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March 2002

COMBUSTION PERFORMANCE SAFETY ACTION LEVELS FOR DOMESTIC GAS APPLIANCES

Advantica report designation: R5205

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Combustion Performance Safety Action Levels for Domestic Gas Appliances

Executive Summary

An earlier report concerning the possibility of using absolute CO measurements on the flue products of appliances as servicing or safety indicators inferred that the absolute CO criterion should not be used as an overall safety indicator without further investigation. The CO/CO_2 ratio criterion should be retained, though its value might be reassessed. New work has been undertaken in which the "as-left" ratio of 0.008, traditionally used for boilers and combis, is reassessed and is considered for application to a wider range of appliance types. The values obtained may be appropriate as "safety action levels" for inclusion in the new Code of Practice, BS 7967.

Two approaches have been followed. The first was to calculate the CO/CO_2 ratio that would correspond to an equilibrium CO level of 10 ppm in a stirred room, making assumptions about the maximum levels of spillage and the minimum levels of room ventilation likely to be acceptable. The second was to re-examine the full range of valid data from the 1991 National Combustion Performance Survey, by appliance type, to assess the feasibility of adjusting all appliances of the type to meet the CO/CO_2 ratio criterion suggested by calculation.

Calculation indicated that for all open flue appliances the critical ratio should ideally be lower than 0.01: then the value 0.008, previously used for boilers and combis, was first investigated. Because of the desirability of the widest application of one ratio value, balanced flue appliances, though not so critical, were included. Appliances which are operated without flues were subject to different calculations, each calculation appropriate to the operating conditions of the respective appliance type, and each leading to a different critical ratio proposal. These possible criteria were then checked for feasibility, using the 1991 data.

It is concluded that an "as-left" or "safety action level" CO/CO_2 ratio of 0.008 is feasible for all flued appliances, except some open flue gas fires. A further investigation is desirable to clarify the situation for fires and cooker grills. For other unflued appliances different ratio criteria are suggested, all of which appear feasible.

If the appliance manufacturer specifies a combustion performance criterion for a working installation, this should always take precedence. If this involves a CO/CO_2 ratio higher than the "safety action level" proposed here, then, in the event of the appliance failing to meet the safety action level after rectification, the manufacturer's figure would be the final criterion. This proposal should be discussed with manufacturers.

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Combustion Performance Safety Action Levels for Domestic Gas Appliances

1 INTRODUCTION

A number of earlier reports (References 1 to 4) have examined the feasibility of using absolute CO as a measure of the combustion performance of domestic gas appliances, instead of the more accepted ratio of carbon monoxide to carbon dioxide (ie CO/CO_2) in the flue products. Some of this work was based on recent measurements, but much more information has been extracted from a database compiled from a National Appliance Combustion Survey performed in 1991. The findings from the report (Reference 3) have been somewhat inconclusive for a variety of reasons, so the new study aims to revisit the problem and devise specific and practical values for the safe servicing of appliances. In doing so it ignores the recommendation of Reference 3 suggesting an improved approach to the use of absolute CO as a safety criterion. Also, there is a need for an accepted safety "action level" criterion for any appliance which is tested for any reason, not necessarily for servicing, and this approach has already been drafted in terms of CO/CO_2 ratio for the new Code of Practice, BS 7967.

2 MANUFACTURER'S INSTRUCTIONS AND ACCEPTANCE TESTS

Part 2 of Reference 5 recommends the servicing of domestic gas appliances according to manufacturer's instructions. If these instructions require a test of CO/CO_2 ratio, then the manufacturer's limiting value should in principle be accepted. Logically, a figure lower than 0.02 should have been set, bearing in mind that when this value was used in acceptance testing to old appliance British Standards, it applied to high levels of "overload" on heat input (eg 20%, or more recently, 15%). Overloading was traditionally performed by raising the inlet pressure of the gas as a means of deliberately degrading the appliance combustion performance. It was assumed that the following four factors that raise the value of the CO/CO_2 ratio would thereby have been effectively simulated:

- Production tolerances, allowing some appliances to perform less well than the sample prepared for acceptance testing.
- Higher gas inlet pressure, particularly where the appliance has no governor.
- A gas at the upper limit of Wobbe Number permitted for normal distribution (ie +3% over that of methane) rather than the NGA or G20 gases used on test.
- Deterioration in use between annual service visits.

Immediately after servicing, the appliance will be operated without deterioration in use, and with no more than 5% excess gas pressure. It is therefore logical to argue that a CO/CO_2 ratio criterion lower than 0.02 should be adopted, such that, if the gas pressure rises and/or the appliance deteriorates, the CO/CO_2 ratio would then still not exceed 0.02.

