SUPPLEMENTARY MATERIAL

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

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S-1 SUMMARY OF STANDARD TESTING METHODS

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

EPA Method 28 is a standard testing protocol to certify residential biomass heaters' compliance with the Agency's PM emission limits. These 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. 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 [1].

EPA Method 28 provides standard test procedures to characterize PM mass emission rates from both wood and pellet heaters. The heater is mounted on platform scale with 0.1-lbs resolution to monitor the fuel burn rate during testing, and fitted with a steel flue pipe that extends 8.5 feet (2.6 m) above the scale. Above the steel flue pipe, an insulated chimney section extends to a total height of 15 feet (4.6 m) above the scale [2]. Emissions may be measured using one of two standard methods: (1) EPA Method 5G: Determination of Particulate Matter Emissions from Wood Heaters (Dilution Tunnel Sampling Location) or (2) EPA Method 5H: Determination of Particulate Matter Emissions from Wood Heaters from a Stack Location [3,4].

In Method 5G, 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. 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 and has baffles to promote complete mixing of the ambient air and heater emissions. Downstream, the sampling section is a 9-foot long segment of straight ducting 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 duct flow rate of 4 ± 0.4 m^3/min.

Method 5G outlines three sampling train options for gravimetric PM measurement. During gravimetric PM measurement, air is pulled through an aerosol filter at a known flow rate. The aerosol filter is weighed both before and after the sampling event, and the difference between the two sets of measurements represents the mass of PM captured on the filter. The average PM concentration during the sampling period is calculated using measurements of the PM mass collected and the total air volume sampled. In this review, we only describe the first of three sampling train options: One dual-filter dry sampling train operated at about 0.015 m^3/min (0.5 CFM). The other two options are described briefly in the standard, and provide the same overall result.

The PM sampling train starts with a stainless steel probe centered in the dilution tunnel, in line with the flow [3]. Emissions are drawn from the probe through two "glass fiber filters with a minimum diameter of 100 mm (4 in.), without organic binder, exhibiting at least 99.95 percent [PM filtration] efficiency" [3]. The two filters are mounted in series, with a temperature sensor placed between the two. The flow temperature at this point must be maintained below 32 ºC throughout testing. Following the filter assembly, the sample flow passes through a dryer, vacuum pump, and dry gas meter to measure the total air volume sampled. The sample flow rate through the train is set to around 0.015 m^3/min, and adjusted through testing such that the ratio of the flow velocities in the PM probe and dilution tunnel is held constant. The mass of PM collected on both filters in series is determined separately and summed.

Method 5H provides instructions for measuring PM emissions directly from the heater flue. In this method, a stainless steel PM sample probe is mounted in line with the flue's central axis. The exhaust flow rate is determined by measuring CO and CO_2 concentrations in the flue, and performing a carbon mass balance that accounts for the fuel burned. For this calculation, the wood is "assumed to have the following weight percent composition: 51 percent carbon, 7.3 percent hydrogen, 41 percent oxygen" [4]. Alternatively, the exhaust flow rate exhaust can be determined by injecting a tracer gas (SO_2) of known concentration into the flue at a constant rate. The tracer gas mixes with the exhaust, and the resulting concentration is measured further downstream to determine the exhaust flow rate through the flue.

The PM sampling train is largely similar to that used in Method 5G. The sample flow passes through two aerosol filters in series, but there is a set of impingers mounted between the two. The filter closest to the probe is mounted in a heated box maintained at a temperature no higher than 120 ºC. The probe and sample lines are both heated to the same temperature to prevent condensation (the heater exhaust is saturated with water vapor). The temperature at the silica gel outlet, directly downstream of the second aerosol filter, must be maintained below 20 ºC. The mass of PM collected on both filters in series is determined separately and summed. Throughout sampling, the ratio of flow velocities in the PM probe and flue must be held constant.

