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Preliminary Development of a Certification Protocol for Conventional Fireplaces

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ABSTRACT

In order to attain and maintain federal and state air quality standards for particulate matter, some local agencies in California have adopted rules and regulations to control emissions from wood burning devices. Some of these rules restricted the use or installation of new masonry fireplaces. The purpose of this study was to begin development of a test protocol that would provide for consistent measurement of particulate emissions from conventional fireplaces and could be useful for compliance determinations or possible certification of a fireplace design or model.

A modified California Air Resources Board Stationary Source Test Method 5 was used to determine particulate emissions from a conventional brick fireplace on the California Polytechnic State University campus in San Luis Obispo. The mean total particulate emission rate for five test burns with dual sampling trains was 79.7 grams per hour with a standard deviation of 18.1 grams per hour. An average of 20.2 kilograms of Douglas fir were burned in each fire resulting in an emission factor of 8.6 grams of particulate per kilogram of dry wood burned.

EPA Reference Method 28 for the certification of wood heaters was closely followed with slight modifications to account for the physical differences between wood heaters and conventional fireplaces. The results of this study and the recommendations presented here can be used to further develop standardized operating procedures for compliance determinations and/or certification of conventional fireplaces.

INTRODUCTION

Wood smoke from residential wood combustion contains all of the criteria pollutants: carbon monoxide, particulate matter (PM), hydrocarbons, nitrogen oxides, and sulfur oxides. In addition, wood burning produces formaldehyde and large amounts of carbon dioxide. Of particular concern are toxic hydrocarbon air pollutants including polycyclic aromatic hydrocarbons (PAH). A number of polycyclic aromatic hydrocarbons including benzo-a-pyrene (BaP) are known to cause cancer.[1] The United States Environmental Protection Agency (EPA) listed 17 priority pollutants and 22 carcinogens among the

toxic hydrocarbon air pollutants present in wood combustion smoke from residential metal heating stoves.[1]

Particulate matter (PM) from residential wood combustion consists of "microscopic solid or liquid particles" (smoke), "very small droplets of condensed organic vapors (wood tars and gases), unburned fuel, soot (unburned carbon), and ash (unburnable minerals)."[2] Studies by McCrillis and Jaasma have determined that most of the particulate matter in wood smoke is smaller than one micron.[3] Ten microns is the aerodynamic cut diameter (called PM_{10}) that was previously used as an indicator for inhalable particles that penetrate deep into the lungs. Deposition in the respiratory tract causes irritation and restriction of the air passages, and could lead to diseases of the lung including emphysema and cancer.

The United States Department of Energy (DOE) predicts that wood fuel usage in the United States will reach 200 million dry tons by the year 2000.[4] Other studies have determined that in some areas where wood is used as a primary house heating fuel, up to 80 percent of the wintertime ambient PM_{10} concentration may be attributed to wood stoves.[3]

The United States Environmental Protection Agency (EPA) started to develop standards for the regulation of new wood stoves in 1985.[5] The EPA chose to regulate particulate emissions instead of polycyclic organic matter (POM) with the assumption that controls used to reduce particulate emissions would also reduce carbon monoxide and toxic hydrocarbon emissions.[6]

Oregon passed technology-forcing legislation to regulate wood burning devices in 1984. By July 1986, new wood burning stoves had to be certified to emit less than fifteen grams per hour of particulate matter. Catalytic stoves were limited to six grams per hour. The particulate emission rates for certification were lowered to nine grams per hour for noncatalytic stoves and four grams per hour for catalytic stoves by 1988.[6]

The EPA followed Oregon's lead in 1988 and adopted federal "Standards of Performance for New Residential Wood Heaters" (NSPS Subpart AAA) that set maximum limits for particulate matter emissions to be implemented in two phases. Phase I required that affected devices meet particulate matter limits of 5.5 g/hr for catalytic stoves and 8.5 g/hr for noncatalytic stoves. These limits were based on weighted averages determined by measuring emissions at a range of specified burn rates.[7]

Phase II required that wood heaters sold after July 1, 1992, comply with weighted average particulate matter emission limits of 4.1 g/hr for catalytic stoves and 7.5 g/hr for noncatalytic stoves.[7] With the full implementation of Phase II standards, catalytic wood stoves were expected to emit 86 percent less particulate while noncatalytic wood stoves should emit 75 percent less than conventional stoves.[8]

Subpart AAA specifies acceptable test methods and certification procedures for wood heaters. EPA Reference Method 5G is specified for particulate matter emissions sampling with a dilution tunnel and Method 5H is specified for sampling from a stack location. EPA Reference Method 28 provides for the certification and auditing of wood heaters while Method 28A is used primarily to establish the air-to-fuel ratio and determine whether the wood stove in question is subject to the New Source Performance Standards. Open masonry fireplaces are explicitly excluded from this regulation as "non-affected devices."[7]

A fireplace is defined as a wood burning device that is primarily made of masonry (brick or stone). It is typically assembled on site with a permanent chimney attached and is an integral part of a residence or structure. A fireplace may be equipped with doors or louvers and a damper. To ensure sufficient

combustion air, the doors, louvers, and dampers are normally left open. Fuel is introduced by hand. For the purpose of this paper the terms "fireplace" and "conventional fireplace" are used interchangeably.

