Appendix C Particulate Matter Emission Measurement Methods

EPA's current particulate matter (PM) laboratory test method to determine emission rates for residential wood heaters relies on gravimetric filter samples ("pulls") off of a dilution tunnel. While test labs and EPA have a high degree of comfort with the method, the filter technology has many limitations. This manual measurement method eliminates the capacity to adequately characterize emissions in start-up, steady state and shutdown conditions and provide time-resolved data or data in real-time. States have expressed concerns that the current test procedure does not adequately capture the large emissions that occur in the first hours when a unit is refueled, and labs have indicated that the startup PM concentrations are too high to be measured with a filter method. Other issues with the filter method include the inability to measure short term emissions, potential loss of semi-volatile material that occurs both during sampling and between removal from the dilution tunnel and final filter mass measurement, and potential formation of acid gas (such as SO2) artifacts on the glass fiber filters.

This report identifies possible real-time alternatives to the current filter test method and assesses their suitability for both laboratory (dilution tunnel) performance certification tests and for field measurements that reflect real-world operating conditions. Several key performance requirements are considered for each method:

- Provide continuous real-time data in order to easily gather data on short term emissions and to reduce the time and costs associated with testing
- Minimize loss of "condensables", e.g., semivolatile organic carbon PM. This requirement ideally includes three factors:
    - PM measurements are made reasonably close to laboratory (or ambient if a field test) temperature (no higher than ~10-15° C above lab/ambient temperature)
    - For stack testing (without a dilution tunnel), a method should allow for a sufficient dilution ratio to reduce the high PM concentrations that occur during dirty burn/startup conditions that otherwise can overload measurement methods
    - For stack testing, a measurement method should allow sufficient post-dilution residence time for the stack gas temperature to cool down and for gas to particle phase condensation to occur
- Measure PM concentrations over a wide dynamic range of 5,000 to 10,000 to be able to measure PM from high loading cold starts in some boilers (~ 5-10 g/m^3 in the stack), as well as low loading periods such as hot clean burns from a woodstove (~ 1 mg/m^3 in the stack)
- Capacity for long run times – A method must be able to run for long period of times (8-10 hours). Missing data periods (if required for filter changes or other operating conditions that result in

missing data) should be minimal - no more than 15 minutes in any one hour, and ideally less
- For use in field tests, the ability to run outside in the winter - e.g. with temperatures as low as -10 C (14 F)
- For use in field tests, the ability to sample directly from the stack
- Commercially available

For each technology reviewed, this report lists manufacturer's specifications for key parameters and expected advantages and disadvantages of each method based on those specifications and hands-on experience. Ease of use and cost are included in this assessment.

This method assessment does not include measurement of stack flow, as this is a separate task and none of these methods are capable of this measurement. Note that for in-stack measurements, stack flow must be measured to allow calculation of mass emission rates (e.g., grams per hour). The ability to measure other stack parameters including oxygen (O2), carbon monoxide (CO), and temperature measurements is of interest but not essential for this portion of this assessment. For instruments that measure these stack parameters, it is noted in the method summaries.

1 Summary of Candidate Methods

In this section, each candidate measurement method is summarized with respect to key performance requirements. This includes the measurement principle and a list of advantages and disadvantages for each method. Instruments evaluated fall into two broad categories:

- Devices designed to sample directly from the stack with no additional dilution
- Devices that require external sample dilution to reduce PM concentrations to the range that can be measured and to control for combustion-related water.

The Wöhler SM500 and testo 380 are designed to sample from the stack. The Thermo pDR-1500 ("pDR") and Thermo 1400AB/1405 ("1400 Teom") instruments all require sample dilution.

1.1 Wöhler SM500 Suspended Particulate Analyzer

The Wöhler SM500 measurement method is based on inertial mass measurement, similar to the TEOM® method (Tapered Element Oscillating Microbalance). Sampled particles are collected on a filter cartridge that is attached to the tip of an oscillating element; the frequency of oscillation decreases as the mass on the filter increases with particle loading. The rate of change in the mass over time and the sample flow provides the mass concentration in real time. The Wöhler SM500 is designed to sample directly from the stack; it does not dilute the sample. This requires the filter to be heated to ~ 75 C to avoid condensation of water from the stack gas, but "condensable" (semi-volatile organic carbon) PM can be lost at this elevated temperature. For regulatory testing use, a proprietary correction factor is used to account for this loss; the test results reported here are without any correction factor since this is the only way to get highly time-resolved data from the instrument. The Wöhler SM500 is intended to be used for routine indoor performance checks on clean-burning devices and is not intended for in-stack sampling under very dirty-burn conditions. It can sample from a dilution tunnel or other diluted sample stream, but the temperature of the sample filter cannot be changed to a lower value.

