Recent Laboratory and Field Testing of Masonry Heater and Masonry Fireplace Emissions

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For Presentation at the
87th Annual Meeting & Exhibition of
Air & Waste Management Association
Cincinnati, Ohio
June 19-24, 1994

INTRODUCTION

Particulate matter (PM) is the current focus of EPA woodstove regulations. Prior to 1991, no field data on masonry fireplace PM emissions existed. Limited work since then indicates emission factors comparable to old technology woodstoves. On the other hand, related appliances known as masonry heaters have produced extremely low emissions in EPA-audited field tests.

Masonry fireplaces have been with us for a long time. Masonry heaters, however, are an unknown technology in North America prior to 1981 and remain outside the realm of the conventional. By contrast, they are a 100+ year old technology in several European cultures, with a penetration in new housing that, in the case of Finland, exceeds 90%. Although they often look very similar to a fireplace they are fired in a radically different fashion. A charge of up to 25 kg of fuel is burned very rapidly and the resulting heat is transferred to and then stored in a masonry mass, from which it is gradually released into the heated space. Typical specs. are 50 kWh of storage and a 2 - 3 kW average output for 18 to 24 hours.

European emissions standards differ from country to country and tend to focus on CO, so we have very little masonry heater PM data. Recent work in North America suggests that the ratios between masonry fireplace and masonry heater PM emissions factors are around 10:1. With the advent of fireplace bans in some Western airsheds, the availability of this established alternate technology merits serious consideration by the regulatory community as well as the masonry and housing industries.

The author and collaborator J. Frisch have conducted more detailed testing on a contraflow masonry heater using a Condar (Oregon Method 41) dilution tunnel and a 4 gas analyzer and have confirmed the results from EPA-audited field tests on 7 masonry heaters.

HISTORY OF TESTING

Background

EPA Regulation. The 1988 EPA woodstove regulation quickly became a benchmark. It defined emissions testing for domestic wood-burning appliances, where previously several proposed testing standards were in the running. While Europe tends to use CO to define clean combustion, PM, specifically EPA Method 5H (EPA-M5H) PM, is now the name of the game for anyone wanting to sell woodstoves in the United States. At the same time, woodstoves were defined rather narrowly to exclude fireplaces, masonry heaters, cookstoves and furnaces from the regulation. Also, burn rate is measured by putting the appliance and its venting system on a scale, making it for all intents and purposes unusable for high mass appliances to the required accuracy.

It soon became convenient for regulators in Clean Air Act non-attainment areas to mandate the use of EPA certified appliances in SIP’s (State Implementation Plans) as one strategy for reducing PM emissions into the airshed. Some clean appliances, such as masonry heaters, were uncertifiable under the EPA woodstove definition. Builders of masonry heating systems first encountered a problem in the state of Washington. A homeowner could not use his $10,000 masonry heater on a no-burn day, unlike his neighbor with a $500 EPA woodstove. Ironically, the EPA reg. itself states the following:

> “The 800 kg. cutoff was established as an easy means of excluding the high-mass fast-burn wood-burning appliances ... (which) typically operate at hot, fast burn rates and cannot be damped. It is also likely that they are incapable of meeting the 5 kg/hr minimum burn rate. The intent of the committee was to exempt from the standards these appliances which rely on clean-burning air-rich conditions and which have high combustion efficiencies. It should be noted,

> however, the exclusion does not apply to appliances which exceed the 800 kg threshold only because of masonry or other materials which are not sold by the manufacturer as integral parts of the appliance."[1]

Washington State members of MHA (The Masonry Heater Association of North America) negotiated with the State, and the Department of Ecology agreed to grant an exemption for masonry heaters that could prove their cleanliness claims. An immediate problem became evident: the lack of particulate emission data for masonry heaters. The bigger challenge however, was that in 1988 there was no recognized test method for obtaining PM numbers in either masonry heaters or masonry fireplaces.

Laboratory Methods

Colorado Fireplace Report. The only relevant prior work was the Colorado Fireplace Report[2], published in 1987 by Shelton Research. Most of its work revolved around establishing a fueling protocol, and I will attempt to demonstrate that this is really the main issue in masonry heater and fireplace testing.

It was self-evident that the fuel load defined in the EPA standard is inappropriate for fireplace emissions testing. Particularly in larger fireplaces, the load was deemed "unrealistically large, dangerous and impractical." A 36" fireplace would require a burn rate of around 37 kg/hr. Shelton suggested a fuel load and protocol involving the addition of single log loads at a fixed time interval to achieve a pre-selected fueling rate. Testing conducted during the kindling phase led to the conclusion that hot-to-hot tests would not distort the relative ranking of the appliances studied. One benefit of this scheme was that it was equally applicable to factory-built and masonry fireplaces, since the appliance does not need to be weighed. A masonry fireplace is essentially unweighable at the 0.1 lb resolution required in the EPA stove protocol, particularly in view of the hygroscopicity of masonry materials. Most of the test series was used to develop the fueling protocol and make the fire look realistic. The actual protocol itself was used for only a few tests at the end of the project.

WHA/FERC (Fireplace Emissions Research Coalition) Report[3]. In 1988 Washington State members of MHA in association with WHA (Wood Heating Alliance) persuaded both the masonry and the factory fireplace industries that is was in their interest to proactively help fund the development of an emissions testing protocol for fireplaces. A masonry heater protocol was included in the project as an example of forward thinking masonry fireplace technology.