A wood heater is a wood burning device primarily used for heating residences or other structures. A wood heater is fully enclosed with controls for combustion air. To be classified as an "affected device" under the federal new source performance standards (NSPS Subpart AAA), a wood heater must meet several criteria including a size limitation, maximum air to fuel ratio, and minimum burn rate standard. Open fireplaces are not classified as "affected devices."[8] For the purpose of this paper the terms "wood heater," "wood burning stove," and "wood stove" are used interchangeably.

In 1997 the EPA added two new national ambient air quality standards (NAAQS) for $PM_{2.5}$ and revised the existing PM_{10} standard. $PM_{2.5}$ is considered "fine" particulate which is linked to adverse health and welfare effects while PM_{10} is now considered "coarse" particulate. The infrastructure for monitoring is not yet in place and the logistics and reporting requirements for monitoring stations are still under consideration.[9]

In order to attain and maintain federal and state air quality standards for particulate matter, some local agencies in California have adopted rules and regulations to control emissions from wood burning devices. Some of these rules restrict the use or installation of new masonry fireplaces. To support policy decisions and regulations, a standardized procedure may be needed to determine particulate emissions from conventional masonry fireplaces.

The present field study was conducted in conjunction with the Monitoring and Laboratory Division of the California Air Resources Board. The purpose of this study was to begin development of a test protocol that could be used with established EPA or state approved methods for consistent and repeatable measurement of particulate emissions from conventional fireplaces. A standardized protocol would allow air pollution control and air quality management districts to make compliance determinations or possibly certify fireplace designs or models as clean-burning devices.

Prior to this study, wood heaters were the focus of technology development and emission studies. Minimal effort was put into improving conventional fireplaces or trying to understand how they function. As a result, few studies of particulate emissions from conventional fireplaces were conducted. To this date an approved particulate testing and certification procedure for masonry fireplaces has not been developed.

LITERATURE REVIEW

Snowden studied one brick fireplace in the Seattle area that was considered to be a representative fireplace based on a survey of fireplace characteristics done as part of the study.[10] The study was completed in 1975 and is frequently referenced in more recent studies and publications including the EPA publication, AP-42, Compilation of Air Pollutant Emission Factors.

A slightly modified EPA Method 5 was used to collect eighteen samples of particulate. Five types of fuel, including Douglas fir and coal, were burned to determine emissions of particulate and polycyclic organic matter (POM). Conditions of startup (kindling phase), stable or steady-state burning, and smolder were sampled in separate test runs.[10] The type of fuel and burning conditions were recorded in the results for each test run.

Particulate emission averages pertaining to Douglas fir were of interest for comparison to the present

study. For all tests using Douglas fir the average particulate matter emission rate was 71.9 grams per hour (g/hr) with minimal variation for different burning conditions. Whereas, for all test runs burning four different wood species the overall average particulate matter emission rate was 76.1 g/hr.

The particulate emission factor showed some variation with different burning conditions. When Douglas fir was burned the average particulate emission factors were 8.8 grams of particulate per kilogram of fuel burned (g/kg) for start-up conditions and 13.1 g/kg for stable burning conditions. The average emission factor for all runs burning Douglas fir was 12.1 g/kg. The smolder condition with decreasing combustion rate was not measured for Douglas fir.

For all species of wood burned the average particulate emission factor was 10.4 grams per kilogram of wood burned. A cascade impactor was used to determine that the mean particle size was 3.0 microns.[10]

A study by Kosel used EPA Method 5 to determine particulate emission factors from two metal stoves and a single brick fireplace at high altitude conditions. The fireplace was located in Homewood, California on the western shore of Lake Tahoe at an elevation over 6,000 feet above sea level. Locally available oak was burned in all test runs.[11]

The fireplace was equipped with glass doors which were closed for two test runs and left open for two additional test runs. Sampling was conducted under warm-start conditions (after the kindling had been burned) and burn rates were determined using a carbon balance method.

