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Very Low Emissions Cordwood Combustion in High Burn Rate Appliances - Early Results with Possible Implications

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INTRODUCTION

The author and colleague J. Frisch have conducted a multi-year testing program on masonry heaters and masonry fireplaces. Fueling and combustion parameters affecting particulate matter (PM) and carbon monoxide (CO) emissions were studied. The goal is to define a minimum emissions appliance/operator system. Preliminary indications are that some high burn rate cordwood fueled appliances are able to operate with emissions similar to the cleanest pellet stoves. An unexpected result was that a standard masonry fireplace could be modified to achieve similar PM emissions performance.

Fuelwood is a renewable energy source. It is the author's opinion that domestic scale biomass combustion is likely to be a key component in most scenarios for achieving sustainability. For example, some current atmospheric carbon reduction models[1] require an eventual per capita reduction of fossil fuel use of 80% to 90% for the average North American. In such a scenario, the continued widespread use of petroleum for low grade applications, such as home heating, is clearly a physical impossibility. This will lead to a serious examination of renewable fuel options. Emissions will immediately become a critical national issue for cordwood fueled appliances. The presence of smoldering combustion can increase the particulate emissions from wood fuel by up to two orders of magnitude, which would be intolerable in densely populated areas. Will this require conversion to processed fuels, such as wood pellets and briquettes, or can we develop techniques for cordwood combustion that are an order of magnitude cleaner than current United States Environmental Protection Agency (US-EPA) requirements?

Masonry Heaters

Masonry heaters are high burn rate domestic appliances that use a thermal mass to store heat. They are native to the colder regions of Europe, with the exception of Britain and France. Typical systems being built in North America today often resemble traditional masonry fireplaces in outside appearance. In contrast with a fireplace, all of the fuel charge is loaded and combusted at once. Internal flue gas heat exchange channels transfer energy to the masonry. Typical external surface temperatures of 140 F. provide the additional benefit of a true radiant heating system, i.e., the energy is in the longwave range of the infrared spectrum.

The ability to store thermal energy allows the burn rate to be decoupled from the heat output. This scheme avoids smoldering combustion, which is the main technical challenge in conventional stove design. This problem is most intractable in high efficiency houses, where heat demand can be very low (<2 kW) for prolonged periods.

Masonry Fireplaces

These appliances are typically site-built by fireplace masons. The system studied at Lopez Labs consist of a precast refractory firebox embedded in insulating castable refractory. It is connected to an 8" diameter insulated metal chimney and fitted with an airtight ceramic glass door. Conventional masonry fireplaces usually are built under the locally applicable building code. Codes typically assume that masonry fireplaces will not be fitted with doors and do not address the issue of additional clearances to combustibles that may then become necessary because of higher firebox temperatures.

Canadian studies[2,3] have shown that a positive feedback loop can result from a direct coupling of the combustion air supply, and potentially the burn rate, to chimney draft. A runaway fire may result. Tests conducted by the author and J. Frisch (Lopez Labs) indicate that the air inlet may also be configured so that the coupling yields a controlled, clean burn.

TEST METHOD

The Condar Dilution Tunnel Method

The Condar Method is used at Lopez Labs to measure particulate emissions. Developed by the late Dr. Stockton (Skip) Barnett, the Condar is a very simple piece of equipment. It is a dilution tunnel design. A sample probe extends about 1/2 inch into the stack, from which the gases immediately enter a 6 inch diameter cylinder which is attached to a pump. In front of the pump is a filter. The dilution is provided by a series of 24 holes drilled into the face, providing a dilution ratio of approximately 20:1. The orifice is calibrated, and the pump is regulated to provide a constant pressure at the dilution chamber, insuring a constant sample flow. As the filters load with particulate, a Variac control on the motor provides pressure compensation to maintain constant flow. The temperature after dilution is under 90 degrees F., assuring condensation of atmospheric particulates prior to filtering. The Condar design allows real-time monitoring of emissions simply by pulling the filters at anytime and weighing them.

The Condar Method is approved by Oregon and is known as Oregon Method 41. The Condar has been used to develop the very cleanest burning woodstoves.

Quality Control Procedures

A quality control manual has been written for the Lopez test method and is used for all tests. It includes a checklist that is followed for the complete test process. Included are calibration histories for the gas analyzer and the analytical balance, and a detailed fueling protocol, described later.

A separate section of the manual deals with the handling of the particulate filters. Handling and weighing the filters is the most sensitive part of the test procedure. The fiberglass filters used are moderately sensitive to ambient humidity. Filters are held in the drying cabinet for 24 hours and then conditioned in ambient air for 30 minutes prior to their final weighings. A control filter is kept alongside the other filters. A running record of the control filter, as well as a reference mass, serves as a double check of the weighing procedure. A spreadsheet routine adjusts filter weights in accordance with small moisture induced changes in the control filter while filters are out of the drying cabinet. Filters are 150 mm diameter with a typical weight of 1000 mg. A front and rear filter is used, and filters are changed in the Condar after the first 15 minutes, for a total of 4 filters per run. Typical filter catches are 50 mg for the front and 2 mg for the rear filter. An analytical balance with a resolution of 0.1 milligram is used. As a double check, filters are batch weighed after being weighed individually. A spreadsheet routine flags any discrepancies.

