
Note: This method does not include all the specifications (e.g. equipment and supplies) and procedures (e.g., sample and analytical) essential to its performance. Some material is incorporated by reference from other methods. Therefore, to obtain reliable results, persons using this method shall have a thorough knowledge of at least the following EPA Tests

- Method 1 - Sample and Velocity Traverses for Stationary Sources
- Method 2 - Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)
- Method 3 – Gas Analysis for the Determination of Dry Molecular Weight
- Method 4 – Determination of Moisture Content in Stack Gases
- Method 5G – Determination of Particulate Matter from Appliances (Dilution Tunnel Sampling Location)
- Method 10 - Carbon Monoxide - Instrumental Analyzer

1. **Scope and Application**

1.1. This test method applies to automatic feed, wood-fired hydronic heating that utilizes an external buffer tank(s) (sometimes called thermal storage) as integral to the appliance operation. The units typically transfer heat through the 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. This test method measures particulate matter (PM) emissions, carbon monoxide, and delivered heating efficiency at specified heat demands based on the appliances rated heat capacity.

1.3. Particulate emissions are measured by the dilution tunnel method as specified in ASTM E2515 Standard Test Method for Determination of Particulate Matter Emissions Collected in a Dilution Tunnel using only Emfab Pallflex filters. Additional particulate matter emissions measurements may also use the Tapered Element Oscillating Microbalance (TEOM) continuous PM method, as detailed in this test method.

1.4. For this protocol, annual fuel use efficiency is represented by the average efficiency over the entire test run. Steady-state efficiency, which is reflective of efficiency measurements in current EPA Federal reference methods is determined by calculating the efficiency at the high load and low steady-state periods of the test run, which Phases 1, 2, and 5. Delivered efficiency is determined by measurement of the usable heat output
(determined through measurement of the flow rate and temperature change of water circulated through a heat exchanger external to the appliance) and the heat input (determined from the mass of dry fuel burned and its higher heating value). Delivered efficiency does not attempt to account for pipeline loss.

1.5. 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. These products may be used with or without external thermal storage only for the hot water service.

1.6. Distinguishing features of products covered by this standard include:

1.6.1. The manufacturer specifies installation either inside a building or outside.

1.6.2. Products that automatically feed fuels, such as pelletized wood or wood chips.

1.6.3. An aquastat that controls the combustion air supply to maintain the liquid in the appliance within a predetermined temperature range.

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

1.7. 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.

1.8. 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.


1.10. Data Quality Objectives.

1.10.1. Adherence to the requirements of this method will enhance the quality of the data obtained from air pollutant sampling methods.

1.10.2. Measurement of emissions and 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.

1.10.3. This is a laboratory method intended to capture operating periods that are representative of actual field use without excessive test burden.
2. Referenced Methods


2.2. ASTM 2515: Standard Test Method for Determination of Particulate matter Emissions Collected in a Dilution Tunnel or latest approved EPA version.

2.3. NESCAUM Standard Operating Practices for Thermo 1405 TEOM

2.4. NIST Monograph 175, Standard Limits of Error
3. Definitions

3.1. 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.

3.2. Catch - any mass from the sample probe system other than the PM on the front filter.

3.3. Certification or audit test - a series of at least three test runs conducted for certification or audit purposes that meets specifications detailed in Section 8.

3.4. Delivered Efficiency – The percentage of heat available in a test fuel charge that the appliance delivers to a simulated heating load as specified in this test method.

3.5. Emission factor – the emission of a pollutant expressed in mass per unit of energy (typically) output from the appliance

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

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

3.8. Firebox - the chamber in the appliance in which the test fuel charge is placed and combusted.

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

3.10. 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.

3.11. 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 during Phase 1 and Phase 5 of the test protocol.

3.12. NIST – National Institute of Standards and Technology

3.13. Relative humidity measurement with accuracy of 2% RH between 5 and 95% RH.

3.14. Secondary air supply - air supply that introduces air to the appliance such that the burn rate is not altered by more than 10 percent when the secondary air supply is adjusted during the test run. The appliance manufacturer or test facility can document this through design drawings that show the secondary air is introduced only into a mixing chamber or secondary chamber outside the firebox.
3.15. Test – means the data for all test runs conducted on the heating appliance.

3.16. Test facility - the area in which the heating appliance is installed, operated, and sampled for emissions.

3.17. Test run - An individual emission test, which encompasses the time required to complete all specified phases of the test profile.

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

3.19. Appliance - an enclosed, woodburning appliance capable of and intended for space heating or domestic water heating, as defined in the applicable regulation.
4. Summary of Test Method

4.1. Dilution Tunnel. Emissions are determined using the “dilution tunnel” method specified in ASTM E2515-11 *Standard Test Method for Determination of Particulate Matter Emissions Collected in a Dilution Tunnel*. The flow rate in the dilution tunnel is maintained at a constant level throughout the test cycle and accurately measured. Samples of the dilution tunnel flow stream are extracted at a constant flow rate and drawn through high-efficiency filters. The filters are equilibrated and weighed before and after each test to determine the emissions catch, 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 method also includes optional use of a real-time particulate matter measurement that allows for providing one-minute data, which can be used to provide one hour and test phase emissions information.

4.2. Particulate Matter. PM emissions are determined using a dilution tunnel method specified in ASTM 2515-11 *Standard Test Method for Determination of Particulate matter Emissions Collected in a Dilution Tunnel* with exceptions as defined in Section 8 and 9.4 of this test method. 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.

4.2.1. Filter-based method. Samples of the dilution tunnel flow stream are extracted at a constant flow rate and drawn through high-efficiency filters as defined in ASTM E2515-11 using Teflon coated filters such as Pallflex Emfab (TX40) with a maximum diameter of 47 mm, without organic binder, exhibiting at least 99.95 percent efficiency. The filters are equilibrated 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.

4.2.2. Real-time PM Measurements. The second method is a real-time particulate measurement method based on a Tapered Element Oscillating Microbalance (TEOM) instrument, Thermo model 1405 TEOM or its equivalent, operated using the specifications detailed in the document titled, “NESCAUM Standard Operating Procedures for Using TEOM 1405 in a Dilution Tunnel” available at: https://www.nescaum.org/topics/test-methods.

4.3. Carbon Monoxide. The CO measured in the flue, before dilution, is used in the stack loss efficiency determination.

4.4. Combustion Efficiency. The efficiency determination involves determination of stack losses. The stack loss determination involves measurement of the flue gas temperature, CO₂, 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.

4.5. Operation. Appliance operation is conducted on a cold-to-hot test cycle, meaning that the appliance starts the test run at room temperature and ends with the appliance in fully heated state. The appliance is operated at a variety of heat demand loads representing start-up emissions, high heat demand, low heat demand, cycling, idling, and recovery from night time set back. The appliance is operated through six heating phases during the test run. To complete the certification test, a minimum of three full test runs are averaged to determine the test results. For automatic feed systems, fuel is fed as determined by appliance delivery systems.
5. Significance and Use

5.1. The measurement of particulate matter emission 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 manufacturers' 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.
6. **Test Equipment and Supplies.** The following items are required for sample collection:

6.1. **Anemometer.** A device capable of detecting air velocities less than 0.10 m/sec (20 ft/min), for measuring air velocities near the test appliance.

6.2. **Barometer.** Aneroid or other barometer capable of measuring atmospheric pressure to within 2.5 mm Hg (0.1 in. Hg).

6.3. **Draft Gauge.** Electromanometer or other device for the determination of flue draft or static pressure readable to within 0.50 Pa (0.002 in. H2O).

6.4. **Dilution Tunnel temperature and relative humidity measurement.** A probe capable of measuring tunnel temperature to within 0.5 C and tunnel RH to within 2%, such as the Omega HX85-A.

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

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

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

6.8. **Humidity Gauge.** Psychrometer or hygrometer for measuring room humidity.