The study reported an average emission factor of 20.2 grams of particulate per kilogram of fuel consumed (40.3 lb/ton) for the brick fireplace with open doors and 46.0 g/kg (92.0 lb/ton) with the doors closed. The average emission factor for the brick fireplace was 33.1 g/kg (66.1 lb/ton) under all operating conditions.

Kosel concluded that emissions vary widely from fireplace to fireplace, from fuel to fuel, between similar fires, and even during the course of the same fire. Variability of emissions during the course of individual fires was so large that the effects of fuel and fireplace type were masked. The relatively high results may be attributed to very high excess air ratios of 830 to 1633 percent and the effects of altitudes over 6,000 feet.[11]

The EPA publication, AP-42, Compilation of Air Pollutant Emission Factors, listed the PM_{10} emission factor for wood combustion in residential fireplaces as 34.6 pounds of pollutant per ton of dry wood burned (17.3 g/kg). The carbon monoxide emission factor was listed as 252.6 lb/ton (126.3 g/kg). It should be noted that these factors were partially based on the results from the Snowden and Kosel studies mentioned above.[12]

A recent study by Stern examined fuel and operating parameters in a single factory built metal fireplace. Particulate emissions were strongly affected by moisture and pitch content, shape and size of the fuel. Variables having less effect on emissions included the number of logs in each reload, the placement of the reloads, the location of the coals at reload, the presence or absence of a grate, and a higher draft chimney. Spacing between logs in a reload, species of fuel, and fuel density had little or no effect on particulate emissions.[13]

Particulate emissions were measured with EPA Method 5G. The average particulate emission rate for main loads (stable burn conditions) was 32 g/hr with a range of 19.1 to 48.2 g/hr and a standard deviation of 8.1 g/hr. Particulate emissions for the kindling phase with a cold start were considerably higher with an average of 44 g/hr and a standard deviation of 9.6 g/hr. Particulate matter emission

factors averaged 10.0 grams of particulate per kilogram of dry wood burned. The emission factors ranged from 4.4 to 15.4 g/kg with a standard deviation of 2.6 g/kg.[13]

There is a wealth of literature discussing wood heater performance standards, certification, fuel characteristics, emission rates and factors for different wood species and densified logs, indoor air pollution, thermal efficiency, and correlations between various particulate sampling methods. Although some operating parameters and emission characteristics for wood heaters would be applicable to fireplaces, caution should be exercised when trying to compare emission results from wood heater or metal fireplace studies to results from masonry fireplace studies. Wood heaters and metal fireplaces have different operating characteristics than masonry fireplaces and different particulate sampling methods produce different results. For example, results from EPA Method 5G samples tend to be lower than results from either EPA Method 5 or CARB Method 5. In addition, some particulate sampling methods include the condensable fraction that is captured in the impingers while other methods simply measure the front-end filter catch.

Equations for correlating the results from one established particulate measurement method to results from another have been published, and frequently emission rates are requested in terms of EPA Method 5H equivalents. However, the correlation equations have been determined for wood heaters and it is uncertain whether the same equations would apply to fireplaces. For certification and compliance determinations, only one particulate measuring method should be specified until comparison testing can be achieved to provide the necessary correlation equation.

EXPERIMENTAL DESIGN

EPA Reference Method 28 provides for the certification and auditing of wood heaters.[14] However, conventional fireplaces are considerably different from wood heaters. Most conventional fireplaces do not have dilution air controls or closed doors. In addition, it is impractical if not impossible to weigh an existing brick fireplace on a scale to determine instantaneous burn rates.

In order to develop a standardized, repeatable test protocol, an attempt was made to follow the procedures of EPA Method 28 as closely as possible with necessary changes to accommodate the differences in fireplace operating and design characteristics. Test fuel properties and specifications, including moisture content, size, species, and load spacing as well as operating parameters and acceptable test methods are included in Method 28. The primary modifications made to Method 28 to accommodate fireplaces are outlined below. Section references correspond to the section numbers as published in EPA, 40 C.F.R. Pt. 60, Appendix A, Method 28, (1992).

EPA Reference Method 28A is used primarily to establish the air-to-fuel ratio and determine whether the wood stove in question is subject to the New Source Performance Standards.[15] An open fireplace requires a minimum air-to-fuel ratio above 100-to-1 and typically is operated in the maximum burn rate category.[16] In addition, fireplaces rarely have primary or secondary combustion controls. For these reasons, EPA Method 28A in its entirety and the sections of Method 28 dealing with combustion air controls were disregarded.