To-day's EN Standards for boilers and combination boilers set acceptance tests with smaller overloads and a dry, air-free CO figure of 1000 ppm, which corresponds to a CO/CO_2 ratio of approximately 0.0085. Another overload test is made with the incomplete combustion test gas, G21, against a CO limit of 2000 ppm (ratio approx. 0.017). However, this test would be unrealistic for an installed appliance, because G21 gas has a Wobbe Number of 54.76 MJ/m^3, compared with the normal distribution upper limit of approximately 52 MJ/m^3. The CO/CO_2 ratio of 0.01 was derived in 1989 (Reference 6) as the then accepted figure for installed central heating boilers, although a practical level of 0.008 was recommended.

3 ROOM CO CRITERIA

Current criteria for room CO have to be taken into account. The chief criterion is the World Health Organisation 8-hour time weighted average figure of 10 ppm. Most appliances would not be operated for as long as 8 hours at a time, so the adoption of the 10 ppm standard is probably correct. It is proposed in Part 1 of Reference 5 that, if necessary, tests should proceed until the room CO level reaches equilibrium, unless the level reaches a maximum and then falls.

It is clearly important that appliances whose flues and ventilation meet the requirements of the Standards, should not, when newly installed or after being serviced to manufacturer's instructions, be found to cause excess CO levels in rooms, even where ventilation rate is the lowest acceptable and where flue height and terminal position are the least favourable permitted. It is possible to link the room CO level and the appliance emission CO/CO_2 ratio by calculation, provided a number of approximations and assumptions are made, as detailed in the following section.

4 CALCULATIONS

The equilibrium level of any pollutant emitting steadily into a mixed enclosed volume or room can be worked out using a simple continuity equation, providing the rate of emission and other input data are correctly assumed. The level that will have built up after any given time can be calculated as an appropriate fraction of the equilibrium value, but the effect of the starting conditions will not be included in this calculation. The rate of emission of CO depends on the fraction of spillage and on the flue gas CO/CO_2 ratio, both of which could be higher than their equilibrium values in the first few minutes after light-up. It follows that the longer the build-up time, the greater the accuracy of the calculated figure. In all these calculations, a figure of 9 ppm CO has been taken as the maximum increase that should be allowed, on the assumption that the outside ambient level will be approximately 1 ppm. If the ambient level was to be

measured and was found to exceed 1 ppm, then the contribution permitted through spillage or leakage from an appliance should be correspondingly less.

Theoretically, what the continuity equation calculates is the average concentration in the mixture that leaves the room. For an open-flue appliance, operating in a relatively "tight" room, the point at which the room atmosphere is extracted is the appliance draught diverter. So if concentration measurements are made at draught diverter height and not too far from the appliance, the measured and calculated figures might be expected to be close. On the other hand, a room-sealed appliance does not extract air from the room at all, so if there were any slight leakage of products, this would almost certainly rise to the ceiling, mixing to some extent. Stack and wind effects would determine that the pollutant was removed through upper level porosity, and the tops of window and doorframes. Hence, it will be more difficult to match measured and calculated levels closely. It is proposed in Reference 5 that concentrations should be measured 2 metres above the floor in all cases. To allow for different concentrations at different levels, therefore, "stratification factors" have been introduced into the calculation.

The equations used in the calculations presented in Table 1 are as below. They are based on the relationships developed in the Appendix. The parameters H, n, V, S and F are defined in the Table column headings and discussed in the next section:

CO/CO_2 Ratio = $(9 \times n \times V \times 39) / (F \times 3.6 \times 10^6 \times H \times S / 100)$

30-minute CO = $9 \times [1 - \exp(-0.5 \times n)]$

Equilibrium CO_2 = $(F \times H \times 3.6 \times S) / (39 \times n \times V)$

Note that the actual CO level could be greater than that calculated, because of start-up CO and initial spillage. For all flued appliances, the basic equations have been adapted to calculate the critical CO/CO_2 ratio appropriate to an equilibrium 9 ppm CO level measured at 2 metres height. For unflued appliances, where equilibrium conditions do not apply, a value has been assumed for the ratio and the peak CO has been calculated. The examples in Table 1 have been chosen for their relevance, but the calculations could be used with any other sets of assumptions. This is likely to be necessary if certain of the test conditions in Reference 5 are changed.

5 INPUT TO CALCULATIONS

Most of the values assumed for input to the calculations, particularly the equilibrium calculations, are based on experience, or in some cases taken from Standards. The most controversial are probably the spillage values. All the assumptions are now discussed in more detail.

