Evaluation of The Northern Sonoma County Wood-Burning Fireplace and Masonry Heater Emissions Testing Protocols

Prepared by

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Preface

The Northern Sonoma County Air Quality Management District is in the process of drafting a performance standard for wood-burning masonry fireplaces and masonry heaters. OMNI Environmental Services, Inc., as a U.S. EPA accredited test laboratory under 40 CFR Part 60 Subpart AAA, is required to regularly participate in an EPA-administered program to demonstrate proficiency in testing certified wood-burning stoves using standardized procedures specified by the EPA in 40 CFR Part 60 Appendix A . The woodstove proficiency testing conducted by OMNI in the November 1999 through February 2000 time period was expanded to include fireplace and masonry heater models and to include the performance of the draft Northern Sonoma County testing procedures. The results of this expanded testing program allow for the evaluation of the Northern Sonoma County draft testing procedure relative to the methods specified by the EPA for testing woodstoves. Because of the importance of this work to the manufacturers of fireplaces and masonry heaters and as a prototype procedure for other air quality jurisdictions, a number of sponsors participated in the study. These were:

Northern Sonoma County Air Quality Management District
150 Matheson Street
Healdsburg, California, 95448-4908

Bay Area Air Quality Management District
939 Ellis Street
San Francisco, California 94109

Hearth Products Association
7840 Madison Avenue
Suite 185
Fair Oaks, California 95628

Brick Industry Association
11490 Commerce Park Drive
Reston, Virginia 22091

Western States Clay Products
2550 Beverly Boulevard
Los Angles, California, 90057

McNear Brick and Block
1 McNear Brickyard Road
San Rafael, California 94901

Lopez Quarries
111 Barbara Lane
Everett, Washington 98203

Buckley Rumford Company
1035 Monroe Street
Port Townsend, Washington 98368

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1. Introduction

The primary objective of the study reported here was to determine the relationship(s) between fireplace and masonry heater particulate emissions values produced by using the draft Northern Sonoma County Air Quality Management District (NSC-AQMD) testing protocols and fireplace and masonry heater particulate emissions values produced by using the U.S. EPA woodstove New Source Performance Standard (NSPS 40 CFR Part 60, SubPart AAA) reference sampling Methods 5G and 5H (40 CFR Part 60, Appendix A) in conjunction with their associated fueling and operating protocols specified in EPA's Method 28 (40 CFR Part 60, Appendix A). Related secondary objectives were to measure fireplace and masonry heater thermal efficiency using the draft NSC-AQMD protocols and to investigate proposed methods for establishing equivalency between EPA's wood-fired heater emissions standard and fireplace and masonry heater emissions measured by the draft NSC-AQMD testing protocols.

In addition, the data generated and analyzed in this study were added to data obtained through a comprehensive survey of pertinent existing fireplace emissions literature. Additional analyses of this combined data set were performed to determine the level of fireplace emissions that represents the best performing 12% of fireplace models. The "12%" analyses were performed as if fireplaces and masonry heaters were subject to EPA's Maximum Achievable Control Technology (MACT) requirements contained in Section 112 (d)(3) of the Clean Air Act Amendments of 1990. This "MACT" analysis is presented in Appendix A to this report.

Twenty-eight separate test runs were conducted for this study. An EPA certified non-catalytic woodstove (the Quadrafire Model 2100), a manufactured zero-clearance metal fireplace, three masonry fireplace models, and a masonry heater were tested. The Quadrafire 2100 stove was supplied by the EPA as part of its "round-robin" proficiency testing program. Each of the 28 test runs was conducted using duplicate Method 5G sampling trains, duplicate Method 5H sampling trains, and duplicate Northern Sonoma County-specified Emissions Sampling Systems (ESS). Due to the inherent flue-gas flow rate differences between woodstoves and fireplaces, some modifications in Method 5G procedures were necessary and are described.

In addition to testing the various sampler and appliance types, fuel loading-door status (open/closed), fuel loading protocols (i.e., EPA Method 28 and draft NSC-AQMD protocols), and fuel burn rates were variables in the study matrix. A total of 168 data sets were generated by this study as presented in Table 1.

Since numerous measurement steps and intermediate calculations involved in the generation of final emissions results for each of the EPA methods used are well documented in 40CFR Part 60 Appendix A, the calculation of woodstove and fireplace emissions using Methods 5G and 5H (and their associated fueling protocols contained in Method 28) have not been subject to evaluation as part of this study. Similarly, the sampling procedures, sample processing, and data reduction procedures contained in the draft NSC-AQMD protocols are straight forward and have previously undergone quality assurance evaluations as presented in Table 2[1].

Two important aspects of the test procedures used in this study are given in-depth evaluations: 1. Fuel moisture and flue-gas moisture determinations, and 2. Those flue-gas flow determinations which are based on a combination of flue-gas combustion-product concentrations and fuel mass burn rate measurements. These aspects were chosen for additional scrutiny because they both directly effect the calculation of emissions and thermal efficiency results.

Particulate emissions, in terms of both emissions rates (mass particles per unit time) and emissions factors (mass particles per unit mass of dry fuel burned) were calculated for each of the 168 matrix components presented in Table 1. Statistical relationships between emissions data collected with each sampler type were calculated to evaluate the draft NSC-AQMD-prescribed emission sampling system (ESS). Overall thermal efficiencies (the product of combustion and heat transfer efficiencies) were calculated in two formats for each test conducted. One uses the lower heat of fuel combustion as the total energy input and assumes the latent heat of resultant water is not recoverable for use in space heating (realistic) and the other uses the higher heat of fuel combustion as the total energy input with the resultant latent heat of water being available for heating purposes (theoretical). The realistic format is, as the name implies, representative of the way residential wood combustion is actually (“realistically”)” carried out: ie, it is impractical to try to recover the latent heat of vaporization from flue gases. The theoretical format is presented here as a benchmark to compare efficiencies of the appliances tested in this study to other space heating appliance types such as oil- and gas-fired heaters which are usually graded in North America by the theoretical convention.

Specific recommendations regarding a particulate emission passing threshold (i.e., the passing grade) for masonry fireplaces and masonry heaters have not been made, as it is outside the scope of this study. However, the particulate emission factors, particulate emission rates, and thermal efficiencies reported here do provide key information for such regulatory decisions and some suggested approaches are discussed.

2. Study Design

Tests with the woodstove, fireplaces, and a masonry heater were conducted between November 1999 and February 2000 at OMNI’s Beaverton, Oregon laboratory facilities. The same test booth was used for all tests. Duplicate EPA Method 5G, EPA Method 5H, and ESS sampling trains were used for each test run conducted producing a total of 168 complete data sets. The

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[1] The ESS was based on the design of an earlier sampling system developed by OMNI which was known as the Automated Woodstove Emissions Sampler (AWES) and later the Automated Emission Sampler (AES). The sampling, sample processing and data reduction aspects of the ESS and its predecessor models are very similar. They have undergone rigorous quality assurance evaluations for four U.S. EPA projects as presented in Table 2.

Table 1
Study Matrix

Test Run Number	Description
1	Stove - Closed - EPA Fuel - 1.2 kg/hr
2	Stove - Closed - EPA Fuel - 3.8 kg/hr
3	Stove - Closed - EPA Fuel - 1.6 kg/hr
4	Stove - Closed - EPA Fuel - 1.1 kg/hr
5	Stove - Closed - EPA Fuel - 1.0 kg/hr
6	Stove - Closed - EPA Fuel - 4.6 kg/hr
7	Stove - Closed - EPA Fuel - 1.3 kg/hr
8	Stove - Closed - EPA Fuel - 1.0 kg/hr
9	Stove - Closed - EPA Fuel - 4.2 kg/hr
10	Stove - Closed - EPA Fuel - 0.9 kg/hr
11	Stove - Open - NSC Fuel - 3.4 kg/hr
12	Stove - Open - NSC Fuel - 3.7 kg/hr
13	Stove - Closed - NSC Fuel - 3.2 kg/hr
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr
16	Stove - Open - NSC Fuel - 3.1 kg/hr
17	Stove - Closed - NSC Fuel - 2.7 kg/hr
18	Stove - Closed - NSC Fuel - 2.4 kg/hr
19	Stove - Closed - EPA Fuel - 1.8 kg/hr
20	Stove - Closed - EPA Fuel - 2.1 kg/hr
21	FP A - Closed - NSC Fuel - 6.9 kg/hr
22	FP A - Open - NSC Fuel - 10 kg/hr
23	FP B - Closed - NSC Fuel - 4.1 kg/hr
24	FP B - Open - NSC Fuel - 5.9 kg/hr
25	FP C - Open - NSC Fuel - 7.6 kg/hr
26	FP C - Closed - NSC Fuel - 4.9 kg/hr
27	FP D - Open - NSC Fuel - 7.9 kg/hr
28	FP D - Closed - NSC Fuel - 8.6 kg/hr

X

Sampling Method
5G Train I
5G Train II
5H Train I
5H Train II
ESS Train I
ESS Train II

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Total Data Points

168

Table 2
Quality Assurance History of the Emission Sampling System (ESS)

1. Quality Assurance Plan for: Performance Monitoring of Advance Technology Wood Stoves: Field Testing for Fuel Savings, Creosote Buildup and Emissions, EPA/600/7-87-026.

- RTI Review and Acceptance of Quality Assurance Plan, February 1986
- RTI Interim Audit of Data Quality, December 1986
- RTI Final Technical System and Performance Evaluation Audit, April 1987
- RTI Final Audit of Data Quality, November 1987

2. Quality Assurance Plan for: Field Performance of Advanced Technology Woodstoves in Glens Falls, New York, 1988-1989, EPA/660/7-90-019.

- RTI Review and Acceptance of Quality Assurance Plan, December 1988
- RTI Technical Systems and Performance Evaluation Audit, February 1989
- RTI Second Performance Audit, May 1989
- RTI Interim Audit of Data Quality, November 1989

3. Quality Assurance Plan for: Woodstove Emission Sampling Methods Comparability Analysis and *In-situ* Evaluation of New Technology, EPA-600/7-89-002.

- RTI Review and Acceptance of Quality Assurance Plan, March 1987
- RTI Final Audit Report, April 1987

4. Technical system and performance evaluation audits were conducted by RTI on automated emission sampler protocols and data for masonry heaters. Final audit reports were completed April, 1992. The audits were conducted to support the inclusion of masonry heater data in section 1.10 of AP-42.

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[1] Research Triangle Institute (RTI) was under contract with the U.S. EPA to provide independent third party quality assurance audits.

EPA Methods 5G and 5H, along with their associated EPA Method 28 fueling protocols, were used for each of the closed-door woodstove tests conducted (test runs 1-10, 19, and 20). Duplicate NSC-AQMD ESS samplers were also operated along with the Method 5G and 5H sampling trains to permit sampling method comparison analyses. Although the EPA Methods 5G and 5H were modified slightly, as described below for some of the tested source configurations, all three sampler types were used on all of the remaining test runs which were run using the NSC-AQMD fueling protocols. These test runs were: 1. The woodstove with the doors-open configuration (i.e., test runs 11, 12, and 16), 2. Three additional woodstove test runs in the doors-closed configuration (i.e., test runs 13, 17 and 18), and 3. All test runs conducted on the fireplaces and masonry heaters (i.e., test runs 14, 15 and 21-28).

As mentioned above, several minor modifications to Methods 5G and 5H were necessary to adapt them for use in testing fireplace emissions. Because fireplace chimney flue-gas flow rates are substantially higher than woodstove flue-gas flow rates, the EPA Method 5G dilution tunnel, which must capture all of the flue-gases generated by an appliance being tested, had to be modified to provide increased flow above the EPA Method 5G-specified 140 standard cubic feet per minute (scfm). To capture all fireplace flue-gas emissions, the dilution tunnel flows had to be increased to between 300 and 400 scfm. It was found that even with this increase in tunnel flow, the resulting concentrations of diluted particles in the tunnel were greater than is characteristic of the tunnel when used in conjunction with a woodstove at the specified 140 scfm flow. For that reason the flow through the sample filters was reduced from the 0.5 cfm specified in Method 5G to 0.3 cfm to prevent filter overloading.

Finally, because the NSC-AQMD fueling protocol is a “cold start” method, there were no initial tracer-gas concentrations on which to base initial Method 5H sampling rates. Initial tracer-gas concentrations and the resulting Method 5H-calculated sampling rates based on them are used to maintain sampling rates consistently proportional to flue-gas flow rates throughout a test. Therefore, an estimate of an appropriate initial tracer-gas concentration was made for each test based on concentrations measured when practice test runs were conducted. It should be noted that this approach only potentially effects sampling to the extent that if an initial sampling rate is estimated too high, the sampler may not have the capacity to sample fast enough to maintain proportional sampling rates when flue-gas flows increase later on in the test. On the other hand, if an initial sampling rate is estimated too low, the sampling system may not collect enough sample during the test for accurately measuring filter catch weights. These potential problems were monitored but neither of these conditions were experienced during any of the cold-start tests conducted for this study.

A key difference between the EPA’s Method 28 woodstove operating protocol and the draft NSC-AQMD operating protocol is fuel loading procedures. For that reason, some woodstove test runs were conducted using the draft NSC-AQMD fuel loading protocols. Data from these tests then provide a comparison with the majority of test runs conducted using the EPA Method 28 woodstove fueling protocols. To start with, the EPA Method 28 protocol is a hot-start procedure (i.e., emissions sampling is initiated when test fuel is loaded on a hot, burning coal bed). The draft NSC-AQMD protocols, on the other hand, is a cold-start procedure (i.e., sampling is initiated immediately after the kindling fire is ignited at the beginning of a test run).

In addition to the hot-start/cold-start difference, the Method 28 fueling protocol is based on a single wood load, whereas the draft NSC-AQMD protocols specify three successively loaded fuel loads.

Both the EPA Method 28 and the draft NSC-AQMD protocols also determine fuel load sizes differently. The Method 28 fuel load size is based on the useable volume of the woodstove firebox whereas the draft NSC-AQMD protocols base the fuel load size on the hearth (or grate) area of the fireplace being tested. The data presented in Table 3 illustrate the difference in fuel load sizes that occurs when the two different methods are applied to the same woodstove or fireplace. As can be seen by the data, following the draft NSC-AQMD protocols, produces a slightly larger fuel load for the woodstove. However, the data more dramatically illustrate that following the EPA Method 28 protocols for a fireplace produces an unrealistically large fuel load. This is because the typical EPA Method 28 fuel load is intended to completely fill a woodstove firebox which is completely inappropriate for fireplaces. Therefore, the necessity of basing the fuel load for fireplaces on hearth (or grate) area rather than volume is clear.

It should also be noted that the fuel load-size data illustrate that considerably larger fuel loads are calculated by the draft NSC-AQMD protocols if a fireplace or masonry heater is designed to be used without a grate. The 36-inch zero clearance fireplace (test runs 14 and 15) and masonry fireplace B (test runs 23 and 24) were tested with grates for supporting the fuel. Masonry fireplace A (test runs 21 and 22), masonry fireplace C (test runs 25 and 26) and masonry fireplace D (better described as masonry heater) (test runs 27 and 28) were tested without grates.

3. Moisture Determinations

The determination wood fuel moisture content is fundamental to the calculation of emission factors since emission factors are based on mass of pollutant generated per unit mass of dry fuel burned during a test. It is also fundamental to the calculation of flue-gas flow rates which, in turn, are used to calculate emission factors and rates. Since dry burn rate is used in the draft NSC-AQMD protocols to calculate flue-gas flow, it is critical that it be measured accurately (see Section 5 of this report).

To obtain dry fuel weight for this study, the total wet fuel mass was measured directly on a calibrated electronic strain-gauge scale from which fuel moisture content was subtracted. In accordance with EPA Method 28, wood moisture was measured using a “pin-type” electrical resistance meter. To assess the precision of this method for the study reported here, five technicians “blindly” measured the moisture content of a single sample of wood fuel. The results of this experiment are presented in Table 4. As can be seen from these data, the standard deviation of the measurement set was slightly larger than 10% of the average moisture percentage value.