A statistical snapshot of all Lopez test runs to date for which filter controls were in effect is provided by the histograms in Figures 2 and 3. Figure 2 shows the distribution of the discrepancies between individual and batch filter weighings. A resolution of 0.1 g/kg in the PM emissions factor would represent about 2.5 mg of filter catch. The average moisture adjustment is 6.7 mg, or approximately 0.3 g/kg. The asymmetric distribution of these adjustments adds about 0.1 g/kg PM factor to the average test run.

Flue Gas Analysis

A Sun Model SGA-9000 automotive emissions analyzer is used for the flue gas analysis. A problem with the accuracy of the O_2 cell used in this type of instrument resulted in a decision to calculate the flue gas O_2 from CO and CO_2. After consulting experts in the field[4] the following formula, based on test results for douglas fir, was used: $O_2 = 20.55 - CO_2 - 0.5CO$. The CO_2 and CO accuracy of the gas analyzer is very good. Previously reported results for 1993 were corrected and are given in Table 1, with the run number prefix “A”.

The Lopez Fueling Protocol

A rule of thumb from past experience is that, for masonry heaters, fireplaces and woodstoves alike, field test emissions factors for PM tend to be about twice that of laboratory results. This may stem from the fact that most laboratory protocols so far have used fuel that consists of carefully spaced pieces of dimensioned lumber[5,6,7].

Since it was felt that fueling protocol was likely to be one of the main variables affecting emissions, particular attention was paid in this area. A goal of the Lopez protocol is to duplicate in-home conditions as much as possible. This is because in-home testing has become the only recognized method of establishing performance figures for appliances that are not covered by the EPA woodstove regulations.

The Lopez Labs fueling protocol for masonry heaters includes the following items:

- heaters are fired on a 24 hour cycle, which is typical of in-home use
- fuel is old growth Douglas Fir cordwood with no bark
- each piece of fuel is:
    - measured for moisture content
    - weighed
    - measured for length and circumference
    - numbered
- fuel load is spread out on floor of lab in sequence and photographed
- fuel is stacked in sequence
- fuel load in firebox is photographed
- the weight of kindling is held constant

Test data is entered into a spreadsheet that is programmed to perform the necessary calculations. An example of the data form is shown in Figure 1. It is programmed in Excel for Windows. A graph of stack temperature and the CO_2, CO and HC readings is drawn dynamically on the screen as the data is entered. The time cell includes an underlying note field, allowing text or sound notes to be attached to the readings. Notes are printed out as part of the test documentation.

TEST RESULTS

Masonry Heaters
Results from 1992 and 1993 tests were reported in a previous paper[8]. For 1994, the same contraflow heater was used. In addition, a new prototype heater was constructed, thus allowing two contraflow heater tests per day. The main difference from the stock heater was an increase in firebox width from 18" (4570 mm) to 27" (6860 mm). The sloped back wall of the firebox was changed to a straight wall to allow the inclusion of a bakeoven above the firebox. Table 1 summarizes the results from 49 test runs on masonry heaters. Run names are coded by prefix as follows: CF: 18" firebox; HK: 27" firebox; A: 1993; B: 1994.

Of particular interest from the 1994 series were the last 4 runs on the 27" heater, which are reported separately in Table 2. On run HK-B13 a slightly different kindling method was used, with the fire kindled from the bottom front of the pile, near the air inlet. One observation had been that a large amount of initial air significantly reduced the chances of a CO spike during startup. It was hypothesized that flaming from the virgin wood surface is greater due to surface drying and the lack of a char layer. There is a tendency on startup towards rich (high CO) conditions that is aggravated by reduced reactivity with combustion air until the firebox is warmed up. One goal was to find methods for controlling the initial flaming sequence in the firebox. With the configuration of run HK-B13, there was a fast ignition of the kindling which then ignited only the front part of the pile. This maintained sufficiently fast flaming to ensure a good start without igniting the whole pile at once and causing rich conditions. The notes from this run are instructive:

Start: Initial stack temperature: 120; Time to start from ignition: 1 minute. Wood stacked 30 minutes before ignition. Large pieces. About 1" gap between front top of pile and angle iron (forms a throat).

5 minutes: Door open a crack (about 0.5"). Good flaming start.

15 minutes: At 17 minutes, flaming is drastically reduced due to larger pieces with less surface area. Fire is burning mainly above pile. Front of pile is char, not burning. Closed door at 17 minutes.

30 minutes: Short flames dancing off bottom wood surfaces. Good flaming above, not too brisk.

The average CO from this run was quite low at 18 g/kg. One advantage of the Condar Method is that it can provide a preliminary particulate number immediately. Filter weights on this run translated to 0.62 g/kg after 24 hr. drying, or about an order of magnitude lower that the US-EPA woodstove limit[9].

There were only 3 test slots left for the year, and they were used to do repeat runs of HK-B13. The result was a very consistent 4 run series with little apparent data scatter. Average particulate emission factor was 0.58 g/kg with a 95% confidence level of 0.09 g/kg. A statistical summary of other parameters is presented in Table 2. A good first order validation of these runs is provided by the fact that tests were conducted on 4 other systems during this interval, and there is no indication of unusual results in the other data sets.