6.9. **Insulated Solid Pack Chimney.** For installation of appliances. Solid pack insulated chimneys shall have a minimum of 2.5 cm (1 in.) solid-pack insulating material surrounding the entire flue and possess a label demonstrating conformance to U.L. 103 (incorporated by reference—see §60.17).

6.10. **Lab Scale.** For measuring the mass of the test fuel charges. Accuracy of ± 0.01 pounds (± 0.00045 kg).

6.11. **Optional Recirculation Pump.** Circulating pump used during the certification test to prevent temperature stratification, in the appliance, of liquid being heated.

6.12. **Platform Scale and Monitor.** A platform scale capable of weighing the appliance under test and associated parts and accessories when completely filled with water to an
accuracy of ± 0.10 pound (± 0.045 kg) and a readout resolution of ± 0.01 pound (± 0.00045 kg).

6.13. Test Facility. The test facility shall meet the following requirements during testing:

6.13.1. The test facility temperature shall be maintained between 18 and 32°C (65 and 90°F) during each test run.

6.13.2. Air velocities within 0.6 m (2 ft) of the test appliance and exhaust system shall be less than 0.25 m/sec (50 ft/min) without fire in the unit.

6.13.3. The flue shall discharge into the same space or into space freely communicating with the test facility. Any hood or similar device used to vent combustion products shall not induce a draft greater than 1.25 Pa (0.005 in. H₂O) on the appliance measured when the appliance is not operating.

6.13.4. For test facilities with artificially induced barometric pressures (e.g., pressurized chambers), the barometric pressure in the test facility shall not exceed 775 mm Hg (30.5 in. Hg) during any test run.

6.14. Test Facility Temperature Monitor. A thermistor, RTD, or other equivalent device, located centrally in a vertically oriented 150 mm (6 in.) long, 50 mm (2 in.) diameter pipe shield that is open at both ends, capable of measuring temperature to within 1-degree Fahrenheit of expected temperatures.

6.15. Appliance Flue.

6.15.1. Steel flue pipe extending to 2.6 ±0.15 m (8.5 ±0.5 ft) above the top of the platform scale, and above this level, insulated solid pack type chimney extending to 4.6 ±0.3 m (15 ±1 ft) above the platform scale, and of the size specified by the appliance manufacturer. This applies to both freestanding and inserts type appliances.

6.15.2. Other chimney types (e.g., solid pack insulated pipe) may be used in place of the steel flue pipe if the appliance manufacturer's written appliance specifications require such chimney for home installation (e.g., zero clearance appliance inserts). Such alternative chimney or flue pipe must remain and be sealed with the appliance following the certification test.

6.16. 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 °F (± 0.5 °C). Other temperature measurement methods may be used if the temperature difference measurement uncertainty is equal to or less than ± 1.0 °F (± 0.50 °C). This measurement uncertainty shall include the temperature sensor, sensor well arrangement,
6.17. 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 the measured flow.

6.17.1. Appliance Side Water Flow Meter (optional). A water flow meter with an accuracy of ± 1% of the flow rate is recommended to monitor the supply-side water flow rate.

6.18. 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.

6.19. Appliance Temperature Monitors. Seven, each capable of measuring temperature with standard Type J or K thermocouple accuracy of +/- 0.75% of expected absolute temperatures.
7. Safety

7.1. Disclaimer. This method may involve hazardous materials, operations, and equipment. This test method may not address all the safety problems associated with its use. It is the responsibility of the user of this test method to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to performing this test method.

7.2. These tests involve combustion of wood, which releases substantial amounts of heat and combustion products. 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. **Sampling, Test Specimens, and Test Appliances**

8.1. **Particulate Matter Sampling.** PM emissions allow the use of two options to obtain integrated results and one-hour emissions data.

8.1.1. **Option 1** - three ASTM E2515 trains will be used for this testing.

8.1.1.1. Proportionality shall be limited to ± 10%, using 10-minute data.

8.1.1.2. **Train 1:** Start-up Measurement. A measurement of the start-up phase will be reported using one ASTM 2515 train. This measurement will commence at the beginning of the test and ends sixty (60) minutes after commencing the test.

8.1.1.3. **ASTM 2515 Trains 2 and 3:** Integrated load measurement. Two, dual ASTM 2515 trains will measure particulate for the entire test run.

8.1.1.4. **Option 3** use two ASTM 2515 trains, both pull one hour.

8.1.2. **Option 2** – 2 ASTM 2515 trains and TEOM.

8.1.2.1. **ASTM 2515 Trains 1 and 2:** Integrated load measurement. Two, dual ASTM 2515 trains will measure particulate for the entire test run.

8.1.2.2. **TEOM** data will be collected at 10-second intervals and averaged up to 1-minute intervals for reporting. TEOM operation shall follow the procedures listed in the TEOM SOP detailed in Appendix A. TEOM data shall be recorded on an excel spreadsheet following the minimum data reporting requirements. Emissions from the ASTM 2515 trains shall serve as the primary PM emission measurement. The TEOM data will be used to report emissions for the first, one-hour period.

8.2. **Sample Collection.** The following reagents are required for sample collection:

8.2.1. Teflon coated glass fiber filters such as Pallflex Emfab (TX40) with a maximum diameter of 47 mm, without organic binder, exhibiting at least 99.95 percent efficiency.

8.2.2. Same as Method 5, in Section 7.2.

8.2.3. **Sample Analysis.** Two reagents are required for the sample analysis:

8.2.4. **Acetone.** Same as Method 5, in Section 7.2.

8.2.5. **Saturated salt solution of magnesium chloride,** if weigh room RH will exceed 40%.

8.3. **Test Fuel.** This method can be used with wood pellet fuels.

8.3.1. **Pelletized fuels**

8.3.1.1. Fuel used must be PFI, CANplus, ENPlus certified, or other equivalent fuel certification standard.
8.3.1.2. Test fuel must undergo and report ultimate/proximate analysis by an independent lab.

8.3.1.3. All fuels used for testing must have a temperature no greater than 75F when loaded into the appliance.

8.3.2. Wood chip fuels shall conform to the following requirements:

8.3.2.1. Fuel used for testing must undergo ultimate/proximate analysis by an independent lab.

8.3.2.2. Fuel used for testing must be characterized by ANSI/ASABE AD17225-4:2014 FEB2018 Solid biofuels — Fuel specifications and classes — Part 4: Graded wood chips

9. Sample Collection, Preservation, Storage, and Transport

9.1. Test Specimens. Appliances shall be supplied as complete appliances, including all controls and accessories necessary for installation at the test facility including thermal storage tank description and volume. A full set of specifications, designs, and assembly drawings shall be provided when the product is placed under certification of a third-party agency. The manufacturer shall provide a tank with the minimum volume needed for operation and any parts that are specific for operation, as shown in Method 28 WHH PTS. Examples of parts to be supplied by the manufacturer would be a thermostat or various sensors required for communicating tank temperature to the appliance, recirculation loops (if needed), specific pump (if needed), all fittings for coming off the tank, etc.

9.2. User Guide. The manufacturer must supply a one-page user guide that will direct certain portions of the test protocol. The User Guide must be provided to the lab and the consumer as a single sheet and documented in the test report. The user guide shall be the only directions provided and used by the testing facility for certification purposes; it shall address key user operations, and it shall conform to the following requirements. Manufacturers are not allowed to direct or inform any portion of testing or deviate from operations specified in the User Guide, as the User Guide is the only information that can be used to inform appliance operation during certification testing. User Guide Layout Requirements – the User Guide shall conform to the following design specifications:

9.2.1. Directions must be illustrated by text and pictures

9.2.1.1. Font size – minimum font size is 12.

9.2.1.2. Use of columns allowed

9.2.1.3. Margins – must have a minimum of ¾” inch margins
9.2.1.4. A minimum of 40% of the user guide must use graphics or photos to support text directions.

