January 2001

COMPARISON OF MEASUREMENTS OF ABSOLUTE CO AND CO/CO_2 RATIO AS COMBUSTION PERFORMANCE INDICATORS

Advantica report designation: R4188

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Executive Summary

A database of over 5000 on-site service visits during which measurements were made on gas appliances with combustion performance testers has been evaluated. A comparison has been made between the number of servicing issues which would have been picked up by a servicing method based on the absolute CO levels given by the testers and one based upon the CO/CO_2 value derived by the testers.

The database records were extracted by one of two methods;

- The absolute CO level values recorded exceeded a threshold value
- The CO/CO_2 ratio values recorded exceeded 0.008

Where either method extracted a record from the database, this indicated that a potential servicing issue existed for that set of measurements, the collection picked up by either method being termed the issue records, or simply issues. Comparisons were made on the issues highlighted by each of the two methods.

Where a CO threshold was set at 650 ppm, there were no issues highlighted by the absolute CO method that were not picked up by the ratio method set to pick up issues at a level of 0.008.

16% of the issues were picked up only by the ratio method, ie these were left undetected by the absolute CO method, which translated to a performance improvement over the CO-only method of 20%. However, the additional complexity of the dual-channel combustion testers has been ascribed as the cause of the higher on-site failure rate of 4% of the issues, leading to an overall improvement of servicing issue detection of 15% over the absolute CO method.

Other assessment methods that correct for air dilution, such as air-free CO measurements, can offer advantages similar to the CO/CO_2 ratio method, provided any cited trigger levels are based upon an analysis of a database of similar scope to the field data examined (5000+ usable records).

No compelling evidence has been found that issue detection by either method is more favourable for any appliance type group.

Based upon the results presented, it is considered that a servicing indicator method reliant solely upon absolute CO measurements is less reliable than the CO/CO_2 methodology, as currently used when examining central heating boilers in the UK.

Other methods that take account of the sample quality in a similar manner as the CO/CO_2 method (such as “air-free” CO measurements) are likely to offer similar benefits over the absolute CO measurement method.

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Contents

1 Introduction 1
2 Review of Best Practice and/or Standards Overseas 1
3 Available Data 2
4 Data Analysis 3
4.1 Further Analysis of Issue Records into Categories 4
5 Results 5
5.1 Issue Records Identified by Each Method 5
5.2 Issues Picked Up by the Absolute CO Method Only 7
5.3 Issues Picked Up by the Ratio Method Only 8
5.4 Comparison of Techniques with CO Level at 650 ppm 8
5.5 Instrument Operational Considerations 10
5.5.1 Hydrogen cross-sensitivity 10
5.5.2 Logic of operation and training issues 11
5.5.3 CO method highlighted issues indicating instrument problem 11
6 Conclusions and Recommendations 12
7 Summary 12

1 INTRODUCTION

Some operational procedures and codes of practice relating to the servicing of gas-fired appliances specify levels of carbon monoxide (CO) to carbon dioxide (CO_2) ratios in the secondary flue gases or CO as an indicator of service requirement.

For example, the British Gas Services operational procedures [1] refer to two levels of CO/CO_2 ratio, one at which servicing should be carried out (0.004), and another beyond which remedial action must be taken to reduce the ratio (0.008).

Other countries employ standards or best practice guidelines which require measurements of absolute CO levels rather than CO/CO_2 ratios. The ratios used for boiler servicing in the UK have been in use for a number of years and have been demonstrably successful. However, studies involving other types of appliance have yielded less clear results. In order to address this point, this report assesses the likely consequences of using an absolute CO measurement instead of the current ratio method using data taken during service visits to appliances other than boilers.

2 REVIEW OF BEST PRACTICE AND/OR STANDARDS OVERSEAS

A search has been carried out to obtain references to residential/domestic appliance servicing policies, procedures, protocols, best practice guides or standards which are published by government agencies or relevant gas industry sources. Whilst many documents exist which refer to appliances when they are being manufactured and sold, very few are available in the public domain that apply to servicing gas appliances when a service engineer conducts on-site maintenance.