Firstly, the appliance heat input, H. Values are either the maximum permitted without ventilation (see Reference 7) as for gas fires, or the overall maximum permitted (as for unflued water heaters) or are typical or large values.

Secondly, the number, n, of air changes per hour. For most rooms where there are gas appliances, in order for the rooms to be habitable, the rate of air change would not normally be much lower than one per hour. For open types of fire, where it is known that flue gas concentrations are low, higher ventilation rates have been assumed. For the purposes of calculating the CO/CO_2 ratio, based on the equilibrium value of CO, it is the ventilation rate that is needed. This, using the symbols in the Table, is the product n x V. Note that the air change rate only, not the volume, V, affects the rate of build-up to equilibrium.

For the room volume, V, in general, a worst case small volume has been assumed, though some larger room examples have also been worked for comparison. The smallest kitchen volume permitted without purpose-made ventilation is 10 m^3, and the smallest room volume for an unflued water heater is 20 m^3. This assumes that the unventilated case is probably the worst. The same principle has been applied to the fixed unflued heater.

Probably the most controversial is the spillage factor, S, and it can be seen from the calculations that this figure is quite critical. The figures for conventional and open gas fires, 3% and 5% respectively, are, or used to be, generally agreed as the worst acceptable. For other open flue appliances, which have purpose-designed draught diverters and are usually connected to a double insulated flue or a liner-and-chimney system (where the metal has radiation-reflecting properties to maintain products temperatures, and a terminal is fitted) the lower figure of 1% has been adopted. The figure of 0.5% used for room sealed appliances is lower in all examples by comparison with the 1 m^3/h leakage permitted in acceptance testing to BS EN 483 (Reference 8) but particularly so for the smaller input appliances. It is suggested (somewhat arbitrarily) that because of the high pressure differential (0.5 mbar) employed in the acceptance testing, and because the test allows for combustion air as well as products to leak, it is reasonable to reduce the 1 m^3/h to one-quarter of this figure for products leakage into the room. This could still amount to more than 1% leakage for a small appliance, so perhaps the figures derived for open flue appliances should be used only as a guide, with the possible exception of the 30 kW combination boiler.

The stratification factor, F, is designed to allow for the difference in the CO level measured at 2 metres height and the calculated figure. It was intended to deduce values for flued appliances from the data obtained elsewhere (References 9 and 10). In most of those tests, except for a few with a gas fire, the spillage was total, leading to strong displacement currents in the room. In some tests with a gas fire, where the flue restriction had been progressively reduced (and therefore it might be assumed that substantial volumes of products were in these tests being removed from the room via the draught diverter) the CO and CO_2 concentrations were found to change very little with height. Steeper profiles have been assumed for the higher mounted appliances, though better justification continues to be sought.

For unflued appliances, previous work (References 10 and 11) has provided the stratification data. A stratification factor of 1.4 has been deduced from the 5-minute and 10-minute CO_2 concentration profiles in Reference 10, because the CO figures for these operating times were too low. For a single cooker burner, a stratification

factor of 1.2 has been deduced from the 30-minute CO profiles in Reference 11. The values are only approximate, being the means of values from a number of ventilation conditions, all roughly similar to those assumed though not numerically defined.

6 INTERIM CONCLUSIONS

a) For all open flue appliances, including all types of gas fire, it is desirable to agree the lowest CO/CO_2 criterion, and 0.008 is suggested. Only for floor mounted appliances, which extract room atmosphere at low level (but not fires) would a value of 0.01 probably be workable.

b) For all balanced flue appliances it is also desirable to adopt the lowest acceptable CO/CO_2 ratio criterion, and 0.008 is again suggested. From experience, the possibility of correctly installed appliances generating excess room CO is extremely unlikely at ratios below 0.01.

c) For fixed flueless space heaters to meet the requirements of the room test defined in Section 3.4.4.3 of Part 1 of Reference 5, the CO/CO_2 ratio needs to be lower than 0.004. These appliances could be regarded as a special case.

d) According to Section 4.1 of Part 1 of Reference 5, one 3kW cooker burner being allowed to operate for as long as 30 minutes at full rate would be unacceptable, unless the CO/CO_2 ratio were less than 0.004 (deduced from calculated figures). This is probably lower than is compatible with practice related to cooker grills (see below) so either the test or the ratio criterion will have to be modified.

e) For unflued instantaneous sink water heaters, the calculations show that a CO/CO_2 ratio of 0.01, as assumed initially, will give room CO levels much higher than those required to pass the room tests in Part 1 of Reference 5. In practice, however, the situation appears to be different. In Reference 6, an appliance was used where the CO/CO_2 ratio, unvitiated, seems to have been of the order of 0.0005. Initial reference to the small number of unflued sink heaters in the 1991 appliance combustion survey indicates that most of these could be made to operate at similar low ratios. The calculations were then repeated for a CO/CO_2 ratio of 0.001, showing that the CO criterion in the test is reasonable, though there remains considerable doubt about the proposed CO_2 limit of 0.08%.