9.2.1.5. Must fit on a single side of an 8 x 11.5-inch sheet of paper

9.2.1.6. Must be provided in a laminated form to the consumer.

9.2.2. User Guide elements – The User Guide cannot contradict or deviate from user instructions provided in the appliance user manual. The User Guide shall include information on the following items.

9.2.2.1. Appliance preparation – what must be done to the appliance prior to starting a fire to include appliance setpoints and software settings. Settings must reflect use in high-temperature heating systems.

9.2.2.2. Fuel properties – what types of fuel and fuel moisture requirements are allowed for use in the appliance. The fuel properties detailed in the User Guide are for homeowner use, for certification testing, fuel requirements shall follow the protocols detailed in this method.

9.2.2.3. Start-up procedures – general guidelines for properly starting the appliance to include starting procedures and appliance settings to include software configurations.

9.2.2.4. Reloading procedures – If applicable, guidelines for properly reloading fuel once a fire has been started in the appliance.

9.3. Pretest Recordkeeping.

9.3.1. Record data and detailed information on all testing or burning completed on the appliance including all pre-test burns conducted at the testing facility or by the manufacturer at a maximum of 10-minute intervals. Aging conducted at the manufacturer shall conform to the same requirements as the test facility. This information shall include the amount of pellets burned, air settings, burn times and dates, appliance and stack temperature data.

9.4. Modifications to ASTM 2515 requirements.

9.4.1. Liquid water should not be present anywhere in the sampling system for a valid sample.

9.4.2. Dilution tunnel temperature and relative humidity shall be measured and logged near the sample probe to calculate tunnel dewpoint. Filter temperature shall be measured and logged using a measurement method with an accuracy of 0.5 degrees Celsius (C) or better.

9.4.3. For a valid test run the following conditions shall not exceed any of the following conditions for a period of more than five minutes in total:
9.4.3.1. Filter temperature shall remain between 80 and 90 deg. F (26.7 to 32.2 C)

9.4.3.2. The dilution tunnel temperature shall be no more than 104 deg. F (40 C) for any rolling 10-minute average.

9.4.3.3. Tunnel relative humidity shall not exceed 95%.

9.4.3.4. Tunnel dew point temperature shall be at least 3.6 deg. F (2 deg. C) less than filter temperature.

9.4.3.5. If any parameter is exceeded, the test report should explicitly note the results of the sampling train liquid water inspection.

9.4.4. Proportionality shall be limited to ± 10%, using, at a minimum, 10-minute data.

9.5. Test Facility Conditions.

9.5.1. Locate the test facility temperature monitor on the horizontal plane that includes the primary air intake opening for the appliance. Locate the temperature monitor 1 to 2 m (3 to 6 ft) from the front of the appliance in the 90° sector in front of the appliance.

Use an anemometer to measure the air velocity. Measure and record the room air velocity before the pretest ignition period (Section 8.7) and once immediately following the test run completion.

9.5.2. Measure and record the test facility's ambient relative humidity, barometric pressure, and temperature before and after each test run.

Measure and record the flue draft or static pressure in the flue at a location no greater than 0.3 m (1ft) above the flue connector at the appliance exhaust during the test run at the recording intervals.

9.6. Appliance Installation.

9.6.1. Appliances 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. 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.

9.6.2. Assemble the appliance and parts in conformance with the manufacturer's written installation instructions. A representative of the manufacturer may assist in appliance installation.

9.6.3. Place the appliance centrally on the platform scale capable of weighing the appliance fully loaded with a resolution of ±0.10 lb (0.05 kg).

9.6.4. The appliance shall be fitted with the type of chimney recommended or provided by the manufacturer and extending to 15 ±0.5ft (4.6 ± 0.15m) 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 $8 \pm 0.5$ feet above the scale shall be a single wall stove pipe, and the remainder of the flue shall be double-wall insulated Class A chimney.

9.7. Optional Equipment Use

9.7.1. 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.

9.7.2. 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 to reflect a high-temperature installation, unless the manufacturer specifies that the appliance is for use only in low-temperature installations.

9.8. Starting Weight. Prior to filling the appliance with water, weigh and record the appliance mass.

9.9. Heat Exchanger

9.9.1. 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.

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

9.9.3. 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.

9.9.4. 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.

9.9.5. 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.
9.9.6. The reported heat output rate shall be based on measurements made on the load side of the heat exchanger.

9.9.7. Temperature instrumentation 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.

9.9.8. 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. Calibration, Standardization and Quality Control

10.1. ASTM E2515-11. Perform all calibrations required by ASTM E2515-11

10.2. Water Temperature Sensors. Temperature measuring equipment shall be calibrated before initial use and at least semi-annually thereafter. Calibrations shall follow NIST Monograph 175, Standard Limits of Error.

10.3. Heat Exchanger Load Side Water Flow Meter. 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. The 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.

10.4. Scales. Perform a multipoint calibration (at least five points spanning the operational range) of the platform scale before its initial use. The scale manufacturer’s calibration results are sufficient for this purpose. Before each certification test, audit the scale with the appliance in place by weighing at least one calibration weight (Class F) that corresponds to between 20 percent and 80 percent of the expected test fuel charge weight. If the scale cannot reproduce the value of the calibration weight within 0.0045 kg (0.01 lb.) or 1 percent of the expected test fuel charge weight, whichever is greater, recalibrate the scale before use with at least five calibration weights spanning the operational range of the scale. The
scales used to weigh the appliance, and test fuel charge shall be calibrated using NIST-traceable methods at least once every 6 months.

10.5. **Balance (optional).** Calibrate as described in Section 10.1.

10.6. **Anemometer.** Calibrate the anemometer as specified by the manufacturer's instructions before the first certification test and semiannually thereafter.

10.7. **Barometer.** Calibrate against a mercury barometer before the first certification test and semiannually thereafter.

10.8. **Draft Gauge.** Calibrate as per the manufacturer's instructions; a liquid manometer does not require calibration.

10.9. **Humidity Gauge.** Calibrate as per the manufacturer's instructions before the first certification test and semiannually thereafter.

10.10. **Flue Gas Analyzers.** In accordance with CSA B415.1-2010, Clause 6.8.

10.11. **Weigh room conditions.** The following conditions shall be met:

   10.11.1. The facility shall use an active ionizing air blower (or 210Polonium alpha sources) to neutralize charge associated with the filter. 210Polonium alpha sources must be replaced annually or more often.

   10.11.2. Temperature range of 68 to 78 deg. F.

   10.11.3. Relative humidity shall be no higher than 45%.

10.12. **Filter equilibration / conditioning post sample collection.** Use of desiccation is not allowed. Equilibrate filters at a relative humidity between 30 and 40% for at least 24 hours. A saturated salt solution of magnesium chloride (33% RH) can be used.

10.13. **Filter weight measurements.** Report the following filter measurements:

   10.13.1. Day zero – initial filter measurement immediately after completing testing.

   10.13.2. Final filter measurement or day seven measurement, whichever measurement comes first.

10.14. **Blanks.** Test reports shall measure and report data on blanks as follows:

   10.14.1. Lab blank, which is removed from each filter batch, stored in a protective environment, and weighed during each weighing session.
10.14.2. Room blank collected during every test run. The blank shall be placed within 2 feet of the intake for the dilution air and shall be placed at a minimum of 10 feet away from any combustion activities.

10.15. Probe Catch: Report sampling system catch as a separate number from back filter catch.

11. Conditioning

11.1. Appliance Aging. Prior to testing, the appliance shall be operated for a minimum of 50 hours using a variety of heat demands. The conditioning may take place at the manufacturer’s facility prior to testing or at the certification facility.

11.2. Appliance Aging Documentation. A appliance of any type shall be aged before initiating a certification test. The aging procedure shall be conducted and documented by the manufacturer or the certified testing laboratory. All aging data must be reported and shall include the hours of operation, heat demands for aging.