The moisture content of flue gas is also fundamental to the determination of thermal efficiency since sensible and latent heat losses associated with water are always significant contributors to biomass combustion-based thermal energy losses. The method for the determination of flue-gas

Table 3. Fuel Loading Comparisons

Woodstove

EPA protocol 1.49 cu ft X 7 lbs/cu ft = 10.4 lbs.

NSC-APCD protocol 1.74 sq ft (hearth) X 7 lbs/sq ft = 12.2 lbs.

36-inch Fireplace

EPA protocol 5.96 cu ft X 7 lbs/cu ft = 41.7 lbs.

NSC-APCD protocol (hearth) 2.98 sq ft X 7 lbs/sq ft. = 20.9 lbs.

NSC-APCD protocol (grate) 1.14 sq ft X 7 lbs/sq ft X 1.5 = 12.0

Table 4. Precision of Wood Moisture Determination

Technician	**Average % DB**	**Std. Dev.**	**Individual Measurements: % DB**				
1	25.42	2.19	24.6	24.7	29.3	24.0	24.5
2	24.44	1.11	24.6	24.4	23.0	26.1	24.1
3	27.14	4.58	33.1	31.0	24.8	23.2	23.6
4	27.08	2.53	24.4	26.2	31.2	26.3	27.3
5	27.32	3.28	31.2	24.8	30.5	25.8	24.3
Overall	**26.28**	**2.74**	**Average**	26.28			
			Std. Dev.	2.95			

Delmhorst Moisture Meter Model J-2000; OMNI ID# 00183

Douglas Fir: nominal 2x4, 20" long: 70 °F moisture prescribed by the draft NSC-AQMD protocols sums the moisture directly evaporated from the wood fuel (measured as fuel moisture with the electrical resistance meter) and water formed by the combustion of fuel hydrogen. For example, the NSC-AQMD protocols assume the protocol-specified wood fuel contains 6.3% hydrogen.

To test the efficacy of measuring flue-gas moisture contents by using the draft NSC-AQMD protocols, flue-gas moisture contents were sampled directly using the volume of water condensed in the back-half of the Method 5H impinger set (i.e., performance of EPA Method 4 for flue-gas moisture in 40 CFR Part 60, Appendix A). A plot of the results generated by performing flue-gas moisture contents determinations using the two different methods are presented in Figure 1. This plot shows a reasonable correlation between the direct EPA Method 5/Method 4 and the draft NSC-AQMD protocols. In contrast to the precision obtained from the 5-technician repetitive measurements cited above, this correlation also confirms an acceptable accuracy for the use of the electrical resistance moisture meter.

4. Flue-Gas Flow

Flue-gas flow is a fundamental parameter in the calculation of emission rates and emission factors by the draft NSC-AQMD protocols. The draft NSC-AQMD protocols emissions rate equation used in this study is as follows:

$$\text{Emission Rate} = (\text{mass of particles/unit volume}) \times (\text{volume/time})$$

Where: The mass of particles/unit volume term is measured using the ESS and the volume/time term is the flue-gas flow rate.

The draft NSC-AQMD protocols emissions factor equation used in this study is as follow:

$$\text{Emission Factor} = \frac{(\text{mass of particles/unit volume}) \times (\text{total flue-gas volume})}{(\text{total dry wood mass})}$$

Where: The total flue-gas volume term is simply the average flue-gas flow multiplied by the length of time of the test.

The draft NSC-AQMD protocols equation for calculating flue-gas flow is as follows:

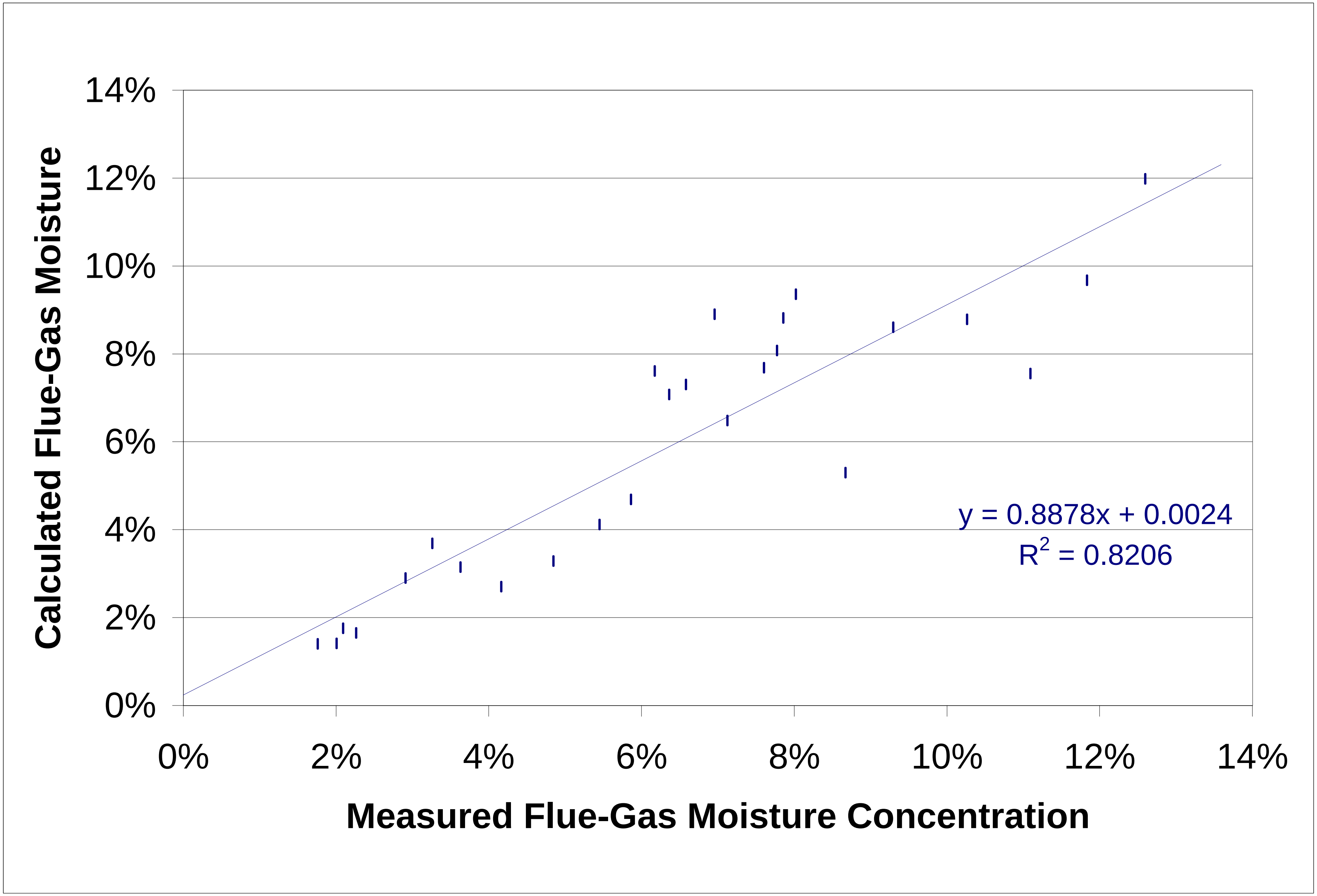

Figure 1. Comparison of Measured Flue-Gas Moisture and Values Calculated from Wood Fuel Moisture Measurements and the Stoichiometric Production of Water from Combustion.

$$\text{Flue-Gas Flow} = \frac{(\text{conversion factor constant}) \times (\text{carbon in wood}) \times (\text{dry burn rate})}{(Y_{CO_2} + Y_{CO} + Y_{HC})},$$

Where: The carbon in wood, as defined in U.S. EPA Method 5, is 0.51 weight fraction,
Y_{CO_2} is the mole (or volume) fraction of carbon dioxide in the flue gas,
Y_{CO} is the mole (or volume) fraction of carbon monoxide in the flue gas, and
Y_{HC} is the mole (or volume) fraction of hydrocarbons in the flue gas. This value is defined in EPA Method 5H as 0.0132 for non-catalytic woodstoves. As will be demonstrated later, dropping this term when the equation is used for fireplace testing provides a more realistic estimate of flue-gas flow.

For this study, the preceding equation was used to calculate flue-gas flows for both the draft NSC-AQMD protocols and for the EPA Method 5H (with and without the Y_{HC} term). It should also be noted that there was a difference between the methods on how overall test averages were determined. With the EPA Method 5H approach, data collected at a frequency of once every ten- minutes over the course of each test period were used to calculate flue-gas flows for each ten minute interval. These 10-minute flue-gas flow data were then averaged for the test run average. On the other hand, the draft NSC-AQMD protocols only use a single overall average burn rate and a single measurement of carbon dioxide and carbon monoxide gases in the gas bag sample collected at a constant rate over the course of the entire test.

Because two EPA Method 5G trains were also operated with each test run, a third independent method for assessing flue-gas flow was available and used. EPA Method 5G-derived flue-gas flows for each woodstove and fireplace test conducted for this study were obtained by applying the ratio of flue-gas carbon dioxide concentrations and dilution tunnel carbon dioxide concentrations to the EPA Method 1-measured (40 CFR Part 60 Appendix A) dilution tunnel flow rates. The equation for calculating flue-gas flow using this EPA Method 5G-based carbon dioxide tracer-gas method is as follows:

$$\text{Flue-Gas Flow} = \frac{(\text{Tunnel Flow}) \times (\text{Tunnel } CO_2 - \text{Indoor } CO_2)}{(\text{Flue } CO_2 - \text{Indoor } CO_2)}$$

Where: tunnel CO_2 = mole (or volume) fraction carbon dioxide in the dilution tunnel,
indoor CO_2 = mole (or volume) fraction carbon dioxide in the laboratory indoor air, and
flue-gas CO_2 = mole (or volume) fraction carbon dioxide in the fireplace or woodstove flue-gas.

As can be seen from these two flue-gas flow equations, flue-gas flow is directly dependent on

CO_2 and CO concentration measurements. In addition, CO_2, CO, and O_2 measurements are needed for the thermal efficiency calculations contained in the NSC-AQMD draft protocols. For these reasons, comparisons of gas measurements were made as a first step in assessing the quality of flue-gas flow and efficiency data.

For each test run there were three independent measurements of oxygen: 1. A continuous, real-time gas analyzer connected directly to the flue. Oxygen measurements made by this instrument were recorded every ten minutes and averaged for each test period, 2. Each ESS unit is equipped with a gas sampling bag into which flue-gas is collected at a constant rate during the course each test period. The contents of these gas bag samples are analyzed with the continuous real-time oxygen analyzer after the completion of each test period, and 3. Internal electrochemical oxygen sensors built into each ESS sampling system. These electrochemical oxygen cells provide automatically recorded oxygen concentration averages for every five-minute test interval over the course each test period.

For each test run there were two independent measurements of both carbon monoxide and carbon dioxide: 1. Continuous, real-time carbon monoxide and carbon dioxide analyzers sampled directly from the flue and recorded respective gas concentration measurements at a frequency of once every ten minutes during each complete test run. These data were averaged over each entire test run., 2. Carbon monoxide and carbon dioxide were also measured in each of the two ESS gas sample bags using the continuous, real-time gas analyzers at the completion of each test run.

The mean flue-gas oxygen, carbon dioxide, and carbon monoxide concentrations for each of the 28 test runs conducted and as determined by each of the methods discussed above, are presented in Figures 2, 3, and 4 respectively. The overall means, averaged for each method across all test runs, are presented and compared in Table 5. As can be seen from the data, the comparisons show good correlations between the gas concentrations measured by each method. In addition, it is believed that the quality of the carbon dioxide concentration measurements could be further improved by the selection of calibration gases in a more narrow range of the actual flue-gas concentrations measured..

Flue-gas flows were calculated 13 different ways and their values were compared by linear regressions as presented in Table 6. The terms “weighted” and “un-weighted” shown in Table 6 refer to whether the flue-gas flow calculations were performed on each of the ten-minute data sets and then averaged for the test run (weighted) or whether the flue-gas constituent concentrations were averaged for the test run and then used in the calculation of flue-gas flows (un-weighted). In addition, flue-gas flows were calculated using data from the ESS bag sample method and from the continuous, real-time gas analyzer method with and without the EPA’s hydrocarbon value for non-catalytic woodstoves included in the equation.

In addition to the direct flue-gas samples collected in the ESS gas-sample bags, an incinerated flue-gas sample was also collected over the course of each test run. To obtain these incinerated samples, flue-gas was withdrawn from the flue at a constant rate and passed through quartz wool maintained at 800°F. At the end of each test run, carbon dioxide concentrations were measured

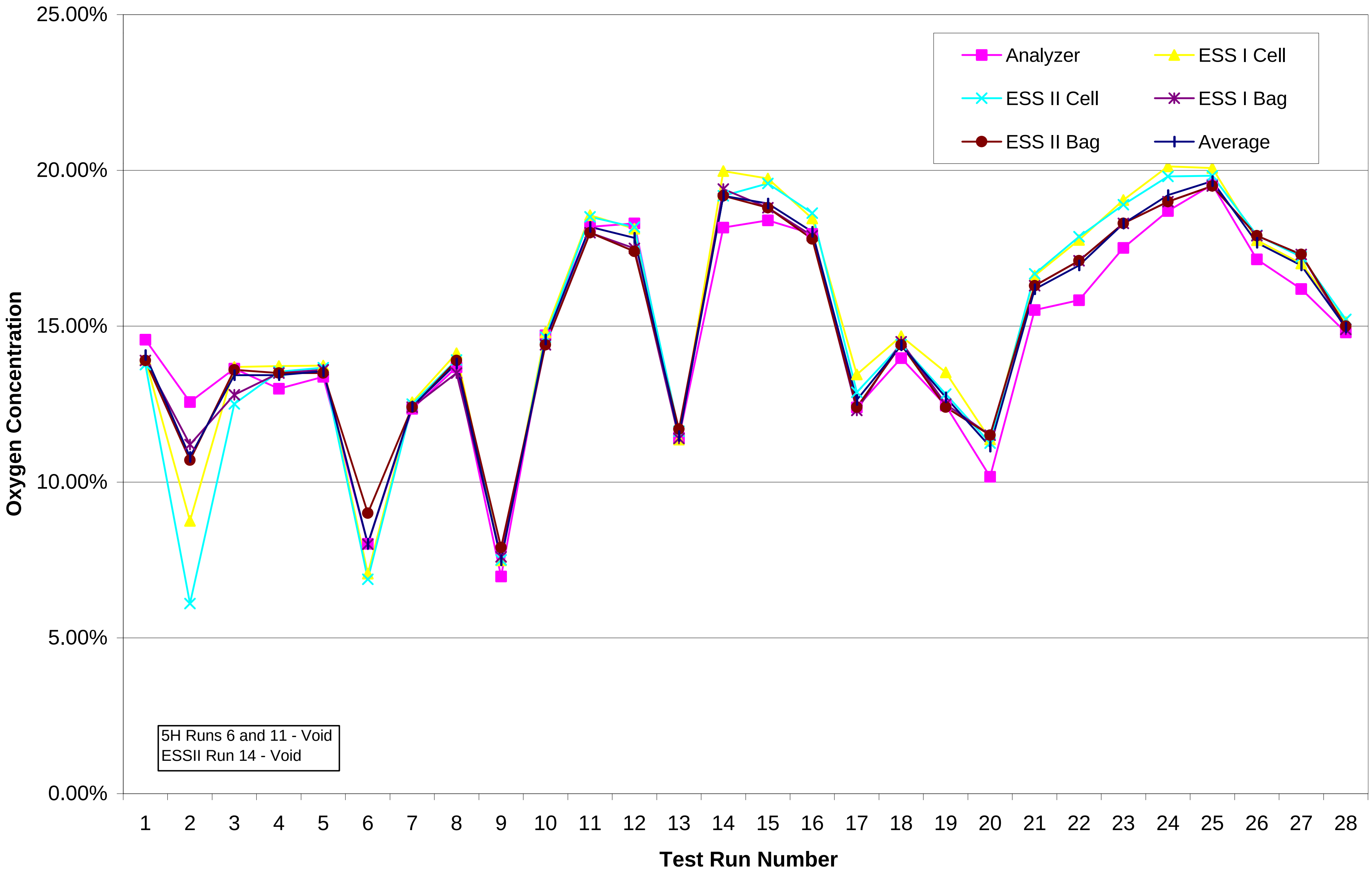

Figure 2. Comparison of Average O_2 Concentrations Measured by a Continuous, Real-Time Flue-Gas Analyzer in ESS Bag Samples, and by the Continuous ESS Oxygen Cell Analyzers.

