Innovative fine particulate measurement systems for the Wood Stove Design Challenge

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ABSTRACT

The rising price of fossil resources has contributed to the increase in the amount of wood-fired residential heating appliances. Wood stoves are often overlooked by the public as a clean and renewable source due to concerns about particulate (PM) emissions. In order to gain acceptance in the market the Alliance for Green Heat and *Popular Mechanics* magazine initiated a Wood Stove Design Challenge (WSDC). The selected teams designed stoves that incorporated the best practices in design and operation to maximize efficiency and minimize PM and carbon monoxide (CO) emissions since most often high emissions are seen as a result of incomplete combustion. Further, a testing protocol for the challenge was developed specifically to measure the emissions in a non-laboratory setting. Standard testing procedures may not be representative of in-use fuel and operational practices and, due to the competition venue and schedule contstraints, could not be used for the WSDC. New portable PM sampling technology released in the European market recently was adopted for the competition and evaluated to current U.S. PM measurement methods to build a correlation.

INTRODUCTION

As the price of heating oil has increased, more residents in the northeastern region of the United States have returned to heating with wood. Most existing wood stoves date from before the Environmental Protection Agency (EPA) implemented emission certification requirements for these devices. These less efficient wood stoves often cause high amounts of smoke, yielding particulates known to trigger coughs, throat and mucosal irritation, acute respiratory infections, occurrence of asthma and other diseases over prolonged exposure[1]. A review from Bølling et al. reported residential wood combustion has also been reported to contribute significantly to raised levels of air pollution locally, both with respect to increased levels of fine particles (particulate matter with an equivalent aerodynamic diameter < 2.5 μm; $PM_{2.5}$), the organic particle fraction, particle bound polycyclic aromatic hydrocarbons (PAH) and volatile organic compounds[2]. Even those wood stoves that do meet EPA's Phase II requirements may have unacceptably high emissions once in use. This is due to several factors including the design of the appliance,

[1] Riddervold et al., "Effects of wood smoke particles from wood-burning stoves on the respiratory health of atopic humans", *Particle and Fibre Toxicology.,* **9:12**, 2012.
[2] Bølling et al., "Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties", *Particle and Fibre Toxicology.,* **6:9**, 2009.

weather patterns and location, combustion activity, wood species and quality, and operator habits. While the EPA is developing new regulations, the test method used for certification is not representative of in-use fueling and operational practices.

Designs that improve combustion and emission performance, thermal efficiency, and operational variability are needed in the U.S. heating market. Modern wood stoves have shown reduced reported emission factors compared to conventional wood stoves, 34-330 mg/MJ from 50-2100 mg/MJ, respectively[3]. However, if the modern stoves are not operated correctly the combustion performance can be compromised yielding higher emissions. The Alliance for Green Heat and *Popular Mechanics* Magazine initiated the Wood Stove Design Challenge (WSDC), an international competition modeled after the Department of Energy's (DOE) Solar Decathlon, to address these needs by developing a competition for manufacturers, innovators, and university teams. The WSDC challenged teams to design and build wood stoves that were low-emission, high efficiency, extremely innovative, affordable and marketable.

This event showcased advanced technologies that could help address the problem of increased particulate emissions and enable the continued use of wood as a renewable fuel. The teams selected came from various backgrounds, ranging from established wood stove companies to independent inventors and engineering student teams. Some of the stoves selected for the WSDC were controlled by microprocessors and connected to smartphones while others were ultra-efficient stoves based on 17th century Scandinavian designs. Several state-of-the-art hybrid stoves that are already on the market were also included[4]. Six of the 12 finalists were from Europe.

Teams were judged on their innovation, emission and efficiency performance, affordability and consumer ease. In November 2013 on the National Mall in Washington D.C., ten judges (made up of leading experts from *Popular Mechanics*, the New York State Energy and Research Development Authority (NYSERDA), the U.S. Forest Service, Washington State Department of Ecology, DOE's Brookhaven National Laboratory (BNL), The Biomass Thermal Energy Council (BTEC), the Osprey Foundation, the Masonry Heater Association and UC Berkeley) tested and assessed the 12 stove finalists and announced an overall winner as well as winners in specific categories.

A key challenge in this competition was measuring the particulate emissions accurately in a field environment. This project sought to develop an energy efficiency and emissions testing protocol for the WSDC which reduces the variability due to fuel and operations. The current standard test method (EPA Method 28) involves testing stoves using a dilution tunnel. Since the WSDC was held at the mall in Washington D.C., this test method would not suit and so there was the

[3] Bølling et al., "Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties", *Particle and Fibre Toxicology.,* **6:9**, 2009.

[4] Bollman, Melissa., "Finalists Announced for International Competition to Build Cleaner Wood Stove", *Alliance for Green Heat.*, January 2013. Web.

challenge of measuring the emissions in a repeatable real-time way, in a non-laboratory environment. Recently, new portable particulate measurement systems have been introduced in Europe for field inspection of biomass heating systems. Two specific products were selected for use in this project the Testo 380 and Wöhler SM 500. Both analyzers are a low cost option and offer the advantage of ease and portability.

To determine the accuracy, precision, instrument range, and applicability for use in the WSDC for thermal efficiency and emissions of these portable direct measure analyzers, an evaluation was conducted while simultaneously following the standard methods for determining the emissions. From laboratory testing, BNL developed a testing protocol implementing the analyzers for the competition.