11.3. Appliance Aging operations. Operate the appliance using manufacturer designated fuel. The appliance shall be operated at a variety of burn phases. The test report shall detail the amount of fuel burned, fuel parameters (species, heat demands, and fuel types), air and control settings used, and note the time spent in each air setting phase.

11.3.1. If the appliance uses a catalytic combustor, it must be engaged according to manufacturer’s instructions and operate for at least 50 hours during the break-in period. Report hourly catalyst exit temperature data and the hours of operation.


12.1. A representative of the manufacturer may observe testing but may not provide instructions to the certification lab, in any form, with testing staff or equipment once the certification tests begin. The names of testing witnesses cannot be withheld as confidential business information (CBI).

12.2. During certification testing, the unit cannot be connected for remote access. Nor can the appliance be operated remotely. For example, the unit cannot be connected to the internet unless remote access is to allow for remote witnessing or recording of the test. Remote access may only be granted by the certification laboratory. If remote access is granted, witness list shall reflect those who have been granted remote witness capacity and provide recordings of remote activities as part of the test report.

12.3. For certification testing, all system control settings shall be tested with all controls and software set as-the manufacturer will ship or install, often referred to as default settings. These default settings shall be defined by the manufacturer, communicated to the lab, documented in the test report, and match those communicated in owner’s manual and
installation instructions 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.

12.3.1. Where the manufacturer defines several operational control logic parameters and heat load settings, one shall be defined in the appliance documentation as the default or standard-setting. It is expected that this will be the configuration for use with a simple baseboard high-temperature heating system. This is the configuration to be followed for these tests. The manufacturer’s documentation shall define the other control settings as optional or alternative settings.

12.4. Sampling Equipment.
12.4.1. Prepare the sampling equipment as defined by ASTM E2515-11 with modifications defined in 9.4 of this method, and if using the TEOM, using the SOP referenced.
12.4.2. Sample Flow Corrections for Water Vapor: Corrections shall use the average of actual tunnel dew point measurements during a sample run, use of the assumed dew point value is prohibited.

12.5. Instructions
12.5.1. Appliance Operation and Adjustments. Set the air inlet supply controls as designated in the User Guide, as defined in Section 9.2 of this test method. Record all adjustments made to the air supply controls, adjustments to and additions or subtractions of fuel, and any other changes to appliance operations that occur during the test period. Record fuel weight data and appliance temperature measurements at 1-minute intervals.
12.5.2. Before each test run, the firebox shall be vacuumed. Testing shall begin without any ash or other materials in the appliance.

12.6. Test Run Procedure. The table below summarizes the phases that encompass a complete test run. Addition of cooling water during the testing is not allowed. A complete test run requires completion of all five phases of the test protocol, as described below.

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### 12.6.1. Start-up Phase

**12.6.1.1.** Appliance operation – during this phase, the appliance shall start from a cold condition and ramp up until the heat demand is 100% of the appliances’ maximum rated heat output \(^1\) for a period of five minutes.

**12.6.1.2.** Definition for end of start-up phase – cold start phase shall end when the appliance is within the modulation setpoints, prescribed by manufacturer and maximum heat demand can be maintained for a period of at least five minutes without a rise in water and stack temperature (+/- 10°F).

Complete 60-minute average calculation to confirm as this will impact phase 2 setting.

**12.6.1.3.** Lockout access to thermal storage during the first 30 minutes of Phase 1.

**12.6.2.** The appliance shall remain at Phase 1 – 100% heat demand for a period of 60 minutes.

**12.6.2.1.1.** Appliance controls should target operation at the maximum firing rate. Following cold start, cooling water will not be turned on until after the

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\(^1\) If the maximum output is ± 10% of the manufacturers stated capacity, the appliance rating must be changed to reflect actual tested values.
appliance reaches appliance/storage setpoints, and storage is above operating conditions programmed by the manufacturer. 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.

12.6.2.1.2. The appliance shall fire at its maximum burn rate for the entire period. The appliance water temperature, however, may increase during this time period.

12.6.2.1.3. If at any time, the appliance temperature is rising and approaching the operating limit, the output rate shall be increased to prevent the appliance from cycling off or from modulating to a lower firing rate.

12.6.2.2. Appliance temperature: For Run #1, the appliance shall be at ambient room temperature, which cannot exceed 80 F must room temperature. Before each test run and IR photo shall be taken of the appliance and thermal storage. For the first run (Run #1), the appliance and buffer tank (or thermal storage) shall not exceed 120 F. No appliance temperature requirements for Run #2 or #3. Temperature measurements for the external and internal temperatures shall be taken 15 minutes before starting the test and shall be reported in the test report.

12.6.2.3. Record and report the weight of the appliance at the beginning and end of Phase 1.

12.6.2.4. End of Phase 1. The end of Phase 1 is defined by a period of 60 minutes of maximum heat demand placed on the appliance.

12.6.2.5. To determine average maximum heat output, all replicates shall be averaged and no individual run shall have a heat output rate +/- 10%.

12.6.2.6. Heat Output Capacity Validation. During Phase 1, 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 2, 3, and 4 may still meet the requirements of Table 1, and a re-test may not be required.

12.6.3. Phase 2 – Low Heat Demand Phase. This phase commences immediately after Phase 12.6.3.1. Appliance operation – the appliance heat demand is reduced to 13%+/- 2% of the appliance's maximum rated heat output. The appliance stays at this heat demand for a period of 120 minutes or one complete cycle, whichever comes...
first. Ramp down to this heat load must be made in a period of fewer than 10 minutes. The test report shall indicate the time period used for ramp down.

12.6.3.2. Record and report the weight of the appliance at the beginning and end of Phase 2.

12.6.3.3. Operational Parameters: Heat demand on the appliance is placed at 13% +/- 2% of maximum output as the unit is delivered to the customer.

12.6.3.4. End of Phase – the end of Phase 2 is defined by the appliance is defined by a period of 120 minutes at 13% +/-2% heat demand placed on the appliance or after one cycle, whichever comes first.

12.6.3.5. The time at which the unit cycles in Phase 2 shall determine how many cycles must be completed in Phase 4.

12.6.3.5.1. If the unit begins to cycle within 0-30 minutes of Phase 2, 6 cycles must be completed in Phase 4.

12.6.3.5.2. If the unit begins to cycle within 31-60 minutes of Phase 2, 4 cycles must be completed in Phase 4.

12.6.3.5.3. If the unit cycles within 61-90 minutes of Phase 2, 3 cycles must be completed in Phase 4.

12.6.3.5.4. If the unit cycles within 91-120 minutes of Phase 2, 2 cycles must be completed in Phase 4. If the unit does not cycle during Phase 2, only 1 cycle must be completed in Phase 4.

12.6.4. Phase 3 – No Heat Demand (Idling) Phase. This phase commences immediately after Phase 2.

12.6.4.1. Appliance operation – Appliance heat demand is 0%, and the appliance is turned off. The appliance stays at this heat demand for a period of 45 minutes. Ramp down to this heat load must be made in a period of fewer than 5 minutes. The test report shall indicate the time period used for ramp down.

12.6.4.2. No appliance temperature requirements for Phase 3.

12.6.4.3. Record and report the weight of the appliance at the beginning and end of Phase 3.

12.6.4.4. End of Phase. The end of Phase 3 occurs when the appliance spends a minimum of 45 minutes at no load ends and the boiler cools to a setpoint where the boiler will cycle on at the beginning of Phase 4. This may be completed by manual setting a cooling load.

