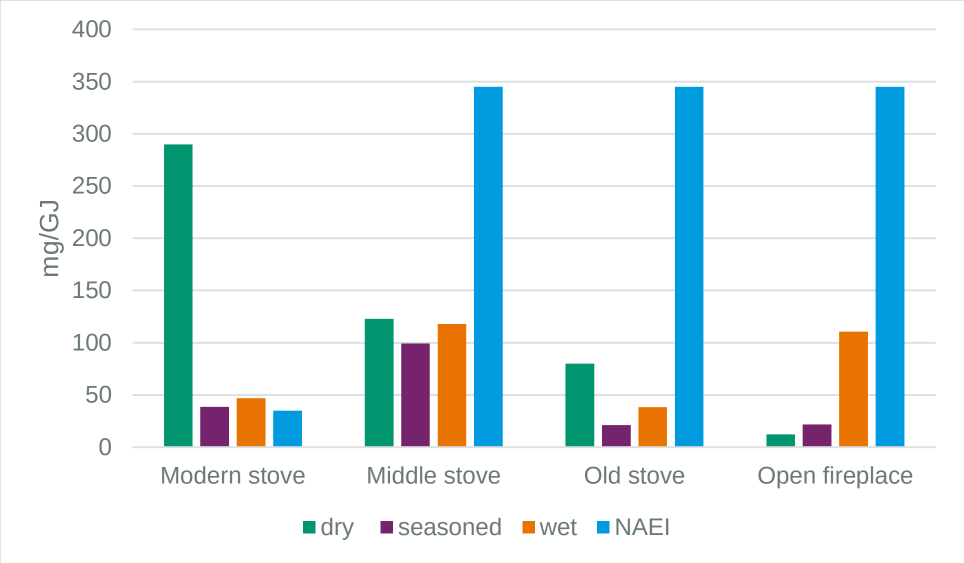
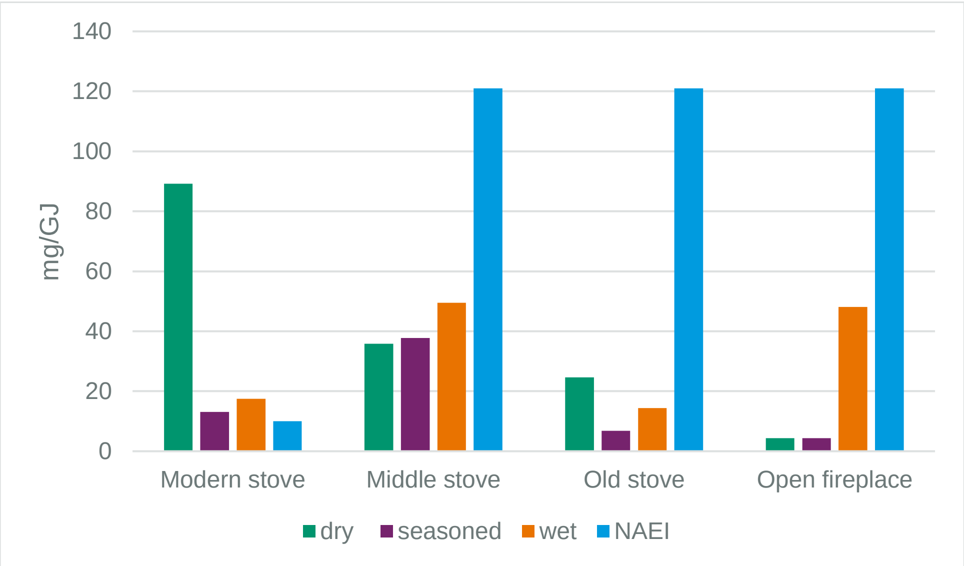


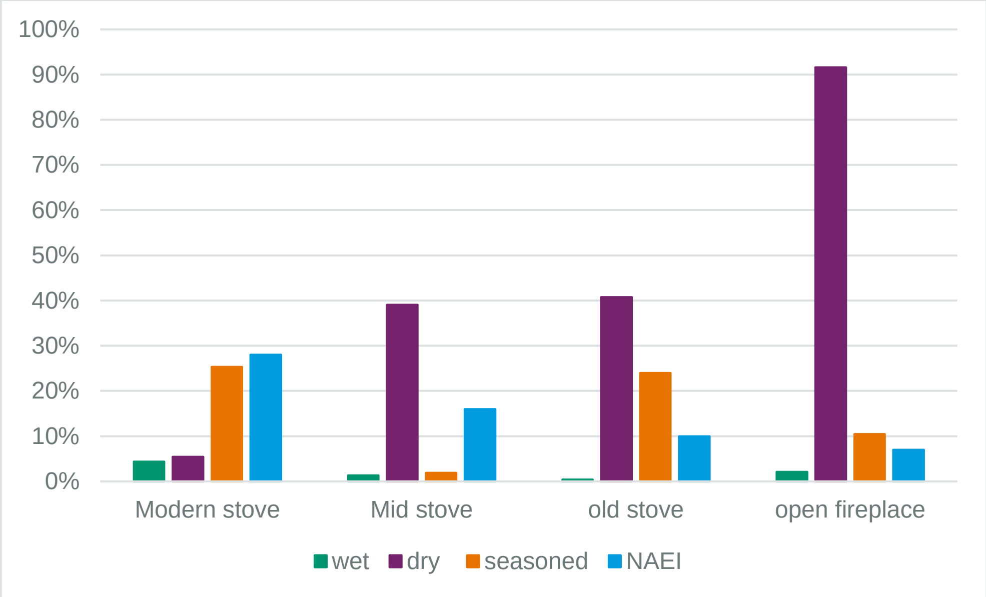
Figure 7-13 Benzo(a)pyrene emission factors



7.2.8 Black Carbon

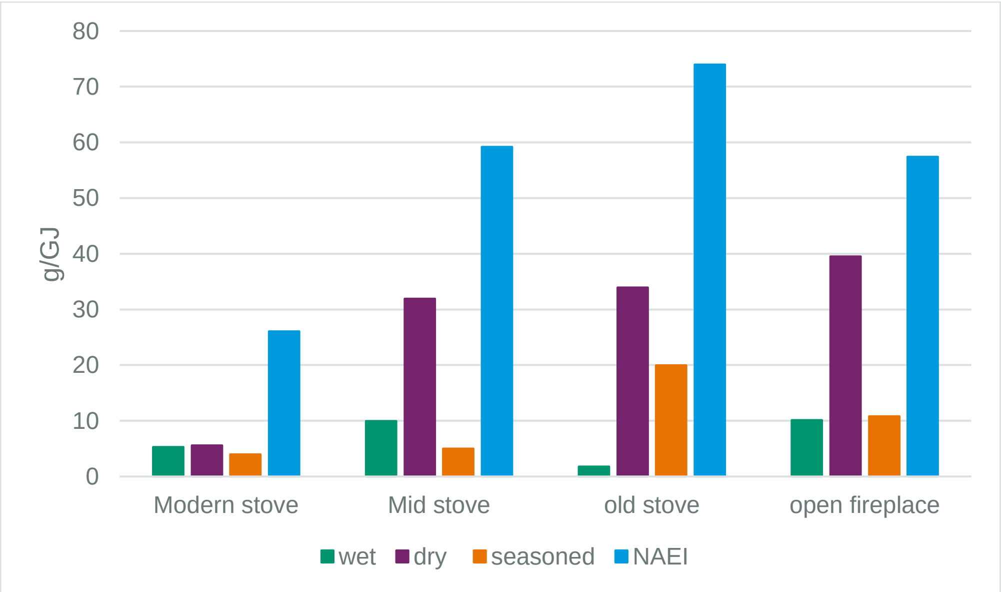
Black carbon measurements are derived from analysis of short-term samples for elemental carbon. The Black carbon emission is expressed as a percentage of the $PM_{2.5}$ emission factor for comparison with emission factors published in the EMEP/EEA Guidebook. Note that only one sample was collected for each appliance and fuel combination (each other pollutant is an aggregation of three measurements). Emission data are derived from short sampling periods (<5 minutes) in selected phases of operation, consequently uncertainty is considered relatively high. Black carbon emission percentages are highest for dry wood for each appliance. Although Black carbon emissions for the modern and old stove are broadly comparable with the current NAEI emission factors, the emission percentages determined for the middle stove and open fireplace are lower. Due to the limited data and higher uncertainty no modifications to the NAEI emission factors are proposed at this stage.

Figure 7-14 Black Carbon emission factors as a percentage of $PM_{2.5}$



The percentage is calculated using the $PM_{2.5}$ data from the test in which the black carbon was measured. for the middle stove seasoned wood and average of the 3 runs was used for the PM2.5 value as the data for the run in which the black carbon was measured is not available

Figure 7-15 Black Carbon emission factors



7.3 COMPARISON WITH CURRENT NAEI EMISSION ESTIMATES

In September 2022 the results from this study were presented to the NAEI Air Quality Inventory Steering Group, which is a separate body of UK experts with responsibility for overseeing and approving major changes to the UK NAEI. In addition to the information presented earlier in this report and appendices, the AQISG reviewed the likely changes to the NAEI emissions as a result of implementing the new emission factors produced by this study. A series of comparative charts reviewed by the AQISG are shown below. In general, although substantial changes can be seen for estimates from wood-burning, the impact of changes on all residential emission estimates is generally small and the impact on UK national emissions is small.

7.3.1 Particulate matter

The changes reduce $PM_{2.5}$ emissions to air from wood-burning by about 5 ktonnes in 2020 with larger changes earlier in the time series. This is an important reduction in emissions from the residential sector; it is a small but significant reduction for national emissions.

Figure 7-16 Impact of new EFs on $PM_{2.5}$ emissions in domestic combustion (wood burning) sector

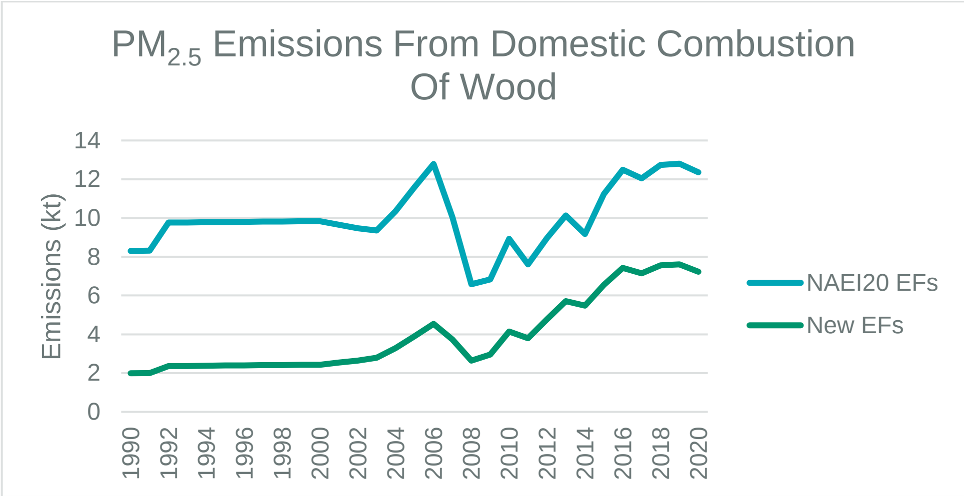


Figure 7-17 Impact of new EFs on $PM_{2.5}$ emissions in domestic combustion sector

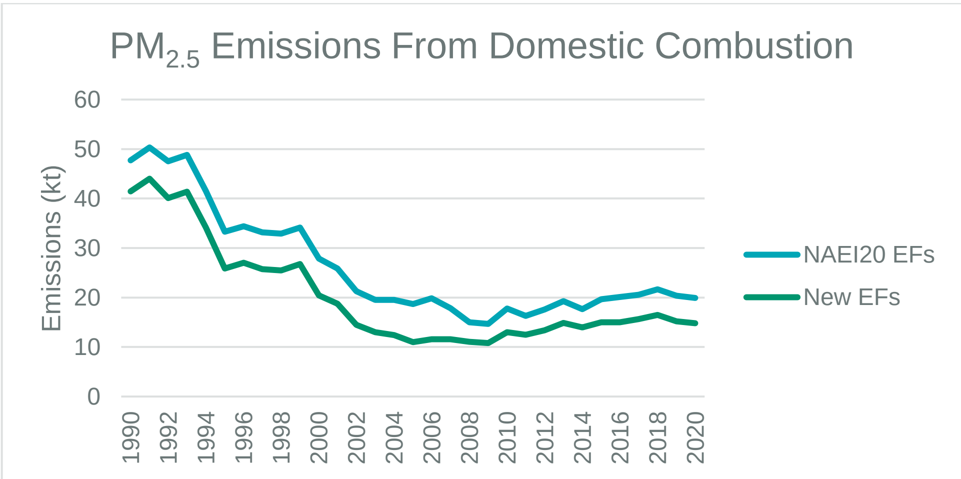
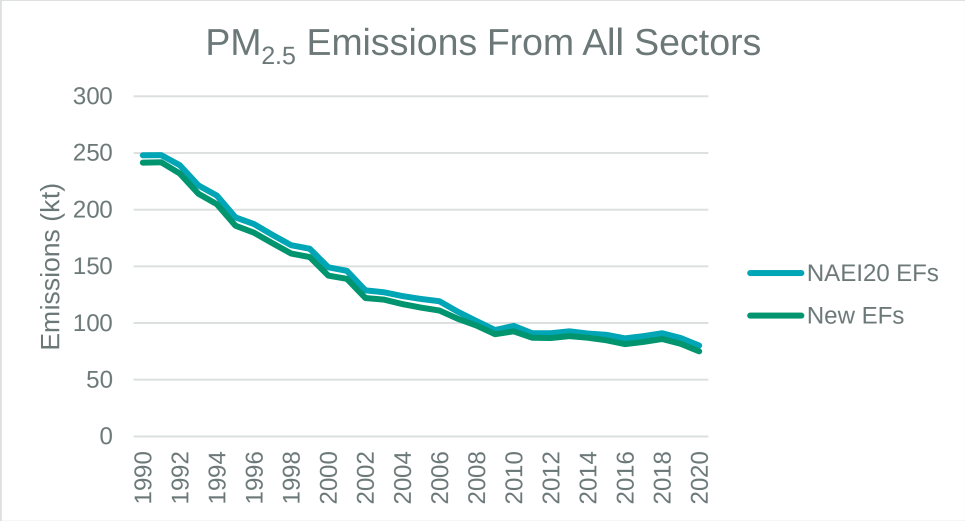


Figure 7-18 Impact of new EFs on $PM_{2.5}$ emissions in all sectors



7.3.2 Non-Methane Volatile Organic Compounds

The main changes are in earlier years in the timeseries (before introduction of the newer stove types) however, NMVOC emissions from wood-burning (and domestic combustion) are a relatively small contribution to national emissions which are dominated by solvent activities.

Figure 7-19 Historic impact of new EFs on NMVOC emissions in domestic combustion (wood burning) sector

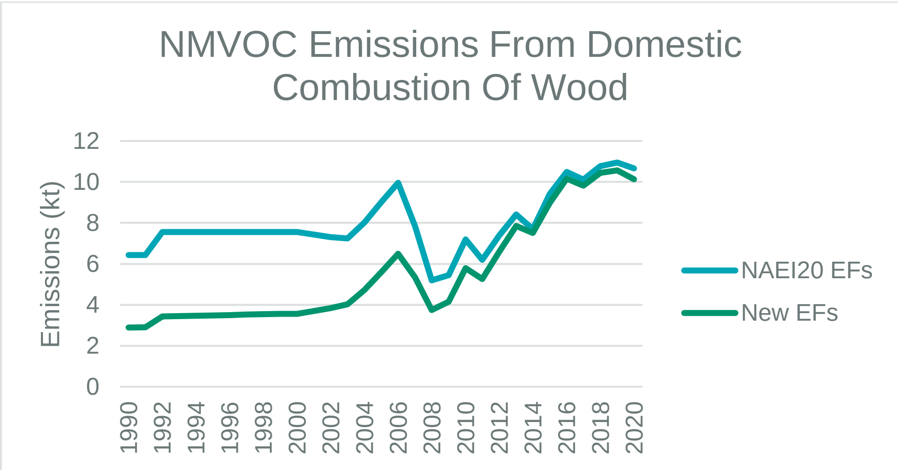


Figure 7-20 Historic impact of new EFs on NMVOC emissions in domestic combustion sector

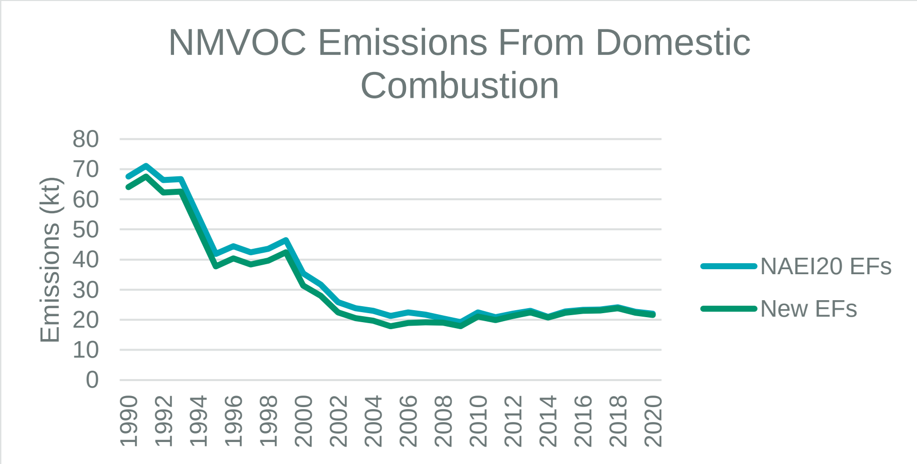
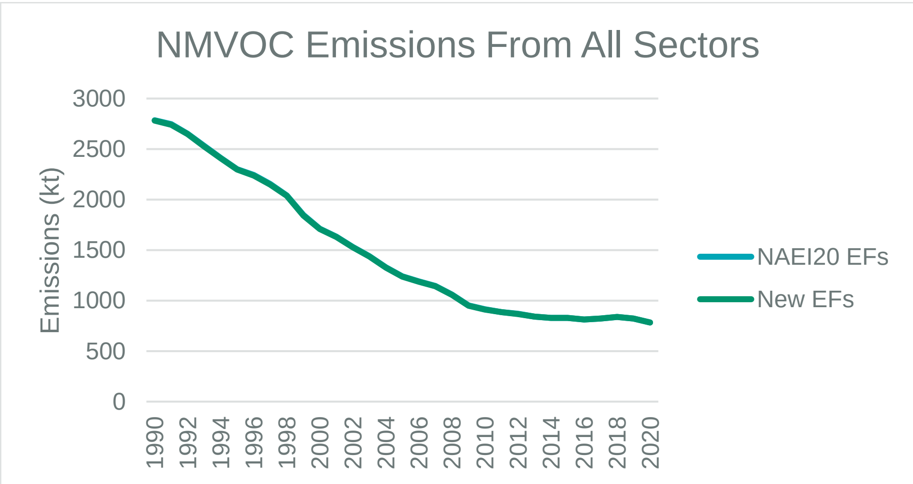


Figure 7-21 Historic impact of new EFs on NMVOC emissions in all sectors



7.3.3 Oxides of nitrogen

The emission factors are lower than applied currently for the newer stove types and consequently emission estimates for recent years are reduced however, NOx emissions from wood-burning are a relatively small element of residential combustion and national emissions.

Figure 7-22 Impact of new EFs on NO_x emissions in domestic combustion (wood burning) sector

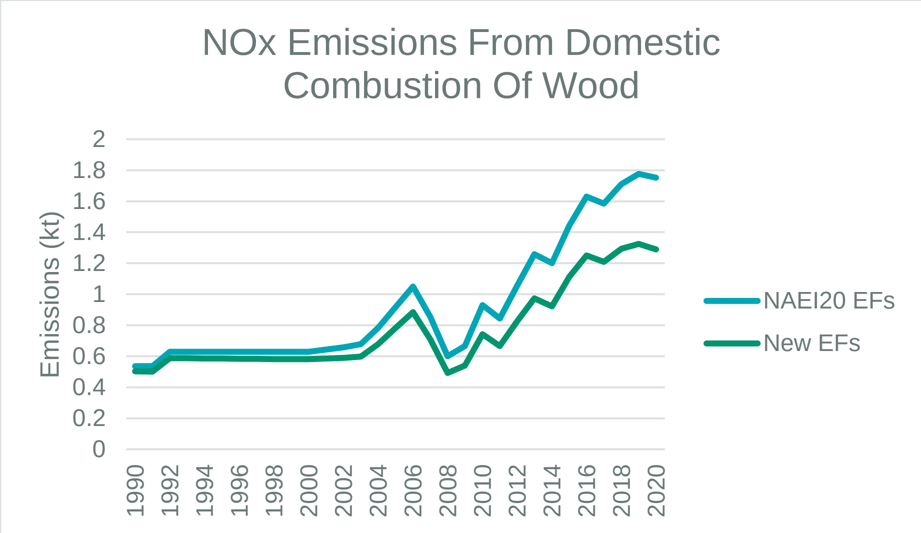


Figure 7-23 Impact of new EFs on NO_x emissions in domestic combustion sector

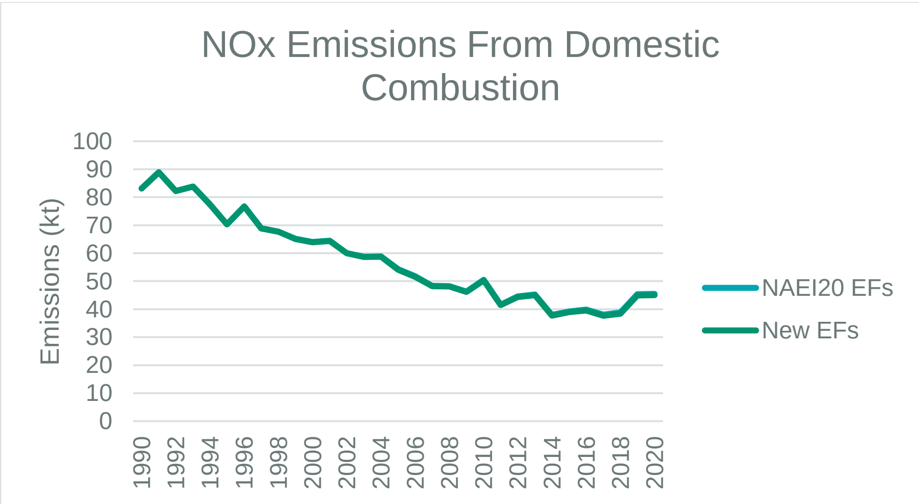
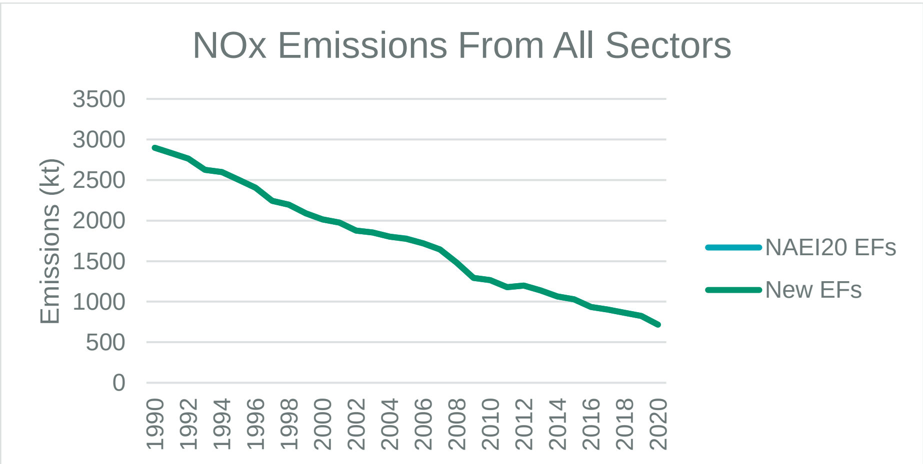


Figure 7-24 Impact of new EFs on NO_x emissions in all sectors



7.3.4 Sulphur dioxide

The emission factors are lower than applied currently for all appliance types and consequently emission estimates are reduced however, SO_2 from wood-burning is a contribution to residential combustion and national emissions.

Figure 7-25 Impact of new EFs on SO_2 emissions in domestic combustion (wood burning) sector

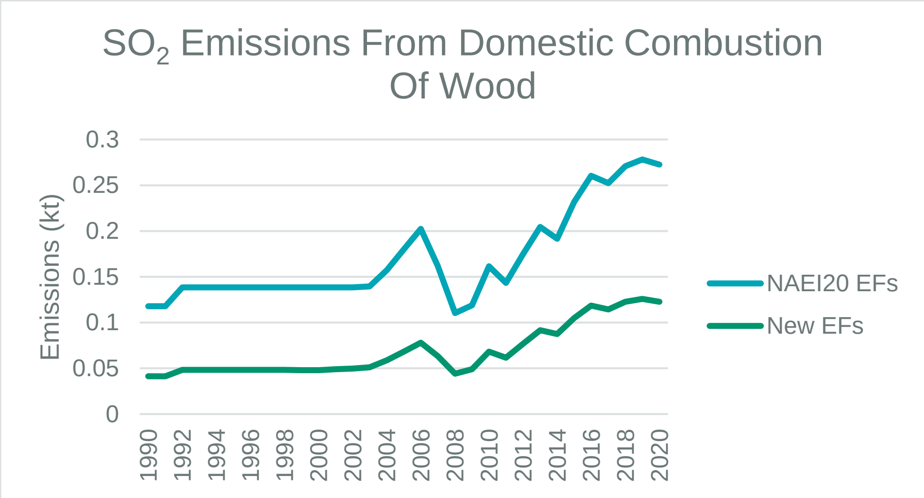


Figure 7-26 Impact of new EFs on SO_2 emissions in domestic combustion sector

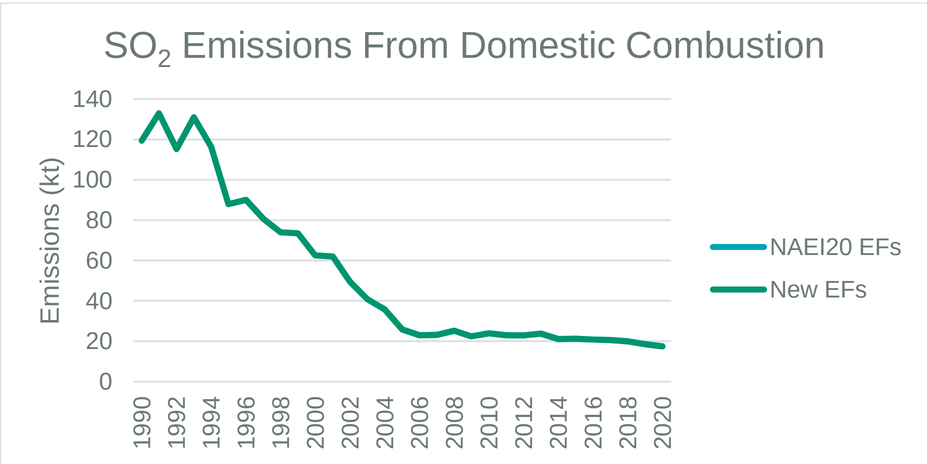
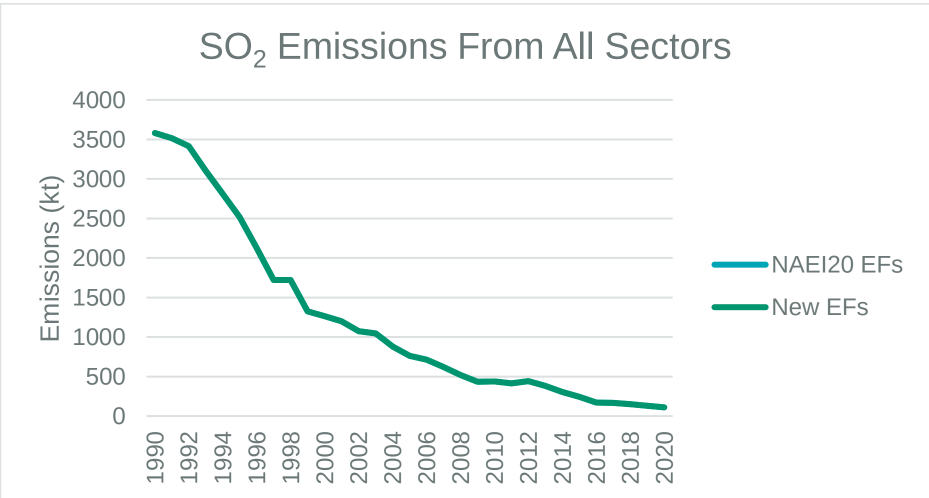


Figure 7-27 Impact of new EFs on SO_2 emissions in all sectors



7.3.5 Carbon monoxide

Although the changes reduce CO emissions to air from wood-burning by over 30 ktonnes in 2020, this is a relatively small change in comparison to all residential emissions and all UK sectors.