In the FERC project, fireplace fueling protocol work was continued at Shelton Research using factory fireplaces. At the VPI (Virginia Polytechnic Institute) Combustion Lab in Blacksburg, MHA built a 30" and a 36" masonry fireplace as well as an underfire and an overfire air masonry heater, along with masonry chimneys. Underfire air is characterized by combustion air supplied through a grate in the firebox floor. Fueling protocol again became the main issue in testing design. A stated objective was that "the most important aspect of the laboratory test method is that its results correlate with field results."[4] The main debate was between real world fuel on the one hand and laboratory repeatability on the other. With the masonry heaters in particular, there was no prior North American testing base. One of the elements at the start of the study was interviews with industry experts to survey existing practice. VPI used a modified EPA 5G dilution tunnel, and sampled PM in accordance with EPA-M5G.

<u>Results:</u> A total of 35 test runs were done on the masonry heaters. Of the 17 fireplace tests, 5 were done on the masonry fireplaces. Different average daily burn rates on the masonry heaters were arrived at by

varying the firing interval. There was an order of magnitude difference between the masonry heaters and the fireplaces. Test results are summarized in Table 2.

Field Methods

VPI. In the WHA/FERC study the VPI woodstove sampler, already in existence, was used as a basis for an initial masonry heater field sampler design. Development of the field sampler began in 1989, along with the development of the draft standard laboratory test method. Parallel testing was conducted and analyzed, but it was concluded that the PM correlation was not acceptable and that further testing was needed. VPI also developed a fireplace field sampler during the study[5], and acceptable correlations were demonstrated between field sampler and dilution tunnel PM and CO numbers.

OMNI Environmental. In 1990 regulatory activities against fireplaces in Fresno California got Western States Clay Products Association interested in obtaining some baseline field emission numbers. EPA was using 14 grams per kilogram, and they wanted to see if it was accurate. OMNI Environmental was commissioned to do a study. Masonry heaters were added because they looked promising, and Rosin and Rumford fireplaces were included as well.

MHA members were very fortunate, after the study, to meet the late Dr. Stockton (Skip) Barnett. MHA arranged for OMNI to set up a 2 day course with the title "Short Course on Masonry Fireplace and Masonry Heaters Emissions Testing Methods and Combustion Design[6]." The course took place in October 1991, a year before Dr. Barnett's death. It marked a turning point in our understanding of masonry heater performance issues - Dr. Barnett was uniquely qualified to give us an informed and broad overview of the testing and emission questions that we were puzzling over at the time. Most of the attendees were stovemasons, people who are hands-on, and Dr. Barnett's down-to-earth style allowed him to transfer a great deal of information directly to where it was needed.[7] Dr. Barnett stated that the study was designed to come up with information that would be most beneficial in the regulatory arena so that regulations could be developed so that all stakeholders could be most fairly treated. The research was not concocted to portray an industry point of view.

The AWES method. The methodology involved the AWES (Automated Woodstove Emissions Sampler), developed by OMNI and in use for six years. It was used in all but one of the major woodstove field studies done since 1985. Essentially it is an automated system that detects when the appliance is being fired, samples the stack gases continuously and captures the PM in filters and a sample bag which are then brought to a laboratory for analysis. In addition, a computer generates gas curves that provide additional information about combustion conditions in the appliance over a one week sampling period. Most importantly, a reliable bridge has been established between AWES PM numbers and EPA Method 5H (EPA-M5H), which is the reference method used for woodstoves.

Dr. Barnett stated that the primary goal was to establish a baseline factor for conventional fireplaces. He told us that there had been NO fireplace studies done in homes in which there's been burning conducted anything like the way homeowners burn, that the literature was empty in this regard. There had been no studies of fireplaces, let alone masonry fireplaces and therefore no baseline. The baseline is required by the SIP's (State Implementation Plans, required by the Clean Air Act). He explained SIP's try to project into the future an attainment scenario, and that this is founded on the baseline. Then, if technologies are identified that reduce emissions by a certain percentage, emission reductions can be addressed and quantified. A second goal was to measure emissions from some advanced fireplace designs that were available such as the Rosin aerodynamic firebox.

The emissions factors on conventional fireplaces came in substantially higher than the VPI lab. numbers. See the summary of test results in Table 2. On the other hand, a database was established on how fireplaces are burned. Instead of being burned around the clock like woodstoves, fireplaces tend to be burned 3 1/2 to 4 hours per day instead. A good baseline was developed, with over 350 hours of burning. There was also good news on alternate fireplace designs. One of the designs studied was the Rosin firebox. It was developed in 1937-39 by Professor P.O. Rosin for the British Coal Utilization Research Association[8]. Rosin built extensive fluid models and used dye tracking techniques and dimensional analysis to study air flow patterns in open fireplaces. OMNI studied two Rosin installations. One was an original equipment model. For the second one, they monitored an existing residential masonry fireplace for a week with the AWES. MHA members then retrofitted a Rosin firebox and the monitoring was repeated. The Rosin aerodynamic firebox got a 50% reduction in emissions[9], both as original equipment and as a simple retrofit. Dr. Barnett summarized for us the potential for airshed improvement as follows:

> If you take a look at a community like Reno or Fresno and you ask "what's it going to take, what can you do, to reduce emissions from fireplaces?". Well, we can go out and sell new fireplaces, but every one that we sell, we're going to add to the level of emissions in the air. What's the key? It's getting rid of the established base of fireplaces. This has been a big job, because its easier to support with woodstoves. I submit that fireplaces are going to be a lot harder to get rid of. They're not going to move. But you have the opportunity to go into an airshed, and I think this is a big bargaining chip, and say that for every Rosin we sell we can reduce that house's emissions by 50% right of the bat.

The study for Western States Clay Products also included in-home tests on 2 masonry heaters.[10] One heater was an early home-built one, and did not get very good numbers. The second one was the same model underfire contraflow heater tested at VPI. PM with cordwood fuel was reasonable at 5.6 g/kg, and about double the lab. results on dimensioned lumber fuel.