Both Methods 5H and 5G are derived from the more generalized methodology presented in EPA Method 5: Determination of Particulate Matter Emissions from Stationary Sources. Introduced in 1971, EPA Method 5 is the first national protocol for the measurement of stack emissions, and forms the basis for many of the biomass heater testing protocols used around the world [5]. Method 5G also provides instructions for the optional measurement of CO and CO_2. This data may be used for calculating the heater's efficiency, but the EPA heater certification Method 28 does not provide instructions for this calculation. EPA Methods 28, 5G and 5H were introduced in 1988, when the New Source Performance Standards (NSPS) issued that year first mandated nationwide heater certifications [6].

Regardless of the emissions sampling protocol chosen, heaters must be evaluated according to the test cycle defined in EPA Method 28 [2]. The test cycle changes slightly depending on the type of fuel used and whether the heater is fitted with a catalytic converter. In all cases, the certification test cycle is preceded by a break-in procedure: Heaters must be operated at a medium burn rate setting for at least 50 hours when fitted with a catalytic converter, or 10 hours for noncatalytic units. The standard test cycle consists of four test runs, each conducted within different fuel burn rate 'category'. The maximum burn rate is defined as that achieved when the heater's primary air inlet and thermostat (where fitted) are adjusted to their maximum settings.

EPA Method 28 mainly focuses on certifying firewood stoves using 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 [2]. 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.

Each test run begins with a 'Pre-Test Ignition' phase. During this phase, a fire is lit using the same type of lumber as that used in the test fuel crib, the heater is set to the desired burn rate, and 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 "achieve uniform charcoalization of the test fuel bed prior to loading the test fuel charge" [2]. When 20 to 25% of the pre-test fuel remains, the test fuel crib is loaded. At this point, gravimetric PM sampling commences and various stove parameters, such as mass and surface temperatures, are recorded every 10 minutes (at least, more frequent datalogging is also acceptable). 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)" [2]. In order to ensure that the heater operated at thermal equilibrium, the heater's average surface temperature at the end of the test run must be within 70ºC of the average temperature recorded at the beginning. Method 28 also provides a test cycle for pellet heaters that is identical to that described above for wood heaters, except that the test run ends at 2 hours irrespective of the fuel charge remaining (pellets must have a moisture content < 20% on a wet basis). However, Method 28 does not provide instructions for testing heaters using cordwood, although cordwood heaters are specifically regulated under the EPA emission limits that came into force in 2020. A working group has been formed to discuss the inclusion of cordwood testing in the Method, but thus far no final actions have been taken [7].

For each of the four test runs in the EPA test cycle, an average PM emission rate is calculated according to the methods provided, 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 regulatory certification. Method 28 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" [2]. 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 minimum total test cycle duration is 12 hours: 1 hour of Pre-Test Ignition and at least 2 hours of sampling for each of the four test runs.

S-1.2 ASTM Method E2780 – 10: Standard Test Method for Determining Particulate Matter Emissions from Wood Heaters

This method from the American Society for Testing and Materials (ASTM) applies only to pellet heaters and is largely similar to EPA Method 28. The ASTM test cycle consists of three test runs at varying burn rates, shown in Table S1.

The minimum burn rate is defined as that achieved 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" [8]. 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.

Table S1. ASTM Method E2779 – 10 fuel burn rate categories. At least one test run is conducted in each category for the duration specified [8].

Burn Rate Segment	Maximum	Medium	Minimum
Description	Maximum achievable	≤ 50% of maximum	Minimum achievable
Time (minutes)	60 +5/-0	180 +5/-0	180 +5/-0

Prior to testing, the heater must be pre-conditioned for at least 48 hours. During pre-conditioning, the heater is operated at a medium burn rate using the same fuel as that used during testing. The standard 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 Test Method E711. Like in EPA Method 28, each test run begins with a 1-hour pre-ignition period, followed by the test run itself. During the test run, PM concentrations in the duct are measured gravimetrically according to the methods specified in ASTM Method E2515 – 11: Determination of Particulate Matter Emissions Collected by a Dilution Tunnel.