Figure 7-28 Impact of new EFs on CO emissions in domestic combustion (wood burning) sector

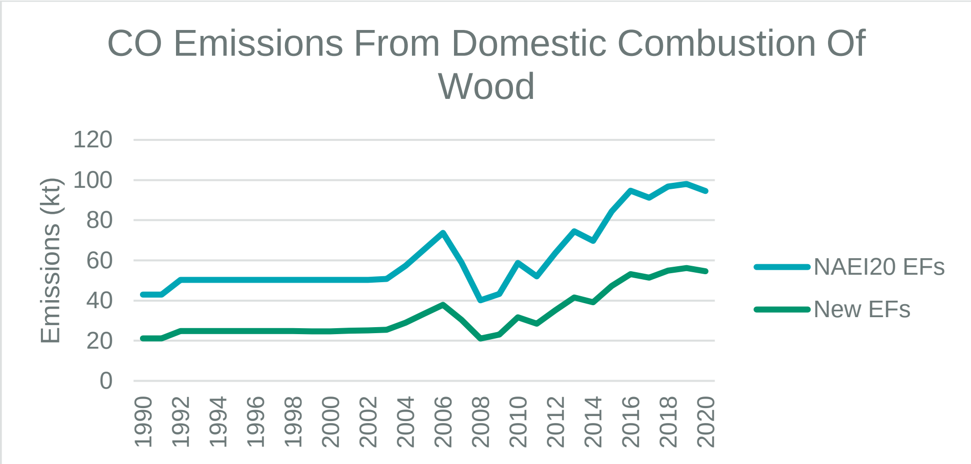


Figure 7-29 Impact of new EFs on CO emissions in domestic combustion sector

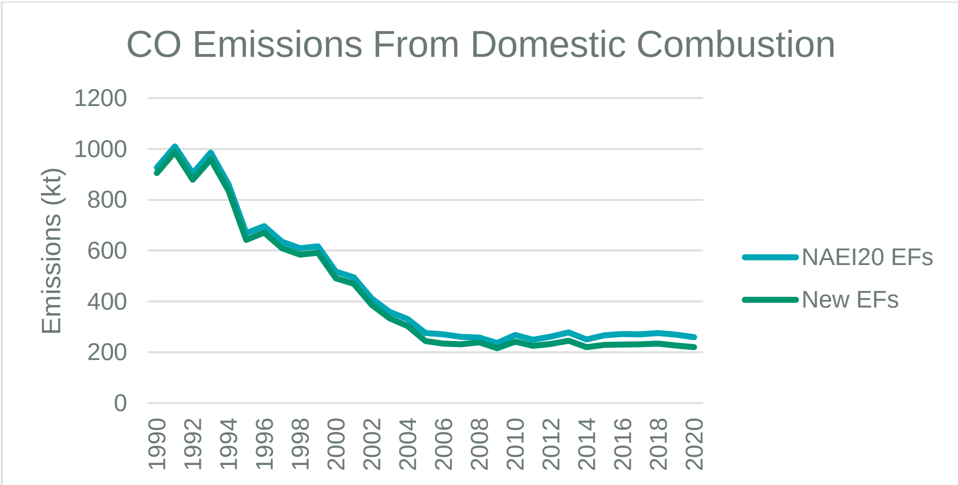
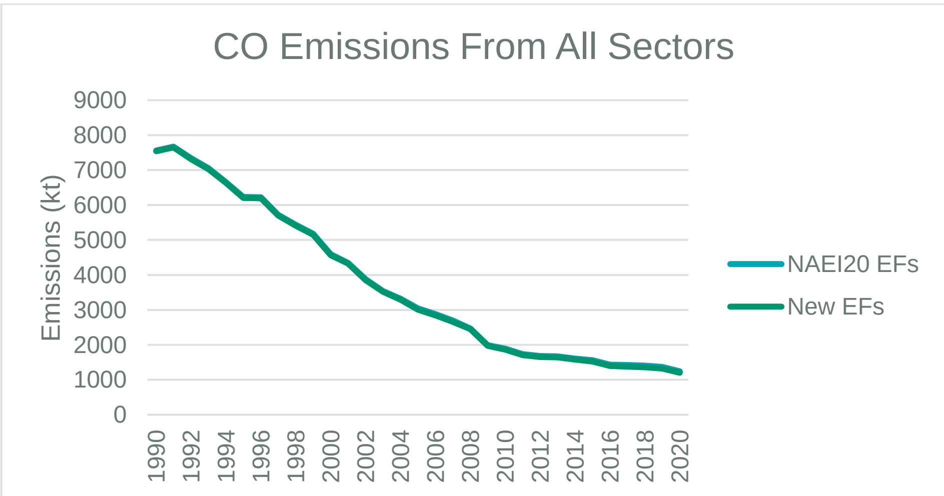


Figure 7-30 Impact of new EFs on CO emissions in all sectors



7.3.6 Dioxins and furans (PCDD/F)

The PCDD/F emission factors determined for wood-burning were all lower than the NAEI default emission factors and this has a large impact on emissions from residential wood combustion (Figure 7-31) and from residential combustion (Figure 7-32). However, changes in national emissions are relatively small.

Figure 7-31 Impact of new EFs on PCDD/F emissions in domestic combustion (wood burning) sector

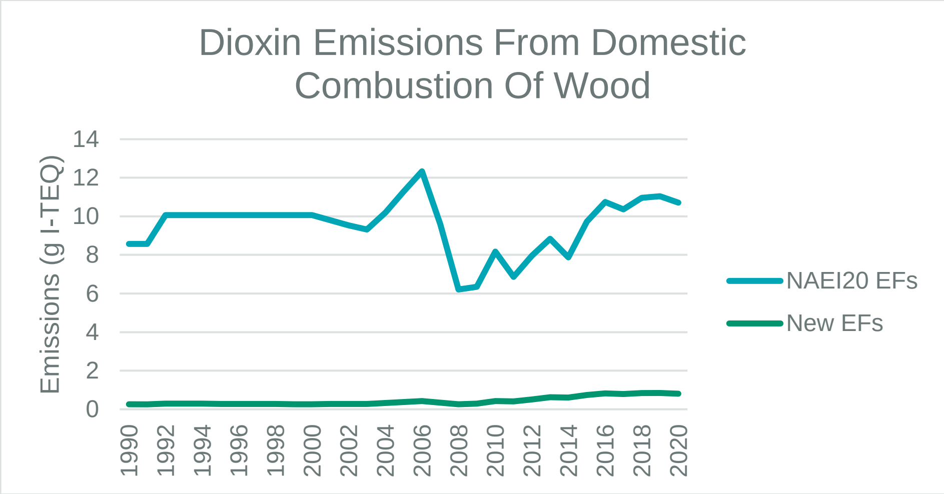


Figure 7-32 Impact of new EFs on PCDD/F emissions in domestic combustion sector

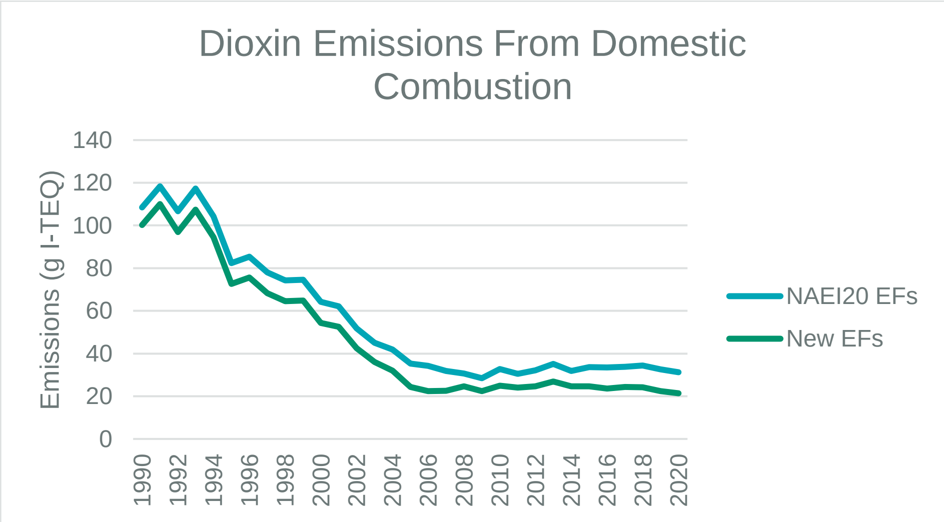
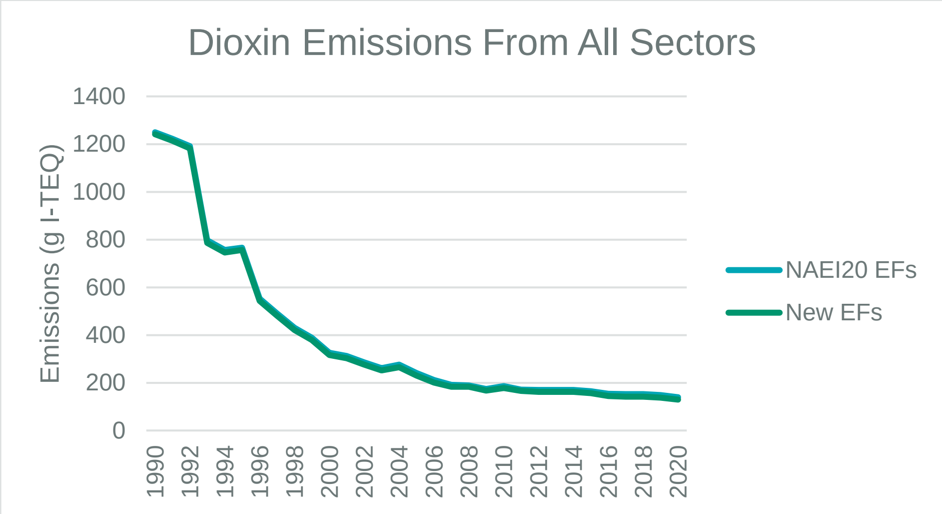


Figure 7-33 Impact of new EFs on PCDD/F emissions in all sectors



7.3.7 PAH (Benzo[a]pyrene)

The emission factors for PAH including Benzo(a)pyrene are lower than applied currently by the NAEI and consequently emission estimates for all years are reduced. Residential combustion is the main source of Benzo(a)pyrene in national emission estimates with wood and other solid fuels contributing to emissions. PAH emissions from wood-burning are a significant contribution to national emission estimates (Figure 7-36).

Figure 7-34 Impact of new EFs on total PAH emissions in domestic combustion (wood burning) sector

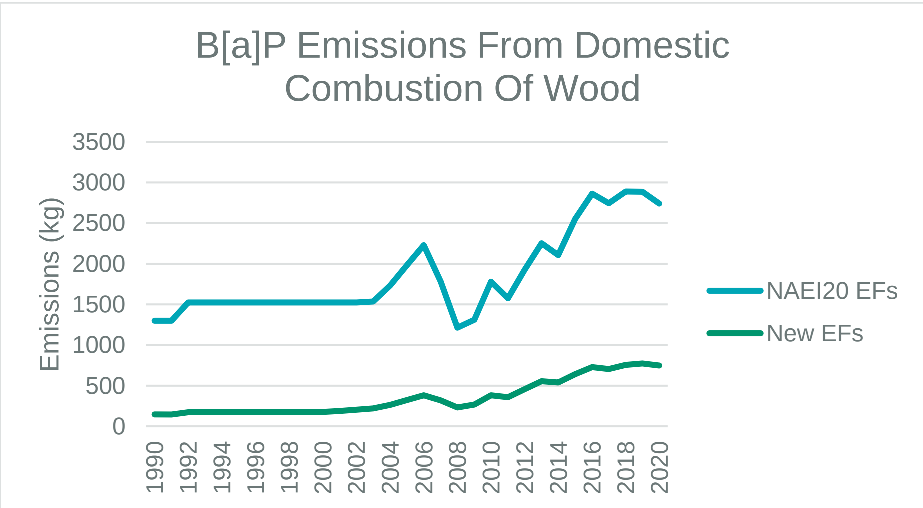


Figure 7-35 Impact of new EFs on total PAH emissions in domestic combustion sector

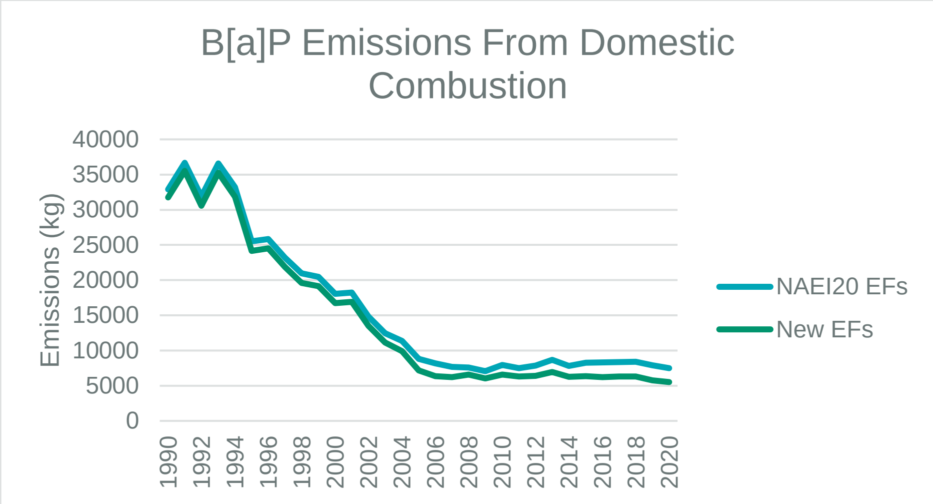
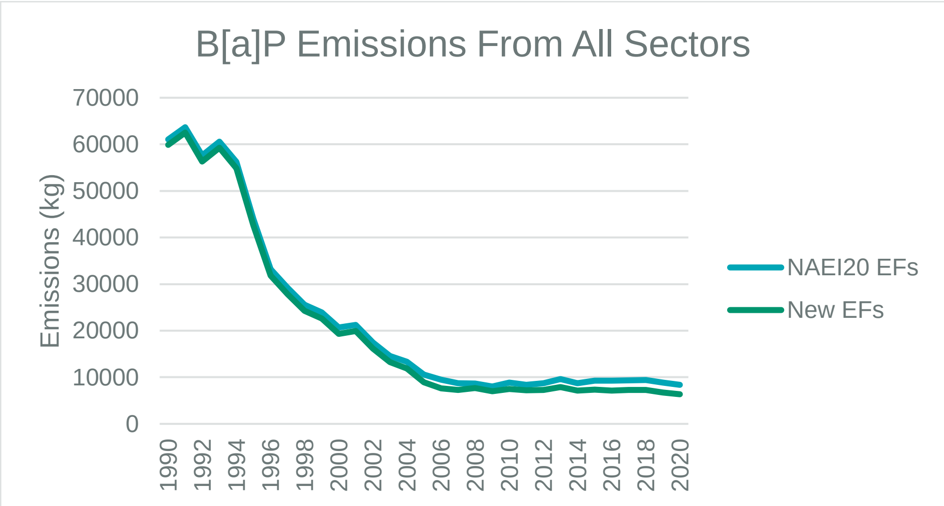


Figure 7-36 Impact of new EFs on total PAH emissions in all sectors



7.4 INCLUSION OF EFDSF PROJECT EMISSION FACTORS IN THE UK NAEI

7.4.1 Overview

The NAEI uses emission estimation methodologies which are consistent with international guidance on emission inventories and in particular the EMEP/EEA Emission Inventory Guidebook (EIG). The EIG sets out methodologies for activities required for international reporting. Different methodology levels ('Tiers') are applied with higher tier methods providing improved uncertainty, but require a more detailed understanding of the activity. Inventory compilers can improve uncertainty by application of country-specific emission factors and/or higher tier methods, for example more detailed modelling of an activity.

For residential combustion of wood, the NAEI uses estimates of wood burned at UK-level from UK energy statistics and EIG 'Tier 2' default emission factors which cover several residential wood-burning technologies:

- Open fireplace
- Stoves (conventional, high efficiency, advanced/ecolabelled)
- Boilers
- Pellet stoves and boilers

The recent Defra Domestic Burning Survey has led to a revision of residential energy data for wood-burning, provided improved understanding of the types of appliances used and also allows further disaggregation of fuel use for different wood moisture levels. Understanding the impacts of moisture is a priority for Defra to assess the impacts" of recent legislation to restrict use of wet wood in England. The Defra Emission Factors for Domestic Solid Fuel (EFDSF) project has been developed to provide emission factors which can be used with disaggregated wood fuel data and, where appropriate, allow application of country-specific emission factors rather than EIG default factors.

The EFDSF project steering group has endorsed the test protocol, appliances tested and the use of selected emission factors. The emission factors were presented to AQISG in September 2022. AQISG wanted more information to facilitate a decision on inclusion including uncertainty and evidence that the proposed EFs are better than current EIG default EFs.

The following commentary compares EFDSF data with the EIG default Tier 2 emission factors and sets out where the EFDSF project emission factors can provide the NAEI with more appropriate country-specific emission factors for residential wood-burning.

Information on uncertainty has been provided at Section 6.10 however it is not possible to provide a full uncertainty budget for the emission factors. The EFDSF project team is investigating ways to extend the measurement uncertainty to account for the data manipulation/handling operations (including dilution correction, normalisation of concentrations and the conversion of concentrations to emission factor) as well as other approaches to assessing a confidence interval, however, there are a range of wider uncertainty factors where quantification is not straightforward and not within the scope of the EFDSF project (see Section 6.10).

In the PM datasets (and others including CO) the emission factors determined for the stoves might be expected to increase with the age of stove across each of the fuel types. However, this is not always evident in the measured data. In part, this is likely due to how each appliance has been operated, variability between manufacturers, efficiency of the combustion chambers, and the condition of each individual appliance (particularly relevant for the older pre-owned stoves). All appliances were tested at 5kW and 16 Pa draught, but the manufacturer's rating of the 'middle stove' has a larger rated output and was in poor condition and although serviceable, may not have been in comparable condition to other appliances. Features of the test protocol, including retention of bark on the wood logs (more representative of real-life use of the stoves), result in more heterogenicity between fuel loadings which means that it is harder to assess trends. There are many variables to consider to fully characterise emissions and operation and these have not been tested in isolation within the test programme.

7.4.2 Comparison of EFDSF and Guidebook Tier 2 default emission factor references

Selected reference papers for the EIG Tier 2 emission factors have been reviewed and compared with the test protocol used in this project.

The EIG emission factors for residential biomass use are drawn from peer-reviewed scientific literature and include several relatively recent references. Emissions from residential biomass use has been a very active research area in recent years and there is additional information that could be incorporated into the EIG. Some examples of recent papers are included in Appendix A.10.

The evolution of voluntary and mandatory Ecolabels, National and EU Regulatory controls on solid fuel heating appliances means that there are appliances in the market which have different emission characteristics to the range of appliances provided in the EIG. Most recently, the Ecodesign Regulations have set minimum emission requirements for solid fuel room heater and boiler products.

The EFDSF project test protocol has been designed to reflect the use of appliances in the UK including evidence from the Defra Burning Survey on residential wood-burning practise in the UK. The EIG references have applied a variety of test protocols and whilst there are similarities there are also significant differences which arise from the aims and scope of the individual studies. These are summarised in Appendix A.10 and the key points are outlined below:

- Test periods – the test periods in EIG reference studies are generally shorter than the Defra Burning Survey which informed the EFDSF project test period.
- Test cycles (the phases of appliance operation included in the test period) - different test cycles are applied compared to the EFDSF project but with a lack of clarity in some studies about whether

measurements include ignition and burnout phases, there is exclusion of cold start/ignition periods in some EIG references, but the main difference is use of fewer refuels.

- Laboratory/field measurements – in common with the EFDSF project most EIG reference testing is laboratory-based but the EIG references also include a Swedish and a Danish study of emissions from houses.
- Repeat measurements – this aspect is often not clearly stated in references but where information has been provided there are typically fewer than the three measurements used in EFDSF project and in two studies referenced by EIG **no repeat tests** were undertaken on several appliances.
- Fuels - a number of the EIG reference papers are concerned with wood types and wood-based fuels which are not typical of the UK. Several reference papers include mixed fuels including waste and waste woods. The EFDSF project has used beech only for wood and not looked at fuel mixes.
- Fuel quantity - different quantities of fuel have been used between the studies with, generally, higher weights in refuel batches in the EIG references suggesting larger appliances/higher output.
- Fuel moisture – the EIG does not provide separate EFs for different wood moisture contents. Several EIG reference studies consider moisture effects and there are moisture data provided for most fuels but limited information to derive EFs for different technologies and pollutants. The EFDSF project has assessed emissions for three moisture levels for the pollutants measured.
- Pollutants - the EIG references multiple papers for each technology type. The EFDSF test protocol does not cover all pollutants required for the EIG/NAEI, but measurements were all undertaken in the same test cycles and for the same appliance – use of data from different test cycles and appliances is an additional uncertainty which the EFDSF data avoids.
- Appliances – the technology descriptions used in the EIG are broad and no Ecodesign-compliant appliances are included in the EIG reference studies (the EU Ecodesign Regulation for roomheaters was published in 2015 but only came into force in 2022); the number of EN13240-compliant stoves is also unclear, many appliances tested predate this EN Standard (which is harmonised to the Construction Products Regulation). In addition, the EIG Tier 2 EFs for ecolabelled wood stoves predate current versions of, for example, Blue Angel, Nordic Swan, Flamme Verte as well as the minimum requirements of the Ecodesign regulation. The EIG Tier 2 EF reference studies include several types of biomass appliance that are not common technologies in the UK – in particular slow heat release stoves, masonry stoves and sauna stoves. These are all available in the UK but are not typical UK appliance types. Sauna stoves are very basic technology for heating sauna rocks – a very limited application in the UK. Masonry (known as kachelofen/putzofen elsewhere and typically constructed in situ) and slow heat release stoves (factory-built) are typically larger devices with a large combustion chamber surrounded by heat-retaining masonry/ceramic materials which absorb and release heat over a longer period. Operation can be similar to a typical UK stove but typically these appliances burn a single very large fuel batch rather than multiple small batches.
  In addition, most of the EIG reference studies assessed wood-burning stoves. The EFDSF project included two multifuel stoves because older UK stoves are commonly multifuel devices (capable of burning wood and/or mineral fuels) with a different grate and air management provision.
- Range of appliances - the EFDSF project has monitored emissions from only one appliance for each technology type, but some EIG Tier 2 emission factors are also assigned to a single reference with only a single relevant appliance or, indicating an aggregation of emission factors for the different technologies covered in the paper.
- Appliance draught –The draught influences the air supply to the appliance and hence burn rate. In the EFDSF project a draught of 16 Pa based on UK measurements provided by the steering group which is higher than used in EN appliance testing but there is limited data in EIG reference studies to confirm applicability to the UK.
- Measurement approaches – a range of measurement approaches have been applied in EIG references including novel approaches, short-term measurement and semi-continuous monitoring however for EDFDSF we have applied EN or CEN/TS pollutant-specific test methods and accredited testhouses. The EFDSF project has identified where deviations from full compliance with EN approaches has been adopted – primarily to allow fewer sampling systems to avoid practical issues in emission sampling on a small duct.

Although some EIG emission factors are based on multiple references, there are EIG Tier 2 pollutant emission factors for residential wood use which appear to be based on single appliances (or aggregations of different appliance types). Aggregation of emission factors for different appliances includes a wide range of appliance and operating conditions. Some types of appliance considered in the EIG reference studies are little used in the UK. Consequently, the EFDSF project team considers that the proposed country-specific emission factors:

- Better represent UK operating practise with respect to burn duration, number of refuels, fuel load, draught and wood species.
- Are based on three replicate test cycles – this is equivalent to or better than most studies referenced in the EIG.
- Better represents appliances used in the UK:
    a. Traditional multifuel open fireplace,
    b. Old basic multifuel stove,
    c. Old multifuel stove with secondary air (EN13240) and,
    d. An Ecodesign-compliant wood burning stove.
- Are based on tests for the same appliance and the same test cycles for measured pollutants.
- Provide data measured by accredited test houses using test approaches which are consistent with EN and CEN/TS approaches for emission measurement.
- Allow application of emission factors for different moisture levels.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Emission factors have been developed and agreed for use in the NAEI for dry, seasoned and wet wood for the four appliance types for NOx, SO_2, CO, NMVOC, PAH, PCDD/F. These emission factors were adopted in NAEI 2021 (submission spring 2023).

In general, although substantial changes can be seen for estimates from wood-burning, the impact of changes on UK national emissions is generally small. However, the new emission factors for PAH including Benzo(a)pyrene contribute to a significant reduction in national emissions.

Further emission factors have been developed for dry, seasoned and wet wood for the four appliance types for PM, PM_{10}, $PM_{2.5}$, PM_1. In a deviation from the intended approach, these emission factors were developed solely from the particle size measurements data due to some measurement issues. This has been proposed as a pragmatic and conservative approach. Further work is proposed to validate these emission factors using additional data in WP3, before incorporating them into the NAEI. WP3 includes burning of wood fuels in a number of additional stoves of the same type/category as tested as part of WP1. Although we do not expect the new test results to be dramatically different from the previous ones, the PM emission factors presented here are subject to minor changes once the final part of the project's test programme is completed.

In addition, condensable PM emission factors have been determined (these are not currently applied in the NAEI as total filterable+condensable emissions are reported).

The proposed country-specific emission factors are an improvement on current emission factors used by the NAEI because they:

- Better represent UK operating practise with respect to burn duration, number of refuels, fuel load, draught and wood species.
- Are based on three replicate test cycles – this is equivalent to or better than most studies referenced in the EIG.
- Better represents appliances used in the UK.
- Are based on tests for the same appliance and the same test cycles for measured pollutants.
- Provide data measured by accredited test houses using test approaches that are consistent with EN and CEN/TS approaches for emission measurement.
- Allow application of emission factors for different moisture levels.

Black Carbon emission factors have also been developed in the measurement programme but are for a more limited dataset, with only one measurement taken for each appliance-fuel combination in each phase of the burn cycle (rather than three repeat measurements). In Work Package 3, three repeat measurements will be made for black carbon. This will allow verification of the data collected so far, and the WP1 data will be combined with the WP3 data to produce a black carbon emission factor for each category of appliance, for dry, seasoned and wet wood.

8.2 RECOMMENDATIONS

The following recommendations are made:

1. To include the emissions factors for dioxins and furans, PAHs, SO_2, CO, NO_x and NMVOCs in the NAEI21.
2. To use PM data from the dilution tunnel particle size measurement data (Dekati) for WP1 – these emission factors are generally higher and represent a more conservative approach than the comparative measurements. Where the particulate emission factors determined using the particle size equipment at the dilution tunnel are lower than at the appliance outlet (a situation for one set of tests at the open fire), the project team propose to apply the dilution tunnel data to the appliance outlet. This approach will be reviewed prior to incorporation of new emission factors into the NAEI, when more data are available from the wider range of appliances being tested in WP3.
3. To delay incorporation of the PM emission factors into the NAEI until 2025, when more data are available from WP3, subject to review and approval by the AQISG.
4. Revising black carbon (elemental carbon) measurements in WP3 to provide more measurements data for selected appliances and fuels.

APPENDICES

A.1 ROUND ROBIN TESTS

Summary

The Round Robin included mandatory measurements of burn rate, appliance outlet temperature, carbon monoxide (CO), oxides of nitrogen (NO_x) and particulate matter (>PM_{10}, PM_{10}, $PM_{2.5}$ and Total PM). The results of these measurements are shown in Appendix A.2.

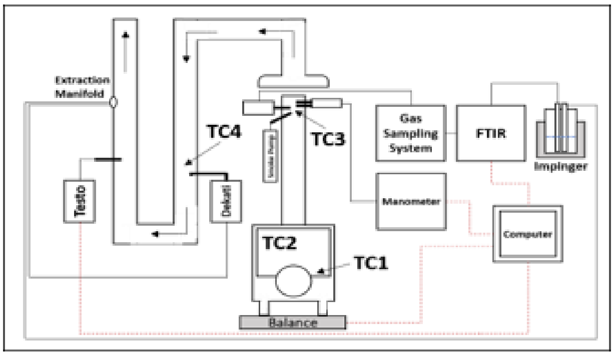
Some of the laboratories carried out additional measurements and analysis, which are described here for completeness.

Leeds University Round Robin Testing

Figure A1 shows a schematic of the test facility at Leeds University and a photograph showing the installed stove and some of the associated measurement instrumentation.

Figure A 1 (left) Schematic of the stove test facility at Leeds University (right) Photograph of the installed Dovre stove with some of the associated instrumentation.

FTIR= Fourier Transform Infra-Red spectroscopy
TC=thermocouple



Round Robin tests at Leeds were undertaken over three weeks: 22nd November to 10th December, 2021. The stove, Dovre 500MRF (rated at about 5-7 kW and a recommended flue pressure of 14.9 Pa) was set up using the value of 12 ± 2 Pa. There were various issues with the stove (Large air leak around the door, and large leak around the secondary air inlet control. Even after repair, the poor stove design results in low CO_2 values in the flue gas.). Due to time spent troubleshooting during commissioning, three test cycles were completed rather than the planned five.

Observations

The fuel was loaded as a crib as shown in Figure A2 During reload batches the log at the back burned first with the front log remaining in a smouldering state. When the rear log was burned out the front log would start burning properly. It is likely that the air bypasses the front log and feeds the rear log. When the rear log burns out there is sufficient air for the front log to burn. Videos were made of all the experiments. The stove has a high thermal mass, and the ignition batch is critical for raising the temperature of the stove to give good combustion in the subsequent refuelling. This was noticeable in the third test cycle, where the ignition batch did not burn as evenly, and this impacted the burning rates observed in the reload batches. The ignition batch was very smoky and overloaded the particulate sampler; thus particulate was only captured for ca. 2/3 of the ignition load combustion.

