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THE DEVELOPMENT AND TESTING OF A METHODOLOGY FOR USING FLUE GAS ANALYSER MEASUREMENTS TO ASSESS DOMESTIC GAS APPLIANCE COMBUSTION PERFORMANCE

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PREPARED FOR:
Transco, HSE, British Gas Services and CoGDEM

PREPARED BY:

Sonya Marks & Martin Brown

Advantica Ltd
Ashby Road
Loughborough Leicestershire
LE11 3GR
United Kingdom
Tel: +44 (0)1509 282000
Fax: +44 (0)1509 283131
E-mail: info.uk@advantica.biz
Website: www.advantica.biz

Executive Summary

A detailed study of the emissions from a number of domestic gas-fired appliances has been undertaken. This project supported by Transco, British Gas Services, CoGDEM and the HSE, aimed to develop an understanding of combustion performance ratio measurements and the potential for using these to assist in fault diagnosis by service engineers and emergency response engineers. An assessment is made on the suitability of using portable flue gas analysers (FGAs) to measure emissions and relate the values obtained in a diagnostic manner.

The project extends a previous study to include a wider range of appliances including fires, boilers and air heaters.

The project comprises two main parts or phases. Initially nine appliances have been tested under controlled laboratory conditions to determine emissions levels and time-dependent emission behaviour as a function of appliance operation. This included inducing faults onto the appliance and noting the change to the emissions when a fault was present. Data were recorded using Siemens gas analysers (non-dispersive IR cells for measurement of CO and CO_2, together with an electrochemical sensor measurement for O_2). A supplementary activity included the use of a number of sampling probe designs and assessment of the data obtained. Analysis of the results from this first phase yielded a protocol or procedure for the second phase.

In the second phase, Emergency Response (ER) Engineers from Transco undertook a number of tests on each of the nine domestic appliances. Here, portable FGA equipment was used by the ER engineers, alongside the Siemens IR analysers. The measured emissions from both types of analyser were compared.

The results from Phase 1 show that emissions behaviour of the appliances is dependent on the type of fault present and that time-dependence of the emission profile provides significant additional information. Typically there is high CO emission on ignition of an appliance that subsides to a steady operating level. Most appliances achieve a steady operation in less than ten minutes. However, it is apparent that although appliances may have a fault present, the combustion performance ratio was not always excessive. The results from Phase 2 show that the portable FGA operated effectively and the readings correlated well with those from the IR analysers and with the phase 1 results.

In conclusion:

- The project successfully demonstrated emissions to be a function of the appliance type, the nature of the fault on the appliance and the effect of sampling probe type and location
- There are certain situations when even though the appliance was operating under fault conditions, the combustion performance ratio was within acceptable limits.
- If the combustion performance ratio was high, this was invariably a reliable indicator of unsatisfactory operation.

- Portable FGA can track the time-dependence of the emissions and function as a diagnostic tool.

It is recommended to extend the studies to appliances in the field rather than the laboratory.

Contents

1 INTRODUCTION

The potential for making a measurement of the CO/CO_2 ratio, the so-called combustion performance ratio, on a gas-fired appliance/installation and using this figure, or a characteristic of this figure with time, has been suggested to be the basis not only upon which the servicing of an appliance can be evaluated but also its safe operation.

British Gas Services have employed combustion performance ratio criteria for a number of years to assist in appliance servicing procedures. This approach was based upon a considerable amount of research co-ordinated by the then British Gas R&D. It involved a detailed evaluation of large amounts of field data to support performance criteria that define whether an appliance will continue to operate safely throughout the next servicing interval.

The possibility of using the combustion performance ratio to determine whether an appliance/installation is safe to leave has also been suggested and is to some extent being explored as the BS 7967 “draft-for-review” is under discussion [1]. This draft standard is defining the way in which portable flue gas analysers, and ambient air monitors, can be used to assess domestic gas-fired installations. However, it is recognised that flue gas analysis and combustion performance ratio is not the only indicator of a faulty installation and constitutes but one “tool” in the engineers portfolio to assist in appliance diagnosis.

There is some concern, however, that the procedure for identifying the source of excessive combustion product contamination within a property may prove to be time consuming primarily because some appliances can require significant periods during which combustion needs to stabilise before providing meaningful combustion performance data. Data from cold starts might give misleading results and the standard suggests it is important to study an installation only when steady operation has been established.

This project extends one already conducted for Transco [2] using a limited number of appliances and associated faults to determine whether the time required for meaningful data to be obtained is as long as has been suggested. The study completed for Transco used three appliances, a decorative fuel effect fire, a boiler and a combi-boiler. These were operated as per manufacturer’s instructions and then with a fault set up to compare the time-based CO/CO_2 ratio obtained in either case. Whilst the instrumentation used to record the data was more sophisticated than a typical flue gas analyser, it was concluded that characteristics of the data obtained with time could be used to distinguish between the correctly operating and mal-operating condition over a short (5-10 minute) period following cold start.

This sample of appliances tested to date and their associated fault conditions is recognised to be small particularly if the draft for review is to be based upon as general a set of conditions as possible. It was therefore proposed to extend this study to a more representative number of appliances/installations and associated fault conditions and with the express objective of defining a process for identifying an unsafe situation using readily available portable flue gas analyser instrumentation. The scope for providing meaningful data in a short time scale will be explored.

A supplementary aspect of the work will involve making a limited, but representative, number of combustion performance ratio measurements using some of the more recent models of domestic boiler in order to determine whether such models still conform broadly to the criteria used since 1992 by British Gas Services associated with servicing. There is some concern that more modern designs, in particular those featuring narrow finned heat exchangers, do not necessarily fit into the 0.004/0.008 ratio criteria. Additional information on CO emission levels associated with incident data is collated by the Health and Safety Executive (HSE) [3].

Measurement of the combustion performance ratio can also be dependent on the type and location of sampling probe used. A number of probes will be selected for this study and the location of the probe in the combustion product gas stream will be assessed to determine measurement sensitivity.

2 SCOPE

This work is intended to provide practical evidence upon which to base objective decisions concerning how an emergency response engineer might carry out work at a property where fumes have been reported. In particular it may assist in making sound judgements as to the safety of a domestic gas installation suspected of operating under fault conditions and which has the potential for causing toxic levels of carbon monoxide to build-up in the property.

Currently, an engineer spends a 30-minute period during which time visual inspection and gas tightness checks are performed. The work undertaken in this study may demonstrate there is scope for an engineer to make flue gas analysis measurements in a practical time period. This, in turn, could improve the chances of identifying one or more mal-operating appliances rather than the gas supply having to be turned off to the whole property as the make safe action.

Such an approach would inevitably be adopted with due care to operational procedures in order to maintain the customer’s safety as the paramount objective.

Any procedure so developed during the project will be trialled using a number of Transco engineers at Advantica’s facilities in Loughborough.

The work will also be of direct relevance towards developing the synergies between the emergency response engineer and the follow-on CORGI registered service engineer. In addition, the project scope will assist in providing evidence that particular appliance designs may be less amenable to combustion performance analysis than most.

3 PROGRAMME OF WORK

The range of appliances involved covers the following:

- Open-flue boiler
- Open-flue combi-boiler
- Open-flue warm air heater
- Unflued sink water heater

- Inset live fuel effect fire
- Flueless fire
- Balanced flue boiler
- Balanced flue boiler – pre-mixed burner
- Balanced flue fire

Each appliance will be operated as per the manufacturer's instructions, in addition to being operated under fault conditions, and faults may render the appliance/installation unsafe to leave. Examples of such fault conditions are:

- Blocked flue
- Restricted heat exchanger (partially blocked)
- Linted burner
- High gas supply pressure
- Low supply pressure
- Restricted air intake (partial blockage)

The list is not exclusive, and a combination of faults may be present on an appliance. This will require operating appliances in a number of different controlled situations and recording the combustion performance information (both CO/CO_2 and absolute CO concentration) with time for evaluation afterwards. These data will then be used to define how, by using a portable flue gas analyser, the operator might judge the appliance/installation to be operating safely or otherwise, in as short a time as possible.

3.1 Test Equipment and facilities

The test rig comprises:

1) Appliance under test
2) Gas supply system (including pressure variation)
3) Water flow circuit for boiler tests (including flow and temperature measurement)
4) Extractive gas sampling probe and combustion product conditioning system
5) Siemens Ultramat 23 combustion product gas analysers

The apparatus is shown schematically in Figure 1. The appliance is installed in a test facility with a gas supply provided from the main gas supply. The gas supply pressure is controlled by a governor (Donkin type RC1 FIG 226, ranges 12.5 – 35 mbar, or 35 – 75 mbar). Gas pressure is measured by means of a pressure transmitter (Druck type PMP 1400, range 250 mbar). The probe samples combustion product gas from the flue or within the body of the appliance. The sampled gas first passes through a Dreschel bottle "knock-out pot" to remove the bulk of the water and then to a bespoke sample drying system. This drying system approach has been developed and shown not to affect the combustion product gas composition. The drying system contains two dryers ("Perma Pure") linked in series and with a cross-flow of dry air supplied by means of a small dehumidifier coupled to two drying columns filled with self-indicating desiccant. The dry gas sample then passes to the Siemens Ultramat 23 analyser and the CO, CO_2 and O_2 concentrations are measured. This means that the measured values are quoted on a dry basis. The analysers provide a digital LCD display of the measured values and the analogue output signals are logged though an InstruNet interface coupled to a PC running the HPvee interface software. The output from the Druck pressure transmitter is also logged. The HPvee software enables a signal value to be logged every fifteen seconds and the data is input to a Microsoft Excel spreadsheet.

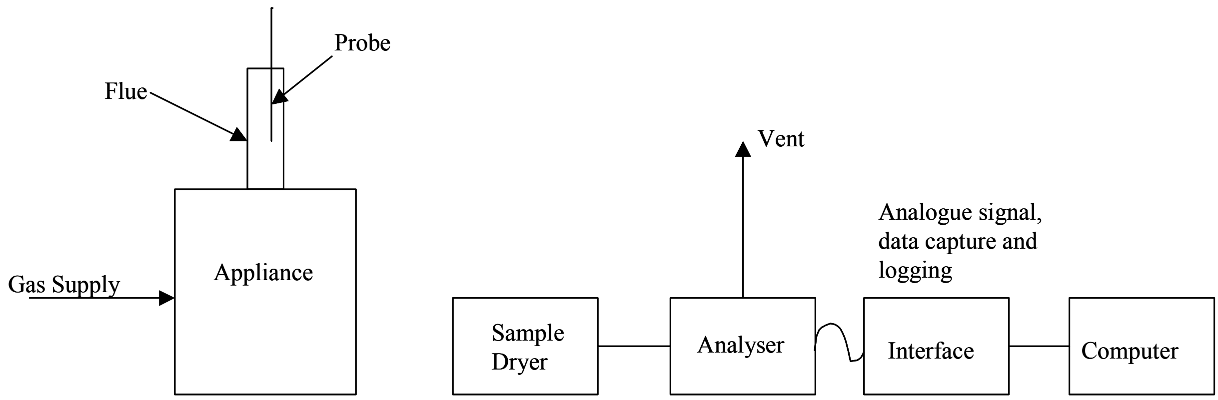

Figure 1: Schematic diagram of apparatus

The format of the experiments is the same for all tests:

1) Establish "normal" operation with a characteristic gas supply pressure and the appliance set-up as per the manufacturers instructions. This may include setting correct water flows and temperatures for boiler tests.
2) Log the emissions performance under "normal" conditions, from light-up.
3) Introduce a range of faults and log data for each fault individually
4) Compare the emissions performance under a range of fault conditions with that under "normal" operation.

In addition, extra analyses are made if the appliance is "brand new" to establish if emissions from newly installed appliances are different to those of other, used appliances.

As well as the standard analytical instrumentation approach, additional analysis is made for certain tests to measure "spillage" of combustion products from the appliance in addition to the measurements made in the flue. For "normal" tests, a check is made that no "spillage" is present. However, for certain fault tests, especially blocked or partially blocked flue, there is a propensity for the combustion products to exit the appliance through vents other than the flue. Both portable and spectroscopic analysers will be used to ascertain the extent of the "spillage".

Once the data have been fully analysed and assessed a methodology will then be developed and tested on selected emergency response engineers, to confirm whether the procedure is robust.

3.1.1 Sample probe designs

The sampling probes used during the work will enable practical information to be offered to the BS7967 panel that supports the drafting of the standard. The range of probes is shown in Figure 2. The draft standard recommended testing and validation of new probe designs and this is being covered in the current test programme.

The multi-point probes are shown in more detail in Figure 3 (a and b).

Figure 2: Probes used in the combustion tests

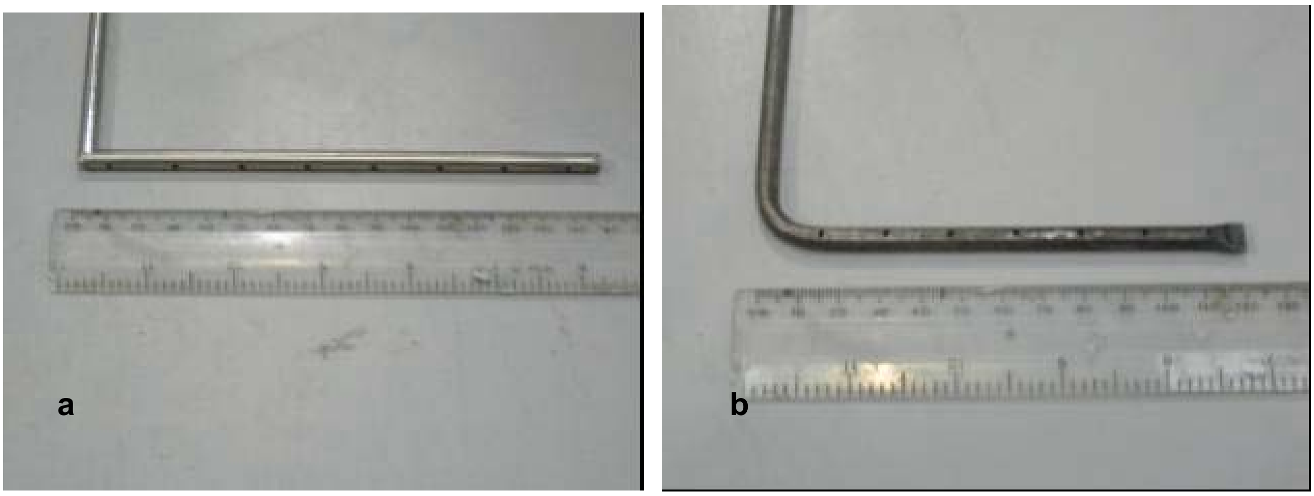

Figure 3: Detail of two multi-point sample probes

3.1.2 Modern boiler designs

A number of sets of combustion performance ratio measurements (minimum 50) will be made in the field by British Gas Services engineers on a range of boilers. These data sets are not included in the present report but will be reported separately after the next annual service visit has been made to the customers properties. These measurements may be able to provide additional information on whether certain appliance designs still comply with the combustion performance criteria used by British Gas Services when servicing at 12-monthly intervals.

3.2 Combustion performance ratios

The combustion performance ratio for a domestic gas-fired appliance is an indicator of the overall combustion within the appliance. It is defined as:

$$Combustion\ perfomance\ ratio = \frac{CO\ concentration\ in\ flue\ gas\ (\%)}{CO_2\ concentration\ in\ flue\ gas\ (\%)}$$

It relates the volumetric measurement of carbon monoxide to that for carbon dioxide. In this way it removes dilution effects and overall air:fuel ratio effects.

An extensive and comprehensive set of emissions measurements on central heating boilers was performed by British Gas during the 1980’s. The measurements were made on installed appliances in the home. This was aimed at determining whether the combustion performance of an appliance could be measured in terms of the carbon monoxide and carbon dioxide present in the flue gases and whether specific trigger values could be demonstrated to correspond with acceptable and unacceptable combustion performance from a servicing perspective.

Analysis of the data collected in the field suggested that two trigger values could be justified, namely 0.004 and 0.008 for the combustion performance ratio.

If the emissions from the appliance had a CO/CO_2 ratio less than 0.004, then its combustion was deemed to be good enough to remain until the next annual service without further attention.

A CO/CO_2 ratio between 0.004 and 0.008 suggested the boiler should be stripped and cleaned and then re-measured to ensure its ratio had fallen to below 0.004.

A combustion performance ratio greater than 0.008 represented an appliance which not only had poor combustion, but which had a fault requiring rectification. Once corrected, together with a strip and clean, the appliance would then be re-measured and considered to be operating correctly if the combustion ratio was below 0.004.

Whilst the 0.004 and 0.008 values have become widely used for boilers there remains the issue of acceptable and unacceptable combustion performance on other types of appliance. For some appliances the value of 0.02 for the combustion performance ratio in the flue is used in developing the new British Standard [2].

In this report, for comparative purposes, only the 0.004 and 0.008 values are used.

4 PHASE 1 – APPLIANCE TESTS

4.1 Flueless Fire

A flueless fire representative of this type was used.

The fire was installed and first operated according to the manufacturers instructions. The performance of the fire was good, igniting easily and rapidly warming-up. Combustion product emissions were sampled, monitored and logged. Measurements of combustion product concentrations were made both inside the firebox before the catalyst and external to the fire in the standard flue vent. The locations of the probes can be seen in the photographs (Figure 4, Figure 5, Figure 6 and Figure 7).

The second aspect of work involved setting-up fault conditions, including:

- High gas pressure
- Low gas pressure
- Re-arranged coals
- Partially obstructed catalyst

Other faults were introduced but the fire would not operate and so only the four tests mentioned were undertaken. The quantity of dilution air varied from test to test. To reduce this variation, the ratio of carbon monoxide to carbon dioxide is used to provide a more representative measure of the combustion performance of the appliance. The values obtained in the tests are shown in Figure 8. These measurements were taken inside the firebox. (Figure 8 features an “open-door” measurement in addition to the other faults already mentioned.)

The combustion products pass from the firebox through a catalyst to oxidise the carbon monoxide to carbon dioxide before being vented. The second sample probe, situated after the catalyst, measures the emissions issuing into the atmosphere from the appliance. The results from this probe are shown in Figure 9. In one test the external probe was initially positioned above the gap between the partially open door. The contents of the firebox were sampled by the probe in this position. When the position of the probe was changed so that samples were taken from combustion product gas that had passed through the catalyst, no carbon monoxide was detected.

Measuring combustion product gas concentrations after the catalyst will not show up problems with the fire as the carbon monoxide is oxidised to carbon dioxide. For this appliance only single-point, open-ended probes were used.

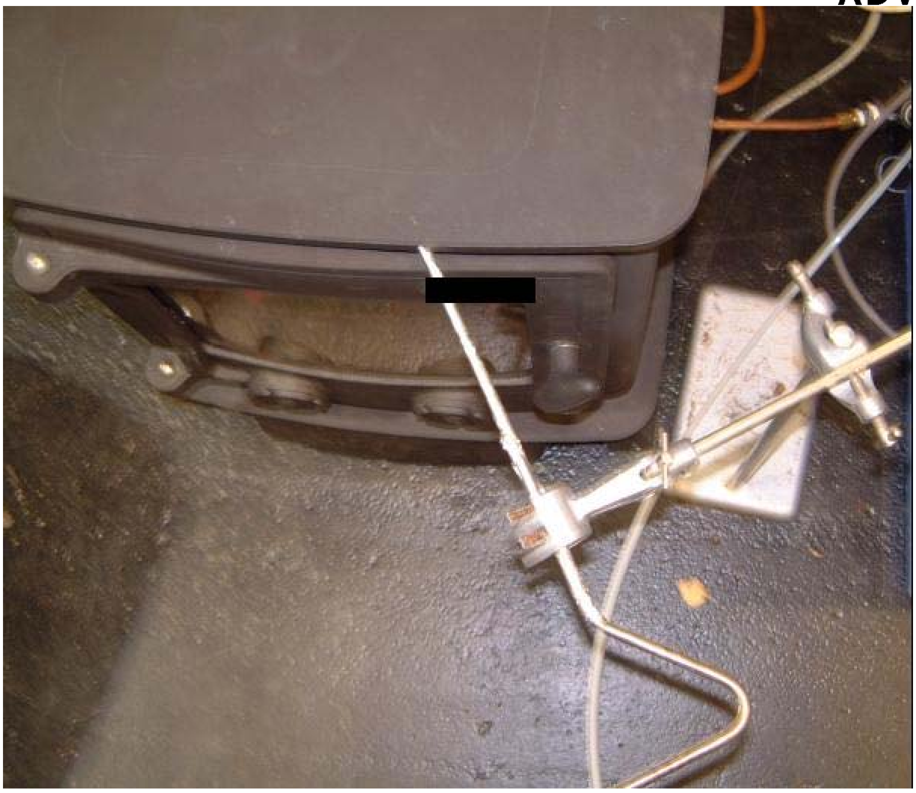

Figure 4: Position of external sample probe from above

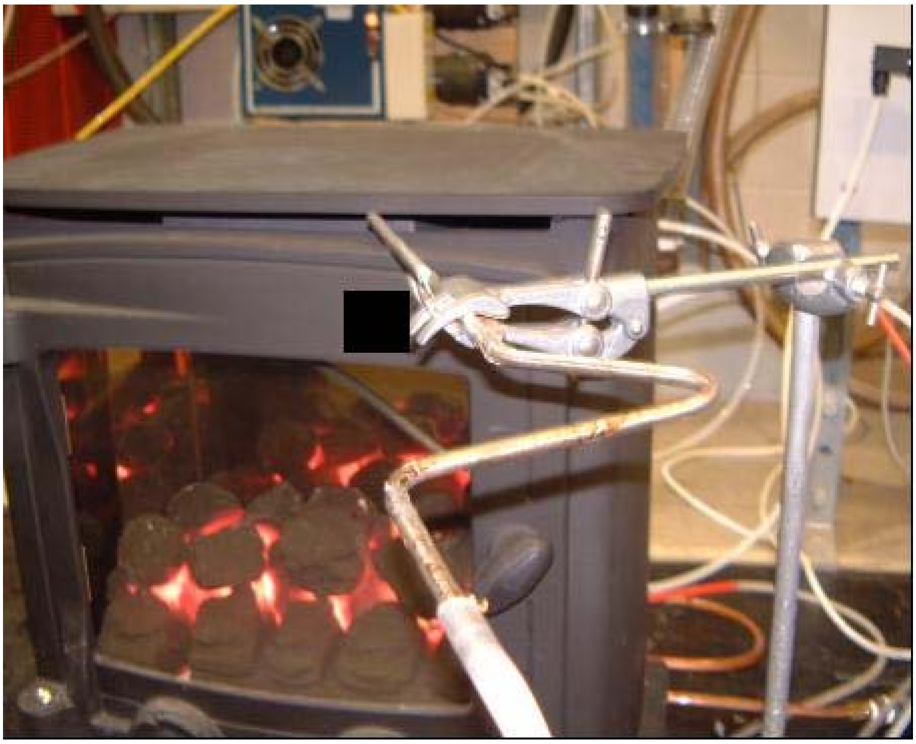

Figure 5: Position of external sample probe from front

Figure 6: Position of internal sample probe (1)

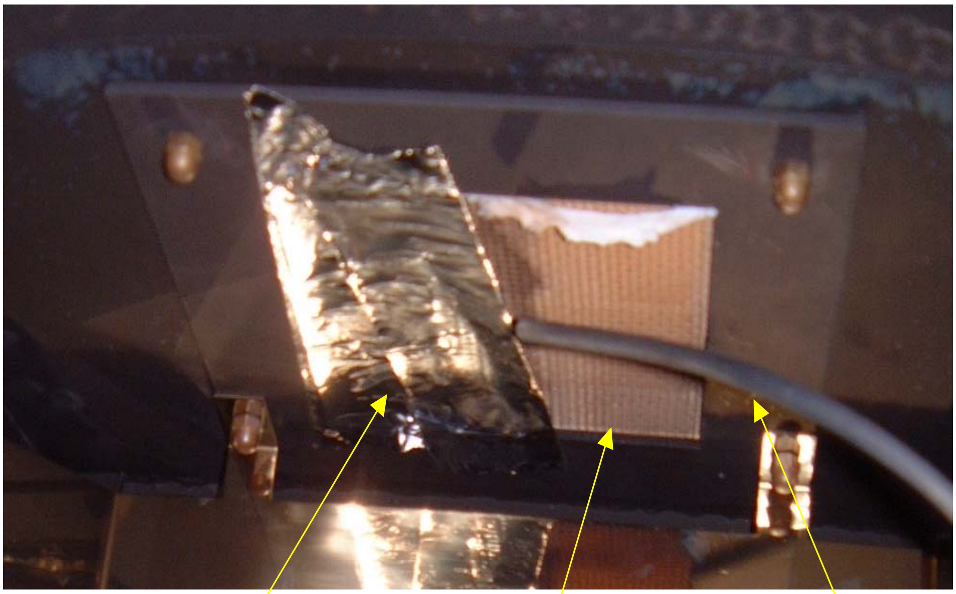

Figure 7: Blockage of catalyst

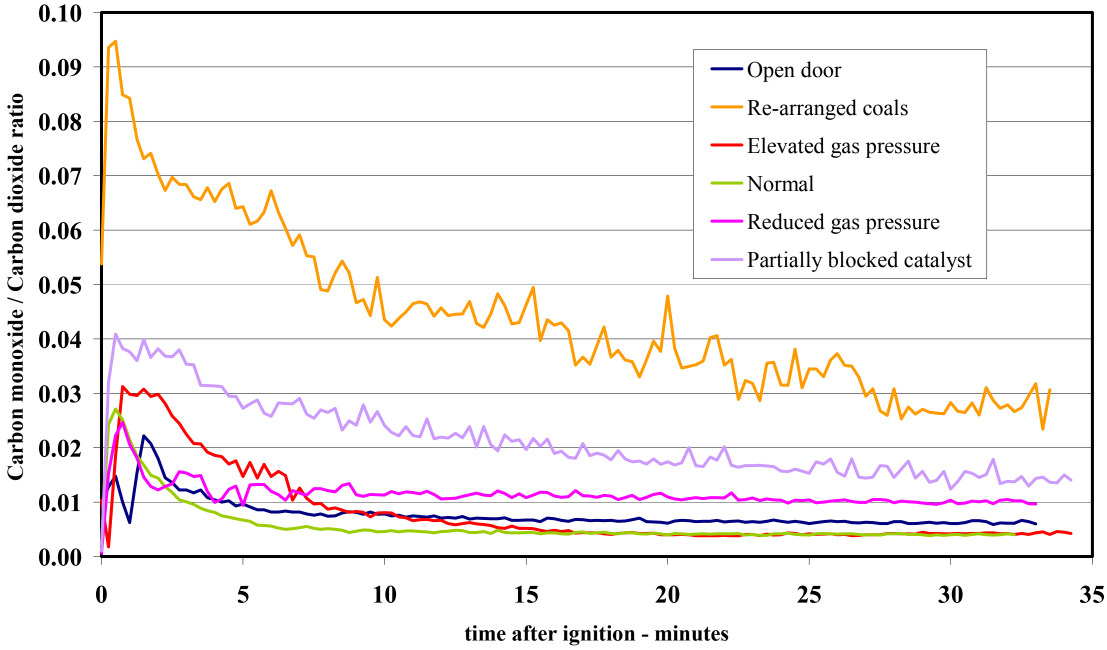

Figure 8: Flueless fire data inside firebox

The results from this series of fault tests show that the CO/CO_2 ratio once combustion has stabilised and the appliance has warmed-up, is never greater than 0.005. Peak values following ignition and initial appliance warming-up can be significantly higher but these high values subside after about 2 – 3 minutes of operation.