ASTM Method E2515-11 is essentially identical to EPA Method 5G, but some important differences should be noted. The dilution tunnel is fitted with two replicate PM sampling trains, rather than one. The PM sampling trains are the same as that as used in Method 5G, each comprising two 47-mm glass-fiber filters in series. 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 [9]. 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 5 gravimetric filters are used for each ASTM test run.

The standard also provides an optional method to characterize the heater's thermal efficiency by measuring exhaust temperature and CO/CO_2 concentrations in the heater flue. This supplemental ATSM method largely references the CSA B415.1 standard, and so a full description is provided in the corresponding section (Section 2.4) of this report. When determining heater efficiency using this method, the chemical composition of the fuel (oxygen, hydrogen, nitrogen, and carbon mass content) must be cited or measured.

The PM emission rates from each test run are weighted according to the average fuel burn rate, and averaged to provide a single PM emission score for each test cycle. 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 (as with EPA Method 28). More than one test run may be conducted for any of the three burn rate categories. This ASTM method provides 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. Optionally, the method can also be used to determine the heater's thermal heat output and efficiency during each test run. If only a single test run is conducted for each burn rate setting, the test cycle takes a minimum of 9 hours to complete.

S-1.3 ASTM Method E2779 – 10: Standard Test Method for Determining Particulate Matter Emissions from Pellet Heaters

This method is analogous to ASTM Method E2779 – 10, but applies to heaters fueled using wood rather than pellets. The Method focuses on testing using fuel cribs, but also provides instructions for cordwood testing. 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 28, the crib must be constructed such that the fuel load density is around 112 Kg of fuel per cubic meter of usable firebox volume. 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 Method E2515-11, but the test cycle differs slightly from that used to evaluate pellet heaters. The three burn rate categories are defined in Table S2 below in absolute terms (Kg of fuel per hour) 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 heater is operated for at least two hours, and 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" [10]. PM emission rates are calculated for each test run, and then a single weighted average score is computed according to the methods presented for ASTM Method E2779-10. The minimum test cycle duration is 9 hours (if heater extinguishes at 2-hour minimum duration for all three test runs).

Table S2. ASTM Method E2780 – 10: Fuel burn rate categories. All three test runs must be defined in either absolute (Kg/h) or relative terms (% of maximum) [10].

	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-1.4 CSA Method B415.1 – 10: Performance testing of solid-fuel burning heating appliances

CSA Method B415.1 [11] is structurally very similar to EPA Method 28, and follows many of the same fundamental procedures for PM emission measurement. 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 Method E2515-11.

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 S3 below. Note that the absolute burn rate limits for each category are the same as that used in EPA Method 28. Test cycles are also defined for thermostatically controlled appliances that do not allow direct modulation of the burn rate.

Table S3. CSA Method B415.1 – 10fuel burn rate categories. All four test runs must be defined in either absolute (Kg/h) or relative terms (% of maximum) [11].

	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

The CSA protocols for firewood and pellet heater testing are essentially identical to that outlined in the ASTM methods, and therefore will not be repeated here. Firewood heaters may be tested using cordwood or cribs. Cordwood should preferably be Douglas Fir, as fuel specifications are provided in the standard 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" [11]. A sample of the test fuel should be analyzed for moisture content, chemical composition, and higher heating value.

Unlike the EPA and ASTM methods, the CSA method also provides instructions for measuring the heater's gaseous pollutant emissions and thermal efficiency. Real-time 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 standard 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). Multiple test runs may be conducted in any of the burn rate categories. The standard 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 S4. Overall, CSA Method B415.1 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 S4. CSA 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) [11].