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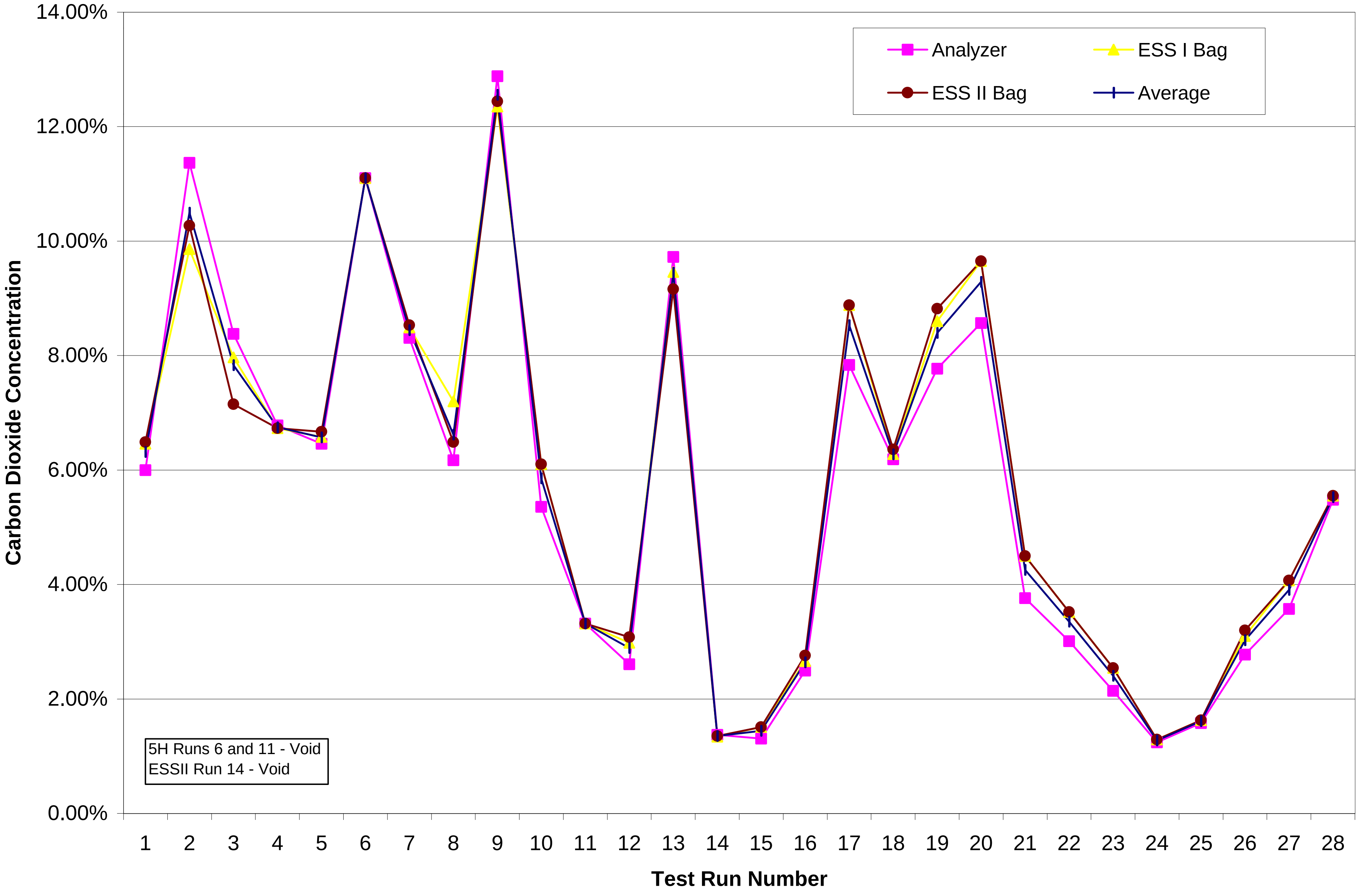

Figure 3. Comparison of Average CO_2 Concentrations Measured by a Continuous, Real-Time Flue-Gas Analyzer and in ESS Bag Samples.

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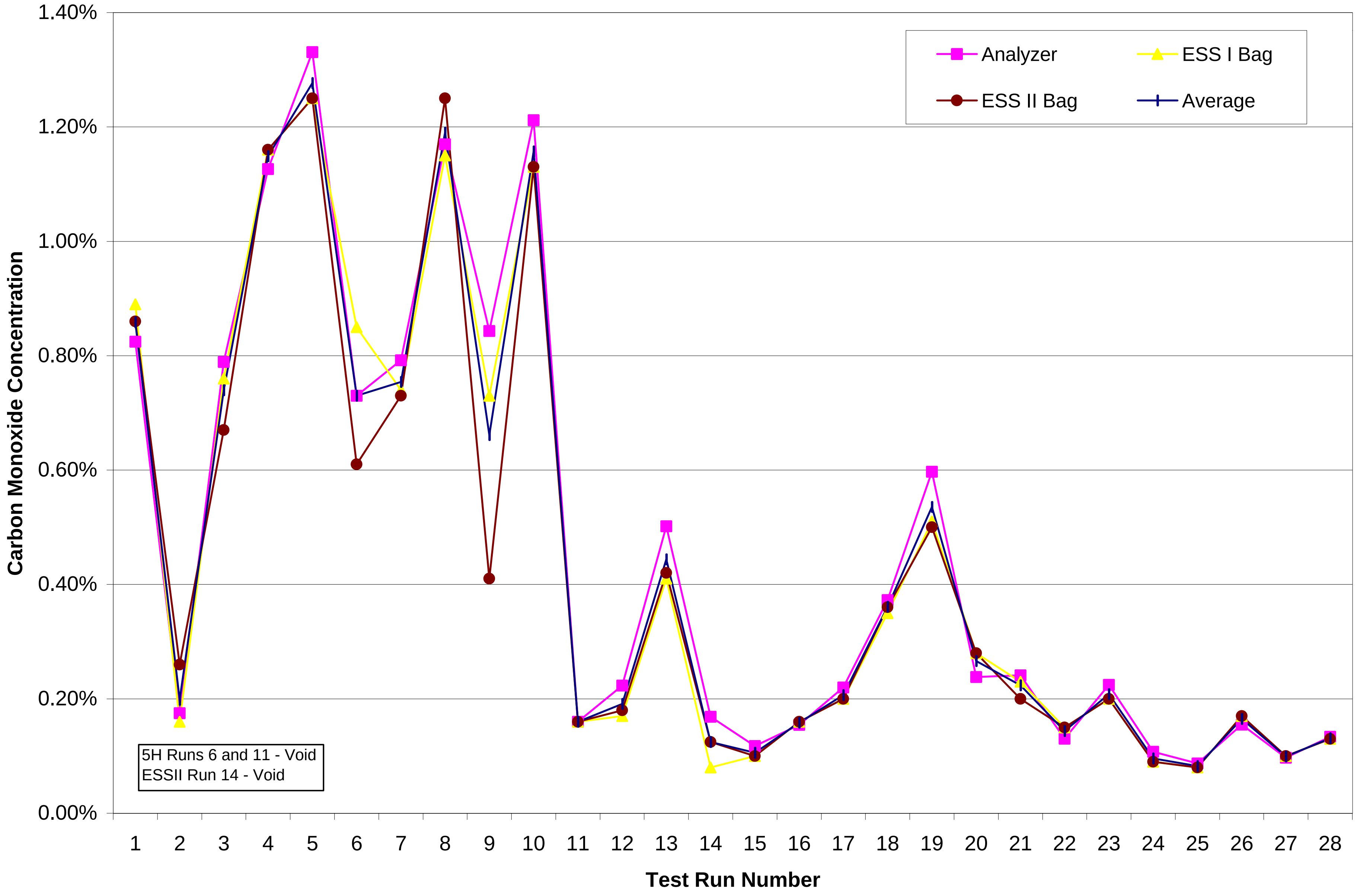

Figure 4. Comparison of Average CO Concentrations Measured by a Continuous, Real-Time Analyzer and in ESS Bag Samples.

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Table 5. Comparison of Flue-Gas Analysis Methods

	Average	n
O_2 Cell	14.89%	55
O_2 Bag	14.77%	55
O_2 Analyzer	14.20%	27
Overall Average O_2	14.82%	136

	Absolute Difference	Relative Percentage of Overall Average
Cell - Bag	0.12%	0.8%
Bag - Analyzer	0.58%	3.9%
Analyzer - Cell	-0.69%	-4.7%

	Average	n
CO_2 Bag	5.84%	56
CO_2 Analyzer	5.30%	27
Overall Average CO_2	5.73%	82

	Absolute Difference	Relative Percentage of Overall Average
Bag - Analyzer	0.54%	9.3%

	Average	n
CO Bag	0.44%	55
CO Analyzer	0.45%	27
Overall Average CO	0.45%	81

	Absolute Difference	Relative Percentage of Overall Average
Bag - Analyzer	-0.01%	-1.3%

Table 6. Calculated Flue-Gas Flow Rates

(all flows are in standard cubic feet per minute)

Test Run Number	Description	Weighted CO_2 Flue/Tunnel (wet)	Unweighted CO_2 Flue/Tunnel (wet)	Average % Moisture (WB)	Weighted CO_2 Flue/Tunnel (dry)	Unweighted CO_2 Flue/Tunnel (dry)	ESS I Bag EPA w/o HC	ESS II Bag EPA w/o HC	Avg. ESS Bag EPA w/o HC	ESS Incinerated Bag EPA	ESS I Bag EPA w/ HC	ESS II Bag EPA w/ HC	Avg. ESS Bag EPA w/ HC	Weighted Analyzer Gas EPA w/ HC (5H)	Weighted Analyzer Gas EPA w/o HC	Unweighted Analyzer Gas EPA w/ HC	Unweighted Analyzer Gas EPA w/o HC
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	12.7	12.3	6.58%	11.9	11.5	9.5	9.5	9.5	10.3	8.1	8.1	8.1	10.5	14.0	8.6	10.3
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	25.3	25.4	11.83%	22.3	22.4	22.8	21.7	22.3	22.8	20.2	19.3	19.7	18.9	21.3	17.7	19.8
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	10.5	11.4	7.77%	9.7	10.5	11.2	12.5	11.8	11.9	9.7	10.7	10.2	8.9	10.3	9.3	10.6
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	7.7	7.7	7.60%	7.1	7.2	8.5	8.5	8.5	9.1	7.3	7.3	7.3	6.7	7.7	7.2	5.6
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	7.1	7.2	6.17%	6.7	6.8	7.6	7.5	7.6	7.1	6.5	6.4	6.5	6.3	7.4	6.6	7.7
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	ND	ND	ND	ND	ND	23.0	23.5	23.2	23.0	20.7	21.1	20.9	ND	ND	ND	ND
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	8.7	8.8	6.96%	8.1	8.2	8.6	8.6	8.6	8.6	7.5	7.5	7.5	6.8	7.7	7.6	8.7
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	8.0	7.5	11.09%	7.1	6.7	7.0	7.5	7.3	7.8	6.0	6.4	6.2	6.3	7.5	6.7	7.9
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	21.0	21.6	12.59%	18.4	18.9	19.4	19.8	19.6	19.7	17.6	17.9	17.8	15.8	17.3	16.8	18.5
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	8.6	8.8	6.36%	8.1	8.3	7.5	7.5	7.5	7.1	6.3	6.3	6.3	6.6	7.9	6.8	8.2
11	Stove - Open - NSC Fuel - 3.4 kg/hr	ND	ND	ND	ND	ND	59.0	59.0	59.0	56.8	42.8	42.8	42.8	ND	ND	ND	ND
12	Stove - Open - NSC Fuel - 3.7 kg/hr	75.8	79.2	3.63%	73.1	76.3	69.9	67.6	68.7	69.3	49.3	48.1	48.7	50.6	78.5	52.6	77.1
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	18.6	19.1	10.26%	16.7	17.2	19.7	20.3	20.0	20.1	17.4	17.8	17.6	20.8	31.8	17.0	19.3
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	193.4	197.5	1.76%	190.0	194.0	174.6	ND	174.6	192.1	90.5	ND	90.5	83.0	157.5	88.3	166.8
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	171.9	178.1	2.26%	168.0	174.1	154.0	154.0	154.0	153.9	84.6	84.6	84.6	84.1	161.5	87.8	169.1
16	Stove - Open - NSC Fuel - 3.1 kg/hr	83.3	84.9	2.91%	80.9	82.4	65.3	63.1	64.2	62.1	44.5	43.4	44.0	46.9	72.9	47.2	70.8
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	18.0	20.0	9.29%	16.3	18.1	17.8	17.8	17.8	17.6	15.6	15.6	15.6	17.3	22.5	17.0	19.7
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	37.3	28.0	7.12%	34.6	26.0	21.7	21.7	21.7	20.5	18.1	18.1	18.1	16.6	20.9	18.1	21.7
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	9.6	9.7	7.85%	8.8	9.0	11.6	11.3	11.4	11.6	10.1	9.9	10.0	9.9	11.5	10.9	12.6
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	9.8	9.6	8.02%	9.0	8.8	12.9	12.9	12.9	13.1	11.4	11.4	11.4	11.0	12.6	12.6	14.5
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	105.6	112.3	5.86%	99.4	105.7	87.7	88.2	87.9	88.3	68.5	68.9	68.7	86.1	131.7	77.8	103.5
22	FP A - Open - NSC Fuel - 10 kg/hr	169.7	179.2	3.26%	164.2	173.3	164.0	164.0	164.0	166.2	120.6	120.6	120.6	148.0	246.7	134.7	191.3
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	105.5	109.5	4.16%	101.1	104.9	89.4	89.4	89.4	89.4	60.3	60.3	60.3	67.5	111.9	65.8	102.5
24	FP B - Open - NSC Fuel - 5.9 kg/hr	280.8	279.2	2.00%	275.2	273.6	256.4	256.4	256.4	254.6	131.1	131.1	131.1	132.7	280.0	132.1	261.2
25	FP C - Open - NSC Fuel - 7.6 kg/hr	259.2	263.5	2.09%	253.8	258.0	266.8	266.8	266.8	263.8	150.5	150.5	150.5	159.8	297.6	156.5	285.9
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	98.4	101.6	4.84%	93.6	96.7	90.0	87.3	88.7	86.5	64.1	62.7	63.4	74.2	123.7	69.1	100.3
27	FP D - Open - NSC Fuel - 7.9 kg/hr	125.9	132.5	5.45%	119.0	125.3	113.4	113.4	113.4	110.8	86.2	86.2	86.2	102.6	154.9	94.6	128.7
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	85.4	89.7	8.67%	78.0	81.9	91.3	91.3	91.3	91.8	74.1	74.1	74.1	86.0	120.3	74.7	92.2
	number of data points	26	26	26	26	26	28	27	28	28	28	27	28	26	26	26	26

