A Test Method for Certification of Cord Wood-Fired Hydronic Heating Appliances Based on a Load Profile: Measurement of Particulate Matter (PM) and Carbon Monoxide (CO) Emissions and Heating Efficiency of Wood-Fired Hydronic Heating Appliances

1.0 Scope and Application

1.1 This test method applies to wood-fired hydronic heating appliances without heat storage external to the appliance. The units typically transfer heat through circulation of a liquid heat exchange media such as water or a water-antifreeze mixture. Throughout this document, the term “water” will be used to denote any of the heat transfer liquids approved for use by the manufacturer.

1.2 The test method measures PM and CO emissions and delivered heating efficiency over a fuel charge and thermal load profile.

1.3 PM emissions are measured by the dilution tunnel method as specified in EPA Method 28 WHH and the standards referenced therein with the exceptions noted in Section 12.5.6. Delivered Efficiency is measured through the measurement of stack loss efficiency and jacket loss. Delivered efficiency does not attempt to account for pipeline loss.

1.4 Products covered by this test method include both pressurized and non-pressurized hydronic heating appliances intended to be fired with wood and for which the manufacturer specifies for indoor or outdoor installation. The system is commonly connected to a heat exchanger by insulated pipes and normally includes a pump to circulate heated liquid. These systems are used to heat structures such as homes, barns, schools, and greenhouses. They also provide heat for domestic hot water, spas and swimming pools. The products covered by this test method typically have larger internal water volumes and do not use external thermal storage for heating applications. These products, when used for domestic hot water applications may use external thermal storage only for the hot water service.

1.5 Distinguishing features of products covered by this standard include:

1.5.1 The manufacturer specifies the application for either indoor or outdoor installation.

1.5.2 A firebox with an access door for hand loading of fuel.

1.5.3 Typically an aquastat mounted as part of the appliance that controls combustion air supply to maintain the liquid in the appliance within a predetermined temperature range provided sufficient fuel is available in the firebox. The appliance may be equipped with other devices to control combustion.

1.5.4 A chimney or vent that exhausts combustion products from the appliance.

1.5.5 The heating appliances do not require external thermal storage for heating applications and are typically installed without external thermal storage.

1.6 The values stated are to be regarded as the standard whether in I-P or SI units. The values given in parentheses are for information only.

1.7 Persons using this method should have a thorough knowledge of at least the following additional EPA test methods: Method 1, Method 2, Method 3, Method 4, Method 5, Method 5G, and Method 28.

2.0 Summary of Method and References

2.1 PM and CO emissions are measured from a wood–fired hydronic heating appliance burning a prepared test fuel charge in a test facility maintained at a set of prescribed conditions. Procedures for determining heat output rates, PM and CO emissions, and efficiency and for reducing data are provided.

2.2 Referenced Documents

2.2.1 EPA Standards

2.2.1.1 Method 28 Certification and Auditing of Wood Heaters

2.2.1.2 Method 28 WHH Measurement of Particulate Emissions and Heating Efficiency of Wood-Fired Hydronic Heating Appliances and the standards referenced therein. This test method is incorporated in the EPA Hydronic Heater Program Phase 2 Partnership Agreement, 10/12/2011, http://www.epa.gov/burnwise/pdfs/owhphase2agreement.pdf .

2.2.2 Other Standards

2.2.2.1 CAN/CSA-B415.1-2010 *Performance Testing of Solid-Fuel-Burning Heating Appliances*

2.2.2.2 ASTM E2515-11 Standard Test Method for Determination of Particulate Matter Emissions Collected by a Dilution Tunnel

3.0 Terminology

3.1 Definitions

3.1.1 Hydronic Heating – A heating system in which a heat source supplies energy to a liquid heat exchange media such as water that is circulated to a heating load and returned to the heat source through pipes.

3.1.2 Aquastat – A control device that opens or closes a circuit to control the rate of fuel consumption in response to the temperature of the heating media in the heating appliance.

3.1.3 Delivered Efficiency – The percentage of heat available in a test fuel charge that is delivered to a simulated heating load as specified in this test method.

3.1.4 Emission factor – the emission of a pollutant expressed in mass per unit of energy (typically) output from the boiler

3.1.5 Emission index – the emission of a pollutant expressed in mass per unit mass of fuel used

3.1.6 Emission rate – the emission of a pollutant expressed in mass per unit time

3.1.7 Manufacturer's Rated Heat Output Capacity −The value in Btu/hr (MJ/hr) that the manufacturer specifies that a particular model of hydronic heating appliance is capable of supplying at its design capacity as verified by testing, in accordance with Section 12.5.4.

3.1.8 Heat output rate − The average rate of energy output from the appliance during a specific test period in Btu/hr (MJ/hr)

3.1.9 Firebox − The chamber in the appliance in which the test fuel charge is placed and combusted.

3.1.10 NIST – National Institute of Standards and Technology

3.1.11 Test fuel charge − The collection of test fuel placed in the appliance at the start of a phase of a test run.

3.1.12 Test Run – An individual emission test which encompasses the time required to complete all specified phases of the test profile.

3.1.13 Overall Efficiency, also known as Stack Loss Efficiency – The efficiency for each test run as determined using the CSA B415.1-2010 Stack Loss Method (SLM).

3.1.14 Phases of a Burn Cycle. This test procedure specifies 10 different phases of operation that comprise one complete test which is completed in one day. These phases are defined in Table 1 and include cold start and operation at different loads.

3.1.15 Thermopile - A device consisting of a number of thermocouples connected in series, used for measuring differential temperature.

4.0 Summary of Test Method

4.1 Dilution Tunnel. Emissions are determined using the “dilution tunnel” method specified in EPA Method 28 WHH and the standards referenced therein. The flow rate in the dilution tunnel is maintained at a constant level throughout the test cycle and accurately measured. Two different particulate sampling methods are used in this test method. The first is a filter-based method. Samples of the dilution tunnel flow stream are extracted at a constant flow rate and drawn through high efficiency filters. The filters are dried and weighed before and after the test to determine the emissions collected and this value is multiplied by the ratio of tunnel flow to filter flow to determine the total particulate emissions produced in the test cycle. The second method is a real-time particulate measurement method based on a Tapered Element Oscillating Microbalance (TEOM) instrument, or equivalent. Flue gas carbon monoxide are also measured in the dilution tunnel and in the flue. The carbon monoxide (CO) measured in the dilution tunnel is used to determine the CO emission rate. The CO measured in the flue, before dilution, is used in the stack loss efficiency determination.

4.2 Efficiency. The efficiency determination involves both determination of stack losses and jacket loss. The stack loss determination involves measurement of the flue gas temperature, CO_2, and CO. This is combined with measured fuel heating value and moisture content as well as assumed dry fuel ultimate analysis. The flue losses are then calculated as a percentage of the fuel input energy. This provides a stack loss efficiency. Subtracted from this is the rate of heat loss from the boiler jacket to the surrounding space, also expressed as a percentage of the fuel input energy. The jacket loss determination involves measurement of the jacket surface temperature and calculation of the rate of heat loss to the surrounding room by convection and radiation. In this test method heat output is measured to determine the full load output capacity of the hydronic heater and to enable tests to be done at specific load levels. The heat output is not directly used in the efficiency determination.

4.3 Operation. A single test of the hydronic heater involves operation in 10 different phases. In summary these include:

Cold start and ramp up to full output;
Reduction of the load to achieve operation at 25%, 50% of full load and burnout;
Reload and operation at 15% of full load;
Operation with the load cycling on and off.

This test is completed in one day. The test is done three times and results averaged.

All test operations and measurements shall be conducted by personnel of the laboratory responsible for the submission of the test report.

5.0 Significance and Use

5.1 The measurement of particulate matter emission and CO rates is an important test method widely used in the practice of air pollution control.

5.1.1 These measurements, when approved by state or federal agencies, are often required for the purpose of determining compliance with regulations and statutes.

5.1.2 The measurements made before and after design modifications are necessary to demonstrate the effectiveness of design changes in reducing emissions and make this standard an important tool in manufacturer's research and development programs.

5.2 Measurement of heating efficiency provides a uniform basis for comparison of product performance that is useful to the consumer. It is also required to relate emissions produced to the useful heat production.

5.3 This is a laboratory method intended to capture operating periods that are representative of actual field use without excessive test burden. It is recognized that users of hand-fired wood burning equipment have a great deal of influence over the performance of any wood-burning appliance. Some compromises in realism have been made in the interest of providing a reliable and repeatable test method.

6.0 Test Equipment

6.1 Scale. A platform scale capable of weighing the boiler under test and associated parts and accessories when completely filled with water to an accuracy of ± 1.0 pound (± 0.5 kg) and a readout resolution of ± 0.2 pound (± 0.1 kg).

6.2 Heat Exchanger. A water-to-water heat exchanger capable of dissipating the expected heat output from the system under test.