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

(a) PM Limits for each test run

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

(b) PM Limits for test cycle weighted-average

S-1.5 EN Method 16510: Residential solid fuel burning appliances

In addition to providing experimental protocols for emissions testing, this European standard regulates nearly all aspects of residential wood heater manufacturing and implementation, including installation, construction materials, safety, labels, and requisite documentation for the consumer. The standard provides instructions for sampling emissions directly from the flue and using a dilution tunnel. The dilution tunnel method is very similar that used in the North

American standards, and will not be described here. In the experimental setup, the heater is fitted with a custom flue attachment, known as the measurement section, that contains thermocouples and probes for emissions sampling. Emissions are drawn from the measurement section using a collection hood (or 'gather') and inline fan that exhausts to the environment [12]. The heater is operated on a scale within a 'trihedron test hearth' used for safety testing methods not described here.

The measurement section is insulated and outfitted with a probe for PM sampling, two probes for gaseous pollutant sampling, a draft (static) pressure port, and an unshielded thermocouple or pyrometer [12]. PM emissions are measured gravimetrically using the sampling train. A single gravimetric filter samples heater emissions through a probe located at the center of the flue, in line with the flow. The filter holder and sample lines are heated to a temperature ranging from 70 to 160 °C so as to prevent condensation in the sampling system. Downstream of the filter, a dryer, valve, and dry gas meter are used to condition, control, and measure the flow rate of flue gas pumped through the sampling train.

The standard also requires continuous monitoring of CO, CO_2, O_2, nitrogen oxides (NO_x), and volatile organic compound (VOC) concentrations in the flue. Detailed protocols are provided for the measurement of NOx and VOC concentrations. Unlike EPA Method 5H, the experimental setup does not include a pitot tube, tracer gas injection port, or other device to measure the flow rate of gases through the flue. Instead, mass flow rate is calculated indirectly using the fuel's chemical composition specifications (combustible carbon, hydrogen, and moisture content), and real time measurements of flue gas temperature, fuel burn rate, and CO/CO_2 concentrations in the flue. Thermal efficiency is calculated indirectly using this same dataset, following methods similar to that outlined in CSA Method B415.1-10 [12].

The emissions test cycle consists of three phases: nominal heat output, part load heat output, and slow combustion and recovery. A minimum of two consecutive test runs must be conducted for each phase. For wood heaters, a minimum of three test runs are required for each phase, two of which must be consecutive. Wood heaters are tested using cordwood, no instructions are provided for test crib construction. When the heater is cold, test runs are preceded by an ignition and pre-test period. During the pre-test period, the heater is operated at the desired heat output setting for at least one hour until it reaches steady-state and a bed of coals is established for testing. Draft (static) pressure in the flue's measurement section is set as a function of nominal heat output [12]. The exhaust fan speed is adjusted such that flue draft is held within 1 Pa of the specified value throughout the test run. At the beginning of each consecutive test run, the mass of fuel remaining from the previous burn must not differ by more than 100 g. The standard also includes a safety test cycle, but this method is outside the scope of this review.

At the beginning of the test run, the fuel batch is loaded into the heater with the "basic firebed" established and emissions sampling is initiated. During the test run, the heater must be operated without tending or intervention for the minimum duration specified in Table S5. The heater may be refueled when the remaining fuel mass in the heater is the same as that recorded at the beginning of the test run, but at intervals no greater than the minimum test duration. After the minimum test duration has been reached, the test ends either when the remaining fuel mass returns to its initial value, or when the CO_2 concentration in the flue is $4 \pm 0.5\%$. Whichever criterium is chosen for ending the test run, it must be applied consistently throughout the test cycle.

Table S5. Minimum duration and number of test-runs that must be conducted during the nominal heat output and slow combustion phases of the EN Method 16510-1 test cycle. Requirements vary depending on the appliances' operational mode and fuel [13].

Appliance	**Fuel**	**Test Period**	
		Minimum duration	**Minimum number**
Nominal Heat Output			
Automatically controlled	Wood, lignite briquettes, peat briquettes	1 hour	2
	All other solid mineral fuel	3 hours	2
Manually controlled	Wood, lignite briquettes, peat briquettes	1 hour	2
	All other solid mineral fuel	2 hours	2
Slow or reduced combustion			

Continuous operation	Wood, lignite briquettes, peat briquettes	3 hours	2
	All other solid mineral fuel	12 hours	2
Intermittent operation	Wood, lignite briquettes, peat briquettes	No requirement	
	All other solid mineral fuel	No requirement	

* The wood fuel category includes both cordwood and wood pellets. A minimum of 3 three test runs are required for cordwood heaters, at least two of which must be consecutive.