Advantages of the Wöhler SM500 include:

- True mass measurement (not a surrogate measurement)
- Direct stack sample; no separate dilutor needed
- Can be run off a dilution tunnel (but may not be sensitive enough during clean burns)
- Measures stack CO, O2 and temperature
- Should provide good data when burns are hot and clean and most of the particle organic carbon is burned in a secondary burn chamber or catalyst

Limitations of the Wöhler SM500 include:

- Sample is collected at 75 C, causing loss of semi-volatile PM. This could be an issue when there is unburned organic carbon in the sample (e.g., dirty burn modes).
- Sample is not diluted, limiting proper measurement of organic condensable PM.
- Cannot measure the high in-stack concentrations expected with a cold-start OWB test.
- Does not have sufficient dynamic range for all test conditions (stack and tunnel).
- Not designed to run in outdoor winter temperature conditions (5 C minimum temperature).

1.2 testo 380 Fine Particle Analyzer

The testo 380 is a quartz crystal microbalance (QCM) that samples particles directly from the stack and dilutes them using a "rotating disk" technique to provide a variable dilution ratio. The sample is then collected by impaction (as opposed to filtration) on a quartz crystal. As the collected mass increases, the frequency of the crystal's vibration decreases; mass is then calculated in a similar manner as the Wöhler SM500 or TEOM methods. The sample can be collected at ~ 25 C above ambient; some "condensable" (semi-volatile organic carbon) mass may be lost at this elevated temperature. Like the Wöhler SM500, this instrument is designed for indoor routine performance checks on clean-burning devices. The testo 380 includes the testo 330 comustion gas analyzer as the control unit for the system.

Advantages of the testo 380 include:

- True mass measurement (not a surrogate measurement)
- Can sample directly from the stack; no separate dilutor needed (uses rotating disk dilutor)
- Measures stack CO, O_2 and temperature

Limitations of the testo 380 include:

- Instrument response may vary with particle size distribution. Impaction efficiently captures PM at larger sizes (dirty burn modes) but is less efficient for PM from clean (hot) burns where most of the particulate carbon is burned in a secondary burn chamber or catalyst.
- Sample is diluted with minimal residence time, which may limit proper measurement of organic condensable PM
- Cannot measure dirty burn phases directly from the stack (maximum stack concentration is ~300 mg/m_3)
- Not designed to be run in outdoor winter temperature conditions (5 C minimum temperature)

1.3 Portable Dilution Systems

1.3.1 Dekati Diluters: FPS and eDiluter™

Dekati dilution systems are complete integrated solutions for dilution of combustion gases. The FPS4000 has been used for almost two decades, primarily for sampling engine exhaust. In 2018, Dekati introduced the eDiluter, an updated dilution system. The operating principles are similar, but the eDiluter is much more compact, simpler to run, and can be operated remotely. NESCAUM has used both systems, but going forward will only be using the eDiluter. There is a version of the eDilutor ("Pro") that has variable dilution factors (DF), but the fixed DF version is used here since it is simpler (more robust) and less expensive.

The Dekati eDiluter dilutes the stack sample by a DF of approximately 36 with particle free dry air. It uses two ejector diluters in series, each with a DF of 6. The first stage is heated to about 200 C to prevent condensation of water. The second state is unheated. The outlet stream is near room temperature and very dry. The only connection needed for diluter operation is pressurized dry air (70 lpm at 60 psi), supplied by a Nation dryer fed by a pair of piston compressor pumps in parallel. The diluter power requirement is approximately 5 amps. The outlet flow of the diluter is approximately 40 lpm, sufficient to provide samples to several PM measurement instruments. A Method 5G filter sample can be taken from the dilutor, either along with a TEOM as a QC check, or as the only PM measurement. For the latter case, proportionality with stack flow must be observed by varying the filter sample flow. Proportionality is not needed for PM emission rates from Teom or pDR1500 PM data, since all of the data (stack flow, stack temperature, and PM concentration) are processed into PM emission rates using 1-minute data. When the 5G filter is run as the primary data source and sampling is done proportionally, the Dekati-Teom PM data (which is not proportional since all flows must be fixed during a single sampling run) can be compared to the 5G filter data using a grams/hour metric, not a PM concentration metric.

