SUPPLEMENTARY MATERIAL

A Review of Regulatory Standard Test Methods for Residential Wood Heaters and Recommendations for their Advancement

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Table of Contents

S-1 SUMMARY OF STANDARD TESTING METHODS

Table 1. Comparison of standardized wood heater test methods.

Standard Designation (Country of Origin)	Fuel	Emissions Measurement		Overall Efficiency Determination*	Test cycle				Regulated Performance Metric	Ref.
		Pollutants Monitored	Emissions Sampling Method		Pretest	Burn Rates	# of required Burn Cycles per Burn Rate	Burn Cycle End Criteria		
EPA Method 28R (United States)	Crib wood per ASTM E2780-10 with exceptions	PM per ASTM E2515-11 with modifications CO per CSA B415.1-10	Dilution tunnel per ASTM E2515-11	Indirect per CSA B415.1-10	Establish bed of embers within prescribed fuel weight limit; operate ≥ 1 hour with controls set to first burn rate test	1. Maximum: Fully open controls 2. 1.25 to 1.90 kg/hr 3. 0.8 to 1.25 kg/hr 4. < 0.8 kg/hr	1	≥ 2 hrs operation & remaining weight of test fuel is 0.00 kg (0.0 lbs) or less for 30 seconds	g of PM per hr	[1]
ASTM E2779-10 (United States)	Pellets	PM per ASTM E2515-11 with modifications	Dilution Tunnel per ASTM E2515-11	Indirect per CSA B415.1-10	≥ 1 hr operation at max burn rate	1. Max achievable 2. ≤ 50% of max 3. Minimum achievable	1	1. Max: 60 min 2. Med: 120 min 3. Min: 180 min	g of PM per hr	[2]
EPA ALT-140 (United States)	Cordwood	PM per ASTM E2515-11 CO, CO_2	Dilution Tunnel per ASTM E2515-11	Indirect	None stated	1. Start-up 2. High 3. Maintenance 4. Low	3	1. Specified by fuel load calculator 2. 90% test fuel burned 3. 90% test fuel burned 4. 90% test fuel burned	g of PM per hr	[3]
CSA B415.1-10 (Canada)	All biomass fuels (no coal)	PM, CO, CO_2, O_2	Dilution Tunnel	Indirect	≥ 1 hr operation at max burn rate	1. Max burn rate 2. 53% to 76% max 3. 35% to 52% max 4. < 35% max Or use EPA Method 28R burn rates	1	Pellets: ≥ 2 hrs operation Crib and cordwood: remaining weight of test fuel is 0.00 kg (0.0 lbs) or less for 30 seconds	g of PM per hr	[4]
CSA B415.1:22 (Canada)	All biomass fuels (no coal)	PM, CO, CO_2, O_2	Dilution tunnel per ASTM E2515	Indirect	ASTM E2780 for crib wood ASTM E3053 for cordwood ASTM E2779 for pellets	ASTM E2780 for crib wood ASTM E3053 for cordwood ASTM E2779 for pellets	1	ASTM E2780 for crib wood ASTM E3053 for cordwood ASTM E2779 for pellets	g of PM per hr	[5]
ASTM E2780-10 (United States)	Crib wood	PM	Dilution tunnel per ASTM E2515	Indirect per CSA B415.1	Establish bed of embers within prescribed fuel weight limit; operate ≥ 1 hour with controls set to first burn rate test	1. Maximum 2. 1.16 to 1.75 kg/hr or 36%-53% max 3. 0.60 to 1.15 kg/hr or 18% to 35% max	1	Remaining weight of test fuel is 0.00 kg (0.0 lbs) or less for 30 seconds	g of PM per hr	[6]
ASTM E3053-18e2 (United States)	Cordwood	PM	Dilution tunnel per ASTM E2515	Indirect per CSA B415.1	Establish bed of embers within prescribed fuel weight limit; operate with controls set to high burn rate	1. High 2. Medium 3. Low (8 hr or <1.15 kg/h)	1	High: 90 ± 1% of test fuel weight is consumed Medium and Low: 0.00 kg (0.0 lbs) or less for 30 seconds or 90% fuel consumed, no measurable weight loss for 30 min	g of PM per hr	[7]

EN 16510-1:2022 (European Union)	All solid fuels	PM, CO, CO2, O2, NOx, OGC	Flue	Indirect	≥ 1 hr at a burn rate of nominal output or 33 ±5% for wood logs and 25 ± 5% for peat, lignite or briquettes during slow combustion and recovery tests	1. Nominal (≥ 95% of rated value) 2. Partial load that is a function of nominal 3. Slow combustion (specified by manufacturer)	3 for wood-based fuels 2 for all other fuels	Cordwood – test fuel is exhausted or CO_2 criteria met Pellets - minimum cycle duration	PM, CO, NOx, and OGC in mg/m3 and efficiency**	[8]
GB/T 16157-1996/XG1-2017 (China)	Any fuel	PM, CO, CO_2, O_2	Flue	Not applicable: Stack emission measurement standard						[9]
AS/NZS 4012:2014 & AS/NZS 4013:2014 (Australia/NZ)	Cordwood & Coal	PM (CO Optional)	Dilution Tunnel per AS/NZS4013	Direct	Operate at mean average power to establish bed of embers within prescribed fuel weight limit	1. High: Fully open 2. Low: Minimum setting 3. Medium: midpoint of high and low burn time or set using controls	3	±0.5% of test fuel remains	g of PM per kg of fuel burned and efficiency	[10,11]
AS/NZS 5078:2007 & AS/NZS 4886:2007 (Australia/NZ)	Pellets	PM (CO Optional)	Dilution Tunnel per AS/NZS4886	Direct	≥ 1 hr at a burn rate within 10% of first burn rate burn cycle. Must achieve steady-state power output.	1. High: Max setting 2. Low: Minimum setting 3. Medium: ±10% midpoint of high and low burn rate	2	2 hours for each burn rate	g of PM per kg of fuel burned and efficiency	[12,13]
PD 6434:1969 & BS 3841-2:1994 (United Kingdom)	Solid fuels	PM CO, CO2, O2, VOC, and OGC recommended using EN or ISO standards	Dilution Tunnel or electro-static precipitator per BS 3841-2:1994	Only heat output required per Domestic Solid Fuel Appliances Approved Council	Operate heater to achieve steady-state conditions. Ignition emissions are ignored.	1. Rated output 2. Minimum output 3. Intermediate output if available	5	Sufficient to establish the effects, on smoke emission, of accumulations of soot, shale or ash within the appliance if these can occur.	g of PM per hour	[14,15]
NS 3058-1:1994 & NS 3058-2:1994 (Norway)	Crib wood	PM	Dilution Tunnel per NS3058-2:1994	None specified	≥ 1 hr operation at first burn rate settings. weight of charcoal bed must be 20 to 25% of first burn rate fuel charge	Four burn rate categories that depend on heater grade	1	Scale indicates burn cycle fuel is completely consumed	g of PM per hour	[16,17]

* Defined as the total energy content of the fuel consumed minus energy losses through the appliance vent.