The following were identified after internet searches had been carried out ;

- UK: 0.008CO/CO_2 ratio (also action level at 0.004) [1]
- USA – Chicago Protocol [2]

  50 ppm as-measured (for Gas Fired Furnaces, Boilers, Water Heaters, Vented Space Heaters, Fireplaces, Flame-Effect fires)

  800 ppm air-free (Gas Cookers & Ovens)
- USA/Ohio [3]

  400 ppm (Furnaces, Boilers, Hot water heaters)

  100ppm (unvented appliances, cookers)
- USA/Iowa [4] 400 ppm

[1] British Gas Operational Procedures for Customer Service
[2] http://www.karg.com/CO Protocol.htm 2000
[3] http://home.att.net/~cobusters1/coprotocol.htm 2000
[4] http://www.ae.iastate.edu/aen175.htm 2000

The following were identified from the Advantica involvement with European standards committees and dialogue with European gas companies ;

- Italy: 1000 ppm air-free [5]
- Germany – "Some states" : 1000 ppm air-free [6]

Absolute as-measured CO concentration measurements are commonly used for servicing diagnostics as "most field analysts in the US have access to as-measured equipment only" [7,2]. Using such measurements may lead to recommendations for servicing actions at low CO levels as noted above.

The drawbacks of absolute CO level measurements as an indicator are acknowledged in the USA guidelines found, with an "air-free" correction method being cited for some measurements, particularly those associated with measurements on the open burners found on cookers, for example.

Similar requirements to measure the CO concentrations as air-free have been found in the Italian and German documents. Air-free CO values are always greater than the as-measured values, since they are what would have been measured had no diluent air been present at the sampling point. The calculation to derive the air-free is discussed in Section 5.2 on page 7, and it effectively introduces a similar air-referencing process which is used in the determination of the CO/CO_2 ratio.

It was noted that the manufacturing certification standards for gas appliances in Australia are cited [8] as a CO/CO_2 ratio (at 0.02), making this the only standard we have found citing the ratio except for the UK British Gas servicing guidelines[1].

3 AVAILABLE DATA

Advantica has ownership of and access to data originally acquired in 1994 by BG Technology (formerly British Gas Research & Technology) in collaboration with British Gas Services [9,10,11].

[5] CENELEC Standards Committee – unpublished working group draft 2000
[6] Thuga Aktiengesellschaft, Munich. Private communication August 1991
[7] Rick Karg [rjkarg@karg.com] ; e-mail to author, November 2000
R.J. Karg is a full member of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the Association of Energy Engineers (AEE) and a member of the Air Conditioning Contractors of America (ACCA), and the American Society of Training and Development. Before founding R.J. Karg Associates, he was a college teacher and a building contractor.
[8] Chris Wealthy, Melbourne gas, private e-mail, cites AG102-2000/AS 4552-2000 "Gas Water Heaters"
[9] M. Ranzetta; "Interim Report on the Analysis of Data from the Southern Region Trial" – British Gas Research & Technology GRC R 0377, April 1994 {Confidential}
[10] C.M. White, M. Ranzetta; "Interim Report on the Analysis of Data from the 'Southern Region' Telegan Trial" – British Gas Research & Technology, November 1994 {Confidential}
[11] C.M. White, M. Ranzetta; "Final Report on the Analysis of Data from the 'Southern Region' Telegan Trial" – British Gas Research & Technology GRC R 0846, June 1995 {Confidential}

This data consists of about 5000 records of service visits. For each on-site visit, up to four sets of CO, CO_2 and CO/CO_2 ratio were recorded, depending on which survey group the visit was in and the state of the appliance upon testing.

The number of survey visits broken down by appliance type are shown in Table 1.

The study was carried out to assess aspects of extending the methodology employed for central heating boilers in the British Gas Services operational procedures [1] to other appliance types, so no central heating boilers appeared in this study. Measurements were recorded using early models of Telegan Performance Tester units.