Diluter performance can be assessed in real-time by measuring CO in the stack and the diluter outlet. The ratio of CO is the actual DF. To accommodate different stack PM concentrations with a fixed dilution factor, the TEOM flow can be changed to achieve the desired sensitivity.

To measure pm emission rates, the stack flow and temperature must also be measured. A Höntzsch model ZS25/25-350GE/500/p10/ZG4 vane wheel anemometer is inserted into the centerline of stack sufficiently downstream of any obstructions (typically several duct diameters). It is sensitive enough to measure flows even at low burn stove air settings, and is rated up to 500 degrees C (930 F). Stack temperature is measured with a type K thermocouple probe just above the flow measurement. Using the 1-minute stack temperature, the stack flow is adjusted to EPA STP (25 C, 1 ATM) on a 1-minute basis for use with the 1-minute STP TEOM data to calculate 1-minute PM emission rates at STP. The 1-minute emission rate data is averaged up to the run duration for a run average PM rate.

1.4 Real-time PM Measurement Systems combined with Portable Dilution systems

1.4.1 Thermo pDR-1500 with dilution system

The Thermo pDR-1500 (pDR) measures particle light scattering, a surrogate of PM, with fast response time and a very large concentration range. The sample flows through a sensing chamber where forward light scattering is measured with very high time-resolution. It is designed for occupational sampling use but has been shown to work well for ambient air sampling of PM2.5. It is not designed for stack sampling and thus requires sample dilution and conditioning. The pDR is calibrated for mass concentration; the instrument's response can be affected by particle size, especially for particles smaller than 0.2 μm diameter.

Advantages of the Thermo pDR-1500 used with a dilution system include:

- Small, lightweight, can be battery powered
- Fast response (seconds), long run-times (> 8 hours).
- Measures PM at ambient conditions (no heating, no loss of semi-volatile PM)
- Can be used in winter conditions (-10 C)
- Measures the sampling chamber's temperature and relative humidity
- Can measure very high PM concentrations typical of cold start/dirty burn modes that other methods may not be able to capture
- Large dynamic range: ~ .005 to 450 mg/m3 (90,000 times)

Limitations of the Thermo pDR-1500 with dilution system include:

- Surrogate measurement of PM; accuracy may be degraded under certain burn conditions
- Instrument response under-measures PM when concentrations are low and particle size is very small (hot, clean burn conditions)
- Cannot sample directly from the stack; requires dilution

1.4.2 Thermo Scientific 1400AB/1405 Teom with Dekati eDiluter

The Thermo 1400AB or 1405 ambient version of the Teom (without the FDMS or SES options) can be used with the Dekati eDiluter if instrument settings are customized for high PM concentrations, fast response, and minimal filter heating. This version of the Teom cannot be run outside in cold weather.

Advantages of the 1400 Teom and Dekati eDiluter include:

- True mass measurement
- Minimal heating of sample
- No water in the sample (dry sample stream)

Limitations of the 1400 Teom with Dekati eDiluter include:

- Can not measure probe catch
- Not designed to be run in outdoor winter temperature conditions (~5 C minimum temperature)

2 Data on Device Performance

NESCAUM and Brookhaven National Lab staff completed testing with several wood burning appliances to obtain data on side by side measurements. The following sections detail the results of that work.

2.1 October 2013 Testing

2.1.1 Results

The initial testing for this project was performed at BNL October 28-29, 2013. Continuous PM was measured by the testo 380 (10/29 only), the Thermo pDR, and two Thermo PDM (personal Teom). The Wöhler SM500 was not working and not run. Filter samples were collected using GVS Maine Glass Fiber Filters with organic binder (Grade G15, with Binders; Borosilicate matrix bonded by acrylic resin), Thermo-Fisher part # G15WP04700. These are not the kind of filters required by EPA test methods (no organic binder, different pore size), and were used to avoid filter tearing due to condensed water on the filters. All tests were done using a catalytic wood stove with sampling off of the BNL dilution tunnel.