6.3 Water Temperature Difference Measurement. A Type –T 'special limits' thermopile with a minimum of 5 pairs of junctions shall be used to measure the temperature difference in water entering and leaving the heat exchanger. The temperature difference measurement uncertainty of this type of thermopile is equal to or less than ± 1.0 ºF (± 0.5 ºC). Other temperature measurement methods may be used if the temperature difference measurement uncertainty is equal to or less than ± 1.0 ºF (± 0.50 ºC). This measurement uncertainty shall include the temperature sensor, sensor well arrangement, piping arrangements, lead wire, and measurement / recording system. The response time of the temperature measurement system shall be less than half of the time interval at which temperature measurements are recorded.

6.4 Water Flow Meter. A water flow meter shall be installed in the inlet to the load side of the heat exchanger. The flow meter shall have an accuracy of ± 1% of measured flow.

6.4.1 Optional - Appliance side water flow meter. A water flow meter with an accuracy of ± 1% of the flow rate is recommended to monitor supply side water flow rate.

6.5 Optional Recirculation Pump. Circulating pump used during test to prevent stratification, in the boiler, of liquid being heated.

6.6 Water Temperature Measurement – Thermocouples or other temperature sensors to measure the water temperature at the inlet and outlet of the load side of the heat exchanger must meet the calibration requirements specified in 10.1 of this method.

6.7 Lab Scale – For measuring the mass of the test fuel charges. Accuracy of ± 0.1 pounds.

6.8 Wood Moisture Meter – Calibrated electrical resistance meter capable of measuring test fuel moisture to within 1% moisture content. Must meet the calibration requirements specified in 10.4

6.9 Flue Gas Temperature Measurement – Must meet the requirements of CSA B415.1-2010, Clause 6.2.2.

6.10 Test Room Temperature Measurement – Must meet the requirements of CSA B415.1-2010, Clause 6.2.1.

6.11 Flue Gas Composition Measurement – Must meet the requirements of CSA B415.1-2010, Clauses 6.3.1 through 6.3.3.

6.12 Dilution Tunnel CO Measurement – In parallel with the flue gas composition measurements, the CO concentration in the dilution tunnel shall also be measured and reported at time intervals not to exceed one minute. This analyzer shall meet the zero and span drift requirements of CSA B415.1-2012. In addition, the measurement uncertainty shall be better than ±15 ppm over the range of CO levels observed in the dilution tunnel.

6.13 Boiler Jacket Surface Temperature Measurement – For the determination of boiler jacket loss, the surface temperature of the jacket is required. Boiler surface temperatures will be measured using an infrared (IR) camera with a minimum thermal resolution of 160 X 120 pixels.

7.0 Safety

7.1 These tests involve combustion of wood fuel and substantial release of heat and products of combustion. The heating system also produces large quantities of very hot water and the potential for steam production and system pressurization. Appropriate precautions must be taken to protect personnel from burn hazards and respiration of products of combustion. Exposure of personnel to unsafe levels of carbon monoxide must be avoided and the use of continuous ambient carbon monoxide monitoring is strongly recommended.

8.0 Sampling, Test Specimens and Test Appliances

8.1 Test specimens shall be supplied as complete appliances, as described in marketing materials, including all controls and accessories necessary for installation in the test facility. A full set of specifications, installation and operating instructions, and design and assembly drawings shall be provided when the product is to be placed under certification of a third-party agency. The manufacturer's written installation and operating instructions are to be used as a guide in the set-up and testing of the appliance and shall be part of the test record. A representative of the manufacturer may assist in the installation and startup of the unit. A representative of the manufacturer may observe testing but all testing must be done by the staff of the certified testing organization. During testing the unit cannot be connected for remote access. For example, the unit cannot be connected to the internet.

8.2 All system control settings shall be the as-shipped, default settings. These default settings shall be the same as those communicated in a document to the installer or end user. These control settings and the documentation of the control settings as to be provided to the installer or end user shall be part of the test record. *Informational note: these units typically have an operating limit at about 180 °F and a safety high limit at about 195 °F. If the unit reaches the safety limit a manual reset is commonly required. As noted above, the actual settings shall be based on the manufacturer's default settings.*

8.3 Where the manufacturer defines several alternatives for the connection and loading arrangement, one shall be defined in the appliance documentation as the default or standard installation. It is expected that this will be the configuration for use with a simple baseboard heating system. This is the configuration to be followed for these tests. The manufacturer's documentation shall define the other arrangements as optional or alternative arrangements.

9.0 Preparation of Test Equipment

9.1 The appliance is to be placed on a scale meeting the requirements of Section 6.1.

9.2 The appliance shall be fitted with the type of chimney recommended or provided by the manufacturer and extending to 15 ± 0.5 feet (4.6 ± 0.15 m) from the upper surface of the scale. If no flue or chimney system is recommended or provided by the manufacturer, connect the appliance to a flue of a diameter equal to the flue outlet of the appliance. The flue section from the appliance flue collar to 8 ± 0.5 feet above the scale shall be single wall stove pipe and the remainder of the flue shall be double wall insulated class A chimney.

9.3 Optional Equipment Use

9.3.1 A recirculation pump may be installed between connections at the top and bottom of the appliance to minimize thermal stratification if specified by the manufacturer's instructions shipped with the unit. If specified by the manufacturer, the manufacturer shall provide all piping, pumps, and controls necessary for the recirculation system. The pump shall not be installed in such a way as to change or affect the flow rate between the appliance and the heat exchanger.

9.3.2 If the manufacturer's instructions shipped with the unit specify that a thermal control valve or other device be installed and set to control the return water temperature to a specific set point, the valve or other device shall be installed and set per the manufacturer's written instructions.

9.4 Prior to filling the boiler with water, weigh and record the appliance mass.

9.5 Heat Exchanger

9.5.1 Plumb the unit to a water-to-water heat exchanger with sufficient capacity to draw off heat at the maximum rate anticipated. Route hoses and electrical cables and instrument wires in a manner that does not influence the weighing accuracy of the scale as indicated by placing dead weights on the platform and verifying the scale's accuracy.

9.5.2 Locate temperature sensors to measure the water temperature at the inlet and outlet of the load side of the heat exchanger.

9.5.3 Install a thermopile (or equivalent instrumentation) meeting the requirements of Section 6.3 to measure the water temperature difference between the inlet and outlet of the load side of the heat exchanger.

9.5.4 Install a calibrated water flow meter in the heat exchanger load side supply line. The water flow meter is to be installed on the cooling water inlet side of the heat exchanger so that it will operate at the temperature at which it is calibrated.

9.5.5 Place the heat exchanger in a box with 2 in. (50 mm) of expanded polystyrene (EPS) foam insulation surrounding it to minimize heat losses from the heat exchanger.

9.5.6 The reported heat output rate shall be based on measurements made on the load side of the heat exchanger.

9.5.7 Temperature instrumentation per Section 6.6 shall be installed in the appliance outlet and return lines. The average of the outlet and return water temperature on the supply side of the system shall be considered the average appliance temperature. Installation of a water flow meter in the supply side of the system is optional.

9.7 Fill the system with water. Determine the total weight of the water in the appliance when the water is circulating. Verify that the scale indicates a stable weight under operating conditions. Make sure air is purged properly.

10.0 Calibration and Standardization

10.1 Water Temperature Sensors. Temperature measuring equipment shall be calibrated before initial use and at least semi-annually thereafter. Calibrations shall be in compliance with National Institute of Standards and Technology (NIST) Monograph 175, Standard Limits of Error.

10.2 Heat Exchanger Load Side Water Flow Meter.

10.2.1 The heat exchanger load side water flow meter shall be calibrated within the flow range used for the test run using NIST-traceable methods. Verify the calibration of the water flow meter before and after each test run and at least once during each test run by comparing the water flow rate indicated by the flow meter to the mass of water collected from the outlet of the heat exchanger over a timed interval. Volume of the collected water shall be determined based on the water density calculated from Section 13, Eq. 12, using the water temperature measured at the flow meter. The uncertainty in the verification procedure used shall be 1% or less. The water flow rate determined by the collection and weighing method shall be within 1% of the flow rate indicated by the water flow meter.

10.3 Scales. The scales used to weigh the appliance and test fuel charge shall be calibrated using NIST-traceable methods at least once every 6 months.

10.4 Flue Gas Analyzers – In accordance with CSA B415.1-2010, Clause 6.8.

11.0 Conditioning

11.1 Prior to testing, a non-catalytic appliance is to be operated for a minimum of 20 hours using a medium heat draw rate. Catalytic units shall be operated for a minimum of 50 hours using a medium heat draw rate. The pre-burn for the first test can be included as part of the conditioning requirement. If conditioning is included in pre-burn, then the appliance shall be aged with fuel meeting the specifications outlined in Sections 12.2 with a moisture content between 19 and 25 percent on a dry basis. Record and report hourly flue gas exit temperature data and the hours of operation. The aging procedure shall be conducted and documented by a testing laboratory.

12.0 Procedure

12.1 Appliance Installation. Assemble the appliance and parts in conformance with the manufacturer's written installation instructions. Clean the flue with an appropriately sized, wire chimney brush before each certification test series.