Fuel sizing. In the author's opinion, fueling parameters are the main variables observed in masonry heaters, once basic errors relating to combustion air location and sizing are avoided. A detailed fueling protocol has been developed at Lopez that allows the tracking, among other things, of the ratio of surface area to volume of fuel. This is used as an indicator of fuel sizing. The statistical distribution of fuel sizing for 38 masonry heater tests for which this data is available is shown in Figure 4. Figure 5 shows a histogram of the distribution of particulate emissions factor against the fuel sizing ratio for 41 tests.

Masonry Fireplaces

For the 1994 test series, a decision was made to use the fireplace tests as a control for the overall test procedure and simply repeat the same burn every day. Two changes were made from 1993. The conventional "cowbell" combustion air inlet on either sidewall was replaced by a length of 1.5" i.d. steel tubing, aimed directly at the fire. In addition, a fast start was used. The fireplace was run as the last test of the day, and the day's accumulation of cold and hot charcoal was used as a starter.

Table 3 compares the results from the standard air supply in 1993 with the modified air supply. In addition to a large particulate emissions reduction, the most obvious change observed was in excess air, which was reduced from 1000% to 410%. Qualitatively, this was observed as a "blowtorch" effect with the new air supply. With an airtight door, all of the chimney pressure is available at the firebox combustion air inlet to maximize the velocity of combustion air at the inlet opening. Less air is able to bypass the combustion process, resulting in a higher burn rate and higher stack pressure. A conventional fireplace lacks a heat exchanger, and therefore a higher burn rate, assuming equivalent excess air, results immediately in higher stack temperature. Stack temperature and burn rate become coupled by the combustion air. The flow in the air tube is most likely still laminar, however. For a pressure difference of 40 pa across a circular orifice, calculated air velocity is around 1 ft/sec. For air in a 1" dia. pipe, the critical velocity (transition from laminar to turbulent flow) is approximately 3 ft./sec.

The blowtorch effect mentioned above has been flagged as a potential safety problem by CMHC (Canada Mortgage and Housing Corporation)[10]. This effect was not observed, however, with the previous "cowbell" air setup. With the cowbell, air first hits a deflector and is bounced away from the fire. Much of the air bypasses the fire, as evidenced by the 250% increase in excess air. This illustrates the great influence of geometry-dependent parameters in fireplace combustion. It is the author's opinion that they will prove to be the key variables once a larger testing database on fireplaces is developed. Accordingly, geometry dependent parameters should be carefully accounted for in test protocols.

There was an indication that the nozzle could be reduced to the point of creating a very "normal" looking fire without a significant PM penalty. The air tubes were changed from 1.5" to 1" starting with run FC-B09. Using a fast start as before, the 10 minute observation from this run reads as follows:

> "10: Much slower start with the 1" air tubes. Much more controlled. More realistic, no runaway fire."

PM remains low, although CO is up to 40 g/kg.

Actual air consumption can be approximated as follows:

stochiometric air for wood	= approximately 4000 l/kg.[11]
observed burn rate	= 6 kg/h (dry)
excess air	= 400%
	(= 100 x "stack dilution factor" from Condar method, which is 20.9/(20.9-Average_O_2))
total combustion air flow	=4000 x 6 x 4 / 3600 = 26.7 l/s

If a ballpark value of -50 pa is used for stack pressure, a calculated flow[12] for the two 1" air tubes is about 8.0 l/sec.

Up to this point in the fireplace runs, it was assumed that the low PM factor was related to the hot start, which is not typical of field conditions for fireplace use. For the next run, FC-B10, it was decided to try a conventional cold start. This resulted in the lowest PM number of the two year series, at 0.77 g/kg. CO was still elevated at 37 g/kg. The next run was a repeat, FC-B11, which unfortunately was the last test in the series. Again, PM was low at 1.7 g/kg and CO was elevated at 47 g/kg. Results for the two cold start tests with the 1" air tubes are reported in Table 2 and compared with the last 4 masonry heater runs. Table 3 provides a summary of all Lopez fireplace tests, including a comparison with overall averages from field testing for other appliances, as compiled by US-EPA[13].

CONCLUSIONS

Masonry Heaters

North American masonry heater testing to date clearly establishes that, as an appliance class, they operate well below EPA Phase II limits for particulate emissions set for woodstoves. Testing conducted at Lopez Labs, though not conclusive, strongly suggests that sustained performance at a PM factor below 1 g/kg may be possible. This could qualify some masonry heaters for use in airsheds with some of the strictest RWC (Residential Wood Combustion) regulations, such as Reno-Sparks[14].

Masonry Fireplaces

PM emissions performance equivalent to EPA Phase II pellet stoves has been demonstrated for a site-built masonry fireplace retrofitted with an airtight door and a simple high-velocity air supply. The lack of additional data points at this time limits further conclusions. However, it is significant that this is the first report in the literature of the potential for site-built, cordwood-fueled masonry fireplaces to be clean burning.

DISCUSSION

Repeatability

Although it is a limited data set, the repeatability demonstrated during the last four masonry heater runs is new, and has not been demonstrated before by other test protocols. Nothing in the Lopez fueling protocol or the Condar Method indicates any inherent lack of resolution or repeatability, vis-à-vis other methods.