10/28/13 Results (PM in mg/m3)

Measurement Type	Sampling Period		
	Start up #1	Start up #2	Steady State
Train 1	178.67	4.74	3.44
Train 2	158.98	7.85	2.33
pDR	255.36	0.78	0.56

10/29/13 Results (PM in mg/m3)

Measurement Type	Sampling Period		
	Start up	Steady State #1	Steady State #2
Train 1	321.5	34	1058.6
Train 2	347.9	38.6	1090.7
testo 1	291.9	75.6	147.7
testo 2	271.6	80.6	142.9
pDR	166.7	14.2	1236.5

The PDM was run with a 15-minute running average configuration (the default), making it difficult to compare with the filter measurements; these data are not reported here. It is unknown what if any effect use of the glass fiber filter with organic binder would have on the filter data. The pDR response was highly variable relative to the filter PM, sometimes reading substantially higher and sometimes lower. The two testo instruments (collocated) were run using the manufacture's default settings for temperatures. They agreed well with each other but PM was inconsistent with the filter data.

Overall, the only useful information from these tests may be that the pDR cannot be used alone as a real-time PM monitor for this purpose; this is consistent with the wide range of particle size and composition present in the test aerosols.

2.2 February 2015 Testing

2.2.1 Test plan

The primary goal of the February 2015 woodsmoke PM measurement tests at BNL was to compare the performance of several different methods sampling from a dilution tunnel, including multiple systems of manual gravimetric filter sampling and continuous instruments, to explore questions raised during the previous round of testing where the PM from the glass fiber filter sampling train was higher than PM measured by both Teoms. Mass lost from filters during post-sampling equilibration is evaluated since it affects the results of the continuous PM method evaluation. An additional goal for these tests was to assess short-term (10 to 30 minutes duration) cold start PM emissions and the ability of various PM measurement methods to handle the sometimes very high concentrations from cold starts.

All sampling was off of a dilution tunnel without isokinetic sampling. This was an essential step before doing any direct stack sampling tests, since fundamental measurement issues must be identified and resolved before attempting more complex testing scenarios that introduce other measurement variables. The woodsmoke source for most samples was a NSPS non-catalytic wood stove burning hard and softwoods from the northeast US; a limited number of samples were from a thermal storage wood furnace. A wide range of burn conditions was measured, including cold starts and char burns. Sampling duration was usually 30 minutes, but was longer or shorter for some samples to accommodate different burn modes and filter loadings. A variety of cordwood was burned, including red oak, a mix of northern New England hardwoods, and very fresh green pine.

The following measurement methods were used.

- Traditional Method 28 sampling train with front and back glass fiber filters at ~ 7 lpm
- Traditional Method 28 sampling train with front and back Pall Emfab™ TX40 Teflon coated glass fiber filters at ~ 7 lpm
- 47 mm Teflon membrane filter (as used in ambient regulatory PM sampling) at 1 lpm

- Wöhler SM500 continuous stack PM analyzer, without internal correction factors
- testo 380 continuous stack PM analyzer with custom software
- Thermo 1400AB "ambient" Teom run in custom low flow, fast response configuration
- Thermo PDM 3600 personal Teom run in custom low flow, fast response configuration (requiring access to the "Expert" mode)
- Thermo pDR 1500 personal light scattering PM monitor

The two Teoms use Emfab filter media. The Wöhler uses Teflon coated glass fiber media. The testo collects PM via impaction (no filter media is used). See the method evaluation report for detailed descriptions of the continuous PM measurement instruments.

Only the front filter PM is used from the Emfab filter train for consistency with the continuous PM samplers; the back-filter and "probe catch" mass was not used. The glass fiber filter data are used only for comparison with the Emfab samples, and were not used for comparison with the continuous PM methods. There is no data comparison for the testo 380, since it malfunctioned during the testing. The 1400 Teom is a robust PM measurement relative to the Thermo pDR. Those measurements were considered ancillary for these tests (to collect performance data for future work), and are not reported here. The RH data from the pDR was used as a surrogate measurement of RH for the filter measurements (both were at room temperature).

Although the initial goal of this project was to evaluate the performance of continuous PM methods, issues with variability in the filter PM measurements needed to be addressed first. The filter PM data from these tests were reviewed to assess data quality and evaluate potential issues of artifacts on glass fiber filters and effects of different post-sampling equilibration times on filter mass loss.

Glass fiber filters have been used for testing wood burning appliances, but there is potential for an acid gas artifact (HCl and SO2 for example), and the filter can stick to filter holder surfaces. An alternative filter media that meets the Method 5 requirements for inert filter material, particle collection efficiency, and loading characteristics is Teflon-coated glass fiber, commercially available as Pall Emfab TX-40. All samples were collected on both glass fiber and Emfab filter media to evaluate their performance. Stretched Teflon membrane filter samples were also collected; this is the filter media used for ambient PM2.5 regulatory monitoring.