** Efficiency is not required to be reported during slow combustion except for appliances which are intended for open and closed door operation

S-1.1 EPA Method 28R: Certification and Auditing of Wood Heaters

EPA Method 28R is a standard test method to certify residential biomass heaters' compliance with the Agency's PM emission limits [1]. EPA's mandatory PM emission limits were set to 4.5 grams per hour from 2015 to 2020, and then reduced to 2.0 grams per hour for heaters sold from May 2020 onwards [18]. These limits apply to heaters both with and without catalytic converters. Heaters tested with unprocessed firewood (cordwood) may emit up to 2.5 grams of PM per hour.

Method 28R provides test procedures for certifying wood-fired room heaters and fireplace inserts using crib wood – a specified grade of dimensional lumber – and incorporates provisions from ASTM E2780-10 (Determining Particulate Matter Emissions from Wood Heaters) [6]. Emissions are sampled following ASTM E2515-11 (Determination of Particulate Matter Emissions Collected by a Dilution Tunnel) with modifications that include leak checking the PM sampling train [19]. Equipment, supplies, and calibration follow EPA Method 5G: Determination of Particulate Matter Emissions from Wood Heaters (Dilution Tunnel Sampling Location) or EPA Method 5H: Determination of Particulate Matter Emissions from Wood Heaters from a Stack Location [20,21]. Although 5G and 5H are not used for the measurement procedure in Method 28R, requests could be made for approved use.

In ASTM E2515-11, emissions from the heater are captured in a conical hood together with ambient air, and a blower draws this mixture through a steel ducting system known as the dilution tunnel [19]. The dilution tunnel consists of three major sections: (1) the mixing section (2) the sampling section and (3) the blower and exhaust section. The mixing section consists of at least two 90-degree elbows to promote complete mixing of the ambient air and heater emissions. Downstream, the sampling section consists of a minimum a long segment of straight ducting (at least 12 diameters in length) that allows the flow velocity profile to fully develop for sampling. The sampling section is fitted with a pitot tube to measure flow velocity, and probes to sample PM and gaseous emissions. Downstream of the sampling section, the blower and damper are adjusted to maintain a set duct flow rates.

Duplicate sample trains, containing two filters in series, are used to collect PM from the gas extracted from the sample section of the dilution tunnel. Samples are extracted at a consistently proportional rate from the sampling point in the center of the dilution tunnel. During sampling, filters cannot exceed 90F. The mass of particulate matter is determined gravimetrically after uncombined water is removed. Total particulate emissions during the test is determined by measuring the total particulate mass collected on the filters and then multiplying by the ratio of dilution tunnel flow to sample flow. The PM mass measurements derived from each of the two sampling trains "shall not differ by more than 7.5 % from the average total emissions value or the difference between the emissions factors for the two trains shall not be greater than 0.5 grams [of PM] per kilogram of dry fuel", otherwise the test results are invalid. If the two sets of PM mass measurements meet these conditions, they are averaged to yield a single emission rate per test run. A third PM sampling train (with only a single aerosol filter) must also be operated in the test facility to monitor background concentrations drawn into the dilution tunnel along with the heater emissions. As a result, a total of 7 gravimetric filters are used for each ASTM test run, as a separate sample is collected during the first hour of operation.

Method 28R uses test fuel cribs made of “untreated, air-dried, Douglas fir lumber” (standard 2x4 and 4x4 pieces used in construction) with a moisture content ranging from 16 to 20% on wet basis [1]. The lumber is nailed together with spacers into specified arrangements such that the fuel loading density is 112 ± 11 kg of fuel per cubic meter of usable firebox volume. The method shows a subset of acceptable crib arrangements. These crib specifications strictly standardize the test fuel charge to help ensure that test results are replicable and comparable across heater models.

Prior to conducting any tests, heaters must be operated at a medium burn rate setting for at least 50 hours. Each test run begins with a ‘Pre-Test Ignition’ burn cycle. During this burn cycle, a fire is lit using the same type of lumber as that used in the test fuel crib and the heater is set to the desired burn rate. The fire is maintained for at least 1 hour with minimal manipulation. The purpose of this Pre-Test is to get the heater up to working temperature and establish a bed of embers prior to loading the burn cycle test fuel. When 20 to 25% of the pre-test fuel remains, the test fuel crib is loaded and the certification test begins. The gravimetric PM sampling commences and various heater parameters, such as mass and surface temperatures, are recorded. The test run continues for at least 2 hours, and ends when the remaining weight of the test fuel charge is 0.00 kg (0.0 lb) or less for at least 30 seconds. The test cycle consists of operating the heater at four burn rates shown in Table S-1. The maximum burn rate is defined as the heater’s primary air inlet and thermostat (where fitted) are adjusted to their maximum settings.

Table S1. Method 28R fuel burn rate categories. At least one burn cycle is conducted at each burn rate category for the duration specified [1].

	Category 1	Category 2	Category 3	Category 4
kg/hr	<0.80	0.80 to 1.25	1.25 to 1.90	Maximum
lbs/hr	< 1.76	1.76 to 2.76	2.76 to 4.19	Maximum

For each of four burn rates, an average PM emission rate is calculated and weighted as a function of the average fuel burn rate (weighted probabilities are provided in Table 28-1 of Method 28). The weighted emission rates are averaged to yield a single PM emission score for certification. Method 28R stipulates that at least 1 test run be conducted in each of the burn rate categories, but multiple test runs may be conducted in any category if desired. If multiple test runs are conducted within a burn rate category, then “the results from at least two-thirds of the test runs in that burn rate category shall be used in calculating the weighted average emission rate.” Ultimately, the weighted average PM emission rate for the test cycle as a whole, and the PM emission and fuel burn rates for each individual test run are the only analytical outputs generated by the Method. If only a single test run is conducted for each burn rate category, the total test cycle duration may exceed 12 hours, as the tests are not run sequentially. After each burn cycle in a specified category, the heater is cooled, emptied and another pre-test is run prior to starting the next burn cycle category.

Overall efficiency of the wood heater is determined using CSA B415.1-10, which provides an indirect method (calculation) [4]. The method requires measurement of exhaust temperature, CO concentrations, and CO_2 concentrations in the heater flue. Additionally the chemical composition of the fuel (oxygen, hydrogen, nitrogen, and carbon mass content) must be cited or measured.

Additional details for the calculating overall efficiency can be found in Method 28R or CSA B415.1-10 [1,4].