	slope	intercept	r squared
Weighted CO2 Flue/Tunnel vs. Unweighted CO2 Flue/Tunnel	0.98	-0.19	0.9986
Weighted CO2 Flue/Tunnel vs. Avg. ESS Bag EPA w/o HC	1.03	0.87	0.9898
Weighted CO2 Flue/Tunnel vs. ESS Incinerated Bag EPA	1.02	0.99	0.9894
Weighted CO2 Flue/Tunnel vs. Avg. ESS Bag EPA w/ HC	1.77	-8.50	0.9377
Weighted CO2 Flue/Tunnel vs. Weighted Analyzer Gas EPA w/ HC	1.55	-3.99	0.8689
Weighted CO2 Flue/Tunnel vs. Weighted Analyzer Gas EPA w/o HC	0.86	1.39	0.9419
Weighted CO2 Flue/Tunnel vs. Unweighted Analyzer Gas EPA w/ HC	1.66	-7.09	0.9140
Weighted CO2 Flue/Tunnel vs. Unweighted Analyzer Gas EPA w/o HC	0.96	0.74	0.9820
Unweighted CO2 Flue/Tunnel vs. Avg. ESS Bag EPA w/o HC	1.05	30.00	0.9903
Unweighted CO2 Flue/Tunnel vs. ESS Incinerated Bag EPA	1.04	1.22	0.9903
Unweighted CO2 Flue/Tunnel vs. Avg. ESS Bag EPA w/ HC	1.82	-8.86	0.9477
Unweighted CO2 Flue/Tunnel vs. Weighted Analyzer Gas EPA w/ HC	1.59	-4.48	0.8837
Unweighted CO2 Flue/Tunnel vs. Weighted Analyzer Gas EPA w/o HC	0.88	1.35	0.9502
Unweighted CO2 Flue/Tunnel vs. Unweighted Analyzer Gas EPA w/ HC	1.71	-7.54	0.9265
Unweighted CO2 Flue/Tunnel vs. Unweighted Analyzer Gas EPA w/o HC	0.98	0.86	0.9859
Avg. ESS Bag EPA w/o HC vs. ESS Incinerated Bag EPA	0.99	0.30	0.9978
Avg. ESS Bag EPA w/o HC vs. Avg. ESS Bag EPA w/ HC	1.73	-9.91	0.9574
Avg. ESS Bag EPA w/o HC vs. Weighted Analyzer Gas EPA w/ HC	1.52	-5.36	0.8931
Avg. ESS Bag EPA w/o HC vs. Weighted Analyzer Gas EPA w/o HC	0.84	0.22	0.9596
Avg. ESS Bag EPA w/o HC vs. Unweighted Analyzer Gas EPA w/ HC	1.62	-8.11	0.9327
Avg. ESS Bag EPA w/o HC vs. Unweighted Analyzer Gas EPA w/o HC	0.94	-0.16	0.9932

	slope	intercept	r squared
ESS Incinerated Bag EPA vs. Avg. ESS Bag EPA w/ HC	1.74	-9.95	0.9509
ESS Incinerated Bag EPA vs. Weighted Analyzer Gas EPA w/ HC	1.52	-5.07	0.8827
ESS Incinerated Bag EPA vs. Weighted Analyzer Gas EPA w/o HC	0.84	0.46	0.9499
ESS Incinerated Bag EPA vs. Unweighted Analyzer Gas EPA w/ HC	1.63	-7.93	0.9243
ESS Incinerated Bag EPA vs. Unweighted Analyzer Gas EPA w/o HC	0.94	-0.05	0.9870
ESS Bag EPA w/ HC vs. Weighted Analyzer Gas EPA w/ HC	0.90	1.26	0.9825
ESS Bag EPA w/ HC vs. Weighted Analyzer Gas EPA w/o HC	0.48	5.86	0.9900
ESS Bag EPA w/ HC vs. Unweighted Analyzer Gas EPA w/ HC	0.95	0.32	0.9955
ESS Bag EPA w/ HC vs. Unweighted Analyzer Gas EPA w/o HC	0.52	6.64	0.9742
Weighted Analyzer Gas EPA w/ HC vs. Weighted Analyzer Gas EPA w/o HC	0.53	5.83	0.9757
Weighted Analyzer Gas EPA w/ HC vs. Unweighted Analyzer Gas EPA w/ HC	1.04	-0.55	0.9933
Weighted Analyzer Gas EPA w/ HC vs. Unweighted Analyzer Gas EPA w/o HC	0.56	7.45	0.9261
Weighted Analyzer Gas EPA w/o HC vs. Unweighted Analyzer Gas EPA w/ HC	1.94	-10.65	0.9881
Weighted Analyzer Gas EPA w/o HC vs. Unweighted Analyzer Gas EPA w/o HC	1.08	1.80	0.9795
Unweighted Analyzer Gas EPA w/o HC vs. Unweighted Analyzer Gas EPA w/ HC	0.55	7.08	0.9597

in this incinerated flue-gas sample. Carbon dioxide in this incinerated gas sample is, of course, the sum of flue-gas carbon dioxide directly emitted from the wood combustion process plus all of the carbon monoxide and incompletely oxidized hydrocarbons released from the wood combustion process. In accordance with the draft NSC-AQMD protocols, the carbon dioxide concentrations measured in these samples were used to calculate flue-gas flows.

While the data in Table 6 are included for presentation for all data collected, key findings of the flue-gas flow assessment are best illustrated in Figures 5 through 11. Figure 5 illustrates, with an R^2 of 0.997, a slope of 0.98, and an insignificant intercept, that the incinerated gas sampling approach is unnecessary and that the sum of the CO_2 and CO in ESS gas sample bags (non-incinerated) provides essentially the same values. Since the draft NSC-AQMD protocols call for using the incinerated flue-gas measurements for calculating flue-gas flow, Figures 6 through11 use and show “ESS Incinerated Bag” as the x-axis.

Figure 6 is a plot of flue-gas flow calculated by the weighted flue-gas/dilution tunnel CO_2 ratio approach versus the flue-gas flow calculated by the draft NSC-AQMD protocols method. The linear regression has an R^2 value of 0.989, a slope of near unity, and an insignificant intercept. This strongly indicates the two completely independent methods of determining flue-gas flow are in close agreement.

Figure 7 presents a plot of flue-gas flows derived from measurements made by the continuous, real-time analyzer following the standard EPA Method 5H protocol versus flue-gas flows derived from the procedures contained in the draft NSC-AQMD protocols. As can be seen from the R^2 value of 0.88, a slope of 0.58, and an intercept of 8.86, the two methods are in poor agreement. However, if the results are recalculated with the EPA hydrocarbon term (Y_{HC}) omitted from the EPA Method 5H calculations and plotted against the same draft NSC-AQMD protocol-calculated flue-gas flow data, the R^2 improves to 0.95, the slope is near unity (1.13), and the intercept is smaller, showing that there is a reasonable relationship between the two methods. These data are presented in Table 7.

The most probable reason for the difference made by omitting the Y_{HC} term is the fact that the combustion gas component of the flue gases as compared to the entrained air component of the flue gases is far smaller for fireplaces than for woodstoves especially when woodstove fuel-loading doors are closed. This combustion gas/entrained-air relationship in flue gases makes the hydrocarbon (Y_{HC}) value of 0.0132 assigned by the EPA for non-catalytic woodstoves too large and not appropriate for fireplaces or woodstoves when tested with their doors open. The combustion gas/entrained-air relationship combined with the fact that flue-gas flow data from fireplaces and open-door woodstoves statistically dominate the linear regression presented in Figure 9, causes a poor correlation when calculated with the hydrocarbon (Y_{HC}) term included. Notably, the hydrocarbon term does improve the correlation between the EPA Method 5H protocol and the NSC-AQMD method if just closed-door woodstove tests are analyzed (Figures 10 and 11).

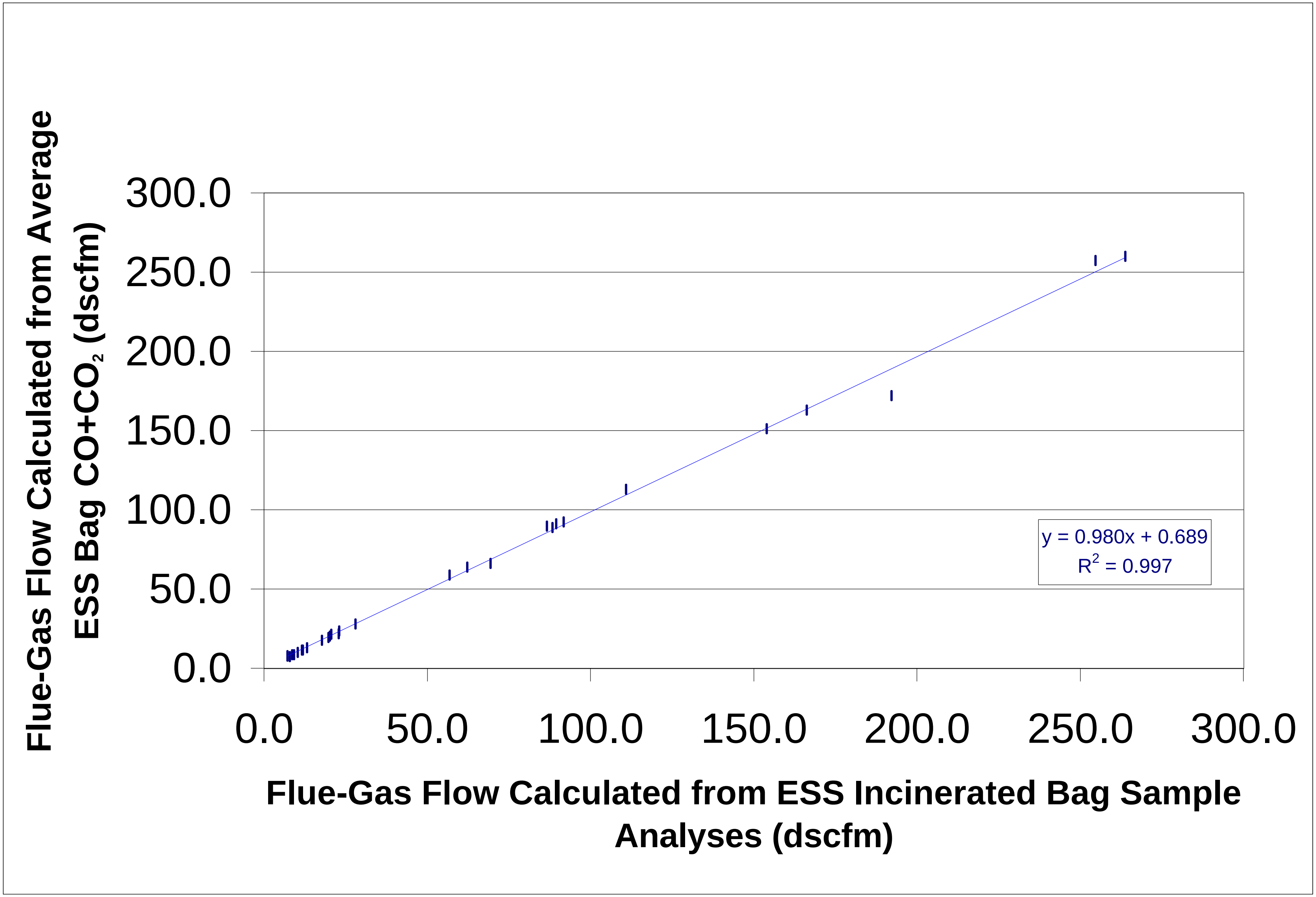

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Figure 5. Comparison of Flue-Gas flows Calculated from CO$_2$ and CO Concentrations and Flue-Gas Flows Calculated from ESS Incinerated Bag Samples

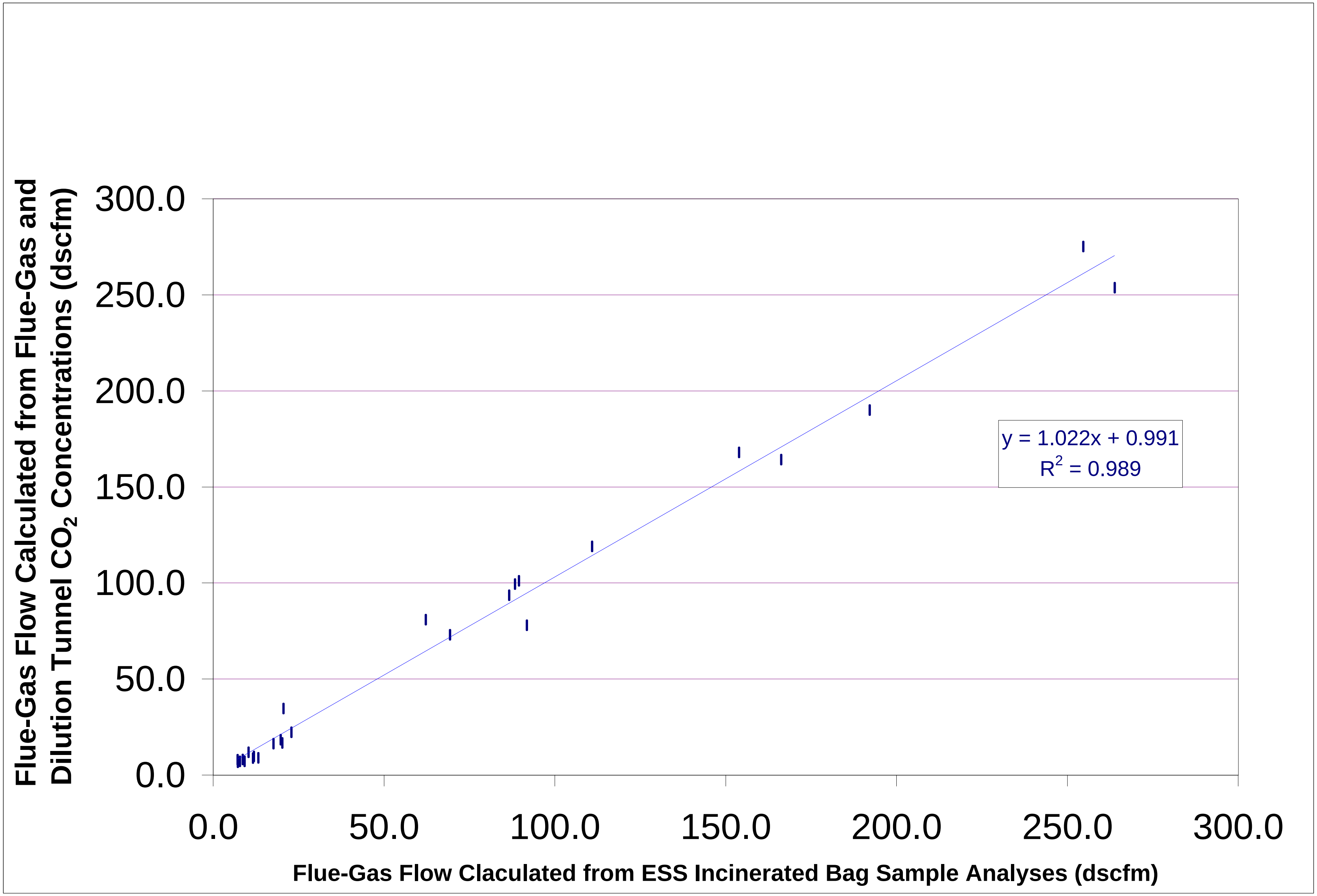

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Figure 6. Comparison of Flue-Gas Flows Calculated from Dilution Tunnel Data and Flue-Gas Flows Calculated from ESS Incinerated Bag Samples.