During the nominal heat output phase, the heater is operated according to the manufacturer's instructions to achieve the appliance's rated heat output. There are no standardized instructions provided regarding fuel batch size or other parameters – all operational settings are specified by the manufacturer. The calculated heat output for each test run must be within 10% of the phase-average, and this phase-average heat output must be within 10% of the manufacturer's claimed value. If these criteria are not met, the test results are considered invalid.

The part load phase is only conducted when the manufacturer provides instructions for this operational mode (not required). The partial heat output setting (P_{part}) is defined as a function of the heater's nominal heat output (P_{nom}) in units of kW:

$$P_{part} = 0.4P_{nom} + 2, \text{when } P_{nom} \geq 5\text{kw}$$

or

$$P_{part} = 0.8P_{nom} + 2, \text{when } P_{nom} < 5\text{kw } [13].$$

The test runs do not need to meet the minimum duration requirements of Table S5 but tests should end according to same criteria as previously described, and the test duration recorded. The slow combustion phase is identical to the nominal heat output phase, except that the heater is operated the lowest heat output setting specified by the manufacturer. At the end of each test run, the heater is configured back to the control settings for nominal heat output. The tester records whether the fire recovers, and if so, the duration of the recovery period.

EN Method 16510 is not specific to firewood or pellet heaters, but instead governs the evaluation of all heaters that use solid fuels, including coal, peat, coke and others [12]. Accurate fuel composition data is crucial since it is used to characterize the heater's thermal performance. Therefore, the standard provides a protocol for evaluating the fuel properties. If the fuel meets the requirements listed in Table B.2 (acceptable moisture content etc.), fuel specification data provided in Table B.1 can be used for the requisite calculations after conducting a single test run in each phase to ensure that the heater operates according to the manufacturer's specifications using the chosen fuel. Otherwise, the fuel must be fully characterized.

For each test run, heat output, thermal efficiency, and the average concentration of all five pollutants are calculated according to the methods provided. Average pollutant concentrations are normalized to 13% oxygen content. Using these results, phase-average values are reported for each of the seven heater performance metrics. For pellet heaters, each test phase consists of a 1-hour pre-ignition period followed by two 1-hour test runs, therefore the minimum test cycle duration is 9 hours. For wood heaters, an additional test run must be conducted during each of the three phases, so the minimum test cycle duration is 12 hours (assuming all three test runs are consecutive).

S-1.6 GB/T Method 16157-1996: The determination of particulates and sampling methods of gaseous pollutants emitted from exhaust gas of stationary source

This Chinese standard is not specific to residential heaters, but rather describes protocols for measuring pollutant emissions from stationary exhaust stacks in general. As such, the standard does not specify a standard 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 Method 16157-1996 also provides protocols 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 standard also provides instructions for sampling gaseous emissions using real-time monitors [14]. 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 standards specifically dedicated to the evaluation of solid-fueled residential heaters. However, standard evaluation methods are provided for other combustion appliances, such as cookstoves and boilers. For example, GB Method 5468-1 outlines a standard test cycle for characterizing PM emissions from boilers [15]. 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 testing protocols provide methods 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 [16]. 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 standards and protocols in place to regulate solid-fueled combustion appliances, many of which could be readily adapted to residential heaters.