12.2 Fuel. Test fuel charge fuel shall be maple (big leaf, red, silver), larch, and birch 19 to 25% moisture content on a dry basis. Piece length shall be 80% of the firebox depth rounded down to the nearest 1-inch (25mm) increment. For example, if the firebox depth is 46 inches (1168mm) the piece length would be 36 inches (46 inches x 0.8 = 36.8 inches round down to 36 inches). Pieces are to be placed in the firebox parallel to the longest firebox dimension. For fireboxes with sloped surfaces that create a non-uniform firebox length, the piece length shall be adjusted for each layer based on 80% of the length at the level where the layer is placed. The test fuel shall be cord wood with cross section dimensions and weight limits as defined in CSA B415.1-2010, Section 8.3, Table 4. The use of kiln dried wood is not allowed.

12.2.1 Fuel Moisture. Using a fuel moisture meter as specified in Section 6.8, determine the fuel moisture for each test fuel piece used for the test fuel load by averaging four moisture meter readings measured parallel to the wood grain. The moisture readings will include two core measurements and two shell measurements. One of the core measurements and one of the shell measurements shall be made at the center of the length of each piece. The second core measurement and the second shell measurement shall be made approximately one inch from one end of each piece. Either end may be selected for this measurement. The shell measurements shall be made with a penetration of the moisture meter insulated electrodes of ¼ inch. The core measurements shall be made with a penetration of the moisture meter insulated electrodes to the center of the piece or a distance of 1.125 inch, whichever is less. For the core measurements, a pilot hole, not greater than twice the diameter of the insulated electrode may be drilled to a distance of not greater than ¼ inch less than the target penetration distance. Each individual moisture content reading shall be in the range of 10 to 35%MC on a dry basis. The average moisture content of each piece of test fuel shall be in the range of 19 to 25%. Moisture shall not be added to previously dried fuel pieces except by storage under high humidity conditions and temperature up to 100°F. Fuel moisture shall be measured within four hours of using the fuel for a test. (adapted from: Smith, W.B., Kohan, N., Huang, H., and Swidel, J., Evaluation of Wood

Fuel Moisture Measurement Accuracy for Cordwood-Fired Advanced Hydronic Heaters, Final Report submitted to NYSERDA, Report 14-12, March 2014)

12.2.2 Firebox Volume. Determine the firebox volume in cubic feet. Firebox volume shall include all areas accessible through the fuel loading door where firewood could reasonably be placed up to the horizontal plane defined by the top of the loading door. A drawing of the firebox showing front, side and plan views or an isometric view with interior dimensions shall be provided by the manufacturer and verified by the laboratory. Calculations for firebox volume from computer aided design (CAD) software programs are acceptable and shall be included in the test report if used. If the firebox volume is calculated by the laboratory the firebox drawings and calculations shall be included in the test report.

12.3 Sampling Equipment. Prepare the particulate emission sampling equipment as defined by EPA Method 28 WHH and the standards referenced therein.

12.4 Operation During Test Runs- The test shall be started with the unit clean and at an average boiler temperature not greater than 10 °F above the ambient room temperature. This section defines the required operating procedures.

12.4.1 Phases of Operation. The unit will be operated in 10 phases as defined in Table 1.

Table 1. Test Phases

Phase	Description	Milestone to Signify End of Phase
Cold Start Fuel charge - kindling + starter fuel		
1	Cold Start: Includes kindling (10% of fuel charge weight) made up of 50% small pieces and 50% larger kindling pieces	Once 80% of kindling fuel has been consumed
1st fuel charge		
2	Ramp-up to full load	Once 20% of 1st fuel charge has been consumed during this phase
3	Maximum Burn Rate	Once 20% of 1st fuel charge has been consumed during this phase
4	Steady State –less than 25% load	1.25 hours
5	Steady State – less than 50% load	Once 20% of 1st fuel charge has been consumed
6	End Phase – burn out**	Once 85% of the 1st fuel charge has been consumed, establishing a coal bed of 15% of the 1st fuel charge
2nd fuel charge		
7	Reload – Equivalent of a hot start	Once 10% of 2nd fuel charge has been consumed during this phase
8	Steady State – less than 15% load	Greater of 2.0 hours and time required for 1 reheat firing cycles
9	Steady State 100% load	Once 20% of 2nd fuel charge has been consumed during this phase
10	Cyclic operation (10 minutes off, 5 minutes on)	Once the boiler temperature has returned back to its starting point of temperature set-point reached
End of Sampling		Let remainder of fuel burn out at max load no sampling

12.4.2 Fuel Load. The first fuel charge will be 10 lb/ft^3 of firebox volume. The cold start fuel charge shall be 10% of the first fuel charge. For the second fuel charge, fuel will be added to within 1 inch of the top of the firebox opening. *Informational note: This is intended to be the maximum amount of fuel that can be practically loaded into the firebox.*

The fuel loading and startup procedure shall follow the manufacturer's instructions. If required by the manufacturer's instructions, the first charge of fuel can be added in two stages but all of the 1st fuel charge must be added before the end of Phase 2 in Table 1. During addition of fuel, the loading door cannot be open for more than 2 minutes.

12.4.3 Operation During Phases 1,2, and 3. During Phases 1,2, and 3 the boiler controls should target operation at maximum firing rate. Following cold start, cooling water will not be turned on until after the boiler reaches

160 °F. After the burner has stabilized at maximum burn rate and the temperature has reached 160 °F, the cooling load shall be set to the nominal output rate.

During Phase 3, the unit should be firing at its maximum burn rate for the entire period. The boiler water temperature, however, may be increasing during this time period.

If, at any time, during Phases 1,2, and 3 the boiler temperature is rising and approaching the operating limit, the output rate shall be increased to prevent the boiler from cycling off or from modulating to a lower firing rate.

12.4.4 Low Boiler Temperature. If, at any time during a test run, the boiler water average temperature falls below 150 °F, the cooling water shall be stopped until the average temperature rises above 160 °F. The occurrence of these events shall be logged in the test record. During a Phase in which this occurs, the load during the Phase, for the purpose of compliance with the loads specified in Table 1, shall be the output load averaged over the entire time period, including the periods during which the cooling water flow is off.

12.4.5 Phase 10. Phase 10 emulates the operation of the boiler responding to a thermostat call. At the start of Phase 10, the cooling water shall be turned off until the boiler temperature rises to the operating limit and the boiler controls act to minimize the burn rate in an “off” or “idle” mode. The transition to this mode is determined either by the control status indication or the stopping of the combustion air / induced draft fan. Following this, the cooling load shall be cycled in a 5 minute on, 10 minute off pattern. During the 5 minutes on period the cooling water flow shall be adjusted for an output of 80-110% of nominal full load output. This cycling pattern shall continue through the time at which the boiler operating controls act to restart the active combustion and reheat the boiler. The transition to this active combustion mode is determined either by the control status indication or restarting of the combustion air/induced draft fan. This phase and the test ends when the boiler has again reached the operating limit temperature and the boiler controls act to minimize the burn rate in an “off” or “idle” mode. During the active combustion/recovery mode, when the system is firing to reheat the boiler, the cooling load will continue to be cycled in the same 5 minute on, 10 minute off pattern. If, during this test, the boiler shuts down on the high temperature safety control, requiring a manual reset, the test is a failed run.

12.5 Test Run Procedures

12.5.1 Measurements and Adjustments

12.5.1.1 Record all water temperatures, differential water temperatures and water flow rates at time intervals of one minute or less. All data collected for regulatory purposes shall be reported at no time period shorter than one minute. Shorter collection times may be used for research but will not be considered for regulatory purposes.

12.5.1.2 During the test run, particulate emissions shall be measured per the requirements of EPA Method 28 WHH and the standards referenced therein. This involves two sampling trains providing an integrated measurement over the entire test period, Phases 1 through 10.

12.5.1.3 During the entire test run, particulate concentration in the dilution tunnel shall also be measured in real time using a Tapered Element Oscillating Microbalance (TEOM) instrument, or equivalent, as per Appendix A to this test method. Section 9 of Appendix A prescribes the methodology to determine the total PM emitted during each Phase and for the entire test run in grams.

12.5.1.4 Record data needed to determine Overall Efficiency (SLM) per the requirements of CSA B415.1-2010 Clauses 6.2.1, 6.2.2, 6.3, 8.5.7, 10.4.3 (a), 10.4.3(f), and 13.7.9.3

12.5.1.4.1 Measure and record the test room air temperature in accordance with the requirements of Clauses 6.2.1, 8.5.7 and 10.4.3 (g).

12.5.1.4.2 Measure and record the flue gas temperature in accordance with the requirements of Clauses 6.2.2, 8.5.7 and 10.4.3 (f).

12.5.1.4.3 Determine and record the Carbon Monoxide (CO) and Carbon Dioxide (CO_2) concentrations in the flue gas in accordance with Clauses 6.3, 8.5.7 and 10.4.3 (i) and (j).

12.5.1.4.4 Measure and record the test fuel weight per the requirements of Clauses 8.5.7 and 10.4.3 (h).

12.5.1.4.5 Record the test run time per the requirements of Clause 10.4.3 (a).

12.5.1.4.6 Record and document all settings and adjustments, if any, made to the boiler as recommended/required by manufacturer’s instruction manual for different combustion conditions or heat loads. These may include temperature setpoints, under and over-fire air adjustment, or other adjustments that could be made by an operator to optimize or alter combustion. All such settings shall be included in the report for each test run.