In contrast, the measurements made inside the firebox, under fault conditions, took at least twice the time to stabilise than for standard operation. The probe sampling location is clearly an important feature of these tests and can influence the results and their interpretation. The probes were located adjacent to the catalyst and centrally within the operating area of the catalyst, as can be seen in Figure 6 and Figure 7. In this way the probes will sample the “bulk-flow” of combustion product gas. If the probes were located close to the edge then emission values changed.

For normal operation, the CO level peaks at over 400 ppm immediately following ignition but rapidly drops to a steady level near zero, with a CO_2 emission of about 4.5%. This shows the effectiveness of the catalyst at oxidising carbon monoxide.

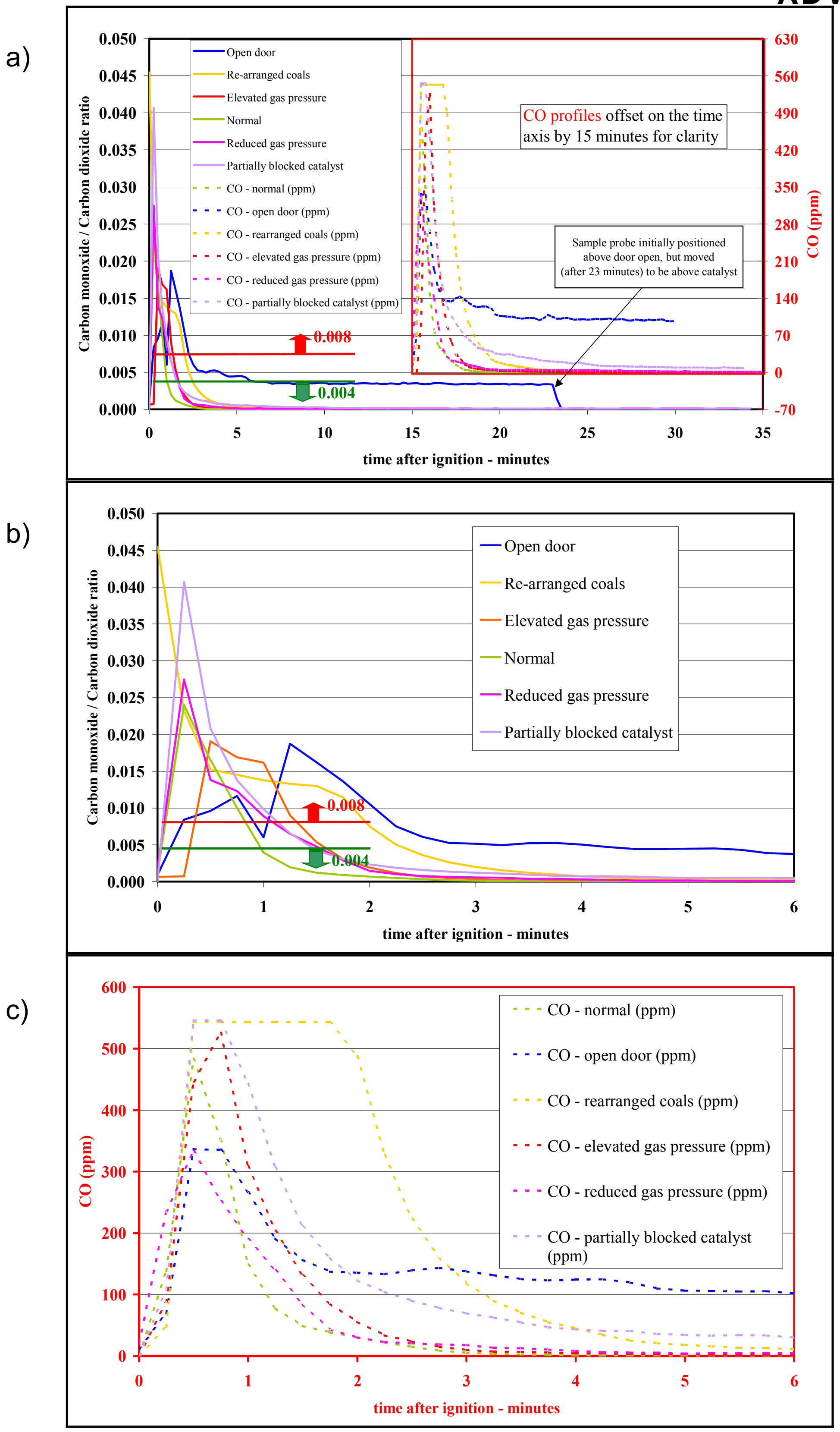

Figure 9: Flueless fire data outside firebox

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

4.2 Balanced Flue Fire

A room sealed inset live fuel effect gas fire representative of the natural draught, balanced flue type was used. Figure 10 shows the appliance.

Figure 10: Balanced Flue fire

This appliance was installed and initially operated in accordance with the manufacturers instructions but without connecting the balanced flue and terminal. Measurements of carbon monoxide, carbon dioxide and oxygen were taken in the flue. For this appliance only a single point probe was used in this study. Figure 11 shows the probe location.

Data were logged and the values of the CO/CO_2 ratio are shown in Figure 12.

The fire did not respond to the adverse conditions of high gas pressure, low gas pressure, loose front glass panel and obstructed air intake. If the air intake was highly obstructed then the quantity of carbon monoxide increased rapidly, but the concentration of carbon dioxide increased also and ultimately exceeded the measurement range of the analyser and a value could not be obtained for the CO/CO_2 ratio. This air blockage is not thought to be realistic and the data are not presented.

Figure 11: Location of the sampling probe in balanced flue fire

To represent a credible fault, the glass panel on the front of the appliance was loosened for one test run. The values for the CO/CO_2 ratio obtained in this test are shown in Figure 12 and can be compared to the “normal” test result. As can be seen the results here are very similar and it was concluded that this appliance either functions well or is completely unusable.

Although the peak CO emission measured during normal operation was in excess of 500 ppm, this level rapidly decayed to a steady state level of about 8 ppm after about 8 minutes of operation. The measured steady-state CO_2 level in the flue was around 8% for this appliance

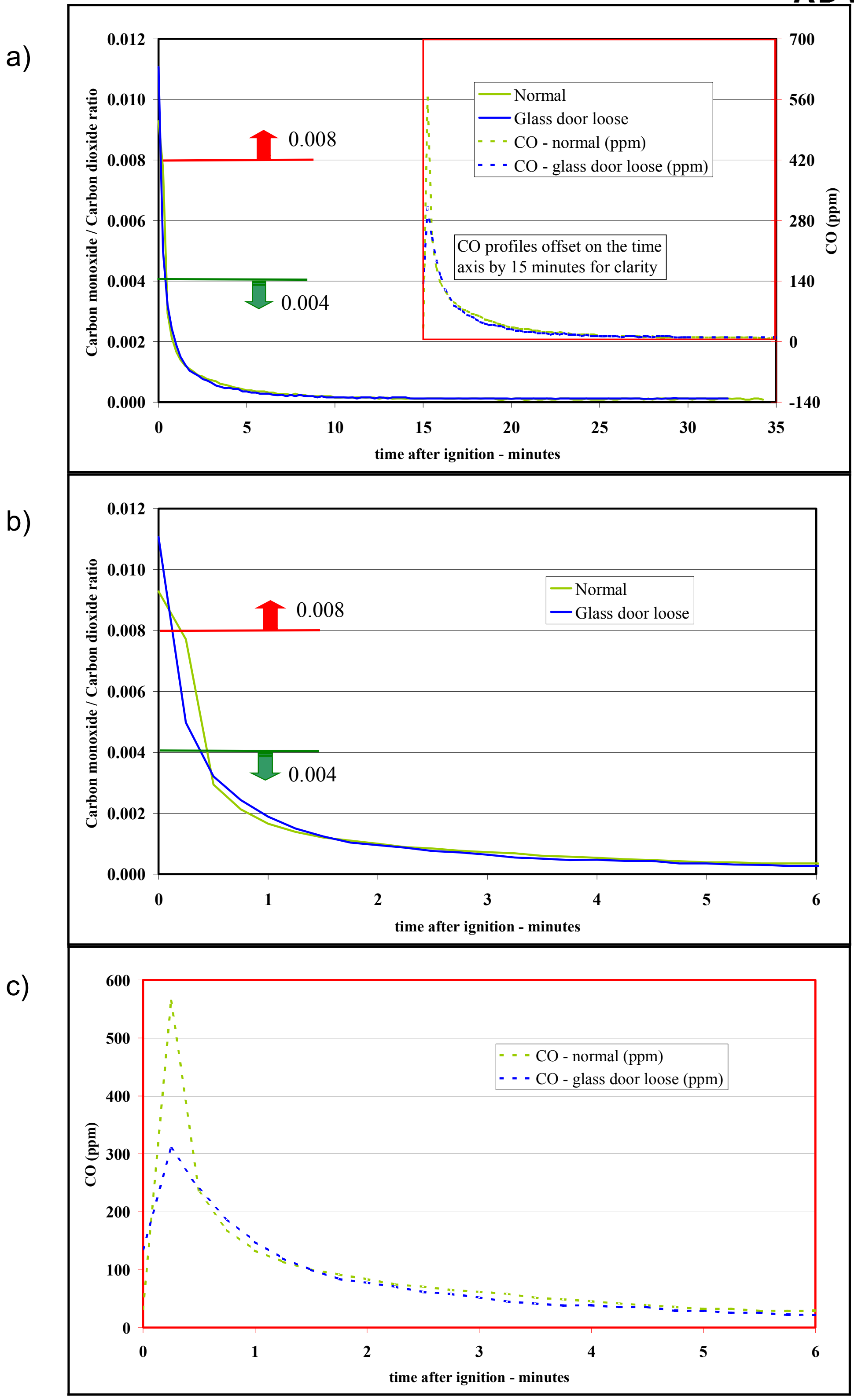

Figure 12: Balanced flue fire data inside flue

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

4.3 Instantaneous water heater

A flueless single-point water heater with atmosphere-sensing device representative of this type was used. The appliance is shown in Figure 13 together with a multi-point sampling probe. Measurements of carbon monoxide, carbon dioxide and oxygen were taken over the grille of the vent from the appliance as can be seen in the figure. The probe position was initially varied to obtain a maximum CO value and then fixed in position to measure the time dependence of the concentration values together with the steady-state values obtained after about three minutes constant operation. Figure 14 shows a photograph of the burner under normal operating conditions. The flames are of moderate height, do not impinge on the heat exchanger and show the characteristic blue colour.

Figure 13: Water heater and probe

This appliance was obtained from the supplier and was installed as detailed in the manufacturers instructions. The first normal operation of the appliance was used to determine any effects from the “newness” of the appliance. The normal operation was repeated to determine if the emissions from the appliance were dependent on the time and use after installation, although such appliances are not normally operated for more than 5 minutes. These results are shown in Figure 15.

Figure 14: Burner under normal operating conditions

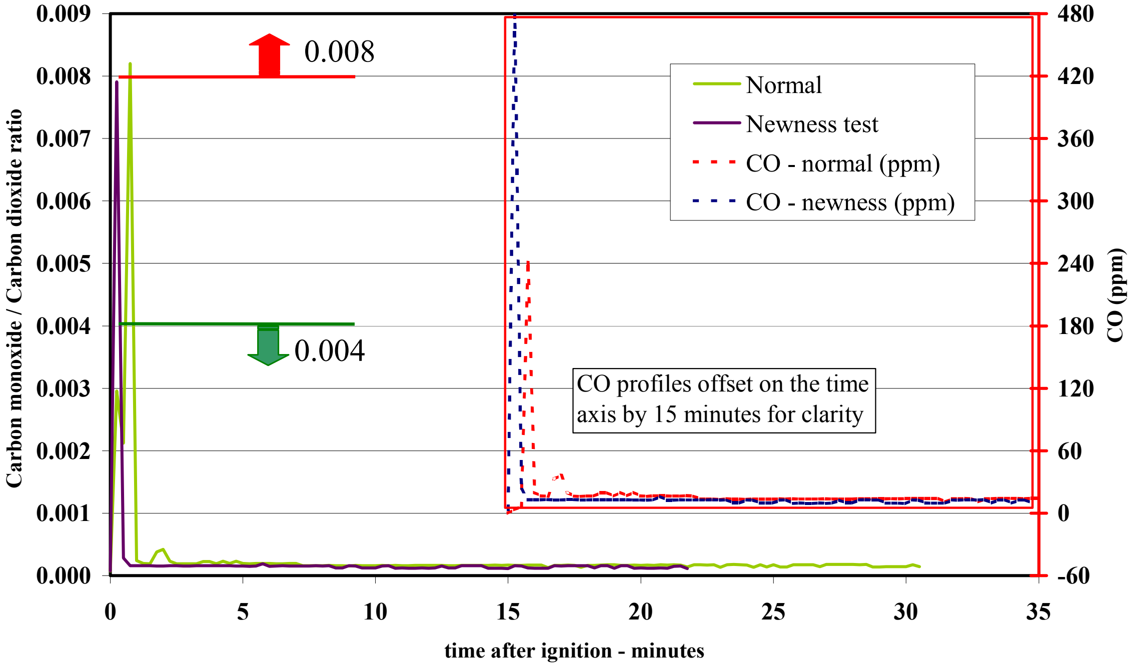

Figure 15: Comparison of "Newness" and "Normal" emissions tests from the water heater

As can be seen (Figure 15), the emissions from new and those from a normal test are in close agreement, including the initial peak in CO/CO_2 ratio. (There is a slight difference in start-up of the appliance caused by the inability to ignite the pilot burner at the first attempt on the "normal" test.)

For the normal operation the CO steady-state level was 14 ppm and CO_2 was 8.5%. The CO profiles are also shown in Figure 15.

Effect of probe type

Emissions from the appliance were monitored using three probes at separate times. The single point probe was used for most tests. Both multi-point probes were used to monitor emissions under normal operation and the results from the three probes can be seen in Figure 16. Although the agreement in the CO/CO_2 ratio is quite good for the three probes it is clear that the sampling is different as the absolute levels of CO and CO_2 show that there is a significant amount of dilution with air for the longer multi-point probe.

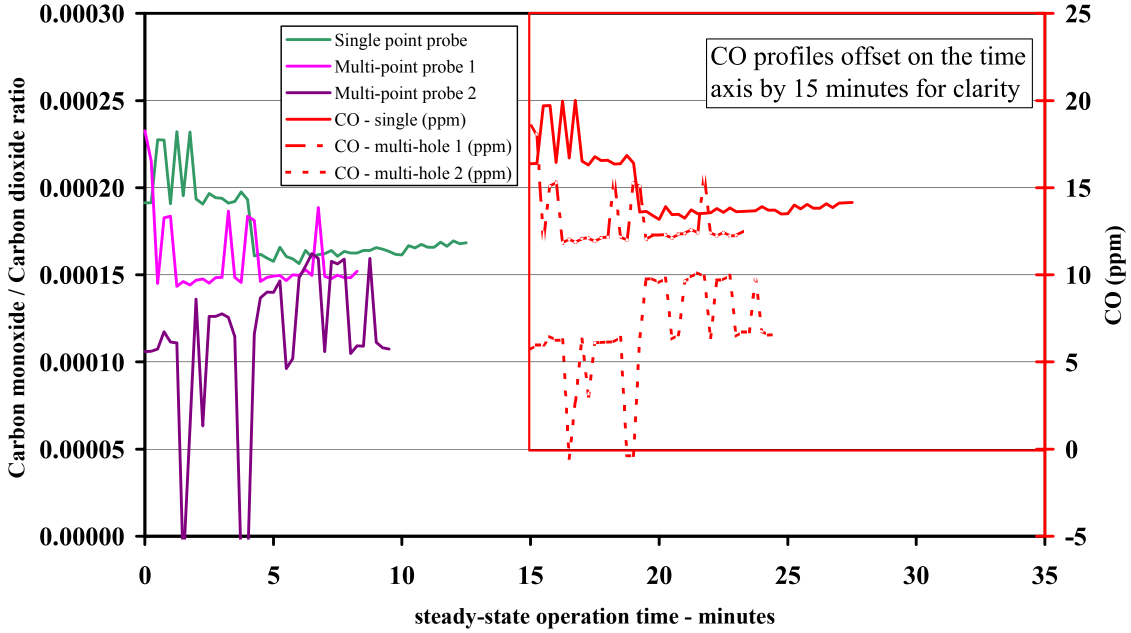

Figure 16: CO/CO_2 ratio from "normal" tests using different probes

The longer multi-point probe (termed "Multi-hole 2" shown in Figure 3a) was difficult to locate over the heat exchanger. The end holes appear to sample air from the side of the heat exchanger and not the combustion product gas stream. Whilst dilution should not impact on the CO/CO_2 ratio, it is clear that the sampling is not uniform for this probe, resulting in a lower combustion performance ratio. The shorter multi-point probe (termed "Multi-hole 1" and shown in Figure 3b) was easier to locate over the heat exchanger and the results correlate well with those from the single point probe. A comparison of the CO and CO_2 emission measurements using the different probes is shown in Table 1.

Probe	Average CO (ppm)	Average CO_2 (%)
Single	13.5	8.4
Multi-hole 1	12.0	8.2
Multi-hole 2	6.0	6.0

Table 1: Comparison of CO and CO_2 emissions from an instantaneous water heater using different probes

As can be seen from information presented in Table 1 and Figure 16, the single and shorter multi-hole probe (Multi-hole 1) produce similar results with a slight increase in dilution with the multi-hole probe. However, the “Multi-hole 2” probe appears to both increase dilution and change the CO/CO_2 ratio significantly.

Induced fault tests

Once the normal test programme had been completed, faults were introduced on the appliance. Initially a range of faults was set-up to see if the appliance would function and give useful results. The faults considered include:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Obstructed vent/grille (external to the appliance)
- Blockage of the heat exchanger (different extents considered)

The preliminary tests showed that the appliance would operate under low and high gas supply pressure. With low gas supply pressure, the flames shortened but remained the same colour, and the appliance reached a steady-state condition that could be maintained. For the high gas supply pressure fault the CO emission increased to 700 ppm but the CO_2 emission increased to over 10% and was over-range for the Ultramat 23 analysers. The higher gas pressure resulted in longer flames, tinged with yellow and impinging on the heat exchanger, quenching the combustion and increasing the CO concentration. CO_2 emission was also increased due to the increased heat input and changes to the air:fuel ratio. This limits the supply pressure that can be used for the actual test. The external grille could be blocked to about 80% from the left-hand side when facing the appliance without preventing the analysers from functioning correctly. All the faults induced were analysed for initial effect on emissions following ignition and for impact on the combustion performance ratio as a function of time to simulate prolonged use of the appliance. An example of the blockage of the heat exchanger is shown in Figure 17.

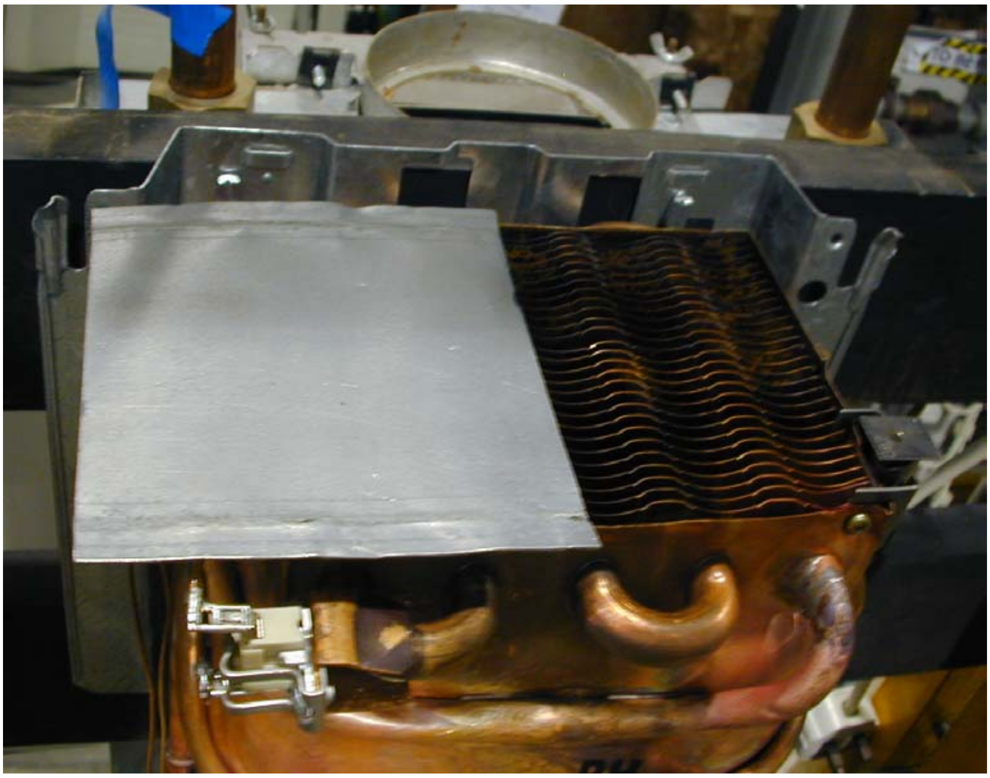

Figure 17: Blockage of water heater heat exchanger

The degree of blockage was difficult to assess but it appears that a blockage area of about 40% is possible before the analyser readings exceed the operating range of the instrument. A 50% heat exchanger blockage test resulted in very high emissions of CO but with CO_2 emissions off-scale.