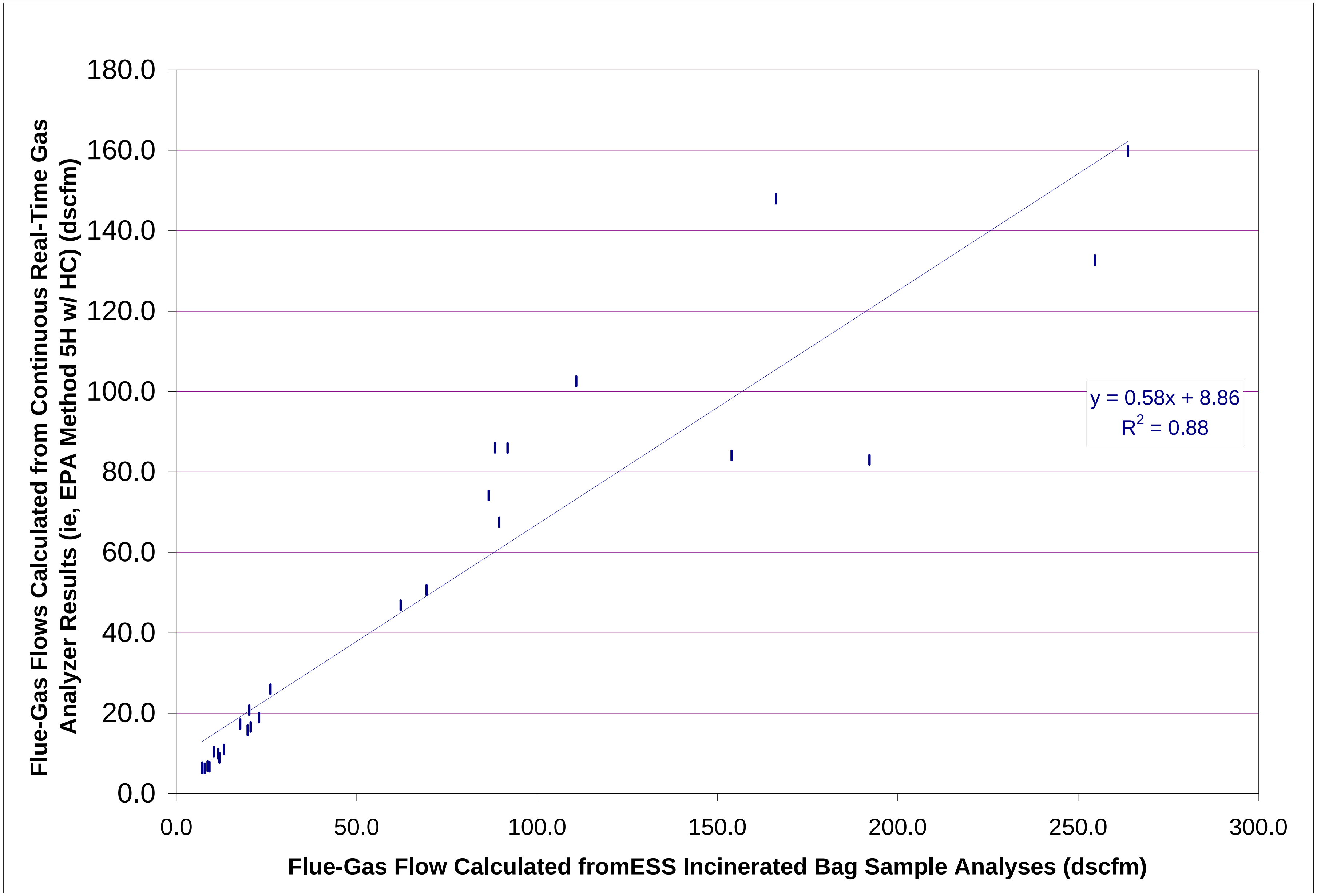

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Figure 7. Comparison of Flue-Gas flows Calculated by the EPA Method 5H Protocol and Flue-Gas Flows Calculated from ESS Incinerated Bag Samples.

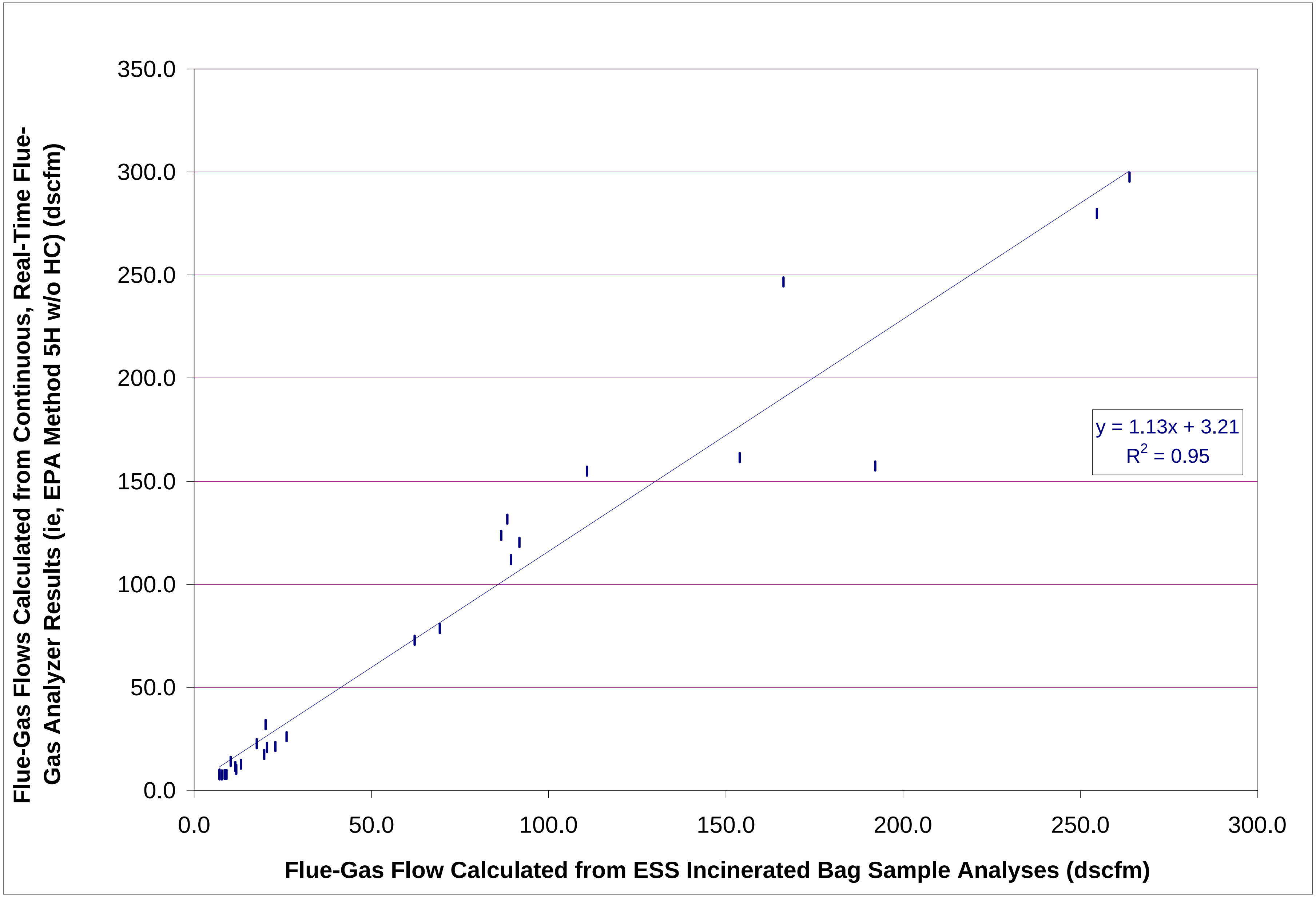

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Figure 8. Comparison of Flue-Gas Flows Calculated by the EPA Method 5H Protocol without the Hydrocarbon Factor and Flue-Gas Flows Calculated from ESS Incinerated Bag Samples.

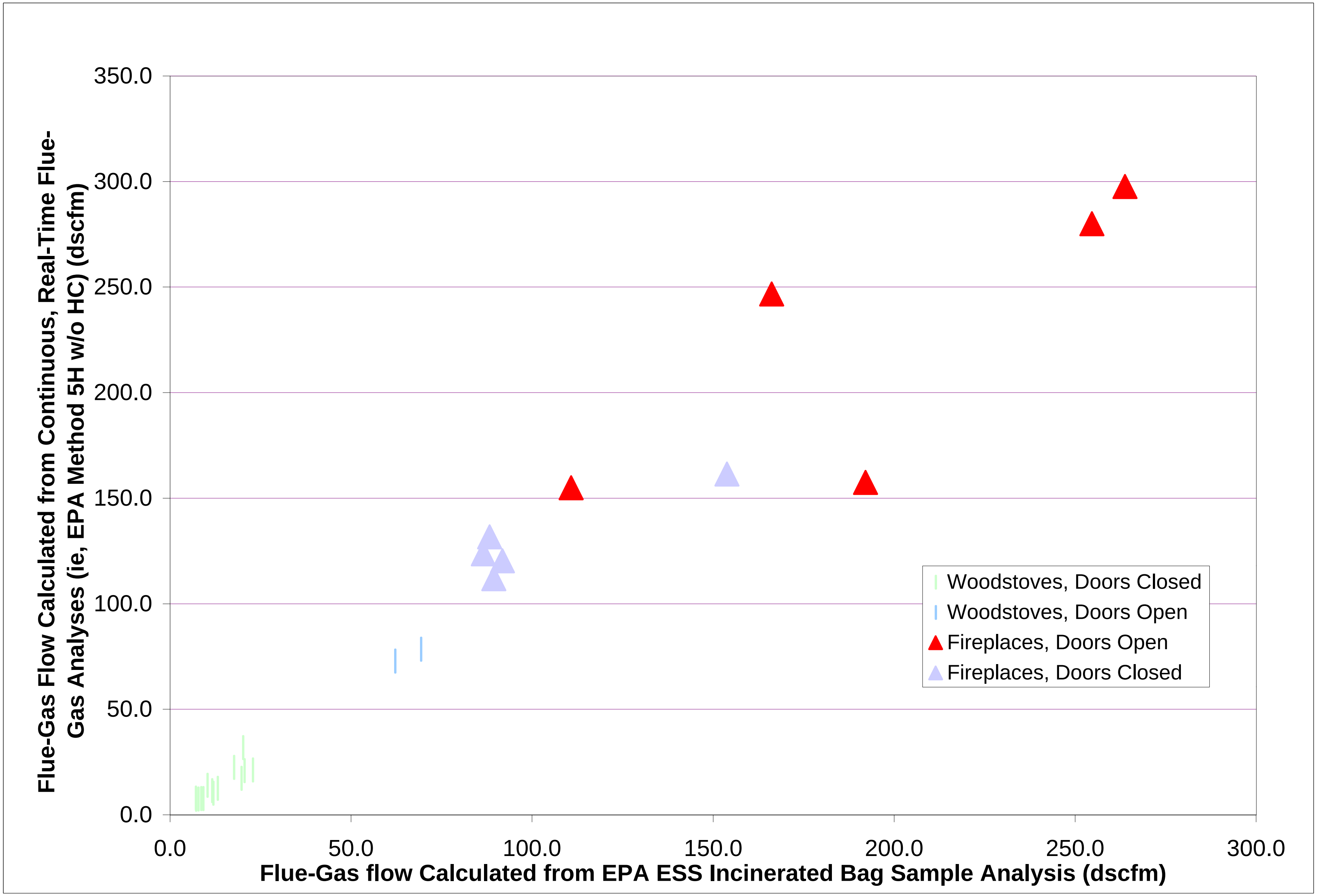

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Figure 9. Comparison of Flue-Gas Flows Calculated by the EPA Method 5H Protocol without the Hydrocarbon Factor and Flue-Gas Flows Calculated from ESS Incinerated Bag Samples For Each Appliance Type Tested.

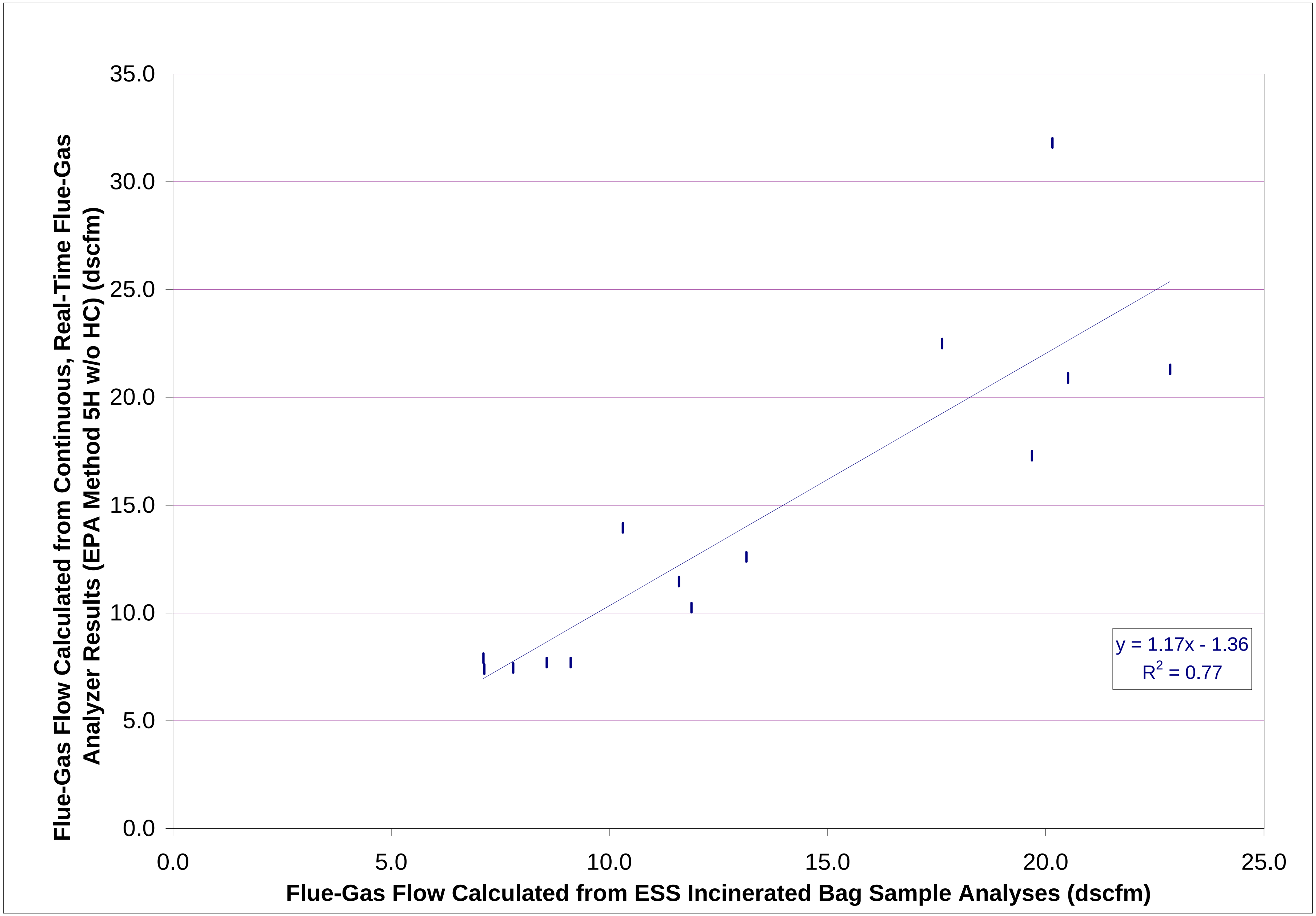

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Figure 10. Comparison of Flue-Gas Flows Calculated by the EPA Method 5H Protocol without the Hydrocarbon Factor and Flue-Gas Flows Calculated from ESS Bag Samples only for Woodstoves Tested with the Fuel Loading Doors Closed.