After the VPI laboratory tests and then the initial OMNI field tests, a consensus was emerging in the masonry heater community that underfire combustion air deserved a more critical appraisal. It was introduced from Europe in 1985[11] and widely adopted in contraflow heaters, and there were indications that PM emissions performance was questionable vis-a-vis heaters with overfire combustion air. We had also seen results from tests that CCRL (Carbonization and Combustion Research Laboratory) of EMR (Energy Mines and Resources) Canada had done on an underfire air contraflow heater in an advanced demonstration house that indicated excess air levels of 1000%, with resulting overall efficiency in the 40% range.

During the OMNI workshop in Oct 1991, MHA was more or less shopping for test methods. Laboratory testing was very expensive, and was unaffordable for small companies often consisting of individual heater builders. Moreover, while valuable work was done in developing a testing method, there were still a lot of unanswered questions about how realistically the dimensioned lumber fueling protocol reflected actual everyday use. One of the valuable things about the initial AWES tests was that it demonstrated that real world masonry heater use was a lot different from wood stoves. The heater tends to get fired the same time every day, with the same fuel type and stacking. The burn progresses pretty much in an identical fashion from day to day. This provides something to capitalize on. Masonry heaters essentially do an end run around several performance issues that metal stoves have to deal with - smoldering at low burn rates, preheated secondary air carefully tuned to each firebox type, etc. The suspicion was that most masonry heater PM originates during the cold start and that the rest of the burn is probably pretty clean.

Regulatory Issues. As the fledgling masonry heating industry faces regulatory issues day in and day out, this is proving to be the biggest challenge - convincing regulators who are completely unfamiliar with this product, which has been in use in Europe for more than 100 years, that it is fundamentally different from airtight stoves and therefore unfair to tar it with the same brush. So the onus is on the industry to prove its point. Since M5H PM has only entered the picture relatively recently, we are unable to go to the database of existing testing in Europe.

Immediately after the OMNI Workshop MHA decided that a good first step would be to extend the AWES database, which so far consisted of a bad homebuilt Russian heater and an underfire air heater, which was actually pretty representative of the majority of heaters getting built in North America in 1992. An AWES test was funded on the second model tested at VPI, which was a handbuilt overfire air heater[12]. At the same time, AP-42 and BACM[13] were in the works and it was starting appear that field testing would be the name of the game for any kind of alternate EPA recognition of so-called non-affected facilities which fell outside of the regulation and were therefore uncertifiable by definition.

To date a total of 7 commercially available masonry heaters have had a one-week in-home AWES test consisting of 7 burns each. In addition, MHA funded OMNI's share of an EPA audit of the Masonry Heater In-Home Test Method. The fuel protocol that EPA insisted was strict: the homeowner uses his own fuel, and is not allowed to get any coaching whatsoever. Interestingly, when the technicians from the auditing company were witnessing the beginning of one of the burns, they ran outside, didn't see any smoke, and assumed that the fire had gone out. Apparently they had never seen this kind of phenomenon before. And, in fact, this is the main challenge facing builders of masonry heaters today - trying to inform regulators about masonry heaters and being taken seriously.

There was some debate as to how to report the overall AWES field results because of an emerging underfire/overfire split. There were three contraflow heaters and four other masonry heaters of various origins. One of these was the same handbuilt overfire unit tested at VPI (.99 g/kg) and it came in at 1.4 g/kg on cordwood. The overall average from 49 total days of use (one must be careful here and define "use" as when the stove is heating the house and not just when it's burning fuel) is 2.7 g/kg, and the AP-42 number is 2.8 g/kg. Together with the VPI tests and with the Lopez tests that I will present shortly, this is it all of the EPA M5H-compatible masonry heater data to date. A common reaction from regulators is one of skepticism, based on unfamiliarity with the fundamental concepts of high mass appliances. To reiterate, masonry heaters are characterized by a single, high, burn rate combined with heat storage.

There is, in my opinion, more to this data than first meets the eye. PM factors (g/kg) for seven heaters were as follows: 5.7, 5.6, 2.9, 1.9, 1.9, 1.4, and 1.4.[14,15,16] The 5.7 and 5.6 were the two underfire air heaters. The 2.9 was from a heater described in its report as a combination of underfire and overfire. So my contention would be that what we see here a is bipolar distribution with the break based solely on whether the combustion air comes up through a grate or not. The changeover from underfire to overfire air is fairly simple. As a matter of fact, we developed a five-minute retrofit for the Heat-Kit system that we tested at Lopez and at VPI and with the AWES. The retrofit would certainly make for an interesting AWES re-test. Based on our Lopez testing, I would expect to see a 70% PM reduction from 5.6 to 1.6, plus or minus .5 g/kg. If we take out the 2 underfire heaters and leave in the 2.9, then we get 1.9 g/kg overall average for 35 days on 5 heaters. Interestingly, if one compares the emissions factor ratio between underfire and overfire, for the dimensioned lumber fuel protocol (VPI) it is 2.8, for the AWES it is 3.0, and for the Lopez testing it is 3.7. As mentioned, underfire air is a bit of an anomaly, and now is one more thing complicating our relationship with regulators. We can live with 2.8, and can arguably claim that this is a conservative scenario.

European Testing

Outside of North America, the most organized testing effort right now is being conducted in Austria. In Austria there is a Stovemason's Guild, and it is several hundred years old. The Austrians arguably build some of the best masonry heaters in the world today. They don't bother much with metal stoves, and you wouldn't sell a single gas log over there. The Stovemason's Guild has its own testing laboratory with Dr. Herman Hofbauer as their chief researcher.