In Method 28, four burn rate categories are used to provide a weighted-average emission rate representative of the full range of wood stove operating characteristics. The entire stove and vent assembly must be weighed on an accurate balance for the duration of the test burn in order to determine the burn rate.[16] It is impractical to weigh an existing brick fireplace on a scale to determine burn rates at ten-minute intervals. In addition, the trial burns conducted in this study indicated that a consistent fire

that was representative of typical usage could only be obtained in an open fireplace at the maximum burn rate. For this reason all test runs were conducted at the maximum burn rate specified in Method 28 which is greater than 1.90 kg/hr (4.18 lb/hr). Because the four burn rate categories could not be achieved, a weighted average emission rate was not calculated.

In freestanding wood stoves, one of the mechanisms for heat transfer is convection from the large surface area. Method 28 requires surface temperature monitors to measure the heat transfer effects. Most of the useful heat transfer from a fireplace is caused by radiation of the fire's heat through the open front and it was determined that surface temperature monitors would not be necessary for fireplace testing. To measure the ambient temperature within the facility a temperature monitor was placed inside a two inch diameter pipe shield, three feet from the fireplace opening in accordance with Sections 3.4 and 6.2.3 of Method 28.[14]

A fireplace grate was not used for this study. The test fuel spacers and fuel charge configuration outlined in Figure 28-2 of Method 28 were sufficient to provide initial air flow underneath the fuel charge until a steady fire was burning. Grates, platforms, or other log supports were not required by Method 28.[14]

Standard grade or better, untreated, air-dried, Douglas fir lumber was used for all tests as specified in Method 28, Section 4.2.1. The test fuel was stored and maintained at the average ambient facility temperature as recommended in Section 4.2.3 and the test fuel spacers were of the same wood species and dimensions outlined in Section 4.3.2.[14]

According to Section 4.3.1, each piece of test fuel should be approximately 5/6 of the length of the usable firebox. The average length of the firebox was 37.5 inches at the bottom resulting in the use of 30.5 inch long pieces for all test runs. Section 4.3.1.3 specifies that all test fuel charges must be made of 4 x 4 nominal dimension lumber (3.5" x 3.5" actual dimensions) when the usable firebox volume is greater than three cubic feet. The test fireplace had a usable firebox volume of approximately 10.5 cubic feet so that 4 x 4 lumber was used. Smaller firebox volumes require the use of 2 x 4 lumber or a combination of 2 x 4's and 4 x 4's.[14]

Method 28 specifies that the fuel charge density should be 7 plus or minus 0.7 pounds of fuel per cubic foot of usable firebox volume. The selected fireplace had a firebox volume of approximately 10.5 cubic feet. In order to meet the Method 28 fuel charge density requirement, the test fuel charge would have to weigh between 66 and 81 pounds and would have consisted of eight or more 30.5 inch lengths of 4 x 4 lumber. A test fuel charge of the required density could have filled the firebox with flames with the potential to ignite a fire in the chimney or surrounding walls. In an attempt to model typical fireplace usage and to provide a modicum of safety, only half of the test fuel charge density required by Section 4.3.3 was used in this study.[14]

A Model J-3 digital moisture meter, manufactured by the Delmhorst Instrument Company, was used to determine the moisture content of the test fuel charges. In accordance with Section 6.2.5 of Method 28, the moisture content of each test fuel piece was measured "by averaging at least three moisture meter readings, one from each of three sides, measured parallel to the wood grain." The moisture content was recorded as measured on a dry basis and converted to a wet basis using the formula in Section 6.2.5.[14]

The pretest fuel charge consisted of six half sheets of crumpled newspaper and kindling. The kindling was made up of split 2 x 4's and whole 2 x 4's in ten inch lengths of the same species and approximate moisture content as the test fuel. No lighter fluid or other fire starting aids were used in any of the test runs.

The guidelines of Section 6.4.1 specify that the pretest fuel and kindling should be burned until only 20 to 25 percent of the test fuel charge weight remains before the sampling begins (warm start). This ensures that steady-state (stable) combustion conditions exist.[14] Without the use of a platform scale, a practical method for determining the burn rate had to be developed.

Initially, an estimate of the remaining pretest fuel charge was subtracted from the weight of the kindling and pretest fuel to find the total fuel charge combusted. A video camera was employed under the premise that visual sizing of the unburned fuel with respect to the initial load would provide a practical estimation method. Use of the video camera was found to be no better than direct observation. The camera and tripod were cumbersome and intrusive, crowded the limited floor space, and disrupted the business activities of the housing office.