INSTRUMENTS

The technology of the portable PM measurement systems includes near real-time, sub-miligram sensitivity, and is the only mass monitoring technology which has these properties and does not depend on surrogate measurements for mass[5]. Each system utilizes the principles of oscillating microbalances, using an inertial mass weighing principle. To begin, the system oscillates at its natural frequency exactly; as an air stream is drawn through the system, particles deposit on a filter or plate resulting in a loss of frequency oscillation. By measuring the change in frequency, the total mass of the particulate matter collected is found. Combining this number with the volume of air drawn through the system provides the particle mass concentration (mg/m^3). The change in mass may be determined from the following equation:

$$\Delta m = K_0 \cdot \left(\frac{1}{{f_f}^2} - \frac{1}{{f_i}^2} \right) + K_{cor}(T, f)$$

Where, Δm = change in mass of particulates, f_i = initial oscillation frequency, f_f = oscillation frequency after the collection of particulates, K_0 = system constant of the oscillator system, K_{cor} = error correction function, and T= temperature of the oscillator system.

Both systems measure the PM in flue gas, O_2, CO, draft, and stack temperature. One of the systems uses a filter for particulate collection. The other uses an inertial impaction technique and, in this case, a correlation correction for the expected low collection efficiency of the very fine particles is also used. Both systems report live measurements with a resolution down to 0.1 mg.

[5] H. Patashnick, M. Meyer, and B. Rogers., "Tapered element oscillating microbalance technology"., *Proceedings of the North American/Ninth U.S. Mine Ventilation Symposium, p. 625-631.*, Kingston, Ontario, Canada., 8-12. June 2002.

TRADITIONAL TEST METHODS

The current standard test procedure for wood stoves (EPA Method 28) provides a fueling and operating procedure for wood heater emission and efficiency testing. Fuel properties, load configuration, pre-test conditions, charcoal bed, loading and start-up time, allowable air supply, fuel adjustments, and other parameters are all specified by Method 28 in order to provide a standardized test for stove certification. Particulates are measured using a dilution tunnel approach. Method 28 uses various measurement procedures to collect the particulate matter. These methods include 5H, G-1, 5G-2, and 5G-3. For the purpose of this study only EPA Method 5G-3 will be discussed in detail.

LABORATORY SET UP

To provide a basis for comparison, the traditional sampling method along with the portable analyzers were operated in side-by-side laboratory tests over various phases of a wood stove burn cycle. Traditional test methods require crib wood fuel (dimensional lumber; 2 X 4's) as an attempt to maximize the consistency and reproducibility from test to test. However, cord wood was used as it was more representative of field use and practices to follow in the WSDC. An EPA certified wood stove (Woodstock Soapstone Co. Fireview model) was provided for this project. The standard catalytic stove had a maximum output 55,000 Btu/hr with a manual draft control.

The traditional EPA Method 5G-3 was used as the sampling procedure for capturing particulates. This filter-based, time-integrated system involved two 47 mm filters in series and sampled from a dilution tunnel which collected all the effluent from the stove's chimney and drew it, with ambient dilution air, through a straight duct at a constant velocity (measured with a pitot tube and digital pressure gauge). The sampled air stream was monitored to maintain a constant flow rate as it was pulled through the filter media, depositing the PM on the filter. The filters were pre- and post-desiccated, following Method 5G-3 to remove all moisture and assure the change in weight was only associated with the particulates collected. With a known volume of air passed through the filter media and weight change, the particle mass concentration (mg/m^3) was determined. Following method 5G-3, it is required that two identical sampling trains be used simultaneously and the results from each train agreed with each other within 7.5% of the mean in order to validate the results. The laboratory experimental set-up may be seen in Figure 1. Gaseous emissions (CO and O_2) were also measured from the dilution tunnel continuously over the full combustion period. Carbon monoxide was measured in the dilution tunnel using a Rosemount Analytical model 880 non-dispersive infrared sensor (NDIR) CO analyzer. The analyzer has a maximum capacity of 5000 ppm, therefore any data above that goes unmeasured. Oxygen measured in the dilution tunnel used a Beckman model 755 oxygen analyzer. Temperature data was also collected using thermocouples, situated at precise locations, logged on a continuous basis over the burn period.

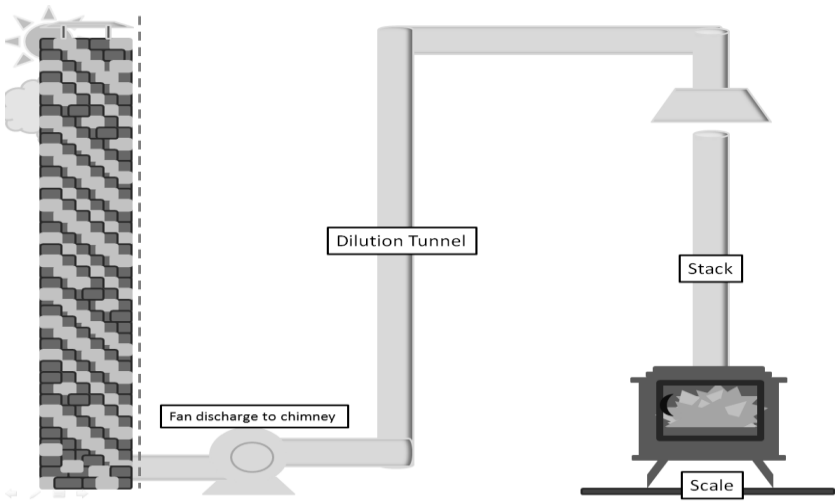


Figure 1: Laboratory set-up

Both of the portable PM analyzers sampled particulate concentration, CO and O_2 concurrently with the traditional test method. However, a disadvantage seen with the portable analyzers is that they are intended and designed for sampling directly from the stack and not from a dilution device. As a result of this, and the temperature of the instrument's head of the sampling probe, the semivolatile (condensable) hydrocarbons are not fully captured and therefore the yielded measurements are not expected to be the same as the dilution tunnel-based method. Both analyzers were situated in the stack perpendicular to each other.