Emissions and clean-burning in most of Europe tends to be defined in terms of CO, lack of which is used as an indicator of good combustion and hence low emissions. So, based on CO, Austrian stovemasons have undertaken a very extensive multi-year research project. MHA has published a report on it.[17]The first thing that they did was a nation-wide series of in-home tests to establish a baseline of the existing stoves. Most of them were clean, but a few weren't. The Guild is very pro-active in exercising its mandate of controlling masonry heater design standards, and if it finds that some particular firebox style tends to burn dirty then it simply isn't allowed to be built anymore. North American clean air authorities could profit from this approach and consider delegating responsibility for masonry heater emissions performance to, say, a high quality industry certification program. Presumably we can all agree that net environmental impact is the real issue here.

In the next project, the Austrians studied operator influence on masonry heater emissions. Basically they looked at how big the wood load was, vis-a-vis the design load, and which ignition method was used.

<u>Burn Rate</u>. This brings up a key concept for masonry heaters - burn rate. This is really the point of departure from conventional woodburning devices, in the following way: Burn rate is not controlled. Heat storage ability is what makes burn rate control unnecessary. Burn rate is calculated in a simple manner. For example, if 20 kg of fuel is burned over two hours, then the burn rate is 10 kg/h, averaged over two hours. Ten kg might only take 90 minutes, so the burn rate would be 6.7 kg/h.

What the Austrians did was very clever. They calculate a maximum design burn rate, ie., wood load, for a given size firebox. Next, they measured CO versus burn rate by using different wood loads and found that there is an optimum burn rate region. If the optimum burn rate region is exceeded, then fueling practices which slow the fire down, such as igniting the load from the top instead of from the bottom, result in a CO improvement. Similarly at the low end. If the wood load is very small then it is advantageous to light it from the bottom in order to increase the burn rate. It would probably be desirable to split the wood smaller as well. In between these two we see a fairly broad optimum burn rate region. An unexpected finding was that in the optimum region, it doesn't matter whether the charge is kindled from the top or the bottom.

The Austrians haven't studied wood sizing or moisture yet, but they intend to. One can reasonably expect that splitting the wood finer should result in a faster burn rate, and that using wetter wood will slow it down. So, the Austrians use the burn rate concept to interpret their emissions results, ie., CO. It is somewhat removed from PM factors and rates.

Condar (Oregon M-41) Method at Lopez Labs

The Condar dilution tunnel method was used at Lopez Labs to measure particulate emissions. Developed by Dr. Barnett, it is a very simple system. It is a dilution tunnel, but of an interesting type. 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 motor is regulated to provide a constant pressure of around -0.1 inches of water. The regulated pressure insures a constant sample flow. As the filters load with particulate, a Variac control is used to run the motor harder to compensate. The temperature after dilution is under 90 degrees F. The Condar design allows real-time monitoring of emissions simply by pulling the filters at anytime and weighing them.

What the Condar is not, like the AWES is not, is an official EPA method. It is not a Method 5. However, it was approved by Oregon and is known as Oregon Method 41. The Condar has been used to develop, interestingly enough, the very cleanest burning woodstoves. They have all come through this method of evaluation. As Dr. Barnett explained “the reason is that it is extremely fast and extremely reliable. All the other techniques, as used on location by manufacturers, have proved to be too slippery. They’re too scientific, too technical, too fidgety. So, they’ve been a problem, but this one is not. We used to take this one around to 5H locations and got the same relationship between this one and 5H. You can’t do that with a dilution tunnel. You probably can’t even do it with 5H and 5H.”

In Barnett’s spreadsheet formulas for the Condar, there is a conversion factor between a Condar PM factor and Method 7. We chose not to apply this conversion - for two reasons. First of all, about half of our PM is non-soluble, probably soot and fly ash, and we would expect the filters to capture 100% of that. Secondly, the correlation work with the Condar was done with conventional woodstoves, and there was no work done at the low end of the PM scale.[18] As an example, 4 g/kg Condar converts to 6 g/kg M-7 equiv., which is a 50% increase; at 27 g/kg. they are even, and above 27 g/kg the M-7 is lower.

Organic Compounds and PAH’s. Barnett also went on to talk about organics. Recent major studies with pellet stoves have shown that pellet stoves have pretty much gotten their organic fraction down. Masonry heaters have the responsibility to do the same. The Austrian Stovemason’s Guild commissioned the Austrian State Institute for Testing of Synthetic Materials to do a study of masonry heater PAH’s in 1985,[19] and they arrived at a value, under good combustion conditions, of 20 $\mu g/Nm^3$. This is near the low end of the values found in 2 pellet stove studies done by OMNI in 1990[20,21].

Comment:

After the OMNI workshop in October 91, MHA consensus was that it was not possible to base low PM masonry heater design on CO testing. Soon thereafter my collaborator, Jerry Frisch, located and purchased a complete Condar[22] dilution tunnel setup, complete with analytical balance, and a SUN SGA-9000 four gas digital analyzer designed for automotive emissions testing.

Since some of the cleanest woodstoves were developed with the Condar, we sought advice from several stove manufacturers who were experienced in its use. We set up Lopez Labs at Jerry’s shop near Seattle in the spring of 1992 and spent about 10 days doing test runs on an underfire contraflow heater. We were basically working out the bugs.

We did a 24 day test series in the spring of 1993. We had three appliances hooked up to the chimney and could switch them in and out with a special damper setup. We had a small underfire contraflow heater that was donated by one of the manufacturers. We had a Rosin fireplace with doors that Lopez was doing development on. And we had a large modular contraflow heater which we used for the testing that I would like to describe here.

This heater, a Heat-Kit, was one of the two units originally studied at VPI and also one of the two heaters in the first AWES tests. So we have an EPA-audited field number and a VPI laboratory fueling protocol number on it with underfire air. It was also the first modular system to be developed in North America, and is probably a good representative of the majority of heaters built here from about 1985 on. It could be termed a North American generic brand (ie., large) contraflow heater.