12.5.1.5 Monitor the average heat output rate on the load side of the heat exchanger based on water temperatures and flow. If the heat output rate over a 10-minute averaging period gets close to the limit of the target range, adjust the water flow through the heat exchanger to compensate. Make changes as infrequently as possible while maintaining the target heat output rate.

12.5.2 Test Fuel Charge Adjustment. It is acceptable to adjust the test fuel charge (i.e. reposition) once during a test run if more than 60 percent of the initial test fuel charge weight has been consumed and more than 10 minutes have elapsed without a measurable (1 lb or 0.5 kg) weight change while the operating control is in the demand mode. The time used to make this adjustment shall be less than 60 seconds.

12.5.3 Test Run Completion
12.5.3.1 At the end of the Phase 10 period, as prescribed in Sectin 12.4.5, stop the particulate sampling instruments and Overall Efficiency (SLM) measurements, and record the run time and all final measurement values.

12.5.3.2 At the end of the test run, continue to apply a thermal load to the heater to allow the remaining fuel to safely be consumed. No measurements are required during this period.

12.5.4 Heat Output Capacity Validation. During Phase 9, the unit must produce an average heat output rate that is within ±10% of the manufacturer's rated heat output capacity. If average heat output is not within these limits, the manufacturer's rated heat output capacity is considered not validated and must be changed. In such cases, the testing may be redone using an adjusted heat output capacity if requested by the manufacturer. If the manufacturer's rated heat output capacity is increased as a result of this requirement, the tests done in Phases 4,5, and 8 may still meet the requirements of Table 1, and a re-test may not be required.

12.5.5 Failure to Operate at All Test Conditions. If an appliance cannot be operated in all of the test Phases without stopped fuel combustion or without achieving a boiler temperature that causes the safety high limit to be activated, requiring a manual reset, the test is a failed run and the unit cannot be tested with this method.

12.5.6 Modification to Measurement Procedure in EPA Method 28 WHH and the standards referenced therein on Averaging Period for Determination of Efficiency by the Stack Loss Method. The methods currently defined in Method 28 WHH allow averaging over 10-minute time periods for flue gas temperature, flue gas CO_2, and flue gas CO for the determination of the efficiency with the Stack Loss Method. However, under some cycling conditions the "on" period may be short relative to this 10-

minute period. For this reason, during cycling operation the averaging period for these parameters may not be longer than the burner on period divided by 10. The averaging period need not be shorter than one minute. During the off period, under cycling operation, averaging periods as specified in EPA Method 28 WHH and the standards referenced therein may be used. Where short averaging times are used, however, the averaging period for fuel consumption may still be at 10 minutes. This average wood consumption rate shall be applied to all of the smaller time intervals included.

12.6 Hydronic Heater Jacket Surface Temperature
During Phase 9, the surface temperature of the boiler jacket shall be determined using an IR camera meeting the requirements of Section 6.13. To set the emissivity for the surface temperature determination, a direct measurement of the surface temperature shall be made at a minimum of one point using a direct contact surface temperature probe with an accuracy of ± 1 °F. The IR camera shall be used to simultaneously measure the temperature just adjacent to this point and the emissivity adjusted until these two temperatures match. The directly measured point temperature and IR image shall be recorded for potential readjustment of the emissivity in later analysis of the IR images using common IR image software. (*informational note – "FLIR Tools" is one example of such software*). For the jacket loss determination, surface temperature of the 4 sides and top of the hydronic heater must be recorded. It is assumed that the loss from the bottom of the boiler is negligible. Each of the 5 sections shall be divided into subsections for analysis of jacket loss as needed such that the maximum difference between the highest and lowest temperature in any subsection does not exceed 30 °F. The area and average temperature of each section and subsection shall be recorded.

13.0 Calculation of Results

13.1 Nomenclature
Aj_k = Area of the jacket in section or subsection k (ft^2)
Cco_d_j = Average CO concentration in the dilution tunnel during Phase j (ppm)
Ecoj = Total CO emissions during Phase j (g)
Ert_j = Total PM emission based on real time measurement during Phase j. See Appendix A. (g)
Et = Total PM emission – entire test period, from dual filter trains (g)
Et_j = Total PM emission during Phase j, from dual filter trains (g)
$EFco_j$ = Emission factor for carbon monoxide during Phase j (lb/MMBtu output)
EFAco = Annual average emission factor for carbon monoxide (lb/MMBtu output)
$EIco_j$ = Emission index for carbon monoxide during Phase j (g/kgfuel)

EIAco = Annual average emission index for carbon monoxide (g/kgfuel)
$ERco_j$ = Emission rate for carbon monoxide during Phase j (g/hr)
ERAco = Annual average emission rate for carbon monoxide (g/hr)
$EFpm_j$ = Emission factor for particulates during Phase j (lb/MMBtu output)
EFApm = Annual average emission factor for particulates (lb/MMBtu output)
$EIpm_j$ = Emission index for particulates during Phase j (g/kgfuel)
EIApm = Annual average emission index for particulates (g/kgfuel)
$ERpm_j$ = Emission rate for particulates during Phase j (g/hr)
ERApm = Annual average emission rate for particulates (g/hr)
F_j = weighting factor for Phase j
HHV = Higher Heating Value of dry fuel = 8600 Btu/lb
HHVaf = Higher Heating Value of the as-fired fuel (Btu/lb)
Lj_k = Loss rate from each jacket section or subsection (Btu/hr)
Lj = Total jacket heat loss rate (Btu/hr)
MC = Average moisture content of the as-fired fuel, dry basis (lb moisture/lb dry fuel)
Qin_j = Total heat input from consumed fuel during Phase j (Btu)
$Qstd_j$ = Average gas flow in the dilution tunnel from ASTM E2515 during Phase j(dscf/min)
Tj_k = Average temperature of jacket section or subsection j during jacket loss test
Tr_j = Average room temperature during Phase j
$Wfuel_j$ = mass of (wet) fuel consumed during Phase j (lb)
WfuelT = total mass of (wet) fuel consumed in a test (lb)
ηSLM_j = Efficiency based on Stack Loss Method during Phase j (%)
ηT_j = Thermal efficiency based on Stack Loss Method and Jacket Loss during Phase j (%)
ηAT = Annual average thermal efficiency based on Stack Loss Method and Jacket Loss (%)
Θ_j = Duration of Phase j (hrs)

13.2 After the test is completed, determine the particulate emissions E_T in accordance with EPA Method 28 WHH and the standards referenced therein.

13.3 Determine the heat input during each phase.

$$Qin_j = Wfuel_j \bullet \frac{HHV}{\left(1 + \frac{MC}{100}\right)}$$

The weight of fuel consumed during each phase is determined from the change in mass of the unit on the weigh scale.

13.4 Determine the efficiency based on the stack loss method for each phase. η_{SLMj} is determined for each Phase using the measurements described in Sections 6.9, 6.10, and 6.11.

Method to Calculate Stack Loss Efficiency of a Wood Appliance
Basis – 100 kg of dry fuel
Inputs:

- Ultimate Analysis of dry fuel (% by weight)
  - Carbon – CA
  - Hydrogen – HY
  - Oxygen – OX
- Moisture Content – mass of water per mass of dry fuel – Mcdb
- Ambient Humidity Ratio – mass of water per unit mass of dry air – ω
- Flue gas temperature (F) – Ts
- Room temperature (F)-Tr
- CO in the dry flue gas (ppm) – PPMco
- CO_2 in the dry flue gas (%) – PCTCO2
- Higher heating value of the dry fuel (lb/MMBtu) – HHV

Combustion Balance Equation:

$$C_xH_yO_z + (1+\alpha)\bullet\gamma(O_2 + 3.76N_2) + \left[\omega\bullet\left(\frac{(1+\alpha)\bullet\gamma\bullet(32+3.76\bullet 28)}{18}\right) + \frac{Mcdb}{18}\right]H_2O$$

$$\rightarrow (x-\beta)CO_2 + \beta CO + (\alpha\bullet\gamma + \frac{\beta}{2})O_2 + (1+\alpha)\bullet\gamma\bullet 3.76N_2 + \left[\frac{y}{2} + \omega\bullet\left(\frac{(1+\alpha)\bullet\gamma\bullet(32+3.76\bullet 28)}{18}\right) + \frac{Mcdb}{18}\right]H_2O$$

Where:

$x = CA/12$

$y = HY$

$z = OX/16$

$\gamma = (x + \frac{y}{4} - \frac{z}{2})$

$\alpha =$ excess air parameter, e.g. if $\alpha =$ 0.5 there is 50 % excess air

From this:

$$PPMco = \frac{1E6\bullet\ \beta}{x + \left(\alpha\bullet\gamma + \frac{\beta}{2}\right) + (1+\alpha)\bullet\gamma\bullet 3.76}$$

$$PCTCO2 = \frac{100 \bullet (x - \beta)}{x + \left(\alpha \bullet \gamma + \frac{\beta}{2} \right) + (1 + \alpha) \bullet \gamma \bullet 3.76}$$

With flue gas CO and CO_2 measured, these two equations can be solved simultaneously for β and α.