Aside from the scope of this project but used for additional data, in some tests, was an optical PM measurement. The Thermo pDR-1500 is designed to measure the concentration of PM using a light-scattering photometer (nephelometer). The intensity of the light scattered is proportional to the concentration of particles passing through the sensors. The Thermo pDR-1500, similar to the Testo and Wöhler, is a real time PM monitor. Humidity, temperature, and pressure are some factors that may affect emission measures; the pDR compensates for these factors and allows for a nominal accuracy to within 5% of the reading[6]. The pDR sampled in the dilution tunnel.

RESULTS AND DISCUSSION

Testing the portable analyzers against laboratory-based test methods and in some cases optical measurements demonstrated the analyzers abilities to produce repeatable, accurate results since there was no opportunity to test each stove to the traditional standard protocols.

All measurement processes have an inherent element of variability of result if the process has sufficiently fine resolution[7]. In combustion systems especially, it is expected to obtain a wider dispersion of results for the experiment if it is repeated under a wide range of ambient

[6] Thermo Fisher Scientific., "pDR-1500", http://www.equipcoservices.com/sales/thermo/pdr-1500.html
[7] Curkeet, Rick and Ferguson, Robert., "EPA Wood Heater Test Method Variability Study"., October 2010.

conditions, such as different temperature, wind, and or humidity condition. EPA's Method 28 has a tremendous amount of variability, which is not unique to only this method. Curkeet and Ferguson[8] [7] summarized the sources of variability which include:

- Fuel density variation from approximately 30 to 40 lb/ft^3 (dry weight basis).
- Fuel moisture content variation from 19 to 25% dry basis (varies in uniformity as well as average).
- Fuel load configuration details.
- Coal bed size (20-25% of fuel load weight) and pre-burn temperature conditions.
- Loading time and start-up procedure.
- Ambient temperature, barometric pressure and humidity.
- Variations in control settings and resulting burn rates.
- Random uncontrollable variables such as when and how the fuel load settles, falls and collapses.

Most notably is the impact these factors have on the appliances' burn rate, which to some degree is related to the emissions performance. With higher burn rates generally producing more complete combustion emissions are ultimately lowered. It is important to note Method 28 strives to reduce the variability within the test method by placing tolerances on the operational and fueling parameters however, variability still exists.

Operating protocols themselves are not the only source of variability; other variability comes from the sampling methods themselves. The variability in Method 5G-3 PM measurements exists in the accuracy of the dilution tunnel gas flow and sample flow measurement and the resulting consistency of proportionality. Weighting errors for weights of filters, probes including front filter housings and filter seals also exist. The measurement uncertainty of method 5G-3 has been determined to be approximately +/- 2.5% of the emission value measured for a typical passing wood stove test[8]. Method 5G-3 was chosen as it demonstrates the lowest uncertainty of the four methods.

There is also variability associated with portable analyzers. Each analyzer builds in an uncertainty value that accounts for the uncertainty of the fueling protocol, stove operation, and measurement. This is the value used for certification in Germany; however numbers recorded for this report were the actual yielded values. In Europe, these analyzers are used to demonstrate that a field installation is operating with PM emissions below a set level (expressed simply as mg/m^3). The measured values are corrected for the uncertainty to evaluate compliance. The uncertainty assigned, for these analyzers, is rather large, 30-50%.

As the dilution tunnel mixes exhaust gases with ambient air, and sampling was done in both the stack and dilution tunnel, a dilution ratio must be calculated and applied to the filter-based and pDR methods in order to compare the each method to the next. To determine a dilution ratio, a

[8] Curkeet, Rick and Ferguson, Robert., "EPA Wood Heater Test Method Variability Study"., October 2010.

heat balance approach was used. A correlation between CO values of the portable analyzers to the NDIR analyzer in the dilution tunnel was attempted, but was unsuccessful. The following calculations show the steps taken to determine a dilution ratio based on temperature.

$$\dot{m}_A C_{p_A}(T_A - T_R) + \dot{m}_S C_{p_S}(T_S - T_R) = \dot{m}_{DT} C_{p_{DT}}(T_{DT} - T_R)$$

Where subscripts A, R, S, and DT are ambient, reference, stack and dilution tunnel, respectively.

$$DR = \frac{\dot{m}_A + \dot{m}_S}{\dot{m}_S}$$

$$DR' = \frac{\dot{m}_A}{\dot{m}_S}$$

$$\therefore DR = \frac{\dot{m}_A}{\dot{m}_S} + 1 \equiv DR' + 1$$

$$\frac{T_A \dot{m}_A + T_S \dot{m}_S}{\dot{m}_{DT}} = T_{DT} \equiv \frac{T_A \dot{m}_A + T_S \dot{m}_S}{\dot{m}_A + \dot{m}_S}$$

$$\therefore T_{DT} = \frac{T_A \frac{\dot{m}_A}{\dot{m}_S} + T_S}{\frac{\dot{m}_A}{\dot{m}_S} + 1}$$