A parallel debate with regulators is the emission factor versus rate question, ie., g/kg of fuel or g/hr. The EPA reg. uses g/hr, but an implicit assumption here is that the appliance has to burn fuel while it is giving off heat. If a 2 hour burn in a masonry heater supplies 24 hours worth of heat, you will obviously have a concentrated PM rate, g/hr, for 2 hours. In terms of net environmental impact, I would submit that the real issue is the total daily emissions compared to a certified appliance. Since my stove stores heat and therefore has no fire on for 22 hours out of the 24, we can only make a non-trivial emissions comparison based on a <u>factor</u> instead of a <u>rate</u>, ie., g/kg of fuel burned. If we both burn equal amounts of wood then our net environmental impact, on average, will be the same with the same PM factor. An alternate formulation is to use a 1 kg/hr nominal burn rate, averaged over 24 hours. In fact, this is very near the average burn rate of the average wood stove. G/hr @ at 1 kg/hr equals g/kg, of course.

This issue was cast in stark relief in Colorado recently. When the Colorado Air Quality Control Commission looked at the OMNI data, they saw a Royal Crown heater at 2.0 g/hr and a Heat-Kit heater at 51.7 g/hr. and concluded that masonry heaters as a class are not clean burning. How can a 51.7 g/hr heater possibly be clean? Colorado would not buy the heat-storage argument, so out job became one not only of documentation, but also of education. Of course, if we take EPA's AP-42 field number for all Phase II woodstoves, at the Heat-Kit's .75 kg/hr average daily burn rate we would get 133 g/day, for the average Phase II stove. To compare that with the Heat-Kit, we have to squeeze it into two hours, yielding 66 g/hr. So our <u>dirtiest</u> heater is 20% cleaner that the <u>average</u> phase II stove, according to EPA's own field data. Although we have landed a man on the moon, we have only recently learned to abolish underfire air, yielding a further 60-70% reduction. I will now attempt to show that the Lopez data indicates, as does the OMNI and the VPI data, that in fact only one variable, the generic air system, separates Colorado's 52 g/hr monster from the cleanest domestic-scale cordwood burning device in existence. A spin-off is that we now have the largest PM emissions database on the Heat-Kit of any masonry heater.

Almost anyone who is new to the field of masonry heaters will invariably assume that they need to be complicated. In reality, a heater is functionally just a refractory firebox with some air, and some extra flue runs on the way to the chimney. In fact, about half of the heat transfer takes place in the firebox itself. Four feet out of the firebox, there is not much heat left to exchange. The heater is run wide open, throttled by the fixed air inlet. Too large an air inlet results in more excess air than necessary. Too little and you don't get a clean burn. Again, heat storage and burn rate independence are two sides of the same coin, and they simplify things enormously when you burn cordwood. You can get 1.5 g/kg PM without getting fancy. However, building a heater that doesn't fall apart from the constant thermal shock is an entirely separate matter.

I will now describe the 23 day Lopez series. Table 1 is a summary of the raw data. On the first run there were still equipment bugs, so it was discarded. On the last run #23, we only have preliminary (undried) filter weights. There is also a filter problem on run #17, evident in a very low PM number. So 3 runs are discarded for mechanical reasons. The raw data is everything else.

The bulk of PM occurs at startup. To duplicate field conditions, firing is conducted on a 24 hour cycle. Twenty four hours are required for the firebox to cool off, otherwise PMs will drop because of the warmer start. Since the chimney and appliance are in an unheated part of the lab, they are actually a little cooler after 24 hours than in the field. In a house the firebox would be at around 150F after 24 hours.

Being limited to 23 tests, parameters were chosen carefully. We did repeat runs in three cases. Our main job was to change the air system on the heater over from underfire to overfire. We had enough data from 1992 that we didn't use up too many runs on underfire air. Only run #18 is a true underfire air run, ie., the previous standard air system used at VPI and OMNI. We got 6.3 g/kg and OMNI got 5.6. This air system was used on all contraflow heaters between 1985 and 1982, both here and abroad.

Fuel Protocol. Our fuel protocol was as follows: We had 16" old growth Douglas Fir cordwood all from one tree. We measured every piece for moisture and for many runs also measured circumference so that surface area could be calculated. We used pretty much the same stacking scheme on every run, and photographed every load. We started out with smaller, European style loads and from run #9 on switched to larger loads more typical of North America. We also used, compared to the Europeans, fairly large pieces of wood more typical of what we see in the field. On 4 runs, we took the wood load and split every piece in half, to see the effect of increased surface area. Finally, we kindled the load from the top instead of the bottom, because we had reason to believe that this results in a cleaner start.

For a baseline we started with no air supply except for cracking the door a quarter of an inch. This is run #2. It should also be mentioned that there was a section of single wall chimney that got insulated starting with run #3. Recent tests by the author on masonry heater air consumption lead us to suspect a leak in the masonry, which would account for our fairly high oxygen numbers. This has no effect on the calculated PM factors except for a loss of some precision in the oxygen readings as they approach ambient.

With the Condar we had a PM number in 24 hours. Each morning, after examining the data a single change would be made in the air supply. These are described in the published results.[23,24] When viewing the graphs in Figures 2, it is useful to know that there is a progression in the runs, from a baseline run #2 to a fairly optimized run #19, with a few detours in between.

Results. Table 2 is a summary of our results. It also provides a comparison of, essentially, all comparable PM testing that has been done on masonry heaters and fireplaces. In arriving at the Lopez averages, the following rationale was used: The overall average is the average of all the raw data, adjusted as described above. We are confident that there is a bipolar distribution between overfire and underfire air, and accordingly this is our categorization. Our underfire factor is from one test, #18.