Appliance Group	Description	Number of visits
1	Warm air unit	1090
2	Combined Warm air unit/Circulator	1577
3	Water heater < 12kw	343
4	Open flued water heater > 12kw	44
5	Balanced flued water heater > 12kw	947
6	Circulator/Storage heater	481
7	Wall heater	585
Total		5067

Table 1: Southern Area survey records broken down by appliance type

A previous study had been carried out on the servicing of boilers, which led to a database record of service visits carried out in the York area starting in 1987. This led to the current policy for boiler servicing currently implemented by British Gas Services [1], but is not currently available in electronic format for further analysis.

An additional data set, recorded to evaluate the operation of hydrogen compensated combustion analysers, is also available. It forms a complementary data set capable of analysis similar to that carried out for this report, but has not been but processed at this time.

4 DATA ANALYSIS

The data from each record was transferred to an Excel spreadsheet, which enabled the extraction of records passing specific criteria.

Criteria were set up to correspond to each of the flue test methodologies being compared. One test flagged records where any of the visit CO/CO_2 ratio measurements had exceeded a ratio threshold value. A second flagged records where the absolute CO measurements exceeded an absolute CO threshold value. The spreadsheet also carried out comparisons between the flags.

For every instance where *either* the CO/CO_2 ratio exceeded the specified threshold *or* the absolute CO value exceeded that threshold, the record was flagged. Each of these records is termed an "issue" in this report, and each is an indication that further action would be required by the service engineer under one of the methods.

The spreadsheet extracted each issue and performed further analysis :

Where both methods flagged an issue, they were categorised as an "agreement" issue.

Where only one of the methods flagged a record as an issue they were further categorised :

- Where the CO/CO2 ratio only flagged a record as an issue, it was categorised as "ratio only"
- Where the absolute CO concentration only flagged a record as an issue, it was categorised as "CO only"

This logic is summarised in Table 2.

CO level exceeded	Ratio exceeded	Spreadsheet Action	Issue ?	Category
No	No	Not extracted	No	---
No	Yes	Extracted	Yes	Ratio only
Yes	No	Extracted	Yes	CO only
Yes	Yes	Extracted	Yes	Agreement

Table 2: Number of survey visits broken down by appliance type

4.1 Further Analysis of Issue Records into Categories

A careful analysis of the issue records were carried out, and tests were incorporated which accounted for some operational discrepancies, such as instrument over-ranging on the CO scale. Here, the CO level must have been at least 2000 ppm, which is the over-range limit, and the CO_2 could not have exceeded 11.9%, yielding a ratio minimum of 0.0168. Hence, these records must correspond to an issue record where both the CO and ratio methods were in agreement. In many instances, the values in the issue record fields indicated that an error had occurred. Where this was the case, an attempt was made to manually inspect the original records with a view to identifying the nature of the error.

A number of possible error sources were identified:

a) Transcription from record sheet to database

b) Inability to communicate Telegan fault via form structure

c) Operation of Telegan (training issue)

d) Survey procedural problem

e) Operation of Telegan (reliability, calibration, hardware or design issue)

Where possible, corrections to the errant records were made to the database copy used. Where no original record was available for inspection, it was removed from the analysis set. Where an obvious transcription error had taken place, either from the instrument to sheet, or from the sheet to the database, it was corrected.

A number of instances of error source b) and/or d) were uncovered, where the operator had written "over range" or had prematurely stopped the procedure when more than 1000 of 1500 ppm CO were observed on the instrument. In these cases, a value was recorded with a "+" symbol or additional writing was often inserted on the sheet, and the value was transcribed verbatim rather than interpreting the result. It was common not to record the CO_2 level displayed when this had occurred, with a value of "not available" being transcribed.

Once all these records had been corrected such that the spreadsheet could interpret the values appropriately, only one record indicated that it was in category c) or e), i.e. the unit was not operated correctly or was faulty in some respect. In this instance, a high level (520 ppm) of CO was recorded, with a CO_2 level of zero, which was the level written on the sheet. This is not a sensible result, and probably indicates a real issue with a poor sampling method, or possibly a problem with the oxygen sensor channel.

Where the values indicated no errors, the records have been used for the results as presented in Section 5.

5 RESULTS

5.1 Issue Records Identified by Each Method

The threshold ratio level set in the spreadsheet was fixed at 0.008. This level was not altered as the procedure for tests returning values in excess of this level requires that remedial action be taken to reduce the value to below the threshold. When a level below 0.008 but above 0.004 is observed, the procedure calls for a service to be carried out and a post-service measurement to be made, but if this value increases but remains below 0.008, then no further action is required.