$$T_{DT} = \frac{DR' T_A + T_S}{DR' + 1}$$

$$DR' T_{DT} + T_{DT} = DR' T_A + T_S$$

$$DR' = \frac{T_S - T_{DT}}{T_{DT} - T_A}$$

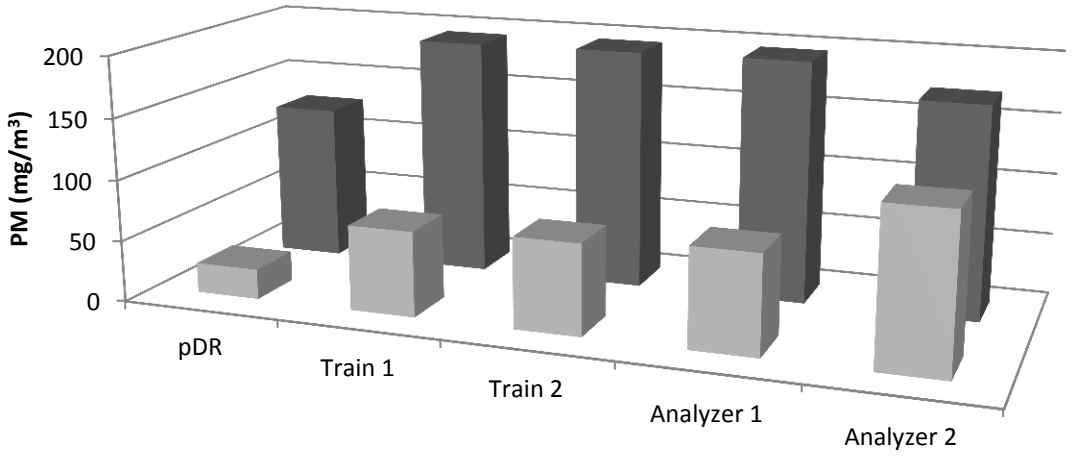
$$\therefore DR = DR' + 1$$

Knowing the temperatures of the room, dilution tunnel and stack (at the top, right before dilution), the dilution ratio can be calculated. In all cases, the dilution ratio was approximately 7.25 during the stoves operation. Knowing this value, the PM concentration determined by the filter-based method and the pDR was multiplied by 7.25 in order to more accurately compare the PM concentrations captured by the portable analyzers sampling in the stack.

The results from three different days and six different tests are shown below. Tests 1 and 2 were run back to back on the given day. The fueling protocol followed for the November 11th test involved a pre-burn to establish a coal bed (described in detail below). Once the coal bed was established, a fuel charge of 11 lb/ft^3 was added (roughly 24lbs for this particular stove). The fuel was red oak (for laboratory experiments only) and had an average moisture content of 20%. Thirty minutes after the addition of this fuel charge, the first steady state burn period was

established (Test 1). Sampling for both Tests 1 and 2 had a duration of 15 minutes. After Test 1's 15 minute sampling period was complete, the fuel charge was left to burn out. Once the coal bed was re-established (20% of the fuel charges weight), a second full fuel charge was added signifying Test 2. Again, after 30 minutes of the fuel charge addition, sampling begun for Test 2. For both tests, the catalyst was engaged and the air damper was set at position two of four.

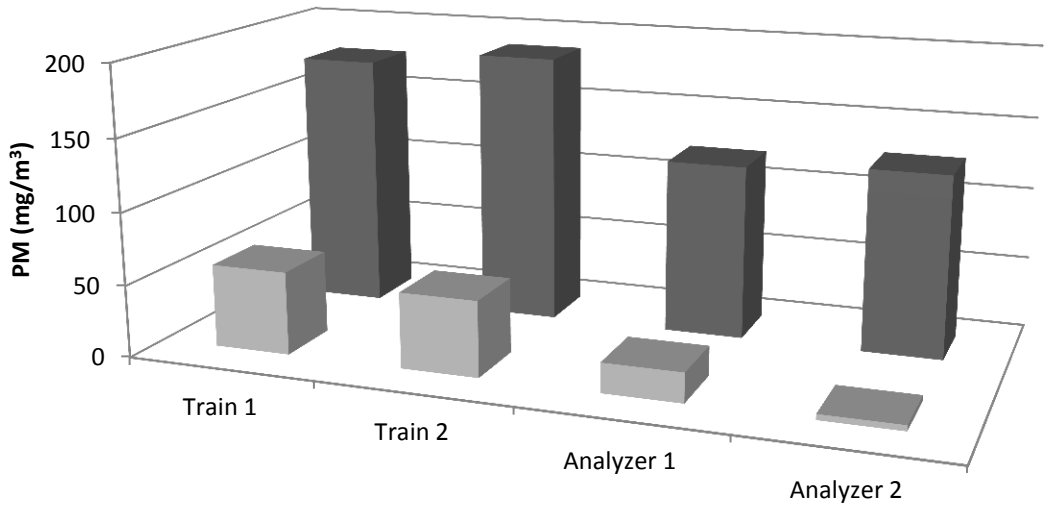
The formal operational procedure was only followed for the first day; however it was not necessary for the comparison of sampling instruments. Therefore, the latter two days followed much less formal fueling procedures. What was most important was all sampling procedures were followed (i.e. Method 5G-3) and all sampling methods were captured simultaneously. Tests 1 and 2 from the December 16th and 17th were still run back to back but this time sampled from one fuel charge only (approximately 24lbs of fuel) throughout the course of the burn. Therefore, these 15 minute tests captured a mix of steady state periods and end of burn periods- a cleaner time period. From the results it can be seen traditional test methods in the dilution tunnel (with the applied dilution ratio) yielded different results than those of the portable analyzers, as expected, but not to a large degree. PM emissions comparisons are provided in Figures 2, 3, and 4. In these figures Train 1 and Train 2 refer to the direct mass measurement using Method 5G-3.



	pDR	Train 1	Train 2	Analyzer 1	Analyzer 2
Test 2	24.7	69.6	74.0	80.5	126.0
Test 1	127.6	193.6	195.0	196.3	172.0