The results from the fault tests for this appliance are shown in Figure 18. The scale on the y-axis has been expanded to show the equilibrium steady-state combustion performance ratio and to give good resolution of the 0.004 and 0.008 limits. It is apparent that the steady-state CO/CO_2 ratio is lower than 0.004 for the majority of tests. Tests with high gas supply pressure and blockage of the heat exchanger resulted in very high initial values of CO. However, this subsides very quickly and the steady state levels are lower than 0.002. Of the tests undertaken, only the high gas supply pressure test resulted in higher steady-state operation values for the CO/CO_2 ratio. The rate of decline of the peak value of the combustion performance ratio provides an indication of the time an engineer could have to make measurements whilst on-site. It should be noted that for this type of appliance it may be easy to miss the peak CO value, as the duration of the peak is particularly short.

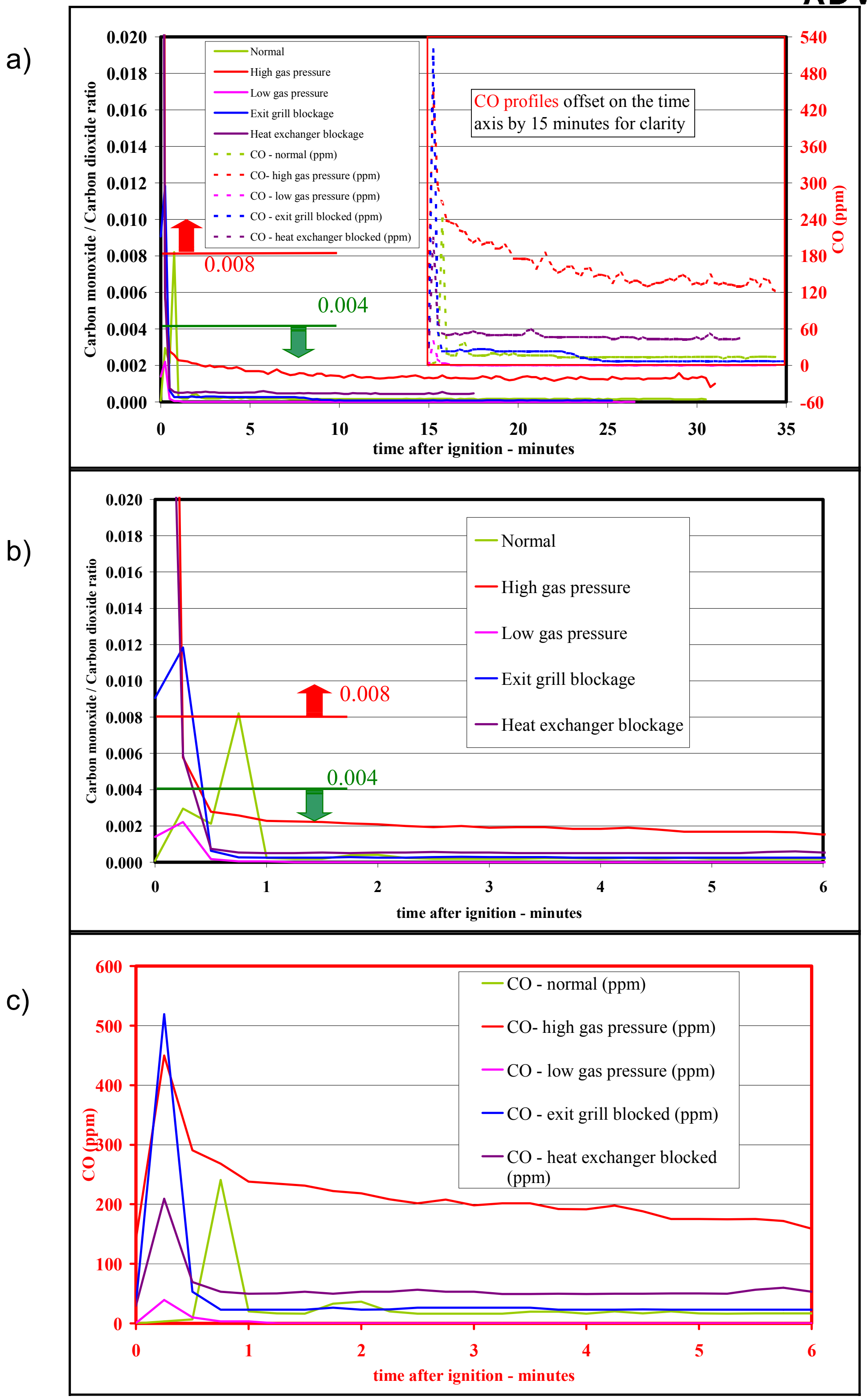

Figure 18: Water heater data for a range of test conditions

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

4.4 Open flue coal-effect gas fire

A coal-effect gas fire representative of this type was used to study emissions of carbon monoxide and carbon dioxide. The appliance is shown in Figure 19, and was installed in an open flue box.

Figure 19: Open flue coal-effect inset gas fire

When setting up the appliance for testing, great care was taken to ensure that the coals were arranged in the manner specified by the appliance manufacturer. The fire was fitted inside a back-box and approximately 2m of standard 5" flue was connected to ensure that the "flue pull" was correctly simulated. A small hole was drilled through the lower section of flue above the back-box to enable the probes to be inserted easily. Once inserted the probes were sealed in position using aluminium adhesive tape. As well as sampling for the combustion products (carbon monoxide, carbon dioxide and oxygen) in the flue using the standard Siemens Ultramat system described earlier, a small portable emissions monitor was used to detect "spillage" of combustion products from the front of the appliance.

The fire was a new appliance and before establishing "normal" operation a series of "newness" tests were performed. These were found to be both useful and necessary, as the binder on the coals appeared to age and produce carbon monoxide.

The location of the single point probe within the flue was chosen to give the peak CO value and this corresponded to a position near to the centre of the flue.

"Newness" tests

Initial tests using this appliance showed that there were substantial CO emission levels (> 2000 ppm) and the decay in the level was slow compared to other appliances tested in this project. It was concluded that the binder on the coals was a potential source of CO and had to be "aged" by repeated heating/cooling cycles. In addition to the high CO emission levels, slight "smoking" of the coals was observed. Some of this "smoke" also spilled from the front of the fire. Repeated ageing of the appliance was undertaken until a consistent low, steady-state level of CO was established and this was then deemed to be the "normal" operation. The results from the "newness" and "normal" operation are shown in Figure 20.

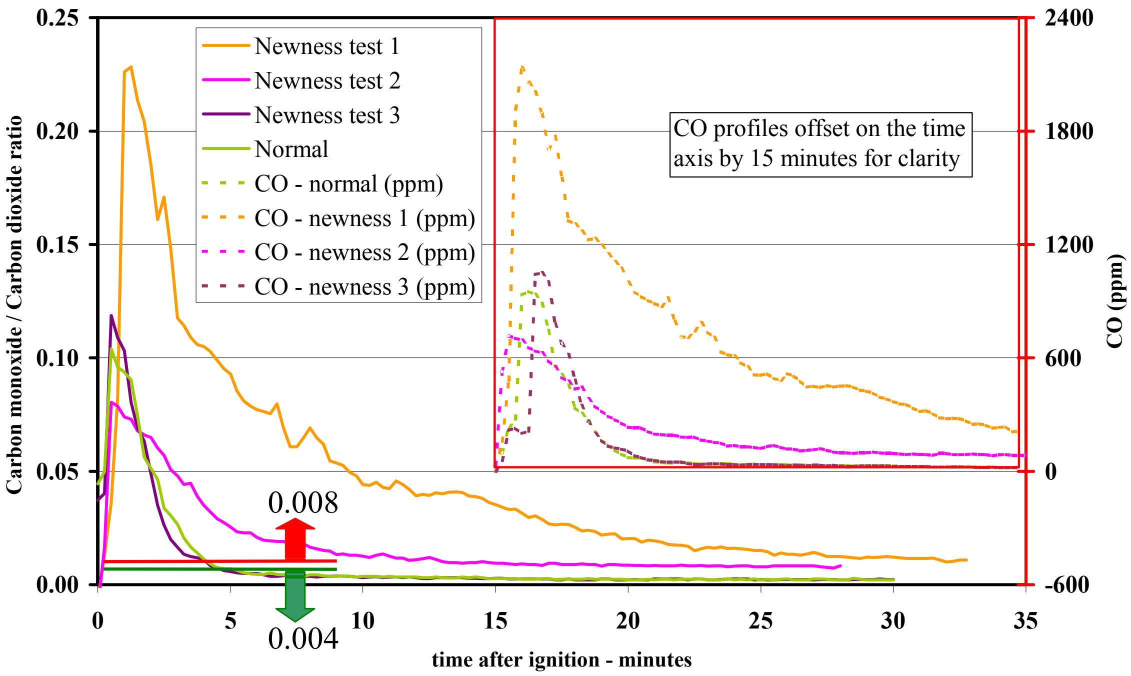

Figure 20: Open flue coal-effect gas fire CO/CO_2 ratio for "newness" and "normal" test conditions

"Normal" test

Once the effect of the binder on the coals had been removed a "normal" test was performed, measuring both the combustion product gas emission levels in the flue and any "spillage" of combustion products from the front of the fire. A photograph of the fire under "normal" operation is show in Figure 21. The single probe was used for the majority of the tests but both the multi-hole probes were tested. For "normal" operation there is an initial peak in the CO emission (giving a peak in the CO/CO_2 ratio), but this subsides and a steady-state level is established after about five minutes continuous operation. The measured values for the "normal" steady-state operation are:

- CO ~ 20 ppm
- CO_2 ~ 0.8%
- O_2 ~ 20.1%

Figure 21: Open flue coal-effect fire under "normal" operation

Effect of probe type

Emissions from the appliance were monitored using the three different sampling probe designs at separate times when operating under "normal" conditions. The results can be seen in Figure 22 and the steady state values for CO, CO_2 and O_2 are shown in Table 2.

Probe	Average CO (ppm)	Average CO_2 (%)	Average O_2 (%)
Single	20	0.81	20.1
Multi-hole 1	16	0.7	20.3
Multi-hole 2	7	0.4	20.8

Table 2: Comparison of CO and CO_2 emissions from the coal-effect gas fire

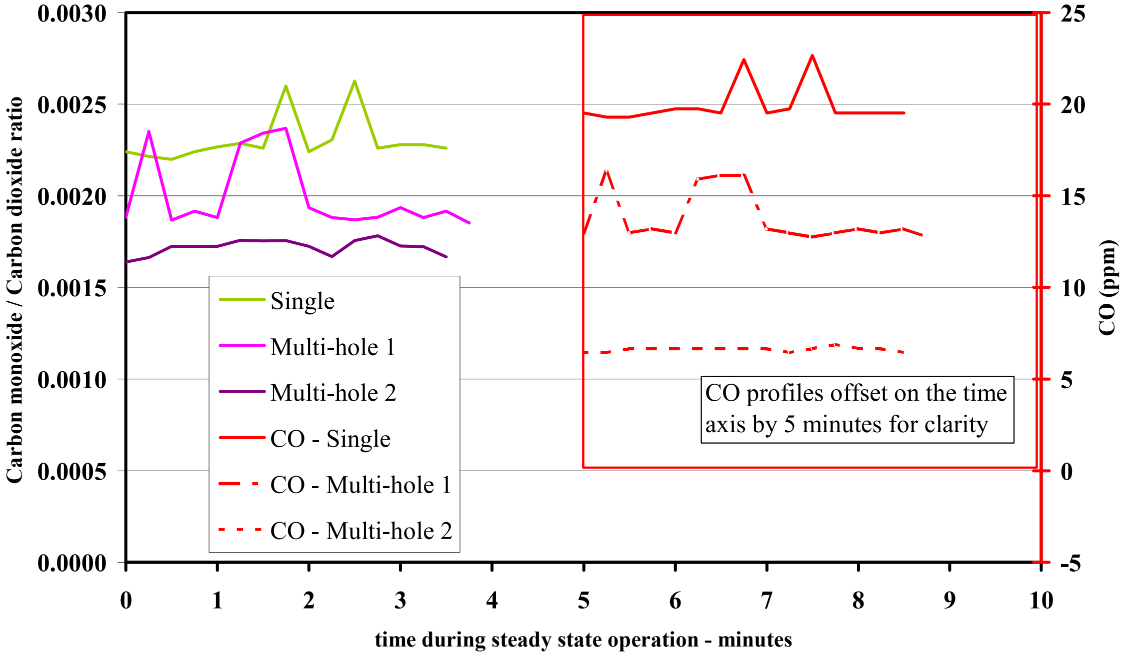

Figure 22: Comparison of emissions measurements using different probes in the flue of an open flue coal-effect gas fire operating under normal conditions

As can be seen from information presented in Table 2 and Figure 22 there are significant differences between the measurements made using the different probes. The single-point probe is located in the centre of the flue and samples flue gas products from the main flow in the flue. The multi-hole probes sample gas from a range of locations across the flue and appear to show increased dilution of the emissions by air. Indeed the larger multi-hole probe (Multi-hole 2) could not fit completely into the flue and the hole nearest the 90° angle of the probe was completely outside the flue and had to be sealed by adhesive aluminium tape to prevent it from sampling the ambient air in the laboratory.

Induced fault tests

Once the “normal” test programme had been completed, faults were introduced on the appliance. Initially a series of short tests were undertaken to see if the appliance would function and give useful results. The faults considered included:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Blockage of the flue (partial, up to 75%)
- Incorrect coal arrangement

The preliminary tests showed that the appliance would operate under low and high gas supply pressure. With low gas supply pressure, the flames shortened but remained the same colour, and the appliance reached a steady-state condition in a similar time to the normal operation. However, the measured emissions were very low and a full test was not performed.

Figure 23: High gas supply pressure fault

For high gas supply pressure, the flame length increased significantly, as can be seen in Figure 23. The fire-box external temperature increased but no “spillage” of combustion products was detected from the front of the fire. The measured CO_2 values were slightly higher than for normal operation and there was a noticeable increase to the CO emission level. The CO/CO_2 ratio for the high gas supply pressure test was 0.006 at steady state.

A series of trials were undertaken to establish the potential range of flue blockage possible that would give noticeable changes to the appliance emissions. With about 25% of the flue blocked there was no difference in the results compared to the “normal” operation. With 50% blockage there was an increase in the level of CO emission and there was also some “spillage” of combustion products from the front of the fire. The blockage was increased to about 75% of the flue and this was used for the formal test. A photograph of the fire operating under these conditions is shown in Figure 24.

Figure 24: Partially blocked flue fault test for coal-effect fire

With 75% of the flue blocked, it was observed that the flames shortened in length and appeared to “veer” towards the side of the appliance that wasn’t blocked. The colour of the flames also changed and a more distinct red glow from the flames was observed. The most noticeable change in the operation was that there was substantial “spillage” of combustion products from the front of the appliance. On ignition the emission levels from the front of the fire were >400 ppm for CO and ~0.4% for CO_2, about 1 cm in front of the top decorative plate and central to the fire. These levels subsided somewhat as the test approached steady-state but were still of the order of 20 ppm CO and 0.1% CO_2. Although the results from the partially blocked flue test were clearly showing incorrect operation of the fire, the CO/CO_2 ratio was still relatively low and certainly not within the 0.004/0.008 range. Results from this test are shown in Figure 25.

The coals for the coal-effect were rearranged in manner completely different from the manufacturers recommended alignment. A similar trend was observed to the high gas supply pressure test with the steady-state CO/CO_2 ratio approach 0.006, with increased CO emission as the CO_2 level was similar to the “normal” test.

A comparison of two normal tests performed on different days and the full range of fault tests is shown in Figure 25.

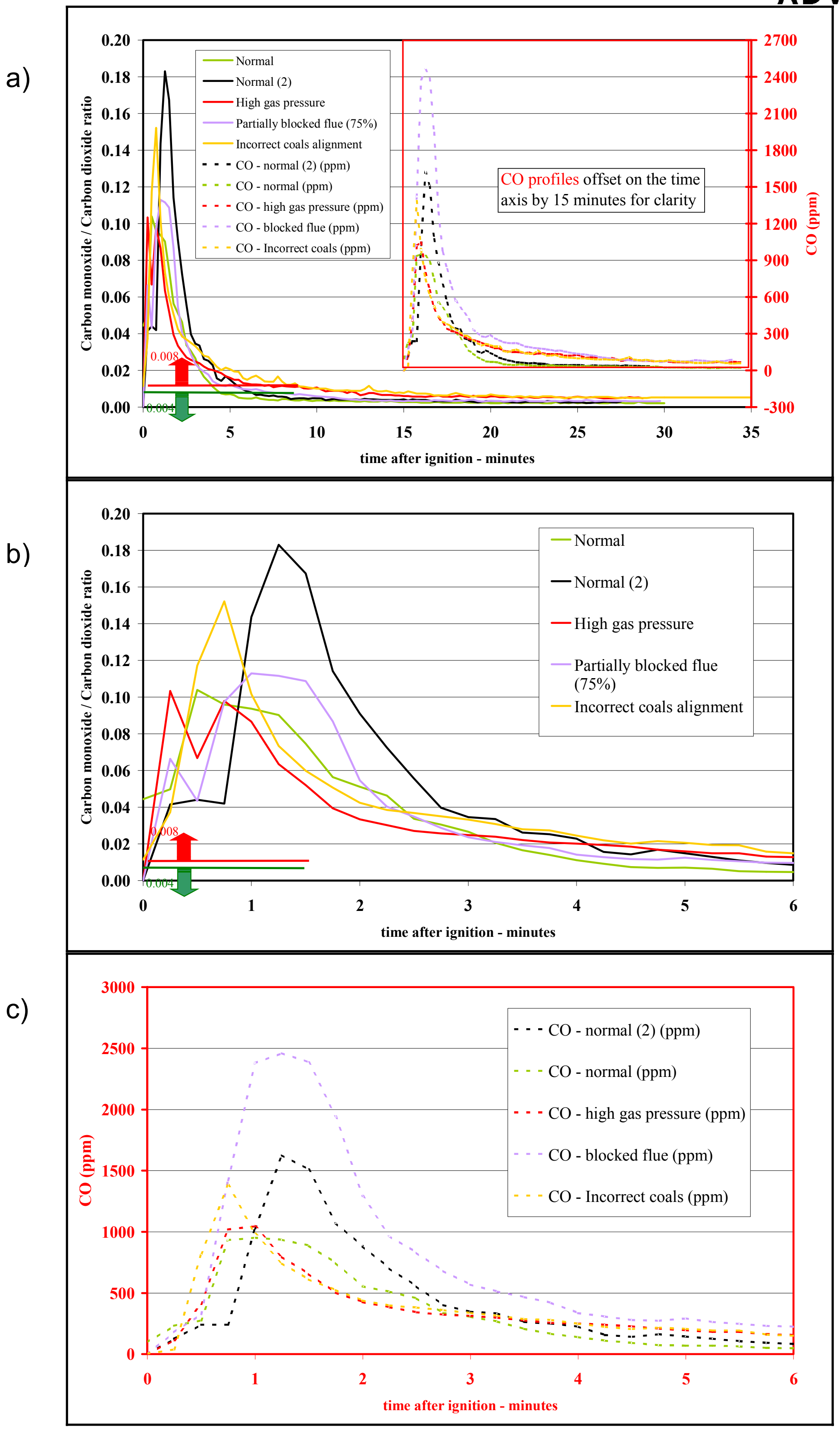

Figure 25: Comparison of "normal" and fault combustion product gas emissions for a coal-effect open flue fire

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

4.5 Open flue boiler

A boiler representative of this type was used to study emissions of carbon monoxide under normal operating conditions and with induced faults.

The appliance was installed according to the manufacturers instructions onto a boiler test rig at Advantica. This rig contains water pumps, water flow and temperature measurement, and a boiler temperature/power interlock to prevent overheating if the induced faults prevent the boilers own safety features from operating correctly. The temperature trip level was set to 90ºC with the temperature measured on the flow-side of the boiler adjacent to the rotameter.

A photograph of the boiler is shown in Figure 26.

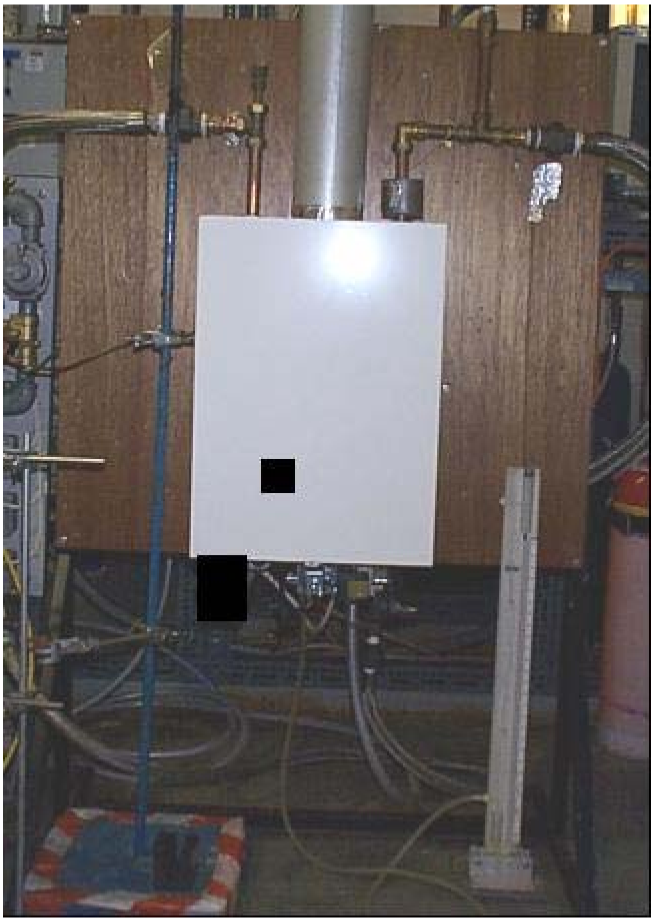

Figure 26: Natural draught open flue boiler

As well as measurements of the gas supply pressure (by means of a pressure transducer and logger), the burner pressure was observed using a manometer, as can be seen in Figure 26. For normal operation the measured burner pressure was around 13 mbar, when the gas supply pressure was 20 mbar, in accordance with the manufacturers installation recommendation.

Initial setting-up of the appliance indicated that the location of the sampling probe was critical to the observations made. Preliminary tests were performed sampling in both the primary and secondary flue. Following several discussions the test measurements were performed in the primary flue as shown in Figure 27.

The water flow around the boiler was indicated on a rotameter and was set to $0.9m^3/hr$ using a valve, in accordance with the recommended values for the boiler detailed in the operating instructions from the manufacturer. The water flow in the secondary heat exchanger was set to give a temperature difference across the boiler of about 11ºC. The water flow temperature for normal operation was between 60 and 67ºC.

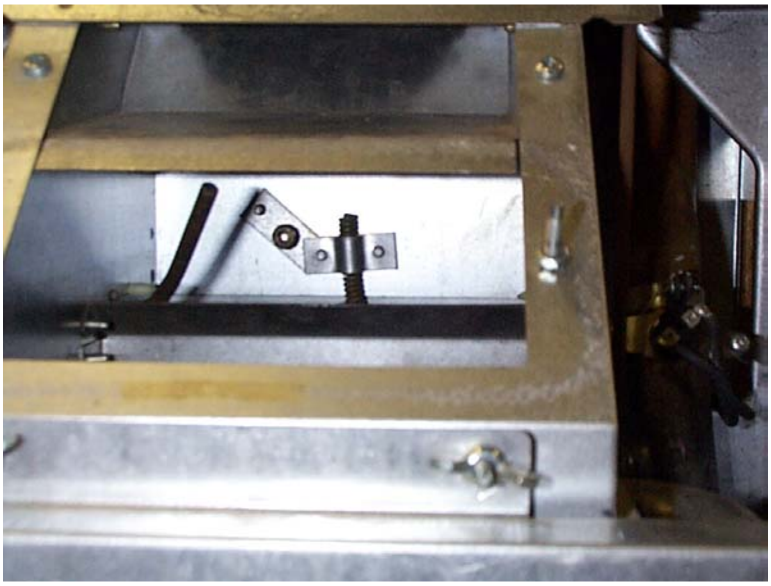

Figure 27: Single point open-ended probe location above heat exchanger in the primary flue

"Normal" test

The format for "normal" operation followed those for tests on other appliances. An unlit baseline operation was logged initially and then the pilot flame of the boiler was lit. Stabilised operation on the pilot alone was established for about one minute and then the main burner was ignited and the boiler operated at full load, at the maximum boiler heat input of 14.65kW.