Hence the value of 0.008 is a "hard" test, always requiring remedial action, whereas the value of 0.004 is used as an indicator of likely future performance, and is thus a "soft" level which is acceptable to exceed.

As noted in Section 2 on page 1, the guidelines in place for Italy require action when the absolute CO concentration measured in the flue rises above 1000 ppm when corrected to air-free. However, the lower the value set, the more issues are identified by the test. Also, the issues identified by a higher limit are a sub-set of those identified by a lower limit – i.e. all the issues identified by a 1000 ppm limit are also identified by a 500 ppm limit.

It was thought that guidelines issued in the USA indicated a limit of nearer 500 ppm [12]. Since this represented a more conservative limit, and would retrieve more issues from the database, this was the threshold value set for the initial comparison analysis carried out.

The analysis procedure outlined in Section 4 using a 500 ppm CO limit yielded the results shown in Table 3.

CO level	Number of Issue Records	Agreement	Ratio Only	Errors Noted	CO Only
500	95	72	15	3	5
by % :	100%	76%	16%	3%	5%

Table 3: Basic results for 500 ppm CO threshold level comparison

The 95 issue records identified by one or both of the methods represents 1.87 % of the service visits made. The basic figures shown in Table 3 were also broken down further by appliance type, as described in Table 1 on page 3. This breakdown is illustrated in Figure 1.