The difficulty of estimating the weight and percentage of pretest fuel remaining before starting the sample trains led to an abandonment of that procedure. For the final four test runs sampling began with the ignition of the fire (cold start) and continued until the fuel was almost completely burned. The remaining fuel, residue, and ash were collected and weighed in a 14 inch diameter, five gallon, metal cook pot with a removable lid. The lid was not completely airtight, but combustion was effectively retarded by the starved air conditions. A Fairbanks scale with an accuracy of plus or minus one ounce was at the test site for weighing the container and contents immediately after removal from the fireplace. The weight of the remaining fuel, residue, and ash at the end of the test run was subtracted from the total weight of the kindling, pretest fuel, and fuel charge, and the result was divided by the total sample time to determine the average burn rate. The weight of the kindling and its burn time were considered as part of the test burn in all test runs except the first one. A minimum of one hour was allowed between consecutive test runs corresponding with Section 6.5.[14]

The above method of determining an average burn rate assumed a cold start and measured particulate emissions during both the kindling and steady-state (stable burning) phases. Some particulate sampling continued during the smolder phase, however, most of the useable fuel was already consumed. This process was judged to be more representative of emissions from general fireplace use than would be achieved during a laboratory induced steady-state burn.

Method 28 defines coalbed raking in Section 6.3.2 as "the use of a metal tool (poker) to stir coals, break burning fuel into smaller pieces, dislodge fuel pieces from positions of poor combustion, and check for the condition of uniform charcoalization." Raking is allowed once prior to the start of the test run. In the Cal Poly study, coalbed raking was reserved for the final phase of the test burn.[14]

Adjustment of the fuel charge with pokers or other tools was allowed on a limited basis to ensure continuous combustion. When the fire appeared to diminish, fuel pieces were rearranged or stacked to promote air circulation. This procedure was a departure from Section 6.4.3 which allows only one fuel charge re-positioning per test run if at least 60 % of the initial weight has been burned.[14] Fuel adjustment or "stoking" was judged to be typical of normal fireplace operation. The time of each fuel adjustment was recorded and the term "stoke" was written on the operation data sheets to indicate that fuel adjustment or coalbed raking had occurred.

CAL POLY FIELD STUDY

A functional fireplace in the Residential Life and Education building on the California Polytechnic State University campus was selected as the test site. This fireplace was used primarily during the winter months to remove the chill in the lobby and used only occasionally during the summer months. The

chimney flue had been cleaned within the last year and a safety screen had been installed at the top of the chimney.[17]

The fireplace was an all brick, open fireplace with a usable firebox volume of approximately 10.5 cubic feet. There were no glass doors or louvers available for inlet combustion air control and the exhaust damper was left fully open throughout the testing to ensure sufficient combustion air.

During the testing process, a twelve foot long, galvanized sheet metal chimney extension with a rectangular cross section was fitted to the outlet of the brick chimney. The interior dimensions of the chimney extension were 10.5 inches by 15.5 inches, the same as the inner dimensions of the chimney. The rectangular extension had an equivalent round stack diameter of 12.5 inches.

Two sampling ports were centered on the shorter sides of the rectangular cross section of the chimney extension. The lower sampling port was ten feet or eight equivalent stack diameters downstream from the nearest flow disturbance (the damper). The upper sampling port was 24 inches (two equivalent stack diameters) downstream from the lower port on the opposite side of the stack extension.

Although EPA Method 28 specifies that Method 5H or 5G be used for particulate sampling, a slightly modified version of California Air Resources Board Stationary Source Test Method 5 (CARB Method 5) was used in the present study. A stack extension was added to the chimney and sample probes were placed at a single point located in the center of the stack extension cross-section. Particulate emission rates were determined from stack gas velocity measurements made with a standard pitot tube at that single point rather than traversing the stack. In addition, a 0-2" water column U-tube manometer and electronic micrometer with 0.0025" w.c. gradations were used instead of an inclined manometer. Dual sample trains were used for each test run.

Before each test run the firebox floor was swept and vacuumed. The ambient room temperature was measured with a mercury thermometer. The barometric pressure of the room was measured with an aneroid barometer. The relative humidity of the room was measured with a sling psychrometer, and room air velocity was measured with an anemometer. When it was confirmed through walkie-talkies that the test crew had successfully performed leak checks and other preliminaries related to the sampling train, then testing was ready to begin.

A two and one-half pound bag of kindling and 8.8 to 11.4 pounds of pretest fuel (one-third length 2 x 4's) were assembled in a tee-pee shaped structure with six half-sheets of newspaper crumpled underneath. When all stations were ready, matches were used to light the newspaper. The sampling trains, data loggers, and data recording started simultaneously except during the first test run when the sampling did not begin until approximately 70 percent of the pretest fuel charge had been consumed.