S-1.2 ASTM E2779-10: Standard Test Method for Determining Particulate Matter Emissions from Pellet Heaters

ASTM E2778-10 is an EPA approved test method for certifying pellet heaters [2]. Similar to Method 28R, PM emissions are captured and measured using a dilution tunnel, as outlined in ASTM E2515-11 and CSA B415.1-10 is used for determining overall efficiency [1,4,19]. Prior to testing, the heater must be pre-conditioned for at least 50 hours. During pre-conditioning, the heater is operated at a medium burn rate using the same fuel as that used during testing. The test method requires that the fuel's moisture content be measured and recorded, but does not specify an acceptable moisture content range. The fuel's higher heating value should also be determined experimentally according to ASTM E711 [22]. Similar to Method 28R, a 1-hour pre-ignition period is conducted prior to starting consecutive burn cycles at different burn rates [1].

The test consists of three burn rates and at least one burn-cycle is required at each burn rate (see Table S2). The minimum burn rate is when the heater controls (such as primary air intake) are "set to the position(s) as specified in the manufacturer's written instructions to achieve the lowest continuously firing burn rate or a burn rate ≤0.50 dry kg/h, whichever is greater". The inverse is true for maximum burn rate. Test run duration is specified for each burn rate setting, ranging from 60 to 180 minutes. Additional instructions are provided for the testing of heaters with only two settings (high/low), or fitted with automatic control features.

PM emissions are sampled continuously over the course of a single 6 hour test, yielding a single integrated emissions value. The weighted probabilities are constant for each of the test cycles conducted at high, medium, and low burn rates, and is not a function of the average burn rate achieved. If repeated burn-cycles at a burn rate are conducted, then at least two-thirds of the repeated burn-cycles are used in calculating the weighted average emission rate. The test method also notes that specifying precision of the procedure is not possible due to the inherent variability of operation. Therefore, the results cannot be used to determine reproducibility or repeatability of this measurement method. If a single test cycle is conducted for each burn rate, then the test cycle takes a minimum of 7 hours to complete.

Table S2. ASTM E2779-10 fuel burn rate categories. At least one burn cycle is conducted at each burn rate for the duration specified [2].

Burn Rate Segment	Maximum	Medium*	Minimum
Description	Maximum achievable	(Max + Min)/2	Minimum achievable
Time (minutes)	60 +5/-0	120 +5/-0	180 +5/-0

* Medium burn rate reflects recommendations according to EPA ALT-146, as ASTM E2779-10 contained an error stating the medium burn should be ≤ 50% of maximum [23].

S-1.3 EPA Method 140: Integrated Duty Cycle Test Method for Certification of Wood Fired Stoves Using Cordwood: Measurement of Particulate Matter (PM) and Carbon Monoxide (CO) Emissions and Heating Efficiency

EPA ALT-140 is an EPA approved method for certifying wood heaters using cordwood. ALT-140 leverages the Integrated Duty Cycle (IDC) test method developed by Northeast States for Coordinated Air Use Management (NESCAUM) to evaluate emission and performance of wood heaters for the New York State Energy Research and Development Authority (NYSERDA) [3,24]. The method was demonstrated on 13 cord-wood heaters using red maple cordwood and comprised 2 catalytic heaters, 8 non-catalytic (tube and no-tube), and 3 hybrid heaters [25]. Moisture content was also varied for 4 heaters, while fuel-wood species was varied for one heater [26]. In addition to PM, the method measures CO and provides an indirect method for determining overall efficiency.

This method aims to improve efficacy of cordwood testing by using time-resolved PM mass measurements and mimic more realistic operating conditions. The method includes four burn rates or "phases": a start-up, high-fire, maintenance-fire, and a low-burn rate. The high-fire is intended to replicate period when homeowners want to quickly heat an area after starting or restarting the appliance. During this burn cycle, the unit has a small coal-bed and the heaters air settings are fully open. The maintenance-fire burn cycle aims to simulate a user trying to maintain a consistent heat output. This burn cycle uses a medium-sized coal bed and a smaller batch of wood. The low-burn rate burn cycle simulates the user maintaining heat over a long period of time, such as overnight or while away for significant periods of time. During this burn cycle, the heater has a large coal bed and is fully loaded with fuel-wood. The adjustable air settings are set to produce the lowest possible burn rate and have the lowest air settings. For all burn cycles except start-up, the burn cycle ends when 90% of the test fuel has been consumed. For start-up, the NYSERDA Fuel Load Calculator provides the end weight, which is 17.5% of the weight of the high-fire fuel load. Allowable fuel species include maple and birch [3].

Fuel size and loading for each burn rate is determined using the NYSERDA Fuel Load Calculator [3]. The IDC also specifies cordwood size, shape, and loading configuration for each burn rate. For example, rectangular shaped pieces of cordwood are to be split into triangles, and the fuel is loaded parallel to the greater of the width and the depth dimensions for all burn rates except start-up, where the fuel can be "criss-cross." Additionally, at least 75% of the fuel test pieces for the high-fire, maintenance-fire, and low-burn must have at least 80% bark on one side.

Similar to other EPA approved methods, PM emissions are captured and measured using a dilution tunnel following ASTM E2515-11 [19]. The minimum flow rate in the dilution tunnel is listed at 600 cfm, higher than other EPA approved test methods. In addition to gravimetric PM sampling, the IDC method requires two Thermo Fisher 1405-D TEOMs (Tapered element oscillating microbalance) for time-resolved PM mass measurements in the dilution tunnel and the room (ambient). Both TEOMs must be calibrated and operated per the instructions provided in the NYSERDA TEOM SOP and data is collected following the NYSERDA TEOM Data Template [3,27].

Gaseous emissions equipment required for demining overall efficiency follows CSA B415.1-10, however, the calculations for overall efficiency differs [4]. Most notably, the IDC calculates losses for each burn cycle using average gaseous emissions (CO and CO2) for the burn cycle, while CSA B415.1-10 calculates losses throughout the test (each burn cycle) at intervals using gaseous emissions and then averages results at the end of the test.

S-1.4 ASTM E2780-10: Standard Test Method for Determining Particulate Matter Emissions from Wood Heaters

ASTM E2780–10 is similar to EPA Method 28R [1,6]. The method focuses on testing using fuel cribs, and also provides instructions for cordwood testing. For crib wood, instructions are provided for the construction of standardized wood cribs from framing lumber (Douglas Fir). The lumber must have a moisture content of 20 to 25 % on a dry basis, and is nailed together with spacers into prescribed arrangements. Like EPA Method 28R, the crib must be constructed such that the fuel load density is around 112 Kg of fuel per cubic meter of usable firebox volume [1].

For cordwood testing, minimum fuel load density is 162 kg of fuel per cubic meter of usable firebox volume. Each piece of cordwood should have a moisture content ranging from 18 to 28% on a dry basis, and be cut into 20 ± 4 inch-long pieces. The total number of cordwood pieces in the firebox and the acceptable cross sectional dimensions and weight of each piece is defined as a function of firebox volume. The test procedure is the same for both crib and cordwood testing.