Test 2 Test 1

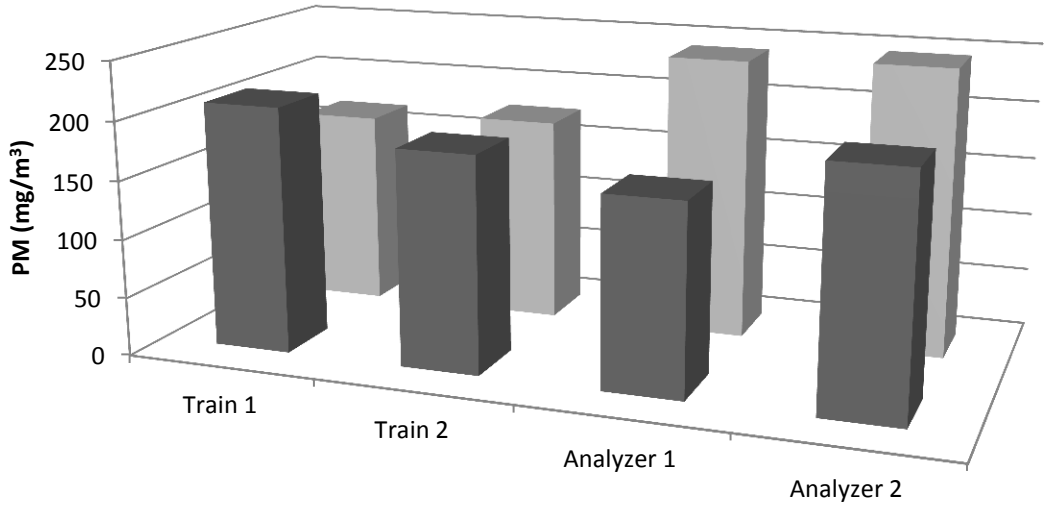
Figure 2: PM concentration on 11/11/2013



	Train 1	Train 2	Analyzer 1	Analyzer 2
Test 2	57.6	52.4	20.6	4.0
Test 1	177.3	187.4	121.4	127.0

Test 2 Test 1

Figure 3: PM concentration on 12/16/2013



	Train 1	Train 2	Analyzer 1	Analyzer 2
Test 1	210.1	184.0	161.6	201.0
Test 2	168.4	176.0	240.6	245.0

Test 1 Test 2

Figure 4: PM concentration on 12/17/2013

Dilution sampling better represents what is emitted into the environment and allows more variables to be measured. The dilution tunnel mixes the stack effluent with clean ambient air, simulating what happens in the plume as emissions exit the appliance's chimney. Sampling via the dilution tunnel captures particulate matter (elements, ions, organic and elemental carbon), semi-volatile organic compounds (SVOCs), and volatile organic compounds (VOCs). The dilution tunnel should capture all of the filterable matter plus any aerosols that condense under simulated plume conditions[9]. This may in turn be the reason for the higher PM concentrations captured via Method 5G-3.

Another thought is the portable analyzers heat their probes and sampling lines to either 80 °C or 120 °C and are modeled after European test methods such as EN 303-5. Method EN 303-5 samples directly in the stack, maintains the filters temperature at an elevated temperature during sampling, and bakes the filter both pre and post test. Previous studies at BNL comparing EN 303-5 to EPA's Method 28 indicated differences in PM concentration between the two. This too relates back to the fact of lower temperatures in the dilution tunnel lead to capturing the condensable particles missed in the hot stack. Another disadvantage seen in test 2 of December 16th, 2013 was analyzer 2 actually lost weight as the sampling period went on. This may due to water interference and this test should be considered invalid.

The pDR was eliminated after the first day of testing due to its results. The pDR is a useful tool to get an idea of the amount of particulates and has the ability to capture very high PM concentrations such as start up unlike other sampling tools. However, the pDR's accuracy seemed to degrade as the burn got cleaner; when the particle size distribution was very small.

Application to the WSDC in D.C.

As the objective was not to certify each unit, but evaluate each stove in terms of its emission and efficiency performance relative to the other stoves in the competition, results from the portable analyzers prior to DC were promising. The competition's venue and time did not allow for a dilution tunnel to be constructed and scale under each stove, therefore traditional test methods were not an option. Data collected from the portable analyzers was repeatable and comparable to one another. Results from prior testing illustrated the analyzers were able to sample directly from the stack and offer good comparative numbers to those attained by traditional test methods. From the testing done at BNL prior to the competition, a test procedure was established which served as a fair basis to compare each stove in terms of its emissions and efficiency during operation.

Twelve stoves competed in the WSDC, each unique to the next. The stoves varied in terms of materials, combustion chamber designs, and controls. Two of the five categories judged included

[9] Wien, S., England, G. C., Loos, K., Ritter, K., Gurney, D., McCarthy, J., Liebowitz, B., Joseph, J. and Franco, G. 2001. $PM_{2.5}$ Speciation Profiles and Emission Factors From Petroleum Industry Gas-Fired Sources. Proceedings *International Emission Inventory Conference*, "*One atmosphere, One inventory, Many challenges.*". May1–32001, Denver, CO.

efficiency and emissions (made up of carbon monoxide and PM). These values were provided by the portable analyzers. To ensure fair and representative data, each stove was tested two times (once which each analyzer) over the course of the competition and during the same part of the burn.

Fueling protocol

The fueling protocol was created by Ben Myren of Myren Consulting. Ben has years of experience in wood burning as Myren Laboratories serves as one of the few EPA certification laboratories. The fueling protocol involved a pre-burn to establish a coal bed. This pre burn included kindling and two ricks (small bundles of wood), each with a specified amount based on the stove's firebox dimensions. Once the coal bed was established, a fuel charge of 11 lb/ft^3 was added. The fuel was a mixed species and average moisture content of 20%. To reduce the variability of the fueling protocol from stove to stove, each piece of fuel has to meet the criteria established; weight and moisture content from the moisture meter was all recorded.