$$\beta = \frac{100 \bullet x \bullet PPMco}{1E6 \bullet PCTCO2 \bullet +100 \bullet PPMco}$$

$$\alpha = \frac{\frac{100 \bullet (x - \beta)}{PCTCO2} - x - \frac{\beta}{2} - 3.76 \bullet \gamma}{4.76 \bullet \gamma}$$

Calculation of the Molar Coefficient for Each of the Products

For the assumption of 100 kg of dry fuel, this is the number of mols of each product for the input conditions

$MFCO = \beta$ Molar Coefficient for CO

$MFCO2 = x - \beta$ Molar Coefficient for CO_2

$MFH2O = \frac{\gamma}{2} + \frac{Mcdb}{18} + \frac{\omega \bullet (1 + \alpha) \bullet \gamma \bullet (32 + 3.76 \bullet 28)}{18}$ Molar Coefficient for H_2O

$MFO2 = \alpha \bullet \gamma + \frac{\beta}{2}$ Molar Coefficient for O_2

$MFN2 = (1 + \alpha) \bullet \gamma \bullet 3.76$ Molar Coefficient for N_2

Heat Capacity of Exhaust Products

The general equation for representing how the heat capacity of the exhaust products varies with temperature is:

$$C = A \bullet Tk + B$$

Where:

C = heat capacity J/mol K or kJ/kgmol K

A and B are constants

Tk = Temperature in °K

The values for A and B for the exhaust components are provided in the table below

Component	A	B
CO	.0026	28.42
CO2	.031	28.55
H2O	.0083	31.32
O2	.0089	26.72
N2	.0037	27.94

For each component, heat capacity is calculated at the stack temperature and at room temperature. The average of these is used to calculate sensible heat loss. Heat capacity data has been obtained from: E.W. Lemmon, M.O. McLinden and D.G. Friend, "Thermophysical Properties of Fluid Systems" in NIST Chemistry Web Book, NIST Standard Reference Database Number 69, Eds. P.J. Linstron and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg, MD, 20899, https://doi.org/10.18434/T4D303, (retrieved November 4, 2018).

Calculation of Heat Losses for Efficiency Determination

$HHVJ = HHV \bullet 2.326$ Higher heating value in kJ/kg (conversion from Btu/lb)

$LHWV = 43969$ Latent heat of water vapor in kJ/kgmol

$Llat = MFH2O \bullet LHWV / HHVJ$ Heat loss in latent heat of water vapor, % of input energy

$Lco = MFCO \bullet 282993 / HHVJ$ Heat loss in chemical energy in CO, % of input energy

$Lsens = (MFCO \bullet C\_COm + MFCO2 \bullet C\_CO2m + MFH2O \bullet C\_H2Om + MFO2 \bullet C\_O2m$

$+ MFN2 \bullet C\_N2) / HHVJ$ Heat loss in sensible heat in flue gas, % of input energy

$Efficiency = 100 - Llat - Lco - Lsens$ Stack loss efficiency, %

13.5 Determine the Jacket Loss Rate for Each Section and Subsection

From the surface and room temperature measurements made, the heat loss rate for each section and subsection shall be calculated using the methodology in ASHRAE Standard 103-2017 Section 8.6.1. This includes the convective and radiative loss rate for each section and subsection based on surface and room temperatures.

13.6 Determine the Total Jacket Loss Rate for Phase 9

$Lj = \sum_k Lj_k$ Total jacket loss rate (Btu/hr)

13.7 Determine the Thermal Efficiency for Each Phase

$$\eta T_j = \eta SLM_j - \frac{100 \bullet \left(Lj \bullet \Theta_j\right)}{Qin_j}$$

13.8 Determine the PM Emission Mass for Each Phase

$$Et_j = Et \bullet \frac{Ert_j}{\sum_m Ert_m}$$

13.9 Determine the PM Emission Factor for Each Phase

$$EFpm_j = \frac{E_j \bullet \frac{1,000,000}{453.6}}{Qin_j \bullet \eta T_j}$$ (lb/MMBtu output)

13.10 Determine the PM Emission Index for Each Phase

$$EIpm_j = \frac{E_j}{Wfuel_j \bullet 0.4536}$$ (g/kg fuel)

13.11 Determine the PM Emission Rate for Each Phase

$$ERpm_j = \frac{E_j}{\Theta_j}$$ (g/hr)

13.12 Determine the CO Emission for Each Phase

$$CO_j = Qstd_j \bullet \Theta_j \bullet Cco\_d_j \bullet \frac{28}{28.96} \bullet 60 \bullet 0.0752 \bullet 453.6 \bullet 1,000,000$$ (g)

13.13 Determine the CO Emission Factor for Each Phase

$$EFco_j = \frac{CO_j \bullet \frac{1,000,000}{453.6}}{Qin_j \bullet \eta T_j}$$ (lb/MMBtu output)

13.14 Determine the CO Emission Index for Each Phase

$$EIco_j = \frac{CO_j}{Wfuel_j \bullet 0.4536}$$ (g/kg fuel)

13.15 Determine the CO Emission Rate for Each Phase

$$ERco_j = \frac{CO_j}{\Theta_j}$$ (g/hr)

13.16 Weighting Factors. Table 2, below provides the weight factors to be used for each phase (F_j)

Table 2 – Phase Weighting Factors

Phase	F_j
1	0.1
2	0.1
3	0.0
4	0.25
5	0.05
6	0.05
7	0.1
8	0.25
9	0.05
10	0.05

13.17 Weighted Annual Parameters
Using the values in Table 2, weighted values for the emission and efficiency parameters shall be calculated as:

$$EFAco = \sum_j F_j \bullet EFco_j$$

$$EIAco = \sum_j F_j \bullet EIco_j$$

$$ERAco = \sum_j F_j \bullet ERco_j$$

$$EFApm = \sum_j F_j \bullet EFpm_j$$

$$EIApm = \sum_j F_j \bullet EIpm_j$$

$$ERApm = \sum_j F_j \bullet ERpm_j$$

$$\eta AT = \sum_j F_j \bullet \eta T_j$$

13.18 Proportional Rate Variation. Calculate the proportional rate (PR) for each 10-minute period following the methods of EPA Method 5G for the filter trains and the TEOM sampling system. If no more than 10 percent of the PR values for all the intervals exceed 95 percent ≤ PR ≤ 105% and if no PR value for any interval exceeds 90 percent ≤ PR ≤ 110 percent the results are acceptable.

14.0 Report

14.1.1 The report shall include the following:

14.1.2 Name and location of the laboratory conducting the test.

14.1.3 A description of the appliance tested and its condition, date of receipt and dates of tests.

14.1.4. A statement that the test results apply only to the specific appliance tested.

14.1.5 A statement that the test report shall not be reproduced except in full, without the written approval of the laboratory.

14.1.6 A description of the test procedures and test equipment including a schematic or other drawing showing the location of all required test equipment. Also, a description of test fuel sourcing, handling and storage practices shall be included.

14.1.7 Documentation of details of deviations from, additions to or exclusions from the test method, and their data quality implications on the test results (if any), as well as information on specific test conditions, such as environmental conditions.

14.1.8 A list of participants and their roles and observers present for the tests.

14.1.9 Data and drawings indicating the fire box size and location of the fuel charge.

14.1.10 Drawings and calculations used to determine firebox volume.

14.1.11 Information for each test run fuel charge including piece size, moisture content and weight.

14.1.12 All required data and applicable blanks for each test run shall be provided in spreadsheet format both in the printed report and in a computer file such that the data can be easily analyzed and calculations easily verified. Formulas used for all calculations shall be accessible for review.

14.1.13 Tables 1A (for each test), 1B (for each test) and 1Cmust be used for presentation of results in test reports. This test protocol is to be run three times for each unit being tested. The average in table 1C is a simple average of the annual averages from each of the three test runs.

14.1.14 A statement of the estimated uncertainty of measurement of the emissions and efficiency test results.

14.1.15 A plot of CO emission rate in grams/minute vs. time, based on 1-minute averages, for the entire test period, for each run.

14.1.16 Raw data, calibration records, and other relevant documentation shall be retained by the laboratory for a minimum of 7 years.

15.0 Precision and Bias

15.1 Precision − It is not possible to specify the precision of the procedure in this test method because the appliance operation and fueling protocols and the appliances themselves produce variable amounts of emissions and cannot be used to determine reproducibility or repeatability of this test method.

15.2 Bias − No definitive information can be presented on the bias of the procedure in this test method for measuring solid fuel burning hydronic heater emissions because no material having an accepted reference value is available.