PM emissions are measured according to the ASTM E2515-11 [19]. As shown in Table S3, the test requires one burn cycle for each of the three burn rates by int terms of kg of fuel per hour (absolute) or relative to the maximum burn rate that the unit can achieve (% of maximum). Instructions are provided for heaters that have automatic controls or cannot operate below 1.15 kg/hour or 35% of the maximum burn rate. Each test run begins with a pre-burn ignition period, during which a fire is started using kindling and the same fuel as will be used during the test run. The heater is adjusted to the desired burn rate setting and operated for at least one hour with minimal tending. When 20 to 25% of the pre-burn fuel charge remains in the heater, the test fuel charge is loaded, and the test run begins (PM sampling is initiated). The test run ends “when the scale has indicated a test fuel charge weight of 0.00 kg (0.0 lb) or less for 30 seconds.” PM emission rates are calculated for each test run, and then a single weighted average score is computed according using the same procedure as ASTM E2779-10 [2]. The minimum test cycle duration is 9 hours assuming each burn cycle is 2 hours.

Table S3. ASTM E2780-10: Fuel burn rate categories [6]. All three burn rates must be defined in either absolute (Kg/h) or relative terms (% of maximum).

	Minimum	**Medium**	**Maximum**
Absolute (Kg/h)	0.60 to 1.15	1.16 to 1.75	Maximum burn rate
Relative (% of maximum)	18 to 35	36 to 53	100

S-1.5 ASTM E3053-18e2: Determining Particulate Matter Emissions from Wood Heaters Using Cordwood Test Fuel

ASTM E3053-18e2 is designed for measuring PM emissions from wood-burning room heaters and fireplace inserts using cordwood, and provides options for determining heat output, efficiency, and carbon monoxide emissions [7]. Similar to the EPA approved methods (although this method is no longer EPA approved), PM emissions are captured in a dilution tunnel following ASTM E2515-11; CSA B415.1-10 is used for determining overall efficiency; and the heater is operated at least 50 hours at medium combustion air setting with cordwood (moisture content between 18 and 28% dry basis) prior to starting tests [4,19,28]. Any cordwood fuel species may be used as long as the specific gravity is between 0.48 and 0.73 on a dry basis. The test method also allows mixtures of cordwood species.

For each test, at least one burn cycle at three burn rates (or category) is required and the test are run consecutively or "hot-to-hot." The burn rates include high-fire, medium-fire, and low-fire. The high-fire includes a cold start and high burn rate operation where the primary combustion air is positioned to the highest setting. The test ends with 90 ± 1% of the test fuel load weight is consumed. For the medium-fire, the primary combustion air is set to no greater than halfway between the lowest and highest settings, as measured on the control actuator. The fuel load is added onto the remaining coal bed from the high-fire burn cycle. The test ends when the test fuel weight is 0.00 kg (0.0 lb) or less for 30 seconds or at least 90% of the test fuel weight has been consumed and no measurable weight loss (<0.05 kg (0.1 lbs) or 1.0% of the test fuel weight, whichever is greater) occurs for at least 30 min. The low-fire burn rate requires primary combustion air to be set to the lowest airflow position or a setting that results in a burn time of at least 8 hours or a minimum burn-rate of 1.15 kg/hr. Similar to the medium-fire, the low-fire test fuel is loaded onto the remaining coal bed from the high-fire burn cycles. Fuel load densities for each burn rate is provided in Table S4.

The calculate PM emissions for certification, a weighted average is used for each burn rate category. Specifically, 20% of the average PM during the start-up/high-fire burn rate plus 40% of the average PM during the low- and medium-fire burn rates. The minimum test cycle duration is 12 hours assuming the high and medium-fire burn rates take 2 hours and the low-fire burn rate takes 8 hours.

Table S4. ASTM E3053-18e2 burn rate categories based on fuel density [7]. The total amount of fuel for each burn rate is determined by multiplying the fuel density by the usable firebox volume. At least one burn cycle must be conducted for each burn rate.

	High	**Medium**	**Low**
Fuel Density	10 lb/ft^3	12 lb/ft^3	12 lb/ft^3
Air controls	Highest position	Halfway	Lowest position

S-1.6 CSA B415.1-10: Performance testing of solid-fuel burning heating appliances

CSA B415.1:22 supersedes CSA B415.1-10, however, EPA Method 28R and several ASTM methods point to CSA B415.1-10 for efficiency calculations [1,2,4–7]. Therefore, a summary of CSA B415.1-10 is included in this paper for completeness.

CSA B415.1-10 is structurally very similar to EPA Method 28R, and follows many of the same fundamental procedures for PM emission measurement [1,4]. The method requires a dilution tunnel to capture and sample the heater emissions, and does not provide alternate instructions for sampling directly from the flue. PM concentrations in the dilution tunnel are measured gravimetrically using two filters in series. Two replicate sampling trains are required, and the two sets of PM concentration measurements must meet the same criteria as outlined in ASTM E2515-11 [19].

The test cycle consists of four test runs, each conducted at a different burn rate. Burn rates for each test run are defined in both absolute terms (kg/hr) and as a percentage of the maximum achievable burn rate in Table S5 below. Note that the absolute burn rate limits for each category are the same as that used in EPA Method 28 [29]. Test cycles are also defined for thermostatically controlled appliances that do not allow direct modulation of the burn rate.

Table S5. CSA B415.1-10 fuel burn rate categories [4]. All four test runs must be defined in either absolute (Kg/h) or relative terms (% of maximum).

	Category 1	Category 2	Category 3	Category 4
Absolute (Kg/h)	≤ 0.80	0.81 to 1.25	1.26 to 1.90	Maximum
Relative (% of maximum)	< 35	36 to 52	53 to 76	100

Firewood heaters may be tested using cordwood or cribs. Cordwood should preferably be Douglas Fir, as fuel specifications are provided in the test method for this wood species (chemical composition, etc.), and must have a specific gravity ranging from 0.60 to 0.73 and moisture content of 18 to 28% on a dry basis. For pellet heater testing, "the test fuel shall be wood pellets of each grade specified by the manufacturer with a moisture content not greater than 8% wet basis"[4]. A sample of the test fuel should be analyzed for moisture content, chemical composition, and higher heating value.