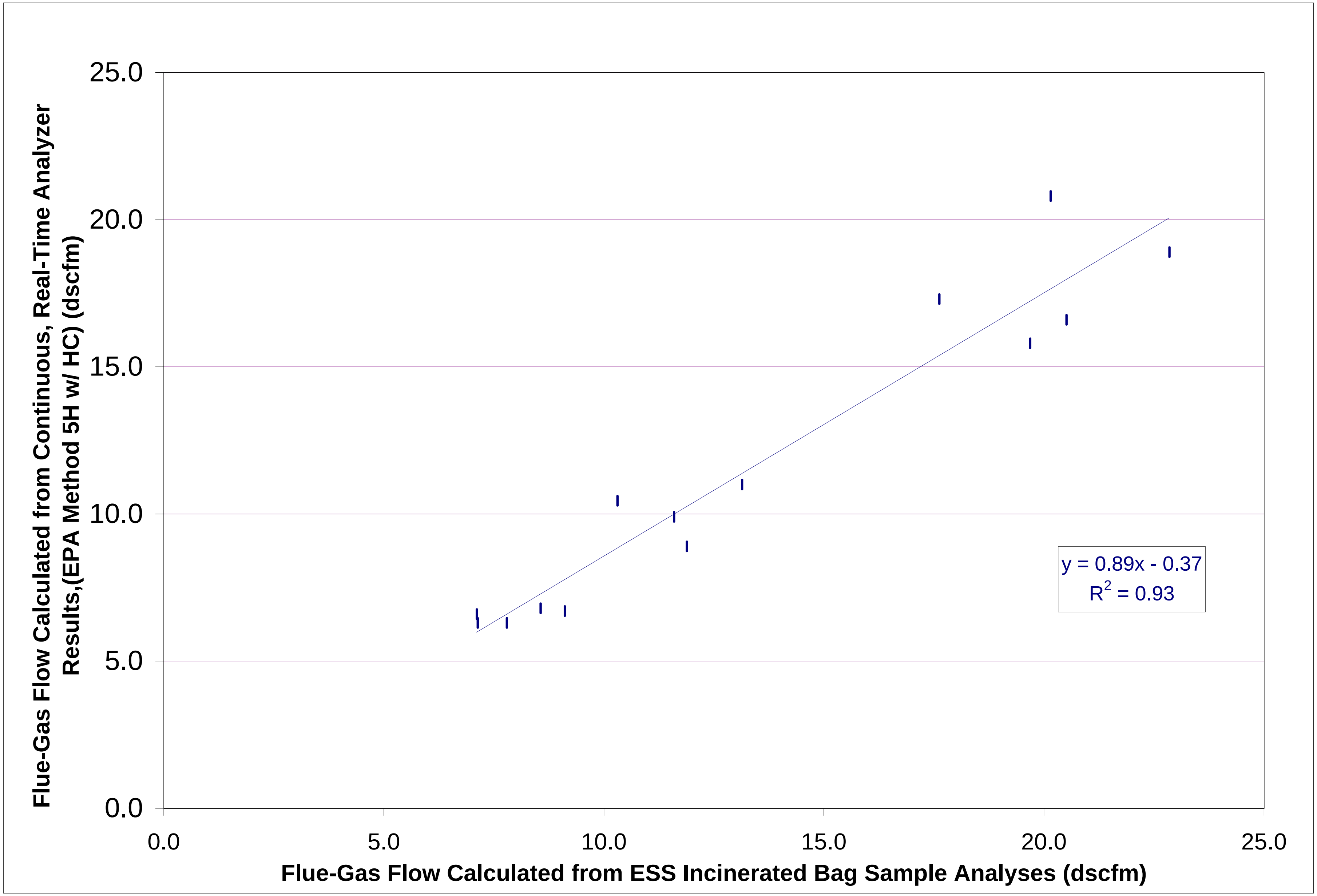

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Figure 11. Comparison of Flue-Gas Flows Calculated by the EPA Method 5H Protocol without the Hydrocarbon Factor and Flue-Gas Flows Calculated from ESS Incinerated Bag Sample Analyses only for Woodstoves with Doors Closed.

Table 7. Summary of Relationships between Particulate Emissions Determined by EPA Methods and the Draft NSC-APCD Protocols.

Dependent variable (“y” term)	R^2	n	Slope	Intercept	Independent variable (“x” term)
Unconverted 5G Emission Rate (g/hr)	0.930	28	0.720	0.318	**ESS Emission Rate (g/hr)**
5H w/o HC Term Emission Rate (g/hr)	0.924	26	0.834	1.14	**ESS Emission Rate (g/hr)**
Converted 5G Emission Rate (g/hr)	0.946	28	0.647	2.85	**ESS Emission Rate (g/hr)**
Unconverted 5G Emission Factor (g/kg)	0.890	28	0.605	0.487	**ESS Emission Factor (g/kg)**
5H w/o HC Term Emission Factor (g/kg)	0.884	26	0.822	0.314	**ESS Emission Factor (g/kg)**
Converted 5G Emission Factor (g/kg)	0.942	28	0.642	0.917	**ESS Emission Factor (g/kg)**

In summary, flue-gas flows calculated using the draft NSC-AQMD protocols and the EPA Method 5H procedures without the hydrocarbon term compare very well to the flue-gas flows calculated by factoring dilution tunnel flow (as measured by EPA Method 1) by the ratio of flue-gas CO_2 to EPA Method 5G dilution tunnel CO_2 (i.e., using CO_2 as the tracer-gas). In addition, CO_2 and CO measurements made on draft NSC-AQMD ESS gas sample bags at the completion of test runs provide adequate data to calculate reliable flue-gas flows.

5. Particulate Emissions Results and Discussion

Table 8 presents particulate emissions results in both the emissions rate (g/hour) and emissions factor reporting units. Emissions rates and factors are presented for each of the individual sampling trains and as replicate sampling train averages. Replicate-pair average Method 5G values have been converted to Method 5H equivalents following EPA's Method 5G conversion protocol. This was done because EPA Method 5G is approved as an alternative to the NSPS-specified EPA Method 5H procedure only when the EPA-specified Method 5G to 5H conversion equation is applied. As can be seen in Table 8, the two EPA methods produce significantly different results with or without applying EPA's conversion equation.

Finally, Method 5H results are presented in two forms: 1. With EPA's Method 5H-specified hydrocarbon term included in the emissions calculations, and 2. without EPA's Method 5H-specified hydrocarbon term included in the emissions calculations. As discussed above in Section 4, calculating particulate emissions using the Method 5H protocol without the hydrocarbon term appears to be more appropriate for open-door woodstoves and fireplaces. It also appears that calculating particulate emissions as specified by EPA Method 5H including the hydrocarbon term is more appropriate for closed-door woodstove testing.

Key relationships between particulate emissions results measured and calculated by all of the various methods studied here are shown in Figures 12 through 15. These are plots of average emissions factor values determined by the different methods for each test run. Emissions factors are used in these method comparison plots because emissions factors take out the potential variable effects that can be caused by additionally applying the burn rate variable to the results.

Figures 12 and 13 show the relationship between emission factors determined by EPA Method 5H with and without EPA's Method 5H specified hydrocarbon term versus EPA Method 5G values unconverted and converted to EPA Method 5H values. As can be seen, dropping the hydrocarbon term improves the relationship between the two methods as does converting the EPA Method 5G values to EPA Method 5H equivalent values.

Figure 14 shows the relationship between emissions factors determined by Method 5H with and without the hydrocarbon term versus the emissions factors determined by following the draft NSC-AQMD protocols (shown as "ESS Emission Factor" on the x-axis). As presented in Section 4 for flue-gas flows, emission factors determined by EPA Method 5H without the

Table 8. Particulate Emissions

Test Run Number	Description	5G Train I Emissions (g/Hour)	5G Train II Emissions (g/Hour)	Average 5G Emissions (g/Hour)	Converted* 5G Emissions (g/Hour)	5G Train I Emissions (g/kg)	5G Train II Emissions (g/kg)	Average 5G Emissions (g/kg)	Converted 5G Emissions (g/kg)	ESS-I Emissions (g/Hour)
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	4.31	4.22	4.26	6.1	3.70	3.63	3.66	5.2	7.9
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	7.16	7.03	7.10	9.3	1.89	1.85	1.87	2.4	12.6
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	2.95	2.40	2.68	4.1	1.83	1.48	1.65	2.5	4.6
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	5.49	4.21	4.85	6.7	4.97	3.81	4.39	6.1	10.6
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	7.85	6.18	7.01	9.2	7.89	6.21	7.05	9.2	14.0
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	13.53	13.89	13.71	16.0	2.96	3.04	3.00	3.5	23.3
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	2.14	2.02	2.08	3.3	1.63	1.53	1.58	2.5	3.3
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	6.77	6.52	6.64	8.8	6.97	6.70	6.83	9.0	12.0
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	11.06	12.21	11.64	14.0	2.62	2.90	2.76	3.3	13.0
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	6.13	6.19	6.16	8.2	6.83	6.90	6.86	9.2	10.0
11	Stove - Open - NSC Fuel - 3.4 kg/hr	21.06	ND	21.06	22.8	6.17	ND	6.17	6.7	23.9
12	Stove - Open - NSC Fuel - 3.7 kg/hr	23.32	23.81	23.57	25.1	6.35	6.48	6.41	6.8	30.3
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	6.47	5.87	6.17	8.2	1.99	1.81	1.90	2.5	5.4
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	41.17	39.69	40.43	39.2	10.00	9.64	9.82	9.5	51.9
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	33.08	33.31	33.19	33.3	8.03	8.09	8.06	8.1	53.0
16	Stove - Open - NSC Fuel - 3.1 kg/hr	11.13	12.57	11.85	14.2	3.56	4.03	3.80	4.5	19.5
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	3.83	3.54	3.68	5.4	1.45	1.34	1.39	2.0	3.3
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	5.11	5.07	5.09	7.0	2.11	2.10	2.11	2.9	8.9
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	1.28	1.58	1.43	2.4	0.73	0.90	0.82	1.4	1.6
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	1.21	1.22	1.21	2.1	0.57	0.57	0.57	1.0	2.9
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	16.61	16.79	16.70	18.8	2.41	2.44	2.42	2.7	22.6
22	FP A - Open - NSC Fuel - 10 kg/hr	34.40	51.10	42.75	34.3	3.44	5.11	4.28	4.1	43.6
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	34.71	34.03	34.37	34.3	8.53	8.36	8.44	8.4	51.8
24	FP B - Open - NSC Fuel - 5.9 kg/hr	36.28	36.92	36.60	36.1	6.17	6.28	6.22	6.1	63.4
25	FP C - Open - NSC Fuel - 7.6 kg/hr	52.13	52.07	52.10	48.4	6.92	6.91	6.92	6.4	78.1
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	19.32	19.06	19.19	21.1	3.95	3.90	3.93	4.3	22.7
27	FP D - Open - NSC Fuel - 7.9 kg/hr	16.36	17.50	16.93	19.0	2.08	2.23	2.15	2.4	27.8
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	10.46	9.29	9.87	12.2	1.21	1.08	1.14	1.4	12.7

Table 8. (continued) Particulate Emissions

Test Run Number	Description	ESS-II Emissions (g/Hour)	Average ESS Emissions (g/Hour)	ESS-I Emissions (g/kg)	ESS-II Emissions (g/kg)	Average ESS Emissions (g/kg)	5H Train I Emissions (g/Hour)	5H Train II Emissions (g/Hour)	Average 5H Emissions (g/Hour)	5H Train I Emissions (g/kg)
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	6.5	7.2	6.7	5.6	6.2	5.3	7.6	6.5	4.6
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	13.2	12.9	3.3	3.5	3.4	5.4	8.1	6.8	1.4
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	4.7	4.7	2.8	2.9	2.9	4.3	2.2	3.3	2.7
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	8.8	9.7	9.6	8.0	8.8	6.0	5.9	5.9	5.4
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	11.0	12.5	14.1	11.0	12.6	4.6	9.6	7.1	4.6
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	28.6	26.0	5.1	6.3	5.7	ND	ND	ND	ND
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	2.9	3.1	2.5	2.2	2.4	1.6	1.9	1.8	1.2
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	12.0	12.0	12.4	12.4	12.4	9.9	10.9	10.4	10.2
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	12.7	12.9	3.1	3.0	3.1	12.2	15.1	13.6	2.9
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	11.9	11.0	11.1	13.2	12.2	8.7	9.1	8.9	9.6
11	Stove - Open - NSC Fuel - 3.4 kg/hr	22.8	23.4	7.0	6.7	6.9	ND	ND	ND	ND
12	Stove - Open - NSC Fuel - 3.7 kg/hr	25.9	28.1	8.3	7.1	7.7	13.6	15.2	14.4	3.7
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	5.2	5.3	1.7	1.6	1.7	4.5	4.0	4.3	1.4
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	ND	51.9	12.6	ND	12.6	18.0	19.6	18.8	4.4
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	42.2	47.6	12.9	10.2	11.6	18.2	24.7	21.4	4.4
16	Stove - Open - NSC Fuel - 3.1 kg/hr	15.3	17.4	6.4	5.0	5.7	10.3	9.4	9.8	3.3
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	3.0	3.2	1.2	1.1	1.2	6.5	ND	6.5	2.4
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	5.6	7.3	3.7	2.3	3.0	5.2	5.5	5.3	2.1
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	1.4	1.5	0.9	0.8	0.9	0.9	1.2	1.1	0.5
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	2.5	2.7	1.4	1.2	1.3	1.2	1.1	1.2	0.6
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	20.8	21.7	3.3	3.0	3.2	16.8	15.4	16.1	2.4
22	FP A - Open - NSC Fuel - 10 kg/hr	39.8	41.7	4.4	4.0	4.2	36.4	29.9	33.2	3.6
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	41.9	46.9	12.7	10.3	11.5	31.0	33.5	32.3	7.6
24	FP B - Open - NSC Fuel - 5.9 kg/hr	67.0	65.2	10.8	11.4	11.1	23.5	22.0	22.7	4.0
25	FP C - Open - NSC Fuel - 7.6 kg/hr	62.6	70.4	10.3	8.3	9.3	35.7	33.0	34.4	4.7
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	18.0	20.4	4.6	3.7	4.2	15.6	15.5	15.6	3.2
27	FP D - Open - NSC Fuel - 7.9 kg/hr	19.9	23.9	3.5	2.5	3.0	16.9	15.9	16.4	2.2
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	11.2	12.0	1.5	1.3	1.4	7.3	7.0	7.1	0.8

Table 8. (continued) Particulate Emissions

Test Run Number	Description	5H Train II Emissions (g/kg)	Average 5H Emissions (g/kg)	5H Train I Emissions (g/Hour) [-y_{HC}]	5H Train II Emissions (g/Hour) [-y_{HC}]	Average 5H Emissions (g/Hour) [-y_{HC}]	5H Train I Emissions (g/kg) [-y_{HC}]	5H Train II Emissions (g/kg) [-y_{HC}]
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	6.5	5.6	6.4	9.0	7.7	5.5	7.8
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	2.1	1.8	6.1	9.0	7.5	1.6	2.4
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	1.4	2.0	4.9	2.6	3.7	3.1	1.6
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	5.3	5.3	6.6	6.8	6.7	6.0	6.2
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	9.6	7.1	5.4	11.2	8.3	5.4	11.2
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	ND	ND	ND	ND	ND	ND	ND
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	1.5	1.3	1.8	2.2	2.0	1.4	1.7
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	11.7	11.0	11.7	12.9	12.3	12.1	13.9
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	3.6	3.2	13.3	16.5	14.9	3.2	3.9
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	10.1	9.9	10.4	10.9	10.7	11.6	12.1
11	Stove - Open - NSC Fuel - 3.4 kg/hr	ND	ND	ND	ND	ND	ND	ND
12	Stove - Open - NSC Fuel - 3.7 kg/hr	4.1	3.9	19.9	22.2	21.1	5.4	6.0
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	1.2	1.3	5.1	4.5	4.8	1.5	1.4
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	4.8	4.6	33.4	37.1	35.3	8.1	9.0
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	6.0	5.2	35.0	47.5	41.2	8.5	11.5
16	Stove - Open - NSC Fuel - 3.1 kg/hr	3.0	3.2	15.4	14.1	14.7	4.9	4.5
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	ND	2.4	7.5	12.5	10.0	2.8	ND
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	2.2	2.2	6.3	6.6	6.4	2.6	2.7
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	0.7	0.6	1.1	1.4	1.2	0.6	0.8
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	0.5	0.5	1.4	1.3	1.3	0.6	0.6
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	2.2	2.3	22.4	20.2	21.3	3.2	2.9
22	FP A - Open - NSC Fuel - 10 kg/hr	3.0	3.3	51.8	42.4	47.1	5.2	4.2
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	8.2	7.9	48.3	52.3	50.3	11.9	12.8
24	FP B - Open - NSC Fuel - 5.9 kg/hr	3.7	3.9	46.4	43.4	44.9	7.9	7.4
25	FP C - Open - NSC Fuel - 7.6 kg/hr	4.4	4.6	66.4	60.7	63.6	8.8	8.1
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	3.2	3.2	22.7	22.5	22.6	4.6	4.6
27	FP D - Open - NSC Fuel - 7.9 kg/hr	2.0	2.1	23.0	21.6	22.3	2.9	2.8
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	0.8	0.8	9.0	8.6	8.8	1.0	1.0

Table 8. (continued) Particulate Emissions

Test Run Number	Description	Average 5H Emissions (g/kg) [$-y_{HC}$]
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	6.6
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	2.0
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	2.3
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	6.1
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	8.3
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	ND
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	1.5
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	13.0
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	3.5
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	11.8
11	Stove - Open - NSC Fuel - 3.4 kg/hr	ND
12	Stove - Open - NSC Fuel - 3.7 kg/hr	5.7
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	1.4
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	8.6
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	10.0
16	Stove - Open - NSC Fuel - 3.1 kg/hr	4.7
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	2.8
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	2.6
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	0.7
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	0.6
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	3.1
22	FP A - Open - NSC Fuel - 10 kg/hr	4.7
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	12.3
24	FP B - Open - NSC Fuel - 5.9 kg/hr	7.7
25	FP C - Open - NSC Fuel - 7.6 kg/hr	8.4
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	4.6
27	FP D - Open - NSC Fuel - 7.9 kg/hr	2.8
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	1.0

hydrocarbon term show a better correlation with the emission factors determined by the draft NSC-AQMD method.