After the first day of testing it was noted the 11 lb/ft^3 was too large of a loading for some stoves causing them to choke, and perform poorly and in a manner unrepresentative of field operation. Therefore, the second day of testing yielded a fueling proposal to stove manufactures'; as low as 8 lbs/ft^3 would be acceptable. Another adjustment made was to the masonry heaters in the competition. The masonry heaters did not have a pre-burn period and simply had the kindling and fuel charge all in one load.

Testing procedure

A test protocol was developed at BNL prior to the competition which was repeatable, representative of the stove's performance, and mindful of time. Due to time constraints each stove was tested two times (once with each analyzer to account for any variability from analyzer to analyzer), both during the steady state burn cycle. The steady state burn period was chosen to start after 30 minutes of the fuel charge addition. Based on European standards that the analyzers follow, a 15 minute window was selected as the measurement time. Both analyzers did have the capability of testing longer, e.g. 30 minutes if desired, however mindful of the time to clean and prep the analyzers and stoves between testing cemented the decision for a 15 minute measurement. Quality control measures were also taken to guarantee each test was executed to the test method.

After the first day or testing, it was noted the 30 minute start time after the fuel charge was added was not always the steady state period of the stove, therefore adjustments were made. In addition, smaller stoves and masonry heaters began testing after 15 minutes as their burns were often short and quick, achieving steady state sooner than 30 minutes.

Initially desired was to test the stoves during their dirtiest burn phase, start up. However, tests at BNL prior to the competition, sampling during the start up period were problematic. Often the analyzers overloaded with PM, generating errors and were unable to sample for the full 15

minutes. The data also showed poor repeatability and at times were ill-matched to each other. Having no emission data and little information on each stove prior, it was difficult to anticipate if the analyzers could sample start up for a minimum of 15 minutes and so, start up testing was eliminated. If time had permitted, those top competing stoves which had the lowest emissions would have had the ability to be tested during their start up.

RESULTS

Values for the efficiency and emissions (made up of carbon monoxide and PM) categories were provided by the portable analyzers. The PM concentration in mg/m^3 was generated directly by the analyzers. Carbon monoxide emissions reported by the analyzers were corrected to 13% based on German standards (Austrian standards differ); therefore CO numbers had to be adjusted before reported. The calculation was as follows:

$$CO_{actual} = CO_{analyzer}\left(\frac{21 - O_{2\,analyzer}}{8}\right)$$

From the O_2, temperature (stack and ambient), and CO values obtained, the stack loss efficiency of each stove was determined. The efficiency calculation used for the competition was a stack loss method following CSA B415. The reported values were not an overall efficiency and are only representative of the 15 minute window. The efficiency calculation also did not include jacket losses or wood consumption and only served as a comparative value from stove to stove in the competition; outside the competition this value has little meaning.

The stack loss efficiency calculation is an indirect efficiency test method and often used to determine the efficiency of gas- and oil-fired appliances; however it can be related to solid-fuels but is more complicated. Since ample time did not exist and neither did a scale under each stove at the competition, this method was used as an approximation. The stack loss efficiency calculation took into account the sensible heat loss, latent heat loss and chemical heat loss. The fuel composition in terms of carbon, hydrogen, and oxygen percentages, higher heating value, and moisture content is therefore needed. Ambient temperatures were also needed. Method 28 and CSA B415.1 may be referenced for a more detailed explanation of the calculation. As implemented for the competition, the stack loss method considered the chemical energy in CO emissions but did not consider the chemical energy in hydrocarbon emissions. This parameter was simply not measured. For this reason the reported efficiencies may be slightly higher than actual.

It is well known burning wood is never steady and therefore measured values are constantly changing but the 15 minute window sought to capture the most steady state so the efficiency calculation could be compared to each of the stoves at the competition. The fact that the analyzers were able to measure values every five seconds certainly helped to provide a more accurate result.

Figures 5 to 7 below depict the PM, CO and efficiency results from the WSDC. It is important to note stoves were tested only once a day over the course of four days. Analyzers chosen for a particular stove on a given day were unbiased; for example analyzer one was not run only on day one and three while analyzer two was only run on days two and four.