CSA B415.1-10 also provides instructions for measuring the heater's gaseous pollutant emissions and thermal efficiency [4]. Time-resolved CO and CO_2 analyzers sample flue emissions through a probe installed 50 mm above the thermocouple. Using this gas concentration data, the fuel's chemical composition specifications and burn rate measurements, chemical and thermal energy losses through the flue are calculated. The energy delivered by the heater is taken as the difference between the fuel energy input and the calculated losses through the flue. Thermal efficiency is the ratio of energy delivered relative to the fuel energy input. Since the energy delivered by the heater is not measured directly, this approach is known as the 'indirect method' for thermal efficiency determination. Using this same dataset, total CO mass emissions are calculated, and reported in grams per MJ of energy delivered during each test run. The test method also includes two alternative methods for thermal efficiency characterization: (1) The total combustible carbon method, which is largely similar to the indirect method except that the CO analyzer is replaced by a combustor system to convert all available carbon in the flue to CO_2, and (2) the direct method for central furnaces, in which the temperate and flow rate of air is monitored to determine the furnace's useful energy output.

The PM emission rate from each of the 4 test runs is weighted as a function of burn rate and averaged exactly as outlined in EPA Method 28 (the weighted probabilities and calculation method are identical) [29]. Multiple test runs may be conducted in any of the burn rate categories. The test method defines acceptable PM emission rate limits for each individual test run and the weighted average rate for the entire test cycle, as shown in Table S6. Overall, CSA B415.1-10 characterizes the heater's PM emissions, CO emissions, and thermal efficiency. If only a single test run is conducted for each burn rate setting, the test cycle takes a minimum of 12 hours to complete.

Table S6. CSA B415.1-10 particulate matter (PM) emission limits for wood and pellet heaters, shown both for each test run (a) and for the weighted test cycle average (b) [4].

(a) PM Limits for each test run

Without Catalytic Converter	**Burn rate (kg/h)**	≤ 1.5	1.6 to 8.3	> 8.3
	PM limit	15 g/h	18 g/h	0.20 g/MJ
With Catalytic Converter	**Burn rate (kg/h)**	≤ 2.82	2.83 to 8.3	> 8.3
	PM limit	3.55BR + 4.98 g/h	15 g/h	0.20 g/MJ

(b) PM Limits for test cycle weighted-average

Without Catalytic Converter	4.5 g/h or 0.137 g/MJ
With Catalytic Converter	2.5 g/h or 0.137 g/MJ

S-1.7 CSA B415.1:22: Performance testing of solid-fuel burning heating appliances

CSA B415.1:22 is the updated Canadian standard for testing solid-fuel burning heating appliances, including site-built heating appliances (e.g., fireplaces), room heaters, forced-air furnaces, hydronic heaters, and hybrid appliances [5]. It should be noted that Canada does not currently regulate emissions of wood heaters. Since superseding CSA B415.1-10, CSA B415.1:22 references several other test methods for conducting certification testing of room heaters [4,5]. For example, ASTM E2780 is used for crib wood testing, ASTM E3053 is used for cordwood testing, and ASTM E2779 is used for pellet testing [2,6,7]. Similar to other methods, emissions are sampled using a dilution tunnel following ASTM E2515 [19]. Emission limits are reported in g/h or g/MJ output.

Metrics reported for room heaters are heat outputs, efficiencies, emission levels and composition, and electrical energy consumption and production. Heat outputs reported include delivered, nominal, overall, and space, while efficiencies reported include appliance, combustion, delivered, heat transfer, and overall. Procedures are provided for calculating heat outputs and efficiencies. No thermal performance limits are specified for room heaters. For emissions, PM and CO are reported but only PM is required to meet specified limits. Specifically, a room heater tested with cordwood mush have an average PM emission rate ≤ 2.5 g/h (or 0.15 g/MJ output). Room heaters tested with crib wood or any processed solid biofuel (e.g., pellets or chips), must have an average PM emission rate ≤ 2.0 g/h (or 0.15 g/MJ output).

S-1.8 EN 16510:2022 Residential solid fuel burning appliances Part 1: General requirements and test methods

EN 16510-1:2022 is a European approved method for certifying residential solid fuel burning appliances including wood heaters (room heaters, inset appliances, cookers, boilers, and slow heat release appliances) [8]. In 2021, an initiative to harmonize European test methods for wood-fired room heating appliances occurred and several compliance standards were superseded by EN 16510-1:2022 and its constituents [8,30,31].

EN 16510 includes, Residential solid fuel burning appliances included parts 1: General requires and test methods; 2-1: Room heaters; 2-2 Inset appliances including open fires; 2-3: Cookers; 2-4 Independent boilers — Nominal heat output up to 50 kW; 2-5: Slow heat release appliances; 2-6: Appliances fired by wood pellets. In general, EN-16510-1:2022 set forth specific requirements and methodologies for measuring parameters such as thermal output, combustion efficiency, carbon monoxide (CO) emissions, and particle matter (PM) emissions. The method also addresses safety aspects, including the evaluation of temperature control, appliance stability, and external surface temperatures. Specifically, the following test methods that were withdrawn and those that superseded them include:

- EN 13240: Room heaters fired by solid fuel replaced by EN 16510-1:2022 and EN 16510-2-1:2022 Residential solid fuel burning appliances - Part 2-1: Room heaters
- EN 13229: Inset appliances including open fires fired by solid fuel replaced by EN 16510-1:2022 and EN 16510-2-2:2022 Residential solid fuel burning appliances - Part 2-2: Inset appliances including open fires
- EN 12815: Residential cookers fired by solid fuel replaced by EN 16510-1:2022 and EN 16510-2-3:2022 Residential solid fuel burning appliances - Part 2-3: Cookers
- EN 12809: Residential independent boilers fired by solid fuel - Nominal heat output up to 50 kW replaced by EN 16510-1:2022 and EN 16510-2-4:2022 Residential solid fuel burning appliances - Part 2-4: Independent boilers - Nominal heat output up to 50 kW
- EN 14785: Residential space heating appliances fired by wood pellets replaced by EN 16510-2-6:2022

In the following years, it is expected EN 15250:2007 will be replaced by EN 16510-2-5 Residential solid fuel burning appliances – Part 2-5: Slow heat release appliances and EN 15821:210 will be replaced as laid out in the Standardization Request M/577 [30,31].

EN 16510-1:2022 now follows the EN-PME method which require PM, organic gaseous compounds (OGCs) and other gaseous emissions to be measured directly from the stack—no longer requiring the use of a dilution tunnel and ESP as previous versions had incorporated for national measurements [32]. The method requires the appliances to be operated at their nominal output rate (> 95% of manufacturer's rating), partial load (determined by appliances maximum output), and slow combustion. The partial loads (P_{part}) are calculated as follows:

$$P_{part} < 0.4 \times P_{nom} + 2kw \text{ for appliances} \geq 5\text{kW}$$
$$P_{part} < 0.8 \times P_{nom} \text{ for appliances} < 5\text{kW}$$

Solid woody biomass fuels include the use of cordwood (birch, beech, or hornbeam), pellets, and briquettes (compressed wood, peat or lignite) —both with specified values such as calorific content, moisture content, ash value, and volatile matter. Fuel loading is determined by the calorific value of the fuel, nominal heat output, minimum efficiency, and minimum refueling interval. The method requires triplicates at each burn rate for cordwood and duplicates of all other fuels. Burn rates for replicate burn cycles must be within 10%.