The emissions from the boiler showed an initial peak in CO of over 500ppm but this subsided very rapidly to a level of about 25ppm, within about two minutes of full load being established. The emission then rose to approximately 40ppm as the boiler approached steady, constant temperature operation.

Typical measured values for the "normal" steady-state operation are:

- CO ~ 40 ppm
- CO_2 ~ 8.6%
- O_2 ~ 6.3%

a)

b)

c)

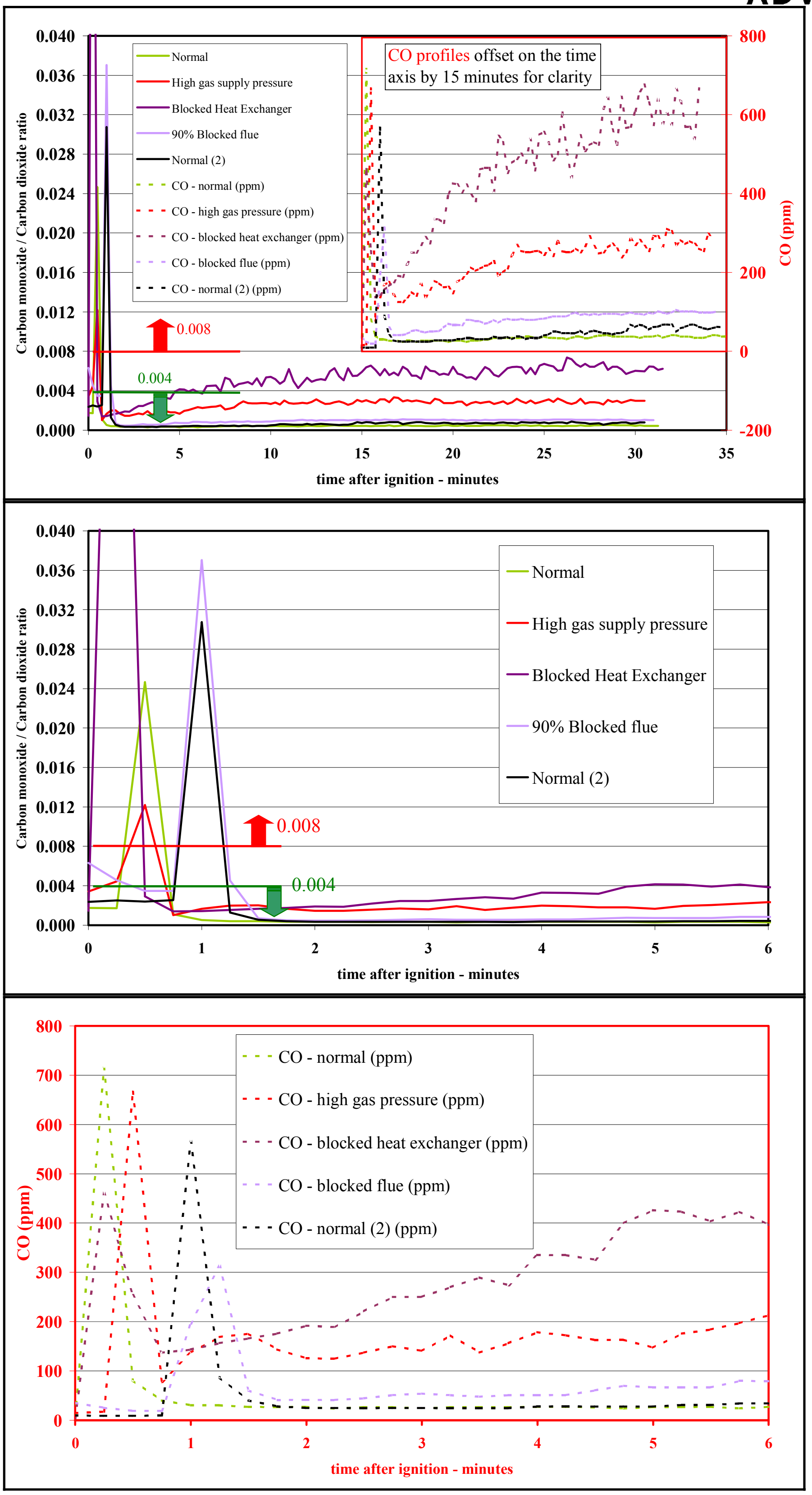

Figure 28: Comparison of “normal” and fault combustion product gas emissions for an open flue boiler

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

Figure 28 shows typical emissions profiles as a function of time for the boiler "normal" operations (two undertaken on different days), together with comparisons with results from induced fault tests. The scale on the y-axis has been expanded to show the equilibrium steady-state combustion performance ratio and to give good resolution of the 0.004 and 0.008 servicing criteria.

Effect of probe type

Emissions from the appliance were monitored using three probes at separate times when operating under "normal" conditions. The results from the three probes can be seen in Figure 29 and the steady state values are shown in Table 3.

Probe	Average CO (ppm)	Average CO_2 (%)	Average O_2 (%)
Single	61	8.4	5.8
Multi-hole 1	30	2.3	16.8
Multi-hole 2	24	2.4	16.6

Table 3: Comparison of CO and CO_2 emissions from the open flue boiler

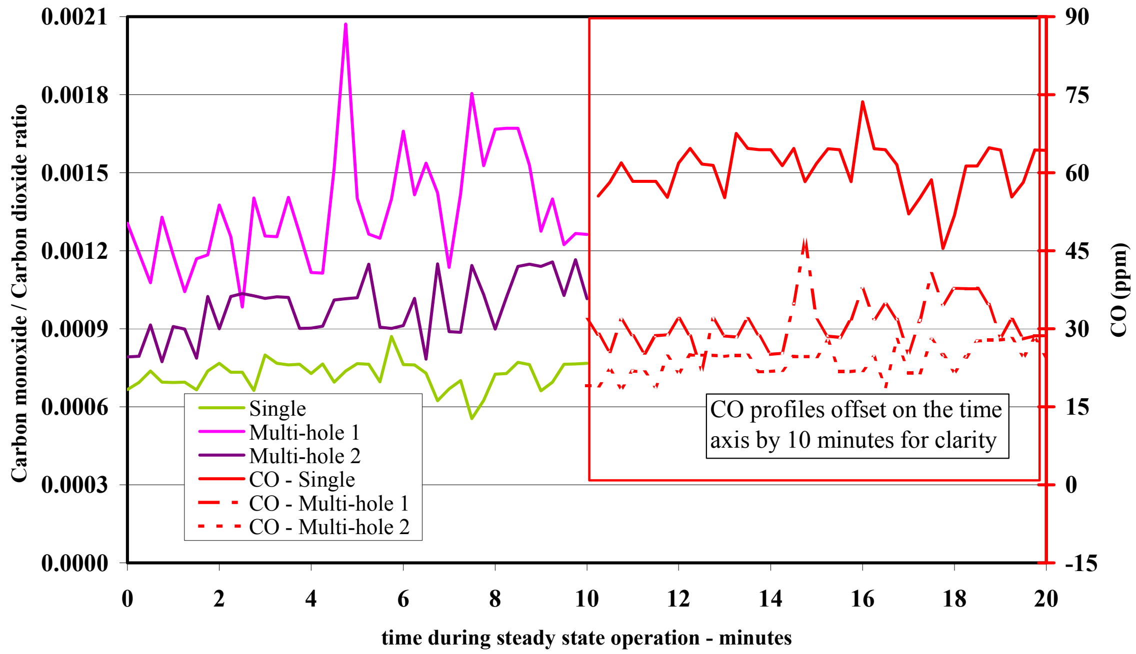

Figure 29: Comparison of emissions measurements using different probes in the flue of an open flue boiler operating under normal conditions

As can be seen from information presented in Table 3 and Figure 29, there are significant differences between the measurements found using the different probes. The single-point probe is located in the centre of the flue and samples flue gas products from the main flow in the flue. The multi-hole probes sample gas from a range of locations across the flue and appear to show increased dilution of the emissions by air. Indeed the larger multi-hole probe (Multi-hole 2) could not fit completely into the flue and the hole nearest the 90° angle of the probe was completely outside the flue and had to be sealed by adhesive aluminium tape to prevent it from sampling the ambient air in the laboratory.

The data shown in Table 3 and Figure 29 reflect the different nature of the probes. The location of the single, open-ended probe was optimised to give a maximum CO reading whereas the multi-point probe locations were chosen to locate the central hole of the probe in approximately the same location as the single-point probe. It is evident that the averaging effect of the multi-point probes has a significant impact on the measured CO and CO_2 levels. The differences cannot be totally attributable to dilution of the sample by air but reflect the fact that the holes are sampling at a range of points in the flue and the combustion product gas distribution is dependent on the location.

Induced fault tests

Once the normal test programme had been completed, faults were introduced on the appliance. Initially a series of short tests were undertaken to see if the appliance would function and give useful results. The faults considered include:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Blockage of the heat exchanger (partial, up to about 80%)
- Blockage of the flue (up to about 90%)
- Blockage of the lint arrestor and additional air intake vents

The preliminary tests showed that the appliance would operate under low and high gas supply pressure. With low gas supply pressure, the performance of the boiler was impaired in that the operating temperature reached was lower than that for the "normal" operation but emissions levels were similar. Blockage of the lint arrestor, to simulate reduced primary air entrainment, did not show any significant impact on emissions. Reduced secondary air intake, through blockage of several vents around the boiler did result in high CO levels but the likelihood of this occurring in domestic operation was thought to be very low, and so a full test was not undertaken.

Detailed tests were performed for the following faults:

- High gas supply pressure (35 mbar)
- Blockage of the heat exchanger (partial, up to about 80%)
- Blockage of the flue (up to about 90%)

Details of the results are shown in Figure 28. A photograph of the blocked heat exchanger is shown in Figure 30. A close-up photograph of the blocked heat exchanger is shown in Figure 31.

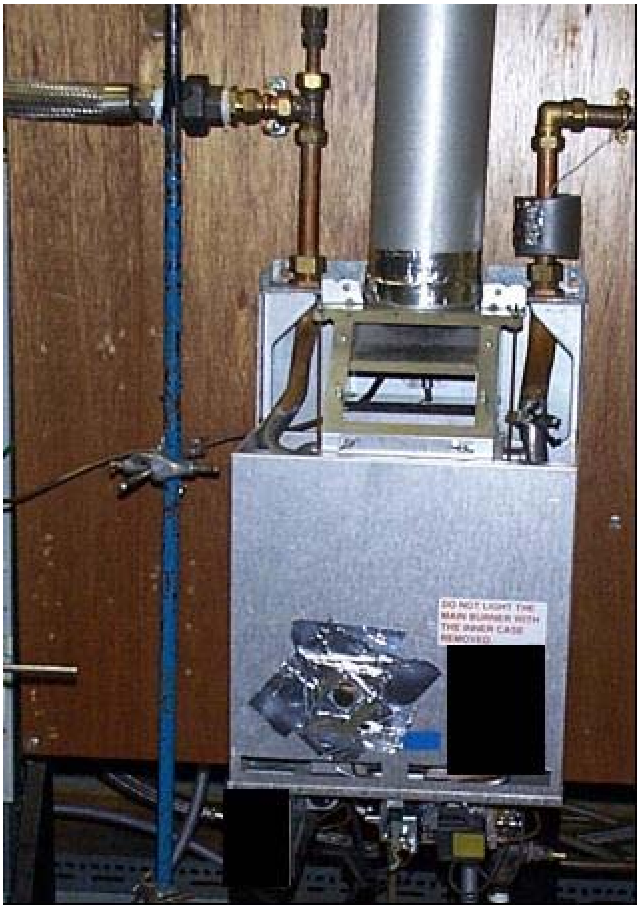

Figure 30: Blocked boiler heat exchanger

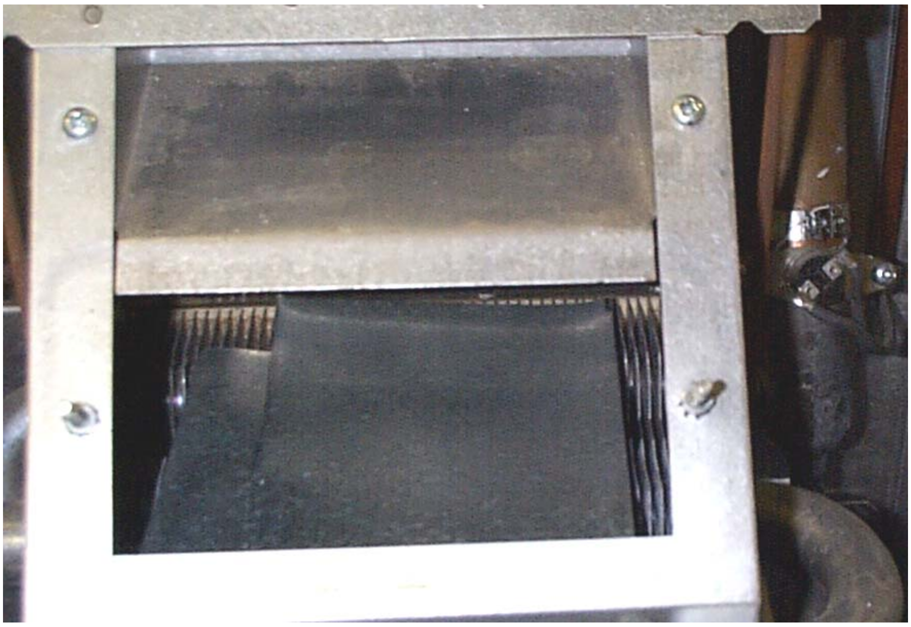

Figure 31: "Close-up" of blocked heat exchanger

Spillage of combustion products around the sides of the boiler was not observed in the fault tests except for the blocked flue test. For the test case of the blocked flue, CO levels of 100-300 ppm were observed dependent on probe location near the side vent and CO_2 levels were 7-8%.

4.6 Fan-flued combi-boiler

A wall-hung, room-sealed, fan-flued condensing combination boiler representative of this type of boiler was used and installed in the laboratory test bay according to the manufacturers instructions. The installation was similar to that for the open flue boiler except for certain additional features present on the combi-boiler that needed to be catered for. A photograph of the boiler is shown in Figure 32.

Figure 32: Fan-flued combi-boiler

The boiler was connected to the controlled gas supply and leak-tested. A horizontal flue assembly was installed. The boiler contains it's own expansion vessel and pump, and the external pump was not used for this appliance. The initial water system pressure was set to between 1.4 and 1.5 bar and a collection vessel was placed under the condensate drain to collect the water discharge. Although the boiler has both the central heating (CH) boiler and direct hot water (DHW) facility only the

CH boiler part was used for the tests. The direct hot water connections were made but not used. The central heating option was chosen by means of pressing a button on the appliance control panel. The boiler has a sophisticated start-up and control system, with a dedicated fault diagnosis indication. The status of the appliance is shown by means of a status code and the operation of the boiler is governed by the automatic burner sequence control. The following sequence was observed for most tests:

- Initial dormant state (code 0)
- Fan starts (code 1)
- Combustion chamber purged with air from fan (code 2)
- Gas valve opens and ignition (code 3)
- Steady boiler operation (code 4)

At the entry point to the flue there is a sample point and this was used for all tests as it represents the most convenient test point for a service engineer. The temperature of the primary water flow is indicated on the front of the appliance and also on the display from the boiler safety cut-out. The water flow was adjusted to about $1m^3/hr$ using a control valve in the primary water flow circuit. Normal operation of the boiler (at an operational setting of 12) gave a primary flow temperature of about 72ºC with the water flow in the secondary heat exchanger adjusted to give a temperature difference across the boiler (flow temperature – return temperature) of about 16ºC.

"Normal" test

The format for "normal" operation was similar to that for other appliances, although there was less manual input in this case as the boiler had a set start-up procedure. Once operating conditions had been determined, the boiler was switched on and the operating procedure was initialised. Following the combustion chamber purge, the burner ignites and the boiler follows a factory pre-set programme to establish steady-state operation. The tests were undertaken at maximum central heating boiler heat input of 20.9kW with the output to the central heating system being 17.7kW.

The emissions from the boiler showed an initial peak in CO of about 40ppm following ignition but this subsided to about 15ppm very rapidly. The gas rate, and consequently the boiler heat output, are controlled by the internal start-up procedure and this controls the air:fuel ratio, fan speed and other operational parameters. The result is that the boiler emissions slowly rise to steady state values.

Figure 33 shows the emissions profiles for this fan-assisted, condensing, combi-boiler.

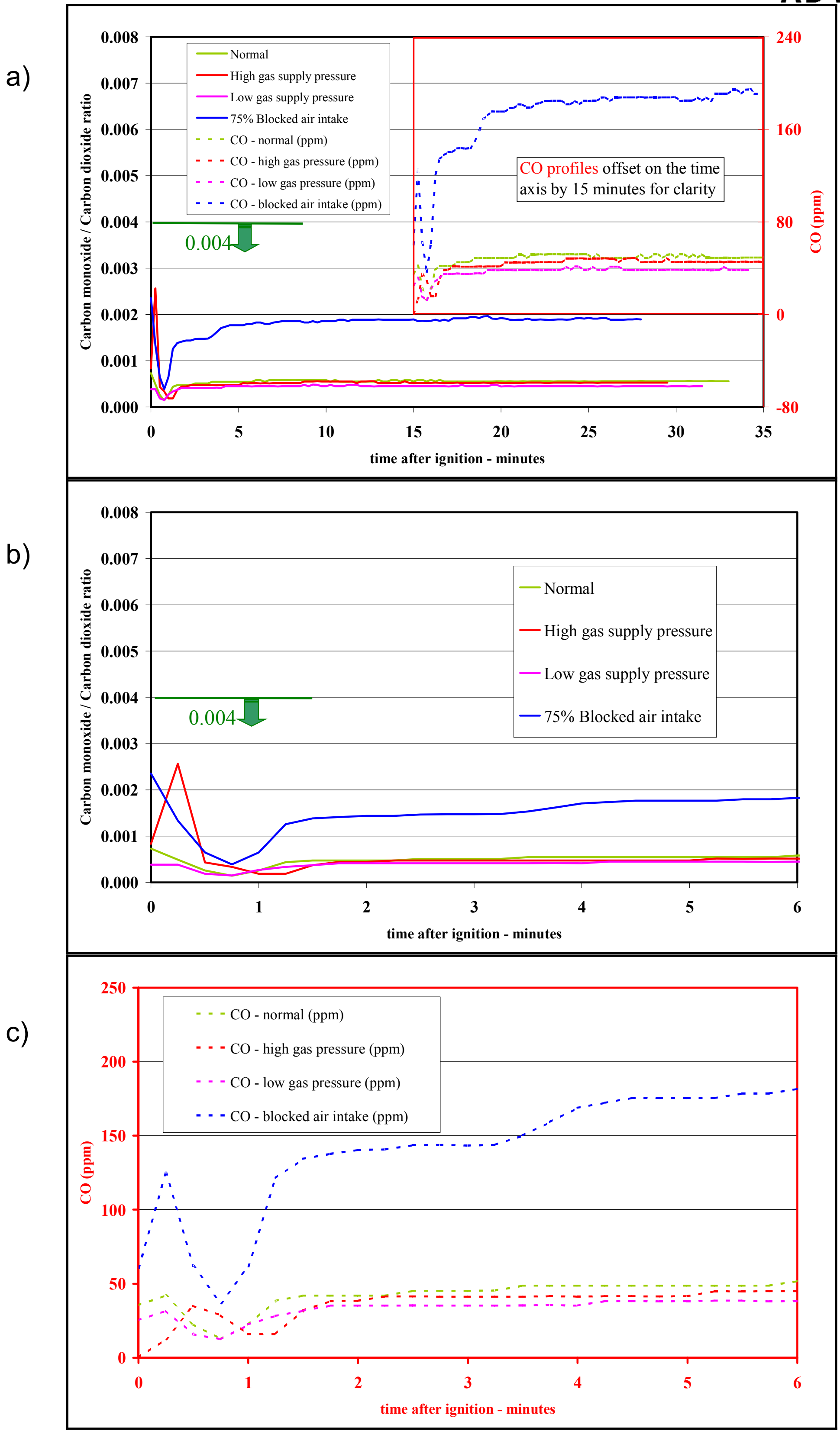

Figure 33: Comparison of "normal" and fault combustion product gas emissions for a fan-flued, condensing, combi-boiler

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

Typical measured values for the "normal" steady-state operation are:

- CO ~ 50 ppm
- CO_2 ~ 8.9%
- O_2 ~ 5.8%

The room-sealed design of this appliance meant that there was no location to test for spillage of combustion products. All combustion products have to vent through the flue.

Effect of probe type

Emissions from the appliance were monitored using the three sampling probe types at separate times when operating under "normal" conditions. The results from these probes can be seen in Table 4 and Figure 34.

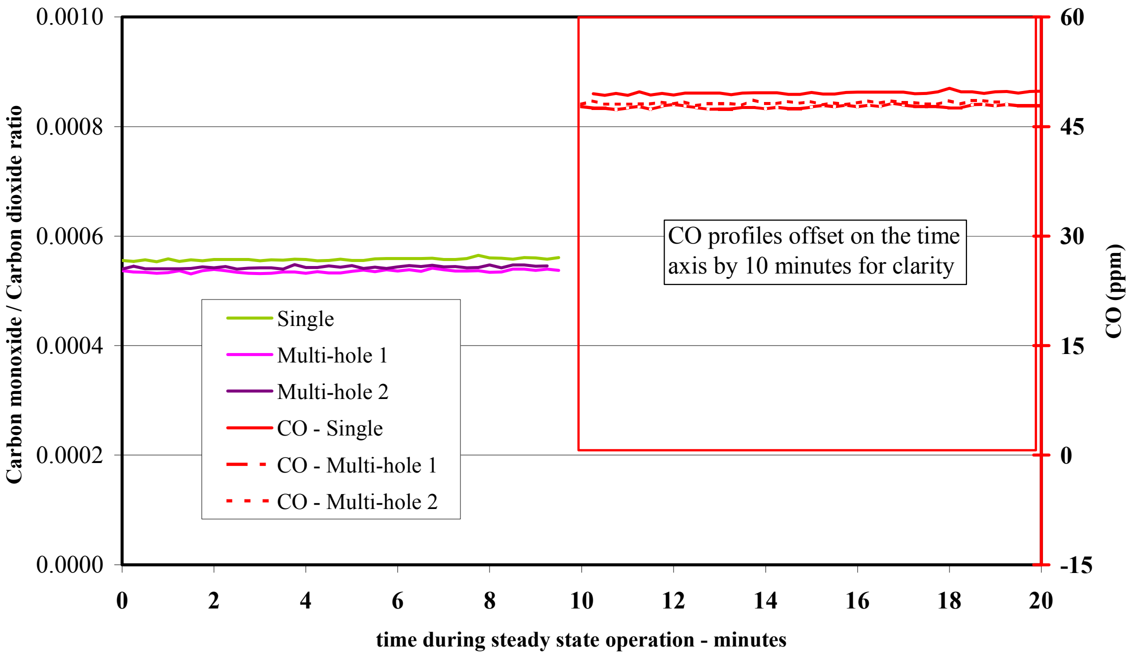

Figure 34: Comparison of CO emissions and combustion performance ratio for the fan-flued, condensing, combi-boiler

The results for the different probes for this boiler are very similar reflecting the fact that it is fan-assisted. This appears to "even-out" the emissions profiles across the flue. For the Multi-hole 2 probe the final hole had to be sealed with aluminium tape as the probe could not be inserted sufficiently into the sample point to completely cover all sample holes.

Probe	Average CO (ppm)	Average CO_2 (%)	Average O_2 (%)
Single	50	8.9	5.8
Multi-hole 1	49	8.9	5.8
Multi-hole 2	48	8.9	5.9

Table 4: Comparison of CO and CO_2 emissions from the fan-flued condensing, combi-boiler

Induced fault tests

Once the normal test programme had been completed, faults were introduced on the appliance. Initially a series of short tests were undertaken to see if the appliance would function and give useful results. The faults considered include:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Blockage of the flue (up to about 90%)
- Blockage of the air intake (up to about 75%)

The preliminary tests showed that the appliance would operate under low and high gas supply pressure. The boiler has a sophisticated control system and changes to the supply pressure were accommodated with change to other process parameters including fan speed to maintain good air:fuel ratio and burner performance. For both the high and low gas pressure fault tests, the output from the boiler was very similar to that for normal operation, i.e. temperature of 73ºC. The similarity of the boiler performance can be seen in Figure 33.