12.6.5. Phase 4 – Cyclic Operations

12.6.5.1. Appliance operation - During Phase 4 the unit shall complete the number of cycles as determined in Phase 2, as defined in 12.6.3.5.
12.6.5.1.1. The appliance must complete the required number of on/off cycles. During on-cycle - cooling water is stopped, the appliance heats to maximum temperature limit. During the off-cycle – the appliance is turned off for a period of 30 minutes, then set cooling water 100% heat demand until appliance reaches minimum operating temperature limit, and the appliance’s controls receive a call for heat.

12.6.5.2. This phase emulates the operation of the appliance, responding to a thermostat call at the start of this phase, power the appliance back on. The heater and storage temperature at the time it powers on will determine whether there is a call for heat or not. This will be indicated by the appliance firing back up, which can be indicated through control status, or starting of the combustion air/induced draft fan or if it stays in an “idle” state, such as standby or slumber.

12.6.5.3. If there is a call for heat, the cooling water shall remain off until the appliance temperature rises to the operating limit, and the appliance controls act to minimize the burn rate in an “off” or “idle” state. The transition to this mode is determined either by the control status indication or the stopping of the combustion air/induced draft fan. This will indicate the end of the on-cycle and start of the off-cycle period. The time of the start of off-cycle will be recorded, and then the heater and storage will sit for 30 minutes. Following this, the cooling load shall be cycled on at 100%. This marks the end of the first cycle. Then allow cooling water flow to be adjusted for an output of 100% of nominal full load output. This pattern shall continue until the time at which the appliance operating controls act to restart the active combustion and reheat the appliance in an on-cycle. 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 appliance has again reached the operating limit temperature, and the appliance controls act to minimize the burn rate in an “off” or “idle” mode and then sat for a period of 30 minutes to complete the second cycle.

12.6.5.4. If, during this test, the appliance shuts down on the high-temperature safety control, requiring a manual reset, the test is a failed run.

12.6.5.5. Appliance temperature: no appliance temperature requirements for Phase 4.

12.6.5.6. Record the weight of the appliance at the beginning and end of Phase 4.

12.6.5.7. Start of Phase – the cycling event begins in an off-cycle.

12.6.5.8. End of Phase – the end of Phase 4 occurs after the 30-minute period after the second cycling event is completed, and the appliance is in an off-cycle.

12.6.6. Phase 5 – Response to Setback Conditions
12.6.6.1. Appliance operation –. The cooling water shall be adjusted for an output of 100% of the nominal full-load output for 60 minutes. If the appliance system (heater and storage) drops below the minimum operating range, as specified by the manufacturer, cooling will stop temporarily until the heater returns to manufacturer specified operating temperature. Cooling water will then be adjusted to continue an output of 100%, or nominal load. The time at which cooling is stopped and continued shall be recorded.

12.6.6.2. Record the weight of the appliance at the beginning and end of the phase.

12.6.6.3. End of Phase – the end of Phase 5 occurs when a period of 60 minutes of 100% heat demand has been placed on the appliance.

12.6.7. End of the Test Run. The test runs ends when all five phases of the test run have been completed in sequence.

12.6.7.1. Test Run Completion. At the end of the Phase 5 period, as prescribed in Section 8, stop the particulate sampling instruments and Overall Efficiency (SLM) measurements, and record the run time and all final measurement values.

12.6.7.2. 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.

12.7. Test run requirements. The following are the pre-testing appliance use requirements for each test run.

12.7.1. Run 1 – appliance must be at lab temperature and wait a minimum of 48 hours without combustion before starting Run 1.

12.7.2. Run 2 – shall not operate for a minimum of 8 hours from the conclusion of Run 1 before commencing Run 2. Appliance coals and ash can remain in the appliance until 1 hour before conducting Run 2. All coals and ash must be removed before commencing Run 2.

12.7.3. Run 3 – shall wait a minimum 8 hours from the conclusion of Run 2 before commencing Run 3. Appliance coals and ash can remain in the appliance until 1 hour before conducting Run 3. All coals and ash must be removed before commencing Run 3.
12.8. Before initiating the compliance test, clean the flue with an appropriately sized wire chimney brush before each certification test. Test documentation should include the date and time of flue cleaning.

12.9. **Failure to Operate at All Test Conditions.** If an appliance cannot operate in all of the test Phases without achieving an appliance temperature that causes the safety high limit to be activated, requiring a manual reset, the test is a failed run. After two failed test runs, the unit is deemed to have failed the test, and the unit cannot be certified with this test method.

12.10. **Consecutive Test Runs.** Consecutive test runs may be conducted, provided that the requirements of Section 12.6 of this method are met.

12.11. **Test Series completion.** A complete test series is defined as the successful completion of three full test runs, as specified in Section 12.6 of this method.

12.11.1. If the appliance fails more than the two test runs, the appliance has failed the certification test.

12.12. **Additional Test Runs.** The testing laboratory may conduct more than three test runs. If more than three test runs are conducted, the results from all valid test runs shall be used in calculating the average emission rate. The measurement data and results of all test runs shall be reported regardless of which values are used in calculating the emission rate. No test run data can be eliminated from the reporting requirements of this method.

12.13. **Low Appliance Temperature.** If at any time, average water temperature falls below minimum operating temperatures set by the manufacturer, then cooling will be stopped until the water temperature averages reach temperature setpoint.
13. Calculation of Results – Calculation of Results

13.1. Nomenclature

\( E_T \) – Total particulate emissions for the full test run as determined per ASTM E2515-11 in grams

\( E_{g/MJ} \) – Emissions rate in grams per megajoule of heat output

\( E_{lb/mmBtu\,output} \) – Emissions rate in pounds per million Btu of heat output

\( E_{g/kg} \) – Emissions factor in grams per kilogram of dry fuel burned

\( E_{g/hr} \) – Emissions factor in grams per hour

\( HHV \) – Higher heating value of fuel = 8600 Btu/lb (19.990 MJ/kg)

\( LHV \) – Lower heating value of fuel = 7988 Btu/lb (18.567 MJ/kg)

\( \Delta T \) – Temperature difference between water entering and exiting the heat exchanger

\( Q_{out} \) – Total heat output in BTU’s (megajoules)

\( Q_{in} \) – Total heat input available in test fuel charge in BTU (megajoules)

\( M \) – Mass flow rate of water in lb/min (kg/min)

\( V_i \) – Volume of water indicated by a totalizing flow meter at the ith reading in gallons (liters)

\( V_f \) – Volumetric flow rate of water in heat exchange system in gallons per minute (liters/min)

\( \Theta \) – Total length of test run in hours

\( t_i \) – Data sampling interval in minutes

\( \eta_{del} \) – Delivered heating efficiency in percent

\( F_i \) – Weighting factor for heat output category i
T1 – Temperature of water at the inlet on the supply side of the heat exchanger

T2 – Temperature of the water at the outlet on the supply side of the heat exchanger

T3 – Temperature of water at the inlet to the load side of the heat exchanger

T4 – Temperature of cooling water at the outlet of the load side of the heat exchanger, °F.

T5 – Temperature of the hot water supply as it leaves the appliance/heater, °F.

T6 – Temperature of return water as it enters the appliance/heater, °F.

TI_{avg} – Average temperature of the appliance and water at start of the test

TI_{avg} = (T1 + T2)/2 at the start of the test, °F

TF_{avg} – Average temperature of the appliance and water at the end of the test

TF_{avg} = (T1 + T2)/2 at the end of the test, °F

TIS1 – Temperature at the inlet to the storage system at the start of the test.

TIS2 – Temperature at the outlet from the storage system at the start of the test.

TFS1 – Temperature at the inlet to the storage system at the end of the test.

TFS2 – Temperature at the outlet from the storage system at the end of the test.

TIS_{avg} – Average temperature of the storage system at the start of the test.

TIS_{avg} = (TIS1 + TIS2)/2 at the end of the test.

TFS_{avg} – Average temperature of the storage system at the end of the test.