The Need for Condar Calibration

The largest uncertainty in the Lopez Labs results is the lack of calibration, at low PM levels, of the Condar Method against the EPA-M5G dilution tunnel method, as well as against the other two field methods (the AWES (Automated Woodstove Emissions Sampler) and the VPI (Virginia Polytechnic Institute) Field Sampler)[15].

In the author's opinion, this lack of calibration is currently one of the main obstacles to developing very clean burning appliances and obtaining recognition and acceptance for such appliances from regulatory authorities. Cordwood burning appliances are more susceptible to operator influence than, for example, pellet stoves. The parameters relating to fuel size, stacking method, and ignition method need to be mapped before optimum real-world strategies can be developed.

The Need for Low Cost Tools

It is wasteful to use expensive and overly elaborate methods if a low cost method is likely to prove adequate, if not equivalent, in accuracy. All three recognized methods for obtaining M5H equivalency involve, among other things, a labor intensive (and environmentally questionable) acetone rinse of equipment, probes and hoses. This added overhead may prove redundant for sub-1 gram systems.

At a testing workshop in 1991[16], Dr. Barnett provided the following description of the Condar:

> "It is extremely fast and extremely reliable. All the other techniques, as used on location by manufacturers, have proved to be too slippery... they've been a problem, but this one has not. We used to take this one around to M5H locations and got the same relationship between it and M5H. You cannot do that with a dilution tunnel. You probably can't even do it with 5H and 5H."

The Condar has no sample hoses to rinse out, nor do we see any significant deposits in the dilution chamber after three years of testing. In addition, we can obtain real-time particulate data, which will be an asset in the study of operator influence.

It is interesting to note that the testing at Lopez Labs started as a grass roots effort by the small community of masonry heater builders. The original seed projects in this field[17] were triggered by regulatory changes imposed from above. However, the main driving force now seems to be individual heater masons recognizing both the lack of, and need for, tuning data to improve masonry heater emissions performance beyond that required by regulators. There appears to be little incentive to manufacturers, for example, to provide leadership for what in the end are brand-independent, generic results. The work at Lopez Labs is a good example of a bottom-up effort.

The Case for Responsible Wood Heat

Most current economic models do not yet incorporate sustainability criteria. These would assess all environmental costs of energy use, including greenhouse gas emissions, against the end user. Suppliers of energy would be prohibited from externalizing these costs onto society. Hawken[18], for example, provides a detailed analysis of the issues surrounding this concept. On a level playing field, the low emissions combustion of sustainably-grown wood fuel could become a viable component of a wider renewable energy strategy.

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Table 1. Summary of masonry heater test results. CF denotes 18” firebox; HK denotes 27” firebox.

RUN No.	**AVE.**	CF-A02	CF-A03	CF-A04	CF-A05	CF-A06	CF-A07	CF-A08	CF-A09	CF-A10	CF-A11	CF-A12	CF-A13	CF-A14	CF-A15	CF-A16	CF-A17
g/kg PM (Condar)	**1.9**	1.41	1.20	4.65	4.04	2.26	1.80	0.79	1.43	1.20	1.29	1.14	1.01	1.01	3.14	3.00	0.70
g/kg CO	**31.2**	50.6	32.7	104.1	60.1	30.8	22.6	24.2	17.4	20.1	30.2	27.9	42.0	22.4	33.6	23.5	18.9
Overall Efficiency, %	**66.5**	75.4	73.5	66.2	66.1	68.5	53.2	52.1	61.0	59.3	58.0	58.4	63.6	68.0	64.2	56.0	60.2
Total Weight, lb	18.8	19.4	15.9	18.8	19.2	22.0	18.5	19.8	19.9	25.3	24.9	24.5	20.0	20.0	20.6	21.4	20.3
Wood Moisture, %	39.7	28.0	28.0	28.0	28.0	33.3	28.0	28.0	45.0	44.0	45.5	45.5	30.0	41.0	43.5	51.0	39.5
Number of Pieces	8.6	5	5	10	10	10	8	7	13	10	11	11	11	7	16	16	11
Surface/Volume, in^{-1}	4.3	4.2	4.3	5.5	5.5	5.0	5.5		4.4	4.2	4.3				4.9	5.0	4.6
Av. Stack Temp, F	300	178	199	192	246	237	335	318	378	364	315	341	243	293	334	348	301
Stack Dilution Factor	4.6	4.1	5.0	5.0	4.8	5.3	7.0	6.2	4.7	5.3	6.5	5.8	7.1	4.7	4.4	5.8	6.2
Burn Rate dry kg/hr	7.4	5.1	5.4	5.2	5.1	5.9	6.9	6.8	9.8	8.1	7.5	6.9	5.5	6.6	9.0	9.1	6.8