S-1.8 IEA Review of Advanced Test Methods for Firewood Stoves

In 2018, the International Energy Agency (IEA) reviewed firewood heater testing standards from Canada, Australia, New Zealand, Britain, the European Union, Norway, the United States, and the International Standards Organization (ISO). Several of these standards have already been covered in the present study, and since those remaining are largely similar, they will not be detailed here to avoid redundancy. However, some additional experimental methods are included in the IEA review which merit description. For example, AS/NZ Method 4013:1999 demonstrates the use of a calorimeter room to directly measure heat output [17]. The calorimeter room provides a closed air volume around the appliance to which heat may be transferred. During testing, the room air temperature is monitored continuously. Some air is circulated through the room to prevent suffocating the heater, and the flow rate and temperature of this circulated air is also recorded. This approach enables direct determination of a residential heater's thermal power output.

PD Method 6434 from Britain presents an alternative method for gravimetric PM emission measurement, using an electrostatic precipitator fitted directly to the flue [17]. Ionizers (high voltage, low current electrodes) in the exhaust stream impart a negative electrical charge to particles as they flow by. Downstream, the particles are attracted to the precipitator's positively charged collection plates and deposited. The precipitator is weighed both before and after sampling on the heater flue, and the difference represents the total mass of PM emitted. Besides gravimetric filter samples, electrostatic precipitators are the only means of directly measuring PM mass emissions.

Using heater testing results from the literature, the IEA report also assesses whether the standard methods provide a valid and accurate assessment of performance in the field. The report shows the pollutant emissions and thermal efficiency of a firewood heater when tested under a variety of different protocols both in the field and laboratory [17]. When tested according to the regulatory standard (EN Method 13240), the heater emissions are ~ 4 times lower and thermal efficiency is ~15% higher than that achieved by a typical residential user. When tested according to the beReal method (Section 2.7), the laboratory results agree much more closely with those measured in the field. The document illustrates that regulatory testing protocols may not accurately represent heaters' real-world performance [17]. This disparity has significant implications for the efficacy of environmental policy that relies on regulatory testing to assess and mitigate heaters' air quality impacts.

S-1.7 beReal: Advanced Testing Methods for Better Real Life Performance of Biomass Room Heating Appliances

Heater testing standards 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 stoves 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 [18].

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 Method 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 real-time CO, CO_2, O_2, NOx, and organic gaseous compound (OGC) concentration measurements. PM and gaseous emissions are monitored according to the protocols presented in EN Method 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 [19].

The pellet heater test cycle consists of four distinct phases. During Phase 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 (Phase 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 (Phase 2). Following another shutdown and 40 minute standby period, the heater is operated at 65% heat output for 180 minutes during Phase 3. Separate gravimetric PM filters are collected during each of the four test phases, and gas concentrations are measured continuously throughout the cycle. Test Phases 1a, 2, and 3 begin when CO concentrations in the flue reach 10 ppm and end after the specified phase duration has elapsed. Gaseous pollutant concentrations in the flue are measured continuously throughout the test cycle. Gravimetric PM sampling starts when the stove is ignited (except Phase 1b) and ends when O_2 concentrations in the flue reach 20% following shutdown (except Phase 1a). In this way, pollutants emissions are monitored during the ignition and shutdown periods typically excluded by other standard test cycles [19].

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. Gaseous pollutant concentrations in the flue are measured in real time 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 test phases or batches, and normalized to 13% oxygen content. Heat output and thermal efficiency are also calculated indirectly for all phases/batches. For each test cycle, a single weighted-average concentration value is reported "by weighting the results derived in the single measurement phases [or batches] according to their produced flue gas volumes" [19]. 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 (Q_{flue}) and the flow rate of exhaust sampled through the instrumentation probe (Q_{probe}).

$$PR = \frac{Q_{flue}}{Q_{probe}} \qquad \text{(S1)}$$

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 ($Q_{dilution}$) and total diluted sample provided to the instrumentation suite ($Q_{instruments}$) 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.

$$Q_{dilution} = Q_{flue}\left(\frac{DR}{PR}\right) \qquad \text{(S2)}$$

$$Q_{instruments} = Q_{dilution}\left(\frac{DR+1}{DR}\right) \qquad \text{(S3)}$$

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