Initial (before sampling) filter weighings for all three kinds of filters were done at the CT-DEEP ambient filter weighing laboratory using a microbalance (necessary for the low loadings on the Teflon membrane filters). Initial weighings for the GFF and Emfab filters were also performed at BNL. All reported net mass values are thus from pre and post sample weighings done on the same balance and laboratory.

Post-sampling weighings (off-weights) for the manual filter methods were done after different equilibration times to asses change in filter mass over time. Emfab and glass fiber mass measurements for "0-Day" (a few minutes) off weights were done at BNL. All other off weights

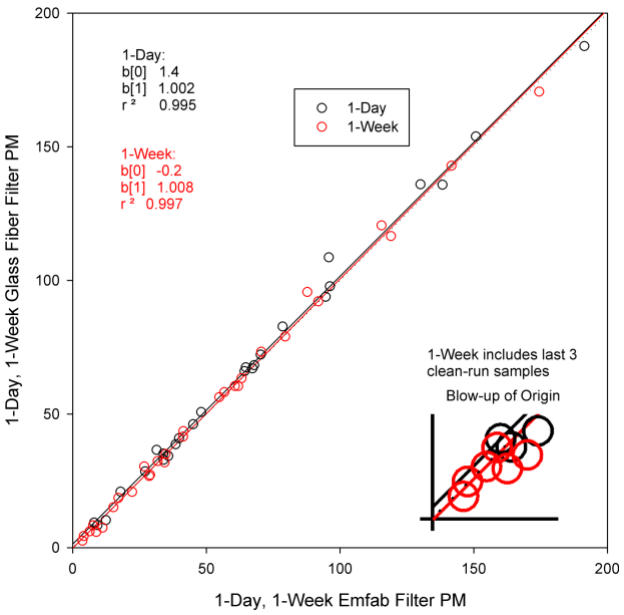
were done on at the CT-DEEP ambient filter weighing lab. These measurements were made with minimal equilibration (~5 hours for Teflon), 1-day, and 1-week (6 or 7 days) equilibration (all filters). Post-sampling filter equilibration was done at ~ 40% (as required for ambient PM samples) instead of the silica gel desiccation usually used for stack sampling filters. Filters were stored and shipped cold to minimize loss of volatile PM prior to mass measurements.

For this report, the focus is on comparison between the Emfab manual PM measurements with 1-day equilibration at 40% RH and two of the continuous PM instruments – the Wöhler and the 1400 Teom. This equilibration period is used as a mid-point filter PM measurement between the 0-day and 1-week equilibration times; both the Emfab and Teflon filters lost approximately 7% of the collected PM after 1-day, and another 7% after 1-week. The glass fiber media PM was unstable at 0-day weighing but stabilized with 1-day equilibration. Mass loss from filter equilibration is discussed in detail elsewhere in this report.

2.2.2 Results of February 2015 BNL Testing

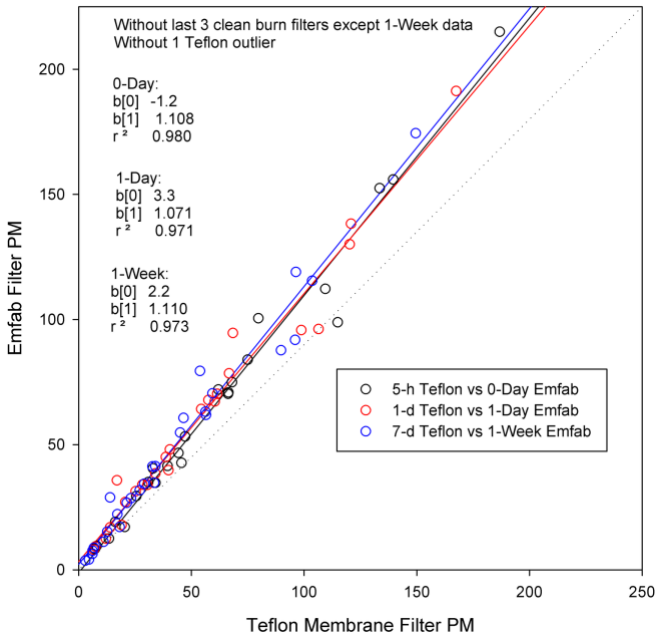
PM data from the GFF sample train is compared with the Emfab filter train data, using 1-day and 1-week equilibration times, with good numerical agreement and correlation.