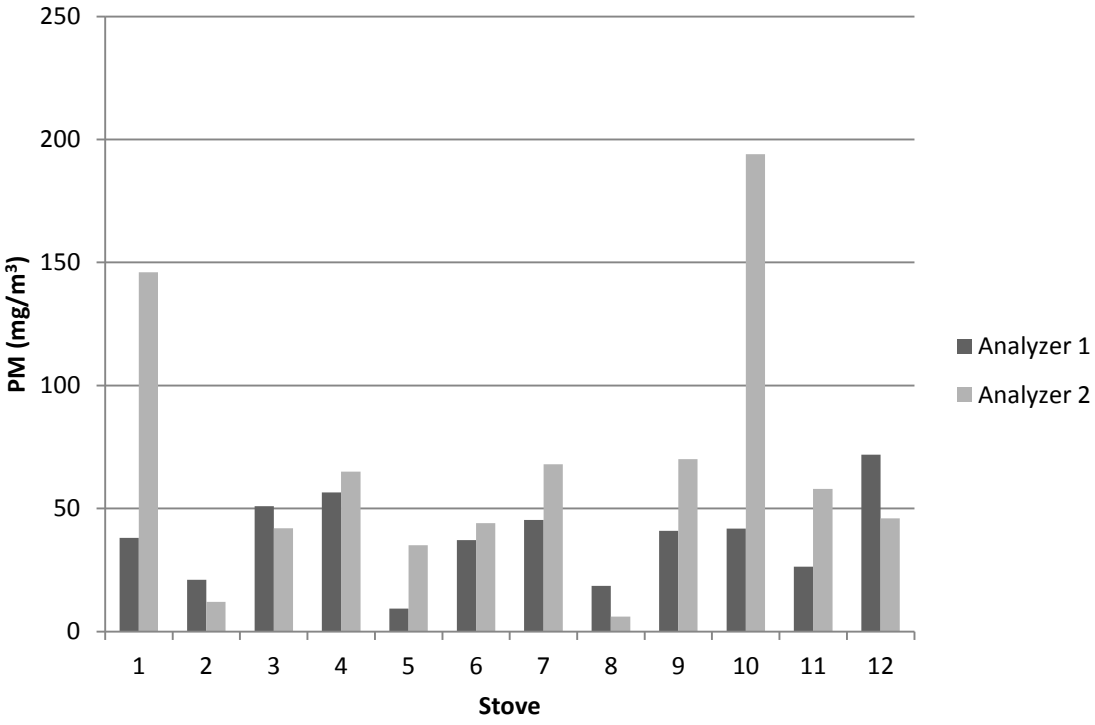


Figure 5: PM emissions of wood stoves at WSDC

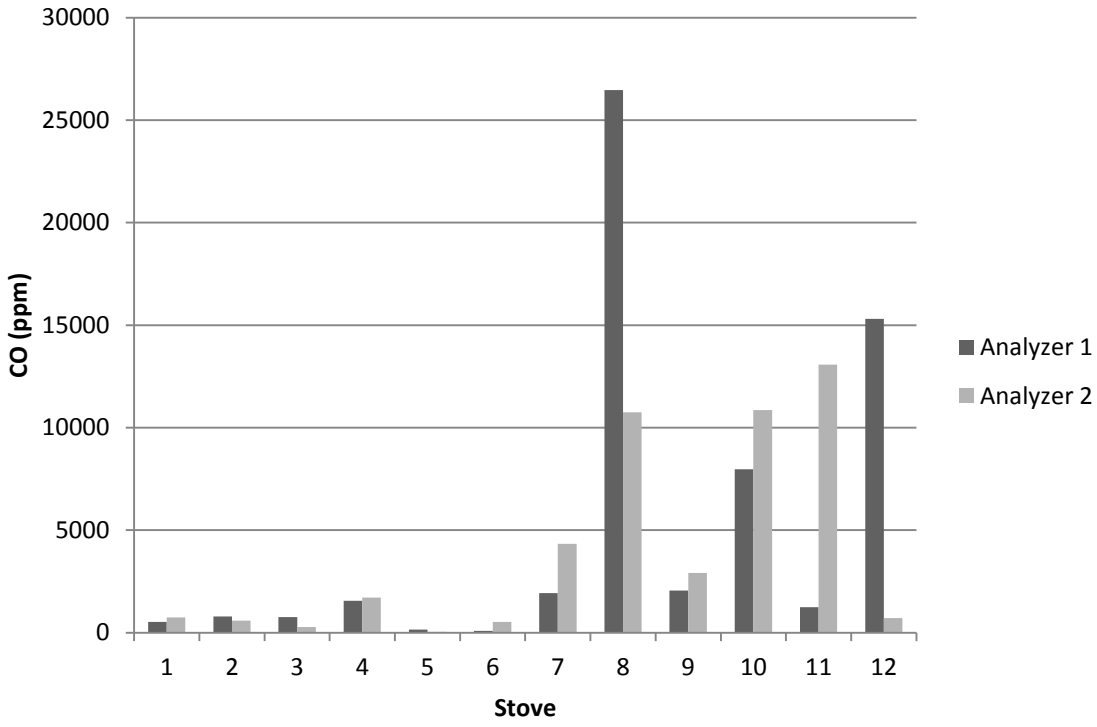


Figure 6: CO emissions of wood stoves at WSDC

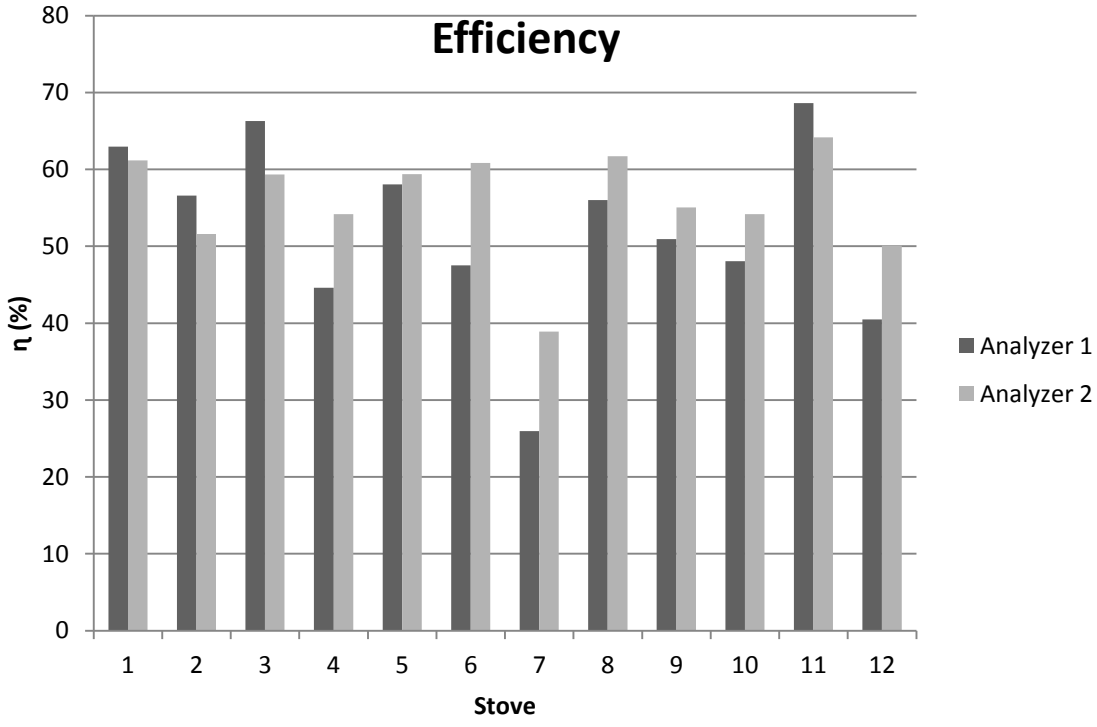


Figure 7: Efficiency numbers based on data from analyzers at WSDC

As one can see from the above results, some results showed a great difference for the same stove. This can be attributed to the variability associated with any test as mentioned earlier. The weather for instance was a major contributor to the variability, some days of the event brought humid and wet conditions while others were cool and breezy. It was well noted the humid and wet conditions caused stoves to have a difficult light off period and therefore offered high emissions.

As the opportunity for variation in the test condition expanded, the variation in the results also increased. The expertise of the judges was called upon especially when considering the results with significant variation. In these cases where the data was unrepresentative of the stove and more so dependent upon ambient conditions, results were neglected. It is also important to note, additional tests were run to provide more representative data and set aside tests where analyzer error occurred. Manufactures were also given the option to petition a test due to generic stove errors such as a sensor failure. The petition was reviewed amongst the judges and either awarded or declined. In other cases, unofficial tests were granted to those who wished to show their stoves potential but had difficulty during official testing. These results were not considered in the emission and efficiency categories but were taken into account in the innovation category.

Ideally, the highest score would be awarded to the stove which offered low PM and low CO. While some stoves had very low PM, they could not be offered top rank if their CO emissions were high, ultimately causing a health concern. As a measure for assessment, European standards which use these instruments certify stoves with a PM concentration of 60 mg/m^3 or less and CO values of 4000 ppm or less. Overall efficiency values reported may be alarming as they are much lower than those typically advertized. However, efficiency values around 80% can be found in industrial solid-fuel combustion appliances but lower values (less than 75% typically) are expected for residential appliances. Variability did exist from one analyzer to another; however there was no one analyzer which generally offered higher or lower values. Therefore, the variability is assumed to be associated with the test itself, not the instruments.