7 RE-EXAMINATION OF THE 1991 COMBUSTION SURVEY DATA

The calculations suggest that, to avoid occasional exceedence of the room CO limit, the CO/CO_2 ratio should in many cases be lower than 0.02, and in some cases lower than 0.01. The advantages of adopting a universal ratio criterion (for all flued appliances) are obvious, and to provide the widest appliance coverage this should be lower than 0.01. The ratio 0.008, which has for many years been proven to work with boilers and combination boilers, was examined first for all flued appliances.

The whole of the available database of CO, CO_2 and ratio measurements made in the 1991 combustion survey has been reviewed. This includes, where appropriate, data sets restored following a previous exercise (Reference 3) in which data not certain to have been obtained wholly by the Telegan performance tester, and/or data which was incomplete, had not been used. One effect of restoring data has been to slightly alter the ratio distribution diagrams, as shown by way of example for some appliance types in Figures 1 to 4.

For the current exercise, the data are classified by appliance type, as shown in Table 2. With the exception of balanced flue fires, appliance types have not been sub-divided by flue type, although it would be possible to do this for boilers and combination boilers if needed. Unflued appliances have been omitted, because they are probably not relevant to a ratio criterion of 0.008. Cooker grills have been listed only to provide a useful comparison.

The database provides sets of “as found” and “as left” measurements. Unfortunately, not all appliances were provided with “as left” data, especially where the appliance initially met the survey ratio criterion of 0.004. Another problem is the lack of the first “as found” measurement, sometimes because of off-scale readings, so that the first valid readings appear in the “as left” columns. Because of these and other problems, it has been necessary to look for 0.008 exceedences in every first recorded set of data, not only in the “as found” data. Plots of CO against ratio that had been made for the previous investigation (Reference 3, for both “as found” and “as left” data) have helped in this, but all restored data have needed to be examined individually. All cases of exceedence have been recorded, in column 4 of Table 2. The fate of all these appliances has been accurately checked, such that on any one line in the Table the sum of the figures in the last four columns should equal the figure in column four, with only one exception as given in the footnote. As far as is known, this exception is the only case in 2886 flued appliances of an “as found” ratio below 0.008 giving rise to an “as left” ratio above 0.008, although several cases were seen where the figure had risen but remained below 0.008.

The position of DFE and ILFE fires requires special mention. These appliances were not included in the previous investigation, partly because (in 1991) many had no GC Numbers and others were not easily identified, and partly because of problems of making the measurements on very dilute flue gas samples. In all, there were 21 of these fires identified in the database by appliance name or description. Data for eight of these were incomplete to the point of being virtually useless, leaving just 13. A search through the GC Numbers of some 85% of the remaining fires has identified one more. It would be possible to complete this search, but because of the outcome for DFE and ILFE fires where the numbers are small and the “as left” position seems to be inadequately recorded, the required effort cannot really be justified.

The total number of all other open flued fires (including BBU fires) is 817, of which 794 had ratios already below 0.008 or were definitely left passing this criterion. This leaves 15 fires where there were no remedial data, two whose final “as left” ratio was recorded as 0.008, and six more that could not be made to meet the 0.008 criterion at all. The proportion of “failures” in the 15 fires without remedial data is thought to be larger than in the sample as a whole, but this does not necessarily mean that

there were more than one or two failures. However, this feature of the statistics makes for a difficult decision on the use of the 0.008 ratio for fires.

The total number of cooker grills was 736, of which the number passing a ratio criterion of 0.008 was 709. The numbers of failures and of those without remedial data are slightly more than those for fires, indicating that a criterion of 0.008 would be even less likely to be acceptable.

A special ratio criterion of 0.001 has been suggested for unflued sink water heaters. The database contains a total of 14 sink heaters, of which 12 were definitely left with a ratio less than 0.001, one of which had been initially below 0.02, and two initially failing but without remedial data. This indicates the likely feasibility of the 0.001 criterion, but more data are needed for confirmation.