The corrected numbers are derived as follows: On the gas curves, it is readily apparent that when the pieces are split in two for run #4, the CO has a huge double spike at startup because combustion conditions in the fire box are too fuel-rich. PM's quadruple to 4.9 g/kg. Run #5 is a repeat of run #4, for verification. The numbers change somewhat, but the double spike geometry remains intact. For run #6 we increase the air supply from 2 to 4 sq. in. and raise the wood moisture 3 points, and things settle back down. There is a similar occurrence on runs #15 and #16. This is evidenced in the fuel piece count, which is the highest of the whole series at 16 pieces for both runs. The Austrian stove builders have a term to describe what I believe happens here. It is "Umkippen der Verbrennung", literally a "tipping over, or loss of equilibrium, of the burn." A contemporary terms might be "non-linear". To get what we term the corrected overfire air number we throw out runs #4,#5 and #15,#16. It is a straightforward matter to ensure that masonry heaters have a proper air supply, because the homeowner doesn't control that air supply, but simply lets the wood burn at its own speed. The Austrian research teaches us that if the fuel load is large and the burn rate needs to be reduced, top ignition can be used.

Sampling**.** The Lopez PM sampling scheme uses the Condar with two back to back filters. The filters are changed at 15 minutes to allow separation of the startup effects. Chart 2 shows a plot of the 15 minute PM, in terms of filter catch, as a fraction of the total catch. The 15 minute filter catch is about 40% of the total, on average, even though only a very small fraction of the fuel has actually been consumed. A real world scenario for this size heater is around 2 - 3 kilowatts output over 24 hours from a 20 kg (dry basis) charge. Approximately 12 out of a total of 30 grams of PM for that airshed over 24 hours are emitted during one 15 minute interval.

Soluble Organic Compounds. OMNI measured the soluble organic fraction in one of the overfire AWES series and it was 39%, ie., a 1.4 g/kg heater emitted 0.5 g/kg of soluble organics. So typical soluble organic PM emissions appear to be in the area of 12 grams per day for large overfire heaters fired on a 24 hour cycle.

CO. One of the questions that we had, and this would be my main question with European test methods, is whether overall CO is an indicator of PM. Figure 1 is a plot of CO Factor against PM factor for 20 cordwood runs at Lopez, 30 dimensioned lumber runs at VPI, and 49 days of in-home testing by OMNI on cordwood. We don't see much overall PM:CO correlation at the low end of the PM scale, although there is some interesting clustering in some of the sub-groupings. In the OMNI field tests, the heater with the lowest CO factor had the highest PM factor, which may explain why there is a discrepancy with certain European research.

HC. Of interest on the Lopez gas curves, in PM terms, is the HC curve. This is hydrocarbons as measured on an automotive emissions analyzer, which is calibrated on propane. Chart 2 shows a plot of the 15 minute HC fraction together with the 15 minute PM fraction. There appears to be a relationship. Also plotted is the ratio of filter catch to total HC, which is taken as the area under the HC curve.

PM. The final item plotted on Chart 2 is the PM factor for the runs which we defined above as overfire, ie., four runs are removed as outlined. I submit that this is a reasonable approximation of what we would expect to see in the field, because essentially we've exposed the stove to 19 runs over a much wider range of air systems than would ever be seen in actual practice, and then discarded 4 runs that have literally gone "over the edge."

CONCLUSIONS

PM testing on masonry heaters and masonry fireplaces has started only recently, so the database is small. Standard masonry fireplaces with large openings and correspondingly large flue diameters are essentially no different from open campfires and have PM factors similar to those of conventional woodstoves. Simple retrofit technology exists that appears to be able to substantially reduce the airshed impact of the existing installed base of masonry fireplaces and deserves further investigation.

Current PM data on masonry heaters is limited but consistent. While PM emissions with a dimensioned lumber fueling protocol are about half those of field-test values, there is a consistent bipolar distribution of PM factors based on whether there is combustion air through a grate. The ratio between overfire and underfire PM factors is consistent across fueling protocols used so far. With masonry heaters restricted to the use of overfire air, EPA-audited in-home particulate emissions for 5 different masonry heaters totaling 35 days of use averaged 1.9 g/kg. These are the among the cleanest numbers ever recorded for cordwood burning appliances in the field and appear to be equal to or better than results for EPA Phase II pellet stoves.

Regulation. One of the greatest challenges facing North American masonry heater builders today is to educate clean-air authorities about their potential. Burn rate independence is the most important concept to get across. It permits combustion design for masonry heaters to follow simple, long-established rules. This permits qualified builders to site-build a wide variety of custom appliance configurations. With AP-42 recognition from EPA, the author feels that is inappropriate to willy-nilly subject a site-built appliance with a demonstrated path towards low-emissions assurance to regulations designed for mass-produced factory appliances. With an expanding emissions database, there appears to be little reason to fear crossing the bounds of good combustion design, since finely tuned secondary air systems are superfluous. Trade certification, based on the Austrian model, may be an appropriate regulatory mechanism.

I would close with the contention that cordwood is a clean fuel. With a heat storing appliance that does not depend on burn rate control by means of throttling combustion air, we have demonstrated prolonged operation in the field at around 1.5 g/kg PM, and indications are that the soluble organic fraction is in the 40% range. If the cordwood fuel is at the same time obtained through sustainable forestry practices, then we achieve the additional benefit of a zero net CO_2 contribution to the atmosphere.