Figure 15 shows the relationship between emissions factors determined by EPA Method 5G versus the emissions factors determined following the draft NSC-AQMD protocols (shown as "ESS Emission Factors" on the x-axis). Both unconverted and converted Method 5G results are shown. The converted Method 5G results show the better correlation with the emission factors determined by the draft NSC-AQMD method.

Emissions factors were also used in the method comparison plots because the purpose of the plots is to compare the efficacy of the sampling methods not to evaluate the performance of the wood burning appliances tested. It should also be noted however, that emissions rates show the same trends as emission factors. By using either emissions rates or emission factors, the data demonstrate that there is a strong and understandable correlation between the EPA reference Methods 5G and 5H and the draft NSC-AQMD protocol. The R^2 value for the linear regression of emission factors determined by: 1. Method 5H without the hydrocarbon term, 2. unconverted Method 5G, and 3. converted Method 5G versus the draft NSC-AQMD protocols are, 0.884, 0.890 and 0.942 respectively. The R^2 resulting from using emissions rates rather than emissions factors for the same relationships are 0.924, 0.930, and 0.946, respectively. A summary of these statistical relationships is presented in Table 7.

While it is outside the scope of this study to establish a standard "passing grade" or threshold for fireplaces and/or a masonry heaters, equivalency of fireplace and masonry heater emissions measured using the draft NSC-AQMD protocols to the 7.5 g/hour EPA standard for non-catalytic woodstoves can be estimated. An equivalency can only be estimated because:

1. EPA's Method 28 for operating woodstoves during test periods uses a hot-start procedure and the draft NSC-AQMD protocols use a cold-start procedure. It has been well documented that the kindling and start-up phases of a cold-start burn have significantly higher particulate emissions than occurs during a hot-start burn cycle,

2. The burn-cycle pattern is different between Method 28 and the draft NSC-AQMD protocols. As has been noted above, EPA's Method 28 specifies a single load of fuel for each entire test period whereas the draft NSC-AQMD protocols specify three successively loaded fuel loads for each entire test period. As contemplated by EPA for the single woodstove fuel load burn cycle test protocol in Method 28, the three-load pattern in the draft NSC-AQMD protocols is thought to be more representative of how fireplaces are actually used by consumer users,

3. The calculation of fuel load size is also different between EPA's Method 28 and the draft NSC-AQMD protocols. Again, these methods differ because of the differences in how consumers use the appliances to which they apply. Consumers are most typically perceived to load a woodstove for maximum burn time or

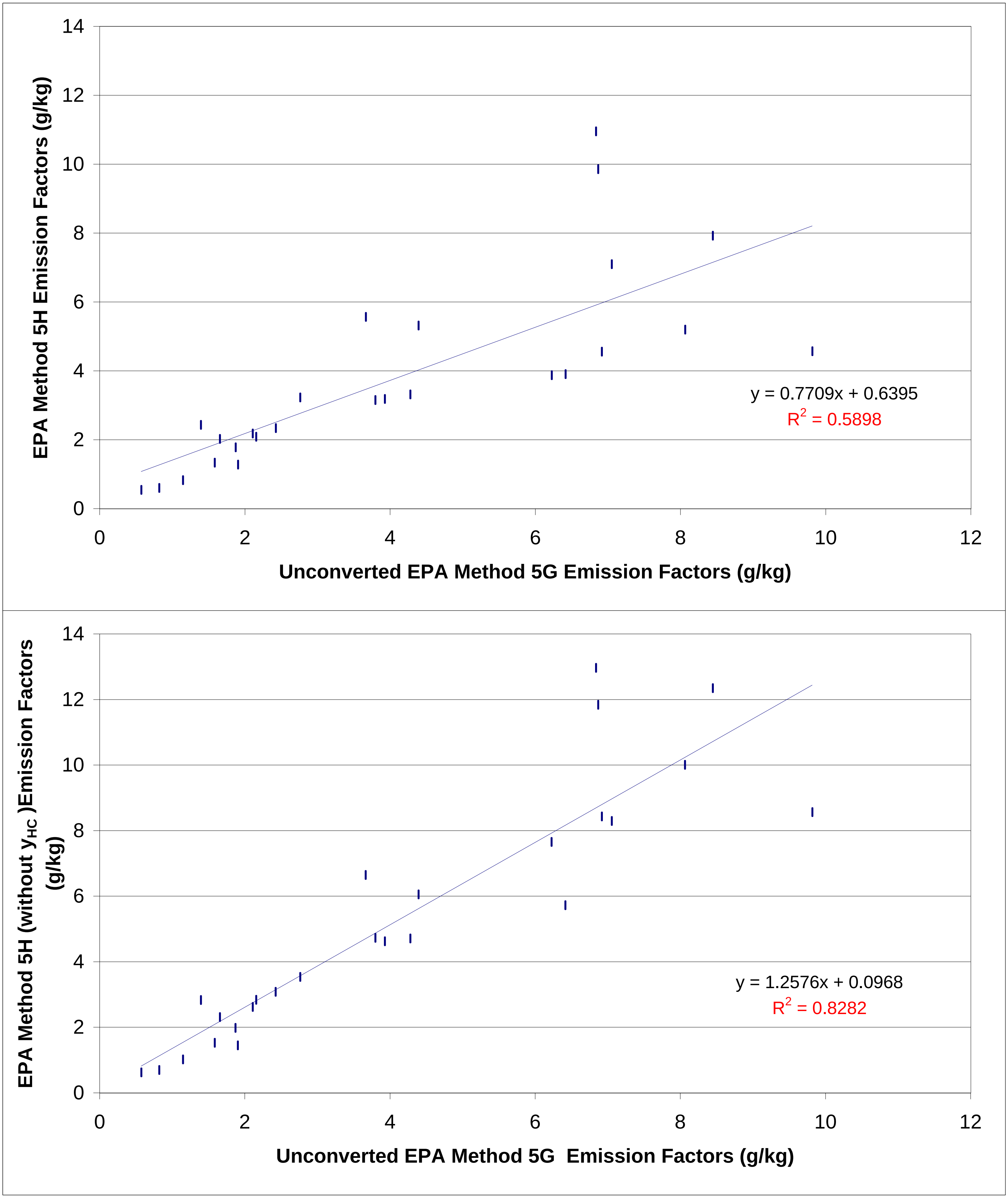

Figure 12. Relationship between Unconverted EPA Method 5G-Derived Emission Factors and EPA Method 5H-Derived Emission Factors.

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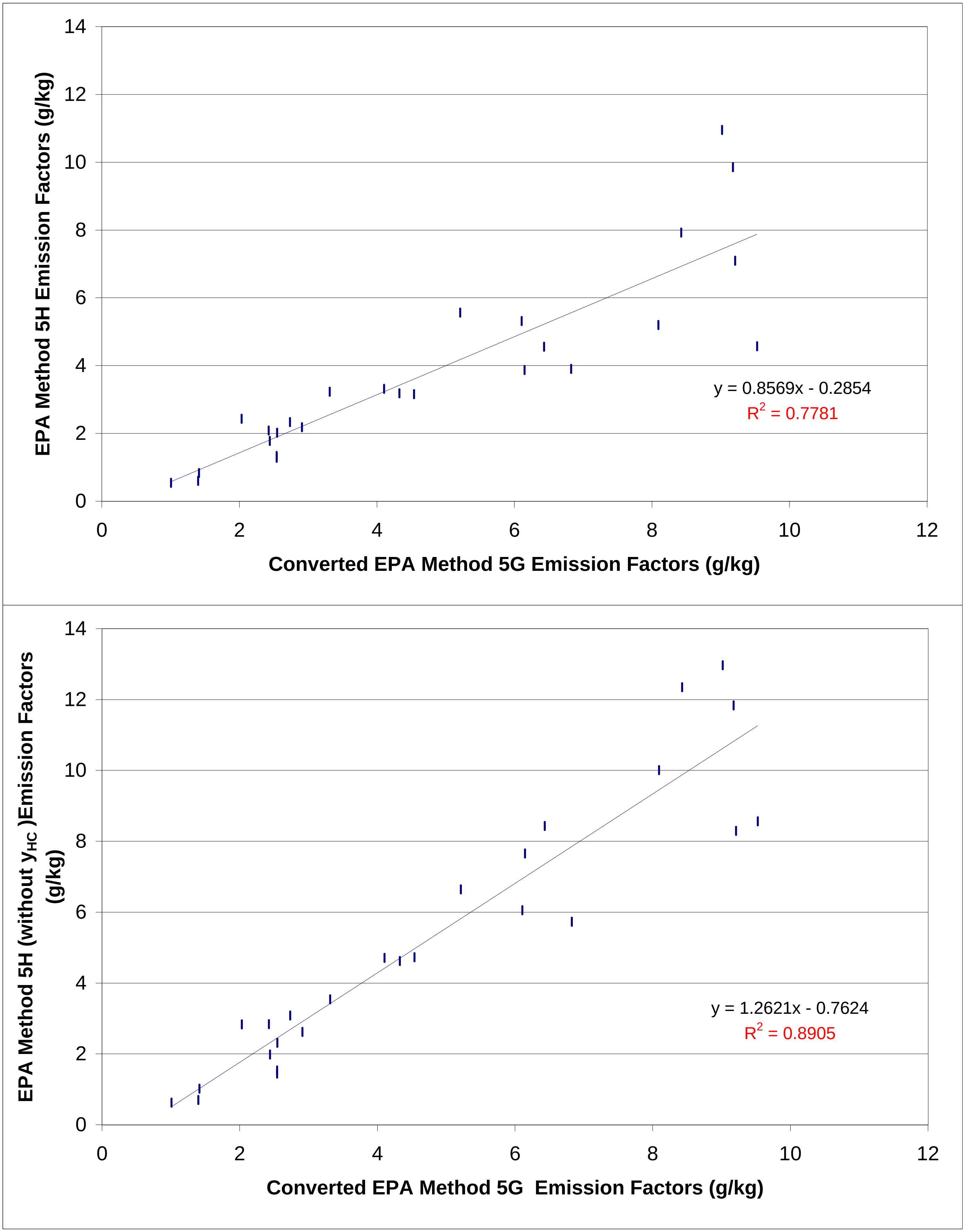

Figure 13. Relationship bewteen Converted EPA Method 5G-Derived Emission Factors and EPA Method 5H-Derived Emission Factors.

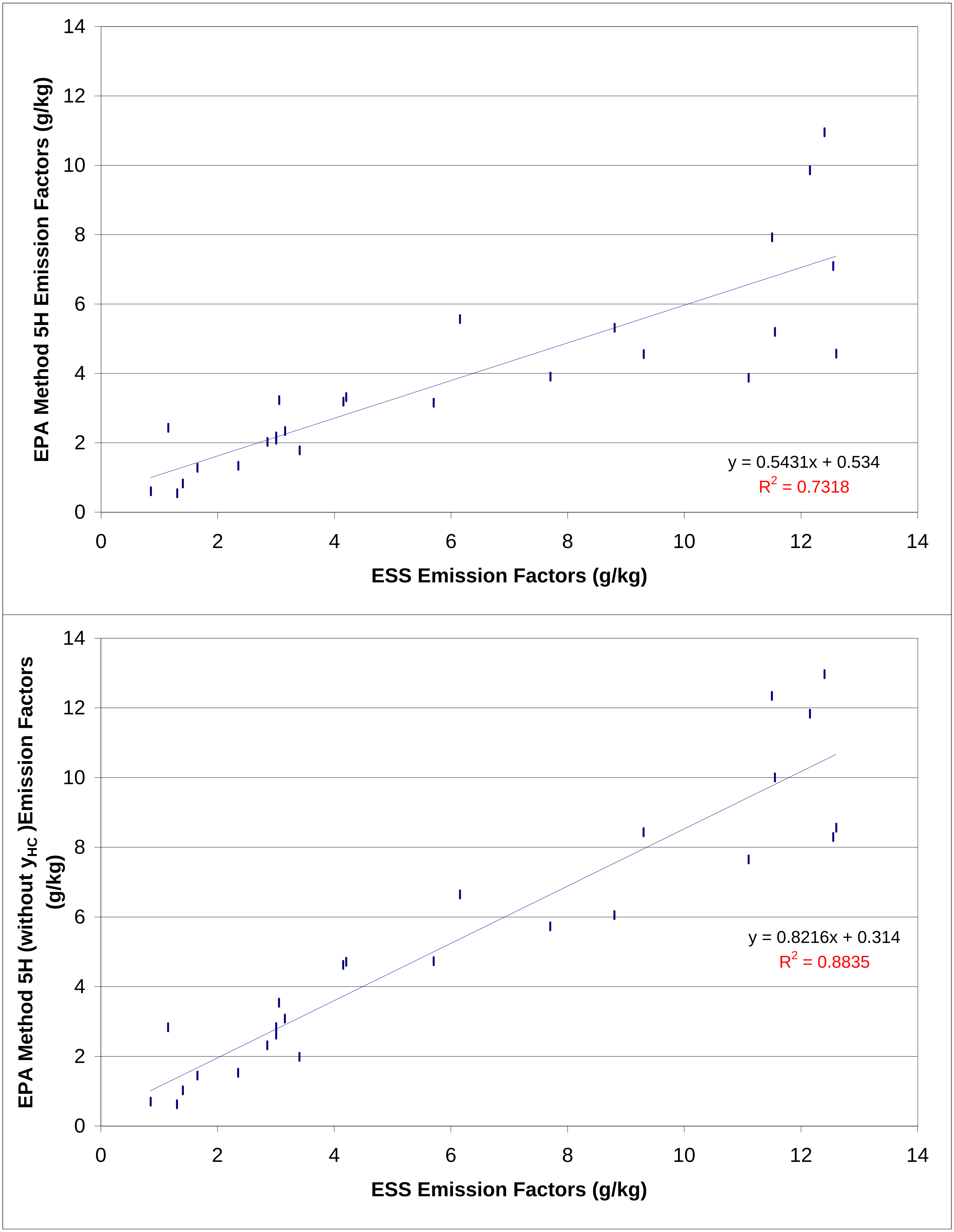

Figure 14. Relationship between ESS-Derived Emission Factors and EPA Method 5H-Derived Emission Factors.