RUN No.		CF-A18	CF-A19	CF-A20	CF-A21	CF-A22	CF-A23	CF-B01	CF-B02	CF-B03	CF-B04	CF-B05	CF-B06	CF-B07	CF-B08	CF-B09	CF-B10
g/kg PM (Condar)		4.5	0.9	1.1	1.8	2.7	3.0	3.2	2.5	1.9	4.0	2.2	3.9	2.6	2.3	1.7	1.7
g/kg CO		42.1	11.0	20.5	25.5	24.7	22.7	27.2	13.6	34.2	66.9	28.3	52.7	61.0	41.9	19.0	17.7
Overall Efficiency, %		41.4	74.1	71.4	66.5	68.7	62.0	72.7	74.5	74.0	68.0	75.6	64.4	63.5	75.0	74.8	71.0
Total Weight, lb		19.6	19.9	20.9	20.4	20.0	20.2	19.5	18.7	18.0	17.5	17.3	16.7	16.7	20.0	16.4	16.7
Wood Moisture, %		43.0	49.5	47.0	46.5	55.3	51.0	37.0	33.0	43.8	38.8	43.0	33.5	31.3	37.0	36.5	32.0
Number of Pieces		9	7	8	8	8	7	6	6	8	8	8	8	8	8	8	8
Surface/Volume, in^{-1}			3.4	3.6	3.5		3.3	3.7	4.2	4.3		4.2	4.4	4.9	4.5	4.5	5.0
Av. Stack Temp, F		368	225	279	265	268	265	222	245	281	305	267	262	299	253	286	343
Stack Dilution Factor		8.0	4.5	3.8	5.3	4.6	6.7	4.8	4.0	2.9	3.3	2.8	5.6	4.8	2.8	3.0	3.2
Burn Rate dry kg/hr		11.8	6.6	6.3	7.5	7.5	6.7	6.6	6.8	8.4	7.5	8.1	6.8	5.9	6.4	6.5	8.8

RUN No.	CF-B11	CF-B12	CF-B13	CF-B14	CF-B15	CF-B16	HK-B02	HK-B03	HK-B04	HK-B05	HK-B06	HK-B07	HK-B08	HK-B09	HK-B10	HK-B11	HK-B12
g/kg PM (Condar)	0.9	1.0	1.2	0.7	1.1	2.4	3.9	1.8	2.2	3.4	3.1	1.0	0.8	1.1	1.2	1.4	1.6
g/kg CO	21.6	32.5	46.1	15.1	14.3	40.6	57.7	21.6	28.7	26.3	42.2	31.5	24.9	20.8	25.5	26.2	28.1
Overall Efficiency, %	74.8	73.2	74.3	71.5	73.1	69.8	60.8	70.9	69.0	66.4	71.4	61.3	66.0	69.7	68.7	65.4	64.8
Total Weight, lb	16.9	19.7	19.7	16.8	16.8	19.7	19.0	17.6	18.5	18.3	16.8	16.9	16.9	17.6	17.1	16.9	16.8
Wood Moisture, %	40.5	31.0	40.5	44.0	43.3	39.3	33.5	37.0	40.8	42.0	45.5	37.5	37.5	42.5	39.5	33.8	41.9
Number of Pieces	8	10	7	8	8	8	6	7	7	8	9	8	8	8	8	9	8
Surface/Volume, in^{-1}	4.3	5.4	4.0	3.9	4.0	4.1	4.2		3.8	4.3	4.1	4.5	4.5	4.1	4.3	4.8	4.1
Av. Stack Temp, F	320	264	264	319	346	309	229	249	291	300.0	285	348	348	335	342	341	352
Stack Dilution Factor	2.6	3.6	2.8	3.5	2.8	3.4	8.1	4.9	4.2	4.7	3.3	5.0	4.1	3.5	3.6	4.3	4.2
Burn Rate dry kg/hr	7.5	7.4	7.2	7.2	8.1	7.1	6.3	7.1	9.5	7.7	8.2	6.9	6.9	7.6	7.3	8.4	7.3

Table 2. Summary of most recent test results - 4 repeat masonry heater runs and 2 repeat fireplace runs.

Masonry Heater (27" Firebox)							
RUN No.	HK-B13	HK-B14	HK-B15	HK-B16	Mean	Stand. Dev.	95% Confidence
g/kg PM (Condar)	0.66	0.48	0.69	0.67	**0.63**	0.10	0.09
g/kg CO	19.8	23.7	19.3	25.2	**22.0**	2.88	2.83
Overall Efficiency, %	64.2	60.4	64.4	63.4	**63.1**	1.88	1.85
Total Weight, lb	55.0	45.3	47.3	42.8	**47.6**		
Wood Moisture, %	20.3	16.8	15.2	17.5	**17.4**		
Number of Pieces	8	8	9	8	**8.3**		
Surface/Volume, in^{-1}	3.6	4.0	3.9	4.0	**3.9**		
Av. Stack Temp, F	410	422	392	374	**399**		
Stack Dilution Factor	3.7	4.2	3.9	4.2	**4.0**		
Burn Rate dry kg/hr	10.0	8.5	9.1	8.0	**8.9**		

Masonry Fireplace (2 - 1" Air Tubes, Cold Start)			
RUN No.	FC-B10	FC-B11	Mean
g/kg PM (Condar)	0.86	1.90	1.38
g/kg CO	41.4	52.9	47.1
Overall Efficiency, %	48.3	55.9	52.1
Total Weight, lb	23.8	23.0	23.4
Wood Moisture, %	17.0	18.0	17.5
Number of Pieces	6	6	6
Surface/Volume, in^{-1}			
Av. Stack Temp, F	483	461	472
Stack Dilution Factor	5.1	4.0	4.6
Burn Rate dry kg/hr	5.9	5.7	5.8