ACKNOWLEDGMENTS

All North American masonry heater builders owe a debt of gratitude to the late Dr. Stockton G. (Skip) Barnett of OMNI labs, who pointed us in the right direction on combustion testing and design. Many of us knew him only briefly, but his spirit lives on in cleaner air everywhere. Tom Stroud got the ball rolling in Washington State. Dr. Dennis Jaasma and Jay Shelton pioneered the field of fueling protocols for high-mass appliances. Rick Crooks from Mutual Materials initiated the original AWES study for Western States Clay Products Association. When the chips were down and we needed more PM data, longtime heater mason Jerry Frisch put together Lopez Labs out of his own pocket. None of this work would have happened without the Masonry Heater Association of North America, which has served as the front for many a worthy endeavor hugely out of scale with its size. The heater masons across the continent who pay their dues every year are the lifeblood of the organization.

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Table 1. Summary of 21 contraflow heater PM emissions test runs using Oregon Method 41 (24 hour burn cycle).

Run Number	CA-02	CA-03	CA-04	CA-05	CA-06	CA-07	CA-08	CA-09	CA-10	CA-11	CA-12	CA-13	CA-14	CA-15	CA-16	CA-17	CA-18	CA-19	CA-20	CA-21	CA-22
Wood Moisture	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	19.6	19.9	20.9	20.4	20.0
Total Weight	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	43.0	49.5	47.0	46.5	55.3
Kindling Weight	3.0	2.5	3.0	3.0	3.0	3.0	3.0	2.5	4.0	3.5	3.0	3.0	3.0	3.0	2.0	2.5	2.0	4.0	2.0	2.5	2.3
Number of Pieces	5	5	10	10	10	8	7	13	10	11	11	11	7	16	16	11	9	7	8	8	8
Run Length	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.7	1.8	2.1	2.2	2.0	2.3	1.8	2.0	2.1	1.3	2.7	2.7	2.3	2.7
Av. Stack Temp	112	133	126	180	171	269	252	312	298	249	274	243	227	268	282	235	302	159	213	199	203
Av. O2%	16.4	17.0	17.2	16.9	17.4	18.4	18.0	17.0	17.6	18.4	17.9	18.4	17.2	17.0	18.1	18.5	19.1	17.3	16.8	18.0	17.6
Av. CO%	0.21	0.11	0.35	0.21	0.10	0.05	0.07	0.06	0.06	0.08	0.08	0.10	0.08	0.13	0.07	0.05	0.09	0.04	0.09	0.08	0.09
Burn Rate dry kg/hr	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	11.8	6.6	6.3	7.5	7.5
Latent Heat Loss	10.9	11.0	11.0	11.2	11.2	11.6	11.6	11.8	11.8	11.5	11.7	11.5	11.4	11.6	11.7	11.5	11.8	11.1	11.4	11.3	11.3
CO Loss %	6.5	4.0	13.0	7.4	3.9	3.0	3.2	2.3	2.7	4.4	3.8	5.5	3.0	4.5	3.4	3.0	7.0	1.6	3.1	4.0	3.9
HC Loss %	0.90	0.74	2.75	2.39	1.40	1.19	0.55	0.93	0.83	0.95	0.78	0.71	0.70	2.06	2.11	0.57	3.50	0.68	0.84	1.40	2.10
Dry Gas Loss %	3.4	5.9	5.5	10.0	10.4	28.5	25.2	22.7	25.0	26.1	24.9	24.9	15.3	18.3	27.5	25.1	47.2	9.1	12.6	16.4	14.7
Filter Catch gm.	.0822	.0562	.2181	.1923	.0967	.0412	.0208	.0528	.0441	.0449	.0452	.0325	.0537	.1324	.1094	.0257	.0795	.0621	.0859	.0868	.1796
PM g/kg Condar	1.51	1.22	4.87	4.18	2.38	2.02	0.90	1.56	1.38	1.58	1.30	1.18	1.16	3.58	3.67	0.94	6.34	1.13	1.40	2.39	3.65
CO g/kg	57.1	35.2	114.9	65.4	34.1	26.4	28.6	19.9	24.0	38.8	33.4	49.0	26.8	40.0	30.0	26.5	61.4	14.5	27.1	35.0	34.4
Combustion Effic.	92.6	95.3	84.2	90.2	94.7	95.8	96.2	96.8	96.5	94.7	95.4	93.7	96.3	93.4	94.5	96.4	89.5	97.7	96.1	94.6	94.0
Heat Trans. Effic.	85.7	83.1	83.5	78.8	78.4	59.9	63.2	65.5	63.2	62.4	63.4	63.6	73.3	70.0	60.8	63.4	41.1	79.8	76.0	72.3	74.0
Overall Efficiency	79.4	79.2	70.4	71.0	74.3	57.4	60.8	63.4	61.0	59.0	60.5	59.6	70.5	65.4	57.5	61.1	36.8	77.9	73.1	68.4	69.5

Table 2. Summary of Field (F) and Laboratory (L) PM Factors For Masonry Fireplaces and Heaters (g/kg)

		Cordwood				Lumber (4x4)
		F	F	L	L	L
		AP-42	AWES	Lopez Corrected	Lopez All	VPI
Masonry Fireplaces						
	Open Standard	17.3	24.9			11.0
	Open Rosin		10.4			12.0
Masonry Heaters						
	All	2.8	2.7	2.4	2.4	1.4
	Underfire		5.7	6.3	6.3	2.8
	Overfire		1.9	1.7	2.2	1.0
	Ratio of Underfire to Overfire PM		3.0	3.7	2.8	2.8
Woodstoves (Non-Cat)						
	Conventional	15.3				
	Phase II	7.3				
Pellet Stoves						
	Non EPA	4.4				
	Phase II	2.1				