TFS_{avg} = (TFS1 + TFS2)/2.
MC – Fuel moisture content in percent dry basis

$MC_i$ – Average moisture content as determined by ultimate/proximate analysis

$\sigma$ – Density of water in pounds per gallon

$C_p$ – Specific heat of water in Btu /lb, °F

$C_{steel}$ – Specific heat of steel (0.1 Btu/ lb, °F)

$W_{fuel}$ – Fuel charge weight in pounds (kg)

$W_i$ – Weight of fuel in pounds (kg)

$W_{app}$ – Weight of empty appliance in pounds

$W_{wa}$ – Weight of water in the supply side of the system in pounds

$W_{StorageTank}$ – Weight of the storage tank empty in pounds (kg)

$WWaterStorage$ – Weight of the water in the storage tank at $TIS_{avg}$ in pounds (kg).

NOTE: For proportioning emission factors and rates per phase according to Appendix A, variables will have subscript added to determine the relevancy of phase i.e. $E_{TIP1}$ indicates Total particulate emissions for Phase 1 and $E_{g/hrP2}$ indicates emissions factor in grams per hour for Phase 2.

13.2. Test Run Reporting.

13.2.1. 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.

13.2.2. 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

13.2.3. Measure and record the test room air temperature in accordance with the requirements of CSA B415.1-2010 Clauses 6.2.1, 8.5.7, and 10.4.3 (g).

13.2.4. Measure and record the flue gas temperature in accordance with the requirements of CSA B415.1-2010 Clauses 6.2.2, 8.5.7, and 10.4.3 (f).
13.2.5. Determine and record the Carbon Monoxide (CO) and Carbon Dioxide (CO₂) concentrations in the flue gas in accordance with CSA B415.1-2010 Clauses 6.3, 8.5.7, and 10.4.3 (i) and (j).

13.2.6. Measure and record the test fuel weight per the requirements of CSA B415.1-2010 Clauses 8.5.7 and 10.4.3 (h).

13.2.7. CSA B415.1-2010 Record the test run time per the requirements of Clause 10.4.3

13.2.8. Record and document all settings and adjustments, if any, made to the appliance as recommended/required by manufacturers 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.

13.2.9. 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.

13.3. Measurements and Adjustments

13.3.1. Modification to measurement procedure 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 CO₂, 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. The stack loss analysis must also use actual fuel values obtained from the required ultimate/proximate pellet analysis completed as part of the stack loss calculation.

13.4. Emission Calculations. Particulate matter, carbon dioxide, and carbon monoxide shall be calculated using the following methodology and reported in grams per hour, grams per kilogram and pounds per million British Therma Unit (Btu) per hour based on heat output:

13.4.1. Two PM measurements shall be reported
13.4.1.1. 60-minute reporting. Emissions from the first sixty minutes shall be reported. The 60 minute periods begins at match light. 60-minute data shall be collected and reported as a separate ASTM 2515-11 train or the TEOM data calculated per the SOP.

13.4.1.2. Integrated Result. The results two, dual ASTM E2515-11 trains, shall integrate into a single result the appliance performance over the five phases of this test method’s operational protocol.

13.4.2. Particulate Matter emissions.

13.4.2.1. During the test run, particulate emissions shall be measured per the requirements of ASTM E2515-11, with exceptions noted in 9.4 of this test method. This involves two sampling trains providing an integrated measurement over the entire test period, Phases 1 through 5, and

13.4.2.1.1. A third ASTM 2515-11 train to obtain 60-minute reporting data, or

13.4.2.1.2. Use of 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.

13.5. Particulate Matter Emissions Rates. After the test is completed determine the particulate matter emissions rate $E_r$ in accordance with ASTM E2515-11 for each test run. If using ASTM E2515-11 for one-hour data, prepare calculations for each first hour of operation.

13.6. Average Fuel Load Content. Determine average fuel load content using the results of the ultimate/proximate analysis.


$$Q_{in} = (W_{fuel}/(1+(MC/100))) \times HHV, \text{ BTU}$$

$$Q_{in \ LHV} = (W_{fuel}/(1+(MC/100))) \times LHV, \text{ BTU}$$

13.8. Determine Heat Output and Delivered Efficiency

$$Q_{out} = \Sigma \text{[Heat output determined for each sampling time interval]} + \text{ Change in heat stored in the appliance.}$$

$$Q_{out} = [\Sigma (C_{p} \cdot \Delta T \cdot M \cdot t)] + (W_{app} \cdot C_{steel} + C_{pa} \cdot W_{water}) \cdot (T_{avg} - T_{iavg}), \text{ BTU}$$

Note: The subscript (i) indicates the parameter value for sampling time interval ti.

$Mi = \text{Mass flow rate} = \text{gal/min} \times \text{density of water (lb/gal)} = \text{lb/min}$

$Mi = Vfi \cdot \sigma i, \text{ lb/min}$
σi = (62.56 + (-0.0003413 x T3i) + (-0.00006225 x T3i^2)) 0.1337, lbs/gal
Cp = 1.0014 + (-0.00003485 x T3i) Btu/lb, °F
Csteel = 0.1 Btu/lb, °F
Cpa = 1.0014 + (-0.00003485 x (T1avg + T2avg)/2), Btu/lb·°F
Vfi = (Vi – Vi-1)/(ti-ti-1), gal/min

Note: Vi is the total water volume at the end of interval i and Vi-1 is the total water volume at the beginning of the time interval. This calculation is necessary when a totalizing type water meter is used.

13.9. Determine Heat Output and Delivered Efficiency With External Thermal Storage
Qout = Σ [Heat output determined for each sampling time interval] + Change in heat stored in the appliance + Change in heat in storage tank.

Qout = Σ[Cpi ∙ Δ Ti ∙ Mi ∙ ti] + (Wapp ∙ Csteel + Wwater ∙ Cpa) ∙ (TFavg – TIavg) + (WStorageTank ∙ Csteel + WWaterStorage ∙ Cpa) ∙ (TFSavg – TISavg) Btu (MJ)

Note: The subscript (i) indicates the parameter value for sampling time interval ti.

13.9.1. Determine heat output rate as:

Heat Output Rate = Qout/Θ, BTU/hr

13.9.2. Determine emission rates and emission factors as:

Eg/MJ = E_T/(Q_out x 0.001055), g/MJ
Em/MMBTU output = (E_T/453.59)/(Q_output x 10^-6), lb/mmBtu Out
Eg/kg = E_T/(W_fuel/(1+MC/100)), g/dry kg
Eg/hr = E_T/Θ, g/hr

13.9.3. Determine delivered efficiency as:

ηdel = (Q_out/Q_in) x 100, %
ηdel LHV = (Q_out/Q_in LHV) x 100, %

13.9.4. Determine ηSLM - Overall Efficiency (SLM) using Stack Loss

13.9.4.1. For determination of the average overall thermal efficiency (ηSLM) for the test run, use the data collected over the full test run and the calculations in accordance with CSA B415.1-10. The averaging period for determination of efficiency by the stack loss method allows averaging over 10-minute time periods for flue gas temperature, flue gas CO₂, and flue gas CO for the determination of the efficiency. 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, the averaging periods specified 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. Fuel values from ultimate proximate analysis shall be used to conduct stack loss calculations.

13.9.4.2. Whenever the CSA B415.1-10 overall efficiency is found to be lower than the overall efficiency based on load side measurements, as determined by this method, the test report must include a discussion of the reasons for this result. Any result which finds efficiency greater than 5% shall result in a failed test run.