Figure 1. PM concentration (mg/m3) from Emfab TX40 and glass fiber filter media, 1-day, and 1-week equilibration times.



The 0-day equilibration glass fiber filter PM has a large positive bias on several samples that goes away after 1-day equilibration. Figure 2 shows very good correlation of the Teflon membrane filter samples with the Emfab samples at all equilibration times. This confirms it is the 0-day glass fiber PM samples that are unstable, not the Emfab 0-day samples. The 1400 Teom data also support this conclusion (see below).

Figure 2. PM concentration (mg/m3) from Emfab and Teflon membrane filter media, 0-day, 1-day, and 1-week equilibration times.



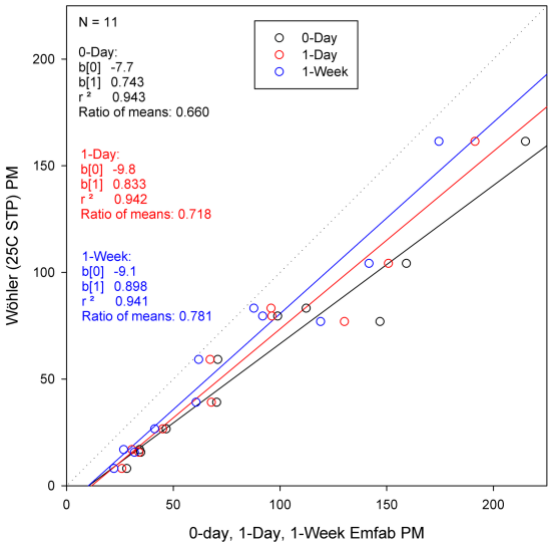
The Teflon membrane filter PM is 7 to 11% lower than the Emfab filter PM (as well as the glass fiber filter PM at 1-day and 1-week) but highly correlated. The Teflon membrane filter media is the same as used in regulatory ambient PM2.5 Federal Reference Method samplers. Flow measurements for the Teflon filters were done using a certified flowmeter at EPA STP of 25C and 1 atm. The face velocity for these samples was 7 times less than for the Emfab samples, but this would tend to increase the measured mass (reduced loss of SVM), not reduce it. Thus, this bias can not be explained, and may need additional tests to resolve.

Comparison of Continuous PM methods with Emfab filter PM.

Two continuous PM methods are evaluated here: the Wöhler SM-500 and the Thermo 1400AB Teom. The Wöhler is designed for in-stack sampling of wood stoves but also can be used in a dilution tunnel. The Thermo 1400 Teom is an ambient PM sampler than can be adapted for dilution tunnel sampling.

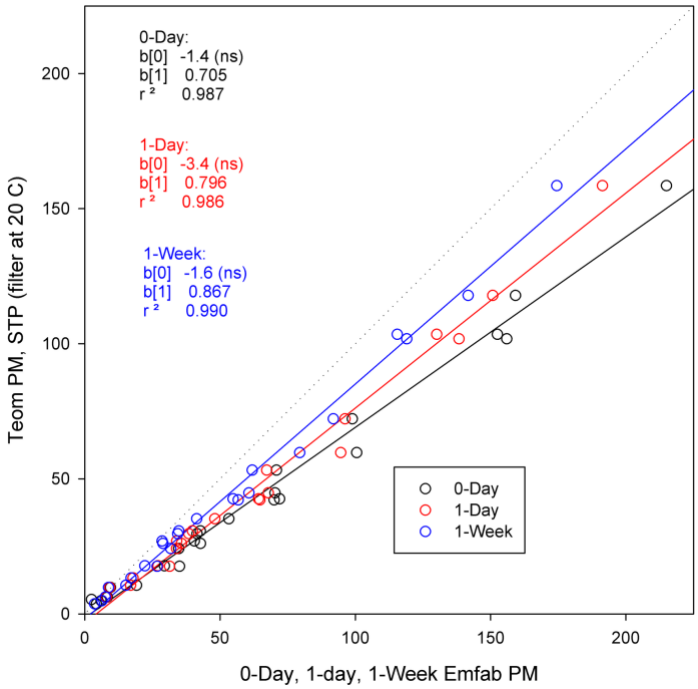
All Wöhler data presented here are calculated from the raw 1-second filter mass and reported flow rate, since the normal European regulatory data are only available as a 15-minute average concentration. Thus the Wöhler data presented here do not have any correction for loss of water or semi-volatile PM. There are a limited number of Wöhler samples (11) available for evaluation; the instrument failed half way through the test week. Figure 3 compares the Wöhler PM with the day-1 Emfab filter sample PM for all valid collocated runs; correlation is good over this large dynamic range of PM concentrations but the continuous data are lower than the filter data, with a -10 mg/m3 intercept (significant at p=0.05). For samples with Emfab PM less than 50 mg/m3, the Wohler PM is less than half the Emfab filter PM. All PM data are reported at EPA STP (25C, 1 Atm).