Blockage of the flue was investigated. For lower levels of flue blockage the boiler performance was unchanged. However, as the blocked area approached 80-90% of the flue area the boiler temperature appeared to drop to about 65ºC and the measured CO level dropped to 26ppm. But the boiler was not operating in a stable manner and after about 5 minutes of operation the control system for the boiler "tripped". Repeated attempts to operate for 30 minutes with a blocked flue failed and so this was not used as a full fault test.

The air intake to the burner is a two-stage system. There is the balanced flue annulus to allow air into the boiler box and then a funnel arrangement within the boiler casing to allow air to be drawn by the fan to the burner. In attempting to induce a fault here blockage of the annulus was ignored and only blockage of the funnel was attempted.

The internal section of the boiler showing the blockage is presented in Figure 35 and a close-up photograph of the blocked air intake funnel in Figure 36. Initially the air intake funnel was blocked to about 50% of its active area and the observed changes to the emissions and boiler performance were small. CO emission level increased to 60ppm, but the CO_2 level remained constant and the boiler operating temperature remained at 72ºC. when the degree of blockage was increased to 75%, CO levels rose to about 200ppm and the CO_2 level increased to 10.4%. Attempts to increase the blockage to 90% did give rise to high, transient levels of CO but the boiler only operated for a minute before the control system “shut-down” operation.

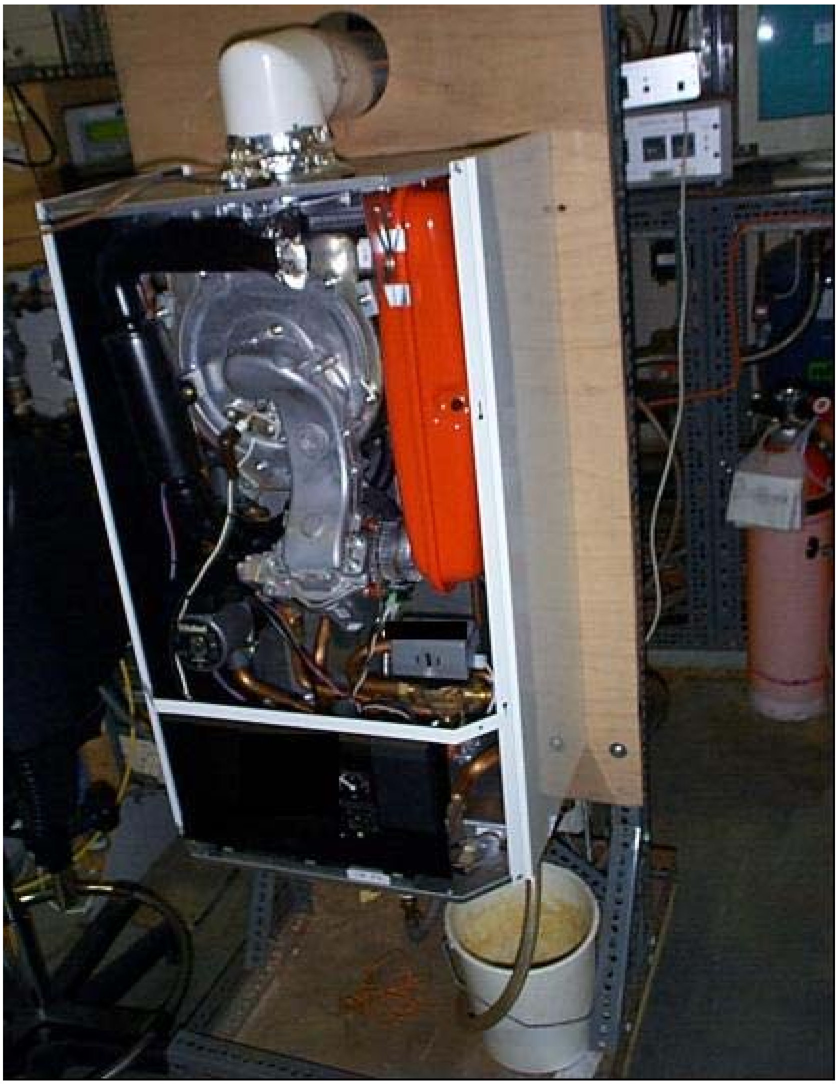

Figure 35: Partially blocked air intake funnel of the combi-boiler

A detailed fault test was thus undertaken for 75% air intake blockage and the results are shown in Figure 33. With the blocked air intake the boiler temperature rose to 76ºC. The time dependence of the emissions profiles remained the same as the normal operation reflecting that the control system was still functioning adequately. The combustion performance ratio for this fault test was significantly higher than for normal operation but it still did not reach the threshold value of 0.004. No “spillage” of combustion products was observed around the sides of the boiler in any of the fault or normal tests.

Figure 36: “Close-up” of partially blocked air intake funnel

4.7 Open flue combi-boiler

A boiler representative of this type was used. The boiler was installed in the test bay and fitted with a 2m flue. The boiler contains an internal pump and so the external pump was not used in this appliance test. All gas and water connections were made so that the boiler could be operated in central heating (CH) and/or direct hot water (DHW) mode. Gas supply connections were made according to the manufacturers instructions. A photograph of the boiler as installed is shown in Figure 37.

Figure 37: Open flue combi-boiler in the test bay

The CH part of the combi-boiler was pressurised to 1.2bar and the boiler was operated in sealed primary system mode. A pressure relief valve was fitted as part of the safety procedure for operating this boiler in the test area.

A sampling point was created in the flue approximately 20cm above the top of the appliance, to comply with the standard test methods as featured in the draft BS7967 standard document regarding insertion depth of the probe to at least 200mm into the secondary flue.

"Normal" test

The format for "normal" operation was similar to that for other boilers. The boiler has a maximum heat input at 20mbar of 27kW to give an output of 24kW, and this setting was used for all normal and fault tests excluding the gas pressure variation tests. The appliance has a governor on the gas supply ensuring that the gas pressure at the burner is controlled. The boiler has a set start-up sequence following switch-on. If there is CH demand then the CH light illuminates and the internal pump starts and the water flow (set externally by means of a control valve) is about 1m^3/hr. The ignition sequence starts and the burner pressure controlled by a governor, is set to 2mbar and the burner ignites. Operation at 2mbar is maintained for about 2 minutes and then the burner pressure ramps to 13mbar over the period of about 1 minute. The boiler temperature on the flow side is about 72ºC and the temperature difference across the boiler (flow – return) is of the order of 15ºC. This temperature difference is controlled by adjusting the cold-water flow through the secondary heat exchanger of the test rig.

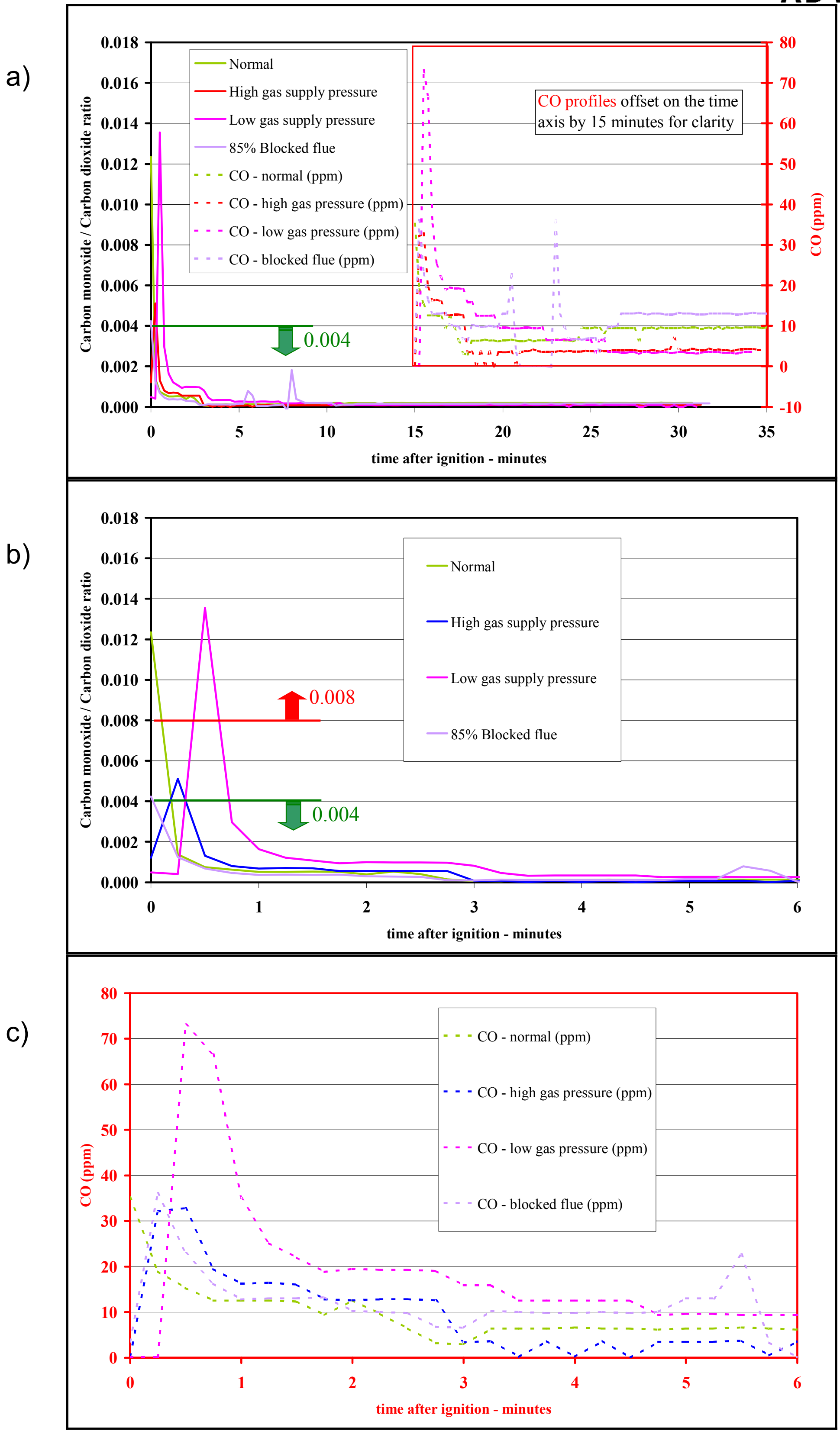

Figure 38: Comparison of "normal" and fault combustion product gas emissions for a combi-boiler (Reduced Scale)

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

Typical CO and combustion performance ratio variation with time are shown in Figure 38 and Figure 39. The format of the emissions profiles is typical of this type of appliance. On ignition at the low burner gas pressure there is an initial peak in the CO emission level (typically of the order of 50ppm), as the appliance is cold. This peak emission rapidly subsides during the low gas pressure operation and CO emission drops to under 5ppm.

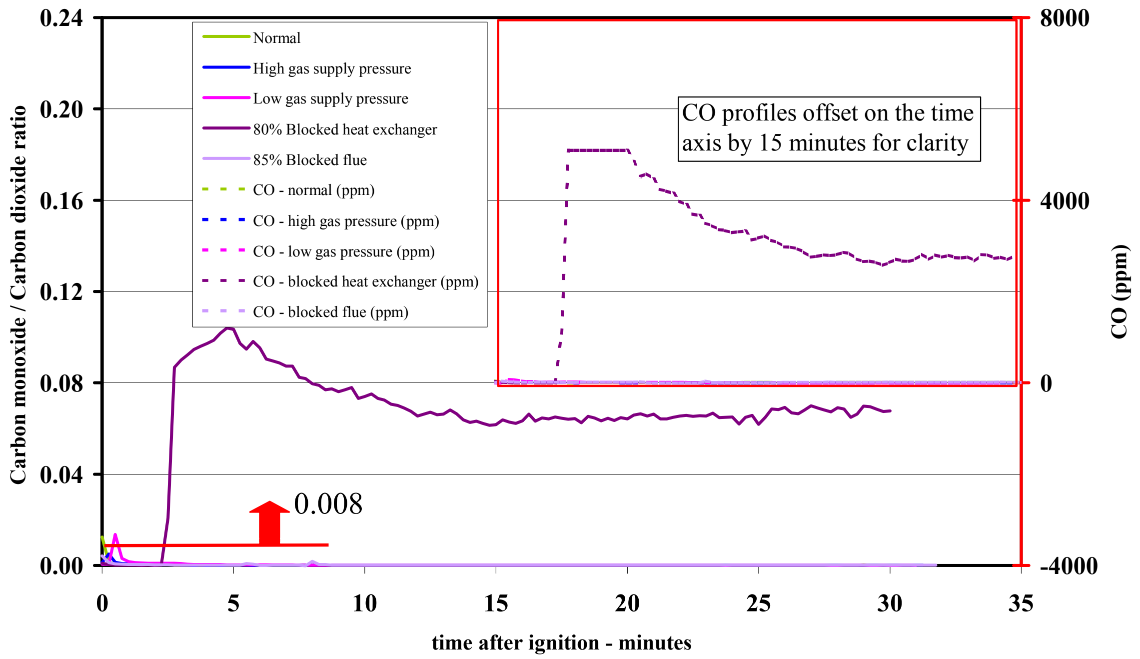

Figure 39: Expanded scale comparison of "normal" and fault combustion product gas emissions for the combi-boiler

As the operation at 2mbar burner gas pressure stabilises, the CO emission levels-off at about 6ppm. When the burner gas pressure increases from 2mbar to 13mbar the CO emission increases to about 10ppm. Although there is an increase in CO emission when the burner gas pressure increases there is a substantial increase in the CO_2 emission and consequently the combustion performance ratio decreases. Under "normal" operation there is no spillage of combustion products from the appliance.

Effect of probe type

Emissions from the appliance were monitored using the three different sampling probe types at separate times when operating under "normal" conditions. The results from these probes are shown in Table 5 and Figure 40.

Probe	Average CO (pip)	Average CO_2 (%)	Average O_2 (%)
Single	10	4.8	12.8
Multi-hole 1	3	4.6	13.0
Multi-hole 2	3	4.6	13.1

Table 5: Comparison of CO and CO_2 emissions for a combi-boiler

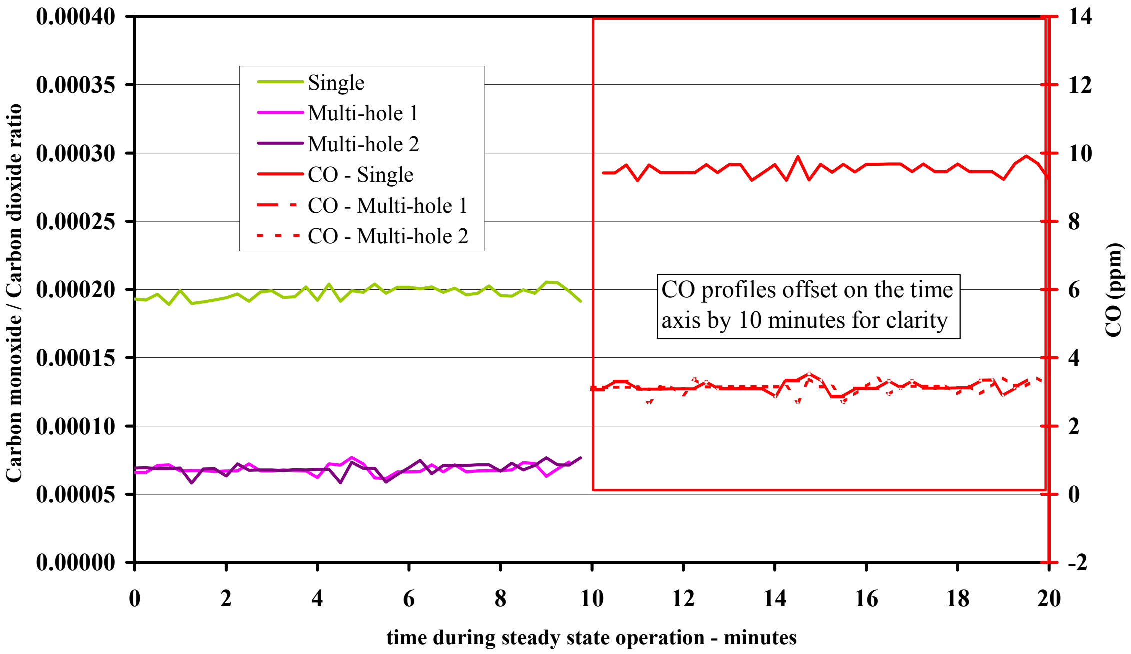

Figure 40: Comparison of CO emissions and combustion performance ratio for different sample probes for the combi-boiler

The appliance has a draught diverter and this impacts on the distribution of combustion products within the flue. The single point open-ended probe shows the highest CO level. The two multi-point probes appear to average the CO level across the flue but interestingly there is no change to the CO_2, and as a consequence there is a significant decrease to the combustion performance ratio.

Induced fault tests

Once the “normal” test programme had been completed, faults were introduced on the appliance. Initially a series of short tests were undertaken to see if the appliance would function and give useful results. The faults considered include:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Blockage of the flue (up to about 80%)
- Blockage of the heat exchanger (up to about 80%)

The preliminary tests showed (see Figure 38 and Figure 39) that the appliance would operate under low and high gas supply pressure. With low gas supply pressure, the performance of the boiler was impaired in terms of boiler temperature but the emissions decreased slightly (CO ~ 3ppm; CO_2 ~ 3.5%). With higher gas pressure, there was no change to boiler performance as the appliance has an internal governor. This resulted in emissions performance equal to the normal test. To overcome this, the internal governor setting was adjusted and a burner gas supply pressure of 22mbar was established with an appliance gas supply pressure of 35mbar. Higher CO emissions were produced but the boiler did not operate in a stable manner, as there appeared to be oscillation of the gas pressure. A full test under these operating conditions was not undertaken. With the blockage of the flue, the spillage shut-off device (TTB) prevented extended operation. However, to enable a full fault test to take place the TTB was unscrewed from the side of the appliance and placed outside of the boiler enclosure. The blocked flue resulted in slightly increased CO emissions and there was clear “spillage” of combustion products from the sides of the appliance.

With the blocked flue tests, the boiler thermal performance did not appear to be adversely affected but there was a significant rise in the CO emissions. With the heat exchanger blocked to about 80% of its active area the CO emissions increased to over 3000ppm resulting in a very high combustion performance ratio. Photographs of the heat exchanger blockage are shown in Figure 41 and Figure 42.

Figure 41: Blocked heat exchanger and internal structure of the combi-boiler

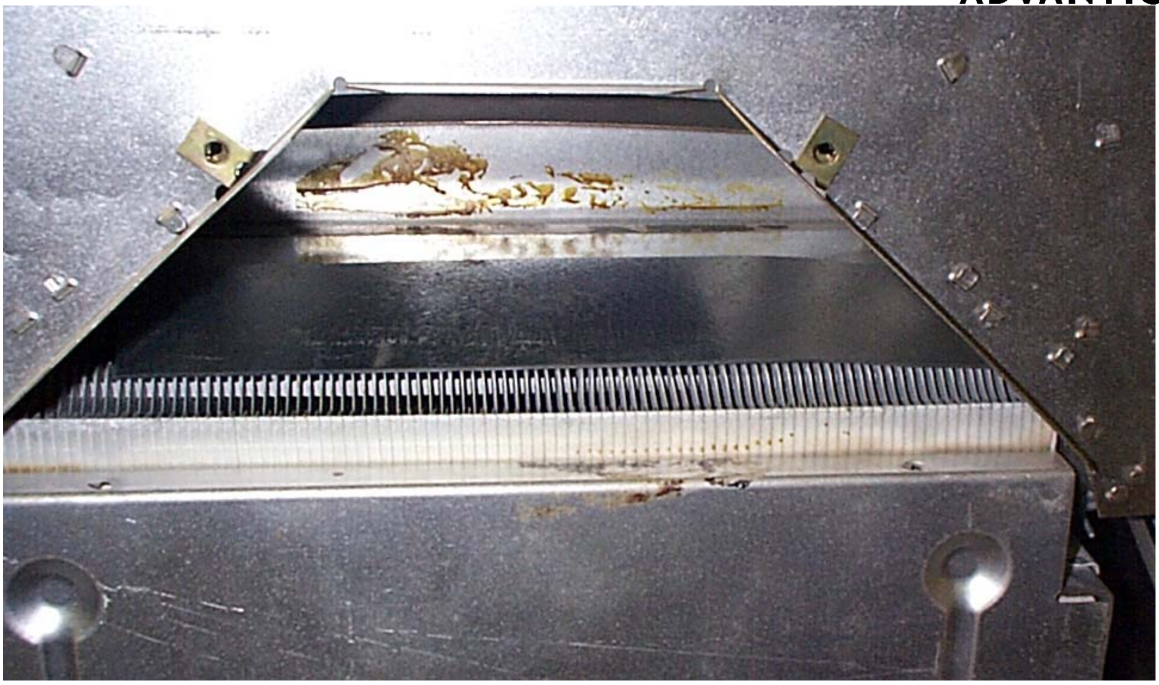

Figure 42: "Close-up" of the blocked heat exchanger

4.8 Combined warm air heater and hot water circulator

A warm air heater coupled with a circulator water heater was installed in the boiler test bay to add a further type of appliance to the study. The warm air heater was an open-flued, fanned circulation, down-flow, ducted warm-air heater mounted on a warm-air plenum. The water circulator which shares the same flue provides primary water flow for an indirect hot water system. A two-metre vertical flue was attached to the top of the appliance to comply with the minimum recommended flue length of 600mm, and the warm air was ducted away safely (see Figure 43). The unit has two burners and each burner has its gas supply controlled by a governor. For the purposes of these tests, both the warm air heater and water circulator were operated at maximum input (12.5kW for the warm air heater @ 14.3mbar; 5.25kW @ 17.0mbar for the water circulator). The water flow rate was adjusted to about $0.08m^3/hr$ as quoted in the operating instructions. The water temperature on the flow side is about 55ºC, in line with the factory set flow temperature of 60ºC. The two burners have independent draught diverters but these are combined before the main flue. A small hole was drilled through the flue to allow probe-access, as it was very difficult to insert the probes through the draught diverter ducts. This enabled the probe to be located at 200mm into the secondary flue.

"Normal" test

The format for the "normal" test is similar to that for other appliances except that in this case two separate burners need to be lit. At the start of the test the electrical supply is connected and the fan for the warm air switched on. Data are logged from this point, initially without the burners lit. After about two minutes, the ignition sequence for the warm air heater commenced. Once the air-heater burner was lit, the ignition sequence for the hot water circulator began. In this way the two burners were lit in series and with a set sequence. This process resulted in a double peak in the CO emission resulting from the start-up of the two burners and this can be seen in Figure 45.

Figure 43: Combined warm air heater/water circulator

These peaks were to levels of about 150 ppm but the CO level did not immediately fall. The CO level remained high for a period of about 10 minutes and then decreased.

Typical measured values for "normal" equilibrium operation are:

- CO ~ 50 ppm
- CO_2 ~ 4%
- O_2 ~ 14%

As the combined system has a common flue it is not possible to differentiate between emissions from the warm air heater and those from the hot water circulator.

Spillage measurements were taken around the appliance during the test and none was observed.

The main observation regarding emissions from this appliance was the apparent sensitivity to air movement in front of the air intake grille. The burners are located near the base of the unit and the combustion air is drawn through the grille, presumably from the lower part. The data presented in Figure 44 and Figure 45 show the variability of the emissions with CO levels showing the highest sensitivity.

Effect of probe type

Emissions from the appliance were monitored using the three different sampling probe types at separate times when operating under "normal" conditions. The probes were used in a fixed sequence and only with the appliance operating a steady, equilibrium state. The results from these probes are shown in Table 6 and Figure 44.