Figure A 2 Arrangement of wood fuel crib in the Dovre 500MRF stove

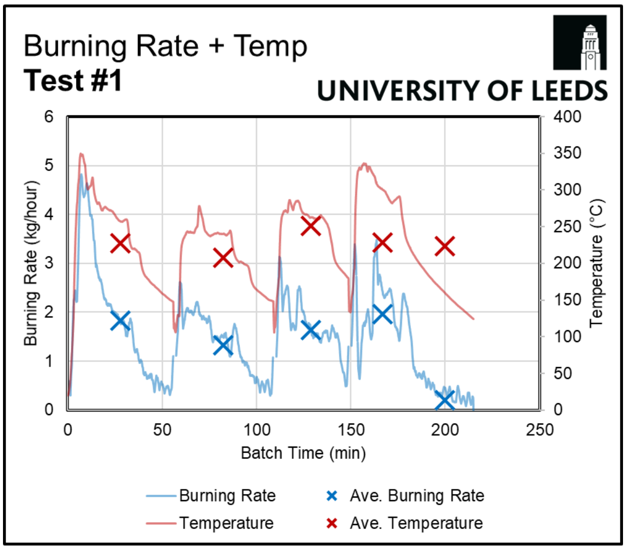
Measurement methods and procedures

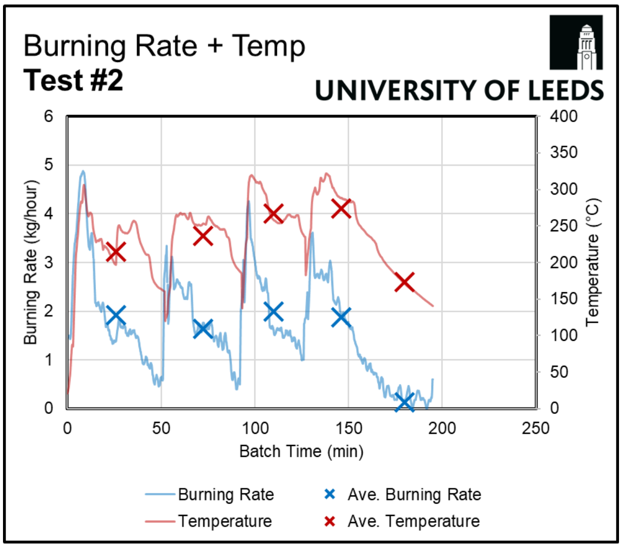
- The dilution factor used was ca. 7 (set by the 12 Pa requirement).
- 1.2 kg of fuel at 10.9% moisture was used for each batch (ignition and reloads).
- Measurement of gas concentrations of O_2, CO_2, CO, NO, CH_4, organics, using Testo and a Gasmet FTIR exhaust gas analyser.
- Particulate was measured at filter temperatures of 30°C using a Dekati PM10 analyser with three stages for ≥10 µm, 2.5-10 µm, 1.0-2.5 µm. A final stage back-up filter (PTFE or Quartz) is used for the collection of PM within the size fraction of 0.3-1 µm.
- Burning rates, flue gas temperatures were logged continuously (every second), and gas concentrations every 60 seconds during the entire test cycle.
- Refuelling was done when the mass of fuel reached 100g (accounting for ash accumulation). Refuelling was not done based on CO concentrations as these were too low to be a reliable indicator
-

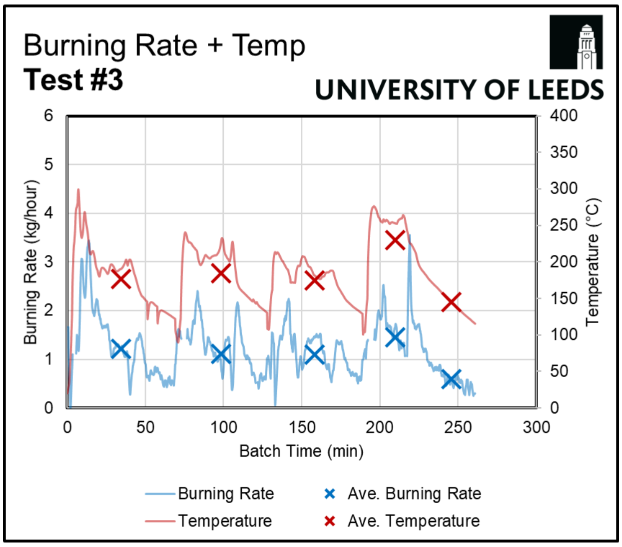
Raw Data

Figure A 3 shows the raw data for burning rates and temperatures for the three tests conducted at Leeds. Each graph includes data for the ignition batch and the three reload tests (the third includes the smouldering stage. Temperatures are the flue temperature measured at TC3 in Figure A 1. There is a weak relationship between flue temperature and burning rate (Figure A 4) , and temperature increases as the stove heats up with additional reload batches. Flue gas temperature is an indication of the flame/combustion temperature and combustion efficiency. Many of the emitted species will be sensitive to temperature.

Figure A 3 Raw data for the three sets of tests conducted at University of Leeds in the Round Robin

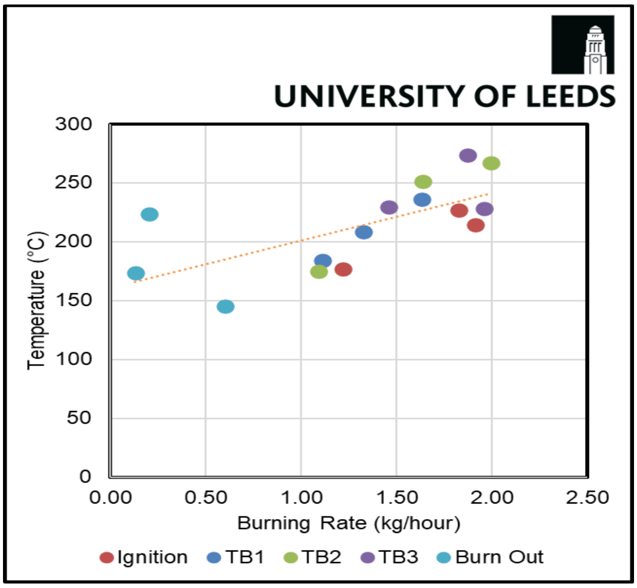






Crosses represent mean values from each batch of fuel

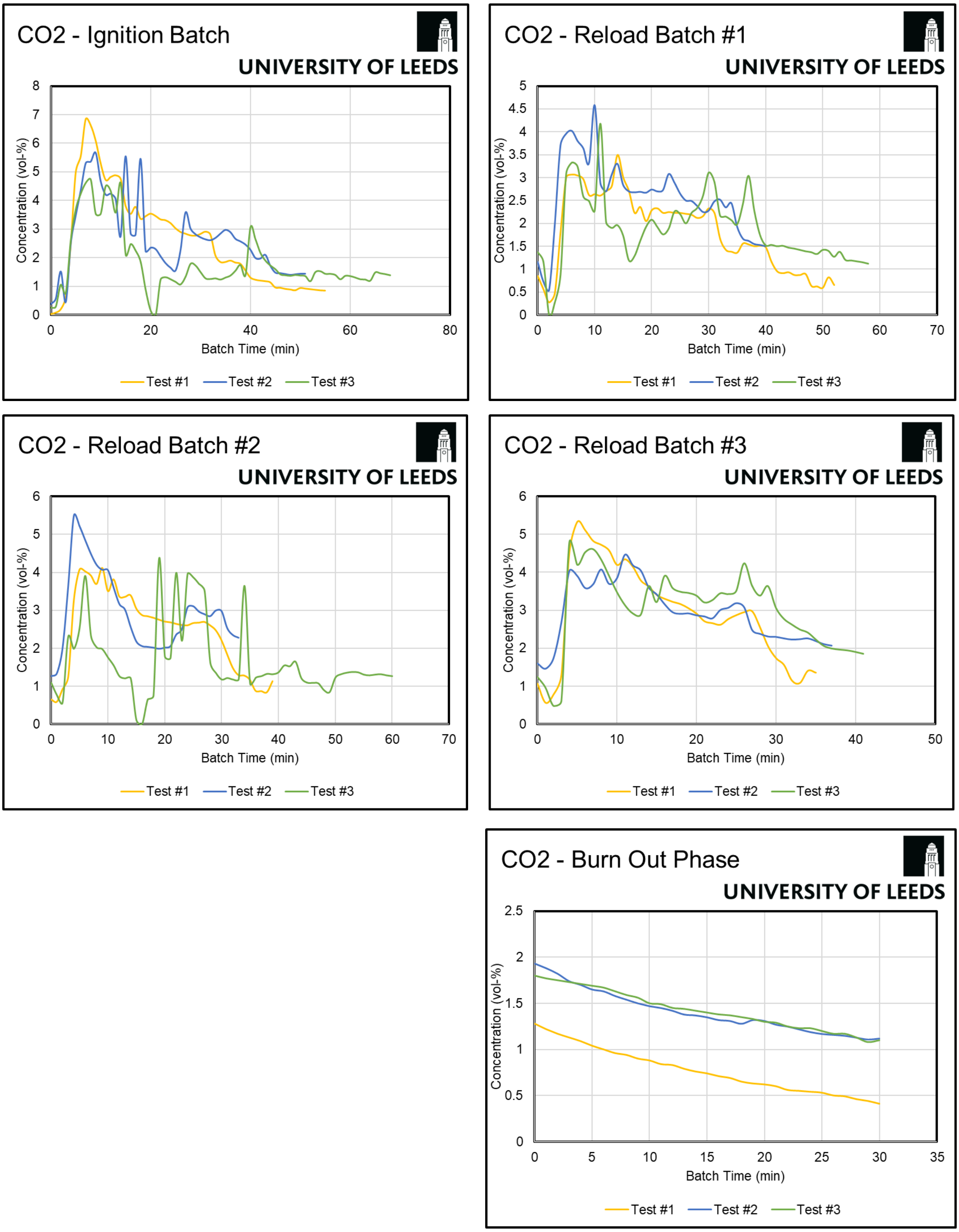
Figure A 4 Relationship between Temperature and Burning Rate during wood fuel combustion in the Dovre 500MRF stove.



TB=Test Batch

Figure A 5 shows the type of raw data provided by the GASMET FTIR instrument, in this case for CO_2 emissions during one of the test cycles. Average values over the test period are used to calculate the emission factors in Appendix A2.

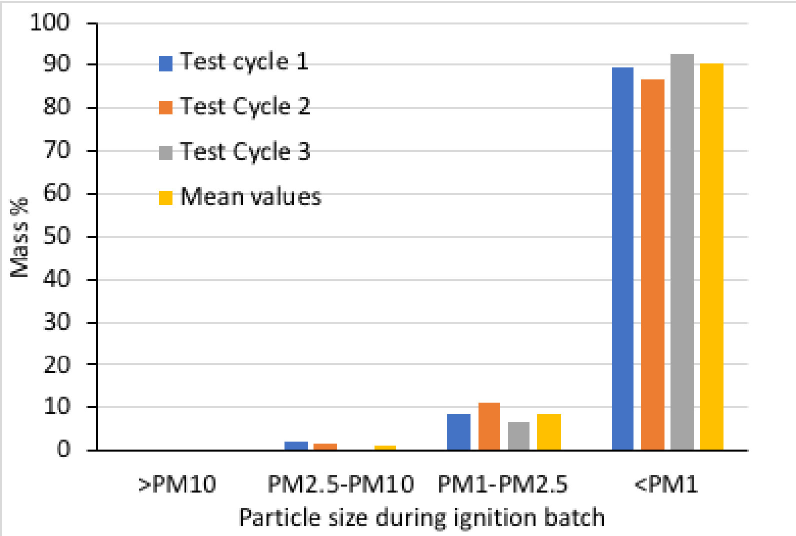
Figure A 5 Illustration of emission variation for CO2 measurements during the three test batches, and for different phases (ignition, reload and burnout).



The following figures (A 6-A 8) illustrate the results from the particulate matter sampling and the particle size distribution observed. In the ignition phase (Figure A 6) the particulate concentration is at its highest as evident from the blackness of the filters. Particles are dominated by <PM1 (approximately 90%) in both the ignition batch and the refuelling batch (Figure A 7). During the final burn-out phase there is a mix of size fractions, but the filter loading is much, much lower (Figure A 8).

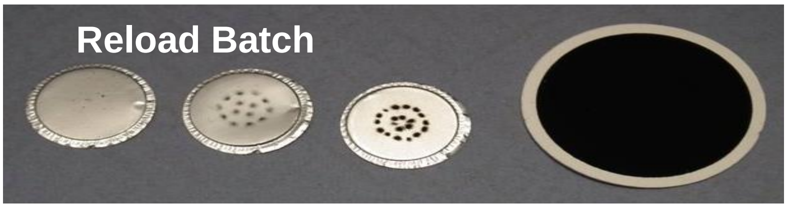
Figure A 6 Filters collected during the ignition batches of the three test cycles, and particle size distributions

>PM_{10} $PM_{2.5}$-PM_{10} PM_{1}-$PM_{2.5}$ $PM_{0.3}$-PM_{1}

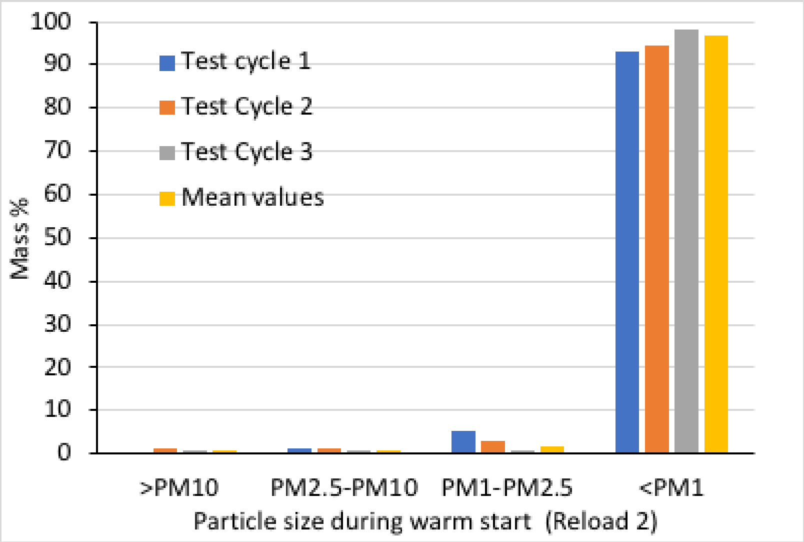


Mean values are shown by the yellow bar

Figure A 7 Filters collected observed during the flaming phase of reload 2 in the three test cycles and size distributions



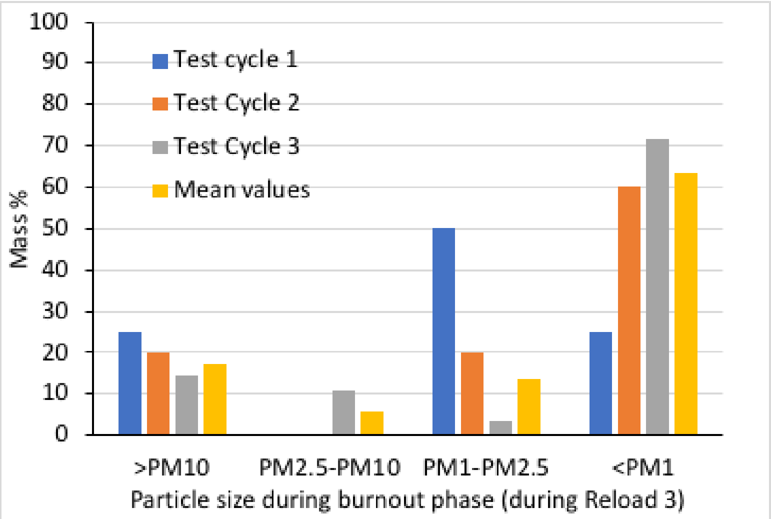
>PM_{10} $PM_{2.5}$-PM_{10} PM_{1}-$PM_{2.5}$ $PM_{0.3}$-PM_{1}



Mean values are shown by the yellow bar

Figure A 8 Filters collected during the smouldering (burn-out) phase (reload 3) of the three test cycles, and particle size distributions

>PM_{10} $PM_{2.5}$-PM_{10} PM_{1}-$PM_{2.5}$ $PM_{0.3}$-PM_{1}



Mean values are shown by the yellow bar

Kiwa Round Robin Testing

5 Round Robin tests were undertaken over two weeks: 22nd, 23rd December 2021, 4th 5th 6th January 2022. The stove, Dovre 500MRF was set up same settings as Leeds during their roud robin test work. As noted by Leeds there were various issues with the stove (Large air leak around the door, and large leak around the secondary air inlet control.

Figures A 9 and A 10 show gas phase data from repeated runs at Kiwa during the round robin exercise to demonstrate repeatability. Each graph represents a single burn through all the phases; Ignition, R1, R2, R3 and Shutdown.

Figure A 9 Carbon Monoxide and Carbon Dioxide Traces from Round Robin Tests

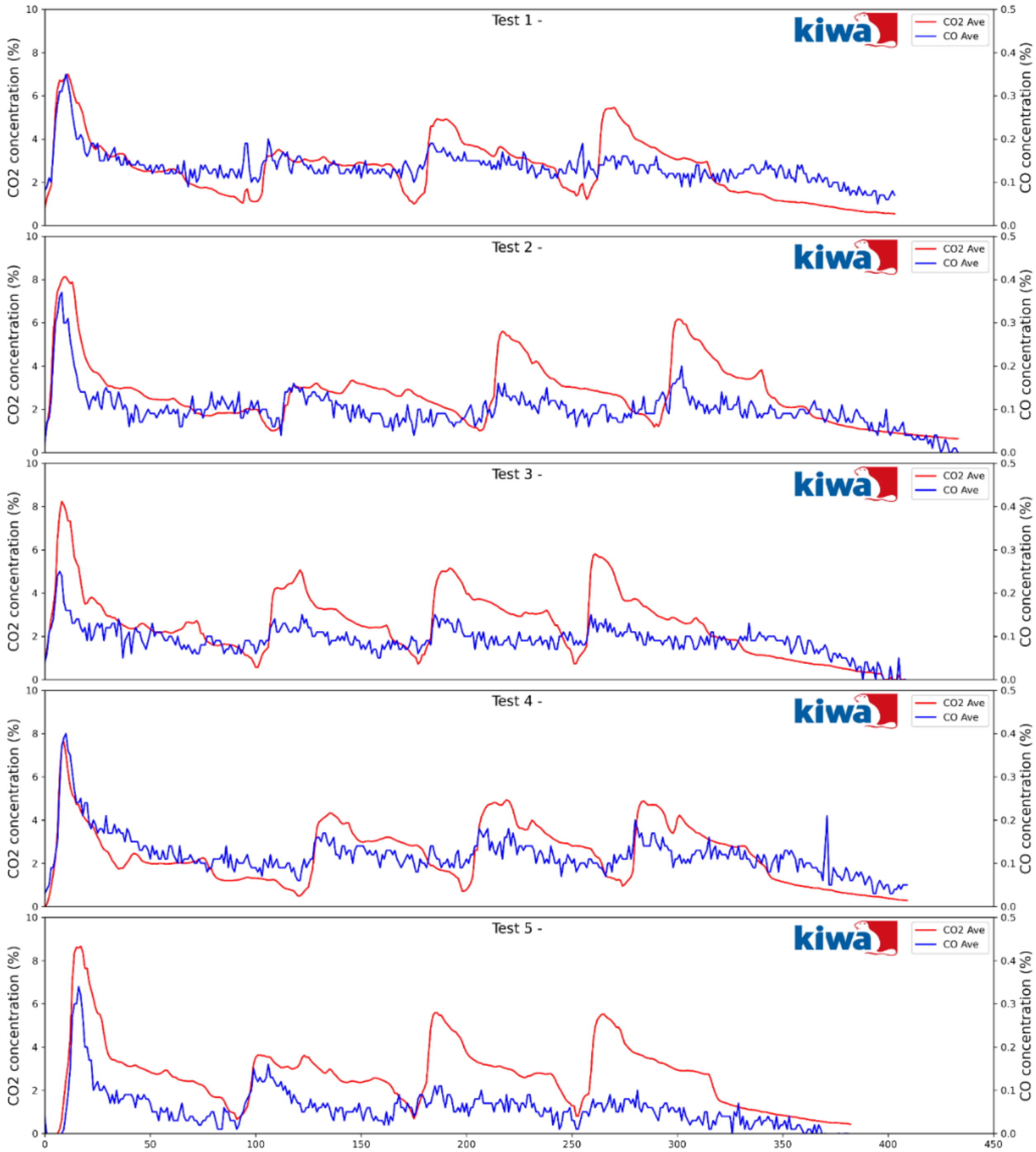
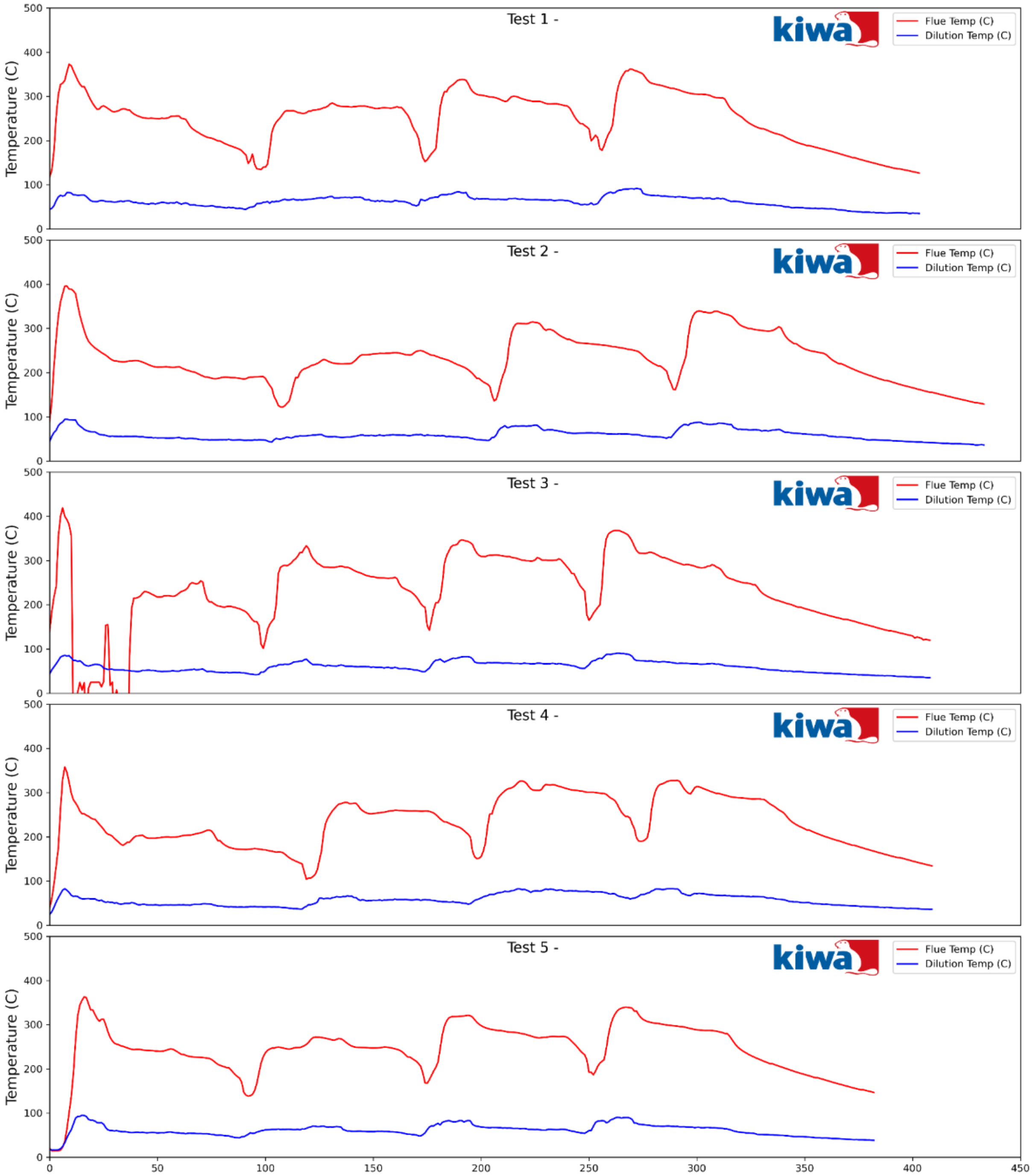


Figure A 10 Temperature Traces for the Flue and Dilution Tunnel from Round Robin Tests



Manchester University Round Robin Testing

Figure A 11 to Figure A 13 shows gas phase data from repeated runs at Manchester during the round robin exercise to demonstrate repeatability. Each bar represents a single burn at the different burn phases; Ignition, R1, R2, R3 and Shutdown.

Figure A 11 Carbon Monoxide Analysis Results from Round Robin Tests

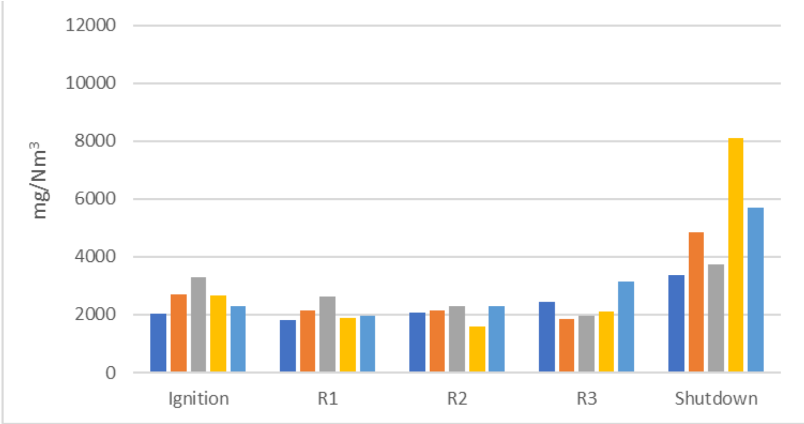


Figure A 12 Oxygen Analysis Results from Round Robin Tests

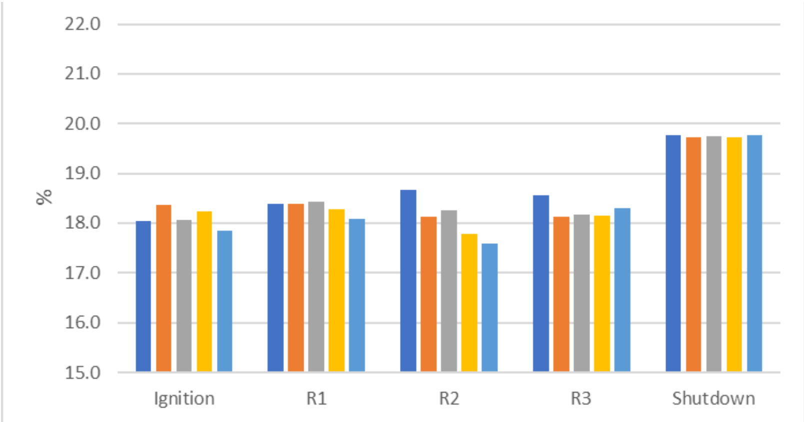
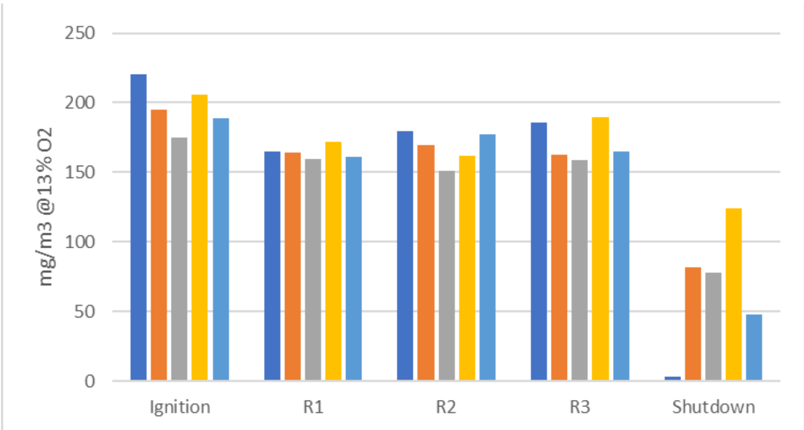


Figure A 13 Nitrogen Oxide Analysis Results from Round Robin Tests



A.2 ROUND ROBIN RESULTS

Table A 1 Burn rates (g/s)

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	0.61	0.53	0.52	0.46	0.66	0.64	0.52	0.52	0.55	0.51	0.50	0.52	0.33
R1	0.46	0.38	0.47	0.50	0.45	0.45	0.44	0.41	0.51	0.38	0.37	0.45	0.31
R2	0.47	0.45	0.50	0.52	0.50	0.34	0.33	0.33	0.46	0.28	0.45	0.55	0.30
R3	0.53	0.54	0.51	0.54	0.53	0.28	0.37	0.55	0.57	0.52	0.54	0.52	0.40
Shutdown	0.08	0.06	0.09	0.08	0.07	0.23	0.34	0.19	0.28	0.21	0.08	0.04	0.17

Table A 2 Appliance outlet temperature (˚C)

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	238	223	156	197	234	176	162	168	167	188	227	215	177
R1	281	255	261	238	239	200	192	180	183	207	208	236	184
R2	281	263	295	285	276	201	216	205	234	235	240	267	175
R3	295	283	295	285	292	182	230	222	245	231	276	274	230
Shutdown	174	171	177	179	193	128	158	139	162	153	161	174	145

Table A 3 Carbon Monoxide at appliance outlet (mg/Nm^3 Normalised to 13% O_2 dry and STP (0°C, 101.3 kPa))

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	5044	5464	3197	5438	2028	2022	2715	3307	2677	2297	5243	4373	4946
R1	4961	3642	3389	4186	2544	1824	2143	2639	1869	1974	5508	3114	4092
R2	4100	2789	3044	3322	1883	2078	2138	2294	1579	2296	4218	2791	3162
R3	3894	3282	3031	4023	1464	2429	1860	1960	2119	3150	3565	3264	2601
Shutdown	11438	5182	8825	11300	1673	3356	4859	3735	8105	5690	63011	13450	8988

Table A 4 Oxides of nitrogen at appliance outlet (mg NO_2/Nm^3 Normalised to 13% O_2 dry and STP (0°C, 101.3 kPa))

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	52	82	112	166	87	220	195	175	206	189	103	98	61
R1	31	33	102	172	83	165	164	159	171	161	65	63	62
R2	24	27	157	144	87	180	170	151	162	178	72	73	39
R3	22	25	149	149	105	185	162	158	189	165	91	78	65
Shutdown	9	7	144	134	73	3	81	78	124	47	318	36	31

Table A 5 >PM_{10} at dilution tunnel (mg/Nm^3 Normalised to 13% O_2 dry and STP (0°C, 101.3 kPa))

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	0.00	0.00	0.00	0.00	0.00	23.76	3.62	0.00	0.00	12.22	0.45	2.71	3.05
R2	0.00	0.00	0.00	0.00	5.53	49.87	4.31	0.00	0.00	0.00	0.65	2.13	2.18
Shutdown	0.00	0.00	0.00	0.00	0.00	63.93	24.71	0.00	0.00	15.01	17.80	10.23	9.31

Table A 6 PM_{10} at dilution tunnel (mg/Nm^3 Normalised to 13% O_2 dry and STP (0°C, 101.3 kPa))

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	249.25	230.59	202.32	43.19	192.86	388.13	325.48	609.03	372.88	329.96	225.98	783.54	751.51
R2	268.74	151.49	232.56	304.66	199.13	332.49	266.91	74.62	128.50	184.95	209.20	176.52	382.89
Shutdown	23.27	0.00	28.73	65.72	20.84	127.86	111.21	0.00	87.25	135.10	53.41	61.39	55.83

Table A 7 $PM_{2.5}$ at dilution tunnel (mg/Nm^3 Normalised to 13% O_2 dry and STP (0°C, 101.3 kPa))

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	244.46	221.18	202.32	43.19	192.86	360.41	300.16	609.03	372.88	329.96	221.48	680.63	748.46
R2	268.74	147.70	226.10	304.66	193.60	282.61	249.69	74.62	128.50	184.95	206.59	162.16	380.40
Shutdown	23.27	0.00	28.73	32.86	20.84	25.57	86.50	0.00	87.25	90.07	53.41	40.93	48.85

Table A 8 TPM at dilution tunnel (mg/Nm^3 Normalised to 13% O_2 dry and STP (0°C, 101.3 kPa))

	Kiwa					Manchester University					University of Leeds		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3	Run 4	Run 5	Run 1	Run 2	Run 3
Ignition	249.25	230.59	202.32	43.19	192.86	411.89	329.09	609.03	372.88	342.18	226.43	786.25	754.57
R2	268.74	151.49	232.56	304.66	204.67	382.36	271.22	74.62	128.50	184.95	209.85	178.65	385.07
Shutdown	23.27	0.00	28.73	65.72	20.84	191.78	135.93	0.00	87.25	150.11	71.22	71.62	65.14

A.3 ANALYSIS OF OC/EC DATA FOR EC (BLACK CARBON) QUANTIFICATION

Objectives

1. Validation of the sampling protocol for black carbon quantification by collection of samples on quartz filters for thermal-optical analysis
2. Determination of an appropriate analysis protocol out of EUSAAR-2, QUARTZ (NIOSH870), or IMPROVE-A (TOR).