Previously, three methods for PM emission determination were used in EN 16510-1:2018—Austrian and German particle test method (DINplus), Norwegian particle test method (NS 3058) and UK particle test method [33]. EN 16510-1:2022 recommends the EN-PME test method where emission sample lines, the filter, and filter holder are heated 180 °C (356 °F) to prevent moisture condensation and particle loss [8,32,34]. To measure OGCs, a pre-filter is set to 180 °C (356 °F) followed by a heated sample line set to a temperature above 180 °C (356 °F) to avoid condensation of OGCs. The sample then enters an instrument to measure water content of the flue gas and then passes through a flame ionization detector operating at 180 °C (356 °F) to measure OGC content. Because all emissions are sampled hot, PM mass collected and OGC measurements may not mimic emissions exhausted into the atmosphere [8]. This new sampling method was likely influenced by previous research investigating different PM sampling methods from wood heaters [35], as EN 16510-1:2022 no longer includes requirements for sampling PM from the dilution tunnel and sampling PM isokinetically.

EN 16510-1:2022 test methods also facilitate the establishment of energy labeling schemes and eco-design requirements for wood heaters. Specifically, thresholds for CO, NOx, OGC, and PM are provided based on appliance type and minimum seasonal space heating efficiency values are required to be met or exceeded. Further, appliances are classified based on their calculated energy efficiency index (EEI) [8].

S-1.9 AS/NZS 4012:2014 Domestic solid fuel burning appliances–Method for determination of power output and efficiency and AS/NZS 4013:2014 Domestic solid fuel burning appliances–Method for determination of flue gas emission

AS/NZS 4012:2014 and AS/NZS 4013:2014 are used for certifying cordwood, coal, and combination heaters (free standing and fireplace inserts) used in Australia and New Zealand [10,11]. AS/NZS4012:2014 is used for evaluating power output and efficiency of cordwood heaters while AS/NZS 4013:2014 is used for sampling emissions.

AS/NZS 4012:2014 provides the fuel load for each burn rate as a function of the firebox volume and provides specifications for wood piece dimensions. Wood species is defined by the manufacturer or AS/NZS 4014.1 [36]. The method recommends conditioning the appliance by operating it at the highest burn rate for at least two separate 8 hr burn periods for non-catalytic heaters and at least three separate 8 hr burn periods for catalytic heaters. AS/NZS 4012:2014 requires conducting a pre-burn cycle to ensure conditions at the beginning of a burn cycle are similar to conditions at the end, and to establish a bed of embers prior to starting the burn rate. Next, the method requires operating the heater at three burn rates (high, low, and medium) and conducting three replicate burn cycles for each burn rate. Overall efficiency is determined directly using a calorimeter room.

AS/NZS 4013:2014 requires a dilution tunnel for sampling PM emissions. PM emission factors for the three replicate tests at each burn rate are averaged [11]. The reported PM emission factor is the average (i.e., arithmetic mean) of the average PM emission factors determined for each burn rate. The methods require reporting the following metrics: maximum average heat output; overall average efficiency; and particulate emission factor (g of PM/kg of fuel). PM emissions limits in Australia are 2.5 g/kg for heaters without a catalyst, and 1.5 g/kg for heaters with a catalyst. In New Zealand, PM emission limits are 1.5 g/kg for all heaters.

S-1.10 AS/NZS 5078:2007 Domestic solid fuel burning appliances–Pellet heaters–Method for determination of power output and efficiency and AS/NZS 4886:2007 Domestic solid fuel burning appliances–Pellet heaters–Determination of flue gas emission

AS/NZS 5078:2007 and AS/NZS 4886:2007 are used for certifying pellet heaters used in Australia and New Zealand [12,13]. Although these test methods are available, pellet heaters are not regulated in Australia or New Zealand because most pellet heaters are imported from Europe and come with certifications (i.e., EN 16510-1:2022) [8]. AS/NZS 5078:2007 provides procedures for evaluating power output and efficiency of pellet heaters while AS/NZS 4886:2007 provides procedures for sampling emissions. Pellet type/species is defined by the manufacturer or AS/NZS 4014.6 [37].

The test procedures and emissions sampling system are almost identical to AS/NZS 4012:2014 and AS/NZS 4013:2014 [10,11]. AS/NZS 5078:2007 requires a pre-burn cycle for a minimum of one hour to ensure the heater reaches steady-state operating conditions. The test method requires two replicate burn cycles at three different burn rates (high, low, and medium), operating for at least 2 hours at each burn rate. The tests method also provides instructions for operating heaters with burn-rate control systems, fans, other controls, and automatic controls. Overall efficiency is determined directly using a calorimeter room.

AS/NZS 4886:2007 requires the same dilution tunnel system for sampling PM as AS/NZS 4013:2014 [11,13]. PM emission factors for the two replicate tests at each burn rate are averaged [13]. The reported PM emission factor is the average (i.e., arithmetic mean) of the average PM emission factors determined for each burn rate. The methods require reporting the following metrics: maximum average heat output; overall average efficiency; and particulate emission factor (g of PM/kg of fuel).

S-1.11 GB/T 16157-1996: The determination of particulates and sampling methods of gaseous pollutants emitted from exhaust gas of stationary source

GB/T 16157-1996 is a Chinese standard test method that is not specific to residential heaters, but rather describes procedures for measuring pollutant emissions from stationary exhaust stacks in general [9]. As such, the test method does not specify a heater test cycle, requisite fuel properties, or performance metrics. The PM sampling probe incorporates a gravimetric filter cartridge and housing, located directly in the flue. The cartridge is made of glass fibers and functions in exactly the same way as a standard gravimetric filter: the cartridge is conditioned and weighed both before and after sampling, and the difference between the two weight measurements represents the mass of PM collected. Downstream of the gravimetric filter probe, a dryer, valve, rotameter and dry gas meter condition and measure the flow rate of flue gases drawn through the system by a vacuum pump. Throughout testing, the flow velocities in the PM sample probe and flue must be equal (isokinetic sampling condition). Flue flow velocity is measured using either a standard or S-type pitot tube, and the PM sample flow rate is adjusted accordingly.

GB/T 16157-1996 also provides procedures for the measurement of gaseous pollutants. One method utilizes an Albright gas analyzer: bottles filled with various chemical reagents absorb specific gaseous species from a fixed volume to determine concentrations of each in the sample. This method is out of date, and will not be detailed here. The test method also provides instructions for sampling gaseous emissions using time-resolved monitors. Exhaust is drawn from the stack through a heated probe and sample lines and then passes through a dehumidifier to prevent condensation. This dried sample gas passes through a vacuum pump and is exhausted to the gas analyzer. The flow rate of sample gas is not monitored. Probe material and temperature specifications are provided for 16 gaseous pollutants including CO_2, CO, and NOx.