Probe	Average CO (ppm)	Average CO_2 (%)	Average O_2 (%)
Single	52	4.0	14.3
Multi-hole 1	50	3.7	14.8
Multi-hole 2	30	2.5	16.9

Table 6: Comparison of CO and CO_2 emissions for the combined air heater and water circulator

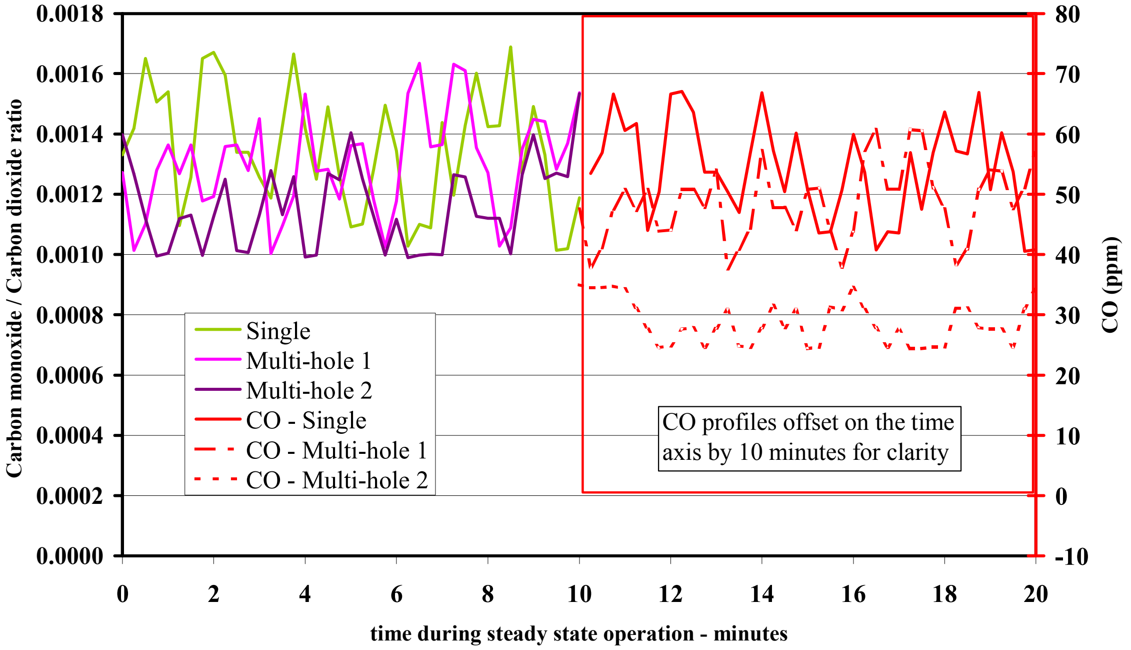

Figure 44: Comparison of CO emissions and combustion performance gas ratio for different sample probes for the combined air heater and water circulator

The appliance is fitted with a draught diverter for each burner, discharging into a common flue. It was impossible to introduce the probe through the draught diverters into the common flue and as a result the probes were inserted into the flue through a hole drilled in the flue side-wall. The measurements show that there is significant variability in the emissions data but on average the single point probe shows higher readings that the multi-point probes. The longer probe (Multi-hole 2) with more holes appeared to give the lowest CO emission reading as a result of sampling a range of points across the flue. This probe also registered the lowest CO_2 reading. The CO/CO_2 ratios for the three probes were similar suggesting that the lower readings for “Multi-hole 2” were a result of dilution by air through the draught diverter.

Induced fault tests

Once the “normal” test programme had been completed, faults were introduced on the appliance. Initially a series of short tests were undertaken to see if the appliance would function and give useful results. The faults considered included:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Blockage of the flue (up to about 80%)
- Blockage of the air intake grille (up to about 90%)

Results of the fault tests are shown in Figure 45.

The preliminary tests showed that the appliance would operate under low and high gas supply pressure, with results similar to normal operation. With low gas supply pressure, the performance of the hot water circulator was slightly impaired in that the outlet temperature was lower by about 5ºC. The CO emissions were significantly lower at 25ppm compared to 50ppm for normal operation. The CO_2 emission was 3.1% compared to 4.0% for normal operation. With higher gas pressure, there was no change to boiler performance as the appliance has an internal governor and the emissions and overall thermal performance was the same as for the normal test.

Partial blockage of the flue was examined. Initially, 80% blockage of the flue area was tested but this resulted in the TTB (thermal down-draught sensor) shutting-down the warm-air heater part of the appliance, as there was significant spillage through the draught diverter. Even though the air heater had shut-down the hot water circulator continued to operate. The TTB trip prevented re-light of the air-heater burner for over 10 minutes. During this shut-down period the partial blockage of the flue was reduced to 60%. A full-fault test was possible with this degree of blockage and the emissions of CO increased to about 150ppm with 7.5% CO_2 emission.

Partial blockage of the air intake grille was tested. 90% of the grille area was blocked and the resulting operation of the appliance monitored. The appliance continued to be sensitive to air movement, especially during the initial start-up and recovery to equilibrium. However, steady, equilibrium operation was maintainable and the emission levels were CO about 35ppm with 4.3% CO_2. Unexpectedly, the CO emission was lower than for normal operation.

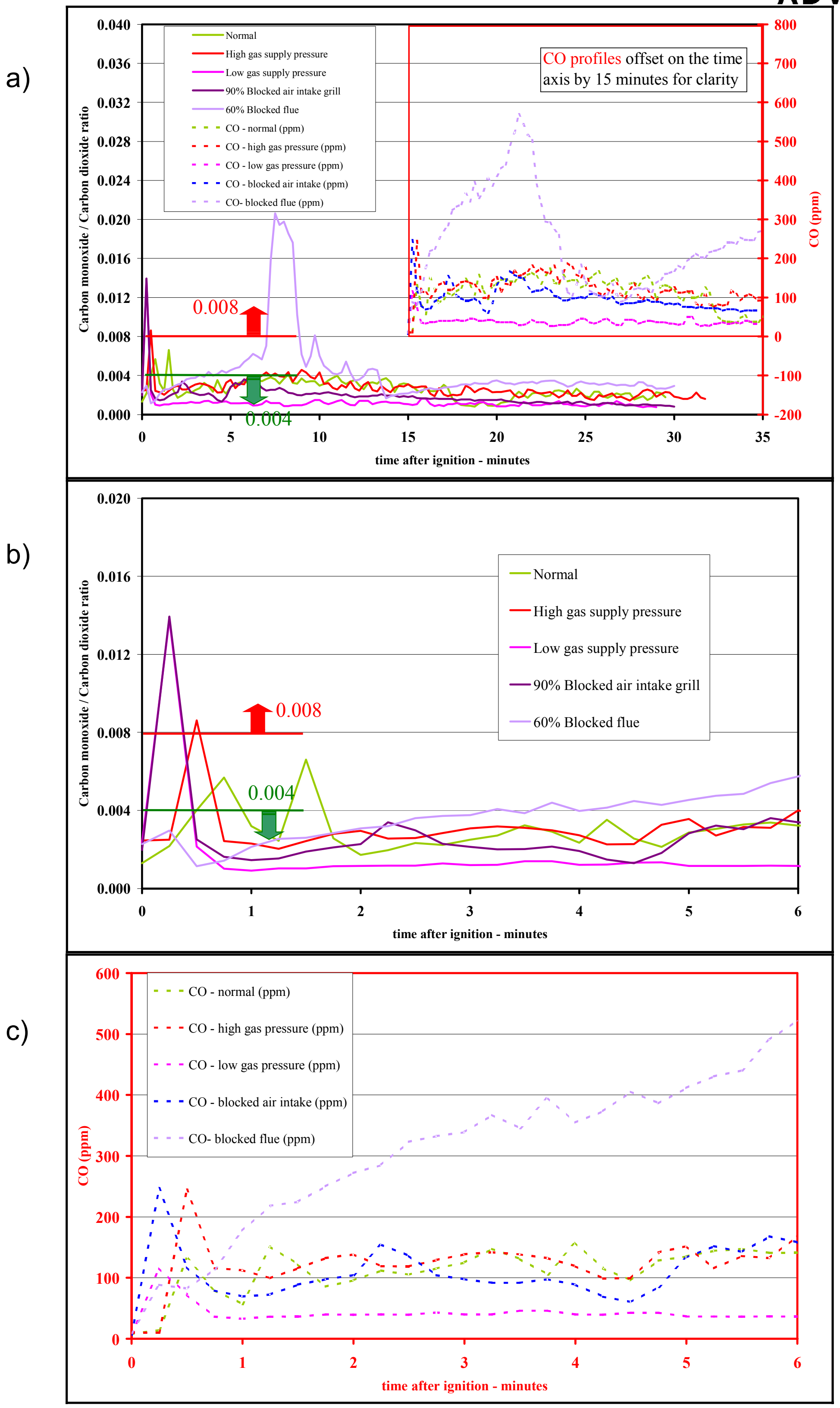

Figure 45: Comparison of "normal" and fault combustion product gas emissions for the combined air heater and water circulator

a) CO/CO_2 and CO b) CO/CO_2 expanded scale c) CO expanded scale

4.9 Fan-flued, wall-hung boiler

A boiler representative of this type was used. This boiler is a wall mounted, balanced fan-flued appliance and is room-sealed. The combustion air is drawn through the balanced flue into the interior of the casing and is then used in the burner. Combustion products are discharged from the appliance through the balanced flue by means of a fan. The boiler uses an external pump and the water flow-rate was controlled and measured using a valve and rotameter arrangement. The water flow-rate was set at about 0.7 m^3/hr in accordance with the manufacturers installation instructions.

A photograph of the appliance is shown in Figure 46.

Sampling of the combustion products was via probe insertion through the end of the flue as no other sampling point was available. Sampling of the combustion products through the appliance was not undertaken, as this would have impacted on the room-sealed nature of the appliance.

All tests on the boiler were performed with at the maximum rating of 10.8kW heat input and 8.8kW boiler output.

Figure 46: Fan-flued boiler

"Newness" tests

The appliance was obtained new from the supplier and as such the first tests investigated the impact of appliance "newness" on the CO emission. The results from the "newness" tests are shown in Figure 47. The tests undertaken show that there is very little difference in emissions between the first operations when the boiler was installed to a test undertaken after several start/shut-down cycles. The form of the emissions is similar to that for other appliances in that there is a peak in CO (and hence CO/CO_2 ratio) following ignition. This peak emission rapidly declines to a very low, steady level. The CO peak is higher for the first test that subsequent ones but this could be attributable to normal variability of operation and the key feature is that the rate of recovery from this high emission to steady operation is very short (less than 2 minutes). There appears to be no "settling-in" period for the boiler and it has very good emissions performance from the moment it began operation.

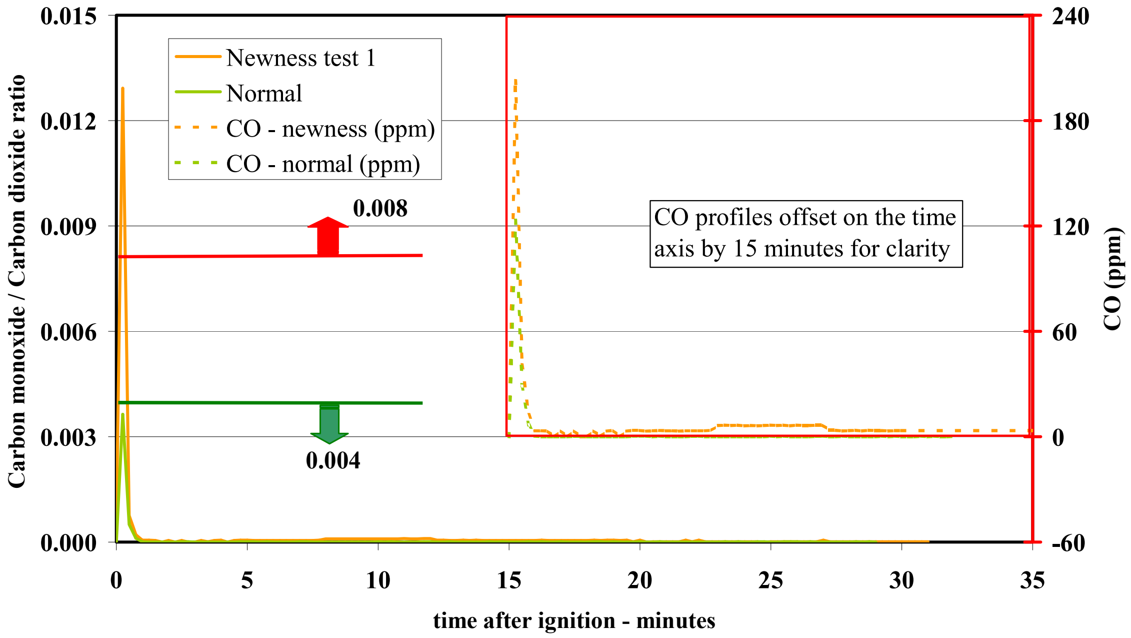

Figure 47: Comparison of "Newness" and "Normal" emissions tests from the fan-flued boiler

"Normal" test

Once the "newness" tests had been completed, "normal" boiler operation was studied. Here the water flow and boiler were set-up in accordance with the manufacturers instructions with burner pressure of 12.4 mbar, water flow of 0.7 m^3/hr, a steady-operation boiler temperature of about 55ºC and a temperature difference across the boiler (flow – return) of 11ºC.

The boiler required approximately 20 minutes to establish thermal equilibrium and CO emissions from the boiler were very low. Typical measured values for "normal" equilibrium operation are:

- $CO \sim 5$ ppm
- $CO_2 \sim 7\%$
- $O_2 \sim 9\%$

One interesting feature of this appliance is that when the boiler is switched off and the fan stops drawing the combustion products from the appliance there is a rise in the measured CO within the flue. This originates from the "switch-off" process and is caused by the fan not discharging the combustion products after the electrical supply to the boiler has been turned-off.

Effect of probe type

Emissions from the appliance were monitored using the three different sampling probe types at separate times when operating under "normal" conditions. The results from these probes can be seen in Table 7 and Figure 48.

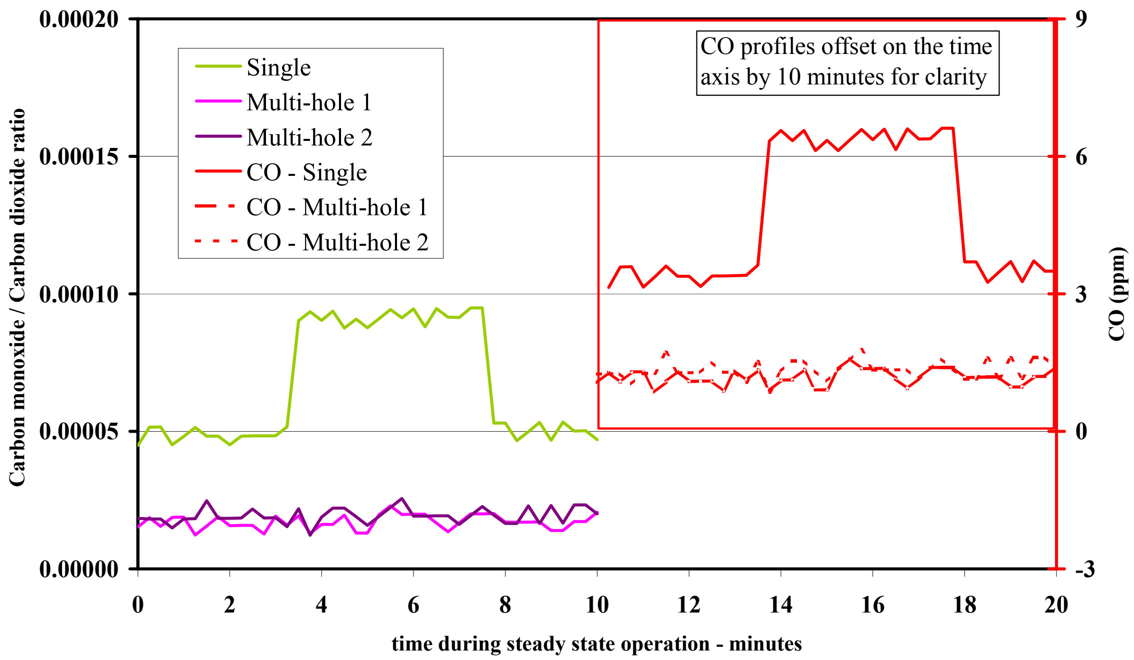

Figure 48: Comparison of CO emissions and combustion performance ratio for different sample probes for the fan-flued boiler

CO emissions from this appliance are very small. Although there is a difference between the single-point and multi-hole probe results this is not significant as the absolute values of CO are less than 7 ppm for all probe types. Locating the multi-hole probes in the flue was not straightforward due to the 90° bend in the probe. However the results for the three probes are consistent.

Probe	Average CO (ppm)	Average CO_2 (%)	Average O_2 (%)
Single	5.4	6.9	8.9
Multi-hole 1	1.2	6.9	8.9
Multi-hole 2	1.4	6.9	8.9

Table 7: Comparison of CO and CO_2 emissions for the fan-flued boiler

Induced fault tests

Once the "normal" test programme had been completed, faults were introduced on the appliance. Initially a series of short tests were undertaken to see if the appliance would function and give useful results. The faults considered include:

- High gas supply pressure (35 mbar)
- Low gas supply pressure (10mbar)
- Blockage of the flue (up to about 90%)
- Blockage of the air intake (up to about 90%)
- Blockage of the heat exchanger (up to about 90%)

The appliance has a governor on the gas supply and so there is no effect on operation of increasing the supply pressure to the boiler. Reducing the supply pressure resulted in lower carbon dioxide emission levels and reduced boiler output temperature for the same water flow settings. With low gas supply pressure no CO emission was registered on the Siemens IR analysers.

Variation of the gas supply pressure did not impact on the response of the boiler in that the time taken to reach a steady emission level remained at around 2 minutes. As with other boiler tests, the time to reach an equilibrated boiler flow and return temperature here takes of the order of 20 minutes.

Results of the normal and fault tests are shown in Figure 49 and Figure 50.

In Figure 50, the scale on the y-axis has been expanded to show the equilibrium steady-state combustion performance ratio and to give good resolution of the 0.004 and 0.008 limits.

Blockage of the heat exchanger results in very high peak CO emission following ignition of the boiler. However, the high levels are not maintained and good emissions performance is established after a few minutes. Blockage levels up to 90% of the open area of the heat exchanger were tested and the outcome of the tests showed that the 0.004 CO/CO_2 emission level was not approached.

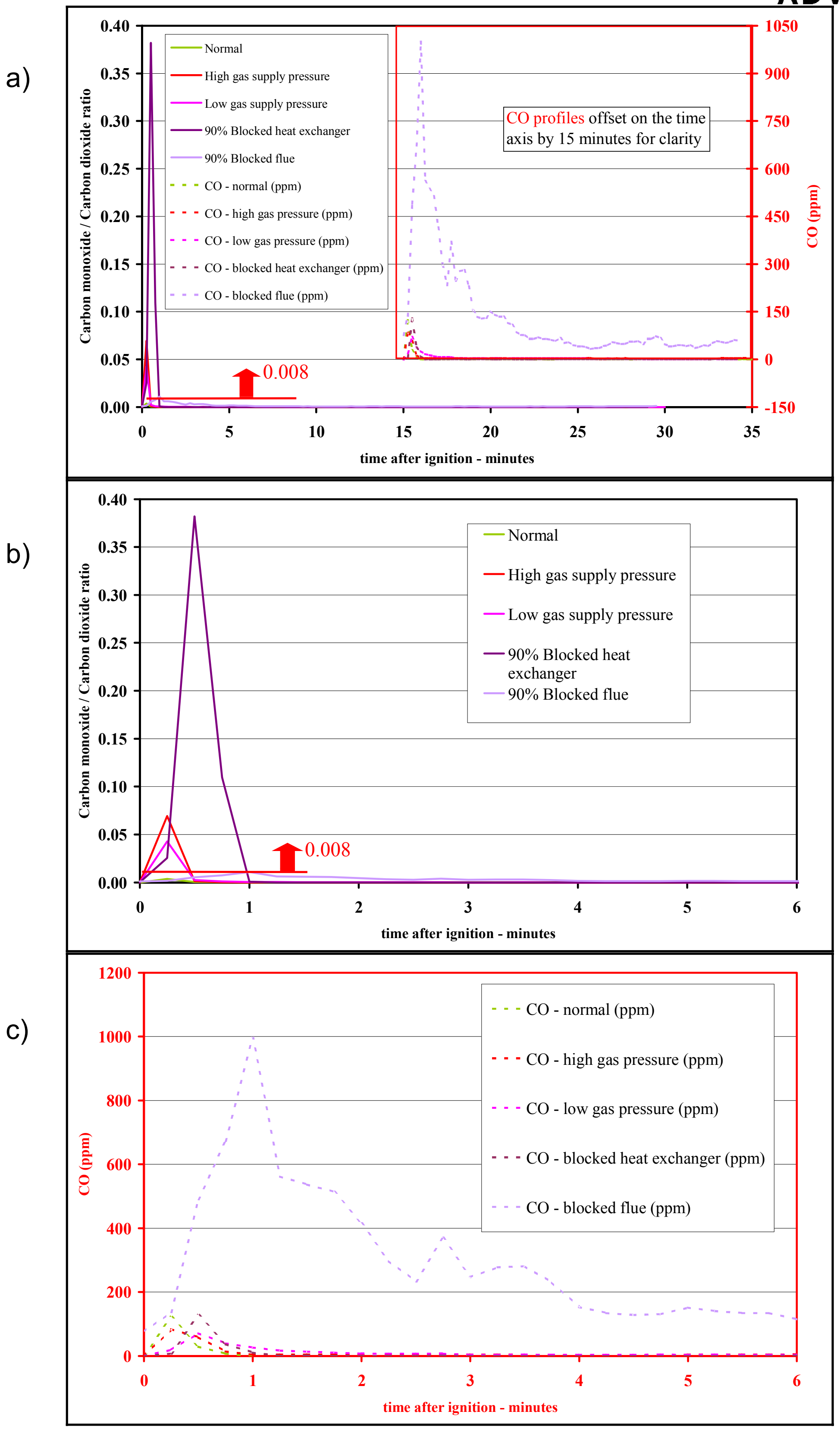

Figure 49: Comparison of "normal" and fault combustion product gas emissions for the fan-flued boiler

a) CO/CO_2 and CO   b) CO/CO_2 expanded scale   c) CO expanded scale

Blockage of the air intake, i.e. the outer annulus of the balanced flue, did result in higher emission levels but the results were very sensitive to the degree of blockage. With blockages of the available area up to about 80%, the results showed no change to the emissions behaviour of the appliance compared to normal operation. An increase in the blocked area to 90% resulted in a transient rise in emissions but the boiler cut-off was activated as a result of the pressure switch. An extended period of operation could not be established with blockages over 80% and so a full test with blocked air intake was not performed.

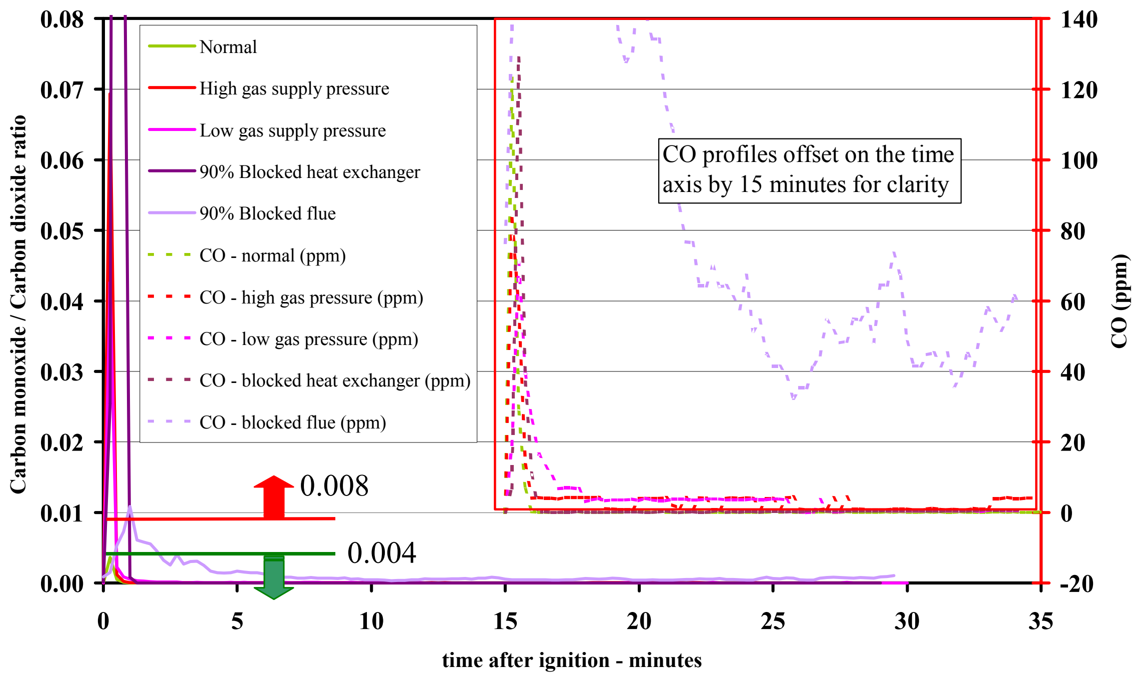

Figure 50: Comparison of "normal" and fault combustion product gas emissions for the fan-flued boiler (expanded scale)

Blockage of the flue was attempted. In the same way as blockage of the air intake, the level of blockage had a significant impact on the operation of the boiler. With blockages up to about 60% there was no change to the emissions over that of a normal test. With 70% blockage there was a small increase to the CO emission level with values of 15ppm observed. With 90% blocked area there was apparent flame lift and pulsing of the flames showing a rapid cycle of lifting and re-attachment. Substantial CO emissions resulted but the CO/CO_2 ratio still equilibrated to less than 0.004. Increasing the blocked area to greater than 90% resulted in tripping the boiler. A full-fault test was performed with about 90% blockage and the results are shown in Figure 49 and Figure 50. The results show two interesting features. Firstly that the peak CO emission is lower following ignition of the boiler and secondly that the decay to the steady level appears to take significantly longer than for normal operation. Although the results show a CO/CO_2 ratio in excess of 0.008 following ignition, this value decays down to less than 0.004.