Table 3. Comparison of masonry fireplace emission factors

Data Source, by Appliance Type	Particulates, g/kg	Carbon Monoxide, g/kg	Net Efficiency %
Lopez Labs. (Douglas Fir cordwood):			
Fireplace (Rosin) w. airtight door - conventional air supply.(16 tests, cold start)	8.1	55	26
Fireplace (Rosin) w. airtight door - high velocity air supply (8 tests, hot start)	2.7	39	55
Fireplace (Rosin) w. airtight door - high velocity air supply (2 tests, cold start)	1.4	47	52
OMNI (in-home tests, owner's fuel)			
Open fireplaces, conventional	24.9	107	25
Open fireplaces, Rosin	10.4	53	30
VPI (dimensioned D.F. lumber)			
Open fireplaces, all	11.5	92	
Comparison with US-EPA AP-42, average of all in-home test data:			
Open Fireplaces, all	17.3	126	
Masonry Heaters, all	2.8	75	58
Phase II Woodstove	7.3	70	68
Phase II Pellet Stoves	2.1	20	68
Conventional Woodstoves	15.3	115	54

LOPEZ LABS EMISSIONS TEST DATA FORM

Rev. 4/05/94

RUN No.	DATA	**SYSTEM**	DATA	DATE		DATA
Wood Moisture............	CALC	Time since last burn....	DATA	Ambient Temperature...		DATA
Total Weight (lb)	CALC	Start Time..................	DATA	Weather.....	DATA	DATA
Kindling Weight (lb)	DATA	**FUELING**				
Number of Pieces.......	CALC	FBox Dimensions........	DATA	DATA		
Fuel Surface/Vol........	CALC	Fuel Type..................	DATA	DATA		
Run Length, hrs	DATA	Fuel Surface/Vol........	CALC	DATA		
Av. Stack Temp (F)	CALC	Unburned Fuel, lbs	CALC	DATA		
Av. O2%.....................	CALC	Unburned Fuel...........	DATA	DATA		
Av. CO%....................	CALC					
Stack Temp. Factor.....	CALC					
Stack Dilution Factor...	CALC					
Burn Rate dry kg/hr....	CALC					
Boiling of Water Loss	CALC					
CO Loss %.................	CALC					
HC Loss %.................	CALC					
Dry Gas Loss %..........	CALC					
Filter Catch gm.	CALC					
g/kg Condar............	CALC					
g/kg CO...................	CALC					
Combustion Effic......	CALC					
Heat Trans. Effic.......	CALC					
Overall Efficiency......	CALC					

Time	StackTemp	O2%x10	CO% x1000	CO2% x10	HC ppm
0					
5	READINGS FROM GAS ANALYZER ARE INPUT IN				
10	THIS SECTION:..............				
15					
20	THE TIME CELLS ARE USED TO STORE				
25	OBSERVATIONS. THEY CAN ALSO STORE SOUND				
30	NOTES IF DESIRED.				
35					
40	DATA	CALC	DATA	DATA	DATA
45	DATA	CALC	DATA	DATA	DATA
50	DATA	CALC	DATA	DATA	DATA
55	DATA	CALC	DATA	DATA	DATA
60	DATA	CALC	DATA	DATA	DATA
65	DATA	CALC	DATA	DATA	DATA
70	DATA	CALC	DATA	DATA	DATA
75	DATA	CALC	DATA	DATA	DATA
80	DATA	CALC	DATA	DATA	DATA
85	DATA	CALC	DATA	DATA	DATA
90	etc	etc	etc	etc	etc
etc					
etc					

THIS IS THE FILTER SECTION:

Filter Number	Clean Filter Wt.	Dirty Filter Wt.	Wt. of Particulat
1	DATA	DATA	CALC
2	DATA	DATA	CALC
3	DATA	DATA	CALC
4	DATA	DATA	CALC
Ctrl 1	DATA	DATA	
Ctrl 2			
	Adjust		CALC
	Total		CALC

Batch Wt. Clean	DATA
Add Individual	CALC
Batch Wt. Dirty	DATA
Add Individual	CALC

EXAMPLE FROM SEPARATE FUEL SHEET:

Piece #	Weight	Moisture	Circumf	Length
1	DATA	DATA	DATA	DATA
2	DATA	DATA	DATA	DATA
3	DATA	DATA	DATA	DATA
4	DATA	DATA	DATA	DATA
etc	etc	etc	etc	etc
etc	etc	etc	etc	etc

Figure 1. A facsimile of the spreadsheet form used to enter and calculate data. Date entry fields are marked "DATA" and calculation fields are marked "CALC".