To the best of the authors' knowledge, there are no Chinese test methods specifically dedicated to the evaluation of solid-fueled residential heaters. However, test methods are provided for other combustion appliances, such as cookstoves and boilers. For example, GB 5468-1 outlines a test cycle for characterizing PM emissions from boilers [38]. During each test, the boiler is operated at a firepower $\geq$ 70% of the maximum setting, and emissions are sampled during the combustion of one full fuel batch (firepower is proportional to fuel burn rate). At least two replicate tests must be conducted. The average PM mass emission rate during each test is calculated and weighted as a function of the boiler's test-average firepower. Greater weights are assigned to lower firepower settings, thereby normalizing the lower PM emission rates that naturally result from lower fuel burn rates. Interestingly, higher weights are defined for boilers that are less than 3 years old, effectively 'penalizing' these younger appliances' operation at lower firepower settings. Regulatory limits for boiler emissions are specified in a separate document (GB 13271 – 2014: Emission standard of air pollutants for boiler). Although the test methods provide procedures for calculating the mass emission rate of air pollutants from the boiler, emission limits for PM, SO_2, NOx, and mercury compounds are all defined in terms of average mass concentrations in the flue [39]. Separate emissions limits must be followed depending on the boiler's fuel (coal, fuel oil, or natural gas) and age (newly-built or in-use). In this way, China has test methods in place to regulate solid-fueled combustion appliances, many of which could be readily adapted to residential heaters.

S-1.12 PD 6434:1969 The design and testing of smoke reducing solid fuel burning domestic appliances and BS 3841-2:1994 Determination of smoke emissions from manufactured solid fuels for domestic use – Part 2: Methods for measuring the smoke emission rate

PD 6434:1969 and BS 3841-2:1994 are approved test methods in the UK used for classifying appliances as "exempt" for use in smoke control areas [14,15,40].

PD 6434:1969, requires five burn cycles at each burn rate, with the smoke emissions in grams per hour and the heat output in watts (Btu/h) calculated and averaged over the test duration. The average results from the five sets of tests for each condition are then averaged again. The mean smoke emission should not exceed 0.1 g/h for each 0.3 kW of heat output. If any individual smoke measurement in a set of five tests exceeds 50% of the permitted mean value for that set, it is required to be reported separately while still being included in the overall calculated mean [14].

BS 3841-2:1994 is applicable to various types of appliances, including those suitable for individual rooms, whole houses, cookers, space heaters, and hot water supply [15]. The test method outlines two methods for measuring smoke emission rates from solid fuel: the electrostatic precipitator (ESP) method and the dilution tunnel method. The ESP method collects and measures particulate matter from the entire volume of flue gas generated during the test period. The mass of smoke emitted is determined by weighing the precipitator before and after the test.

On the other hand, the dilution tunnel method involves isokinetic sampling of diluted flue gas, with the particulate matter collected on a glass fiber filter. The mass of particulate matter is then calculated. Both methods are capable of measuring smoke emissions within the range of 0.5 g/h to 30 g/h and are known to provide consistent results. The optical density of the smoke is also monitored across the test chimney. Once it has been determined that the appliance can operate continuously without causing any significant issues for the user, any smoke produced during the ignition can be disregarded. The tests will be conducted under conditions that closely resemble the steady state operation of the appliance and carried out following the manufacturer's instructions, both at the rated output and at the lower end of its output range [15].

S-1.13 NS 3058-1:1994 Enclosed wood heaters smoke emissions Part 1: Test facility and heating pattern and NS3058-2:1994 Enclosed wood heaters smoke emissions Part 2: Determination of particulate emissions

NS 3058-1:1994 and NS 3058-1:1994 are approved test methods published in 1994 for evaluating wood heaters in Norway [16,17]. Similar to other published methods, emissions are sampled using a dilution tunnel. Unlike other systems, mixing baffles are required between the two 90° sections that connect the hood to the long straight ducting with the sampling section. PM emissions are sampled from the dilution tunnel using a sampling train similar to other methods with a proportionality ratio varying no more than 10% [1,5,6]. Emission rates are reported in g of PM per hour.

For each burn cycle, the amount of wood used is determined by the dimensions of the firebox and the fuel charge density must be 112 ± 11 kg/m^3. The required test fuel is dimensional lumber made of air-dried spruce. A test crib is made using a steel stitcher and two spacers. Moisture content of the wood must be between 16% and 20% on a wet basis or 19% and 25% on a dry basis. Heaters are tested at four different burn rate categories that depend on the heater grade. The heater grade is determined according to the lowest burn rate category. For example, a grade 1 heater will be tested at average burn rates of <0.80 kg/hr, 0.80 to 1.25 kg/hr, 1.26 to 1.90 kg/hr, and >1.90 kg/hr. For the three lowest burn rates, primary air supply is varied to achieve the desired average burn rate. For the highest burn rate, the primary air supply inlet control is fully open, or at maximum. Prior to starting the burn rate burn cycles, the heater is started using the manufacturer's instructions and operated at least one hour at the air supply control setting needed to achieve the first burn rate test. The weight of the charcoal pieces from this pretest must be within a 20 to 25% of the burn cycle fuel charge prior to starting the test. The surface temperature of the heater cannot vary more than 70 °C between the beginning and end of a burn cycle. The burn cycle is complete when the scale indicates that the fuel has been completely consumed.

It should be noted that Norway has kept its standardized test methods (NS 3058-1:1994 and NS 3058-1:1994) due to several concerns with EN 16510-1:2022 [8,16,17]. For example, the EN-PME method for sampling emissions does not adequately measure all PM emissions emitted by wood heaters and does not correlate with NS 3058-2 [17,32,33]. Researchers argue that the EN-PME method fails to capture the full range of PM emissions, including the significant contribution from the condensable fraction as OGC measured by flame ionization detector is not a measure of condensed PM in the flue gas, which has implications for environmental impact, climate change, and human health considerations [41]. More specifically, the direct comparison of the emission values of EN-PME sampling method and NS 3058-2 in parallel showed that emissions from the NS measurements with dilution tunnel were all 7 times higher. Their work showed even for heaters with low emissions, the EN-PME test underrepresents the emissions associated with condensing PM and unburned gases. Kausch et al. specifically point out that the measurement of OGC is not a good indicator for all the PM formed in the atmosphere as it contains methane which will not form particles as it does not condense [41].

Researchers also argued that the EN-PME method does not meet the Ecodesign Mandate which requires PM_{total}, not PM_{10} as the 90 ° sample angle may miss some particles and the PM emissions are not sampled isokinetically therefore, the PM concentration in the flue gas cannot be derived from the mass of PM collected on the filter. Counter arguments have been made that low flue gas velocities (below 2 m/s) make precise isokinetic sampling impossible [32].