4.10 Summary of Phase 1 test results

There are several general comments that arise from analysis of the Phase 1 test results:

- Modern gas-fired appliances are robust and it is difficult to induce faults that give rise to excessive combustion performance ratios.
- Different appliances are most sensitive to different induced faults, eg. boilers appear most sensitive to blockages of heat exchangers or air inlets, whereas fires are most sensitive to arrangement of the "coals".
- Under "normal" operation the establishment of steady-state, equilibrium conditions occurs rapidly, typically less than 10 minutes. However, open-flued, natural draught appliances appear to require longer times to reach steady operating conditions.
- "Newness" effects appear most significant for fires with ceramic simulated fuel elements ("coals") and do not impact on appliances with metal heat exchangers.
- Under "faulty" operation the time to reach steady operating conditions is often longer than for "normal" operation. Boilers appear most sensitive to this.
- CO emissions show a peak following light-up of the appliance. The peak value can be very high (eg. >1000 ppm) but it drops rapidly for most appliances.
- Sampling probe location and design can impact on the measured emission and combustion performance ratio values.

5 PHASE 2 – APPLIANCE TEST PROTOCOL

5.1 Procedure and Protocol

For Phase 2 of this Project, Transco emergency response engineers were invited to perform combustion tests on each of the nine appliances as set up in the laboratory at Advantica, according to a protocol developed in Phase 1 (shown in Appendix 1 and 2). Each appliance was tested twice in one week, once in normal operating condition and once with one of the simulated faults from Phase 1 applied. On arrival the aim of the exercise, use of the analyser and the safety measures in place were explained to each engineer. The engineer was not advised whether the appliance was faulty, so did not know the nature of any fault. The engineer was asked to make the usual visual inspection of the appliances and where there wasn't a designated sampling point, use judgement to decide where the sampling probe should be positioned. A second single probe was used to sample the emission levels for the Siemens analyser that logged the data throughout each test. The engineer was then asked to operate the FGA instrument and to follow the instructions and take the readings required by the protocol, entering the results in a table, and providing short written answers to a few questions (see Appendix 1 and 2). Copies of the questions are included in the Appendix. A filtered FGA (ie. the electrochemical cell in the analyser has a filter to remove contamination effects of other trace components), a stopwatch and the single probe were used throughout this second phase of the project. It was also explained to the engineers that from the protocol point of view, it is thought 10 minutes would be more than sufficient but to increase the level of familiarity an extra reading at 15 minutes was also included in the exercise. To reduce human errors it was requested that the same two engineers attend twice a week, testing the appliances in both normal and fault situations. However for various operational reasons and engineer availability, in total 5 engineers attended the 6 weeks testing period, one attending 6 sessions, two attending 4 sessions and 2 attending two sessions.

5.2 Appliances tested and faults applied

The appliances tested and key faults are shown in Table 8.

Appliance	Simulated Fault(s)
Open flue combi-boiler	80% blocked heat exchanger
Fan-flued boiler	90% blocked flue
Fan-flued combi-boiler	Air intake partially blocked
Open flue boiler	90% blocked heat exchanger
Warm air heater and hot water circulator	80% blocked flue
Flueless water heater	High gas supply pressure
Balanced flue fire	Loose glass front panel
Open flue, coal-effect fire	High gas supply pressure
Flueless fire	Partially blocked catalyst

Table 8: **Appliances and the introduced faults for the Phase 2 tests**

The data from Phase 1 were used to determine the faults to introduce for each appliance. It was thought important to introduce faults that would not be easily seen during a usual inspection and also ones that give rise to elevated emissions in order for the engineers to potentially notice a difference using the portable flue gas analyser.

5.3 Comparison of results

For all of the appliances the CO/CO_2 ratios recorded by the Siemens analyser and the by the engineers using the FGA are plotted and discussed individually.

Open flue combi-boiler

This boiler has a start-up sequence following switch on, operating at 2 mbar for 2 minutes, and then ramping to 13mbar over a period of 1 minute.

The test data are shown in Figure 51.

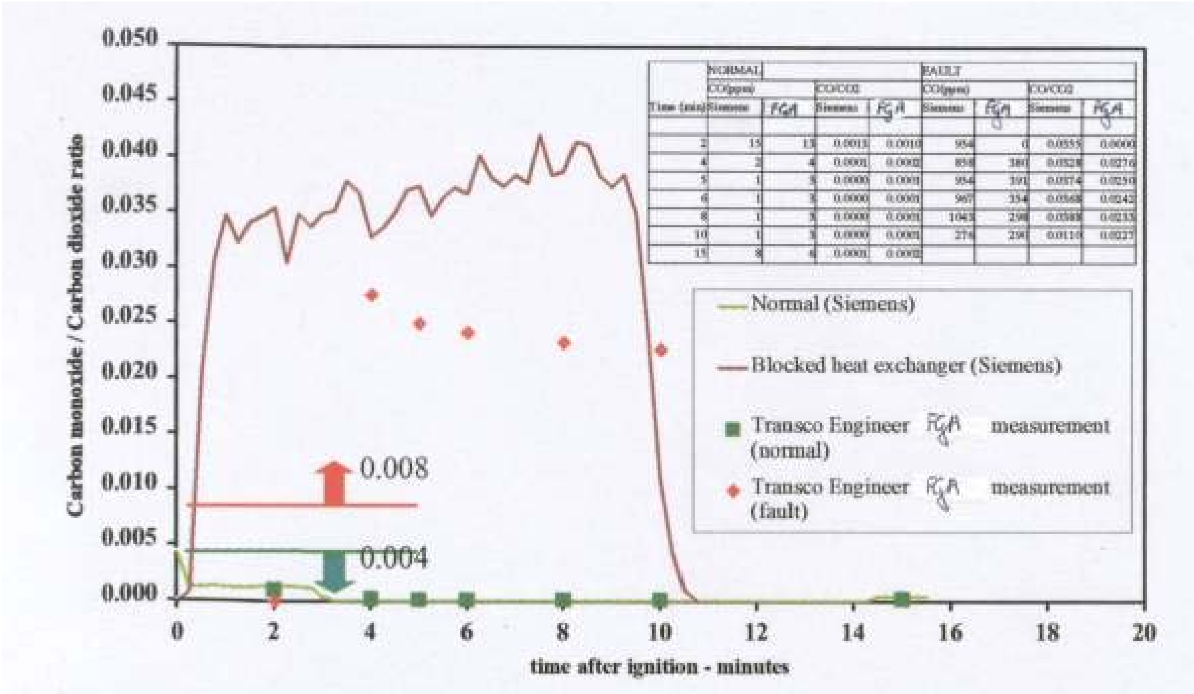

Figure 51: Comparison of engineer tests with logged data for an open flued combi boiler

For normal operation, the Siemens data corresponded well with that recorded by the engineers using the FGA. As in Phase 1, blocking the heat exchanger resulted in high CO/CO_2 but the FGA ratios were lower than those recorded by the Siemens analyser and the CO levels recorded by the Siemens were almost 3 times that recorded by the FGA.

For this appliance there was a slight delay in the engineer turning on the stopwatch and the FGA probe was inserted to a different depth from that for the Siemens analyser. The combination of these factors may have resulted in the lower readings recorded by the FGA.

Fan-flued boiler

For this boiler operating under “normal” conditions, steady state was reached in less than 2 minutes. The readings taken by the engineers using the FGA corresponded well with those recorded by the Siemens analyser.

For the fault condition of blocked flue, readings recorded by the engineer are approximately one minute out of sequence from those recorded by the Siemens, resulting from the late starting of the stopwatch. Taking this into account, the two sets of data recorded by the engineer and the data from the Siemens analyser matched well.

The test data are shown in Figure 52.

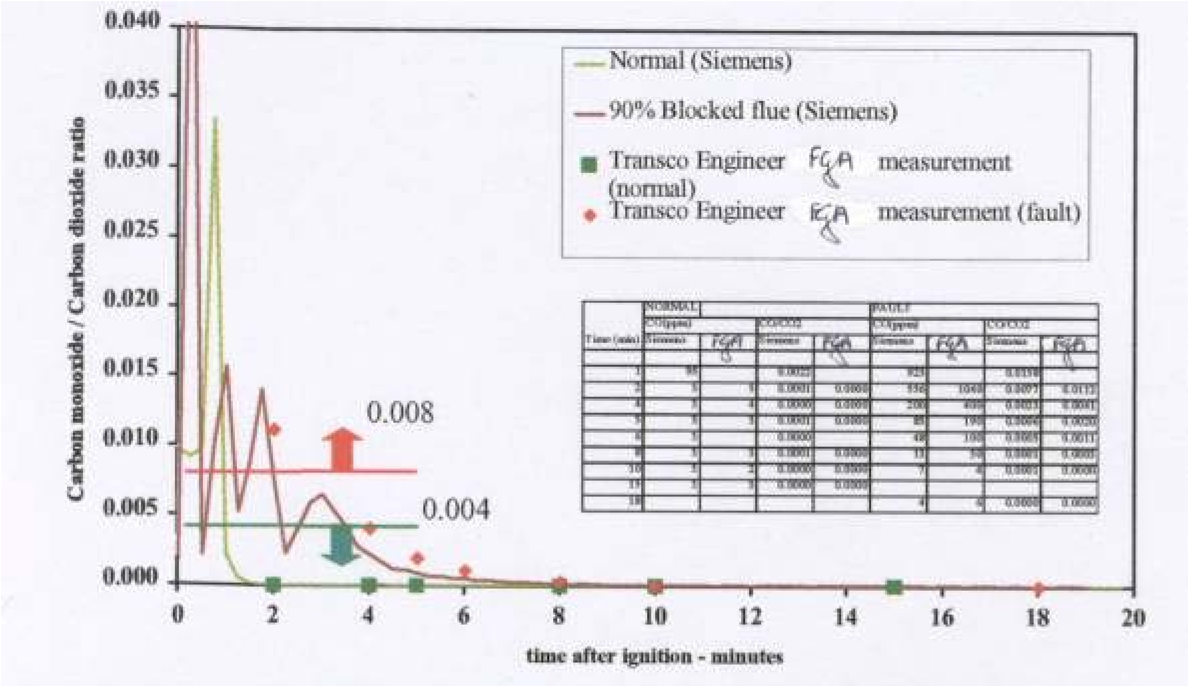

Figure 52: Comparison of engineer tests with logged data for an fan-flued boiler

Fan-flued combi-boiler

This boiler had a complex full sequence ignition and control system, with a sophisticated fault diagnosis indication system. This prevents operation with faults causing excessive emissions. For normal operation, the CO emission levels recorded by the FGA were higher than those recorded by the Siemens analyser, resulting in higher CO/CO_2 ratios.

A similar trend was observed for the blocked air intake fault condition, higher CO/CO_2 ratio being recorded for the FGA than the Siemens.

On the whole, good correlation consistent with a fan-flued appliance was observed.

The test data are shown in Figure 53.

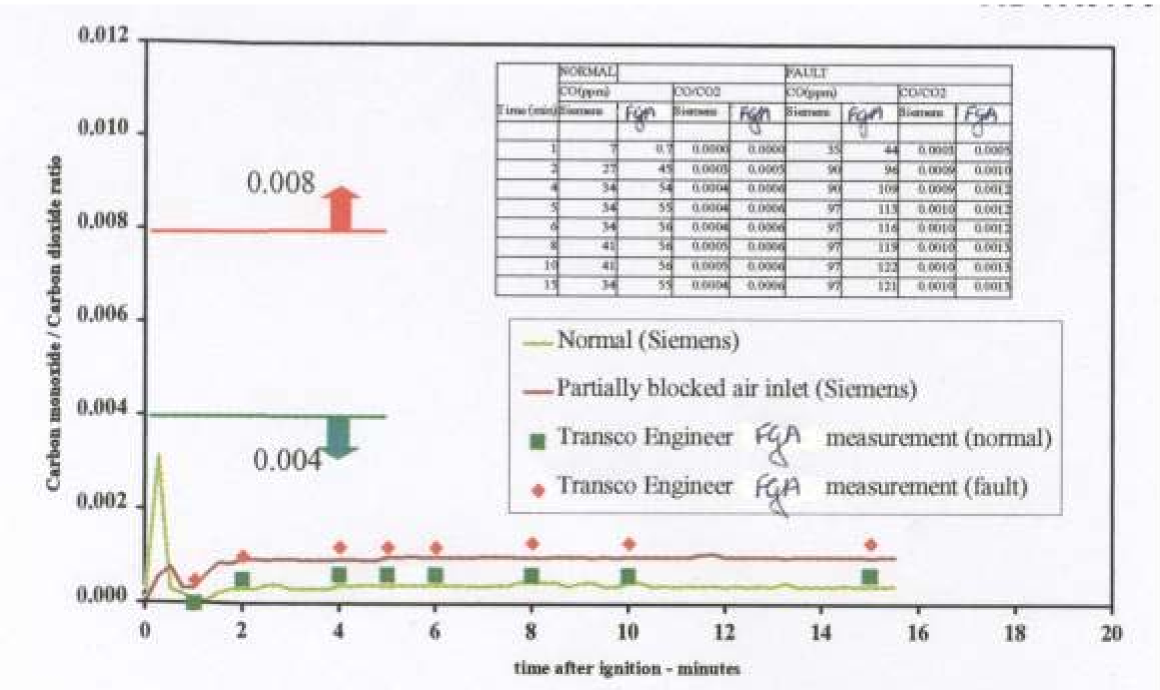

Figure 53: Comparison of engineer tests with logged data for an fan-flued combi boiler

Open flue boiler

For normal operation, steady state was established quickly, in less than 2 minutes. However, for certain fault conditions the time to reach steady operation can be greater than 5 minutes. For both normal and fault operations the FGA CO/CO_2 recordings, measured by the test engineer, were slightly lower than those of the Siemens resulting from lower CO emission levels recorded by the FGA.

Blocking the heat exchanger resulted in a fault condition with CO/CO_2 ratio that increased with time from 0.01 to 0.05 over a period of about 8 minutes. Due to instability of the emission levels the CO levels recorded by the FGA were about 100ppm higher than that recorded by the Siemens at first but this difference increased to nearly 300 ppm over the 15-minute test period. This rise in CO emission levels was reflected in much higher CO/CO_2 ratios having been recorded for the FGA than the Siemens analyser.

For this appliance, the engineer placed the FGA probe within the secondary flue but not centrally as in the case of the sampling probe for the Siemens analyser. Previous tests have demonstrated that in cases of natural draught, open flue appliances, there can be variation in the measured CO and CO_2 emission concentration horizontally and this may account for the differences between the results for different analysers obtained here. The test data are shown in Figure 54.

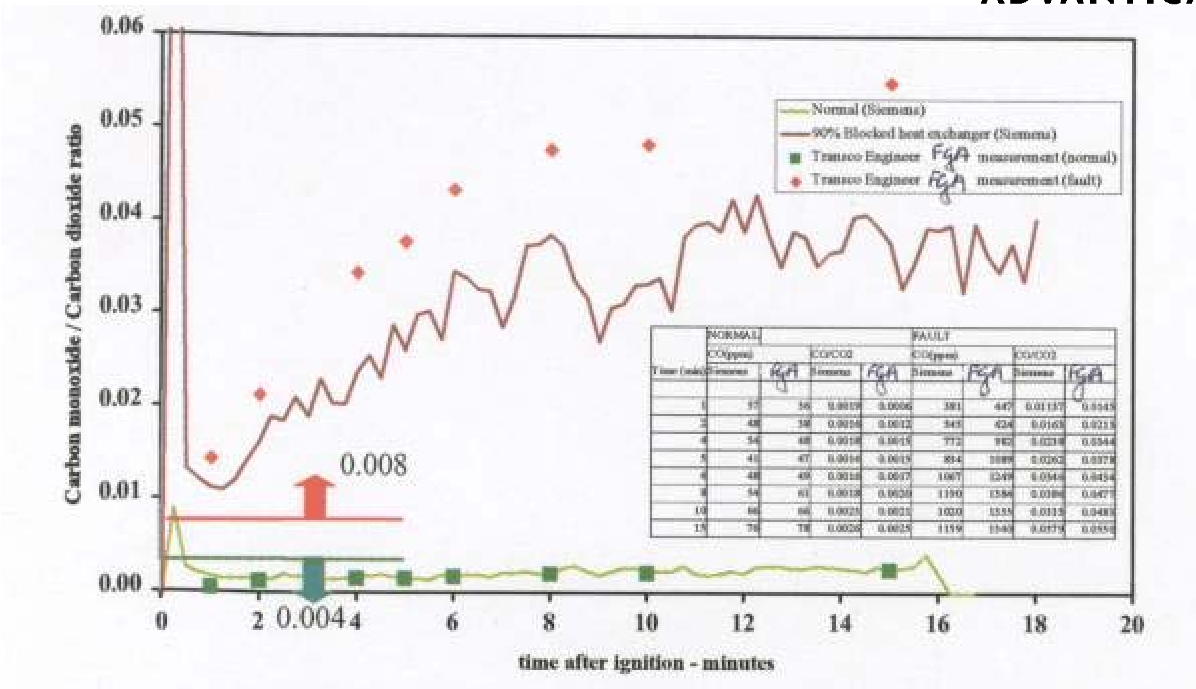

Figure 54: Comparison of engineer tests with logged data for an open flued boiler

Warm air heater and hot water circulator

This is a combined appliance with two independent burners that need to be lit in turn resulting in a difficulty in assigning a “start time” for the test.

For both normal and fault operation, steady state is reached in less than 2 minutes but higher CO and CO/CO_2 ratios were recorded by the FGA than the Siemens analyser.

As in Phase 1, emission levels recorded for this appliance were sensitive to air movement in front of the air intake grille, where the burners are located and where, presumably, combustion air is drawn in. Also around 6-7 minutes after the start up, the TTB for the air heater tripped but the hot water circulator burner continued (having a coupled draft diverter with the air heater). This resulted in a decrease in CO_2 emission levels, which in turn resulted in a peaking of the CO/CO_2 ratios around that time.

The test data are shown in Figure 55.

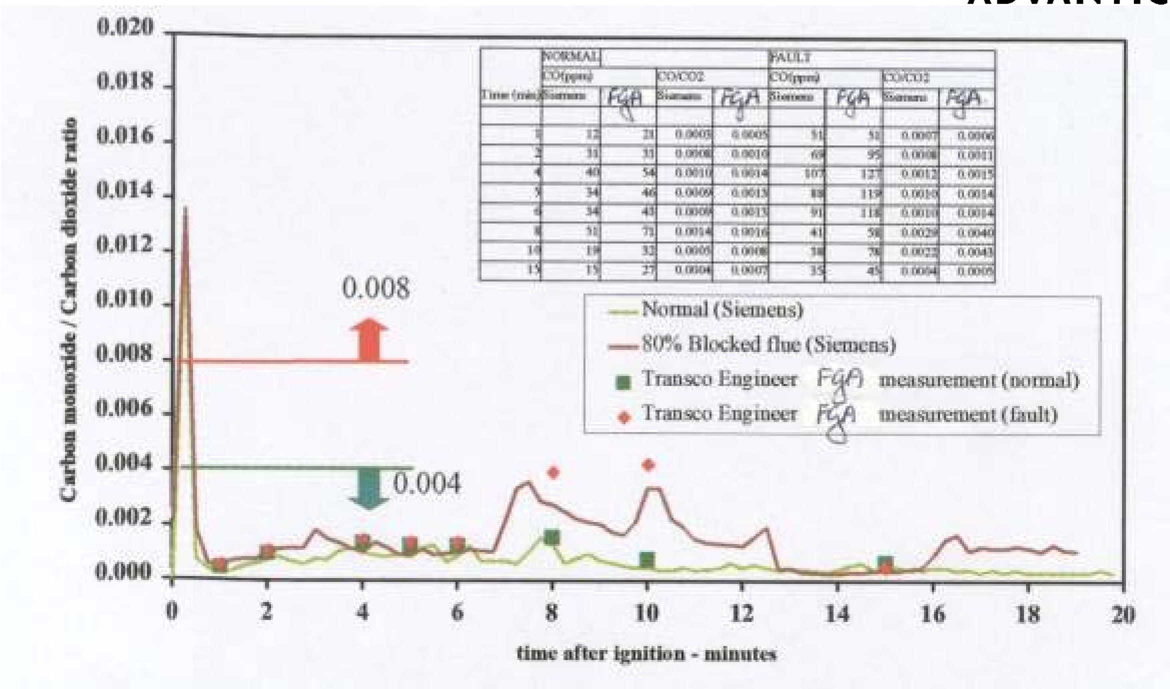

Figure 55: Comparison of engineer tests with logged data for a combined air heater and hot water circulator

Flueless water heater

For normal operation, the CO/CO_2 ratios recorded by the FGA and Siemens compared well. Increasing the gas supply pressure resulted in higher CO/CO_2 ratio for the steady state equilibrium. Surprisingly, very low CO readings were recorded by the engineer using the FGA compared to that for the Siemens [5-7 ppm (FGA) compared to 55-96 ppm (Siemens)]. The CO/CO_2 ratios for the fault condition recorded by the FGA were in fact lower than those recorded for the normal test.

For this appliance, the sampling probe for the Siemens was placed centrally above the heat exchanger but the engineer placed the probe too near the edge of the heat exchanger and was not sampling combustion products from the main flow. These factors resulted in the sample being dilute and then further diluted with air before it was drawn in for analysis by the FGA.

The test data are shown in Figure 56.

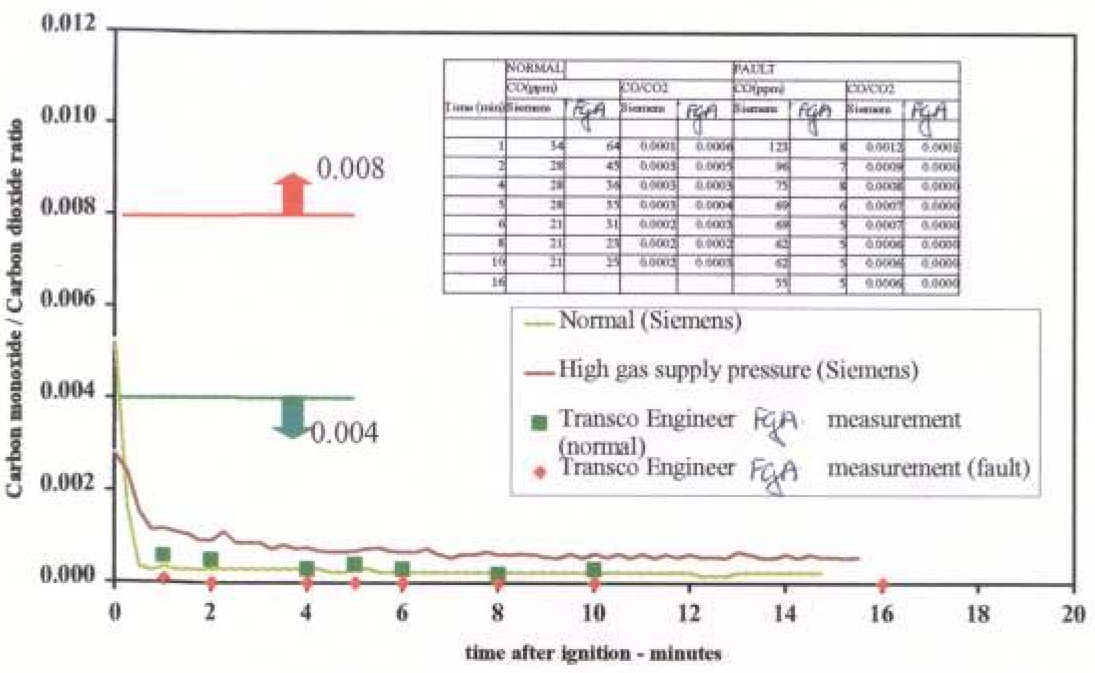

Figure 56: Comparison of engineer tests with logged data for a flueless water heater

Balanced flue fire

This is a room sealed inset live fuel effect fire. The results from Phase 1 indicated that the fire took over 5 minutes to reach steady state. The Phase 1 data show that it is difficult to induce fault conditions and this was observed in this current phase also.