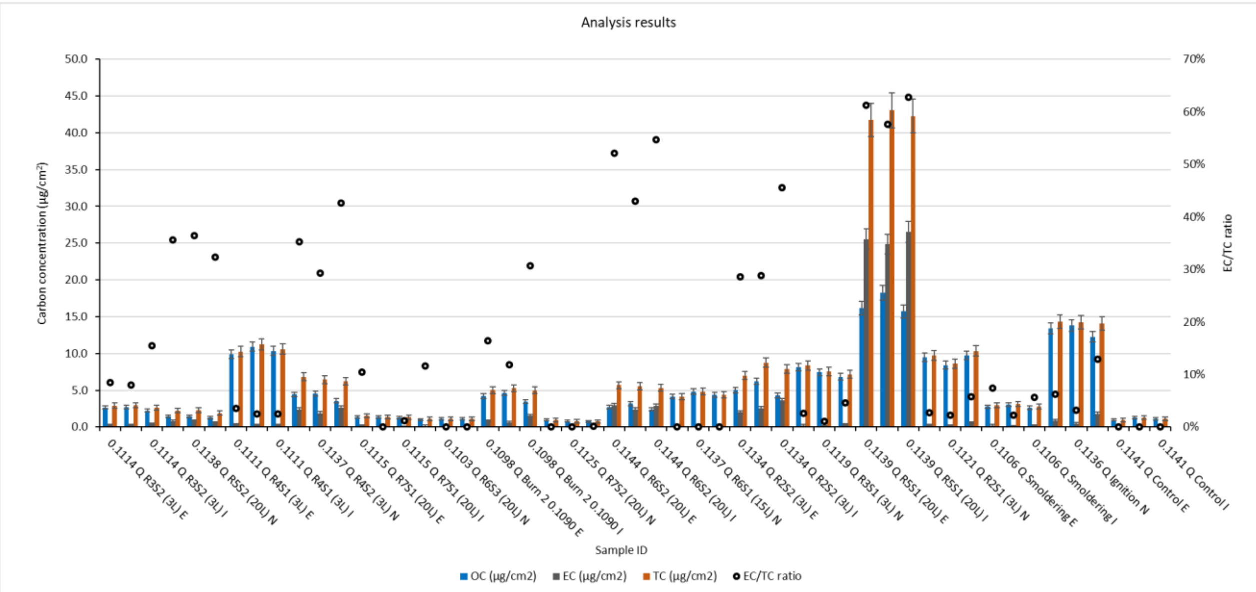
Method

Samples on quartz filters were taken from both the dilution tunnel and flue (heated DIN+) for a variety of wood moisture contents and sent to Sunset Labs in ice packs to be split into three for analysis by the three protocols. This included samples from round robin analysis.

Thermal-optical analysis involves heating the sample in stages, firstly in an inert atmosphere (helium) where evolved organic carbon is detected using a flame ionization detector (FID). The sample is then cooled and heated again in an oxidising atmosphere (helium + oxygen), where elemental carbon is detected. Some organic carbon will pyrolyze rather than evaporate during heating. The formation of pyrolyzed elemental carbon is corrected for by monitoring the transmission of a laser through the filter during the analysis, or in the case of IMPROVE-A, the reflected intensity (Birch and Cary, 1996).

Results

Figure A 14 Per-Filter Analysis as Reported by Sunset Labs



Sunset Labs reported that the concentrations were generally low, Figure A 14. Some of this was to be expected (e.g. blanks) however surprisingly, some of the very low concentrations came from the burn phase of wetter woods (samples R7S2 and R6S3). However, conversely the sample for the ignition phase of dry wood (sample R5S1) was close to saturation for EC (30 µg cm^{-2}). This presumably is because of a lower burn rate, meaning that less emission was captured during the sampling period.

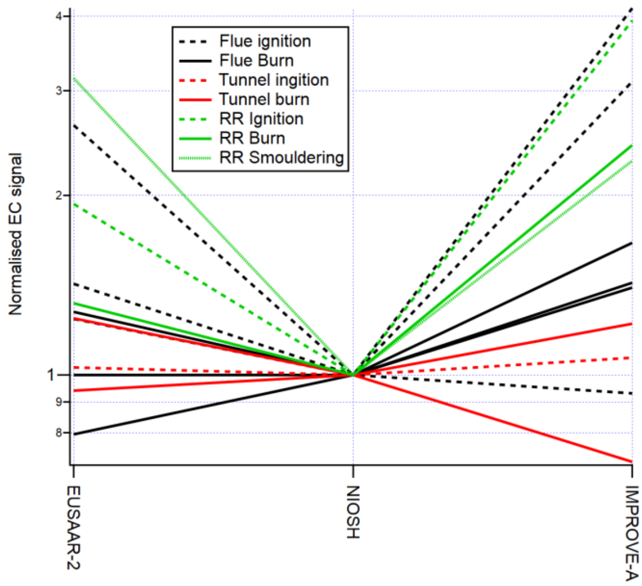
Table A 9 Common Thermal-Optical Protocols, Summarised by Cavalli et al. (2010)

	EPA/NIOSH[b]	NIOSH 5040	IMPROVE[c]	EUSAAR_1 short	EUSAAR_1 Long	He4-550	He4-750	He4-850	EUSAAR_2
STEP	T, duration °C, s	T, duration °C, s	T, duration °C, s	T, duration °C, s	T, duration °C, s	T, duration °C, s	T, duration °C, s	T, duration °C, s	T, duration °C, s
He1	310, 60	250, 60	120, 150–580	200, 120	200, 180	200, 180	200, 180	200, 180	200, 120
He2	475, 60	500, 60	250, 150–580	300, 150	300, 240	300, 240	300, 240	300, 240	300, 150
He3	615, 60	650, 60	450, 150–580	450, 180	450, 240	450, 240	450, 240	450, 240	450, 180
He4	900, 90	850, 90	550, 150–580	650, 180	650, 240	550, 240	750, 240	850, 240	650, 180
$He/O_2$1[a]	600, 45	650, 30	550, 150–580	550, 240	550, 300	550, 300	550, 300	550, 300	500, 120
$He/O_2$2	675, 45	750, 30	700, 150–580	850, 150	850, 180	850, 180	850, 180	850, 180	550, 120
$He/O_2$3	750, 45	850, 30	800, 150–580						700, 70
$He/O_2$4	825, 45	940, 120							850, 80
$He/O_2$5	920, 120								

NIOSH870 is very similar to the NIOSH5040 shown in this table, but with the final temperature of the He phase set to 870 °C.

The results were reported according to EUSAAR-2, NIOSH and IMPROVE-A (Table A9), which are commonly used in the literature (Cavalli et al., 2010). While concerns were raised on the homogeneity of the analyte coverage on the Manchester University filters, based on a visual inspection, the total carbon values from the three techniques were broadly similar, which gives confidence that this was not an issue. The results for all of the valid samples have been normalised to NIOSH and compared, Figure A 15.

Figure A 15 Comparison of Reported EC from the Different Protocols, Relative to NIOSH



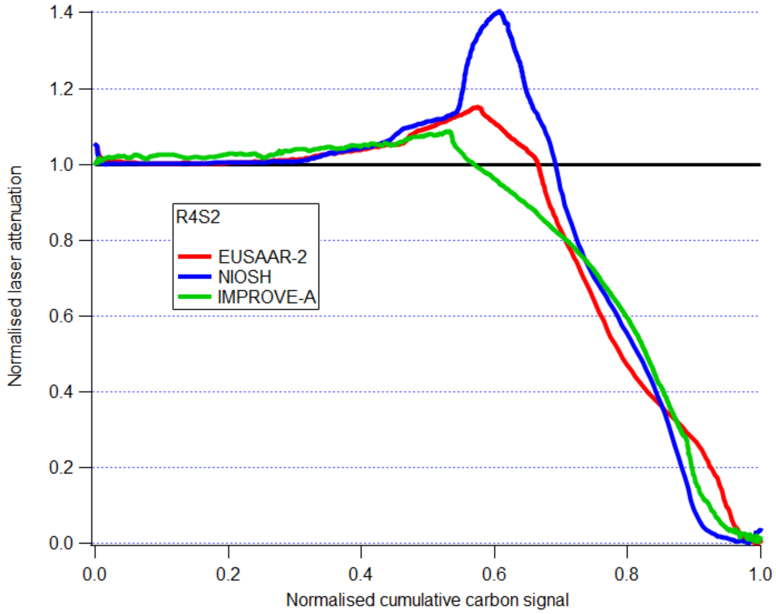
'RR' refers to the round robin experiment

Generally, NIOSH gave the lowest EC values. While there are examples of IMPROVE-A and EUSAAR-2 being lower, in each case there is a counterexample of an equivalent experiment that shows the opposite. While the test protocol is based around sampling on the dilution tunnel, tests were also performed on the flue to verify whether the influence of more volatile organics were a factor.

To further investigate the reasons for the differences, the data was analysed using a version of the AVEC plot (Nicolosi et al., 2018[32]), as suggested by the Steering Group. For the sake of comparability, the cumulative total carbon was normalised, as was the light attenuation, with 1 being minimum attenuation during the He phase and 0 being minimum overall attenuation. The Me-Ox phase (internal calibration) was excluded from each plot.

[32] Nicolosi, E. M. G., Quincey, P., Font, A., and Fuller, G. W.: Light attenuation versus evolved carbon (AVEC) – A new way to look at elemental and organic carbon analysis, Atmos. Environ., 175, 145-153, 10.1016/j.atmosenv.2017.12.011, 2018

Figure A 16 AVEC Comparison of the Three Protocols from the R4S2 Sample



R4SW2 Sample - dry wood, flaming phase, sampled from the flue

Figure A 17 AVEC Comparison of the Three Protocols from the Round Robin Experiment, Taken from the Burn Phase

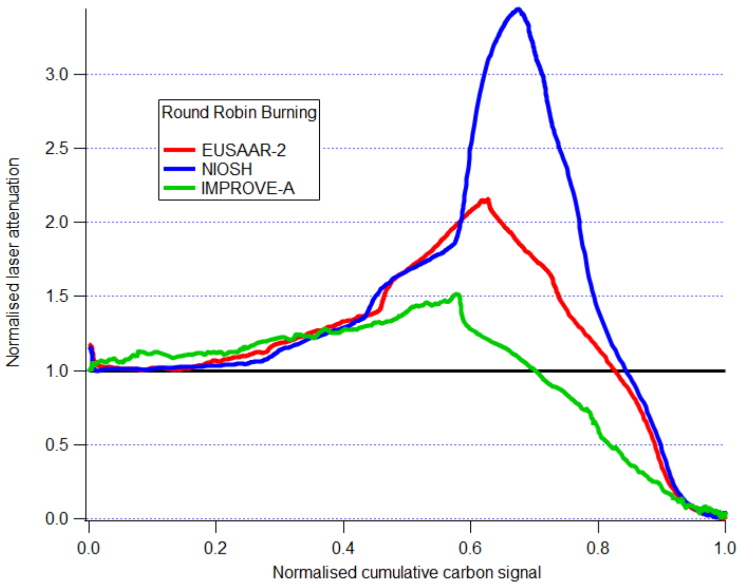
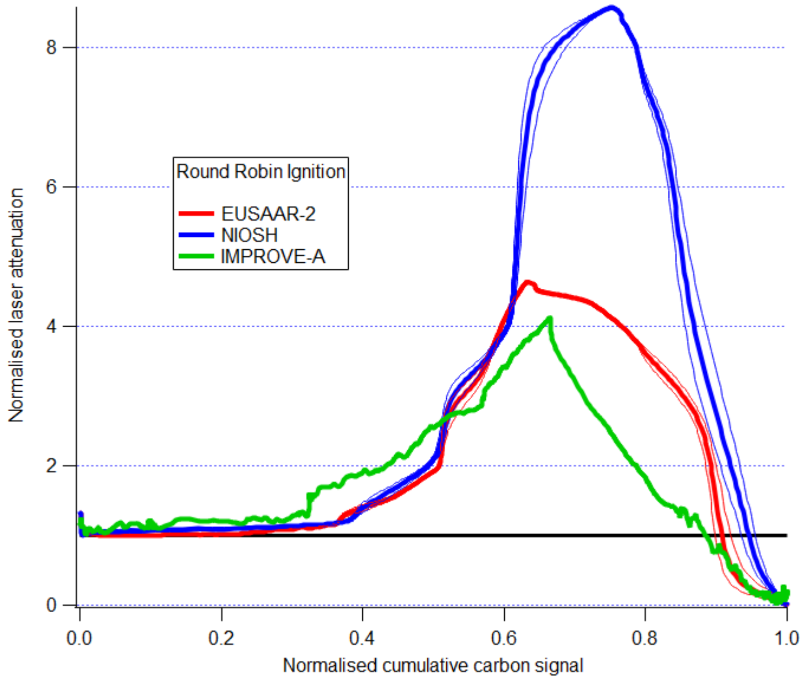


Figure A 16 shows an AVEC comparison of sample R4S2, which had a good level of filter loading for analysis. For each curve, the peak in attenuation represents the end of the He phase of the analysis, before the He-Ox phase starts. The point at which the attenuation returns to 1 is defined as the split point of the analysis, where the normalised cumulative carbon value can be taken to be the OC/TC ratio. The difference between the split point and the peak attenuation can be taken to be the amount of organic carbon that is charred during the He phase.

The most extreme examples of discrepancy in the EC value are when the OC/TC value is high, in particular the ignition and smouldering phases, Figure A 18. Uncertainty lines are added to the NIOSH and EUSAAR-2 lines based on a gas transit uncertainty of 5 seconds (Nicolosi et al., 2018). This indicates that the differences between the techniques are significant relative to this uncertainty, noting that because the same instrument was used to perform these analyses, any errors of this nature are likely to be systematic between analysis runs and not responsible for a difference in the protocols anyway.

Figure A 18 AVEC Comparison of the Three Protocols for the Ignition Phase of the Round Robin Experiment



The extra lines on the EUSAAR-2 and NIOSH indicate uncertainty associated with gas transit time

A common feature of most AVEC plots is that the attenuation for the transmission-based EUSAAR-2 and NIOSH is largely flat for the first (approximately) 20% of the carbon signal. This is to be expected because minimal charring is expected during the first stages of the He phase, and this well-established baseline helps to identify the split point with a high precision. In contrast, the attenuation reported using the reflectance-based IMPROVE-A protocol is noisy and rises gradually during this period. The lack of a clearly defined baseline and the shallow gradient at the split point on the AVEC plot combine to give a large uncertainty in the IMPROVE-A split point making the protocol unsuitable for this test programme.

The majority of samples (certainly those in Figure A 17 and Figure A 18) presented similar features:

- IMPROVE-A measured the least amount of carbon during the He phase, followed by EUSAAR-2, followed by NIOSH measuring the most.
- NIOSH reported the highest peak attenuation, indicating the largest amount of charring, followed by EUSAAR-2, followed by IMPROVE-A.
- NIOSH reported the highest OC/TC ratio, followed by EUSAAR-2, followed by IMPROVE-A

While some counterexamples to the above observations were found, these were found to be marginal (e.g. sample R2S2, where EUSAAR-2 reported the highest OC/TC, but only just) or in samples with low concentrations and thus poor signal quality (e.g. R5S2).

The reduction in charring of EUSAAR-2 compared to NIOSH is expected, as the former is explicitly designed to minimise charring through a lower maximum temperature in the He phase, Table A9.

Our interpretation from these phenomena is that because EUSAAR-2 and IMPROVE-A report less carbon during the He phase, this means that more organic carbon remains on the filter at the end of this stage of the analysis. While some of this will subsequently be removed during the early stages of the He-Ox phase, the fact that these protocols reach the split point sooner as a function of cumulative carbon indicates that some organic carbon still remains on the filter when the split point is reached, in turn meaning that this effectively gets mischaracterised as EC. If this is the case, then this would imply that the NIOSH protocol is the more accurate. While EUSAAR-2 is designed to prevent this by dwelling on the individual temperature stages for longer (compared to NIOSH), this data would suggest that this does not eliminate the problem entirely.

One reported phenomenon that would alter this assessment is if some of the EC were to vaporise in the He phase, which would lead to an overestimate of the OC/TC ratio. The EUSAAR-2 protocol is designed to mitigate this problem by not reaching as high a temperature during the He phase, so could be more accurate if this is the cause of the discrepancy. This process is thought to be enhanced by the presence of metals, in particular iron, which can act as catalysts and promote the EC being oxidised by other components. However, it should be noted that the samples taken during this experiment will not contain the metals associated with ambient particulate or engine emissions (e.g. mineral dust, brake wear, engine wear, lubricating oils).

Another consideration is that EUSAAR-2 is used on ambient networks (Brown et al., 2017). We may wish to conform to this standard for comparability purposes.

Conclusions and Recommendations

The IMPROVE-A protocol gave the least satisfactory results and we concluded that this should not be used in this test programme. The NIOSH and EUSAAR-2 Protocols gave similar but not identical results, with NIOSH generally reporting lower EC/TC ratios. While the NIOSH protocol results in more charring, this is corrected for through the analysis of the optical transmission variation, and we think that the EUSAAR-2 method is not capturing as much refractory OC before the helium-oxygen stage. Due to the analysis above it is recommend that the black carbon samples are analysed according to the QUARTZ/NIOSH870 protocol as opposed to the EUSAAR-2 method originally envisaged.

This protocol can be run at Sunset Labs or NPL. The samples should be shipped to the analysis laboratory using water-based ice packs. While dry ice would remain colder for longer, there is a potential for carbonate contamination, which may further alter the results. For future comparability, some filters have been halved with half sent for analysis and the other retained and frozen for future analysis using EUSAAR-2 or another protocol.

A.4 CONDENSABLE SPECIATION

A range of organic compounds were identified in condensable material (Table A10).

Table A 10 Typical VOC Species Identified by the University of Manchester

Name	Chemical Formula
Phenylethyne	$C_8 H_6$
Benzene, 1,3-dimethyl-	$C_8 H_{10}$
Benzaldehyde, 4-(1-phenyl-2-propenyloxy)-	$C_{16} H_{14} O_2$
2-Propanol, 1-methoxy-	$C_4 H_{10} O_2$
Ethanone, 2-(formyloxy)-1-phenyl	$C_9 H_8 O_3$
Phenylethyne	$C_8 H_6$
Naphthalene, 1,2-dihydro-	$C_{10} H_{10}$
3-Furaldehyde	$C_5 H_4 O_2$
Phenol	$C_6 H_6 O$
Benzene, 1-ethynyl-4-methyl-	$C_9 H_8$
Ethylbenzene	$C_8 H_{10}$
Benzene, 1,2,4-trimethyl-	$C_9 H_{12}$
9H-Fluorene, 9-methylene-	$C_{14} H_{10}$
Acenaphthylene	$C_{12} H_8$
2-Propanol, 1-methoxy-	$C_4 H_{10} O_2$
Cyclohexane, methyl-	$C_7 H_{14}$
Benzofuran	$C_8 H_6 O$
Toluene	$C_7 H_8$

A.5 FUEL ANALYSIS

Table A 11 Summary of Wood Fuel Analysis

	Dry Wood 1*	Dry Wood 2*	Dry Wood 3*	Seasoned Wood	Wet Wood
Free Moisture as received %	6.6	-	-	28.2**	
Total Moisture as received %	10.9	3.0	3.5	30.4**	25.9
Ash Content %	1.5	0.4	0.4	0.4	1.1
Volatile Matter %	-	-	-	-	84.1
Fixed Carbon %	-	-	-	-	14.8
Total Sulphur %	<0.01	0.01	<0.01	<0.01	0.01
Chlorine %	-	-	-	-	0.01
Carbon %	49.0	49.1	48.8	48.8	48.2
Hydrogen %	5.78	5.67	5.76	5.75	6.08
Nitrogen %	0.19	0.14	0.14	0.16	-
Oxygen by Difference %	43.5	44.7	44.9	44.9	-
Gross Calorific Value MJ/kg	19.601	19.392	19.384	19.399	19.566
Net Calorific Value MJ/kg	18.341	18.154	18.127	18.144	18.240
Potassium mg/kg	-	-	-	-	658.68

Fuel was analysed by Alfred H Knight Energy Services Limited
All data is on a dry basis unless otherwise stated
* Dry wood has three samples as it is dried in batches (kiln size restrictions) with analysis taken to check moisture measurements
**The wood was seasoned after it was sent for analysis, this is not the moisture of the wood when used in the tests.

Figure A 19 Certificate of Analysis for Dry Wood 1

CERTIFICATE OF ANALYSIS

JASON POWIS
KIWA UK
KIWA HOUSE
MALVERN VIEW BUSINESS PARK
STELLA WAY
BISHOPS CLEEVE
CHELTENHAM
GL52 7DQ

Test Date(s): **17-Nov-2021 to 26-Nov-2021**
Date of Report: **26-Nov-2021**

Date Received: 17-Nov-2021

AHK Ref: DB/382980
Client Ref: **WOOD LOGS (DEFRA KILN DRIED NOV 21)**

Material Described As: WOOD LOGS

Samples were received by Alfred H Knight Energy Services Ltd and analysis results relate only to the items tested.

Client Ref.	Test	Unit	As Received	Dry Basis	Dry Ash-Free
Wood Logs	(DEFRA Kiln Dried Nov 21)				
	Free Moisture	%	6.6		
	Total Moisture	%	10.9		
	Ash Content	%	1.3	1.5	
	Total Sulphur	%	< 0.01	< 0.01	< 0.01
	Carbon	%	43.7	49.0	49.7
	Hydrogen	%	5.15	5.78	5.87
	Nitrogen	%	0.17	0.19	0.19
	Oxygen By Difference	%	38.8	43.5	44.2
	Gross Calorific Value	MJ/Kg	17.464	19.601	19.900
	Net Calorific Value	MJ/Kg	16.075	18.341	

Gibson Kabaso
Biomass Technical Manager
For and on behalf of Alfred H Knight Energy Services Ltd

Doc Id: DB/382980/3 **Alfred H Knight Energy Services Ltd** Page 1 of 2
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Tel: +44 1563 850 375 Email: solidfuels@ahkgroup.com
ALL WORK IS UNDERTAKEN SUBJECT TO OUR STANDARD TRADING TERMS AND CONDITIONS OF BUSINESS

Figure A 20 Certificate of Analysis for Dry Wood 2

CERTIFICATE OF ANALYSIS

JASON POWIS
KIWA UK
KIWA HOUSE
MALVERN VIEW BUSINESS PARK
STELLA WAY
BISHOPS CLEEVE
CHELTENHAM
GL52 7DQ

Test Date(s): **30-Mar-2022 to 06-Apr-2022**

Date Received: 30-Mar-2022

Date of Report: **08-Apr-2022**

AHK Ref: **DB/386660**

Material Described As: WOOD LOGS

Client Ref: **PROJECT NUMBER 31153**

Samples were received by Alfred H Knight Energy Services Ltd and analysis results relate only to the items tested.

Client Ref.	Test	Unit	As Received	Dry Basis	Dry Ash-Free
Wood logs 31153-OD1					
	Total Moisture	%	3.0		
	Ash Content	%	0.4	0.4	
	Total Sulphur	%	0.01	0.01	0.01
	Carbon	%	47.6	49.1	49.3
	Hydrogen	%	5.50	5.67	5.69
	Nitrogen	%	0.14	0.14	0.14
	Oxygen By Difference	%	43.4	44.7	44.9
	Gross Calorific Value	MJ/Kg	18.810	19.392	19.470
	Net Calorific Value	MJ/Kg	17.536	18.154	

Gibson Kabaso
Biomass Technical Manager
For and on behalf of Alfred H Knight Energy Services Ltd

Doc Id: DB/386660/2

Alfred H Knight Energy Services Ltd

Page 1 of 2

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Figure A 21 Certificate of Analysis for Dry Wood 3

CERTIFICATE OF ANALYSIS

JASON POWIS
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MALVERN VIEW BUSINESS PARK
STELLA WAY
BISHOPS CLEEVE
CHELTENHAM
GL52 7DQ

Date Received: 30-Mar-2022

Test Date(s): **30-Mar-2022 to 06-Apr-2022**
Date of Report: **08-Apr-2022**

AHK Ref: DB/386660
Client Ref: **PROJECT NUMBER 31153**

Material Described As: WOOD LOGS

Samples were received by Alfred H Knight Energy Services Ltd and analysis results relate only to the items tested.