Furthermore, NS 3058-1 tests appliances with natural draught while EN 16510-1:2022 requires a forced draught value based on the appliance's nominal output [8,16]. While a controlled draught allows for precise control of the draught conditions establishing accurate measurements of efficiency and emissions testing and providing a standardized condition for comparing different wood heater models to assess their performance against established criteria, it does not reflect residential operating conditions. Natural draught reflects residential operating conditions, as wood heaters in everyday use typically rely on natural airflow for combustion. Natural draught testing provides insights into the heater's performance under realistic conditions, considering factors such as chimney height, outdoor temperature, wind conditions, and other environmental variables. Ultimately, the efficiency and burn rate are affected by the draught owed to the amount of air supplied to the combustion process and rate at which the fuel is consumed, respectively. Perhaps simulating natural draught in a laboratory as Krüger et al. did using low-cost instrumentation such as thermocouples and pressure sensors would provide reproducible and more realistic conditions over a range of conditions [42].

S-1.14 beReal: Advanced Testing Methods for Better Real Life Performance of Biomass Room Heating Appliances

Standardized test methods for wood heaters primarily serve as an accurate and replicable means of characterizing thermal performance and emissions under controlled laboratory conditions. While these laboratory testing results are useful for demonstrating regulatory compliance, they may not be representative of actual heater performance in the field. The beReal test method attempts to address this disparity by defining a heater testing cycle that more closely approximates operating conditions in users' residences. Although the beReal method is currently just a draft not enforced by any standards organizations, it provides a valuable opportunity to explore different approaches to heater testing.

To inform the development of the beReal test cycle, a survey was conducted with over 2000 European households to determine the prevalence of different heater types and establish typical patterns of operation. The report shows survey responses regarding the households' reliance on solid-fueled heaters as a primary heat source, and heater operation habits (power level setting). Furthermore, heater usage was directly monitored in about 30 households, and the resulting records of user behavior are used to ground the survey results [43].

Using the heater survey and monitoring results, the researchers define separate test cycles for pellet and firewood heaters. Emissions are sampled directly from the heater flue using a measurement section that is identical to that used in EN 16510, except for the location of the PM sample probe. PM emissions are sampled downstream of the gaseous pollutant analyzers (rather than upstream) because the gravimetric filters must be changed during the test run, resulting in flue leakage that would otherwise affect the time-resolved CO, CO_2, O_2, NOx, and organic gaseous compound (OGC) concentration measurements. PM and gaseous emissions are monitored according to the procedures presented in EN 16510, but flue gas velocity (and therefore, flow rate) is measured using a pitot tube fitted downstream of the measurement section, rather than determined indirectly from the fuel composition and burn rate data [44].

The pellet heater test cycle consists of four distinct burn cycles. During Burn cycle 1a, a fire is ignited in the cold heater and operated at maximum heat output (or 'load') for 50 minutes. The heater's combustion air inlet is then closed so the heat output is reduced to ~30% of the maximum value. The heater is operated at this partial load setting for 90 minutes and shutdown (Burn cycle 1b). The heater is allowed to cool down for 40 minutes before a new fire is ignited and maintained at maximum heat output for 50 minutes (Burn cycle 2). Following another shutdown and 40 minute standby period, the heater is operated at 65% heat output for 180 minutes during Burn cycle 3. Separate gravimetric PM filters are collected during each of the four burn cycles, and gas concentrations are measured continuously throughout the cycle. Burn cycles 1a, 2, and 3 begin when CO concentrations in the flue reach 10 ppm and end after the specified duration has elapsed. Gaseous pollutant concentrations in the flue are measured continuously throughout the test cycle. Gravimetric PM sampling starts when the heater is ignited (except Burn cycle 1b) and ends when O_2 concentrations in the flue reach 20% following shutdown (except Burn cycle 1a). In this way, pollutants emissions are monitored during the ignition and shutdown periods typically excluded by other test cycles [44].

Except for some minor geometric differences, the experimental set up for firewood heater testing is functionally identical to that used for pellet heaters and will not be described here. During the firewood heater test cycle, eight fuel batches are burned consecutively. For the first five batches, the mass of fuel and combustion air controls are set according to the manufacturer's instructions for nominal heat output. For the last three batches, the heater is loaded with 50% of the fuel mass used during the nominal batches and operated at partial heat output. The batch ends and the next test fuel charge is loaded when CO_2 concentrations in the flue drop to 25% of the maximum concentration measured during the batch. When the maximum CO_2 concentration is below 12% or above 16%, the batch ends when CO_2 concentrations fall to 3% or 4%, respectively. The test cycle ends after Batch 8, when flue gas temperatures fall to 50 °C. Time-resolved gaseous pollutant concentrations in the flue are measured throughout the test cycle. Gravimetric PM emission measurements are only collected during batches 1, 3, 5, and 7.

The beReal test cycle includes a wide variety of heater operating conditions, such as cold/warm starts, high/low burn rate, varying fuel loads, and transient periods that naturally occur during normal use (ignition/shut down). Average pollutant concentrations are calculated for each of the burn cycles, and normalized to 13% oxygen content. Heat output and thermal efficiency are also calculated indirectly for all burn cycles. For each test cycle, a single weighted-average concentration value is reported "by weighting the results derived in the single measurement burn cycles according to their produced flue gas volumes" [44]. Overall, the beReal method enables characterization of the heater's thermal performance and PM, CO, CO_2, O_2, NOx, and OGC emissions. For pellet heaters, each test cycles take 7.5 hours to complete. The firewood test cycle duration depends on the eight fuel batches' burn times.

S-2 SUPPORTING MATERIALS FOR RECOMMENDATIONS

S-2.1 Supporting equations for direct dilution control

The proportionality ratio (*PR*) is defined as the ratio of the exhaust flow rate through the flue ($\dot{m}_{flue}$) and the flow rate of exhaust sampled through the instrumentation probe ($\dot{m}_{probe}$).

$$PR = \frac{\dot{m}_{flue}}{\dot{m}_{probe}} \qquad \text{(S1)}$$

The proportionality ratio must be held constant throughout the test run. When operating the direct dilution system illustrated in Section 3.1, the flow rates of clean dilution air ($\dot{m}_{dilution}$) and total diluted sample provided to the instrumentation suite ($\dot{m}_{instruments}$) are modulated to achieve a desired dilution ratio (*DR*) while maintaining a constant proportionality ratio. The equations needed to set these two flow rate values are provided below in Equations S2 and S3.

$$\dot{m}_{dilution} = \dot{m}_{flue}\left(\frac{DR}{PR}\right) \qquad (S2)$$

$$\dot{m}_{instruments} = \dot{m}_{dilution}\left(\frac{DR+1}{DR}\right) \qquad (S3)$$

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