16.0 Keywords

16.1 Solid fuel, hydronic heating appliances, wood-burning hydronic heaters, load profile

Table 1A Data Summary Part B Run _____ (Complete for each of the three test runs)

Phase	Target Load	Actual Load	Phase Duration	Wood Consumed	Stack Loss Efficiency	Thermal Efficiency	Min Water Return Temp.			
	Btu/hr	Btu/hr	hours	lbs	%	%	°F			
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Table 1B Data Summary Part B Run _____ (Complete for each of the three test runs)

Phase	EFco	EIco	ERco	EFpm	EIpm	ERpm	E_j	Ert_j		
	Lb/MMBtu output	g/kg fuel	g/hr	Lb/MMBtu output	g/kg fuel	g/hr	g	g		
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
Weighted Average										

Table 1C Data Summary – Annual Averages

	EFAco	EIAco	ERAco	EFApm	EIApm	ERApm	Thermal Efficiency ηTA
	Lb/MMBtu output	g/kg fuel	Lb/hr	Lb/MMBtu output	g/kg fuel	Lb/hr	%
Test 1							
Test 2							
Test 3							
Average of three tests							

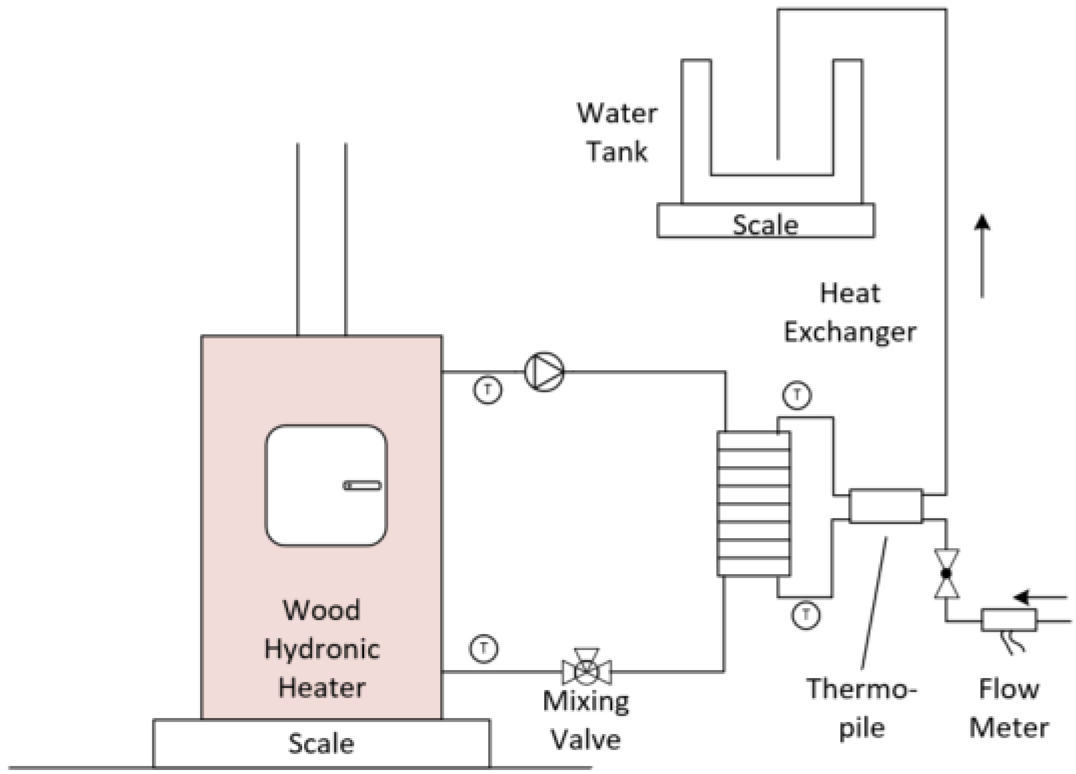

Figure 1. Appliance Piping Arrangement

Appendix A
Standard Operating Procedure for TEOM Instrument
Prepared by NESCAUM, November 2018

Appendix A. Standard Operation Procedures for Thermo 1405 TEOM®
for use in a dilution tunnel

Section 1. Introduction

This document covers operation concepts and procedures for use of the TEOM model 1405 to measure and report continuous particulate matter (PM) measurements in EPA Method 5G dilution tunnel or equivalent dilution method. The Thermo-Scientific model 1405 TEOM is designed for ambient real-time PM measurements. It is an inertial microbalance - a true continuous mass measurement method with resolution of 0.01 µg (0.00001 mg). The TEOM is highly configurable, allowing the instrument to be "tuned" to best meet the needs of a specific application. The version of the TEOM used here is the simplest, without any sample conditioning options such as "SES" or "FDMS". For dilution tunnel PM measurements, the TEOM flows, temperatures, and timing settings are changed from the normal ambient settings. There are no hardware modifications needed. Instrument manuals, software, and related support information are available from the NESCAUM TEOM document collection.1

Flow Setting
Recommended flow setting is 0.5 liters per minute (lpm). If very low tunnel PM concentrations, consistently less than 5 mg/m^3 are expected, higher settings of 1 to 3 lpm can be used. Higher flow gives better sensitivity but shorter filter life. The flow settings should be set to provide the needed sensitivity but also ensure reasonable filter life. For appliances where heavy loading is anticipated a setting of 0.5 lpm shall be used. Appliances with lighter PM loading can use a setting of 1 or 2 lpm depending on the intended use of the data; high time resolution (10 to 15 seconds instead of 1 minute) requires higher flows to achieve the same sensitivity. The TEOM flow must be constant during a test run – it can not be changed while sampling.

Filter Temperature Zones Settings
The three TEOM filter temperature zones are normally set to 30 C (86 F). Temperatures can be set somewhat higher if laboratory temperature is expected to be over 80 F, but no higher than 33C (91F). Temperatures can not be changed during a sampling run. The TEOM filter temperature setting is always a trade-off between stability during highly dynamic burn conditions, minimizing loss of semi-volatile organic carbon mass, and avoiding condensing conditions at the filter temperature. Water is considered a semi-volatile mass (SVM) component, but standard practice is to minimize the amount of water measured as part of the PM. Based on

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1 The TEOM manual is referenced in this SOP, and is available here:
https://www.thermofisher.com/order/catalog/product/TEOM1405
Additional support documents are at https://drive.google.com/open?id=0B4duMFtoHVUENk9uemxsbHRJczA

current data, 30 C represents an appropriate setting assuming the dilution tunnel air dewpoint is controlled within reasonable limits (less than 30C).

TEOM Filter Dynamics

Rapid changes in the sample matrix (PM, gases, water vapor) may result in transient TEOM PM (positive or negative) concentration excursions. This is not an instrument malfunction; it is a result of the mass dynamics occurring on both the TEOM and filter pull filters. The TEOM filter material (Emfab), temperature (30 C), and filter loading are similar to the gravimetric sample train rate (the TEOM filter face velocity is 6.3 cm/sec at 0.5 lpm). Thus, the filter pull PM and TEOM PM measurements should be in agreement and highly correlated if both sampling systems are working properly.

While TEOM PM transients from filter dynamics are usually no longer than 1 or 2 minutes, there can be situations where these filter dynamics can result in data quality issues for an extended period of time. One example is a very rapid transition (a few minutes) from a very dirty burn (as much as 300 mg/m^3 in the tunnel) to a very clean burn (a few mg/m^3 or less), as experienced with some devices during startup or fuel reloads. For that scenario, it may be necessary to change the TEOM filter after a high loading phase to avoid a prolonged period of a large negative bias to the TEOM PM due to loss of SVM off of the filter from the high loading phase. See Section 6 for more information on when to do pre-emptive filter changes (filter changes done to prevent or minimize negative TEOM data).

The TEOM configuration used here allows for fast filter changes with minimal data loss (typically a few minutes) and does not require flows and temperatures to be within predefined instrument limits for valid data for PM concentrations to be reported. Critical instrument parameters are stored with the concentration data and can be used to invalidate data during review and processing as needed.

Instrument Software

RPComm (serial port interface) is the legacy TEOM program and can be used to display the last 15 minutes of data on a graph and read all key operating parameters easily. ePort (ethernet interface) is used to control the instrument remotely and to download data. Both can be used at the same time.

Section 2. Overview of Routine Operation Procedures for Thermo 1405 TEOM

This section is a summary of routine operating procedures.

A. *Quality Assurance checks to be completed after initial installation, and routinely every 6 months:*

1. Modify system settings as detailed in Section 10
2. Perform KO check detailed in Section 5
3. Perform leak check detailed in Section 5

B. *Routine procedures before every test run to be conducted 2-3 hours prior to testing.*

1. Set TEOM filter temperature for the run. Changing this setting requires at least one hour before valid data can be collected. Detailed instructions on this element can be found in Section 3.
    a. The TEOM filter temperature must be at least 1 C above the hottest lab temperature expected during the test. The normal setting is 30 C (84 F) but may be set as high as 33 C (91 F).
    b. All three (3) temperatures zones - cap, air, case – must be set to the same value.

2. Set TEOM flow settings for the run. Changing this setting requires at least one hour before valid data can be collected. Detailed instructions on this element can be found in Section 4. TEOM flow can only be changed before a test run – it can not be changed during a run when the TEOM is sampling.
    a. Set flow
        i. Anticipated tunnel concentrations >5 mg/m^3: 0.5 lpm
        ii. Anticipated tunnel concentrations <5 mg/m^3: 1-3 lpm
    b. Calibrate TEOM flows. This step must be completed whenever the flow is changed.

3. Check the TEOM time.
    a. Changing the time causes an instrument reboot and loss of up to an hour of data.
    b. See note below.

4. Initial filter change
    a. Install a clean filter before each run.
    b. Use the “Advanced” filter change mode.
    c. Perform an external flow check with the clean filter or before the start of a run.
    d. The net flow reading shall be within 2% of the TEOM flow setpoint.