Figure 3. Wöhler PM vs. 0-day, 1-day, and 1-week Emfab filter PM (mg/m3).



There are 25 valid samples with both 1400 Teom and Emfab measurements; three of these are with the very clean burning test device. Figure 4 shows that these data are highly correlated, but the continuous data are ~ 13% lower than the Emfab equilibrated filter data. The 1400 Teom intercept is small and not significantly different than 0 mg/m3.

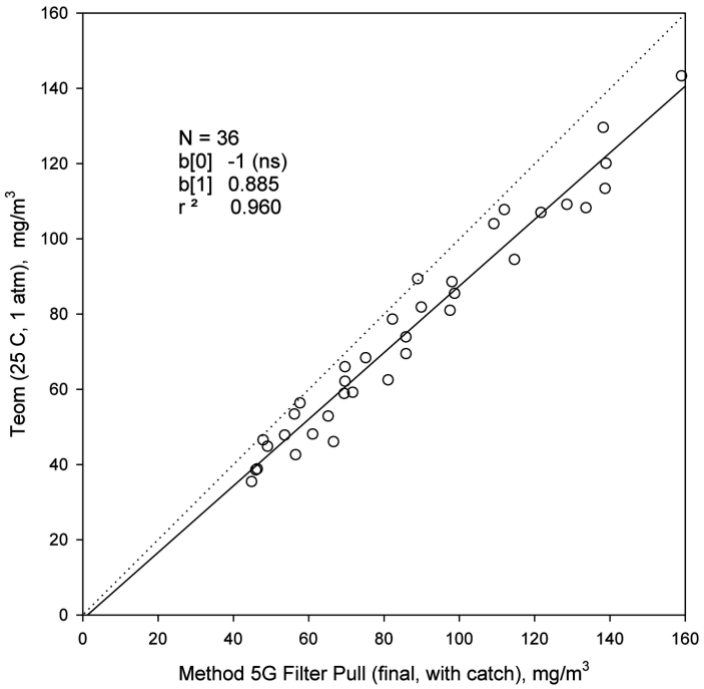
Figure 4. 1400 Teom PM vs. 0-day, 1-day, and 1-week Emfab filter PM (mg/m3).



The cause of this bias is unknown. The 1400 Teom PM measurement is a true mass measurement; sample flows were calibrated with a certified flowmeter, leak tests were performed during the test week, and the Teom K_0 calibration factor has been verified. The 1400 Teom filter temperature is similar to the Emfab filter PM measurement. Filter face velocities are similar: 7 cm/s for Emfab and 5 cm/s for the 1400 Teom. The pressure drop across a loaded filter may be different. A higher pressure drop could result in more loss of SVM, but the very high correlation between these PM measurements with different loadings suggests this is not a large factor.

2.3 Hearth Lab Solutions TEOM Data

A pre-1988 NSPS Vigilant stove was used for 36 crib test runs between 8/23/2016 and 1/4/2017. PM was sampled from a Method 5G dilution tunnel at 200 cfm using both 5G Emfab filter trains and a Thermo TEOM model 1400AB run at 25 C filter temperature with a sample flow of 0.5 lpm. The 5G filter data here are the final equilibrated concentrations.



Dilution tunnel PM measured with the TEOM is highly correlated with the Method 5G filter pull PM, and is about 11% lower, with a zero intercept. Thus 5G filter pull equivalent data can be obtained from TEOM PM data by use of a simple linear correction of 11%. These results are consistent with the results of TEOM and filter pull PM from the BNL work shown in Section 2.2 above.