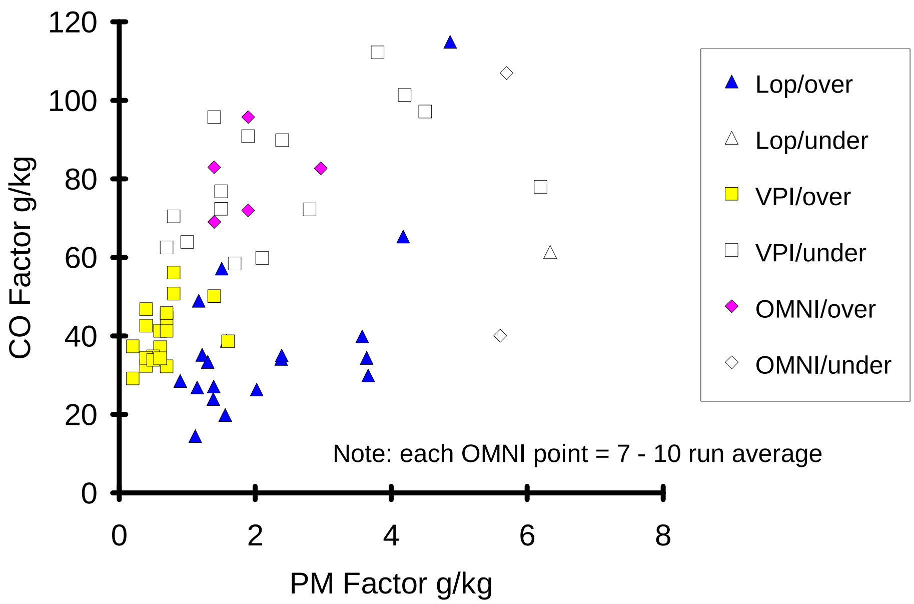

Figure 1. PM:CO correlation, 72 cordwood runs and 34 dimensioned lumber runs.

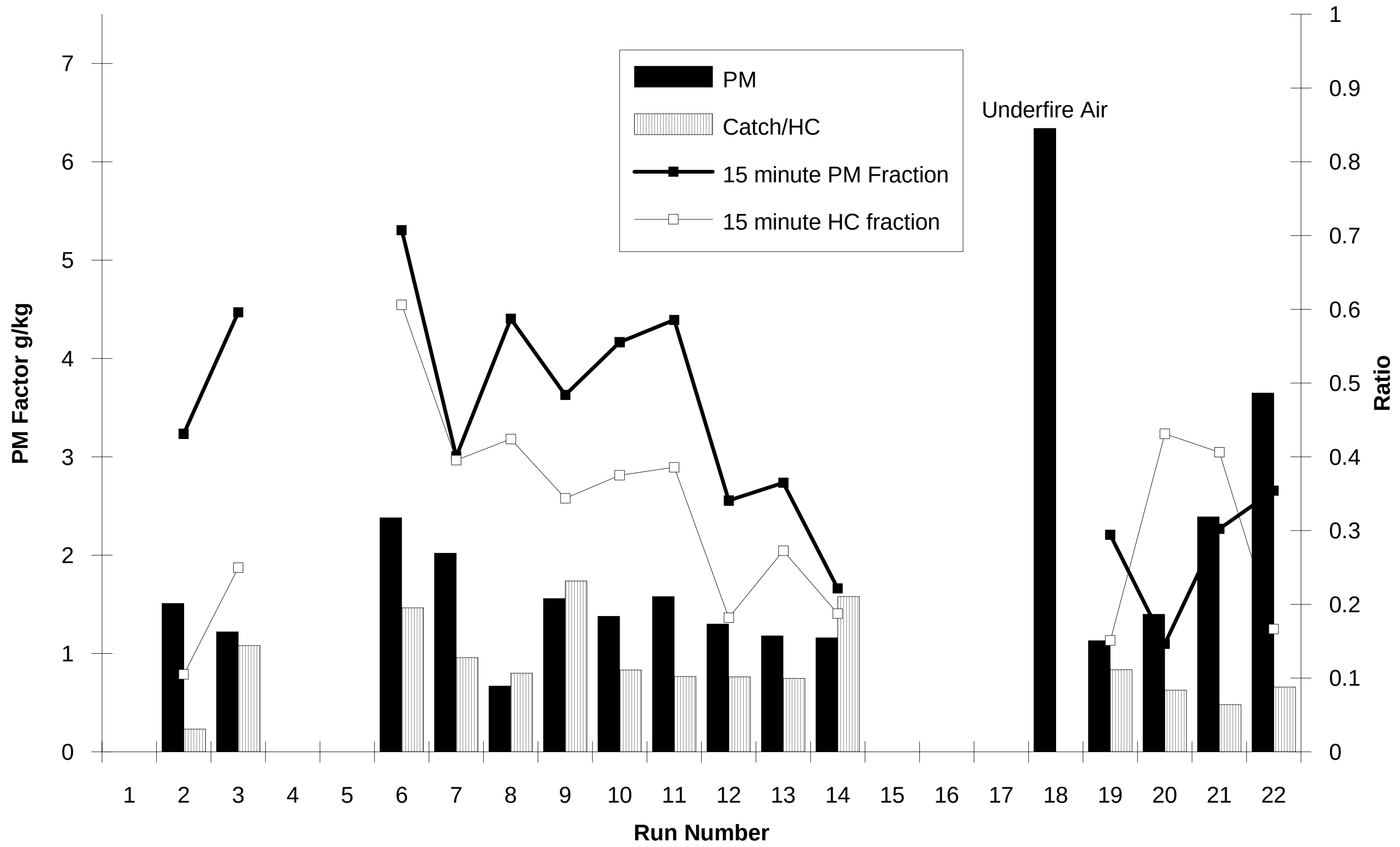

Figure 2. Various relationships between PM and SUN SGA-900 hydrocarbon numbers (overfire contraflow heater).