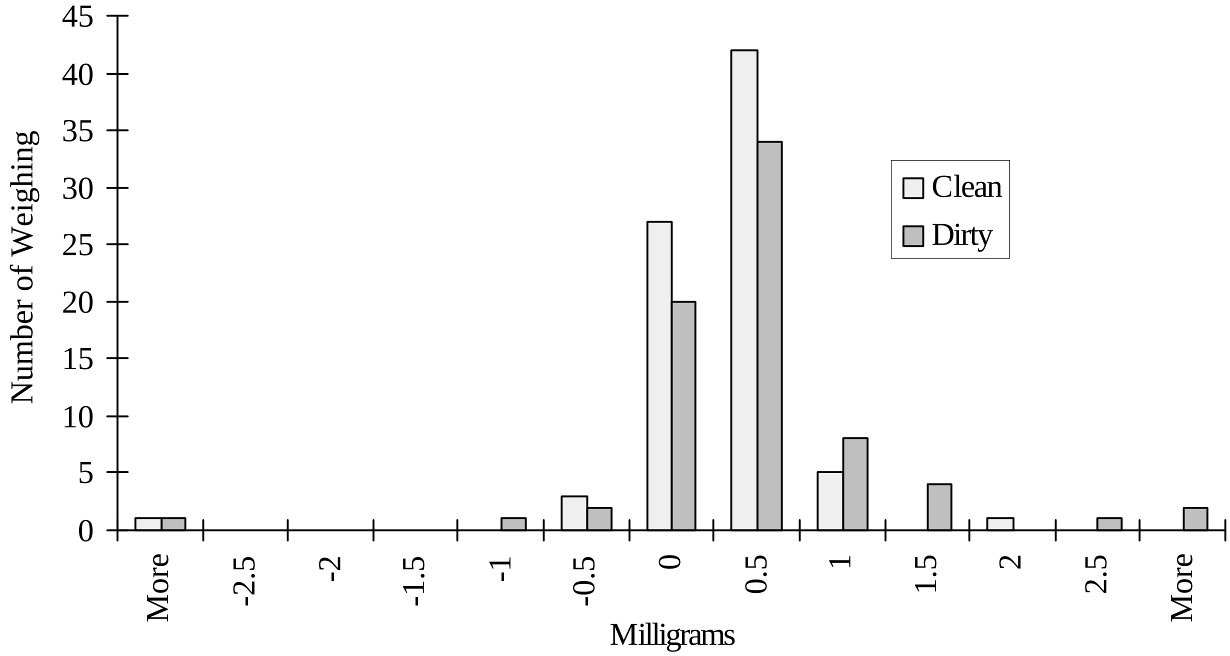

Figure 2. Filter weight discrepancies between batch and individual weights.

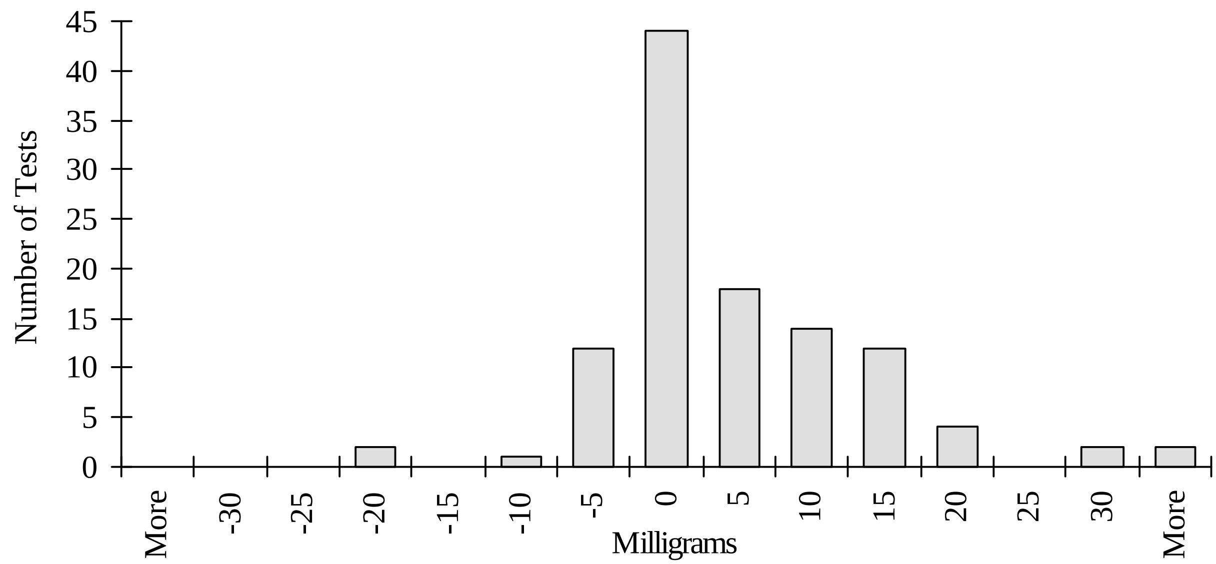

Figure 3. Distribution of filter weight adjustments due to moisture (calculated from weight changes in control filter).