When the pretest fuel charge was burning sufficiently (20 to 40 minutes), the test fuel charges were placed on the fire. Each test fuel charge consisted of a pair of 30.5 inch long 4 x 4's connected by ten inch long spacers. After two test fuel charges were added, the fire was stoked to encourage combustion.

Five test burns were conducted over a three day period. Two sampling trains were run for each test burn, providing a total of ten samples of particulate. During all test burns the ambient room temperature in the immediate fireplace area was measured and recorded at ten minute intervals. In addition, the following results were recorded for each test burn: weight of kindling; weight of fuel load (two test fuel charges); weight of ash; burn time; stack sampling parameters; moisture content of the wood; room barometric pressure; room relative humidity; and outdoor air velocity.

When it appeared that most of the test fuel had been combusted and the fire was starting to smolder with no visible flames, the sampling crews was instructed by walkie-talkie to stop the sampling trains. The time corresponding to the end of test run was recorded on the data sheets. The remaining pieces of fuel, residue, and ashes were shoveled and swept into the containment vessel, the lid was attached and the vessel was removed from the building immediately. The remaining fuel was weighed in the pot and the weight was recorded after subtracting the weight of the empty pot and lid.

RESULTS

The total particulate matter from residential wood combustion devices is assumed to be inhalable particulate, PM_{10} or smaller.[6] For the purpose of this study the filter catch and condensable organic fraction are all considered in the total particulate measurements. Separate weights for the front filters, back filters, probe, and impingers were recorded for each test run.

Results from Test Run No. 1

In test run number one, 17.8 kg (39.2 lb) of fuel were consumed with an average wet moisture content of 15.9 percent. The test fuel was burned for 129 minutes resulting in an average burn rate of 7.0 kg/hr (15.3 lb/hr). A particulate emission rate of 66.1 g/hr was measured by sampling train M5-1 placed in the lower port while 54.3 g/hr was measured by sampling train M5-2 in the upper port. The average particulate emission rate for the two trains was 60.2 g/hr with 7.3 grams of particulate emissions per kilogram of dry wood (14.6 lb/ton).

Results from Test Run No. 2

In test run number two, 19.8 kg (43.7 lb) of wood were burned with an average wet moisture content of 16.7 percent. Burning lasted for 110 minutes resulting in an average burn rate of 9.0 kg/hr (19.9 lb/hr). A particulate emission rate of 100.2 g/hr was measured by sampling train M5-4 placed in the lower port while 92.0 g/hr was measured by sampling train M5-3 in the upper port. The average particulate emission rate for the two trains was 96.1 g/hr with 8.9 grams of particulate emissions per kilogram of dry wood (17.8 lb/ton).

Results from Test Run No. 3

In the third test run, 23.9 kg (52.8 lb) of wood were burned with an average wet moisture content of 16.0 percent. Combustion lasted for 120 minutes resulting in an average burn rate of 10.1 kg/hr (22.2 lb/hr). A particulate emission rate of 86.0 g/hr was measured by sampling train M5-6 placed in the lower port while 97.1 g/hr was measured by sampling train M5-5 in the upper port. The average particulate emission rate for the two trains was 91.6 g/hr with 7.6 grams of particulate emissions per kilogram of dry wood burned (15.3 lb/ton).

Results from Test Run No. 4

In test run number four 19.9 kg (43.9 lb) of wood were burned with an average wet moisture content of 15.4 percent. Testing was conducted for 160 minutes resulting in an average burn rate of 6.3 kg/hr (13.9 lb/hr). A particulate emission rate of 88.1 g/hr was measured by sampling train M5-8 placed in the lower port with a rate of 95.8 g/hr measured by sampling train M5-7 in the upper port. The average particulate emission rate for the two trains was 91.9 g/hr with 12.3 grams of particulate emissions per kilogram of

dry wood burned (24.6 lb/ton).

Results from Test Run No. 5

In test run number five 19.8 kg (43.6 lb) of wood were burned with an average wet moisture content of 13.1 percent. Sampling ran for 140 minutes resulting in an average burn rate of 7.4 kg/hr (16.2 lb/hr). A particulate emission rate of 57.0 g/hr was measured by sampling train M5-9 placed in the lower port while 60.4 g/hr was measured by sampling train M5-10 in the upper port. The average particulate emission rate for the two trains was 58.8 g/hr with 6.9 grams of particulate emissions per kilogram of dry wood burned (13.9 lb/ton).

Results from Test Runs No. 1 through No. 5 are summarized in Table 1.