Regarding fixed flueless heaters, only eight were found. Of these, six were left with a ratio less than 0.004, one 0.0049 and one (originally 0.0065) for which there were no remedial data. Again, the proposal looks feasible, but more confirmatory data are required.

There were three flueless circulators in the survey, two of which were left with ratios less than 0.001, but the third needed deferred remedial action (possibly new parts) to bring the ratio down to 0.0035.

There was one tumble dryer and there were no refrigerators.

8 FINAL CONCLUSIONS

1. The overall conclusion from this and earlier work, is that the proposed use of a CO/CO_2 ratio "as-left" or action level criterion of 0.008 for all flued appliances is feasible, according to 1991 data, with the exception of some gas fires.

2. For flued gas fires, those with balanced flues would be satisfactory. DFE and ILFE fires would most probably be unsatisfactory (though data were too few to be sure) whilst other open flued fires would probably be acceptable, pending confirmatory tests.

3. The only cooker data concern grills, for which a CO/CO_2 ratio criterion would incur a failure rate exceeding 1% (similar to fires) which is not necessarily acceptable. There are no data on ovens or hotplates.

4. Based on small numbers of data, the following CO/CO_2 ratio "as-left" criteria or action levels for other unflued appliances appear to be feasible:

    - Sink water heaters 0.001
    - Fixed flueless space heaters 0.005
    - Flueless circulators 0.004

5. The database includes only one tumble dryer and no refrigerators, hence no recommendations are made for these appliances.

9 FINAL RECOMMENDATIONS

1. It is suggested that the values of CO/CO_2 ratio listed above should become the "as-left" criteria or "action level" target values, but any final recommendation must consider the manufacturer's servicing instructions.

2. If the target ratio for a particular appliance were not achieved, even after servicing to the manufacturer's instructions, then no further action would need to be taken unless there were a room CO problem attributed to that appliance.

3. If, to solve a room CO problem, a newly installed or serviced appliance were to require further adjustment, eg downrating, this should first be discussed with the manufacturer.

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Table 1. CO/CO_2 Calculations

(continued on next page)

Calculations for Worst (but acceptable) Case of Each Type of Appliance
(based on 9 ppm CO rise above ambient, measured 2m above the floor)

Appliance	Heat Input H (kW)	No. AC/h n (h^{-1})	Room Vol. V (m^3)	Spillage S (%)	Stratificn. Factor F*	CO/CO_2 Ratio to Keep CO < 9 ppm at Equilibrium in a Stirred Room	30 min CO Rise (ppm)	CO_2 at Equilibrium (%)	Possibility of Vitiation
Part 5 fire	7	1	20	3	1	0.0093	3.54	0.097	no
Decorative fire	7	2	30	5	1	0.0167	5.69	0.054	no
ILFE fire	7	1.5	20	5	1	0.0084	4.75	0.108	no
OF boiler or air heater, floor mounted	15	1	20	1	1.2	0.0108	3.54	0.083	no
	25	1.5	20	1	1.2	0.0098	4.75	0.092	no
OF combi, floor mounted	30	2	20	1	1.2	0.0108	5.69	0.083	no
OF boiler, wall mounted	15	1	20	1	1.6	0.0081	3.54	0.111	no
	25	1.5	20	1	1.6	0.0073	4.75	0.123	no
OF combi, wall mounted	30	2	20	1	1.6	0.0081	5.69	0.111	no
BF or PF boiler, floor mounted	15	1	20	0.5	1.2	0.0217	3.54	0.042	no
	25	1	30	0.5	1.2	0.0195	3.54	0.046	no

BF/PF combi, floor mounted	30	1	20	0.5	1.2	0.0108	3.54	0.083	no
BF or PF boiler, wall mounted	15	1	20	0.5	1.6	0.0163	3.54	0.055	no
	25	1	20	0.5	1.6	0.0098	3.54	0.092	no
BF/PF combi or water heater, wall mounted	30	1	20	0.5	1.6	0.0081	3.54	0.111	no
Fixed flueless heater, 1.5 kW (in smallest permitted room)	1.5	2	30	100	1	0.0039	N/A	0.231	no
Cooker grill running 30 mins. (or other 3 kW burner)	3	1	10	100	1.2	assume 0.01	131$	1.31$	Yes
Unflued sink heater: 5 min.	12	1	20	100	1.4	assume 0.01	62$	0.62$	no
5 min.	12	1	20	100	1.4	assume 0.001	6.2$	0.62$	no
10 min.	12	1	20	100	1.4	assume 0.01	119$	1.19$	Yes
10 min.	12	1	20	100	1.4	assume 0.001	11.9$	1.19$	Yes
5 min.	12	2	20	100	1.4	assume 0.01	59.5$	0.595$	no
10 min.	12	2	20	100	1.4	assume 0.01	101$	1.01$	Yes

NOTES: * Stratification Factor = concentration at 2 metres height / average concentration in the room.