The trends in emissions are shown in Figure 57 for normal operation and the effect of loosening the front glass front panel.

For both the normal and fault conditions, the data recorded by the FGA and Siemens analysers compared well.

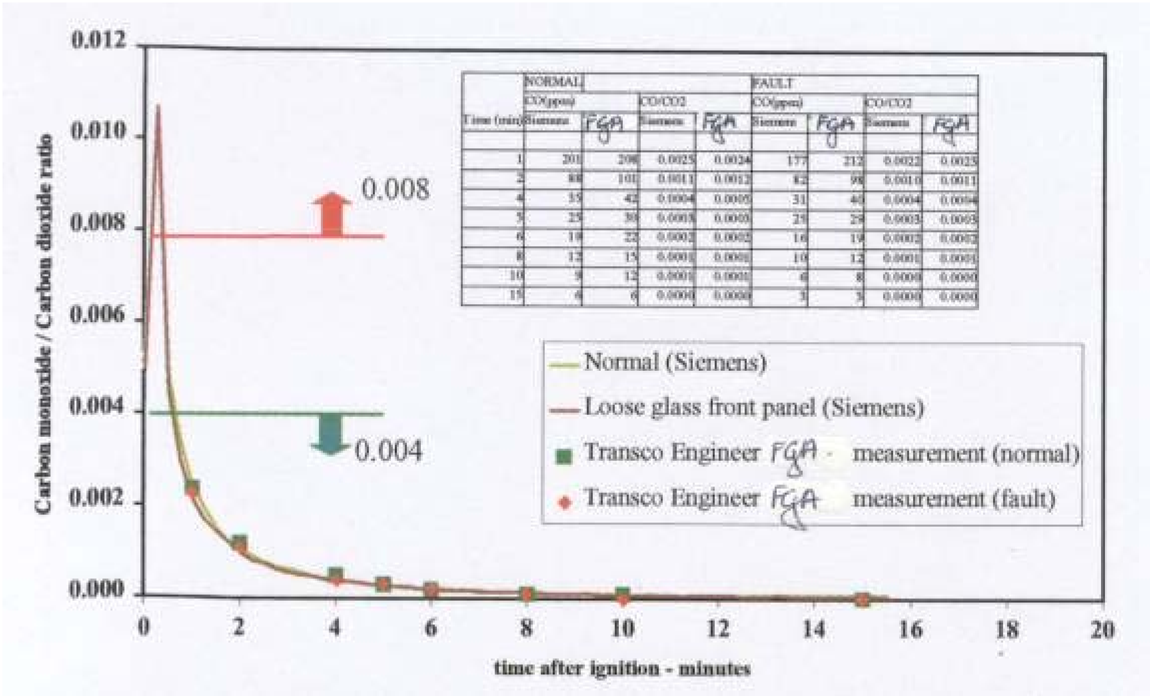

Figure 57: Comparison of engineer tests with logged data for a balanced flue fire

Open flue-coal effect fire

Phase 1 data showed that this open flue fire would produce significant levels of CO under some fault conditions. Initially the plan for Phase 2 was to compare “normal” operation with that involving rearrangement of the decorative coals (ie. a fault condition).

There are several interesting features in the test data for this appliance. In Phase 1, there was a high CO emission attributed to the binders on the coals undergoing a heat release mechanism. This burning off of the binder was thought to be complete after the Phase 1 tests had concluded. After completion of the first phase, the fire was stored away. When the fire was reinstalled for the Phase 2 tests, the coals were again arranged according to manufacturers installation instructions but the coals did not necessarily have the same face exposed to the gas flame. This appeared to result in further release of CO from the heating of the binders during the “normal” test. The fault test was carried out in the afternoon after the coals had been heated for the normal test, for a few hours. This resulted in lower CO emission levels, hence the CO/CO_2 ratios were higher for the normal than the fault test.

During the normal operation of this fire, the engineers commented on the various calls that they receive regarding such fires and in majority of the cases the fault has been due to incorrect arrangement of the coals. Therefore for the purposes of introducing another fault for the engineers, high gas supply pressure was used in the fault operation of this fire instead of the initially planned coal rearrangement.

The double peaking for the normal trend is due to the engineer turning off the appliance in error instead of setting it to maximum heat input.

The test data are shown in Figure 58.

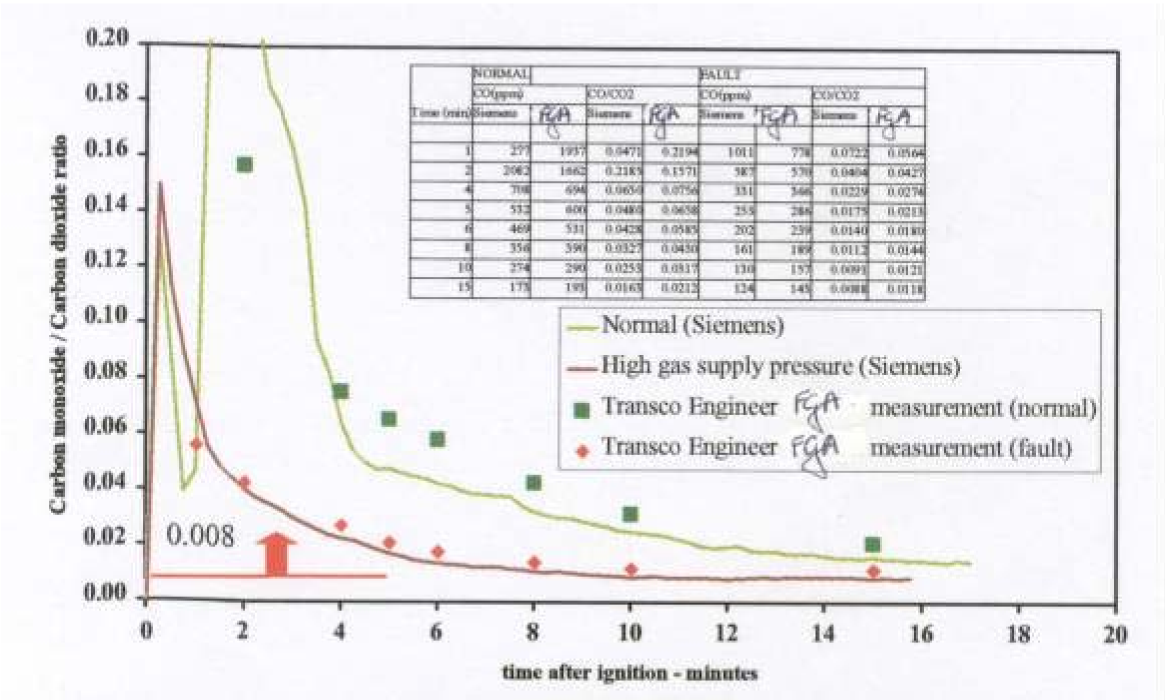

Figure 58: Comparison of engineer tests with logged data for an open flue inset live fuel effect fire

Although the results shown in Figure 58 indicate that emissions from the appliance measured under the high gas supply pressure fault condition are lower than those from the "normal" test, this is attributed to the impact of the binder on the coals and their rearrangement following the Phase 1 tests, as explained in previous sections.

The key feature of tests on this appliance was that the measurements made by the engineer using the portable FGA correlated with those from the Siemens analyser.

Flueless fire

This stove is a flueless fire fitted with a catalyst in the exhaust vent to oxidise the CO to CO_2 before it is vented. Initially before the catalyst has warmed up, high CO levels are recorded by both FGA and Siemens analysers, for both normal and fault operating conditions.

For normal conditions, the FGA recorded higher CO levels than the Siemens. For fault operation, where part of the catalyst was blocked, the Siemens data were similar to those for normal operation. After the initial 2 minutes, the data recorded for both FGA and Siemens were very close.

The difference at the start-up stage was due to the FGA probe having been placed near the edge of the catalyst, compared to that of the Siemens analyser which was placed centrally above the catalyst. The edge of the catalyst is cooler than the centre due to not being in the main combustion product flow and this results in higher CO levels recorded for the FGA than the Siemens analyser.

The test data are shown in Figure 59.

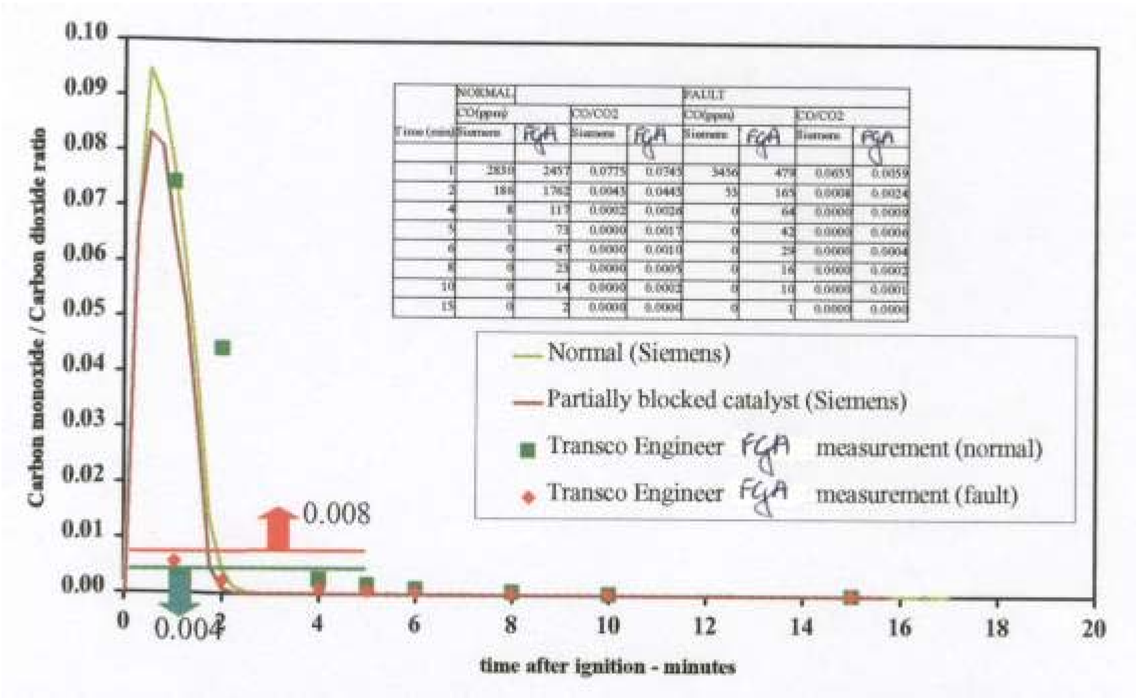

Figure 59: Comparison of engineer tests with logged data for a flueless fire

5.4 Replies to written questions

Replies have been grouped chiefly around four specific questions (see 5.4.1, 5.4.2, 5.4.3, 5.4.4 below). Some test engineers were asked the same questions more than once, and have tended to vary their answers so as to add more detail, or update their views. Some answers varied because of differences between appliances. The questionnaire for the second visit in the test week had extra questions in order to account for the repeatability of the exercise. These questions received fewer replies in total. So the conclusions made cannot be ranked by the frequency of appearance.

Towards the end of the programme, engineers were encouraged to make unsolicited comments. Inevitability some points came out which were best grouped with those for the specific questions. There were one or two independent points recorded.

5.4.1 Test Procedure

All five engineers seemed reasonably happy with the procedure, saying it was easy once it had been fully explained, and when they had become used to it. However, some negative comments were made about the use of the probe, and the problems, for some appliances, of holding the probe steady and having to re-insert it after the FGA had cut out and had been re started. Engineers were generally happy about the 15-minute test at first, but when they saw some of the results, one or two questioned whether 10 minutes would be sufficient. The engineers made the point twice that it could be ‘’dangerous’ to proceed beyond 5 minutes for an unflued water heater.

When it was realised that in a real situation there would be more distractions, one engineer proposed the use of some automatic recorder, or at least some audible warning of the exact times for taking recordings manually. Knowing when to take the first reading caused some problems.

5.4.2 Use of the Analyser

Most comments made were of the type “easy to use”, “very easy”, “easier with practice”, but the sample probe came in for criticism. For difficult locations the probe was said to be “too short and too rigid”.

Floor mounted boilers where the draught diverter may be ‘low down’ would be most difficult for the probe, one engineer thought.

The analyser unit was said to be neat and very easy to handle, although one engineer found it too long in one dimension. Each time the analyser switched off automatically, after 10 to 12 minutes (in the 15 minute testing period) this was criticised.

5.4.3 Practicability of 1- or 2-Minute Readings

Most said the frequency of the readings was no problem in the laboratory but envisaged problems in a busy working environment. 2-minute readings were easier than 1-minute recordings. It would be better, one said, with an audible reminder; or at least the first interval should be set automatically.

One engineer thought the first two readings should be taken together followed by a 5 minute and a 10 minute reading.

Two replies concerned the benefits of frequent reading; it gave immediate indications of warm-up and of change in combustion conditions.

5.4.4 Understanding what Emissions Readings Mean

This question was asked on the engineer's second visit. One said the most important point was the CO/CO_2 ratio, which could be compared with 0.004 for safety, and thought the separate CO and CO_2 were not needed. The 0.004 criteria was criticised however, by another engineer in connection with the obviously over-gassed water heater, which would have passed the 0.004 safety test.

The test engineers had positive views about the use of FGAs to assist in detection of malfunctioning or exhausted catalysts, in that there was no visible means to detect a problem of this kind so the ratio measurement was useful.

5.4.5 Other Points

It was also suggested that the combustion readings could be written on the warning label which is left with the customer.

All in all, a number of useful criticisms of the instrument, probe and the operating procedure have resulted.

5.5 Summary of findings for Phase 2

There are several overall comments related to the results from Phase 2, including:

- The idea of a quick safety test using a portable flue gas analyser has been shown to work effectively, all of 9 appliances being correctly assessed (compared to the levels recorded by the Siemens analyser)
- The protocol is essentially complete in that its use contributed to the correct assessments of combustion performance.
- The deviation in results can be explained in terms of overall test timing or probe position.
- For two out of nine appliances, the final 15-minute reading was necessary to confirm the trend/result. Maybe the revised protocol should include the 15-minute reading and two other readings at 5 and 10 minutes after the start of the test
- All five engineers provided helpful comments.
- The design and operating procedure for the use of the sampling probe should be further investigated.

6 FIELD SURVEY OF OPEN FLUE BOILERS

A supplementary aspect of the FGA project involved making a limited, not representative, number of combustion performance ratio measurements, including some of the more recent models of domestic boiler in order to compare field performance with that in the laboratory with regard to variation of combustion performance ratio with time. It is also necessary to establish that the 0.004/0.008 criteria can continue to be applied to modern designs, in particular those featuring narrow finned heat exchangers.

The boilers will be selected from the database held for all British Gas Service contracts in the north east of England and Scotland. The first set of data has been collected. It is planned that when the same boilers are visited for the next service in a year's time, the same test routine will be repeated. The details of the findings will be documented and distributed to the sponsors at a later date in 2005.

7 DISCUSSION OF RESULTS

In general portable FGA instruments are useful tools in confirming faulty operation for most appliances under certain conditions. However, as it was difficult to introduce faults onto the appliances involved in this project that resulted in excessive combustion performance ratio values, it is not clear if the portable FGA instruments can be used in fault diagnosis.

A low value of combustion performance ratio cannot reliably confirm that an installation is operating safely. There are certain situations when even though the appliance is operating under fault conditions, the combustion performance ratio is within acceptable limits.

However a high combustion performance ratio always identifies a potentially dangerous installation.

The use of combustion performance ratio may be a better indicator of poor combustion for specific appliance types, such as open flued boilers.

7.1 Phase 1

Several different combustion faults were induced on new examples of nine types of appliance, some appliances proving difficult to achieve a CO/CO_2 ratio exceeding 0.004. Boilers and combi boilers seemed most sensitive to restrictions in the heat exchanger, air inlet or the flue. Fuel effect fires seemed most sensitive to alignment of the ceramic "coals".

Measurements showed an initial CO and CO/CO_2 ratio peak following light-up, the height of the peak varying with appliance and with type of induced fault. In most cases fall-off after the peak was rapid, reaching equilibrium quickest for unmodified appliances. The initial spiking occurs in both normal and faulty operations. Even though the rate of decay may vary, the presence, size or the duration of the spike cannot therefore be used in isolation to identify faulty installations.

These data enabled a selection of the most appropriate induced faults to be made for the Phase 2 tests on these appliances.

7.1.1 Appliance "newness" tests

Three of the appliances tested were obtained new from the supplier (open-flued coal-effect fire, instantaneous water heater and fan-flued boiler). Before these appliances underwent the normal and fault test processes a check on their performance was made to assess whether there was an impact of the appliance "newness" on the emissions data.

The instantaneous water heater results (Figure 15) show that there is very little difference between the emissions data and combustion performance ratio for the "newness" and "normal" tests.

Similarly, the fan-flued boiler (Figure 47) showed that the equilibrium, steady-state operation values for the combustion performance ratio and CO emission concentration were consistent. Although for this appliance there was a noticeably larger CO emission peak following ignition in the "newness" test than for the "normal" test.

The most significant difference between "newness" and "normal" tests was demonstrated by the tests on the open flue, coal-effect fire (Figure 20). Here, there is a noticeable difference between "newness" and "normal" operation. Emissions of CO were higher during the "newness" tests and the appliance required longer run-times to establish steady-state operation. Also, the coals appeared to produce "smoke" during the first few tests and it is suggested that the binder on the coals produces both CO and "smoke" as they undergo the heating and cooling cycles during operation. It was found necessary to operate the appliance for three tests before the emissions performance and the combustion performance ratio results became reproducible.

From these tests it appears that boiler and water heaters rapidly lose any impacts from "newness". However, it is clear that the decorative coals on fuel-effect fires require several heating and cooling cycles before representative data can be obtained. Rearrangement of the coals appears to result in additional emissions from the coals as shown in Figure 58.

7.1.2 Effect of probe types on measured combustion performance ratio

The location and type of the sample probe used for the FGA analysis was found to be significant. The single-point, open-ended probe was the easiest to use and locating the probe in the appropriate part of the flue was relatively straightforward. The multi-hole probes were difficult to manipulate and the averaging effect of the multi-holes typically resulted in lower values for both the CO emission and the combustion performance ratio.

Usually the single-point open-ended probe gave the highest CO result, not an unexpected result as the probe location was adjusted to find the maximum CO value. Highest CO emission values did not necessarily result in highest combustion performance ratio values. Trends in combustion performance ratio readings did not necessarily follow the CO readings, particularly for multi-hole probes where the sample "drawn" in to the analyser is from a number of flue locations. The variation in results for the different probes cannot be attributed entirely to a dilution effect, as dilution does not impact directly on combustion performance ratio measurements.

In appliances where the products of combustion were mixed by a fan, results were not sensitive to sample position.

7.2 Phase 2

As in Phase 1, faults were difficult to induce on some appliances – especially since they had to be undetectable on inspection by the test engineer.

On the whole, the nine appliances performed similarly to their performance in Phase 1.

Test engineers thought the protocol was essentially correct and easy to follow, and they became accustomed to it very quickly. The design of and instructions for using sample probes was a problem to some.

The protocol could be simplified by increasing reading intervals to 2 minutes, provided there is a 5- and a 10-minute reading. Still there may be a few appliances, especially malfunctioning appliances, that do not reach equilibrium in 10 minutes.

Test results show minor differences between the analysers, but these can be explained in terms of test timing and probe location. On the whole the FGA and Siemens analysers gave similar results.

8 CONCLUSIONS

The project has successfully demonstrated that:

- Measured emissions values and combustion performance ratio are a function of the appliance type, the nature of the fault on the appliance and the effect of sampling probe type and location
- There are certain situations when even though the appliance was operating under fault conditions, the combustion performance ratio was within acceptable limits.
- If the combustion performance ratio was high, this was invariably a reliable indicator of unsatisfactory operation.
- Portable FGA instruments can track the time-dependence of the emissions and function as a diagnostic tool but they cannot provide categorical information related to safe or unsafe operation of appliances.

9 RECOMMENDATIONS

It is recognised that further study should be carried out using a similar strategy to that in Phase 1 and 2 but to include older appliances. This extended study would be able to focus on faults present in the field rather than simulate faults on new appliances. The effectiveness of FGA as a tool to identify these faults can then be more rigorously assessed.

It is recommended that further work be done in improving probe design and in standardising probe positions for different types of appliance.

It is recommended that the current field survey should be completed. Although this survey involves different appliances, it is effectively testing the 2-minute sampling procedure.

Tentatively it can be recommended that, based on the results from Phases 1 and 2, 10-minute tests would identify the majority of appliances with faulty combustion. However, increasing to 15 minutes will confirm satisfactory operation of some appliances and may help enable some additional faulty installations to be assessed for safe/unsafe operation.

10 REFERENCES

[1] Draft BS 7967-1 “Carbon monoxide in buildings and the combustion performance of gas-fired appliances”. (Parts 1, 2 and 3) BSi, 26 March 2004.

[2] J.A. Cotton, “Cold start-up combustion performance of domestic gas appliances”. Advantica report R4734, December 2001).

[3] M. Moore, “A review of carbon monoxide incident information for 2001/02”. HSE research report published 2003. ISBN 0 7176 2758 6.

A1 FLUE GAS TEST PROTOCOL – 1ST VISIT

Name : ....

Flue Gas Test Protocol (for Laboratory Tests)

This protocol has been designed for Emergency Response engineers testing domestic appliances installed in the laboratory, using standard portable performance tester analysers.

Before the start of the test a short induction to the use of the analyser will be given, as required.

The protocol is as follows:

1. Zero the portable analyser on ambient CO and CO_2 outside the laboratory.

2. Insert the probe supplied with the analyser into the middle of the stream of products, in a position according to the following order of preference:

    - maker's sample point
    - existing sample point in secondary flue
    - in primary flue (open flue appliance), across flue outlet (unflued appliance), or into flue outlet (room sealed appliance).

3. Light up the appliance in accordance to manufacturers instructions. As soon as the main burner comes on, set it to maximum, start timing.

4. Take the readings of CO, CO_2 and CO/CO_2 ratio at the time intervals as shown in the table.

5. Continue until 15 minutes is completed

6. Remove the probe from the appliance.

7. Close down appliance.

See Table overleaf ⇛

TABLE OF RESULTS:

Appliance ……………………………… **Date** ………….

Visual Inspection of appliance before testing: ………………………………………

………………………………………………………………………………………

Time/ minutes	CO/ ppm	CO_2/ percent	CO/CO_2 ratio
2			
4			
5			
6			
8			
10			
15			

Comments

What is your opinion on the Test Procedure ?

How easy was it to use the analyser ?

What is the practicality of taking readings every 1 or 2 minutes ?

Other comments?

A2 FLUE GAS TEST PROTOCOL – 2ND VISIT

Name : ……………………………………………

<u>Flue Gas Test Protocol (for Laboratory Tests)</u>

<u>2nd visit</u>

This protocol has been designed for Emergency Response engineers testing domestic appliances installed in the laboratory, using standard portable performance tester analysers.

Before the start of the test a short induction to the use of the analyser will be given, as required.

The protocol is as follows:

8. Zero the portable analyser on ambient CO and CO_2 outside the laboratory.
9. Insert the probe supplied with the analyser into the middle of the stream of products, in a position according to the following order of preference:
   - maker's sample point
   - existing sample point in secondary flue
   - in primary flue (open flue appliance), across flue outlet (unflued appliance), or into flue outlet (room sealed appliance).
10. Light up the appliance in accordance to manufacturers instructions. As soon as the main burner comes on, set it to maximum, start timing.
11. Take the readings of CO, CO_2 and CO/CO_2 ratio at the time intervals as shown in the table.
12. Continue until 15 minutes is completed
13. Remove the probe from the appliance.
14. Close down appliance.

<u>TABLE OF RESULTS</u>:

Appliance ……………………………… Date …………

Visual Inspection of appliance before testing: ………………………………………

……………………………………………………………………………………………..

Time/ minutes	CO/ ppm	CO_2/ percent	CO/CO_2 ratio
2			
4			
5			
6			
8			
10			
15			

<u>Comments</u>

What is your opinion on the Test Procedure ?

How easy was it to use the analyser second time round?

What is the practicality of taking readings every 1 or 2 minutes ?

Do you feel more confident with the test exercise?

Do you understand more about what the emission readings mean?

Other comments?