[12] USA National Fuel Code

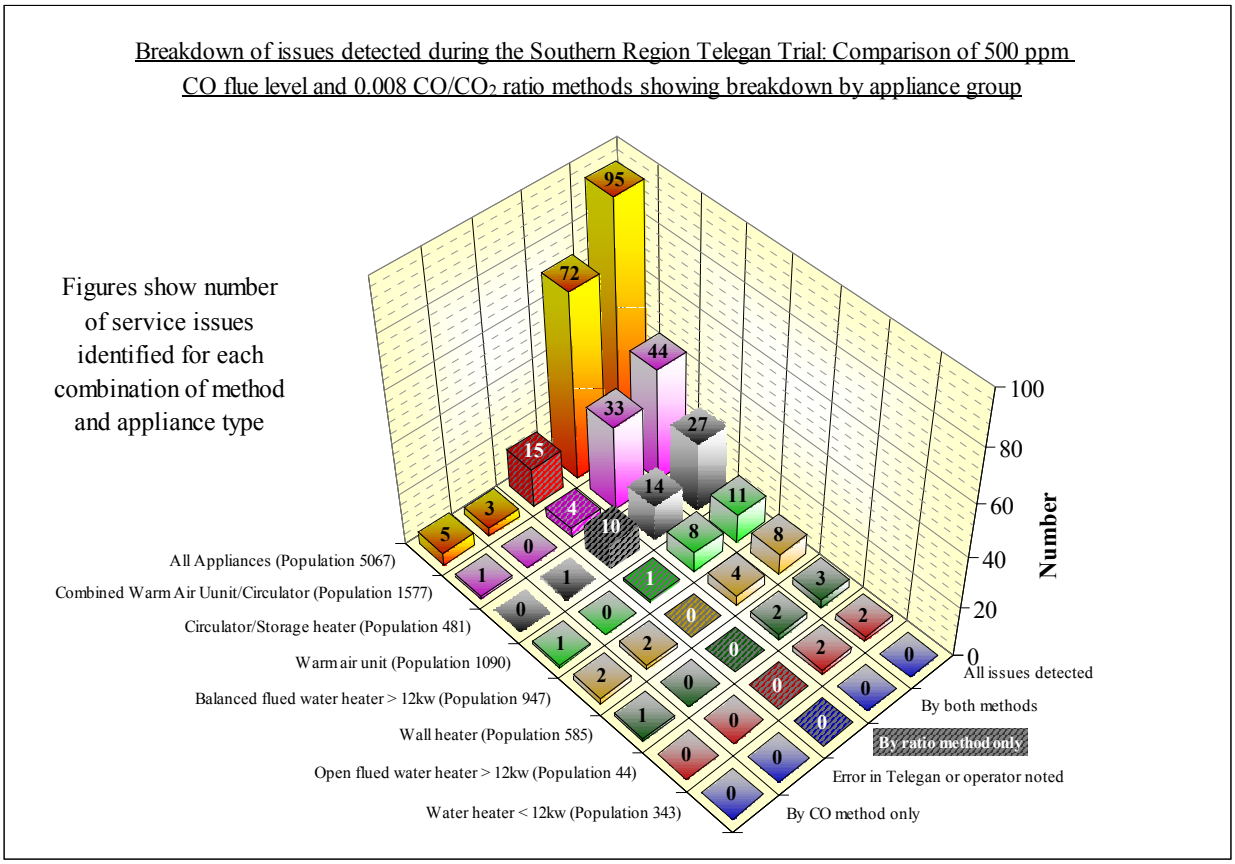

Figure 1: Breakdown of issue records by category and appliance type

5.2 Issues Picked Up by the Absolute CO Method Only

In a preliminary analysis using an absolute CO limit of 1000 ppm, no issues were flagged up by the absolute CO method that were not picked up by the ratio method, with the exception of those arising from Telegan or operator errors.

However, when the more extensive issue set was retrieved by altering the limit to 500 ppm, some issues had been picked up by only the absolute CO method. In total, there were 5 such issue records. Relevant parts of the records are shown in Table 4.

Survey Number	CO (ppm)	CO2 (%)	Recorded Ratio	Recalculated Ratio	Appliance type
A2985	528.0	7.0	0.0068	0.0075	Balanced flued water heater above 12kw input
A1621	562.0	7.4	0.0074	0.0076	Wall heater
A2093	572.0	8.4	0.0068	0.0068	Warm air unit
B3750	630.0	8.4	0.0074	0.0075	Balanced flued water heater above 12kw input
B4819	520.0	7.2	0.0062	0.0072	Combined Warm Air Unit/Circulator

Table 4: Records which were highlighted by 500 ppm CO measurement only

In each case, the absolute CO measurement highlighted the issue rather than the upper limit of the boiler servicing procedure, even when recalculation of the ratio from the provided CO and CO_2 values was carried out. It can be seen from the CO concentration column that in no instance was the CO level in excess of 650 ppm. Hence, if a CO threshold level of 650 ppm had been used in the procedure, no "CO only" issues would have been retrieved from the database. Also, the appliance types were scattered over the appliance population, indicating no appliance type bias.

This means that the trigger level of 0.008 for the CO/CO_2 ratio method can be thought of as equivalent to a direct flue test trigger level of 650 ppm. It should be noted that this is an absolute measurement, not an "air-free" corrected measurement, which is the method indicated in the Italian and German documents we have obtained. [5]

Hence, the ratio method represents a test that lies between limits which may be proposed to guide some European countries [13], and the slightly more conservative limit thought to be a target figure in the USA. This absolute CO level is equivalent to a Telegan ratio reading of 0.0055, which lies on the conservative side of the 0.004-0.008 decision interval currently forming the basis for the British Gas Services boiler guidelines [1].

5.3 Issues Picked Up by the Ratio Method Only

Approximately three times more issues were identified by the ratio method only, than were highlighted solely by the absolute method employing a CO trigger level of 500 ppm.

5.4 Comparison of Techniques with CO Level at 650 ppm

As noted in Section 5.2, a Telegan level of 0.008 may be thought of as equivalent to using the absolute CO method with the level set at 650 ppm.

When the CO limit is changed to 650 ppm, all the CO-only issues are eliminated, leaving only Telegan or operator errors, and increasing method agreement. The figures for an equivalent analysis to that described in Section 5.2, but with a CO level of 650 ppm yielded the results shown in Table 5.