$ Peak value, at the time indicated in the left-hand column, not as the column headings.

Table 2. Appliance Servicing CO/CO_2 Ratio Data

(based on the 1991 combustion survey)

Appliance	Flue Type	Number of Appliances	Number >0.008 on first valid measure[t]	Fate of all appliances known to have exceeded 0.008			
				<0.008	0.008	>0.008	unknown
Convectors	Balanced	95	1	1	0	0	0
Water heaters	BF or SD	91	1	1	0	0	0
Air heaters	All flued	61	1	1	0	0	0
Combis	All flued	78	0	0	0	0	0
Circulators	All flued	36	6	6	0	0	0
Back boilers	Open	258	18	16	0	0	2
BBU fires	Open	204	10	9	0	1	0
Fires	Balanced	24	3	3	0	0	0
All other fires except DFE, ILFE	Open	613*	85	63	2	5	15
DFE, ILFE fires	Open	14	10	0	0	1	9
All other boilers	All flued	676	20	18	0	2[$]	1
Cooker Grills	Unflued	736	66	39	1	8	18
		2886					

NOTES: * This figure may include one or two DFE or ILFE fires.

[$] Both appliances were old open flue boilers (one with an increased ratio).

Figure 1. Combustion Ratio Distribution for Boilers

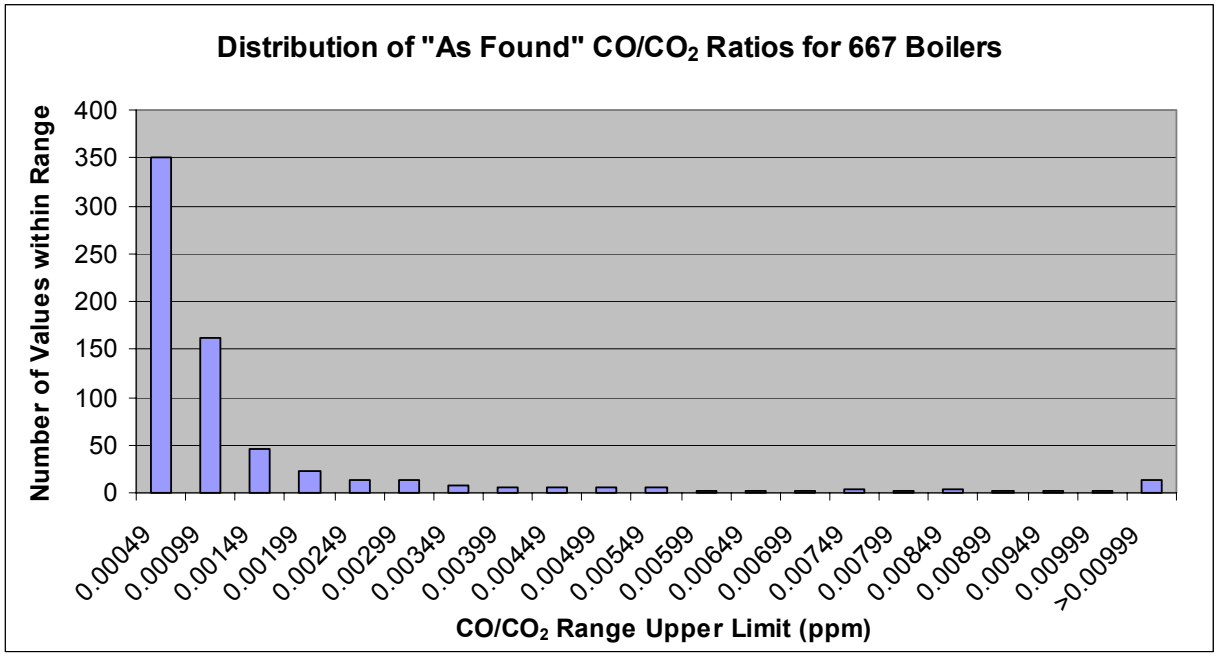


Figure 2. Combustion Ratio Distribution for Cooker Grills

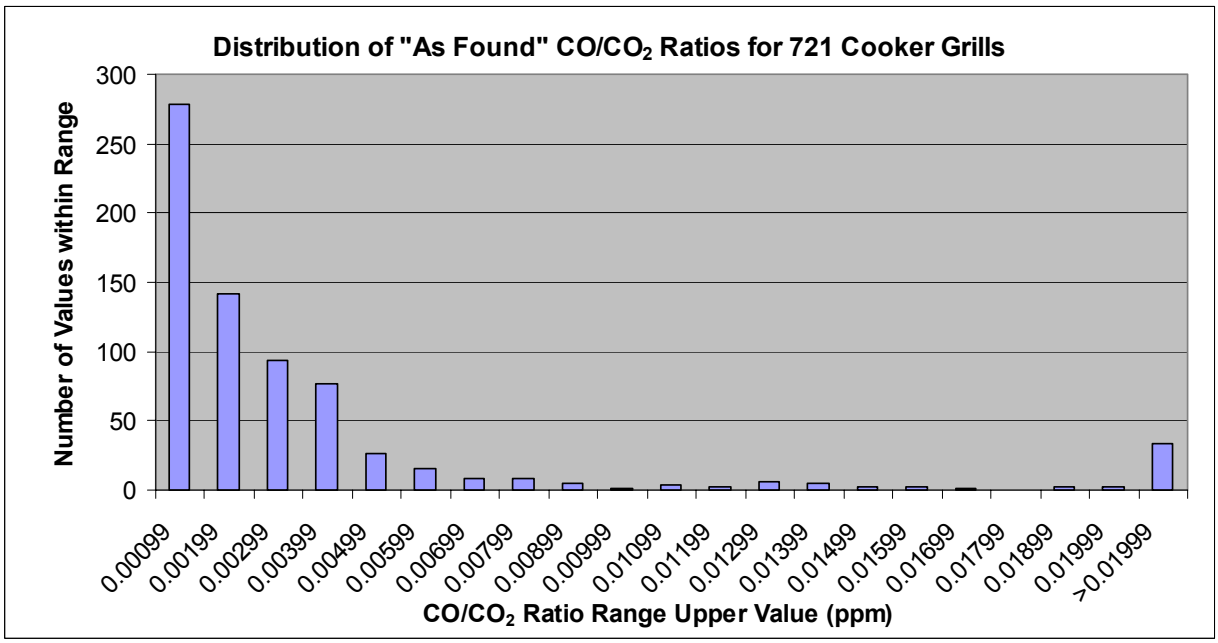


Figure 3. Combustion Ratio Distribution for Air Heaters

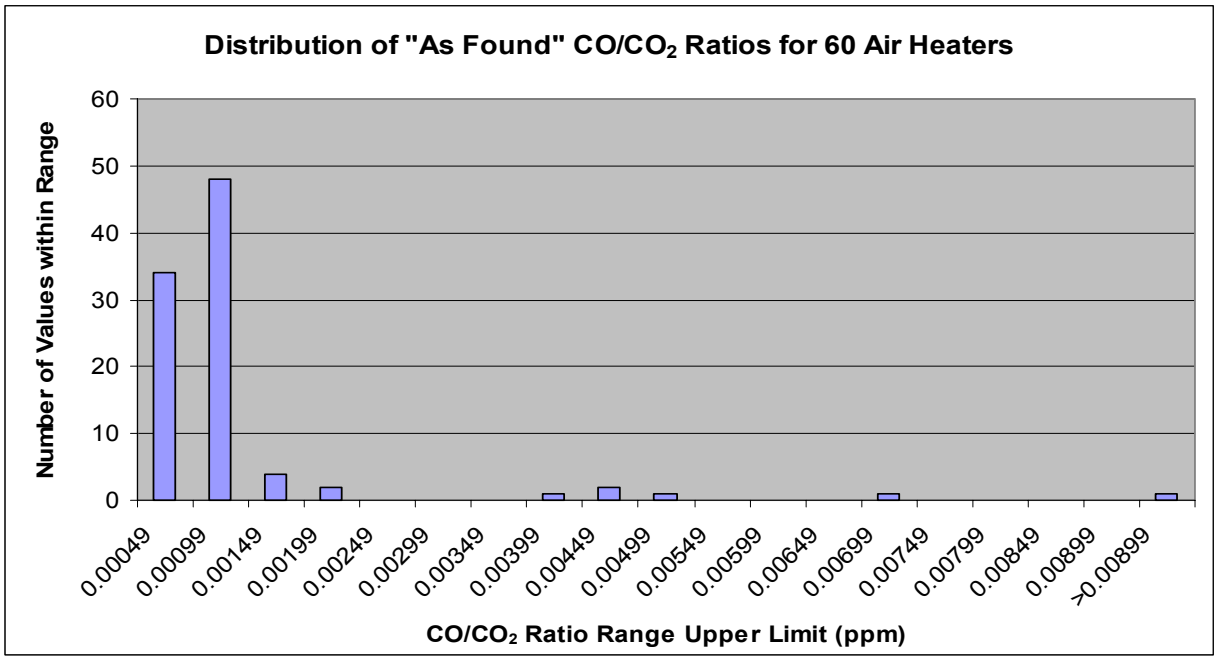
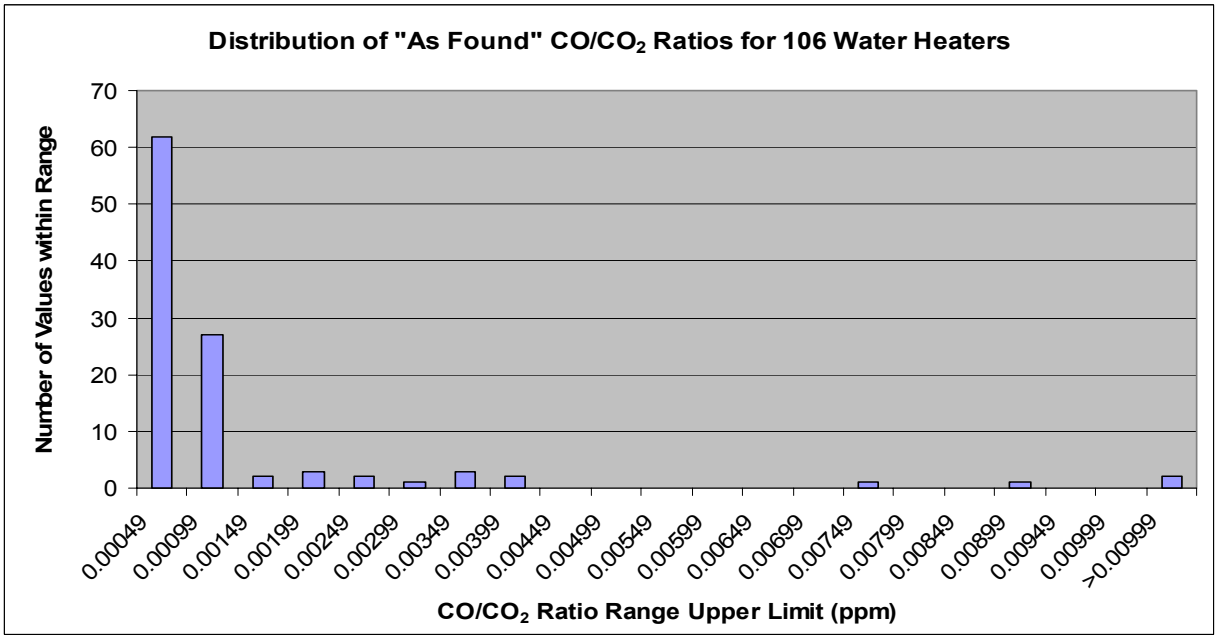


Figure 4. Combustion Ratio Distribution for Water Heaters



Appendix

Concentration of Pollutant in a Room

The percentage of any pollutant P in a fully stirred room, at equilibrium, is given by:-

$$\%P = \frac{100R}{nV} \quad \text{.....(1)}$$

where R = pollutant input rate (m^3/h)) assumed constant
n = no. room air changes per hour (h^{-1}))
V = effective room volume (m^3)

If P is CO_2, then $R = C \times \frac{heatinput(kW) \times 3.6}{CV(MJ/m^3)} \times spillagefraction$

where $C = \frac{vol.CO_2produced}{vol.gas}$ (approx.= 1.0 for natural gas)

If P is CO, then:-

$$R = CO/CO_2ratio \times C \times \frac{heatinput(kW) \times 3.6}{CV(MJ/m^3)} \times spillagefraction$$

Build-up Equation

The approach to equilibrium is covered by the equation:-

$$\%P = \frac{100R}{nV} \times (1 - e^{-nt}) \quad \text{.....(2)}$$

where t is time (h) elapsed since start of pollutant input.

It can be seen that as $t \rightarrow \infty$, the expression in the brackets $\rightarrow 1$, so that at equilibrium equations (1) and (2) become identical.

Vitiation

The above analysis takes no account of vitiation, the effect of which is to increase the CO/CO_2 ratio as O_2 depletes and CO_2 builds up. If there were some sort of mathematical relationship between CO/CO_2 and t, or between CO/CO_2 and P_{CO_2}, then this could be substituted into the CO version of equation (2) to provide a simple CO build-up model.