Client Ref.	Test	Unit	As Received	Dry Basis	Dry Ash-Free
Wood logs 31153-OD2					
	Total Moisture	%	3.5		
	Ash Content	%	0.4	0.4	
	Total Sulphur	%	< 0.01	< 0.01	< 0.01
	Carbon	%	47.1	48.8	49.0
	Hydrogen	%	5.56	5.76	5.78
	Nitrogen	%	0.14	0.14	0.14
	Oxygen By Difference	%	43.3	44.9	45.1
	Gross Calorific Value	MJ/Kg	18.706	19.384	19.462
	Net Calorific Value	MJ/Kg	17.407	18.127	

Gibson Kabaso
Biomass Technical Manager
For and on behalf of Alfred H Knight Energy Services Ltd

Doc Id: DB/386660/2 | Page 2 of 2

Alfred H Knight Energy Services Ltd
Unit 1 Palmermount Industrial Estate, Bypass Road, Dundonald Kilmarnock, KA2 9BL
Tel: +44 1563 850 375 Email: solidfuels@ahkgroup.com
ALL WORK IS UNDERTAKEN SUBJECT TO OUR STANDARD TRADING TERMS AND CONDITIONS OF BUSINESS

Figure A 22 Certificate of Analysis for Seasoned Wood

CERTIFICATE OF ANALYSIS

JON FREEMAN
KIWA UK
KIWA HOUSE
MALVERN VIEW BUSINESS PARK
STELLA WAY
BISHOPS CLEEVE
CHELTENHAM
GL52 7DQ

Date Received: 03 Nov 2021

Test Date(s): **03-Nov-2021 to 12-Nov-2021**
Date of Report: **12-Nov-2021**

AHK Ref: **DB/382610**
Client Ref: **PROJECT NUMBER:- LAB SUPPORT**

Material Described As: WOOD LOGS

Samples were received by Alfred H Knight Energy Services Ltd and analysis results relate only to the items tested.

Client Ref.	Test	Unit	As Received	Dry Basis	Dry Ash Free
Wood Logs (November 21)					
	Free Moisture	%	28.2		
	Total Moisture	%	30.4		
	Ash Content	%	0.3	0.4	
	Total Sulphur	%	< 0.01	< 0.01	< 0.01
	Carbon	%	34.0	48.8	49.0
	Hydrogen	%	4.00	5.75	5.77
	Nitrogen	%	0.11	0.16	0.16
	Oxygen By Difference	%	3?.3	44.9	45.1
	Gross Calorific Value	MJ/Kg	13.502	19.399	19.477
	Net Calorific Value	MJ/Kg	11.886	18.144	

Bioann Katasio
Biomass Technical Manager
For and on behalf of Alfred H Knight Energy Services Ltd

Doc Id: DB/382610/? | Alfred H Knight Energy Services Ltd | Page: 1 of 1

[illegible]

Figure A 23 Certificate of Analysis for Wet Wood

ALFRED H KNIGHT

Page 1 of 2

JON FREEMAN
KIWA UK
KIWA HOUSE
MALVERN VIEW BUSINESS PARK
STELLA WAY
BISHOPS CLEEVE
CHELTENHAM
GL52 7DQ

CERTIFICATE OF ANALYSIS

Certificate No : 0402
Job Ref. : 17788-1 DEF-WET WOOD
Material Desc. : Wood Logs
Date Reported : 20th June 2022

Test	Units	As Received	Dry Basis	Dry Ash Free
Total Moisture	%	25.9		
Ash Content	%	0.8	1.1	
Volatile Matter	%	62.3	84.1	85.0
Fixed Carbon	%	11.0	14.8	15.0
Total Sulphur	%	0.01	0.01	0.01
Chlorine	%	0.01	0.01	0.01
Carbon	%	35.7	48.2	48.7
Hydrogen	%	4.51	6.08	6.15
Gross Calorific Value	MJ/Kg	14.443	19.566	19.708
Net Calorific Value	MJ/Kg	12.883	18.240	

Scott Foster
Client Services Operations Manager
For and on behalf of ALFRED H KNIGHT ENERGY SERVICES LIMITED

Alfred H Knight Energy Services Limited
Unit 1, Palmermount Industrial Estate, Dundonald, Ayrshire, KA2 9BL, Scotland, UK
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ALFRED H KNIGHT

JON FREEMAN
KIWA UK
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STELLA WAY
BISHOPS CLEEVE
CHELTENHAM
GL52 7DQ

CERTIFICATE OF ANALYSIS

Certificate No : **0402**
Job Ref. : **17788-1 DEF-WET WOOD**
Material Desc. : **Wood Logs**
Date Reported : **20th June 2022**

Trace Metal Analysis (Dry Basis)		
Test	**Units**	**Result**
Potassium	mg/Kg	658.68

Scott Foster
Client Services Operations Manager
For and on behalf of ALFRED H KNIGHT ENERGY SERVICES LIMITED

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A.6 KIWA WOOD MOISTURE CONTROL PROCEDURE

Wood delivered to Kiwa is partially seasoned to around 20% - 25% moisture content prior to delivery. For laboratory use this wood is then stored and processed as appropriate for the tests.

Wood is then spot checked using handheld moisture meters.

Procedure for measuring wood moisture:

1. Remove two pieces of wood from the pile, de-bark and slice into kindling-sized slivers of approx. 40g each.
2. Weigh 600g of sliced wood and place each bundle on a separate weighed metal tray.
3. Record weights on a dedicated bulk moisture record sheet.
4. Place the trays with wood in a drying oven at 110C for 24h, or until weight stabilises.
5. Weigh the samples again, subtracting the weight and calculating the moisture lost.
6. Once wood is at a correct moisture content, store in a sealed plastic bag to prevent further drying or absorbing moisture.

This firewood is then stored in a temperature and moisture-controlled room and spot checked using a portable moisture meter prior to being used for tests.

Blank bulk moisture record sheet

Sheet Number : BMD
TESTING SERVICES
FUEL TEST PROCEDURES

Sheet 1 of 1
Issue Date 06/09/2022
Version 2.0

SHEET TITLE - **BULK MOISTURE DETERMINATION**

DATE ______

SAMPLE NAME ______ REF. NUMBER ______

TRAY NUMBER ______ MASS OF TRAY (M_T): ______ g

SCALE FAT NUMBER ______ IN CALIBRATION Y/N ______

OVEN FAT NUMBER ______ IN CALIBRATION Y/N ______

STAGE	TIME	MASS & TRAY + FUEL (g)	MASS REDUCTION (g)
START		(M1)	
AFTER 3 HOURS		($M2_A$)	
1/2 HR INTERVAL		($M2_B$)	
1/2 HR INTERVAL		($M2_C$)	
1/2 HR INTERVAL		($M2_D$)	
AFTER 24 HOURS			

Continue weighing at 1/2 hour intervals until mass reduction is $\leq$ 0.1% of $M1-M_T$

$M1-M_T =$ ______ g   0.1% of $M1-M_T = \frac{(M1-M_T)}{1000} =$ ______ g

BULK MOISTURE = $\frac{(M1-M2_{A...F})}{M1-M_T}$ x 100

BULK MOISTURE = ______ x 100

BULK MOISTURE = ______ %

SIGNED ______

CHECKED ______

A.7 STOVE SPECIFICATIONS

Charnwood C-4 blu – Modern Stove

charnwood

C-FOUR *blu*

Featuring a large picture window the C-Four is the smallest model in the C-Series delivering a heat output to the room of between 2 to 5.5kW. The stove is steel plate lined and can take a log length of up to 282mm (11"). With a rated output of 4.9kW the C-Four, in certain situations, can be installed without the need for external air. This model is SIA Ecodesign ready (blu).

RATED OUTPUT

4.9kW to room (range 2-5.5kW)

NET EFFICIENCY

82%

FLUE OUTLET

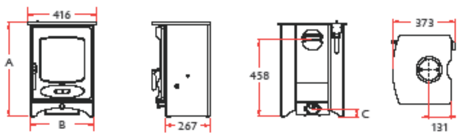
Top or Rear 125mm (5") dia

MAX LOG LENGTH

282mm (11")

MIN DISTANCE TO COMBUSTIBLES

Side: 500mm Rear: 370mm With heatshield - Rear: 175mm



		A	B	C	WEIGHT
LOW LEGS		560	386	45	83KG
STORE STAND		710	386	195	89KG
HIGH LEGS		765	400	248	85.5KG

Dovre 500MRF Cast Iron Stove

Dovre 500MFR/500MFF Cast Iron Stove Installation and Operating Manual

Before commencing with the installation it is important that these instructions are read and fully understood.

When installing the model Dovre 500MFF, follow the installation and operating instructions for the MFR with the following exceptions:

1 ***PAGE 1, ASSEMBLY SECTION 5***
Ignore this instruction which applies only to the model Dovre 500 MFR

2 ***DIAGRAM Fig 5***
Ignore this diagram which refers to the grate system incorporated in the model 500MFR

3 ***DIAGRAM fig 6***
The sketch illustrates the riddling rod which is not applicable to the 500MFF

4 ***PAGE 5, ASH REMOVAL - SECTION 3***
The Dovre MFF is not equipped with a riddling grate mechanism and therefore ashes must be removed from the grate using a conventional poker.

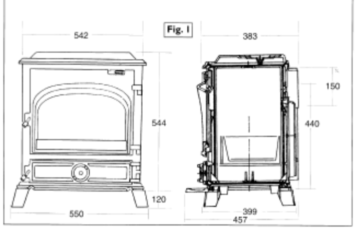


Fig. 1

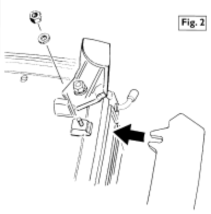


Fig. 2

NOTE: The Dovre 500MFF is the same in all aspects as the 500MFR except for the grate system. The 500MFF is fitted with a one piece cast iron grate suitable to use with wood or smokeless solid fuel. The 500MFF does not incorporate a riddling grate system.

The 500 MFR is a specially designed stove for burning wood and most smokeless fuels. It is essential that when wood is used, it is well-seasoned (min 2 years) and has a maximum moisture content of 20%. If unseasoned wood is used, heat outputs will not be obtained and serious damage will occur in the chimney and flueways.

The dimensions of your new stove are illustrated in fig. 1. Be careful to ensure that your fireplace is going to accept the appliance and that you have allowed for 30cm of hearth space in front of the stove.

REGULATIONS

It is important that the installation is carried out in compliance with current Building Regulations.

1 ASSEMBLY

As the Dovre 500MFR is constructed from heavy cast iron, it is advisable for two people to assemble and position the appliance.

1. Open the stove door and remove all loose parts within.
2. Lay the stove on its back and fit the 4 legs and front ash lip. See fig.2.
3. Fit the circular cast iron flue collar. This can be fitted in one of two positions (see fig.3). For a top flue connection, attach the circular cast iron collar to the aperture located at the top of the appliance, using the nuts, bolts and washers supplied. Use a small amount of fire cement to ensure an air tight seal before fixing. For a rear flue connection, adopt the same procedure using the rear aperture. Fit the cast iron circular cover plate to the unused aperture again using a small amount of fire cement as a seal. The cover plate is attached using the fixing bar and nuts and bolts supplied.
4. Carefully position the stove on the hearth.
5. Fit the solid fuel grate, cradle and riddling arm. See fig.5 page 3

2

2 INSTALLATION

HEARTH REQUIREMENT

The positioning of the appliance and the size and type of hearth are governed by Building Regulations for Class 1 appliances. The Building Regulations state that the hearth must extend at least 30cms to the front of the appliance and 15cms to the sides. If in doubt, expert advice should be sought from your local Building Inspector.

3 CONNECTION TO CHIMNEY

If an existing masonry chimney is installed, the appliance should be connected to the chimney using 150mm diameter 316 grade 1mm stainless steel, cast iron or good quality vitreous enamel flue pipe. It is important to ensure that the connection to the chimney is carried out in such a way that any soot particles are allowed to fall unhindered back into the appliance or flue T-section. See fig.4.

4 ACCESS FOR SWEEPING CHIMNEY

The chimney should be checked and swept at least once a year and it is important to allow provision for gaining access to the chimney. On masonry chimneys, a standard soot door, obtainable from your Dovre dealer, can be used. On other factory made chimneys, it is important to ensure an access cleaning door is provided. It is advisable to ensure that the connecting flue pipe to the chimney has an access door fitted. An access door close to the appliance will also facilitate the use of a chimney vacuum cleaner to ensure clean appliance maintenance.

5 THE CHIMNEY

The chimney must be in good condition and free from cracks and blockages. If the existing chimney is unlined, it is advisable to install a flue liner suitable for use with Class I appliances, with an internal diameter between 150mm and 200mm. Your Dovre dealer can advise further on this subject.
The chimney is responsible for ensuring that flue gases and smoke are taken away from the appliance.

IF THE APPLIANCE EMITS SMOKE INTO YOUR ROOM, IT IS NOT THE FAULT OF THE APPLIANCE. THERE WILL EITHER BE A STRUCTURAL FAULT OR DESIGN FAULT IN THE CHIMNEY OR LACK OF VENTILATION IN THE ROOM.

If an existing chimney is not available, it is possible to install a prefabricated factory chimney system. Your Dovre dealer will provide further information.
It is important to ensure that the chimney structure and design comply with Current Building Regulations for Class I appliances.

THE MINIMUM DRAUGHT REQUIREMENT FOR THE DOVRE 500MFR IS .06" WATER GAUGE.

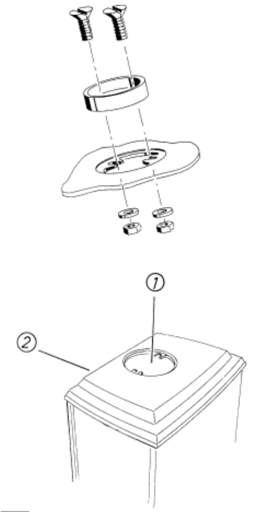


Fig. 3

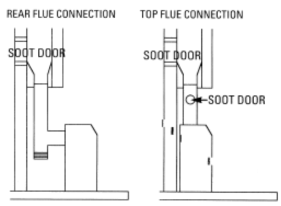


Fig. 4

3

5 THE CHIMNEY (Continued)

Too much draught will cause excessive heat outputs and fuel consumption. Inadequate draught may cause smoke emission to the room and poor combustion resulting in a build up of tar and creosote deposits on the glass, inside walls of the appliance and the chimney.

6 OPERATION

The most important factor for avoiding problems with any stove is to prevent the formation of tar and creosote build up.

IF UNSEASONED WOOD IS USED YOUR APPLIANCE MAY NOT FUNCTION CORRECTLY

HOW TAR IS FORMED

A build up of tar within the stove and/or chimney is caused by burning wood and very low temperatures i.e. burnt slowly. The condition is much worse if the wood is not seasoned properly and contains a high moisture content. If the fire is burned at low temperature, the chimney will be cold. Cold chimneys do not work and difficulty occurs with the cold chimney trying to expel the flue gases and smoke. As a result the gases condense on the walls of the chimney and appliance and become creosote or tar.

Creosote build up is dangerous and most chimney fires are caused as a result.

IT IS ESSENTIAL TO USE WELL-SEASONED WOOD OR QUALITY SMOKELESS FUEL AT ALL TIMES.

7 LIGHTING THE STOVE

Woodburning

Ensure that both the air control wheel and top secondary air control lever are in the fully open position. See fig 6.
Lay a few firelighters (or old newspaper) on the base of the stove. Light the fire and close the door. For the first few minutes, it is advisable not to close the door completely. Leave the door 1 or 2cms from the fully closed position until the fire is blazing brightly, then close the door fully. It is important to heat up the chimney quickly, so ensure that a good hot fire bed is established before adding further fuel.

Smokeless Fuel

Carry out the same procedure as above but do not open the top secondary air control lever. When burning smokeless fuel, this lever should always be in the closed position.

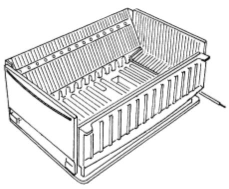


Fig. 5

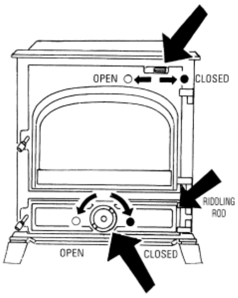


Fig. 6

4

8 ADDING FUEL

Your wood should ideally be 35 to 38cms in length with a diameter of between 5 and 10 cms.

It is good practice, before adding fuel, to separate the ashes from the hot wood embers. To do this, use a fireplace scraper tool to push the ashes to the rear of the stove close to the air inlet. This will help to ensure a faster response with the combustion. When adding fuel, load two or three logs of the dimensions given above, close the door and fully open the lower top air controls, see fig 6.

9 ADJUSTING HEAT OUTPUT

Once the fire has been well established, you can reduce the burning rate by closing the bottom air control wheel (fig. 6). Start by closing the wheel a little at a time. With experience, you will soon find the best positions most suited to your own installation. The top secondary lever should be left in the open position for woodburning except when overnight burning is required. The air settings will vary on different installations, depending on the type of wood being used and the draught the chimney is able to produce.
When using solid fuel, once a hot bed is established, load small quantities of fuel at a time. Use a coal hod and fireplace shovel for convenience in loading. To control the heat output in your Dovre 500MFR, adjust the bottom air spinning wheel to the required setting. THE TOP AIR INLET SHOULD BE IN THE CLOSED POSITION WHEN BURNING SMOKELESS FUELS.

During the first few hours of use, your stove may give off an unpleasant odour as the high temperature paint is cured. This is normal, so don't be alarmed as the condition only occurs during the first period of use.

10 ASH REMOVAL

When removing the ashes from a hot fire bed, try to ensure that some of the hot embers remain in the stove as this will facilitate re-lighting.

NEVER LET THE ASHPAN OVERFILL.

There should always be a good air space between the top of the ashpan and the underside of the grate. Failure to do this will cause premature deterioration of the grate and will make it difficult to empty the ashpan. Your Dovre 500MFR is equipped with a special grate mechanism which allows ashes to be riddled into the ashpan whilst the stove door is closed. The riddling control lever is situated on the right hand side of the front of the stove above the ashpit door. Gently move the lever backwards and forwards to clear the grate of ash.
To remove the ashpan, see fig 7, open the ashpit door and carefully remove the ashpan using the handle tool provided. Ashes must be disposed of carefully and it is a good idea to purchase an ash carrying box for this purpose. Your Dovre dealer will normally be able to supply a suitable ashpan carrier box.
After replacing the empty ashpan in the ashpit compartment, ensure the ashpit door is fully closed.

11 MANAGING YOUR WOOD SUPPLIES

If you are buying wood from a log merchant, try to ensure that the wood has been seasoned for at least 2 years. 3 years is even better. The wood should preferably be cut to lengths of 35 to 38cms and split to a width of between 5 and 10cms. Store your wood under cover to protect from rain but ideally the wood should be stored in. a place where the wind will be allowed to freely ventilate the stack.
Try to obtain hardwoods such as oak, elm, beech or ash. These woods will provide more calorific value per cubic meter than softwoods.

12 TYPES OF SUITABLE SOLID FUEL

Almost all types of smokeless fuels can be used on your 500MFR.
However, avoid the use of petroleum coke.
Anthracite medium or large nuts is an excellent fuel for good heat output but it is somewhat difficult to get started.

NEVER USE HOUSE COAL (BITUMINOUS COAL) ON THE DOVRE 500MFR

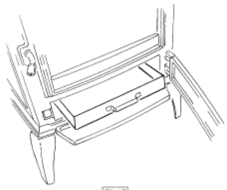


Fig. 7

5

Hunter Oakwood Stove

The specification for the Hunter Oakwood stove (Figure A 24) is not available, we believe it is a 1997 model and as per manufacturer's instructions the turbo baffle system was blocked for the test programme.

Parkray Paragon 16-inch Fire Grate – Open Fire

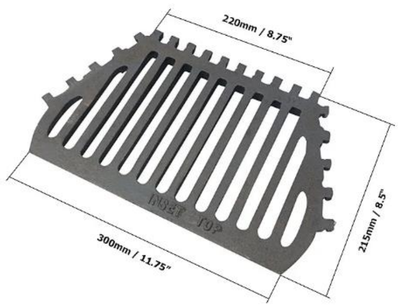


Figure A 24 Images of the appliances used in the test programme

Open fireplace

Hunter Oakwood Stove

Dovre 500MRF Cast Iron Stove

Charnwood C-4 blu Stove

A.8 PARTICULATE MEASUREMENT INVESTIGATIONS

PM Measurement approach

The DINplus (DIN+) certification scheme and equipment used at Kiwa for solid fuel appliance testing comes from the DIN+ certification scheme for "Room Heaters for solid fuels with low-pollution combustion" according to DIN EN 13240 and CEN/TS 15883:2009. This scheme was set up to provide independent testing and a quality mark for solid fuel appliances which met the requirements of the scheme.

For this study, the DIN+ sampling equipment has been applied to the appliance outlet duct and dilution tunnel to measure total filterable particulate. Comparing the Particulate measurement data at these locations provides a measure of the condensable fraction. This method was chosen because it uses standardised equipment and methods which could be repurposed to meet the test programme requirements.

This method provides a particulate concentration by using an extractive sample system with a quartz filter and measurements of the gas flowrate. The quartz filter is first conditioned and weighed before sampling and gas is withdrawn via a heated sample line and passed through the filter, which is also heated. After exposure of the filter for a predetermined time and gas flowrate, the filter is then conditioned and reweighed. The increased mass of the filter is used as the total amount of particulate captured. For the appliance flue section, this provides the total filterable particulate (PM). When applied at the dilution tunnel this captured material is made up of both filterable and 'condensable' particulate matter including elemental carbon (EC) and organic carbon (OC) fractions.

Note that there is no universally agreed definition of the condensable particulate component - quantities of filterable and 'condensable' material are dependent on the sampling conditions (principally temperature but other factors are also relevant) and recent work by the air quality measurement and modelling communities has been to further disaggregate the intermediate and semi-volatile emission fractions, secondary aerosols, OC and also volatile inorganic materials.

The measurement strategy proposed for Particulate Matter (PM) is summarised in Table A12. The measurements are based on well-established periodic, gravimetric sampling approaches that were agreed by the project Steering Group.

Table A 12 Particulate matter sampling in EFDSF project

Location & Measurement	Method	Comment
Appliance outlet		
PM	Heated filter, 'DIN+' sampling equipment	Filterable PM, heated filter sampling equipment used in EN16510-1:2018 and CEN/TS 15883 for appliance testing.
Dilution tunnel		
PM	Heated filter, 'DIN+' sampling equipment	Filterable PM but on diluted flue gases provide total PM (filterable and condensable). The *condensable* PM determined by difference compared to appliance outlet PM.
Particle size ($PM_{10}/PM_{2.5}/PM_1$)	Impactor, Dekati sampling equipment	To provide size distribution of total PM emission.

During Work Package 1 the three measurement systems were sampled simultaneously and at similar flowrates, and at the dilution tunnel, samples were collected from the same sampling location. Consequently, emission data collected by the two heated filter systems were expected to produce comparable measurements to provide a reasonable basis for determination of the condensable fraction.

The simultaneous tests using the heated filter and particle size sampling systems at the dilution tunnel were expected to provide useful validation of the measurements at that location. Recognising that, particularly for low concentrations of PM, there are additional uncertainties associated with combining several weights in the particle size sampler.

Investigations have been carried out to the heated filter sampling method following a measurement audit at Kiwa's test facility. The manufacturer of the DIN+ sampling equipment had determined that the filter holder used in these systems do not require a filter clamp - to allow exposure of the whole filter to the gas flow. The vertical orientation of the holder and the pressure drop across the filter required in the DIN+ system holds the filter in place.

However, because the DIN+ method has been adapted for use in the EFDSF test programme, investigations have been carried out into the method to assess if there was bypass of the DIN+ filters. There was concern that there is a possibility of particulate material evading the surface of the filter by escaping around the sides of the filter in the filter housing.

Following some initial investigation and discussion with the Steering Group the filter holders were modified to include a filter clamp (o-ring), which was implemented during WP2. The test protocol was subsequently modified to include washing the o-ring, to ensure all sampled material was included in the gravimetric analysis.

However, the measurements of particle size (Dekati) and total particulate (heated filter) undertaken with measurement systems operated in parallel at the dilution tunnel show some variation in WP1.

Investigation and outcomes

Filter bypass investigations

Although the heated filter sampling system used by Kiwa is consistent with the EN 16510-1:2018 Standard for testing at the appliance outlet (and Kiwa is UKAS-accredited for heated filter PM measurement), the project team undertook some additional measurements to explore the significance of the issue.

Initially, measurements were undertaken using sampling systems with a second filter placed after the primary filter at the appliance outlet. Material was found on the second filter, but this is expected at this location as condensable material which evaded the primary filter could be collected at the second filter. This can be seen in the images in Figure A 25 showing the second (bypass) filters for the three test phases. Tests were also undertaken with a second filter at the dilution tunnel and indicated some material on the secondary filter however quantities collected were variable with a high weighing uncertainty (Table A 13) and the mechanism for bypass of the primary filter was unclear.

Figure A 25 : Pictures of DIN+ bypass filters at the appliance outlet.

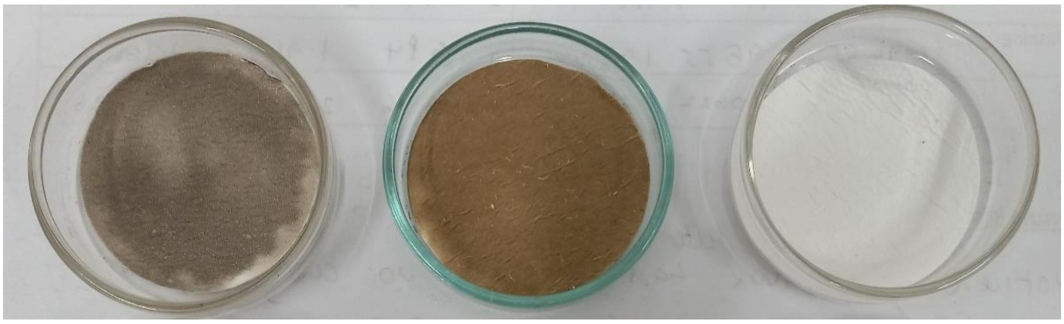


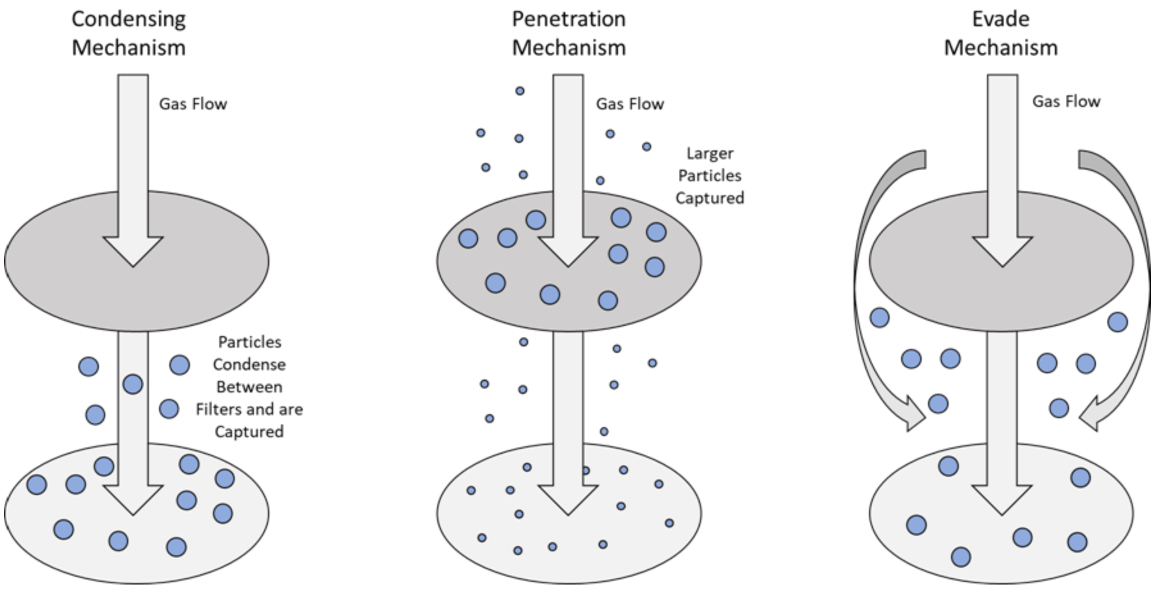
Table A 13 : Dilution tunnel primary and secondary filter weights

	Mass collected, g		
Test phase	Ignition	Refuel	Burnout
Primary filter	0.00740	0.00590	0.00030
Second filter	0.00040	0.00280	0.00013
Bypass (%)	5	32	31

The existence of material on the bypass filters does not in itself demonstrate a problem with the method and it is not unexpected. This is because there are three mechanisms for how particulates may be present on the bypass filter (Figure A 26).

1. Condensing Mechanism – Gas condenses between filters due to the reduction in Temperature / Vapour Pressure and is captured on the bypass filter.
2. Penetration Mechanism – Filters are not 100% efficient. Smaller particles below the filter pore size penetrate through the filter and are captured on the bypass filter.
3. Evasion Mechanism – Particles bypass the filter entirely by moving around the sides of the filter papers which results in material being picked up on the bypass filter.

Figure A 26 : Mechanisms for material to bypass filters



Of the three mechanisms shown in Figure A 26 the one of concern to the test programme is the evade mechanism. Due to the question posed by the filter clamping during the audit, the investigation has set out to quantify this mechanism.

The condensing mechanism and penetration mechanism are expected due to the nature of the work that we are undertaking. The presence of these two mechanisms does not suggest a failure in the DIN+ filter equipment but is a part of undertaking these types of measurements. The presence of evasion does also not demonstrate a failure of the DIN+ equipment as some material will get passed even clamped filters. However, significant levels of evasion will reduce the accuracy and increase the uncertainty of the measurements taken and should be avoided.