13.10. **Determine Steady-State Efficiency.** Determined delivered efficiency over the five phases is representative of annual efficiency. For Steady-State efficiency of high and low heat demands, determine the delivered efficiency of the individual steady-state phases, Phases 1, 2, and 5.

\[
\eta_{\text{del}(p1)} = \frac{Q_{\text{out}(p1)}}{Q_{\text{in}(p1)}} \times 100, \%
\]

\[
\eta_{\text{del}(p2)} = \frac{Q_{\text{out}(p2)}}{Q_{\text{in}(p2)}} \times 100, \%
\]

\[
\eta_{\text{del}(p5)} = \frac{Q_{\text{out}(p5)}}{Q_{\text{in}(p5)}} \times 100, \%
\]

13.11. **Carbon Monoxide Emissions.**

For each minute of the test period, the carbon monoxide emission rate shall be calculated as:

\[
\text{CO}_g/\text{min} = Q_{\text{std}} \cdot \text{CO}_s \cdot 3.30 \times 10^{-5}
\]

Total CO emissions for each of the five test phases (CO$_1$, CO$_2$, CO$_3$, CO$_4$, CO$_5$) shall be calculated as the sum of the emission rates for each of the 1-minute intervals. Total CO emission for the test run, COT, shall be calculated as the sum of CO$_1$, CO$_2$, CO$_3$, CO$_4$, and CO$_5$. 10-minute averages can be used in place of 1-minute intervals if appropriate as 13.8.4.1.
14. Reporting Requirements. The report shall include the following:

14.1. Introduction - no portion of the introduction may be claimed as CBI.

14.1.1. Purpose of test: certification, audit, efficiency, research, and development

14.1.2. Name and location of the laboratory conducting the test.

14.1.3. Wood appliance identification – manufacturer, model number/name, design type, description of the appliance tested, appliance condition, and date of receipt.

14.1.4. Test information – location of testing, date of tests, sampling methods used, number of test runs, a statement detailing any previous testing completed on the wood appliance.

14.1.5. A list of participants, their roles, and any observers present for the tests. The list shall include the participant's name, title, company, contact information and the purpose of their participation.

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

14.2. Summary and Discussion of Results - no portion of the introduction may be claimed as CBI.

14.2.1. Table of results to include test run number, average burn rate for entire run, particulate emission rate for full run, particulate emission rate for start-up, carbon monoxide emission rate for a full run, carbon monoxide for startup, efficiency, burn time – total and by phase.

14.2.2. If the TEOM is used for the entire test, the report shall contain the following:

14.2.2.1. For each test run use the TEOM to apportion filter PM data and use real-time analyzer data for other emissions to report: $\Theta_1, \Theta_2, \Theta_3, CO, CO_2, PM$, and efficiency for (1) the start-up phase and the five individual phases. Calculated results for the emissions reported as total emissions in grams, pounds per million Btu output, grams per MJ, grams per kilogram of dry fuel and grams per hour, and pounds per hour.

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

14.2.2.3. A plot of CO emission rate in grams/minute vs. time, based on 1-minute averages, for the entire test period, for each run. The report shall include a table reporting the maximum 1-minute, 5-minute, and 60-minute grams per hour on a rolling basis for the test run.

14.2.2.4. A plot of CO$_2$ emission rate in grams/minute vs. time, based on 1-minute averages, for the entire test period, for each run. The report shall include a table reporting the maximum 1-minute, 5-minute, and 60-minute grams per hour on a rolling basis for the test run.

14.2.2.5. A plot of PM emission rate in grams/hour vs. time, based on 1-minute averages, for the entire test period, for each run. The report shall include a
table reporting the maximum 1-minute, 5-minute, and 60-minute grams per hour on a rolling basis for the test run.

14.2.2.6. Summary of other data – test facility conditions, surface temperature averages, catalyst averages, pretest fuel weights, test fuel charge weights – total and by phase.

14.3. Emission Calculations. Particulate matter, carbon dioxide, and carbon monoxide shall be calculated using the following methodology and reported in grams per hour, grams per kilogram and pounds per million British Therma Unit (Btu) per hour based on heat output:

14.3.1. Two measurements shall be reported
   14.3.1.1. Start-up. Emissions from match light until the end of the start-up phase shall be collected and reported as a separate element using two ASTM 2515-11 trains. One-hour data shall be reported by a third ASTM 2515-11 train or the TEOM data calculated per the SOP.
   14.3.1.2. Integrated Result. The results two, dual ASTM E2515-11 trains shall integrate into a single result the appliance performance over the five phases of this test methods operational protocol.

14.3.2. Particulate Matter emissions.
   14.3.2.1. During the test run, particulate emissions shall be measured per the requirements of ASTM E2515-11 with exceptions noted in 9.4 of this test method. This involves two sampling trains providing an integrated measurement over the entire test period, Phases 1 through 5.
   14.3.2.2. 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.

14.4. Discussion. - no portion of the discussion may be claimed as CBI.
   14.4.1. Discussion shall include detailed information describing each test conducted on the appliance:
      14.4.1.1. How the test was run
      14.4.1.2. Specific test run problems and solutions
      14.4.1.3. Test run result

14.5. Process description:
   14.5.1. Data and drawings indicating the fire box size and location of the fuel charge.
   14.5.2. Drawings and calculations used to determine firebox volume to include volume, height, width, and lengths, weight and volume adjustments. No portion of this section
14.5.3. Firebox configuration – At a minimum to include air supply locations and operation, air supply introduction location, refractory location and dimensions, catalyst location, baffle and by-pass location and operation (include line drawings or photographs).

14.5.4. Process operation during test – shall supply details on air supply settings and adjustments. No portion of this section can be CBI.

14.5.5. Test fuel properties – species, density, fuel moisture, fuel temperature, and load details. No portion of this section can be CBI.

14.5.6. Sampling. No portion of this section can be CBI.

14.5.6.1. 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.

14.5.6.2. Describe sampling location relative to appliance, include drawing or photographs.

14.5.6.3. Provide data on sampling blanks.

14.6. Quality Control and Assurance Procedures. No portion of this section can be CBI.

14.6.1. Calibration procedures and results certification procedures, sample and analysis procedures.

14.6.2. Test method quality control procedures to include leak-checks, volume meter checks, stratification (velocity) checks, proportionality results.

14.7. Appendices – No data contained in the appendices can be claimed as CBI.

14.7.1. Results and Example Calculations. Complete summary tables and accompanying calculations.

14.7.2. Raw data. Copies of all files or sheets for sampling measurement, temperatures records, and sample recovery data.

14.7.3. Sampling and Analytical procedures. Detailed description of procedures followed by laboratory personnel in conducting the certification test.

14.7.4. Calibration Results. Summary of all calibrations, check and audits pertinent to the certification.

14.7.5. Sampling and Operation Records. Copies of all uncorrected records of activities not included in raw data sheets (e.g. appliance door open, times and durations).

14.7.6. User Guide. Appliance instructions for operating the device during the test following the User Guide specifications detailed in Section 8.1.1.


14.7.8. Test Equipment Calibration and Audit Information. Report calibration and audit...
results for the platform scale test fuel balance, test fuel moisture meter, and sampling equipment, including volume metering systems and gaseous analyzers.

14.7.9. Pre-test procedures. Report all pretest procedures conducted at the lab on the appliance to burns, rates, and amounts.

14.7.10. 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. An explanation of the deviations, additions, or exclusions shall be provided along with an analysis as to why these elements had no impact.

14.7.11. 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.

14.7.12. For each test run: report TEOM flow and temperature and verification of all TEOM parameters presented in the TEOM 1405 SOP.