3 Detailed summary of instrument specifications.

Wöhler SM500 suspended particulate analyzer

Specifications:
Sample filter media: Teflon coated glass fiber
Measurement temperature (temperature of collection filter or measurement chamber): 75 C
Run time: limited by 8 mg filter loading (500 mb); 1-hour @ 44 mg/m3 and 3 lpm
Sample from direct stack or diluted sample: both
PM concentration measurement range: 1 g/m3 maximum, 10 mg/m3 TUV minimum
PM concentration resolution: 1 mg/m3
Minimum particle size sampled: ~10 nm
Accuracy: ~ 20%
Sample inlet flow: 3.0 to 4.5 LPM
Total time in between runs (to change filter, warm up, etc.): 5 to 10 minutes
Time Resolution: 1 second when using raw instrument data
Response Time: data unavailable
Maximum Flue Gas Temperature: 500C
Warm-up time: 15 minutes
Startup time in addition to warm-up time: 1 minute
Instrument operating temperature range: +5 °C to +40 °C
Power Consumption: ~10 amps
Approximate cost: $14,000
Ease of use[1]: Simple

testo 380 fine particle analyzer

Specifications:
Measurement Method: Quartz Crystal Microbalance (QCM)
with collection by impaction @ 400 mb (0.4 atm)
Sample filter media: n/a
Measurement temperature (temperature of collection filter or measurement chamber):
25 C above ambient in wood-chip mode
Probe and sample line can run at ambient T for dilution tunnel use (custom setup)
Run time: limited by loading, 190 mg/m3 for 1-hour
Sample from direct stack or diluted sample: both
PM concentration measurement range: 0 to 300 mg/m; (may be greater, not specified)

[1] Note: Ease of use is a qualitative assessment of the time (effort) and level of operator expertise required to use the method.

PM concentration resolution: 0.1 mg/m; (when measured PM is greater than 5 mg/m;)
Minimum particle size sampled: ~100-200 nm
Accuracy: data unavailable
Sample inlet flow: 0.8 lpm
Total time in between runs (to change filter, cool-down, clean, warm up, etc.): ~ 15 to 30 minutes
Time Resolution: 5 seconds
Response Time: ~ 1 minute
Maximum Flue Gas Temperature: 500 C (930 F)
Warm-up time: 10 to 15 minutes, more when at the low end of the operating temperature range
Startup time in addition to warm-up time: 3 minutes
Instrument operating temperature range: +5° C to +40 °C
Power Consumption: ~1 amp
Approximate cost: estimated at $8,500
Ease of use: Moderate

Thermo 1400ab or 1405 "ambient" Teom (not the SES or FDMS Teom version) with dilution, run in custom configuration

Specifications:
Measurement Method: inertial mass, filter on tapered oscillating element
Sample filter media: Teflon coated glass fiber (Pall TX-40 Emfab)
Measurement temperature (temperature of collection filter):
< ~5 C above room temperature; minimum filter temperature = 10 C
Run time: ~12 hours at 4 mg/m3, 6 hours at 8 mg/m3, 3 hours at 16 mg/m3, etc.
Sample from direct stack or diluted sample: diluted
PM concentration measurement range: 0.1 mg/m^3 to ~100 mg/m^3
Concentration resolution: 0.1 µg/m;
Minimum particle size sampled: < 10 nm
Accuracy: ~10%
Sample inlet flow: 0.5 to 5.0 LPM
Total time in between runs (to change filter, warm up, etc.): 5 minutes
Time Resolution: 10 seconds
Response Time: 1-minute
Maximum Flue Gas Temperature: n/a
Warm-up time: 30-minutes
Startup time in addition to warm-up time: 2-minutes
Instrument Operating Temperature: ~5 °C to 40 °C
Power Consumption: ~3 amps
Approximate cost: $18,000
Ease of use: Moderate

Thermo pDR-1500

Specifications:
Measurement Method: Forward Light Scattering (PM surrogate)
Sample filter media: n/a
Measurement Temperature: Ambient (no heating)
Run Time: unlimited
Sample from direct stack or diluted sample: diluted
PM concentration measurement range: 0.001 to 400 mg/m3 (requires a dilutor)
PM concentration resolution: 0.1 Φg/m;
Minimum particle size sampled: ~ 100 nm
Accuracy: ~ 10 to 15%, less accurate (reduced response) for very clean hot burns
Sample inlet flow: 1.0 LPM
Measurement Duration: Days
Total time in between runs (to change filter, cool-down, warm up, etc.): none
Time Resolution: 1-second
Response Time: 5-seconds
Maximum Flue Gas Temperature: n/a
Warm-up time: 5 minutes or less
Startup time in addition to warm-up time: 0 seconds
Instrument operating temperature range: -10 °C to +50 °C
Power Consumption: ~ 0.5 amps
Approximate cost: $5000
Ease of use: Simple