Potential future role of the portable PM measurement instruments in the U.S.

This new technology is currently being applied to real-world particulate measurement and monitoring requirements in Germany as all wood-fired heaters are now required to be tested in the field every two years. German chimney sweeps play a comparable role as vehicle inspection stations in the U.S., certifying units based their emissions performance. If the emissions exceed the allowable limits, the problem must be addressed or the appliance must be decommissioned. The high precision of the digital mass scales in these systems can verify onsite mass

concentration limits as low as 20 mg/m^3, allowing these systems to provide measurements for compliance testing of solid fuels[10].

Both systems with the available software can log emissions over a one second interval. Attractive for further analysis, data may also be transferred. An overall advantage seen with the portable measurement systems is the mass calibration uncertainty that exists with current tests methods which do not measure mass directly, along with the loss of possible filter handling errors.

As wood heating appliances are now facing more strict regulations on emissions, measures for continuous particulate monitoring must also improve. These portable analyzers use a method that captures real time emissions, better characterizing the emissions throughout the burn cycle and may therefore be used to address concerns about how well test methods represent actual field conditions. Figure 8 demonstrates the instruments ability to provide PM measurements as a function of time over a 30 minute burn period. Perhaps these new instruments may offer an alternative to traditional test methods involving the cumbersome dilution tunnel to ensure they meet EPA emission standards, and or a way to more accurately measure unit's performance in the field.

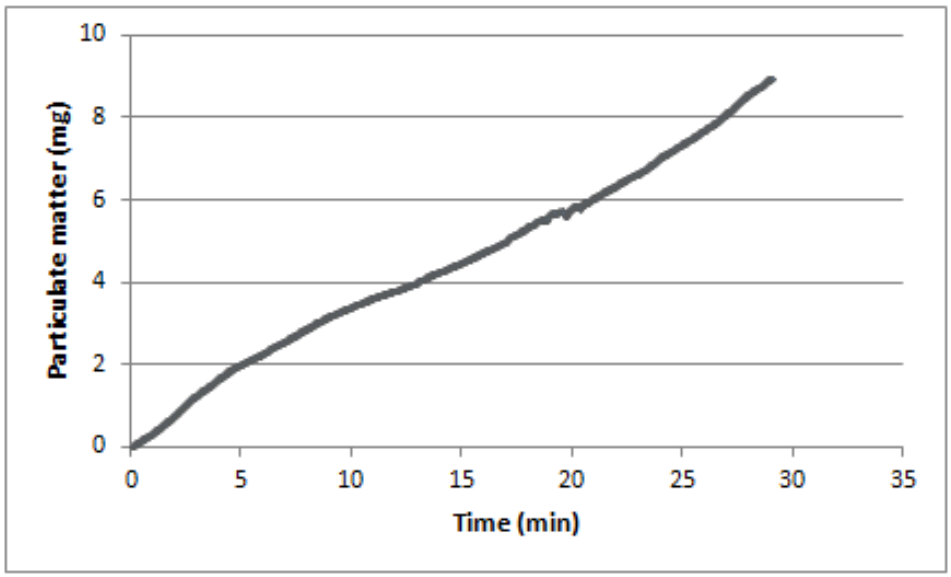


Figure 8: PM as a function of time

[10] "The Measure of Technology: Wohler SM 500 Suspended Particulate Analyzer" –Wohlers paper is written with analyser not z