CO level	Number of Issue Records	Agreement	Ratio Only	Errors Noted	CO Only
650	95	77	15	3	0
by % :	100%	81%	16%	3%	0%

Table 5: Basic results for 500 ppm CO threshold level comparison

[13] The Spanish authorities are believed to be considering this method – unminuted standards committee communication

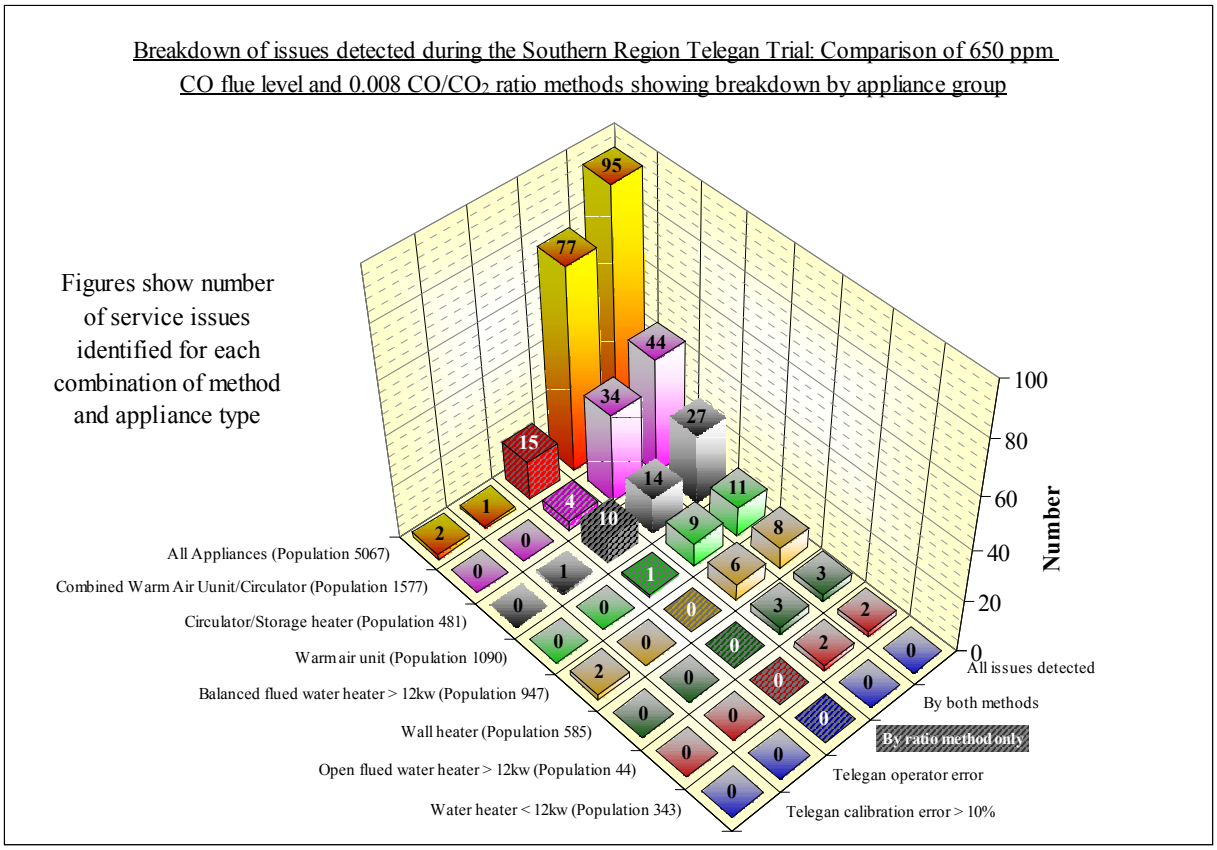

Figure 2; Issues by category and appliance type for 650 pppm CO limit

These figures are illustrated in Figure 2, broken down by appliance group. The values with cross-hatching are the issues picked up by the ratio method only. Also shown are details of the Telegan errors observed.

In this analysis, 81% (77/95) of the highlighted issues are picked up by both methods, but a significant 16% (15/95) are picked up by the ratio method only, representing almost a 20% (15/77) improvement over the CO-only methodology. This is at the expense of a 3% (3/95) instrument failure rate, or almost 4% (3/77) of those issues picked up by either method.