The three mechanisms cause different properties and characteristics in the material deposited on the bypass filter. This allows the material from each mechanism to be identified allowing us to quantify the proportion from each mechanism. Thermogravimetric Analysis (TGA) was used to quantify the OC/EC fractions on filters, and therefore attribute some of the mass to one mechanism or the other. To determine the penetration mechanism the material deposited is more likely to be small particulates as larger particulates are more likely to become trapped in the primary filter. If larger particles are present this would suggest that evasion is the more likely mechanism occurring and may provide a route to quantify this fraction. It is expected that the percentage of material due to penetration will be only a very small fraction as quartz filters have reported efficiencies of 99.9% for particles above 0.3µm. This can change with loading but is not expected to be significant.

Thermogravimetric Analysis by Leeds and Manchester universities on material collected on secondary filters at the appliance outlet with the high sulphur fuel on the Hunter Oakwood Stove during the WP2 test programme indicated that very limited quantities of elemental carbon were present. This suggests that, at the appliance outlet, little filterable material was passing the primary filter.

These issues were presented to the Steering Group in a technical briefing note (17 June 2022) and a meeting (7 July 2022).

Further tests at the appliance outlet with parallel sampling systems were conducted with and without a filter clamp (o-ring). These tests were conducted at the appliance outlet but due to limited sampling ports the samples could not be extracted from the same location (there was a vertical separation between the sample inlets of about 0.5m). The measurements indicated that the sampling location was a more significant factor than the use of a filter clamp.

A series of bespoke measurements were undertaken at the dilution tunnel using co-located parallel sampling systems with and without a filter clamp (o-ring), during combustion of wood in one of the test appliances. These tests showed overall sample masses collected (including the probe washings) were similar but with some uplift in filter retention when using a filter clamp (Table A14).

Table A 14 : Dilution tunnel PM measurements with parallel sampling systems

	Mass on filter, g			Total Mass (inc. washings), g		
Run	1	2	3	1	2	3
Standard Filter holder	0.0015	0.0014	0.0036	0.0060	0.0053	0.0106
Filter holder with clamp	0.0021	0.0019	0.0053	0.0061	0.0052	0.0100
Uplift (% of standard holder)	+35	+33	+45	+2	<-1	-6

Other aspects investigated

We considered several areas in the course of the investigations:

- Proximity of the PM sampling systems – sampling set-up at dilution tunnel is cluttered and there may be an influence but the sample is mainly PM_1 so PM should follow gas flow.
- Differences in start/end times – unlikely to be a significant issue over the extended sampling periods in WP1.
- Uncertainty in weights – measurements are on dilution tunnel, so quantities collected are small but well above weighing thresholds during ignition and refuel measurements.
- Calculation issues – checked and correct. In addition, sampling rate is similar and over same period, and the differences are also apparent in the filter weights before calculation.
- Differences in the physical characteristics of the PM – this would impact where PM is collected in the Dekati impactor but should not influence the overall weight collected. Ultrafines may be relevant but are unlikely to explain weight differences observed.
- Differences in the filter media – different filter media are employed but both types are commonly used for sampling PM in air and emission sources.
- Stratification in the dilution tunnel - there are other sampling probes upstream of the dilution tunnel sampling position – this could be contributing to the issue but sampling nozzles at inlet to sampling trains are adjacent.
- Differences in the volume sampled – checks were undertaken on the sampling rate which led to (small) revisions of volumes sampled during tests.

WP1 Measurements – comparison of PM data at appliance outlet and dilution tunnel

Aggregated emission factor data (aggregated over the different stages of the test cycle and expressed on a net heat input basis) show variation between the sum of the particle size fraction measurements (from the Dekati) and total particulate measurements (measured by the DIN+ method) at the dilution tunnel. In addition, heated filter measurements at the dilution tunnel are sometimes lower than at the appliance outlet (which would indicate a negative mass of condensables). Conversely, the sum of the particle size fractions measured by the Dekati is more often the same or higher than the mass collected by the heated filter at the appliance outlet (in line with expectations, the difference being the condensable fraction). See Tables A15 to A18, data highlighted red are measurements at dilution tunnel which are lower than PM determined at appliance the outlet.

Note that in the WP1 phase of testing (wood fuels), the heated filter samplers (DIN+ method) did not have a filter clamp in place.

Table A 15 : Comparison of WP1 Emission Factors – Modern stove

	PM emission factor, $g.GJ^{-1}$			
Test run	1	2	3	Average
Dry wood				
Appliance outlet, HF	67	65	54	62
Dilution tunnel, HF	70	74	91	78
Dilution tunnel, PM size	111	140	86	112
Seasoned wood				
Appliance outlet, HF	21	27	3	17
Dilution tunnel, HF	7	75	9	31
Dilution tunnel, PM size	21	34	23	26
Wet wood				
Appliance outlet, HF	84	125	117	109
Dilution tunnel, HF	141	127	154	141
Dilution tunnel, PM size	139	345	261	248

Table A 16 : Comparison of WP1 Emission Factors – Middle stove

	PM emission factor, $g.GJ^{-1}$			
Test run	1	2	3	Average
Dry wood				
Appliance outlet, HF	56	48	74	59
Dilution tunnel, HF	80	72	75	76
Dilution tunnel, PM size	86	90	120	99
Seasoned wood				
Appliance outlet, HF	60	75	155	97
Dilution tunnel, HF	163	144	201	169
Dilution tunnel, PM size	257	180	457	298
Wet wood				
Appliance outlet, HF	79	78	178	112
Dilution tunnel, HF	341	323	499	388
Dilution tunnel, PM size	806	788	965	853

Table A 17 : Comparison of WP1 Emission Factors – Old stove

	PM emission factor, g.GJ^{-1}			
Test run	1	2	3	Average
Dry wood				
Appliance outlet, HF	44	51	43	46
Dilution tunnel, HF	45	55	61	54
Dilution tunnel, PM size	93	75	70	79
Seasoned wood				
Appliance outlet, HF	27	42	19	29
Dilution tunnel, HF	42	100	35	59
Dilution tunnel, PM size	99	120	53	91
Wet wood				
Appliance outlet, HF	164	173	391	243
Dilution tunnel, HF	177	149	285	204
Dilution tunnel, PM size	485	343	366	398

Table A 18 : Comparison of WP1 Emission Factors – Open fire

	PM emission factor, g.GJ^{-1}			
Test run	1	2	3	Average
Dry wood				
Appliance outlet, HF	45	195	35	92
Dilution tunnel, HF	49	105	28	61
Dilution tunnel, PM size	49	61	46	52
Seasoned wood				
Appliance outlet, HF	45	42	10	33
Dilution tunnel, HF	39	97	38	58
Dilution tunnel, PM size	92	219	120	144
Wet wood				
Appliance outlet, HF	103	48	75	75
Dilution tunnel, HF	210	298	258	255
Dilution tunnel, PM size	499	693	618	603

WP1 Measurements – comparison of dilution tunnel PM data

Following receipt of the complete measurement data for the WP1 test programme it was evident that there were differences between the total particulate emission factors derived from the heated filter measurements and the particle size measurement system at the dilution tunnel (see tables above).

It is not best practise to derive total particulate data from gravimetric particle size measurements because measurements for particle size are undertaken at a constant sampling rate (compared to isokinetic sampling for total particulate) and data are derived from additional fractions compared to a total particulate measurement (this increases weighing uncertainties) and often are collected from different measurement periods. However, in this project, the measurements were undertaken simultaneously, the sample collection points were located in close proximity at the dilution tunnel and, both systems were sampling at a constant (and similar) flowrate.

In addition, most of the material collected is PM_1 so weighing uncertainty for the main collection stage should be similar to the heated filter measurement.

The ratio of measured PM concentrations (dry gas at 0°C, 101.3 kPa) using the particle size and heated filter sampling equipment during ignition and the (second) refuel phase are shown in Figure A 27 and Figure A 28 respectively.

Ideally, the ratio would be close to 1 (indicating that similar concentrations were measured using both measurement approaches). However, the ratio ranged from 0.2 to 4.5 with an average of about 1.8 (1.6 for ignition phase and 2.0 for refuel phase). The heated filter sampling equipment typically provided lower PM emission concentrations than the particle size sampling equipment. Measured PM concentrations during the shutdown/burnout phase have a slightly wider range but concentrations were generally lower (most were <10 $mg.m^{-3}$) and have higher uncertainty.

Figure A 27 Ratio of PM concentrations from different measurement systems during ignition

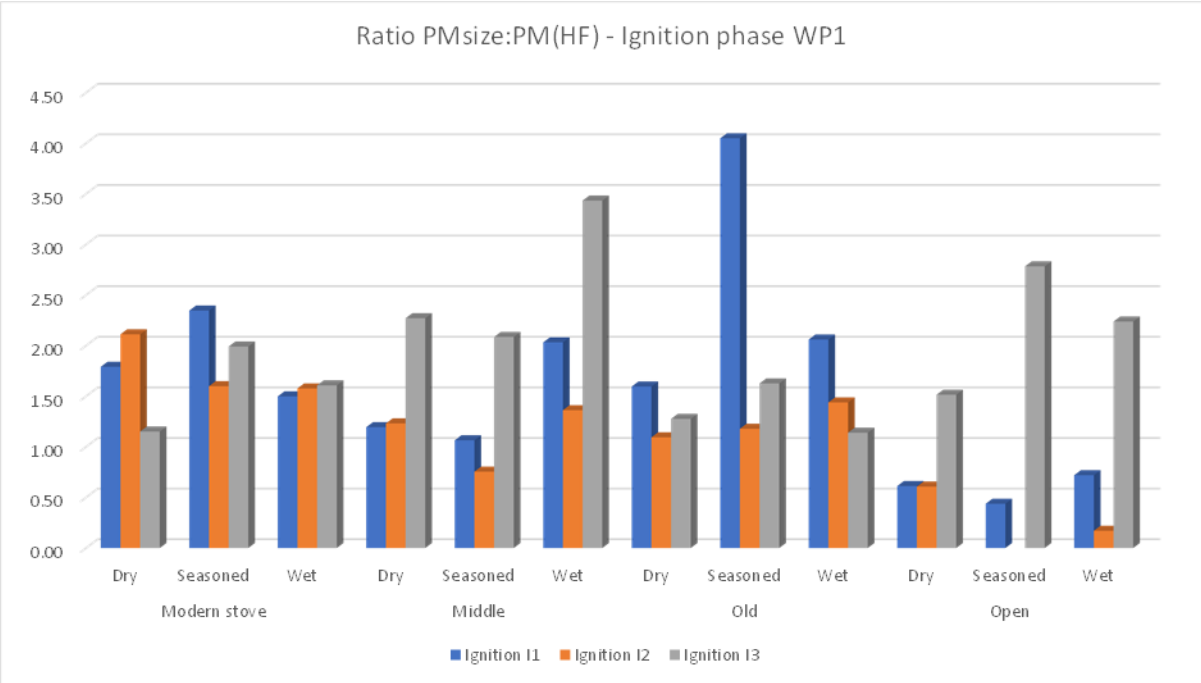
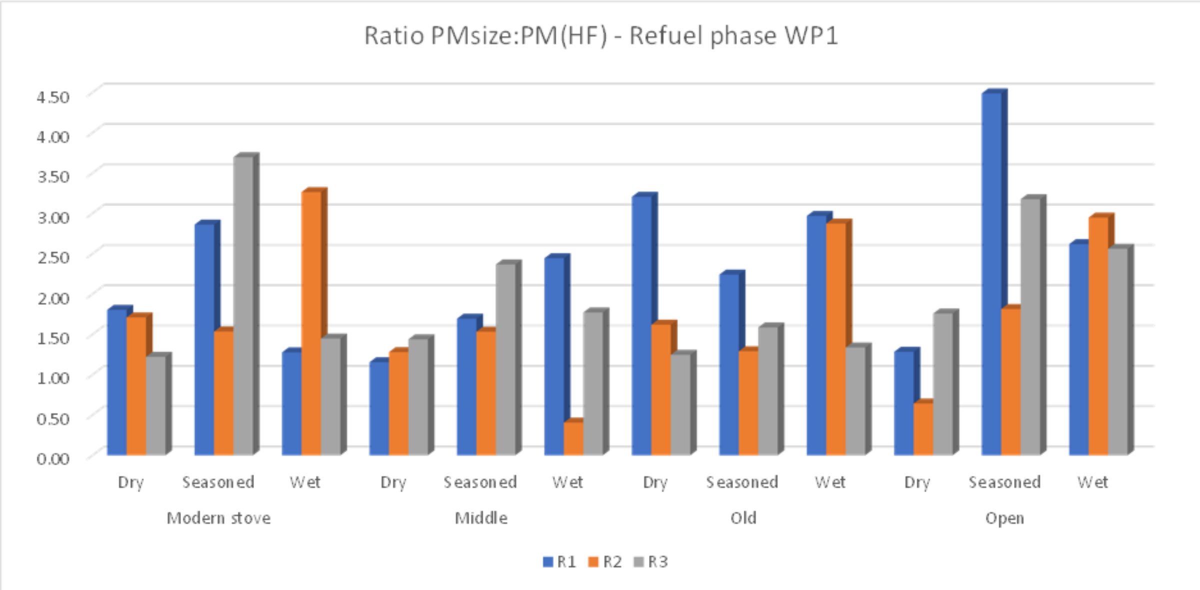


Figure A 28 Ratio of PM concentrations from different measurement systems during refuel phase



During WP1 the filter clamp was not in place on the heated filter sampling systems so may have contributed to relatively low concentrations determined by the heated filter measurements. Despite it not being best practice to derive total particulate data from gravimetric particle size measurements (the particle size sampling equipment), in this situation where we believe there could have been bypass of PM at the heated filter (heated filter sampling equipment), we recommend using the particle size data to ascertain the total PM (filterable plus condensables). This is a pragmatic and conservative approach.

WP2 measurements – comparison with an additional PM measurement system

To provide further evidence, a third set of particulate measurements were undertaken simultaneously with samples for particle size, total PM (HF -heated filter with filter clamp) and a second total PM sampling system (NHF) with an unheated filter typically deployed by ECL for sampling low temperature stacks and vents. This work was undertaken in **WP2** on the modern Charnwood C4 stove with anthracite fuel.

Note that the heated filter sampling system had a modified filter holder compared to that used in WP1 and anthracite is a low volatile matter fuel.

Test periods ranged from 20 minutes to over 2 hours. The concentrations determined using the NHF system were generally (but not always) higher than other systems. These data (see Table A19 and Figure A 29) indicate that the variation between the three sampling systems with broadly similar approaches (periodic, extractive gravimetric sampling system with ex-stack filtration) is significant. However, although the data do not provide a clear indication of the 'best' measurement system, they also do not indicate that any of the methods are under-reporting (the situation found in WP1).

Figure A 30 compares the ratio of the measurements (to the PM concentrations using the heated filter) during ignition and refuel phases. This illustrates that, unlike WP1 (see Figs A25 and A26), the ratios between the PM concentrations determined with the particle size sample (Dekati) and heated filter (DIN+) are lower and closer to 1 (average 0.75) than determined on wood fuels in WP1 (average about 1.8). This suggests that issues with heated filter data in WP1 are resolved or less significant in WP2.

Figure A 29 : Comparison of PM at dilution tunnel with three sampling systems (anthracite, modern stove)

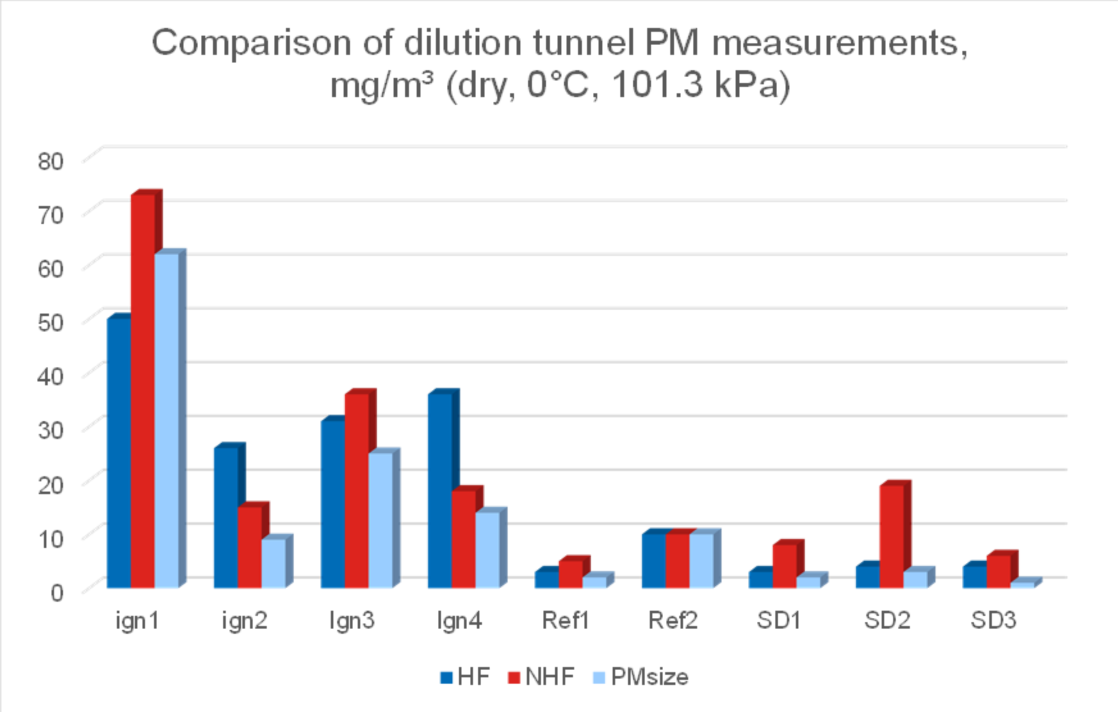


Figure A 30 : Comparison of ratio of PM concentrations at dilution tunnel to heated filter results (anthracite, modern stove)

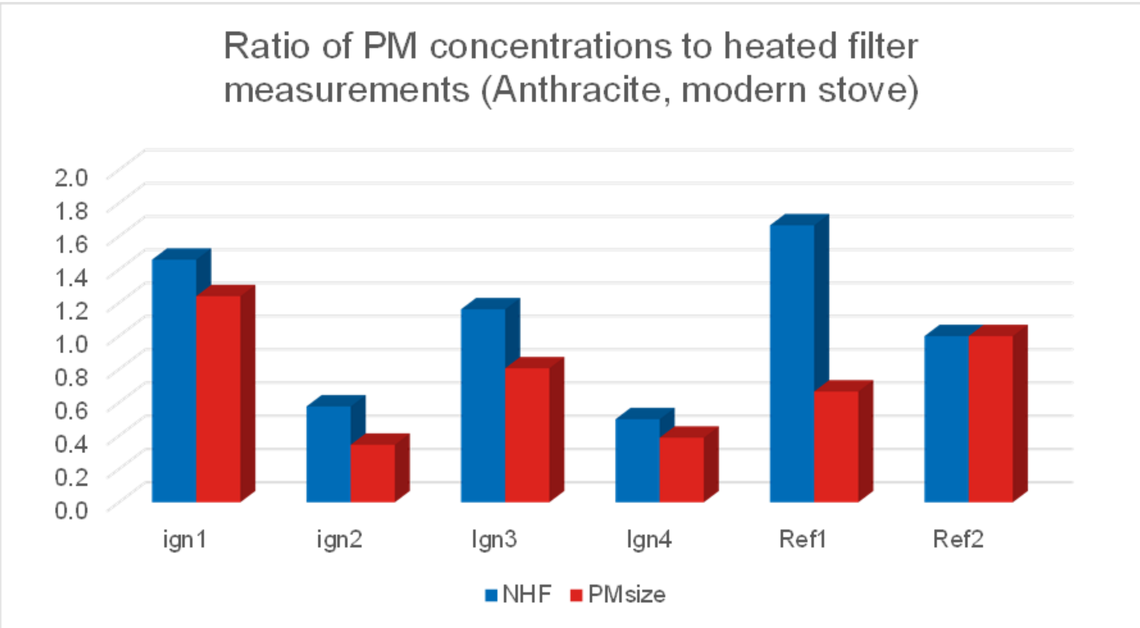


Table A 19 : Summary of comparison measurements using three particulate measurement systems

Test [note 1]	1	3	4	5	6	7	8	9[note 2]	10
Test phase	Ignition	Ignition	Refuel	Shutdown	Ignition	Shutdown	Ignition	Refuel	Shutdown
	Minutes								
Duration	20	48	113	65	50	60	60	155	60
	Concentrations, mg.m^{-3}, dry and STP, 0°C, 101.3kPa								
Total PM (HF)	50	26	3	3	31	4	36	10	4
Total PM (NHF)	73	15	5	8	36	19	18	10	6
Total PM (PM size)	62	9	2	2	25	3	14	10	1
Average	62	17	3	5	31	8	22	10	3
SD	12.0	8.8	1.2	3.2	5.4	9.0	11.7	0.4	2.3
	%								
RSD	19	53	35	68	17	108	52	4	68

Notes:

1. Test 2 was aborted as fire could not be maintained.
2. Test 9 NHF stopped at 120 minutes.

Current NAEI emission factors for wood-burning

The WP1 PM measurement data were compared with emission factors used currently by the NAEI to explore whether the WP1 emission factors would represent an improvement. The NAEI uses emission factors published in the EMEP/EEA Guidebook 2019 and these are compared with the WP1 emission factors in Table A20.

Table A 20 : Summary of NAEI Emission factors for PM fractions

Source	Pollutant	Moisture	Emission factors, $g.GJ^{-1}$ (net heat input)				
			Open	Conv. stove	High eff. stove	Adv/ecolbl stove	Ecodesign
Guidebook	TSP	Not specified	880	800	400	100	100
EFDSF		Dry	52	79	99	-	112
		Seasoned	144	91	298	-	26
		Wet	603	398	853	-	248
Guidebook	PM_{10}	Not specified	840	760	380	95	95
EFDSF		Dry	48	75	91	-	101
		Seasoned	130	75	271	-	23
		Wet	588	375	819	-	229
Guidebook	$PM_{2.5}$	Not specified	820	740	370	93	93
EFDSF		Dry	47	74	87	-	97
		Seasoned	129	73	270	-	22
		Wet	579	372	809	-	228

The Guidebook references are summarised below, measurements were carried out for a range of appliances, fuel types and measurement techniques. The measurements were generally for a single class of PM for example, $PM_{2.5}$ or PM_{10} and other PM fractions have been estimated for each appliance type in the Guidebook using other literature. The Guidebook PM emission factors are based on one appliance for the open fireplace and, at most, five appliances for the stove categories. One reference does not relate to wood log appliances, another did not include emissions at ignition. However, a Danish study sampled real-life operation on appliances in homes. Details of the stoves in the references are too limited to confirm alignment with Guidebook or other categorisation.

Table A 21 : EMEP/EEA Guidebook references for PM pollutants

Type of appliance	Reference information			
	Reference	**Appliances tested**	**Test cycle (No. of tests)**	**PM measurement**
Open fireplace	Alves et al	1	No cold start (3)	$PM_{2.5}$ at dilution tunnel
Conventional stove	Alves et al,	1	No cold start (3)	$PM_{2.5}$ at dilution tunnel
	Glasius et al	4	Real-life (2)	Total PM at dilution tunnel on houses
High efficiency stove	Glasius et al	2	Real-life (2)	Total PM at dilution tunnel on houses. Stoves from 2000-4.

Type of appliance	Reference information			
Advanced/Ecolabel stove	Johansson et al	2 pellet burners, 1 pellet stove	Nominal output Part and nominal output	Total filterable PM, particle number by dilution
	Goncalves et al	1 stove but no tertiary air	Not stated	PM_{10} measurement
	Schmidl et al	1 basic stove 1 stove but no tertiary air	Cold start plus EN13240 (1-6)	PM_{10} at partial flow dilution system. Briquettes and three wood log species

The EFDSF project test protocol has been designed to reflect use of appliances in the UK including evidence from the Defra Burning Survey on residential wood-burning practise in UK. The Guidebook references have applied a variety of test protocols and whilst there are similarities there are also significant differences which arise from the aims and scope of the individual studies. These are summarised in Table A21.

The Guidebook Tier 2 reference studies for PM appear to be for wood stoves, the EFDSF project included two multifuel stoves because older UK stoves are commonly multifuel devices (capable of burning wood and/or mineral fuels) with different grate and air management provision.

- Range of appliances - the EFDSF project has monitored emissions from only one appliance for each technology type, but some Guidebook Tier 2 emission factors are also assigned to a single reference with only a single relevant appliance.
- Appliance draught –The draught influences the air supply to the appliance and hence burn rate. In the EFDSF project a draught of 16 Pa based on UK measurements provided by the steering group which is higher than used in EN appliance testing. One study reports use of 12Pa draught but, in general, there is limited data in the Guidebook reference studies to confirm their applicability to UK.

Recommendations

1. To use PM data from the dilution tunnel particle size measurement data (Dekati) for WP1 – these emission factors are generally higher and represent a more conservative approach than the comparative measurements Where the particulate emission factors determined using the particle size equipment at the dilution tunnel are lower than at the appliance outlet (a situation for one set of tests at the open fire), the project team propose to apply the dilution tunnel data to the appliance outlet.
2. To review data from the parallel dilution tunnel PM measurements to assess whether the recommendations for WP1 data is also applicable to WP2, when these data are available.
3. Undertake a further set of comparison measurements at the dilution tunnel in WP3 on an appliance burning wood. Ideally applying a particle size measurement, modified heated filter PM test, an unmodified heated filter PM test and the alternative PM test method (i.e.: NHF).