Overall Test Results

The mean total particulate emission rate for all test burns was 79.7 grams per hour (0.18 lb/hr) with a standard deviation of 18.1 g/hr. An average of 20.2 kilograms (44.6 lb) of fuel were burned in each fire resulting in an average emission factor of 8.6 grams of particulate per kilogram of fuel burned (17.2 lb/ton).

The test fuel was standard grade or better Douglas fir with an average moisture content of 15.4 percent on a wet basis ranging from 13.1 to 16.7 %. Test runs were 110 to 160 minutes long with an average length of 132 minutes. The mean burn rate was 7.9 kilograms of fuel per hour (17.5 lb/hr) ranging from 6.3 to 10.1 kg/hr (13.9-22.2 lb/hr). The mean, standard deviation, and range for each of these parameters are summarized in Table 2.

DISCUSSION

This section presents a discussion of results, methodology, and implications for further study. The present study will be described as the "Cal Poly study". The study by Snowden, Alguard, Swanson, and Stolberg will be referred to as "Snowden".

The mean total particulate emission rate for the Cal Poly study was 79.7 grams per hour for five test burns with dual sampling trains. The mean particulate emission factor was 8.6 grams per kilogram of fuel burned (17.2 lb/ton). These results are comparable to Snowden's study which reported an average of 76.1 grams of particulate per hour and an average of 10.4 grams per kilogram of fuel burned (20.8 lb/ton) based on four different wood species. In Snowden's study, the five test runs that used Douglas fir had an average of 72.0 g/hr and 11.7 g/kg (23.4 lb/ton).[10]

The emission factor for the Cal Poly study is less than half of the emission factor listed in AP-42 and considerably smaller than the average emission factor reported by Snowden for Douglas fir (see Table 3). This discrepancy may be a function of moisture content in the fuel but there is insufficient data to make a strong conclusion. In addition, residential fireplaces considered in AP-42 included metal prefabricated fireplaces.[12]

The study by Snowden reported average particulate emission rates and particulate emission factors for start-up and stable conditions for each of four wood species tested. There was a significant difference in particulate emission rates for start-up and stable conditions when burning alder and locust. However, when Douglas fir was burned the different burning conditions influenced the particulate emission factors

slightly but not the emission rates.[10]

The comprehensive fireplace study by Snowden provided a solid framework for comparison with results from the Cal Poly study. The Cal Poly study relied on CARB Method 5: the Snowden study used EPA Method 5. Both studies attempted to accurately measure the stack gas velocity rather than estimating it with a carbon balance approach.

The Cal Poly study used a standard pitot tube connected to a manometer and electronic micrometer. The pitot velocity pressure was used to calculate the average stack gas velocity which was 3.16 meters per second (10.36 ft/sec). Calculation of the Reynolds number revealed that the stack gas flow was turbulent for all test runs. The chimney and extension had interior dimensions of 10.5 by 15.5 inches resulting in an equivalent round stack diameter of 12.5 inches. Only one centrally located sample point was used for each sampling probe.

Snowden's study relied on a special expanded inclined manometer. The average stack gas velocity in the Snowden study was 2.15 meters per second (7.05 ft/sec). Snowden used 20 traverse points to sample the 8.75 by 19.25 inch chimney. The chimney had an equivalent diameter of 12 inches. Each traverse point was sampled for two to three minutes depending on the test run.[10] The similarity of particulate emission rates for the two studies suggested that sampling with a centrally located probe or by traversing the stack may produce similar results for stacks with an equivalent diameter of approximately 12 inches.

In the Cal Poly study, test fuel charges and kindling were weighed originally on a digital balance. The remaining residue and ashes were weighed at the site with a beam balance. Both balances had an accuracy better than plus or minus 0.1 pound as required by Method 28. The difficulty in estimating the amount of wood consumed was apparent during the first test run. The determination of average burn rates and particulate emission rates using the combined weight of the kindling and test fuel charges minus the total fuel remaining was considered much more reliable.

In the Snowden study the test fuel charges were weighed with a spring balance. The person stoking the fire estimated the amount of fuel consumed. Burn rates and total weight of wood burned were estimated as a percentage of the wood that was added to the fire.[10]

The Cal Poly study used an electrical resistance type moisture meter to find the average moisture content of the test fuel. The average moisture content of the Douglas fir used in the Cal Poly study was 15.4 percent on a wet basis. However, the moisture meter had probes that were only 5/16 inch long. Method 28 specifies that longer probes should be used for moisture readings on 4 x 4 lumber. The probes were supposed to measure the moisture content at a penetration depth equal to one-fourth of the thickness of the test fuel (0.875 in.) or 0.75 inch whichever is greater.[14] It was assumed that wood at the center of a 4 x 4 cross-section would be more likely to retain moisture because it does not have direct contact with air flow or other drying mechanisms. Moisture readings obtained with shorter probes were expected to be lower than readings taken with the specified long probes.