Hence, when increased instrument failure is accounted for, it can reasonably be concluded that the ratio method represents a 15% ([1+0.2] x [1-0.04] – 1) improvement of issue diagnosis over the absolute CO method,. There is some evidence that this improvement is most noticeable for the circulator/storage heater appliance type, though most appliance groups are under-represented to make reasonable comparisons of this type.

This ratio method advantage may accrue from the more robust nature of the process. When gas samples are taken on-site from real appliances, many difficulties can be encountered in ensuring that a valid combustion product sample is being analysed. One such issue is that of ensuring a sufficient product sample being drawn into the analyser by the deployed hardware.

The ratio method is inherently more robust in that it does not produce a result unless an acceptable flow of combustion products enters the analyser chamber. This highlights a poor sampling situation to the operator, which should lead to a reconfiguration such that an acceptable sample is obtained, yielding a go-no go indication. This also has the advantage of enabling only a partially successful sampling strategy to yield acceptable results, eliminating unnecessary on-site time when it is not required.

Where poor sampling arises, then the absolute CO reading obtained may err towards indicating a safe condition when it should not, and so represents a non-conservative diagnosis in these instances.

In some USA states, it is recognised that absolute measurements are all that are likely to be possible with current testing equipment [7], and limits as low as 50 ppm are quoted as triggering an appliance service. Inputting such a limit change into the analysis spreadsheet indicates that the number of issue records picked up by the absolute CO method increases from 77 to 703, representing over an 9-fold increase in services carried out, inducing a number of service-related faults with no obvious increase in safety.

5.5 Instrument operational considerations

5.5.1 Hydrogen cross-sensitivity

The study carried out has assumed that methods currently in use to determine absolute CO concentrations are equivalent, which may not be the case. The CO cells used in the Telegan model available at the time of the Southern trial had a significant cross-sensitivity to hydrogen (H_2). In Telegan trials, it was found that the CO/H_2 ratio varied between 0.6 to 2.8 when measurements were made in real appliances near typical measurement positions [14], and that a typical CO cell was up to 40% cross-sensitive to H_2. This implies that CO concentration values derived by units using similar cells can be approximately 25 to 110 % in excess of the values actually present (the true CO levels are about 50-80% of the indicated reading)

It is possible to minimise this effect by employing more expensive sensors that have hydrogen compensation, but they have not been incorporated into the standard Telegan Combustion Performance test unit. This is not a significant cause for concern, as the sensor cross-sensitivity leads to an exaggeration of the perceived issue, albeit with a potential to flag servicing issues where a more accurate unit might not. The British Gas Services policy trigger levels were deduced using the more cross-sensitive sensors, making use of the standard unit valid for that policy.

It is also the case that many inexpensive CO-only sensors are based on such uncompensated sensors, so such devices will give conservative CO results, as well as maintain consistency with the data obtained in the Southern trial.

[14] D.R. Wightman, G.C. Arnold & S.C. Day; "Experiments to Determine the CO/H2 Ratio in Flue Gases" – British Gas Research & Technology GRC R 0867, July 1995 {Confidential}

However, it should be noted that where more accurate CO measurements are available, the levels at which they should trigger actions must be modified to account for their more accurate results. The cross-sensitivity issue would complicate efforts made to use absolute CO measurements as a basis for appliance performance monitoring. Defining acceptable cross-sensitivities to all possible species would not be trivial, and the range of expected instrument response across a range of circumstances and appliance configurations may be unacceptably wide.

5.5.2 Logic of operation and training issues

Concern has been expressed that it might be possible for a service engineer to leave a customer premises having solely relied upon the combustion analyser results to ensure the appliance has been left in a safe condition.

This should not be possible provided three conditions are valid at the time of testing:

- The instrument is correctly working and within calibration date.
- The CO sensor has been checked for response to CO.
- The operator is sufficiently familiar with the test equipment and carries out the tests in accordance with the instructions provided.

Since the largest possible measurement of CO_2 in flue gases for a natural gas appliance is 11.9%, if the above conditions hold, it should not be possible for more than 960 ppm to be present in flue products whilst the unit returns a value of less than 0.008. It should be remembered that this is likely to be a 50% over-estimate due to the sensor technology deployed.