A.9 POLLUTANT MEASUREMENTS DATASET

Table A 22 : Charnwood C-4 blu – Modern Stove test results – WET WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	2,853	2,879	3,555	3,095	2,000
CO_2 (weighted) g/GJ	Appliance outlet	69,282	72,642	70,157	70,694	-
NOx (weighted) g/GJ	Appliance outlet	79	48	61	63	95
HC (weighted) g/GJ	Dilution tunnel	806	636	754	732	250
PM g/GJ (filterable)	Appliance outlet	84	125	117	109	-
PM g/GJ (filterable + condensable)	Dilution tunnel	141	127	154	141	100
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	18	13	40	23	100
PAH's mg/GJ	Dilution tunnel	3,351	3,154	2,078	2,861	-
SO_2 g/GJ	Dilution tunnel	4.0	2.7	2.5	3.0	11
Total PM, g/GJ	Dilution tunnel	139	345	261	248	100
PM_{10}, g/GJ	Dilution tunnel	120	317	250	229	95
$PM_{2.5}$, g/GJ	Dilution tunnel	120	317	249	228	93
PM_1, g/GJ	Dilution tunnel	90	267	191	183	-
Condensable PM II g/GJ		55	220	143	139	-
BaP, mg/GJ	Dilution tunnel	9.4	30.1	12.9	17.5	10
Sum PAH (4), mg/GJ	Dilution tunnel	26	81	33	47	35
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	4.4	28

Table A 23 : Charnwood C-4 blu – Modern Stove test results – DRY WOOD

Pollutant + Method	Measurement location	Run 1	Run 2	Run 3	Average	NAEI
CO (weighted) g/GJ	Appliance outlet	2,586	2,686	2,657	2,643	2,000
CO_2 (weighted) g/GJ	Appliance outlet	82,801	79,569	81,831	81,400	-
NOx (weighted) g/GJ	Appliance outlet	33	38	23	31	95
HC (weighted) g/GJ	Dilution tunnel	419	403	485	436	250
PM g/GJ (filterable)	Appliance outlet	67	65	54	62	-
PM g/GJ (filterable + condensable)	Dilution tunnel	70	74	91	78	100
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	22	26	14	21	100
PAH's mg/GJ	Dilution tunnel	8,961	6,889	9,798	8,549	-
SO_2 g/GJ	Dilution tunnel	10	8	7	8	11
Total PM, g/GJ	Dilution tunnel	111	140	86	112	100
PM_{10}, g/GJ	Dilution tunnel	104	120	78	101	95
$PM_{2.5}$, g/GJ	Dilution tunnel	102	116	73	97	93
PM_1, g/GJ	Dilution tunnel	94	106	65	88	-
Condensable PM II g/GJ		45	75	33	51	-
BaP, mg/GJ	Dilution tunnel	99	61	107	89	10
Sum PAH (4), mg/GJ	Dilution tunnel	302	214	354	290	35
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	5.4	10

Table A 24 : Charnwood C-4 blu – Modern Stove test results – SEASONED WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	649	1,456	1,336	1,147	2,000
CO_2 (weighted) g/GJ	Appliance outlet	69,299	80,609	83,356	77,755	-
NOx (weighted) g/GJ	Appliance outlet	42	60	45	49	95
HC (weighted) g/GJ	Dilution tunnel	172	463	265	300	250
PM g/GJ (filterable)	Appliance outlet	21	27	3	17	-
PM g/GJ (filterable + condensable)	Dilution tunnel	7	75	9	31	100
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	33	4	38	25	100
PAH's mg/GJ	Dilution tunnel	786	1,330	2,538	1,551	-
SO_2 g/GJ	Dilution tunnel	2	4	4	3	11
Total PM, g/GJ	Dilution tunnel	21	34	23	26	100
PM_{10}, g/GJ	Dilution tunnel	17	33	21	23	95
$PM_{2.5}$, g/GJ	Dilution tunnel	16	30	21	22	93
PM_1, g/GJ	Dilution tunnel	12	28	20	20	-
Condensable PM II g/GJ		(0)*	7	21	9	-
BaP, mg/GJ	Dilution tunnel	4	9	26	13	10
Sum PAH (4), mg/GJ	Dilution tunnel	11	28	76	39	35
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	25.3	28

*Negative value – moderated to zero

Table A 25 : Dovre 500MRF Cast Iron Stove test results – WET WOOD

Pollutant + Method	Measurement location	Run 1	Run 2	Run 3	Average	NAEI
CO (weighted) g/GJ	Appliance outlet	3,116	3,132	3,567	3,272	4,000
CO_2 (weighted) g/GJ	Appliance outlet	57,516	60,738	64,047	60,767	-
NOx (weighted) g/GJ	Appliance outlet	58	50	57	55	80
HC (weighted) g/GJ	Dilution tunnel	1,195	1,332	1,494	1,340	350
PM g/GJ (filterable)	Appliance outlet	79	78	178	112	-
PM g/GJ (filterable + condensable)	Dilution tunnel	341	323	499	388	400
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	9	5	4	6	250
PAH's mg/GJ	Dilution tunnel	3,938	4,185	7,075	5,066	-
SO_2 g/GJ	Dilution tunnel	4	4	4	4	11
Total PM, g/GJ	Dilution tunnel	806	788	965	853	400
PM_{10}, g/GJ	Dilution tunnel	769	756	932	819	380
$PM_{2.5}$, g/GJ	Dilution tunnel	758	748	921	809	370
PM_1, g/GJ	Dilution tunnel	653	671	765	696	-
Condensable PM II g/GJ		727	710	786	741	-
BaP, mg/GJ	Dilution tunnel	32	28	88	49	121
Sum PAH (4), mg/GJ	Dilution tunnel	85	73	196	118	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	1.3	16

Table A 26 : Dovre 500MRF Cast Iron Stove test results – DRY WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	1,346	1,324	1,434	1,368	4,000
CO_2 (weighted) g/GJ	Appliance outlet	80,018	77,732	77,509	78,420	-
NOx (weighted) g/GJ	Appliance outlet	35	41	39	38	80
HC (weighted) g/GJ	Dilution tunnel	154	183	129	155	350
PM g/GJ (filterable)	Appliance outlet	56	48	74	59	-
PM g/GJ (filterable + condensable)	Dilution tunnel	80	72	75	76	400
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	269	72	186	176	250
PAH's mg/GJ	Dilution tunnel	4,822	4,132	3,441	4,132	-
SO_2 g/GJ	Dilution tunnel	8	6	8	8	11
Total PM, g/GJ	Dilution tunnel	86	90	120	99	400
PM_{10}, g/GJ	Dilution tunnel	84	81	107	91	380
$PM_{2.5}$, g/GJ	Dilution tunnel	82	78	100	87	370
PM_1, g/GJ	Dilution tunnel	73	68	89	77	-
Condensable PM II g/GJ		30	42	47	39	-
BaP, mg/GJ	Dilution tunnel	46	25	36	36	121
Sum PAH (4), mg/GJ	Dilution tunnel	165	88	116	123	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	39.1	16

Table A 27 : Dovre 500MRF Cast Iron Stove test results – SEASONED WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	2,334	2,514	2,298	2,382	4,000
CO_2 (weighted) g/GJ	Appliance outlet	76,734	76,873	72,431	75,346	-
NOx (weighted) g/GJ	Appliance outlet	52	69	74	65	80
HC (weighted) g/GJ	Dilution tunnel	665	978	1338	994	350
PM g/GJ (filterable)	Appliance outlet	60	75	155	97	-
PM g/GJ (filterable + condensable)	Dilution tunnel	163	144	201	169	400
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	27	4	41	24	250
PAH's mg/GJ	Dilution tunnel	3,019	3,280	5,321	3,874	-
SO_2 g/GJ	Dilution tunnel	7	4	6	6	11
Total PM, g/GJ	Dilution tunnel	257	180	457	298	400
PM_{10}, g/GJ	Dilution tunnel	241	146	427	271	380
$PM_{2.5}$, g/GJ	Dilution tunnel	240	144	426	270	370
PM_1, g/GJ	Dilution tunnel	235	142	419	265	-
Condensable PM II g/GJ		197	105	302	202	-
BaP, mg/GJ	Dilution tunnel	35	28	51	38	121
Sum PAH (4), mg/GJ	Dilution tunnel	89	78	132	99	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	1.9	16

Table A 28 : Hunter Oakwood Stove test results – WET WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	3,172	3,147	3,635	3,318	4,000
CO_2 (weighted) g/GJ	Appliance outlet	71,719	73,094	71,270	72,028	-
NOx (weighted) g/GJ	Appliance outlet	54	62	59	59	50
HC (weighted) g/GJ	Dilution tunnel	590	595	588	591	600
PM g/GJ (filterable)	Appliance outlet	164	173	391	243	-
PM g/GJ (filterable + condensable)	Dilution tunnel	177	149	285	204	800
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	7.6	5.1	10.2	7.6	800
PAH's mg/GJ	Dilution tunnel	1,467	1,556	2,485	1,836	-
SO_2 g/GJ	Dilution tunnel	2.9	2.6	3.3	2.9	11
Total PM, g/GJ	Dilution tunnel	485	343	366	398	800
PM_{10}, g/GJ	Dilution tunnel	462	324	338	375	760
$PM_{2.5}$, g/GJ	Dilution tunnel	462	322	333	372	740
PM_1, g/GJ	Dilution tunnel	428	283	294	335	-
Condensable PM II g/GJ		321	170	(0)*	164	-
BaP, mg/GJ	Dilution tunnel	7	14	22	14	121
Sum PAH (4), mg/GJ	Dilution tunnel	19	38	59	38	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	0.4	10

*Negative value – moderated to zero

Table A 29 : Hunter Oakwood Stove test results – DRY WOOD

Pollutant + Method	Measurement location	Run 1	Run 2	Run 3	Average	NAEI
CO (weighted) g/GJ	Appliance outlet	1,652	1,439	1,256	1,449	4,000
CO_2 (weighted) g/GJ	Appliance outlet	81,738	81,718	81,364	81,607	-
NOx (weighted) g/GJ	Appliance outlet	46	56	47	49	50
HC (weighted) g/GJ	Dilution tunnel	623	337	126	362	600
PM g/GJ (filterable)	Appliance outlet	44	51	43	46	-
PM g/GJ (filterable + condensable)	Dilution tunnel	45	55	61	54	800
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	69	45	51	55	800
PAH's mg/GJ	Dilution tunnel	3,080	2,608	1,120	2,269	-
SO_2 g/GJ	Dilution tunnel	5.3	4.1	4.5	4.6	11
Total PM, g/GJ	Dilution tunnel	93	75	70	79	800
PM_{10}, g/GJ	Dilution tunnel	86	72	67	75	760
$PM_{2.5}$, g/GJ	Dilution tunnel	83	72	66	74	740
PM_1, g/GJ	Dilution tunnel	74	65	63	67	-
Condensable PM II g/GJ		49	24	27	33	-
BaP, mg/GJ	Dilution tunnel	35	28	11	25	121
Sum PAH (4), mg/GJ	Dilution tunnel	110	92	38	80	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	40.8	10

Table A 30 : Hunter Oakwood Stove test results – SEASONED WOOD

Pollutant + Method	Measurement location	Run 1	Run 2	Run 3	Average	NAEI
CO (weighted) g/GJ	Appliance outlet	1,757	1,624	1,534	1,638	4,000
CO_2 (weighted) g/GJ	Appliance outlet	78,504	78,282	77,172	77,986	-
NOx (weighted) g/GJ	Appliance outlet	40	48	48	46	50
HC (weighted) g/GJ	Dilution tunnel	182	160	143	162	600
PM g/GJ (filterable)	Appliance outlet	27	42	19	29	-
PM g/GJ (filterable + condensable)	Dilution tunnel	42	100	35	59	800
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	8.5	27.2	105.3	47.0	800
PAH's mg/GJ	Dilution tunnel	1,247	741	808	932	-
SO_2 g/GJ	Dilution tunnel	5.0	3.7	4.5	4.4	11
Total PM, g/GJ	Dilution tunnel	99	120	53	91	800
PM_{10}, g/GJ	Dilution tunnel	84	100	41	75	760
$PM_{2.5}$, g/GJ	Dilution tunnel	83	95	40	73	740
PM_1, g/GJ	Dilution tunnel	80	88	38	69	-
Condensable PM II g/GJ	Dilution tunnel	72	78	34	61	-
BaP, mg/GJ	Dilution tunnel	9.4	5.0	5.9	6.8	121
Sum PAH (4), mg/GJ	Dilution tunnel	30	15	19	21	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	24.0	10

Table A 31 : Parkray Paragon 16-inch Fire Grate – Open Fire test results – WET WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	2,363	3,121	3,192	2,892	4,000
CO_2 (weighted) g/GJ	Appliance outlet	46,701	43,977	47,720	46,133	-
NOx (weighted) g/GJ	Appliance outlet	44	27	47	39	50
HC (weighted) g/GJ	Dilution tunnel	884	1,030	1,147	1,020	600
PM g/GJ (filterable)	Appliance outlet	103	48	75	75	-
PM g/GJ (filterable + condensable)	Dilution tunnel	210	298	258	255	880
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	4.1	11.6	8.0	7.9	800
PAH's mg/GJ	Dilution tunnel	2,827	4,042	5,703	4,191	-
SO_2 g/GJ	Dilution tunnel	1.9	2.3	2.8	2.3	11
Total PM, g/GJ	Dilution tunnel	499	693	618	603	880
PM_{10}, g/GJ	Dilution tunnel	479	685	599	588	840
$PM_{2.5}$, g/GJ	Dilution tunnel	472	674	590	579	820
PM_1, g/GJ	Dilution tunnel	360	539	528	475	-
Condensable PM II g/GJ	Dilution tunnel	396	645	544	528	-
BaP, mg/GJ	Dilution tunnel	22	45	78	48	121
Sum PAH (4), mg/GJ	Dilution tunnel	57	107	168	111	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	2.1	7

Table A 32 : Parkray Paragon 16-inch Fire Grate – Open Fire test results – DRY WOOD

Pollutant + Method	**Measurement location**	**Run 1**	**Run 2**	**Run 3**	**Average**	**NAEI**
CO (weighted) g/GJ	Appliance outlet	1,332	818	923	1,025	4,000
CO_2 (weighted) g/GJ	Appliance outlet	68,498	55,007	71,352	64,953	-
NOx (weighted) g/GJ	Appliance outlet	56	33	42	44	50
HC (weighted) g/GJ	Dilution tunnel	210	166	166	181	600
PM g/GJ (filterable)	Appliance outlet	45	195	35	92	-
PM g/GJ (filterable + condensable)	Dilution tunnel	49	105	28	61	880
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	7.5	5.0	4.3	5.6	800
PAH's mg/GJ	Dilution tunnel	542	590	648	593	-
SO_2 g/GJ	Dilution tunnel	6.3	4.9	4.8	5.3	11
Total PM, g/GJ	Dilution tunnel	49	61	46	52	880
PM_{10}, g/GJ	Dilution tunnel	44	60	41	48	840
$PM_{2.5}$, g/GJ	Dilution tunnel	43	58	40	47	820
PM_1, g/GJ	Dilution tunnel	40	53	34	42	-
Condensable PM II g/GJ	Dilution tunnel	4.4	(0)*	11	5	-
BaP, mg/GJ	Dilution tunnel	4.5	3.8	4.6	4.3	121
Sum PAH (4), mg/GJ	Dilution tunnel	13	11	13	12	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	91.6	7

*Negative value – moderated to zero

Table A 33 : Parkray Paragon 16-inch Fire Grate – Open Fire test results – SEASONED WOOD

Pollutant + Method	Measurement location	Run 1	Run 2	Run 3	Average	NAEI
CO (weighted) g/GJ	Appliance outlet	1,125	2,002	2,006	1,711	4,000
CO_2 (weighted) g/GJ	Appliance outlet	44,752	54,901	75,527	58,393	-
NOx (weighted) g/GJ	Appliance outlet	28	42	64	45	50
HC (weighted) g/GJ	Dilution tunnel	297	521	416	412	600
PM g/GJ (filterable)	Appliance outlet	45	42	10	33	-
PM g/GJ (filterable + condensable)	Dilution tunnel	39	97	38	58	880
Dioxins & Furans nqTEQ/GJ	Dilution tunnel	0.7	10	2.6	4.4	800
PAH's mg/GJ	Dilution tunnel	159	1,566	1,331	1,019	-
SO_2 g/GJ	Dilution tunnel	0.6	3.9	5.7	3.4	11
Total PM, g/GJ	Dilution tunnel	92	219	120	144	880
PM_{10}, g/GJ	Dilution tunnel	85	201	106	130	840
$PM_{2.5}$, g/GJ	Dilution tunnel	84	200	104	129	820
PM_1, g/GJ	Dilution tunnel	81	175	85	113	-
Condensable PM II g/GJ	Dilution tunnel	47	177	110	111	-
BaP, mg/GJ	Dilution tunnel	4.5	3.8	4.6	4.3	121
Sum PAH (4), mg/GJ	Dilution tunnel	2.9	31	31	22	345
Black carbon (% of $PM_{2.5}$)	Dilution tunnel	-	-	-	10.5	7

PCDD and PCDF data

Table A 34 : Charnwood C-4 blu – Modern Stove PCDD and PCDF results – SEASONED WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	1.52	0.0646	0.495	0.692
1,2,3,7,8 - PeCDD	0.287	0.0215	0.0413	0.117
1,2,3,4,7,8 - HxCDD	0.0139	0.00215	0.0578	0.0246
1,2,3,6,7,8 - HxCDD	0.0157	0.0129	0.116	0.048
1,2,3,7,8,9 - HxCDD	0.0122	0.00646	0.0578	0.0255
1,2,3,4,6,7,8 - HpCDD	0.00976	0.000431	0.051	0.0204
OCDD	0.00239	0.0017	0.006	0.00336
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.843	0.174	0.598	0.539
1,2,3,7,8 - PeCDF	0.0976	0.00215	0.0464	0.0487
2,3,4,7,8 - PeCDF	1.02	0.0215	1.03	0.691
1,2,3,4,7,8 - HxCDF	0.0296	0.00215	0.163	0.0649
1,2,3,6,7,8 - HxCDF	0.0505	0.00215	0.165	0.0726

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
2,3,4,6,7,8 - HxCDF	0.0418	0.00215	0.146	0.0635
1,2,3,7,8,9 - HxCDF	0.00348	0.00215	0.00619	0.00394
1,2,3,4,6,7,8 - HpCDF	0.00732	0.00495	0.0615	0.0246
1,2,3,4,7,8,9 - HpCDF	0.000871	0.000431	0.00516	0.00215
OCDF	0.00047	0.000409	0.00159	0.000823
TOTAL PCDD and PCDF	3.95	0.322	3.05	2.44

Table A 35 : Dovre 500MRF Cast Iron Stove PCDD and PCDF results – SEASONED WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.439	0.0711	0.48	0.33
1,2,3,7,8 - PeCDD	0.0462	0.0356	0.132	0.0712
1,2,3,4,7,8 - HxCDD	0.00693	0.00474	0.0168	0.00949
1,2,3,6,7,8 - HxCDD	0.00925	0.00474	0.0216	0.0119
1,2,3,7,8,9 - HxCDD	0.00925	0.00474	0.0264	0.0135
1,2,3,4,6,7,8 - HpCDD	0.018	0.0119	0.017	0.0156
OCDD	0.00548	0.00358	0.00245	0.00383
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.428	0.0806	0.48	0.329
1,2,3,7,8 - PeCDF	0.0693	0.0142	0.0647	0.0494
2,3,4,7,8 - PeCDF	1.06	0.0356	0.839	0.646
1,2,3,4,7,8 - HxCDF	0.0485	0.00474	0.0623	0.0385
1,2,3,6,7,8 - HxCDF	0.0508	0.00474	0.0623	0.0393
2,3,4,6,7,8 - HxCDF	0.0532	0.00474	0.0527	0.0369
1,2,3,7,8,9 - HxCDF	0.00693	0.00474	0.00719	0.00629
1,2,3,4,6,7,8 - HpCDF	0.0129	0.00925	0.017	0.0131
1,2,3,4,7,8,9 - HpCDF	0.00139	0.000474	0.00168	0.00118
OCDF	0.00074	0.000711	0.000671	0.000707
TOTAL PCDD and PCDF	2.27	0.296	2.28	1.62

Table A 36 : Parkray Paragon 16-inch Fire Grate – Open Fire PCDD and PCDF results – SEASONED WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.115	0.753	0.0528	0.307
1,2,3,7,8 - PeCDD	0.0461	0.0502	0.0528	0.0497
1,2,3,4,7,8 - HxCDD	0.00691	0.00502	0.00528	0.00573
1,2,3,6,7,8 - HxCDD	0.0299	0.00502	0.00528	0.0134
1,2,3,7,8,9 - HxCDD	0.0253	0.00502	0.00528	0.0119

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
1,2,3,4,6,7,8 - HpCDD	0.0122	0.011	0.0137	0.0123
OCDD	0.00431	0.00366	0.00272	0.00356
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.161	0.316	0.0897	0.189
1,2,3,7,8 - PeCDF	0.0253	0.0226	0.00264	0.0168
2,3,4,7,8 - PeCDF	0.265	0.0251	0.0264	0.105
1,2,3,4,7,8 - HxCDF	0.00461	0.00502	0.00528	0.00497
1,2,3,6,7,8 - HxCDF	0.00461	0.00502	0.00528	0.00497
2,3,4,6,7,8 - HxCDF	0.00461	0.00502	0.00528	0.00497
1,2,3,7,8,9 - HxCDF	0.00461	0.00753	0.00528	0.0058
1,2,3,4,6,7,8 - HpCDF	0.00461	0.00602	0.00369	0.00477
1,2,3,4,7,8,9 - HpCDF	0.000461	0.000502	0.000264	0.000409
OCDF	0.000138	0.000125	0.000158	0.000141
TOTAL PCDD and PCDF	0.715	1.23	0.282	0.741

Table A 37 : Parkray Paragon 16-inch Fire Grate – Open Fire PCDD and PCDF results – DRY WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.108	0.134	0.101	0.114
1,2,3,7,8 - PeCDD	0.0539	0.0836	0.0845	0.074
1,2,3,4,7,8 - HxCDD	0.0108	0.0167	0.0135	0.0137
1,2,3,6,7,8 - HxCDD	0.0108	0.0167	0.0135	0.0137
1,2,3,7,8,9 - HxCDD	0.0108	0.0134	0.0135	0.0126
1,2,3,4,6,7,8 - HpCDD	0.00826	0.0124	0.00778	0.00947
OCDD	0.00172	0.00445	0.00453	0.00357
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.442	0.515	0.592	0.516
1,2,3,7,8 - PeCDF	0.0269	0.00502	0.00507	0.0123
2,3,4,7,8 - PeCDF	0.431	0.0502	0.0507	0.177
1,2,3,4,7,8 - HxCDF	0.0108	0.01	0.0101	0.0103
1,2,3,6,7,8 - HxCDF	0.0108	0.0134	0.0101	0.0114
2,3,4,6,7,8 - HxCDF	0.0108	0.0569	0.0101	0.0259
1,2,3,7,8,9 - HxCDF	0.0108	0.0134	0.0101	0.0114
1,2,3,4,6,7,8 - HpCDF	0.0169	0.0174	0.0115	0.0153
1,2,3,4,7,8,9 - HpCDF	0.00108	0.001	0.000676	0.000919
OCDF	0.00162	0.000234	0.000203	0.000685
TOTAL PCDD and PCDF	1.17	0.964	0.939	1.02

Table A 38 : Charnwood C-4 blu – Modern Stove PCDD and PCDF results – DRY WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.598	0.309	0.147	0.351
1,2,3,7,8 - PeCDD	0.185	0.126	0.0587	0.123
1,2,3,4,7,8 - HxCDD	0.0142	0.00562	0.0117	0.0105
1,2,3,6,7,8 - HxCDD	0.0142	0.00843	0.0147	0.0124
1,2,3,7,8,9 - HxCDD	0.0142	0.00843	0.0147	0.0124
1,2,3,4,6,7,8 - HpCDD	0.0259	0.0138	0.017	0.0189
OCDD	0.00669	0.00388	0.00496	0.00518
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.0578	0.677	0.349	0.361
1,2,3,7,8 - PeCDF	0.0996	0.0506	0.0543	0.0682
2,3,4,7,8 - PeCDF	0.697	0.885	0.646	0.743
1,2,3,4,7,8 - HxCDF	0.0114	0.0506	0.00881	0.0236
1,2,3,6,7,8 - HxCDF	0.00854	0.0393	0.00881	0.0189
2,3,4,6,7,8 - HxCDF	0.00854	0.0534	0.00881	0.0236
1,2,3,7,8,9 - HxCDF	0.00854	0.00562	0.00881	0.00766
1,2,3,4,6,7,8 - HpCDF	0.0168	0.0124	0.0094	0.0128
1,2,3,4,7,8,9 - HpCDF	0.000854	0.000562	0.000881	0.000766
OCDF	0.00108	0.000702	0.000235	0.000673
TOTAL PCDD and PCDF	1.77	2.25	1.36	1.79

Table A 39 : Dovre 500MRF Cast Iron Stove PCDD and PCDF results – DRY WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	9.74	2.57	6.62	6.31
1,2,3,7,8 - PeCDD	1.81	0.599	1.34	1.25
1,2,3,4,7,8 - HxCDD	0.14	0.0234	0.0406	0.0678
1,2,3,6,7,8 - HxCDD	0.184	0.0321	0.0812	0.0991
1,2,3,7,8,9 - HxCDD	0.133	0.00584	0.0469	0.062
1,2,3,4,6,7,8 - HpCDD	0.0549	0.0178	0.0234	0.032
OCDD	0.00844	0.0026	0.00453	0.00519
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	7.26	0.211	4.78	4.08
1,2,3,7,8 - PeCDF	1.07	0.273	0.62	0.653
2,3,4,7,8 - PeCDF	13	3.07	7.58	7.88
1,2,3,4,7,8 - HxCDF	0.672	0.161	0.306	0.38
1,2,3,6,7,8 - HxCDF	0.485	0.166	0.284	0.312
2,3,4,6,7,8 - HxCDF	0.552	0.123	0.212	0.296
1,2,3,7,8,9 - HxCDF	0.0825	0.0117	0.0219	0.0387
1,2,3,4,6,7,8 - HpCDF	0.0679	0.0155	0.0287	0.0374

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
1,2,3,4,7,8,9 - HpCDF	0.00127	0.000584	0.000625	0.000826
OCDF	0.00111	0.000642	0.000156	0.000636
TOTAL PCDD and PCDF	35.3	7.28	22	21.5

Table A 40 : Hunter Oakwood Stove PCDD and PCDF results – SEASONED WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.116	0.139	1.84	0.699
1,2,3,7,8 - PeCDD	0.139	0.139	0.647	0.308
1,2,3,4,7,8 - HxCDD	0.00697	0.0279	0.0199	0.0183
1,2,3,6,7,8 - HxCDD	0.00697	0.0395	0.0895	0.0453
1,2,3,7,8,9 - HxCDD	0.00697	0.0349	0.0448	0.0289
1,2,3,4,6,7,8 - HpCDD	0.00836	0.0284	0.0343	0.0237
OCDD	0.00304	0.00504	0.00597	0.00468
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.427	0.683	2.37	1.16
1,2,3,7,8 - PeCDF	0.0488	0.0814	0.291	0.14
2,3,4,7,8 - PeCDF	0.0697	1.08	5.33	2.16
1,2,3,4,7,8 - HxCDF	0.0139	0.0116	0.269	0.098
1,2,3,6,7,8 - HxCDF	0.00697	0.0116	0.343	0.121
2,3,4,6,7,8 - HxCDF	0.00697	0.0093	0.331	0.116
1,2,3,7,8,9 - HxCDF	0.00697	0.0093	0.0448	0.0203
1,2,3,4,6,7,8 - HpCDF	0.00557	0.0179	0.0691	0.0309
1,2,3,4,7,8,9 - HpCDF	0.000464	0.000697	0.00671	0.00263
OCDF	0.000604	0.00137	0.00291	0.00163
TOTAL PCDD and PCDF	0.875	2.32	11.7	4.98

Table A 41 : Hunter Oakwood Stove PCDD and PCDF results – DRY WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	1.92	1.28	1.8	1.67
1,2,3,7,8 - PeCDD	0.512	0.28	0.208	0.333
1,2,3,4,7,8 - HxCDD	0.0198	0.0197	0.0485	0.0294
1,2,3,6,7,8 - HxCDD	0.0661	0.109	0.267	0.147
1,2,3,7,8,9 - HxCDD	0.0264	0.0296	0.139	0.0649
1,2,3,4,6,7,8 - HpCDD	0.0407	0.0592	0.167	0.0888
OCDD	0.0118	0.00905	0.0256	0.0155
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	3.1	1.92	2.39	2.47

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
1,2,3,7,8 - PeCDF	0.289	0.199	0.197	0.229
2,3,4,7,8 - PeCDF	3.03	2.24	2.63	2.63
1,2,3,4,7,8 - HxCDF	0.139	0.0987	0.17	0.136
1,2,3,6,7,8 - HxCDF	0.109	0.122	0.118	0.116
2,3,4,6,7,8 - HxCDF	0.0992	0.0889	0.132	0.107
1,2,3,7,8,9 - HxCDF	0.00992	0.0165	0.0173	0.0146
1,2,3,4,6,7,8 - HpCDF	0.0192	0.0184	0.0291	0.0222
1,2,3,4,7,8,9 - HpCDF	0.00264	0.0023	0.00416	0.00303
OCDF	0.00126	0.00145	0.00218	0.00163
TOTAL PCDD and PCDF	9.39	6.49	8.34	8.07

Table A 42 : Hunter Oakwood Stove PCDD and PCDF results – WET WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.103	0.0657	0.0828	0.0837
1,2,3,7,8 - PeCDD	0.0513	0.0438	0.0414	0.0455
1,2,3,4,7,8 - HxCDD	0.00821	0.00876	0.00828	0.00841
1,2,3,6,7,8 - HxCDD	0.00821	0.00876	0.00828	0.00841
1,2,3,7,8,9 - HxCDD	0.00616	0.00657	0.00621	0.00631
1,2,3,4,6,7,8 - HpCDD	0.000616	0.000657	0.0101	0.0038
OCDD	0.00238	0.00221	0.00203	0.00221
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.425	0.274	0.399	0.366
1,2,3,7,8 - PeCDF	0.00616	0.00438	0.00414	0.00489
2,3,4,7,8 - PeCDF	0.0513	0.0328	0.259	0.114
1,2,3,4,7,8 - HxCDF	0.00616	0.00438	0.00414	0.00489
1,2,3,6,7,8 - HxCDF	0.00616	0.00438	0.00414	0.00489
2,3,4,6,7,8 - HxCDF	0.00616	0.00438	0.00414	0.00489
1,2,3,7,8,9 - HxCDF	0.00616	0.00438	0.00414	0.00489
1,2,3,4,6,7,8 - HpCDF	0.00472	0.00416	0.00414	0.00434
1,2,3,4,7,8,9 - HpCDF	0.00041	0.000438	0.000207	0.000352
OCDF	0.00041	0.00046	0.000331	0.0004
TOTAL PCDD and PCDF	0.692	0.47	0.843	0.668

Table A 43 : Charnwood C-4 blu – Modern Stove PCDD and PCDF results – WET WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.0553	0.0414	0.357	0.151
1,2,3,7,8 - PeCDD	0.0369	0.124	0.287	0.149
1,2,3,4,7,8 - HxCDD	0.00922	0.0124	0.0337	0.0184

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
1,2,3,6,7,8 - HxCDD	0.00922	0.0248	0.0912	0.0417
1,2,3,7,8,9 - HxCDD	0.0645	0.0103	0.0396	0.0382
1,2,3,4,6,7,8 - HpCDD	0.00922	0.00868	0.0186	0.0122
OCDD	0.00367	0.00387	0.00315	0.00356
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.238	0.267	0.789	0.431
1,2,3,7,8 - PeCDF	0.0323	0.0289	0.0952	0.0521
2,3,4,7,8 - PeCDF	0.489	0.331	1.06	0.627
1,2,3,4,7,8 - HxCDF	0.00738	0.0517	0.0971	0.0521
1,2,3,6,7,8 - HxCDF	0.059	0.0269	0.0952	0.0603
2,3,4,6,7,8 - HxCDF	0.00738	0.0372	0.0872	0.0439
1,2,3,7,8,9 - HxCDF	0.0516	0.0269	0.00793	0.0288
1,2,3,4,6,7,8 - HpCDF	0.00498	0.00434	0.0149	0.00806
1,2,3,4,7,8,9 - HpCDF	0.00682	0.00165	0.00178	0.00342
OCDF	0.00227	0.00091	0.000813	0.00133
TOTAL PCDD and PCDF	1.09	1	3.08	1.72