One hour before testing

Check TEOM settings for appropriate temperature, flow and time settings. Perform an external flow check as detailed in Section 4 and record the results. For valid results the flow check should be within 2% of the TEOM flow setpoint.

Testing Operations

1. Before initiating the test, run the TEOM while sampling dilution tunnel air for at least 5 minutes. The change of pressure in the tunnel can cause a transient TEOM response.

2. Filter Changes are done pre-emptively as described in Section 6 and whenever the TEOM filter loading reaches 130%, as reported on the TEOM, or when the sample flow starts to drop. The 1405 does NOT have any clear visual warning that the filter needs changing, but it is possible to use the TEOM digital outputs (relay contact closures) to trigger an external alarm at any desired filter loading.

   The "Advanced" filter change wizard mode shall be used to eliminate long equilibration period after the change; this stops the tapered element oscillation and simplifies filter changes. Detailed information on performing filter changes during testing is provided in Section 6 of this document.

3. At the end of the test perform an external flow check as detailed in Section 4 and record the result. For valid results flow check should be within 2% of the TEOM flow setpoint.

4. Download the test data using either the Thermo ePort software (preferred), RPComm, or to a USB thumb drive. Note: the data format is different depending on how the data is downloaded. The ePort software download method is preferred since it follows the parameter order in the instrument setup. The other two methods do not.

Notes:

- It is normal for there to be "Warnings" present for the ambient T/RH sensors (not used). This is the only allowable warning once the system is warmed up and is in use for testing.

- When the TEOM is first turned on or rebooted, no data are recorded until the top of the next hour. If TEOM is not rebooted, data will be recorded regardless of instrument status.

- When the time is changed, the instrument reboots (after many seconds of being hung, with no information on the screen). When it reboots, no data are recorded until after the top of the next hour (see above).

- TEOM PM concentrations are in micrograms per cubic meter, at EPA STP (25C and 1 atmosphere) unless the instrument configuration is changed. Filter mass loading is in micrograms.

Section 3. Filter Temperature Adjustment SOP for 1405 TEOM

The TEOM filter temperature has the capacity to be set between 30 and 55 degrees C, however for testing purposes, the filter temperature should be set to between 30 and 33 C. If the temperature is too low (less than 1 C above room temperature), the instrument may not be able to maintain the temperature set-point, possibly resulting in loss of data. Temperatures higher than necessary may result in excessive loss of semi-volatile PM during sampling. There are three temperature settings - cap, air, case – that shall all be set to the same value.

Temperature Change Procedure.
The TEOM temperatures are set in the Instrument Conditions, Temperatures menu. Temperatures can not be changed during a sampling run.

Note: The **T-Air** temperature zone may take a long time (10 to 30 minutes) to stabilize, especially when the temperature is higher than the setpoint. If the "Case" temperature is within 0.1 C of the setpoint, data are valid.

Section 4. Sample Flow Check and Adjustment for the Thermo 1405 TEOM

Checking the Sample Flow.
The TEOM should be warmed up for at least 30 minutes before checking or adjusting the sample flow. The sample flow can not be changed during a test run. The sample flow should be checked at the sensor inlet with an external mass flow meter that reads in STP; that flow should be within 2 % of the flow on the TEOM display. Flow checks must be done:

A. at the start of every sampling day (with a clean filter),
B. at the end of the run (with the dirty filter), and
C. whenever the flow setting is changed.

Record the external flowmeter reading without flow as the zero and subtract that value from the flowmeter reading with flow to get the measured flow value.

If the post-test flow check (with a loaded filter) is lower than the initial flow check (with a clean filter), that is an indication of a possible leak. A leak test should also be performed whenever the flow check difference (between the TEOM display flow and the external flow meter flow) changes.

If the external flow (at EPA STP, with zero offset correction) is more than 5% off from the TEOM display flow, measure the flow without a filter in the TEOM. If the external flow check result is low with a filter but higher or correct without a filter, that is an indication of a leak.

If the flow is the same with and without a filter and out of spec, the flow calibration routine should be performed. This routine should also be performed whenever the sample flow setting is changed.

Flow settings.
The TEOM sample flow can be set to between 0.5 and 3.0 LPM (all flows are at EPA STP of 1 atm. and 25 C). Lower flow gives longer filter lifetime and less sensitivity. Higher flow gives

shorter filter lifetime and more sensitivity. The flow should be set to provide reasonable filter lifetime (typically at least 30 minutes) for any given test scenario, since about 4 minutes of data are lost when the filter is changed.

For most cases when sampling off a dilution tunnel, the flow should be set to 0.5 LPM. If a high loading burn (tunnel PM greater than 20 mg/m^3) is anticipated, the flow must be set to 0.5 LPM. Flows higher than 1 LPM shall only be used when very light loading is expected (tunnel PM consistently below 2 to 3 mg/m^3).

The sample flow is set in Instrument Conditions, Flows, Flow Rates. Flow is calibrated using the wizard at Service, Calibration, Flow Calibration (page 5-39 of the TEOM manual).

NOTE: The TEOM sample flow cannot be changed during a test run.

Section 5. Leak Test and KO Check Procedure for 1405 TEOM

The Leak Test and K0 Checks described here do not need to be done on a routine basis. They should be done at least every 6 months, or as needed for troubleshooting.

Leak Check
A leak test measures the flow as reported by the TEOM's flow sensor with the inlet closed off. The TEOM leak test flow measurement must be corrected for the TEOM flowmeter's zero offset. To conduct a flow check, follow the procedures below:

1. With the TEOM warmed up for at least 30 minutes, read the TEOM reported flow with the pump turned off. This is the flowmeter zero reading.
2. Close off the inlet to the TEOM with a brass swage cap.
3. Turn on the TEOM pump.
4. Wait one minute and read the TEOM flow.
5. The leak test value is the difference between the reading without and with the pump on.
6. The leak test should be no greater than 0.05 lpm (net value).
7. Turn the pump off and remove the brass swage cap from the TEOM inlet.

K0 Check
In addition to routine pre- and post-sampling flow checks, a K0 check is another test that shall be completed to validate proper operation of the TEOM. K0 checks confirm the calibration factor for the tapered element mass transducer. It is done once per year and as needed. See page 5-50 of the manual.

Section 6. Filter Change Procedure for 1405 TEOM

The TEOM measures the pressure drop across the filter as % of maximum (~ 100 to 130 %), shown on the instrument=s display. A clean filter has a loading of about 5% at 0.5 LPM and ~ 7% at 1 LPM. Filter lifetime will vary widely depending on the PM concentrations being sampled. At very high PM concentrations (several hundred mg/m^3), filter lifetime may be only 10 to 15 minutes. Under typical sampling conditions, lifetime is at least 30 minutes and up to an hour or more with concentrations in the 20 to 50 mg/m3 range. With care, filter changes can be done such that only a few minutes of data are lost.

TEOM filters are changed based on two criteria:
1. The filter must always be changed before the filter mass loading becomes too high and the filter plugs and the sample flow drops.

2. Filters can be changed pre-emptively (before plugging) when TEOM PM data go negative due to heavy filter loading followed by a clean burn period. When data from individual burn phases is desired, pre-emptive filter changes should be done whenever persistent negative TEOM data are observed.

The following are filter handling procedures that shall be followed:

A. Unused clean filters should be stored in the original box, with the silica gel desiccant.
B. Two clean filters should be stored in the mass transducer.
C. Filters should only be handled with the filter change tool that is stored inside the TEOM cabinet.

<u>Filter change procedure.</u> The TEOM manual has illustrated procedures for filter changes starting on page 5-6. Try to minimize the time the mass transducer is open to minimize the time needed to re-stabilize after the filter change.

1. The filter change menu can be located by pushing the Service, Maintenance, Replace Filter. Select Advanced option, and then Next to proceed.

2. Open the TEOM cabinet door, open the box of clean filters, and open the mass transducer. Remove the old filter by sliding the filter tool onto the filter and pulling straight out. Do not twist the tool (to prevent damage to the glass tapered element).

3. Pick up a new filter (stored inside the mass transducer) with the tool. Position it directly over the tapered element and push the filter on gently. Once the filter is on, remove the tool from the filter and fully seat the filter by pushing firmly straight down on the filter with the bottom of the tool (see section 3 of the manual for more information). Store another new filter in the mass transducer.

4. Close the mass transducer, replace the filter box cover, and close the cabinet. Restart the TEOM by completing the filter change wizard.

5. If the PM concentration as read on the RPComm graph hasn't stabilized within 5 minutes, or if the Frequency is close to 0 (~10 instead of a few hundred Hz) the filter may need to be reseated or is defective, or the sensor latch is not closed properly. Repeat the filter change "advanced" procedure and take the filter off and re-seat it. Push it on firmly with the back of the filter tool and make sure the sensor is properly closed and latched. After two attempts, restart the procedure with another new filter.

Note: the PM concentration on the TEOM display will read 0 after a filter change until the top of the next hour. When valid data are being collected, the RPComm graph will indicate the concentration, and the "Total Mass" on the TEOM display will read something other than "0.00".

► There is one exception to this: after an instrument reboot for any reason (including setting the time), data are not stored until after the top of the next hour, even if the RPComm graph is showing data and the Total Mass is not 0.