Even if the CO and O_2 sensors have both drifted by 20 % in a non-conservative way, and no hydrogen is present in the flue gases, the maximum CO that could be present is 1260 ppm. With the more credible presence of hydrogen, this is likely to be in the region of 800 ppm

It should be noted that the design of combustion analysers has progressed considerably since the Southern Trial was carried out. Currently available units exhibit enhanced functionality, combined with reduced unit cost and instrument portability and enhanced operation logic. This combination minimises the original unit shortcomings, which might have been expected to lead to some measurements being unreliable, whilst providing the operator with upgraded diagnostic capability.

In turn, this can enable a higher level of engineer knowledge of the system under test, with the possibility of enhanced customer acceptance and perceived benefit from a service visit.

5.5.3 CO method highlighted issues indicating instrument problem

Two of the three issues highlighted by the 650 CO ppm level method but not by the ratio method can be ascribed to the instrument ratio value being in error by more than 10% from that indicated by the direct values recorded, with the value-based ratio indicating the ratio limit had been exceeded.

This could indicate that there might have been problems with gas concentrations that were varying with time, and it is possible that there could have been a problem associated with a delay between when the ratio was calculated and the individual values being recorded, or another instrument operation issue.

Failure to pick up on some relevant issues by use of a more complex instrument is to be expected, as the ratio method requires two values to be simultaneously available and valid, as well as working with the Telegan instrument limitations and procedures. The failure rates of the instrument sensors are low, but a dual-channel requirement failure rate is higher than the case where results are derived from a single channel.

Strictly speaking, one of these records would have been eliminated by a CO level of 650 ppm being used, as it recorded 648 ppm, but this was very close to the limit, so was included as it was within uncertainty limits. However, this inclusion doubles the apparent incidence of this category.

Despite this, the overall benefit of using the ratio method over the absolute method far outweighs the disadvantages, improving the servicing issue diagnosis by 15%.

6 CONCLUSIONS AND RECOMMENDATIONS

The study shows that the ratio method improves on-site diagnosis of servicing by 15%, while providing the ability to give the perception of enhanced customer benefit by deploying a combustion test unit that is cost-effective.

Hence, it is recommended that the CO/CO_2 ratio methodology should prevail when the method based solely on absolute CO measurements is proposed as an alternative.

Methods based on air-free CO methods hold the possibility of similar benefits to the CO/CO_2 ratio method as they introduce a similar degree of correction to absolute measurements. However, reliable trigger levels must be based upon an analysis of a database of similar scope to the Southern trial (5000+ usable records) to yield comparable value.

Central heating boilers make up the largest single appliance grouping in the UK. This study has only investigated results from a database of service records from appliance types that excluded such central heating boilers. A similar analysis could be performed on a database of central heating boiler servicing records which is also available. This would increase the confidence of the report conclusions to include the widest possible gas appliance database, and number of appliances in current use.

7 SUMMARY

A database of over 5000 on-site service visits during which measurements were made on gas appliances with combustion performance testers has been evaluated. A comparison has been made between the number of servicing issues which would have been picked up by a servicing method based on the absolute CO levels given by the testers and one based upon the CO/CO_2 value derived by the testers.

The database records were extracted by one of two methods;

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16% of the issues were picked up only by the ratio method, ie these were left undetected by the absolute CO method, which translated to a performance improvement over the CO-only method of 20%. However, the additional complexity of the dual-channel combustion testers has been ascribed as the cause of the higher on-site failure rate of 4% of the issues, leading to an overall improvement of servicing issue detection of 15% over the absolute CO method.

Other assessment methods that correct for air dilution, such as air-free CO measurements, can offer advantages similar to the CO/CO_2 ratio method, provided any cited trigger levels are based upon an analysis of a database of similar scope to the field data examined (5000+ usable records).

No compelling evidence has been found that issue detection by either method is more favourable for any appliance type group.

Based upon the results presented, it is considered that a servicing indicator method reliant solely upon absolute CO measurements is less reliable than the CO/CO_2 methodology, as currently used when examining central heating boilers in the UK.

Other methods that take account of the sample quality in a similar manner as the CO/CO_2 method (such as “air-free” CO measurements) are likely to offer similar benefits over the absolute CO measurement method.