14.7.13. Raw data, calibration records, and other relevant documentation shall be retained by the laboratory for a minimum of 7 years.
Table 1A – Must complete a table for each test run, minimum of three

Data Summary Part A - Run 1

<table>
<thead>
<tr>
<th>Phase</th>
<th>Target Load</th>
<th>Actual Load</th>
<th>Phase Duration</th>
<th>Wood Consumed</th>
<th>Stack Loss</th>
<th>Efficiency</th>
<th>Thermal Efficiency</th>
<th>Min Water Return Temp.</th>
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<td>Btu/hr</td>
<td>Btu/hr</td>
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<td>%</td>
<td>%</td>
<td>°F</td>
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Data Summary Part A - Run 2

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<td>%</td>
<td>°F</td>
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Data Summary Part A - Run 3

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<th>Stack Loss</th>
<th>Efficiency</th>
<th>Thermal Efficiency</th>
<th>Min Water Return Temp.</th>
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<td>Btu/hr</td>
<td>hours</td>
<td>lbs</td>
<td>%</td>
<td>%</td>
<td>°F</td>
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Table 1B – Must complete a table for each test run, minimum of three
Data Summary Part B – 60-minute test results

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<th>ERco</th>
<th>EFpm</th>
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<th>ERpm</th>
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<td></td>
<td>Lb/MMBtu output</td>
<td>g/kg fuel</td>
<td>g/hr</td>
<td>Lb/MMBtu output</td>
<td>g/kg fuel</td>
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<td>g</td>
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<td></td>
<td></td>
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<tr>
<td>Run 2</td>
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<tr>
<td>Average of all runs</td>
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Table 1C Data Summary – Averages

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<th>ERApm</th>
<th>Thermal Efficiency ηTA</th>
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<td>Lb/MMBtu output</td>
<td>g/kg fuel</td>
<td>Lb/hr</td>
<td>Lb/MMBtu output</td>
<td>g/kg fuel</td>
<td>Lb/hr</td>
<td>%</td>
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<td>Average of three tests</td>
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Appendix A

Standard Operation Procedures for Thermo 1405 TEOM®
for use in a dilution tunnel or with an extractive dilution system
Version 1.0a, May 17, 2019

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.²

Flow Setting
Recommended flow setting is 0.5 liters per minute (lpm) at EPA STP. If very low PM concentrations consistently less than 5 mg/m³ 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 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

² 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=0B4duMFtoHVUENk9uemxsbHRJezA
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 current data, 30 C represents an appropriate setting.

**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 TX40), 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, download data, and read all key operating parameters easily. The ePort program (ethernet interface) is used to control the instrument remotely and to download data. Both programs 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 concentrations >5 mg/m$^3$: 0.5 lpm
      ii. Anticipated concentrations <5 mg/m$^3$: 1-3 lpm
   b. Calibrate TEOM flows. This step must be completed whenever the flow is changed. An external mass flow meter such as the TSI 4140 is used for flow calibrations.

3. Check the TEOM time and set as needed.
   Changing the time causes an instrument reboot and loss of up to an hour of data. 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.
C. 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.

D. Testing Operations

1. Before initiating the test, run the TEOM while sampling dilution tunnel or diluter air for at least 5 minutes. The change of pressure 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, resets the filter mass measurement, 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 may be different depending on how the data is downloaded.

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. As long as the 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 reported in micrograms, with a resolution of 0.01 micrograms (10^-8 grams).

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 very long time (30 minutes or more) 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 usually 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, the flow should be set to 0.5 LPM. If a high loading burn (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 (PM consistently below 2 to 3 mg/m$^3$).


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 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/m$^3$ range. With care, filter changes can be done such that only a few minutes of data are lost.

The TEOM filter must always be changed before the filter mass loading becomes too high and the filter plugs and the sample flow drops. TEOM filters can also be changed before they overload to minimize negative data.

When TEOM data are the primary data source, The Teom filter gets changed whenever ANY of the following conditions are met. This minimizes negative or negatively biased Teom PM measurements.
2a. Filter plugs
2b. Filter mass loading exceeds 1000 ug AND the filter has been in use for at least 30 minutes. [both conditions have to be met]
2c. Persistent (at least several minutes) negative data of at least -2 mg/m$^3$ is observed that is not due to instrument noise when concentrations are very clean.
For this purpose, negative Teom data should be set to 0 in the final data set.

Filter change procedure.

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.

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: 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 with the RPComm TEOM software. The data file is in .CSV format for importing into a spreadsheet.

Data parameters are saved as follows:
1. Date, Time
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 (temperature on the main TEOM circuit board)
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. Date and 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 in µg/m³. 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 all flows and temperatures are within the defined operating ranges specified below.

1. “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.

2. Flow reported by the instrument should be within 5% of the flow setpoint.

Because of the way the Teom is run here [with a wait time of 0], it never invalidates any data. Thus the data must always be reviewed and cleaned up manually. The wait time is set to 0 to minimize data loss during a filter change, or when the "Cap" temperature is out of range but the data are ok. The Teom reports a concentration of 0 or repeating values when there are no valid data.

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 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., for a clean burn phase that follows a dirty burn phase), and the TEOM filter loses mass. This can be 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 always be set to 0 during data processing. 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 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:

$$PM \text{ at local } T \text{ and } P = PM \text{ at STP} \times \left(\frac{298}{T}\right) \times \left(\frac{P}{29.92}\right)$$

The 1-minute TEOM PM concentration is converted into grams/hour using the stack flow as follows.
Stack flow from the vane anemometer (in m/s at stack temperature) is converted to cubic meters per minute at STP (25 C and 1 ATM.) using the stack diameter and temperature. Flow is then multiplied by Teom PM concentration (at STP) in grams per cubic meter to get PM emission rate in grams per minute. Multiply that by 60 to get grams per hour at 1-minute intervals. The average of all 1-minute PM emission rate measurements is the run-average grams per hour value.

Note: Proportionality with stack flow is not needed for PM emission rates from Teom PM data, since all of the data (stack flow, stack temperature, and PM concentration) are processed into PM emission rates using 1-minute data.

TEOM data can be used to apportion the PM emission rate (g/h) measured by a Method 5G or E2515 regulatory sample train to multiple burn phases by applying a correction factor to the 1-minute Teom data. The correction factor is the ratio of filter pull full run g/h to TEOM full run g/h. The 1-minute TEOM data is then adjusted by this correction factor.

For calculation of lbs/mmbtu, 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. Grams are converted to lbs by multiplying grams by 453.6.

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:

<table>
<thead>
<tr>
<th>PRC</th>
<th>Description</th>
<th>Config Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>storage interval</td>
<td>10</td>
<td>sec</td>
</tr>
<tr>
<td>28</td>
<td>system wait time</td>
<td>0</td>
<td>sec</td>
</tr>
<tr>
<td>35</td>
<td>mass average time</td>
<td>15</td>
<td>sec</td>
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<tr>
<td>48</td>
<td>case temperature set point</td>
<td>30</td>
<td>Deg C or higher as needed to maintain a stable case T</td>
</tr>
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<td>59</td>
<td>cap temperature set point</td>
<td>30</td>
<td>Deg C or higher as needed to maintain a stable case T</td>
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<tr>
<td>74</td>
<td>average temperature set point</td>
<td>25</td>
<td>C</td>
</tr>
<tr>
<td>75</td>
<td>standard temperature set point</td>
<td>25</td>
<td>C</td>
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<tr>
<td>76</td>
<td>average pressure set point</td>
<td>1</td>
<td>atm</td>
</tr>
<tr>
<td>77</td>
<td>standard pressure set point</td>
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<td>atm</td>
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<tr>
<td>91</td>
<td>bypass flow mass set point</td>
<td>0</td>
<td>Can be used as a baseline param for rpcomm plots.</td>
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<tr>
<td>115</td>
<td>TEOMA air tube set point</td>
<td>30</td>
<td>Deg C, or higher as needed to maintain a stable filter T; see also PRC 48 and 59.</td>
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<td>analog output1 minimum</td>
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<td>optional -- ug/m3 as needed for RPComm plot scaling</td>
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<td>optional -- ug/m3 as needed for RPComm plot scaling</td>
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<td>227</td>
<td>TEOMA flow set point</td>
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<td>lpm; or 0.5 to 2 lpm as needed; flow must be recalibrated if changed!</td>
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Note: all 3 temperatures must be set to the same value.
## Data Logging Parameters

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<th>description</th>
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