Section 7. Filter Change Protocol for Method Validation: Matching Filter Pull and TEOM Filter Face Velocities and Mass Loadings for Control of SVOC Loss

Reserved for future use.

Section 8: Data Storage and Download

The TEOM shall be set to store data every 10 seconds. There is storage for several days of data at this storage interval. Data can be downloaded while the TEOM is running.

Data are usually downloaded with the ePort software but if needed can also be downloaded to a USB thumb drive or RPComm. Caution: the data format is different from the ePort download data format when using RPComm or USB drive downloads. The data file is in .CSV format for importing into a spreadsheet.

When ePort is used, data parameters are saved as follows:
1. Time Stamp
2. PM-2.5 raw MC
3. PM-2.5 MC
4. PM-2.5 total mass
5. PM-2.5 30-Min MC
6. Operating mode
7. System status
8. PM-2.5 flow rate
9. PM-2.5 TEOM filter load
10. PM-2.5 TEOM filter pressure
11. Case temperature
12. Cap temperature
13. PM-2.5 air tube temperature
14. Enclosure temperature
15. PM-2.5 TEOM noise
16. PM-2.5 TEOM frequency
17. Vacuum pump pressure

The key parameters for data validation and analysis are:
1. Time – reported as the end of the average interval
2. PM2.5 raw - PM2.5 raw is the same as PM2.5 MC except it is always reported even when

the instrument status is invalid. This minimizes loss of data but also requires manual editing of the data file to remove invalid PM concentrations based on review of the data and critical parameters such as flow and temperatures. Concentration is µg/m^3. A zero value for Mass Conc indicates no data.

3. PM2.5 total mass - the mass loading on the TEOM filter in µg.
4. PM2.5 flow rate - Flow is SLPM unless something else is used in the instrument configuration.
5. PM2.5 TEOM filter load - filter loading as % of maximum.
6. Case temperature, in degrees C.
7. Noise is a data stability metric and should normally be less than 0.10 when pm concentrations are low or zero.

Section 9. Data Validation and Calculations

TEOM data are recorded every 10 seconds to minimize data loss during filter changes. Data validation is performed on the 10 second data and then usually averaged up to 1-minute intervals for reporting use.

TEOM data are valid when:

1. All flows and temperatures are defined operating ranges specified in this document.
2. "Case" temperature is stable and within 0.1 deg C of set-point. Other temperatures can be off as long as the Case temperature is stable and close to the set-point.
3. Flow reported by the instrument should be within 5% of the flow setpoint.

The "Raw MC" PM concentration parameter is reported regardless of instrument conditions and thus includes invalid data that need to be removed during data validation. Normally the only data that need to be removed are during a filter change that occurs during a run. When a filter is changed, the last valid concentration value is repeated until new valid data are available. These repeating data are usually removed manually during validation and considered as "missing" data.

Note: For cumulative PM emission measurements (total grams of PM emitted during a burn phase or run), missing data shall be filled in with best-estimates based on the 1-minute PM concentrations immediately before and after the filter change. Otherwise, the effective emissions for the period with missing data are zero, creating a negative bias in the measurement.

It is common for the TEOM PM concentration to be somewhat negative during some burn phases. This happens when the TEOM filter mass loading is large and PM emissions are relatively low (e.g., a clean burn phase that follows a dirty burn phase), and the TEOM filter loses mass. To some extent, this is controlled by pre-emptive filter changes as described in Section 6. Small negative concentration up to a few mg/m^3 can still occur however. To minimize measurement bias, these small negative concentrations should be set to 0 during data validation. Large and rapid negative data swings in concentration may indicate a problem with the instrument and should normally be considered invalid or missing data (not set to 0).

The output of the TEOM is PM concentration in the dilution tunnel, in µg/m^3 at 25 C and 1 Atmosphere (29.92 inches Hg) pressure. To correct TEOM data to the test or reporting conditions use the following:

PM at local T and P = PM at STP * (298/T) * (P/29.92)

The 1-minute TEOM PM concentration is converted into grams/hour using the tunnel flow as follows:

g/h = 0.000001699 * tunnel flow (in CFM) * PM concentration (in µg/m^3)

The values used for tunnel flow shall be the actual measured values, at intervals of no more than 10 minutes.

Total grams PM emitted is calculated by multiplying the average g/h rate for the test period of interest times the number of hours of that test period.

TEOM data from different burn phases is used to apportion the PM emission rate (g/h) measured by a Method 5G sample train to each burn phase using the TEOM results as follows.
1. Convert the TEOM PM to g/h data as described above.
2. Calculate the average TEOM g/h for the entire test run.
3. Calculate the average TEOM g/h for each of the burn phases.
4. Calculate the % of TEOM g/h for each burn phase relative to the TEOM g/h for the entire run.
5. Apportion the 5G run average g/h to each burn phase using the TEOM % for each phase from step 3.

Note: since actual measured tunnel flows are used to convert TEOM data into g/h, tunnel flow does not need to be controlled other than what is necessary to maintain proportionality between tunnel flows and filter flows.

Section 10: TEOM Configuration Changes for Fast Response and High PM Concentrations, and List of TEOM Parameter Configuration Values.

These settings are for the 1405 TEOM as used in this application that are different from instrument default settings. See the 1405 manual for detailed information on how to change these values.

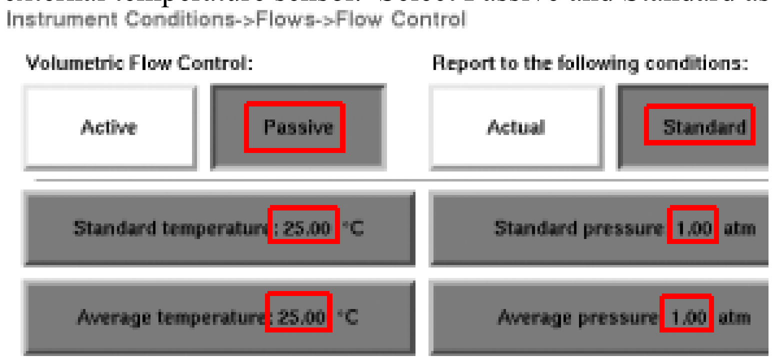
1. Remove the A and B factors [+3 and x1.03] that are used for PM10 FEM status. "Mass Constant A" is set to zero, and "Mass Constant B" is set to 1.00.

2. Change system filtering and wait time settings:
TM (Total Mass Avg time) from 300 to 15 seconds
MR-MC (Mass Rate/Mass Conc Avg time) from 300 to 15 seconds
Wait Time from 1800 to 0 seconds (disabled)

3. Change the sample flow from 3.0 to 0.5 lpm. The bypass flow is set to 0.

4. Change all 3 temperature zones [Case, Air, Cap] to 30 C.

5. Set both the “Avg” and “Std” T/P to 25 C / 1 atm - this is the default for systems without the external temperature sensor. Select Passive and Standard as shown below.



6. Change the Data Storage interval to 10 seconds.

A complete list of 1405 TEOM Settings that are modified from instrument defaults are listed below:

PRC	Description	Config Value	Unit		
12	storage interval	10	sec		
28	system wait time	0	sec		
35	mass average time	15	sec	See also PRC392 -- MRMC	
48	case temperature set point	30	Deg C or higher as needed to maintain a stable case T		See also PRC 115 -- air tube T
59	cap temperature set point	30	Deg C or higher as needed to maintain a stable case T		
74	average temperature set point	25	C	These are for reporting PM at EPA STP	
75	standard temperature set point	25	C	These are for reporting PM at EPA STP	
76	average pressure set point	1	atm	These are for reporting PM at EPA STP	
77	standard pressure set point	1	atm	These are for reporting PM at EPA STP	
91	bypass flow mass set point	0		Can be used as a baseline param for rpcomm plots.	
115	TEOMA air tube set point	30	Deg C, or higher as needed to maintain a stable filter T; see also PRC 48 and 59.		
136	analog output1 minimum	-5000	optional -- ug/m3 as needed for RPComm plot scaling		
144	analog output1 maximum	50000	optional -- ug/m3 as needed for RPComm plot scaling		
227	TEOMA flow set point	1	lpm; or 0.5 to 2 lpm as needed; flow must be recalibrated if changed!		
392	MRMC average time	15	sec		
407	TEOMA mass constant A	0			
408	TEOMA mass constant B	1			
	Note: all 3 temperatures must be set to the same value.				

Data Logging Parameters.

prc	description	var name in data file	Unit
244	raw mass conc	TEOMAMCRaw	ug/m3
245	mass conc	TEOMAMC	ug/m3
243	total filter mass loading	TEOMATotalMass	ug/m3
7	operating mode	OperatingMode	#
8	system status	StatusCondition	#
225	flow rate (STP)	TEOMAFlowMass	lpm
241	filter pressure	TEOMAFilterPressure	raw
242	filter load %	TEOMAFilterLoad	% of max
47	case temperature	CaseHeatTemp	C
58	cap temperature	CapHeatTemp	C
237	air tube temperature	TEOMAAirTubeHeatTemp	C
258	noise	TEOMANoise	ug
257	frequency	TEOMAFrequency	Hz