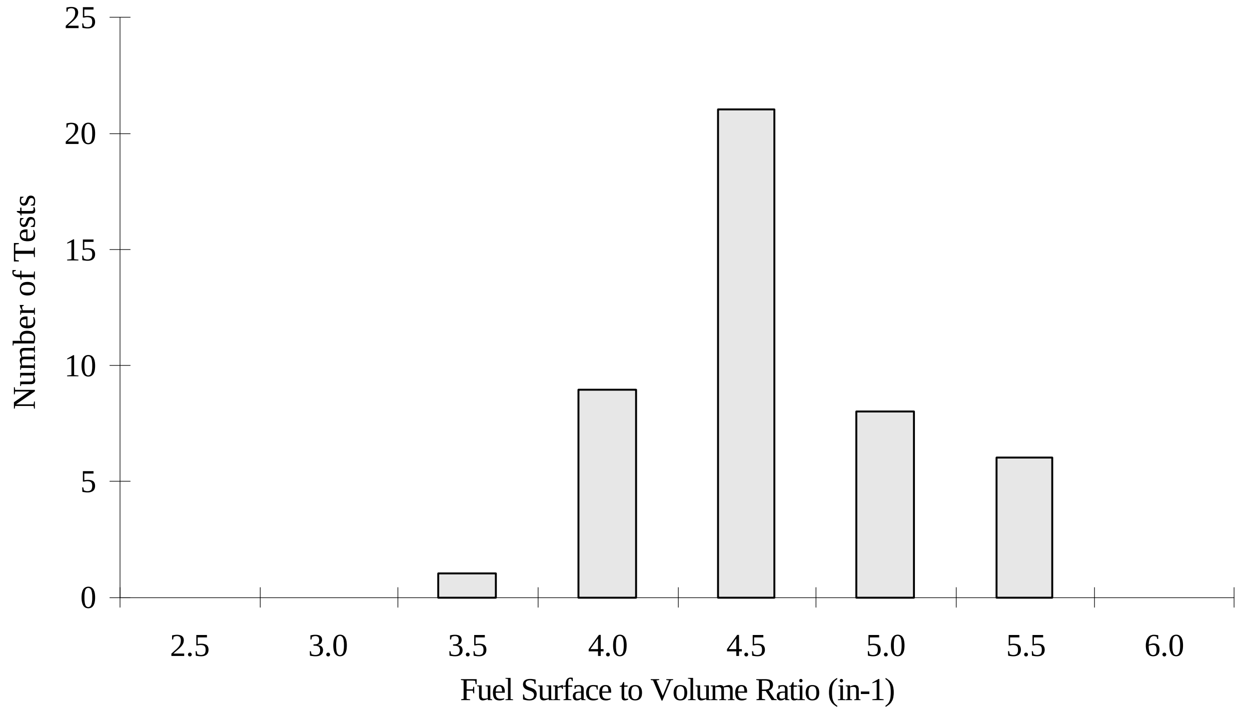

Figure 4. Distribution of average fuel sizing ratio for 45 masonry heater tests.

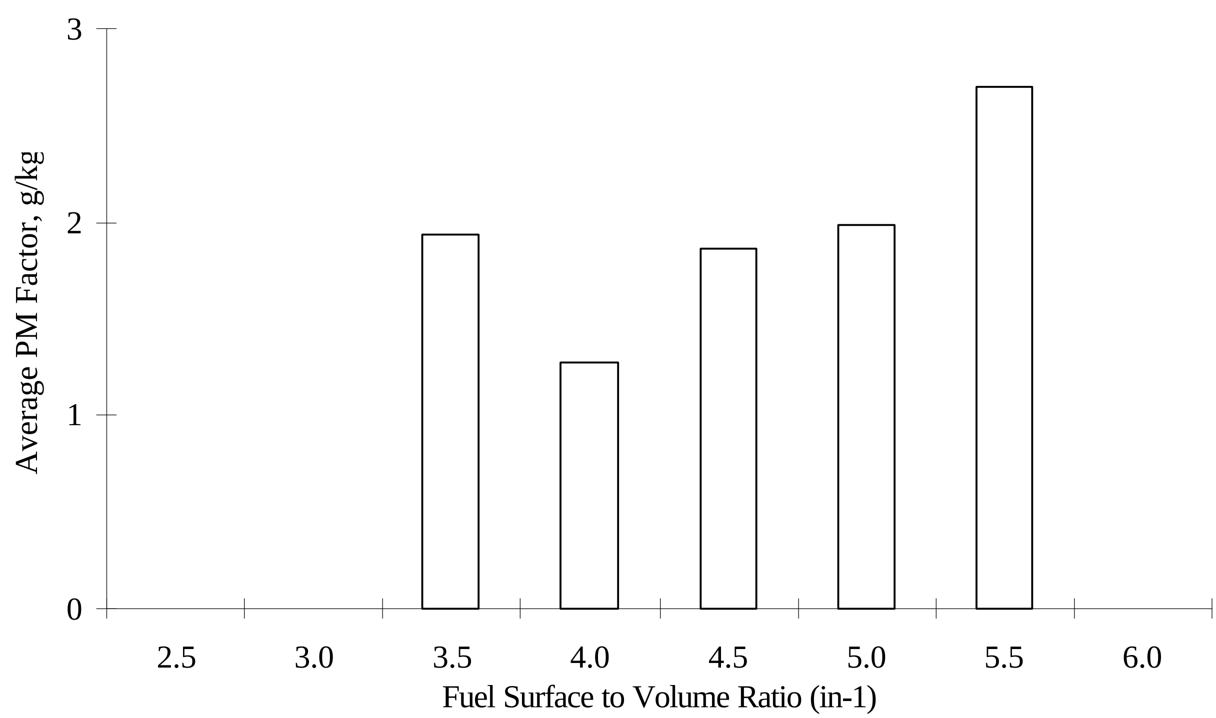

Figure 5. Distribution of PM emission factor by fuel sizing ratio for 46 masonry heater tests.