Table A 44 : Dovre 500MRF Cast Iron Stove PCDD and PCDF results – WET WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.0711	0.0347	0.0554	0.0538
1,2,3,7,8 - PeCDD	0.0534	0.0347	0.0462	0.0447
1,2,3,4,7,8 - HxCDD	0.00534	0.0052	0.00924	0.00659
1,2,3,6,7,8 - HxCDD	0.00534	0.0052	0.00739	0.00598
1,2,3,7,8,9 - HxCDD	0.00534	0.0052	0.00739	0.00598
1,2,3,4,6,7,8 - HpCDD	0.00462	0.00815	0.0048	0.00586
OCDD	0.00219	0.00186	0.0019	0.00198
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.0836	0.00867	0.0129	0.0351
1,2,3,7,8 - PeCDF	0.00445	0.0026	0.0037	0.00358
2,3,4,7,8 - PeCDF	0.249	0.0954	0.037	0.127
1,2,3,4,7,8 - HxCDF	0.00534	0.00347	0.00554	0.00478
1,2,3,6,7,8 - HxCDF	0.00534	0.0243	0.00554	0.0117
2,3,4,6,7,8 - HxCDF	0.00534	0.0225	0.00554	0.0111
1,2,3,7,8,9 - HxCDF	0.00534	0.00347	0.00554	0.00478
1,2,3,4,6,7,8 - HpCDF	0.0048	0.00416	0.00499	0.00465
1,2,3,4,7,8,9 - HpCDF	0.000356	0.000173	0.00037	0.0003
OCDF	0.000107	0.000364	0.000111	0.000194
TOTAL PCDD and PCDF	0.511	0.26	0.214	0.328

Table A 45 : Parkray Paragon 16-inch Fire Grate – Open Fire PCDD and PCDF results – WET WOOD

	Run 1 (TEQng/m3)	Run 2 (TEQng/m3)	Run 3 (TEQng/m3)	Average (TEQng/m3)
Dioxins - 2,3,7,8 Isomers				
2,3,7,8 - TCDD	0.0355	0.0777	0.0455	0.0529
1,2,3,7,8 - PeCDD	0.0532	0.0544	0.0531	0.0536
1,2,3,4,7,8 - HxCDD	0.00887	0.00777	0.00759	0.00808
1,2,3,6,7,8 - HxCDD	0.00532	0.00777	0.00911	0.0074
1,2,3,7,8,9 - HxCDD	0.0106	0.00777	0.00759	0.00867
1,2,3,4,6,7,8 - HpCDD	0.00639	0.0056	0.0159	0.00931
OCDD	0.00263	0.00207	0.00261	0.00244
Furans - 2,3,7,8 Isomers				
2,3,7,8 - TCDF	0.0248	0.0218	0.0486	0.0317
1,2,3,7,8 - PeCDF	0.00177	0.00466	0.00304	0.00316
2,3,4,7,8 - PeCDF	0.169	0.583	0.281	0.344
1,2,3,4,7,8 - HxCDF	0.0284	0.0109	0.00759	0.0156
1,2,3,6,7,8 - HxCDF	0.00355	0.0109	0.00759	0.00734
2,3,4,6,7,8 - HxCDF	0.0213	0.0187	0.0182	0.0194
1,2,3,7,8,9 - HxCDF	0.016	0.014	0.0137	0.0145
1,2,3,4,6,7,8 - HpCDF	0.00461	0.00809	0.0135	0.00874
1,2,3,4,7,8,9 - HpCDF	0.000355	0.000466	0.000607	0.000476
OCDF	0.000958	0.000264	0.000258	0.000494
TOTAL PCDD and PCDF	0.393	0.836	0.535	0.588

PAH Data

Table A 46 : Charnwood C-4 blu – Modern Stove PAH results – SEASONED WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.115	0.143	0.501	0.253
Benzo(a)Anthracene	0.584	0.771	2.190	1.180
Benzo(a)pyrene	0.479	0.713	2.050	1.080
Benzo(b)fluoranthene	0.348	0.558	1.490	0.799
Benzo(b)naptho(2,1-d)thiophene	0.002	0.002	0.003	0.002
Benzo(c)phenanthrene	0.216	0.295	0.780	0.430
Benzo(ghi)Perylene	0.366	0.549	1.610	0.841
Benzo(k)fluoranthene	0.225	0.336	0.924	0.495
Cholanthrene	0.002	0.003	0.014	0.006
Chrysene	0.531	0.737	1.940	1.070
Cyclopenta(cd)pyrene	0.517	0.909	3.670	1.700
Dibenzo (ai) pyrene	1.180	2.670	5.200	3.020
Dibenzo(ah)Anthracene	0.032	0.052	0.151	0.078
Fluoranthene	3.340	4.890	11.700	6.640
Indeno(123-cd)Pyrene	0.350	0.597	1.490	0.812

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Naphthalene	88.3	90.7	165.0	115.0
Total (Excluding Non-Detects)	96.6	104.0	199.0	133.0
Total (Including Non-Detects)	96.6	104.0	199.0	133.0

Table A 47 : Dovre 500MRF Cast Iron Stove PAH results – SEASONED WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.527	0.607	0.480	0.538
Benzo(a)Anthracene	3.140	2.540	3.570	3.080
Benzo(a)pyrene	2.980	2.370	2.830	2.730
Benzo(b)fluoranthene	1.850	1.500	1.820	1.730
Benzo(b)naptho(2,1-d)thiophene	0.009	0.007	0.006	0.007
Benzo(c)phenanthrene	1.040	0.730	0.966	0.914
Benzo(ghi)Perylene	1.350	1.500	1.290	1.380
Benzo(k)fluoranthene	1.320	0.996	1.350	1.220
Cholanthrene	0.017	0.012	0.021	0.017
Chrysene	2.820	2.180	2.730	2.580
Cyclopenta(cd)pyrene	4.040	2.870	3.570	3.500
Dibenzo (ai) pyrene	0.002	0.002	0.002	0.002
Dibenzo(ah)Anthracene	0.153	0.153	0.137	0.148
Fluoranthene	16.800	11.400	15.800	14.600
Indeno(123-cd)Pyrene	1.540	1.700	1.350	1.530
Naphthalene	223.0	249.0	261.0	245.0
Total (Excluding Non-Detects)	261.0	277.0	297.0	279.0
Total (Including Non-Detects)	261.0	277.0	297.0	279.0

Table A 48 : Parkray Paragon 16-inch Fire Grate – Open Fire PAH results – SEASONED WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.249	0.339	0.272	0.286
Benzo(a)Anthracene	1.360	1.640	1.430	1.480
Benzo(a)pyrene	1.120	1.380	1.210	1.240
Benzo(b)fluoranthene	0.707	0.936	0.799	0.814
Benzo(b)naptho(2,1-d)thiophene	0.007	0.009	0.044	0.020
Benzo(c)phenanthrene	0.454	0.529	0.446	0.476
Benzo(ghi)Perylene	0.677	0.793	0.694	0.721
Benzo(k)fluoranthene	0.458	0.612	0.504	0.525
Cholanthrene	0.010	0.011	0.006	0.009
Chrysene	1.210	1.420	1.220	1.280
Cyclopenta(cd)pyrene	1.860	1.940	1.780	1.860
Dibenzo (ai) pyrene	0.002	0.003	0.003	0.002
Dibenzo(ah)Anthracene	0.815	0.110	0.091	0.339

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Fluoranthene	6.840	7.350	6.830	7.010
Indeno(123-cd)Pyrene	0.693	0.888	0.768	0.783
Naphthalene	149.0	173.0	125.0	149.0
Total (Excluding Non-Detects)	166.0	191.0	141.0	166.0
Total (Including Non-Detects)	166.0	191.0	141.0	166.0

Table A 49 : Parkray Paragon 16-inch Fire Grate – Open Fire PAH results – DRY WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.135	0.145	0.189	0.156
Benzo(a)Anthracene	0.841	0.816	1.220	0.959
Benzo(a)pyrene	0.722	0.743	1.020	0.829
Benzo(b)fluoranthene	0.539	0.549	0.757	0.615
Benzo(b)naptho(2,1-d)thiophene	0.015	0.011	0.014	0.013
Benzo(c)phenanthrene	0.278	0.279	0.419	0.325
Benzo(ghi)Perylene	0.474	0.545	0.703	0.574
Benzo(k)fluoranthene	0.319	0.338	0.477	0.378
Cholanthrene	0.004	0.003	0.005	0.004
Chrysene	0.794	0.759	1.120	0.890
Cyclopenta(cd)pyrene	0.877	0.994	1.530	1.130
Dibenzo (ai) pyrene	2.390	2.810	3.690	2.960
Dibenzo(ah)Anthracene	0.047	0.051	0.063	0.054
Fluoranthene	4.530	4.280	6.290	5.030
Indeno(123-cd)Pyrene	0.442	0.465	0.676	0.528
Naphthalene	74.4	101.0	124.0	100.0
Total (Excluding Non-Detects)	86.8	114.0	143.0	114.0
Total (Including Non-Detects)	86.8	114.0	143.0	115.0

Table A 50 : Charnwood C-4 blu – Modern Stove PAH results – DRY WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	1.210	1.160	2.210	1.530
Benzo(a)Anthracene	7.570	4.180	10.600	7.440
Benzo(a)pyrene	8.110	5.080	10.900	8.040
Benzo(b)fluoranthene	5.950	4.300	8.630	6.290
Benzo(b)naptho(2,1-d)thiophene	0.013	0.009	0.015	0.012
Benzo(c)phenanthrene	2.280	1.240	3.110	2.210
Benzo(ghi)Perylene	7.630	6.660	10.900	8.390
Benzo(k)fluoranthene	3.700	2.520	5.640	3.950
Cholanthrene	0.006	0.005	0.004	0.005
Chrysene	7.510	4.270	10.400	7.390
Cyclopenta(cd)pyrene	10.100	5.700	15.300	10.400
Dibenzo (ai) pyrene	2.640	2.240	4.230	3.040

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Dibenzo(ah)Anthracene	0.586	0.399	0.925	0.637
Fluoranthene	50.400	32.900	65.200	49.500
Indeno(123-cd)Pyrene	6.970	5.900	10.800	7.880
Naphthalene	619.0	496.0	837.0	651.0
Total (Excluding Non-Detects)	734.0	573.0	996.0	768.0
Total (Including Non-Detects)	734.0	573.0	996.0	768.0

Table A 51 : Dovre 500MRF Cast Iron Stove PAH results – DRY WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.571	0.476	0.478	0.508
Benzo(a)Anthracene	7.040	2.410	4.690	4.710
Benzo(a)pyrene	5.990	2.560	4.280	4.280
Benzo(b)fluoranthene	5.960	2.040	3.650	3.880
Benzo(b)naptho(2,1-d)thiophene	0.017	0.007	0.014	0.013
Benzo(c)phenanthrene	2.280	0.791	1.460	1.510
Benzo(ghi)Perylene	5.990	3.300	3.870	4.390
Benzo(k)fluoranthene	3.520	1.250	2.190	2.320
Cholanthrene	0.010	0.006	0.007	0.008
Chrysene	7.480	2.230	4.560	4.760
Cyclopenta(cd)pyrene	5.580	1.800	3.120	3.500
Dibenzo (ai) pyrene	31.500	19.700	19.500	23.600
Dibenzo(ah)Anthracene	0.622	0.277	0.340	0.413
Fluoranthene	41.2	15.7	27.6	28.2
Indeno(123-cd)Pyrene	6.030	3.070	3.530	4.210
Naphthalene	504.0	365.0	327.0	398.0
Total (Excluding Non-Detects)	627.0	420.0	406.0	485.0
Total (Including Non-Detects)	627.0	420.0	406.0	485.0

Table A 52 : Hunter Oakwood Stove PAH results – SEASONED WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.107	0.054	0.069	0.077
Benzo(a)Anthracene	1.340	0.625	0.865	0.942
Benzo(a)pyrene	0.968	0.421	0.676	0.688
Benzo(b)fluoranthene	0.801	0.367	0.634	0.601
Benzo(b)naptho(2,1-d)thiophene	0.005	0.002	0.005	0.004
Benzo(c)phenanthrene	0.455	0.208	0.343	0.335
Benzo(ghi)Perylene	0.806	0.328	0.505	0.546
Benzo(k)fluoranthene	0.485	0.203	0.361	0.350
Cholanthrene	0.002	0.003	0.004	0.003
Chrysene	1.300	0.672	1.060	1.010
Cyclopenta(cd)pyrene	0.808	0.400	0.589	0.599
Dibenzo (ai) pyrene	3.830	1.330	2.690	2.620

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Dibenzo(ah)Anthracene	0.072	0.034	0.056	0.054
Fluoranthene	7.800	3.160	5.370	5.440
Indeno(123-cd)Pyrene	0.792	0.281	0.487	0.520
Naphthalene	108.0	54.6	78.3	80.5
Total (Excluding Non-Detects)	128.0	62.7	92.0	94.3
Total (Including Non-Detects)	128.0	62.7	92.0	94.3

Table A 53 : Hunter Oakwood Stove PAH results – DRY WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.532	0.471	0.208	0.404
Benzo(a)Anthracene	5.920	4.410	1.690	4.010
Benzo(a)pyrene	4.600	4.050	1.760	3.470
Benzo(b)fluoranthene	3.640	3.420	1.810	2.960
Benzo(b)naptho(2,1-d)thiophene	0.008	0.006	0.003	0.006
Benzo(c)phenanthrene	1.830	1.480	0.596	1.300
Benzo(ghi)Perylene	3.870	3.780	1.760	3.140
Benzo(k)fluoranthene	2.370	2.090	0.935	1.800
Cholanthrene	0.003	0.008	0.003	0.005
Chrysene	5.880	4.710	1.970	4.190
Cyclopenta(cd)pyrene	3.930	2.520	0.350	2.270
Dibenzo (ai) pyrene	0.102	0.084	0.038	0.075
Dibenzo(ah)Anthracene	0.364	0.318	0.123	0.268
Fluoranthene	33.000	28.000	12.200	24.400
Indeno(123-cd)Pyrene	3.770	3.690	1.710	3.060
Naphthalene	333.0	318.0	156.0	269.0
Total (Excluding Non-Detects)	402.0	377.0	181.0	320.0
Total (Including Non-Detects)	402.0	377.0	181.0	320.0

Table A 54 : Hunter Oakwood Stove PAH results – WET WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.153	0.315	0.288	0.252
Benzo(a)Anthracene	0.837	1.450	2.400	1.560
Benzo(a)pyrene	0.629	1.300	1.850	1.260
Benzo(b)fluoranthene	0.436	0.821	1.270	0.843
Benzo(b)naptho(2,1-d)thiophene	0.003	0.003	0.004	0.003
Benzo(c)phenanthrene	0.280	0.468	0.739	0.496
Benzo(ghi)Perylene	0.386	0.764	0.861	0.671
Benzo(k)fluoranthene	0.269	0.545	0.760	0.525
Cholanthrene	0.006	0.009	0.007	0.007
Chrysene	0.767	1.380	2.110	1.420
Cyclopenta(cd)pyrene	0.866	2.060	2.070	1.670
Dibenzo (ai) pyrene	0.017	0.030	0.032	0.026

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Dibenzo(ah)Anthracene	0.052	0.083	0.106	0.080
Fluoranthene	4.540	7.620	12.200	8.130
Indeno(123-cd)Pyrene	0.399	0.817	0.969	0.728
Naphthalene	123.0	127.0	179.0	143.0
Total (Excluding Non-Detects)	133.0	144.0	205.0	161.0
Total (Including Non-Detects)	133.0	144.0	205.0	161.0

Table A 55 : Charnwood C-4 blu – Modern Stove PAH results – WET WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.136	0.494	0.191	0.274
Benzo(a)Anthracene	0.762	3.160	1.200	1.710
Benzo(a)pyrene	0.585	2.380	0.999	1.320
Benzo(b)fluoranthene	0.411	1.660	0.698	0.924
Benzo(b)naptho(2,1-d)thiophene	0.002	0.005	0.002	0.003
Benzo(c)phenanthrene	0.243	0.901	0.375	0.507
Benzo(ghi)Perylene	0.387	1.270	0.521	0.726
Benzo(k)fluoranthene	0.258	1.030	0.395	0.560
Cholanthrene	0.004	0.015	0.005	0.008
Chrysene	0.743	2.560	1.110	1.470
Cyclopenta(cd)pyrene	0.830	3.510	1.290	1.880
Dibenzo (ai) pyrene	0.022	0.065	0.027	0.038
Dibenzo(ah)Anthracene	0.049	0.155	0.067	0.090
Fluoranthene	4.390	14.400	6.240	8.350
Indeno(123-cd)Pyrene	0.378	1.320	0.486	0.728
Naphthalene	199.0	216.0	147.0	188.0
Total (Excluding Non-Detects)	209.0	249.0	161.0	206.0
Total (Including Non-Detects)	209.0	249.0	161.0	206.0

Table A 56 : Dovre 500MRF Cast Iron Stove PAH results – WET WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.409	0.409	0.882	0.567
Benzo(a)Anthracene	1.810	1.400	4.120	2.440
Benzo(a)pyrene	1.740	1.360	4.900	2.670
Benzo(b)fluoranthene	1.030	0.775	2.220	1.340
Benzo(b)naptho(2,1-d)thiophene	0.006	0.006	0.009	0.007
Benzo(c)phenanthrene	0.564	0.449	1.280	0.764
Benzo(ghi)Perylene	0.941	0.779	2.000	1.240
Benzo(k)fluoranthene	0.681	0.487	1.590	0.918
Cholanthrene	0.007	0.010	0.023	0.013
Chrysene	1.450	1.230	3.340	2.010
Cyclopenta(cd)pyrene	1.870	1.680	5.820	3.120
Dibenzo (ai) pyrene	0.061	0.059	0.094	0.071

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Dibenzo(ah)Anthracene	0.133	0.169	0.266	0.189
Fluoranthene	9.480	7.390	23.300	13.400
Indeno(123-cd)Pyrene	1.120	0.858	2.250	1.410
Naphthalene	190.0	183.0	343.0	239.0
Total (Excluding Non-Detects)	212.0	200.0	395.0	269.0
Total (Including Non-Detects)	212.0	200.0	395.0	269.0

Table A 57 : Parkray Paragon 16-inch Fire Grate – Open Fire PAH results – WET WOOD

	Run 1 (µg/m3)	Run 2 (µg/m3)	Run 3 (µg/m3)	Average (µg/m3)
Anthanthrene	0.550	0.913	1.040	0.834
Benzo(a)Anthracene	2.010	2.660	3.790	2.820
Benzo(a)pyrene	2.080	3.230	5.280	3.530
Benzo(b)fluoranthene	1.220	1.470	1.940	1.540
Benzo(b)naptho(2,1-d)thiophene	0.004	0.006	0.009	0.006
Benzo(c)phenanthrene	0.488	0.756	1.150	0.799
Benzo(ghi)Perylene	1.110	1.530	1.820	1.490
Benzo(k)fluoranthene	0.928	1.070	1.820	1.270
Cholanthrene	0.020	0.020	0.029	0.023
Chrysene	1.590	2.100	3.540	2.410
Cyclopenta(cd)pyrene	2.720	4.140	7.600	4.820
Dibenzo (ai) pyrene	0.060	0.115	0.109	0.095
Dibenzo(ah)Anthracene	0.142	0.219	0.253	0.205
Fluoranthene	7.220	9.830	14.800	10.600
Indeno(123-cd)Pyrene	1.220	2.010	2.280	1.840
Naphthalene	250.0	263.0	339.0	284.0
Total (Excluding Non-Detects)	271.0	293.0	385.0	316.0
Total (Including Non-Detects)	271.0	293.0	385.0	316.0

A.10 COMPARISON OF EFDSF PROJECT TEST PARAMETERS AND SELECTED LITERATURE

Table A 58 Comparison of EFDSF test protocol with selected literature

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
EFDSF project	***No***	*Open fire*		*Wood*	*Y*	*3*	*Y*	*3*	*Approx. 5, 15, 25*	*~240 min*	*1.2 kg per batch*	*All appliances given same approx. fuel load*
		Stove (1997)		*Wood*								*Open fire and older stoves are multifuel devices*
		Stove (2008, EN 13240)		*Wood*								
		Stove (Ecodesign 2020)		*Wood*								
Goncalves, (2012)	**Yes**	Pre Ecodesign	12 (est)	Wood	Y	2 or 3	Y	3 or 4	<15	45-90 min	2 kg per batch	Looked at range of wood species also cold/hot start (although no data reported on latter).
		Open fireplace		Wood								
Hedman (2006)	**Yes**	Slow heat release stove	9	Wood	Y	3	N	No (parallel tests)	16-18	200 -275 min	3.5kg ign then 2.7-3 kg per batch	Also tested two other boilers and looked at wood and straw pellets and (for old boiler) mixed waste. Two tests – normal air and reduced. Samples collected in parallel
		Old (~1975) wood boiler	12	Multifuel	Y	2	Y	No (parallel tests)	16-18	180 min	1kg ignition, 10kg per batch	Wood only test, repeated under smouldering condition. Also tested with mixed waste (up to 10%). Boiler looks to be combined wood/coke/oil device with separate liquid/solid fuel chambers – unlikely to be used in UK but

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
												may be akin to old multifuel ranges with boiler ?.
Alves et al (2011)	**Yes**	Open fireplace		Wood, Briquettes made of waste	N	3	Y	3	8.4-15.5	45-90 min	2kg per batch (3 batches)	Same appliances as Goncalves, range of biomass briquettes
		Conventional woodstove		Wood, Briquettes made of waste	N	3	Y	3	8.4-15.5	45-90 min		
Lamberg et al (2011)	Yes	Six appliances typical for Finland										Includes stoves, masonry heater, sauna stove and pellet boiler. Top-down ignition on stoves. No conventional stoves. .Birch wood logs used.
		Pellet boiler	25	Pellets				4		120-180 min		Continuous operation
		Modern masonry stove	?	Wood	Y	2?	Y?	3	10-13	120 min	4kg per batch	Number of refuels not clear. Samples may be collected in specific phases only.
		Conventional masonry stove	?	Wood	Y	2?	Y?	3	10-13	55 min	1.4 -2.5 kg per batch	Number of refuels not clear. Samples may be collected in specific phases only.
		Conventional masonry stove	?	Wood	Y	2?	Y?	3	10-13	140 min	3-4 kg per batch	Number of refuels not clear. Samples may be collected in specific phases only.
		Conventional masonry stove	?	Wood	Y	2?	Y?	3	10-13	65 min	2.8-3 kg per batch	Number of refuels not clear. Samples may be collected in specific phases only.
		Sauna stove	?	Wood	Y	2?	Y?	3	10-13	55 min	1.5-3 kg per batch	Number of refuels not clear. Samples may be collected in specific phases only.
Tissari et al (2007)	**Yes**	Seven different wood		Birch and Spruce	Y	Y	Y	N	10.1-17.5	Not stated?		Not clear but total fuel load split between 2 to

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
		combustion appliances typically used in Finland,										6 batches. Samples collected from dwelling chimneys. Masonry stoves are assembled in situ (not factory products). Repeat measurements undertaken on a lab-based stove (10 tests)
		2004 SHR stove									16.5 kg	Slow heat release
		2003 oven									12.3 kg	Oven
		1999 sauna stove									7.1 kg	Sauna
		1990 masonry stove									8.9 kg	Masonry
		1998 masonry stove									7.8 kg	Masonry
		1997 Stove									28 kg	
		1992 masonry stove									8 kg	Masonry
Pettersson (2011)	**Yes**	Wood stove ‘commonly installed stove in Sweden’	9	Birch, spruce, pine	N	1	Y	2 or N	8-23	180 min	3 kg	Wood stove operated with and without lining, different moisture levels and high/low draught and large/small logs. Another paper covers a pellet stove. Replicate tests on two conditions only, remaining tests were singles.
Hedberg et al (2002)	**Yes**	A ~2000 commercial soapstone stove (Woodstock Fireview, USA, weight 220kg)	15 (est)	Birch wood	Y	3	Y	Up to 7	Approx. 15	90mins?	6-7 kg	Some shorter tests, no sampling at very start, last refuel approx. 45 minutes. Not clear if repeat tests or additional

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
												samples in same test period. Size from current model.
Johansson et al. (2003)	**Yes**	Two domestic pellet burners	11kW and 22kW (max thermal output)	Wood pellets	Y?	Y?	Y?	?	7.6			Pellet stove and burners with additional larger district heating boiler. Burners tested using heat load providing cyclic operation. Stove operated continuously. Tests for PM and Pno
		Pellet stove	6kW (max thermal output)	Wood pellets				?	7.1			Pellet appliances
Johansson et al. (2004)	**Yes**	Old type and modern wood boilers, pellet burners and boilers, oil burners		Dry wood, Briquettes, wood pellets, bark pellets and oil	Y?	Y?	Y?	?	Wood pellets (7.6), Bark pellets (7.8), Wood briquettes (7.5), wood logs (15/26/38)	3 hours?		Pellet and wood log boilers
Paulrud (2006)	**Yes**	In situ survey of 20 stoves/insert stoves in Sweden	various	Wood	Y	1-3	Y	N	10-18, one at 24	1-2 hours		Measurements at 20 Swedish households, mix of stoves and inserts. Integrated sample for PAH and gases over burn duration (bag sample). Stoves 1975-2005
Glasius (2005)	**Yes**	In situ survey of 6 stoves in Denmark	various	Wood	Y	Y	Y	2	?	Not stated	Not stated	Measurements at 6 stoves, ignition and other details taken from 2008 paper (see below). Integrated samples for PAH, PM and PCDD/F during normal operation. Report indicates clean wood except at one stove. Suggest a link with steel chimneys for PCDD/F. Two

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
												stoves <3yrs old, three >5 years and one older.
Kaivosoja (2012)	No	Sauna stove	18	Wood	Y	2	?	2 or 3 Parallel tests	<7	72-75 min	3.2 kg per batch	Tested with and without flue gas catalyst. Birch wood, very short ignition and batch periods
Kirchsteiger (2021)	No	Stove 1, pre-Ecodesign	8	Wood	Y	2	?	No	6.5-15	Not stated	0.6-4.3 kg per batch	Two sets of tests – as used and optimised for each appliance. Different air control settings each batch. Optimised batches 1.2-2.5 kg.
		Stove 2, pre-Ecodesign	8	Wood	Y	2						
		Stove 3, pre EN13240	8	Wood	Y	2						
		Stove 4, pre-Ecodesign	7.3	Wood	Y	2						
AIRUSE (2016)	No	Pre Ecodesign		Wood	?	3	?	3	8.4-15.5	45-90 min	2 kg per batch	Various species of wood. Looks to be same appliance as Goncalves report
		Open fireplace	9.8-18.2	Wood	?	3	?	3	8.4-15.6	45-90 min		Looks to be same appliance as Goncalves report
		Pre-Ecodesign ?	6	Wood	?	3	?	3	7-14.8	45-90 min		Table 4 for EC/OC data
		Pellet stove	9.5	Wood	?	3	?	3	-	-		
Zhang (2016)	No			Wood								Review, Canada/N America PCDD/F Data for non-waste wood only from two studies both N America; Gullet 2003, Canada 2000
Glasius (2008)	No	Woodstoves, pre-Ecodesign		Wood, waste wood	Y	Y	Y	2	?	Not stated	Total 5-20kg	Denmark – sampling from houses, 12

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
												stoves, one (old) boiler
Kindbom et al (Nordic Council), 2017	No	Simple stove		Wood	N	3	N	2	10-14 (dry) 16-20 (std) 25-30 (wet)	Not stated	Not stated	Tests on various boilers and room heaters, looked at 'standard', dry and moist fuels. High/low burn rates and some assessment of ignition. Also compared EN text cycle and NS.
		Modern stove			Y	3	N	2				
		State of art			N	3	N	N				Downdraught stove but pre- Ecodesign
		Cast iron traditional			N	3	N	N				
		SHR stove			N	3	N	N				Slow heat release
		SHR stove			N	3	N	N				Slow heat release
		Pellet stove			N	3	N	N				
		Sauna stove			N	3	N	N				Sauna
Price-Allison et al (2019)	No	Waterford Stanley Oisin multi-fuel domestic stove	5.7	Beech and spruce	Y	1	?	Each fuel was tested in duplicate	3.6-42.9	45-90 mins	1.2-1.8kg per batch	UK study
Mitchell et al (2020)	No	A Waterford Stanley Oisin Multi-fuel stove (Defra exempt appliance)	5.72	Wheat straw, barley straw, bagasse, miscanthus, commercially made 'Heatlogs' briquettes, commercially made 'Hotmax' briquettes, wood logs (spruce) and	Y	3	Y	?	5.5-9.1 briq. 10, 18% wood logs	Up to 250 mins	0.65-0.85kg per batch	UK study

Paper/study	GB 2019	Appliance type	Size, kW	Fuel	Cold Ignition	Refuels	Burnout	Repeat tests	Fuel Moisture, %	Test duration	Fuel load	Comments
				wood logs (willow)								
Trubetskaya et al (2021)	No	A conventional, multifuel stove	A nominal heat output of 11 kW	Wood logs, TOS briquettes, peat, ecobrite briquettes, smoky coal and firelighter	Y	N	Y	At least twice	15.7 (logs)	2 to 4 hr	For each combustion experiment, ≈3.5 kg of solid fuel and 100 g of solid firelighter Ireland) were placed in the stove.	Ireland study, appears to be a single fuel batch.
		Ecodesign, Waterford Stanley **prototype** multifuel stove	with a nominal output of 9 kW	TOS briquettes, ecobrite briquettes, smoky coal	Y	N	Y	At least twice	15.7 (logs)	2 to 4 hr	As above	Prototype unit
Ozgen et al (2021)	No	Not applicable - Review										Review of literature for NOx emissions from small-scale biomass.

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