Snowden's study determined moisture content by repeatedly drying samples of wood at 105 degrees Celsius until a constant weight was obtained. The constant weight was subtracted from the original weight to calculate the moisture lost which was reported as a percentage of the original weight. The average moisture content for Douglas fir was 10.6 percent in the Snowden study.[10]

CONCLUSION

The present field study was conducted in an attempt to develop a test protocol for obtaining an estimate of particulate emissions from conventional fireplaces. The basic goals were to develop a practical, realistic, and repeatable test procedure that modeled patterns of in-situ residential wood combustion. The results of this field study support the following conclusions:

1. The particulate matter emission rates and factors determined in this field study agree with the previous comprehensive fireplace study by Snowden.

2. California Air Resources Board Stationary Source Test Method 5 with slight modifications could be used as an effective, repeatable test method for measuring the particulate emissions from conventional fireplaces.

3. The recommendations listed below provide a foundation for developing a protocol that could be used for compliance determinations or the certification of a conventional fireplace design or model.

Additional research is necessary to determine whether an average burn rate is representative of actual usage. Emission rates and factors for the start-up, stable, and smolder burning conditions should be examined in detail. Different burn rate categories within the maximum burn range need to be developed in order to calculate a weighted average emission rate that is representative of different operating conditions.

With more studies of fireplaces, an empirical value for the "assumed" mole fraction of hydrocarbons in the stack gas (Y_{HC}) can be obtained. This would enable the use of EPA Method 5H with fireplaces. Method 5H incorporates the moisture content of the wood in the calculation of particulate emission rates.

A study examining the effects of a stack reducer which converts the rectangular chimney into a standard circular duct would be of value. This parameter could be coupled with a comparison of the results obtained by traversing the stack versus sampling at one central location. If the differences were insignificant, all particulate sampling could be accomplished at a single sampling location which is considerably easier than traversing at nine or more sampling points.

Particulate matter was the focus of this study, but additional studies are needed to determine emissions of other air pollutants. Thermal and overall efficiency and the effects of fireplaces and woodstoves on indoor air pollution should also be considered. Additional information was included in the original thesis project completed at Cal Poly in 1994.[18]

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The statements and conclusions in this report are those of the authors and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such

products.

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Table 1. Results of individual test runs.

Test Run Number	Sample Train	Port	Weight Of Wood (kg)	Time (min.)	Burn Rate (kg/hr)	Particulate Emission Rate (g/hr)	Particulate Emission Factor (g/kg)
1	M5-1	lower	17.8	129	6.95	66.1	8.0
	M5-2	upper	17.8	129	6.95	54.3	6.6
2	M5-3	upper	19.8	110	9.01	92.0	8.5
	M5-4	lower	19.8	110	9.01	100.2	9.3
3	M5-5	upper	23.9	120	10.06	97.1	8.1
	M5-6	lower	23.9	120	10.06	86.0	7.2
4	M5-7	upper	19.9	160	6.32	95.8	12.8
	M5-8	lower	19.9	160	6.32	88.1	11.8
5	M5-9	lower	19.8	140	7.37	57.0	6.7
	M5-10	upper	19.8	140	7.37	60.4	7.1

Table 2. Summary for all test runs.

Parameter	Mean	Std. dev.	Range
Weight of fuel burned (kg)	20.2	2.1	17.8-23.9
Percent moisture content (wet basis)	15.4	1.3	13.1-16.7
Sampling time (min.)	131.8	18.2	110-160
Burn rate (kg/hr)	7.9	1.5	6.3-10.1
Particulate emission rate (g/hr)	79.7	18.1	54.3-100.2
Particulate emission per kg. of fuel	8.6	2.1	6.6-12.8

Table 3. Comparison of particulate emission rates and factors.

Study	Fuel (wood species)	Emission Rate (g/hr)	Emission Factor (g/kg)	Test Method
Cal Poly	Douglas fir	79.7	8.6	CARB Method 5
Snowden	Douglas fir	72.0[a]	11.7[a]	USEPA Method 5
Snowden	four species	76.1[a]	10.4[a]	USEPA Method 5
AP-42	all species	N/A	17.3[b]	EPA-approved methods[c]

[a] Snowden et al. 1975.

[b] USEPA. *AP-42: Compilation of Air Pollutant Emission Factors*. 1992.

[c] *AP-42* particulate emission factors were developed from four separate studies including Snowden et al.