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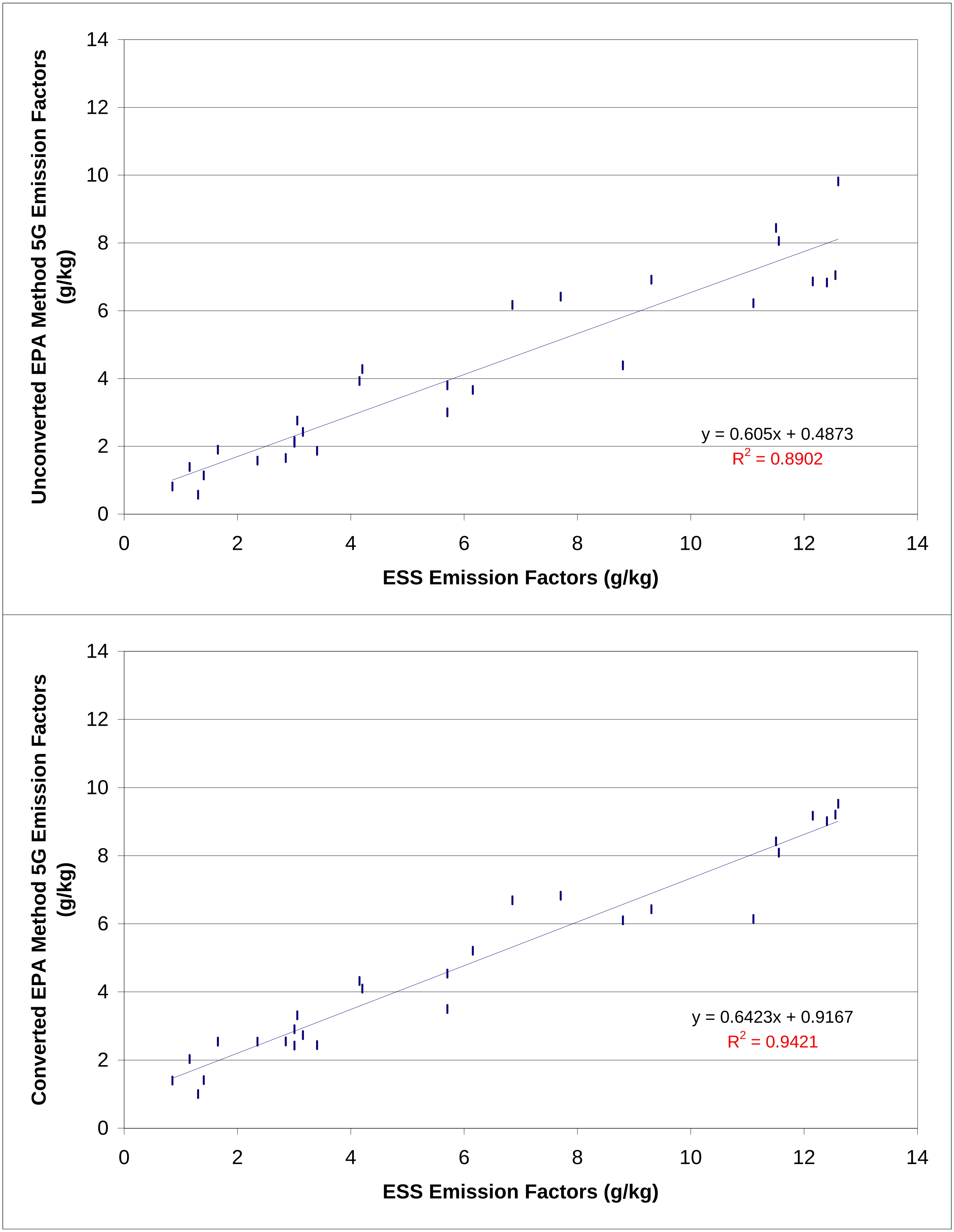

Figure 15. Relationship between ESS-Derived Emission Factors and EPA Method 5G-Derived Emission Factors.

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maximum heat and hence the object is to fill the firebox. On the other hand, consumers are most typically perceived to load fireplaces for viewing the fire and therefore, place fuel loads low in the firebox but not filling the firebox.

EPA Method 28 specifies calculating the fuel load size based on the stove's total useable firebox volume. The draft NSC-AQMD protocols, on the other hand, specify calculating each of the three fuel loads based on hearth or grate area. For comparison, when EPA's Method 28 for woodstoves is used for determining fireplace fuel loads, resultant fuel loads are inappropriately large. For example, the EPA Method 28 fuel load for a typical 36-inch fireplace is 41.7 lbs., whereas the NSC-AQMD protocols fuel load for the same fireplace, based on hearth or grate area, is 20.9 lbs. and 12.0 lbs., respectively,

4. The duration of test burn periods is determined in significantly different ways by the two methods. For EPA Method 28, woodstoves are placed on a scale during testing. The burn period is considered complete when the entire mass of the fuel load is consumed by combustion. Test burn completion as specified in the draft NSC-AQMD protocols is based on flue-gas oxygen levels. This approach is used out of practical necessity because masonry fireplaces and heaters are almost always too heavy and operationally difficult to place on a scale for testing. In addition, it is envisioned that, in some cases, the NSC-AQMD sampling system (i.e., the ESS) may need to be utilized to test site-built fireplaces or masonry heaters in homes where it is totally impractical to use a scale. It needs to be emphasized that in order to determine test period burn rates, the total mass of fuel consumed during the test period must be divided by the duration of the burn. Hence, if all else is equal, the burn rates determined by the two methods will always be different., and

5. Woodstove particulate emissions rates calculated in accordance with the EPA methods are the weighted averages of emissions results measured during a minimum of 4 separate tests one of which is conducted within each of four different burn rate categories specified by the EPA. The median burn rate on which EPA's weighting factors are based is 1.17 kg/hr. Typical fireplace and masonry heater burn rates range from 3 kg/hr to 10 kg/hr; considerably higher than EPA's woodstove median. Consequently, even if a fireplace or masonry heater burns wood as clean as an EPA-certified woodstove per unit mass of fuel burned, (i.e., the emission factors are equal), the emissions rates (g/hr) will be higher.

Given these fundamental differences between woodstoves and fireplaces and masonry heaters and between the ways each type of appliance can be tested, a reasonable approach for establishing an emissions rate equivalency would be to start with EPA's high burn rate cap for non-catalytic woodstoves [40 CFR 60.532 (b)(2)]. This cap is appropriate for application to the characteristically uncontrolled burn rates of fireplaces and masonry heaters since EPA's cap specifies that "...emissions shall not exceed 18 g/hr during any test run [conducted] at a burn rate greater than 1.5 kg/hr...". The fact that EPA established a cap shows EPA's recognition that clean burning stoves may have high burn rates which, only by the laws of physics and general nature, cause their emissions rates to be high and that the gram-per-hour reporting units can hide the fact that they are clean burning.

If the statistical relationship between the emissions measured by the EPA method which best correlates to emissions data generated by the NSC-AQMD ESS system is applied to the 18.0 g/hr EPA Method 5H value, an "equivalent" NSC-AQMD ESS-measured value is obtained. As shown in Figure 16, the relationship between the dual-train (i.e., replicate) emissions rate averages for all tests conducted on all appliances for this study using EPA Method 5G (converted to Method 5H using EPA's conversion formula) and those generated using the draft NSC-AQMD protocols is not only the best of all the method relationships investigated in this study but a good solid relationship in basic statistical terms (i.e., an R^2 of 0.95).

It should also be noted that the slope of 0.65 indicates that emissions measured using the draft NSC-AQMD protocols are consistently higher than those measured using EPA Methods 5G or 5H. This is true because the draft NSC-AQMD protocols not only catch particulate matter on filters, on glassware surfaces, and in impinger condensates like the EPA methods do but the draft NSC-AQMD protocols also more efficiently catch condensible particulate matter on the XAD-2 resin contained in the ESS sampling system.

Applying the mathematical expression of the best NSC-AQMD protocols versus EPA Method 5G/5H relationship (i.e., a slope of 0.65 and an intercept of 2.9) to EPA's 18 g/hour cap results in a draft NSC-AQMD protocol equivalent of 30.6 g/hour.

Additionally, it is estimated from other previous studies that the draft NSC-AQMD protocols cold-start test procedure increases average test run emissions over hot-start test procedures by an additional 11%. Applying this 11% factor to the draft NSC-AQMD protocol equivalent cap of 30.6 g/hour further increases EPA's woodstove cap to 34 g/hour if measured using the draft NSC-AQMD protocols. That is, if the EPA Method 28 testing protocol was based on sampling from a cold start burn-cycle such as specified in the draft NSC-AQMD protocols and emissions were sampled using the ESS in accordance with the draft NSC-AQMD protocols, EPA's woodstove cap equivalent would be 34 g/hour. Figure 17 illustrates the average emission rates as determined by the draft NSC-AQMD protocols for each test run conducted for this study and how these results compare to the 34 g/hour non-catalytic woodstove cap equivalent.

Another approach to equate fireplace emissions as measured by the NSC-AQMD protocols to EPA-certified woodstove emissions in terms of emission factors would be to use the 7.5 g/hr NSPS emission rate (for non-catalytic woodstoves [40 CFR 60.532 (b)(2)] and convert it to an emissions factor using the base data EPA used in establishing its wood heater NSPS. For example, the median burn rate for non-catalytic woodstoves used by EPA in developing the Wood Heater NSPS and for its 4-test weighting scheme is based on average in-home measured

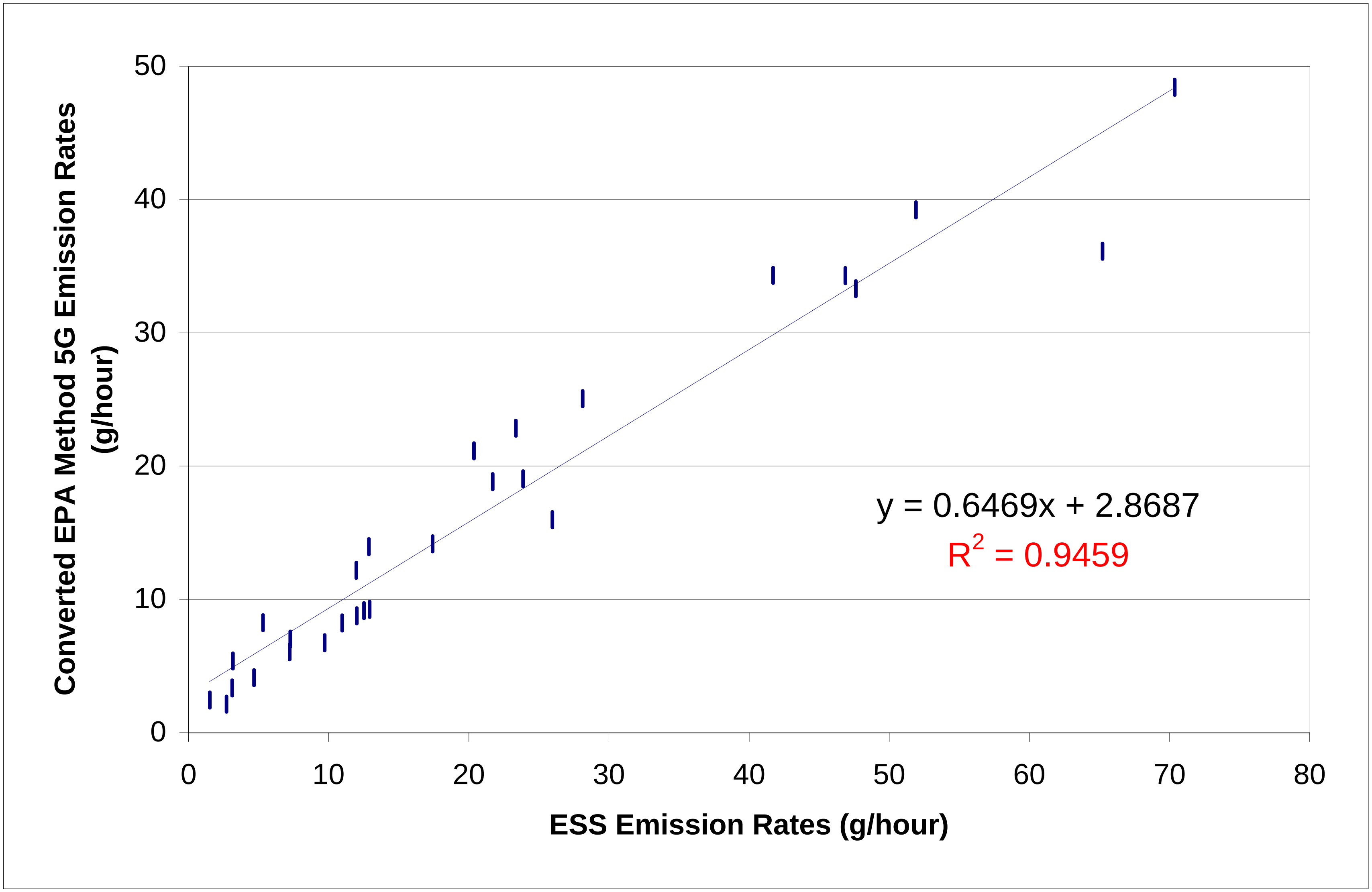

Figure 16. Relationship between Converted EPA Method 5G Emissions Rates and ESS Emissions Rates.

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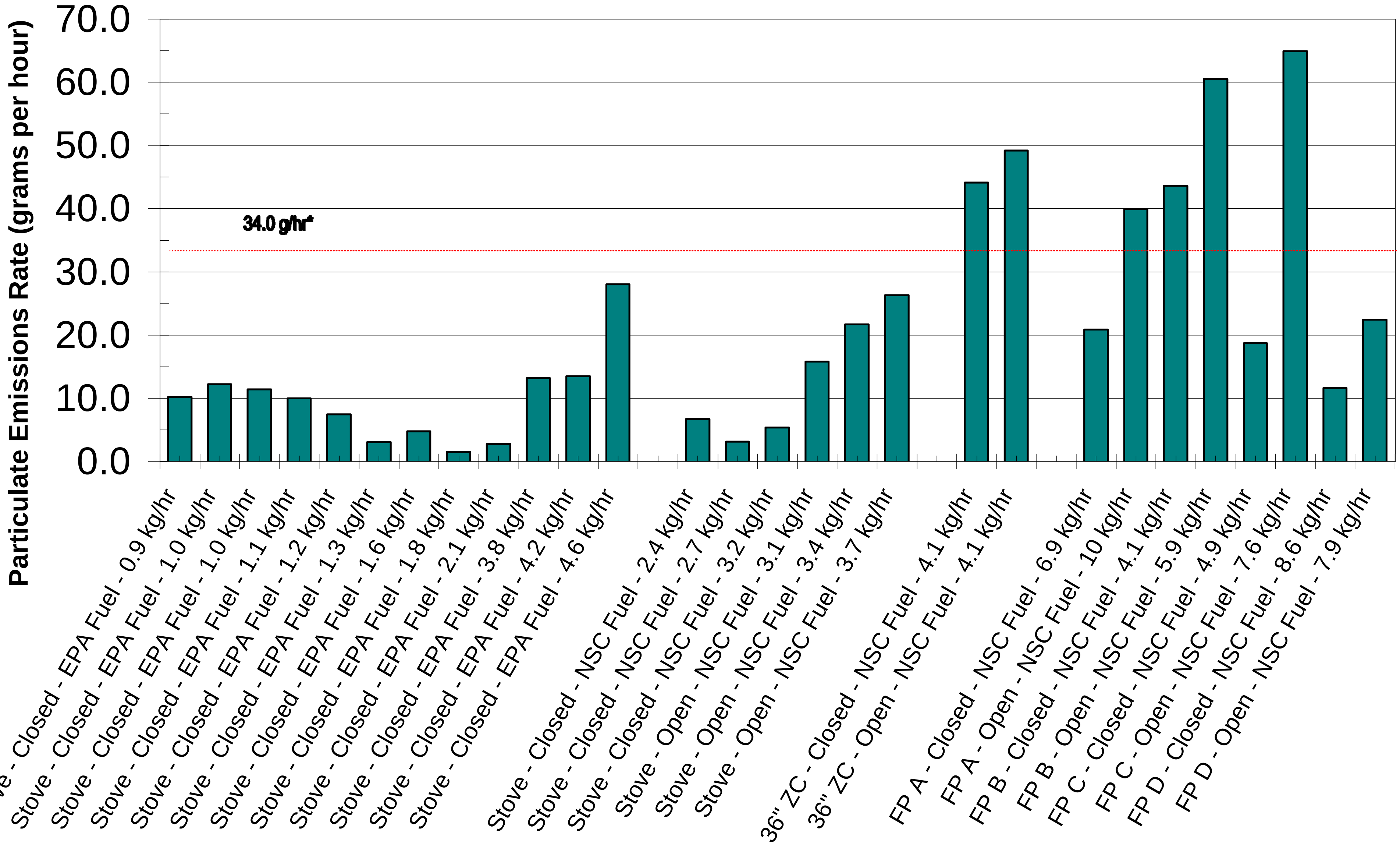

*** 34.0 g/hr is the cap equivalent for woodstoves. See text for explanation**

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Figure 17. ESS Emission Rates for All Tests on All Appliances

burn rates of 1.17 kg/hr (40 CFR, Part 60, Appendix A, Method 28, Table 28-1). Dividing 7.5 g/hour by 1.17 kg dry wood/ hr yields an emission factor of 6.41 g/kg. As proposed for obtaining equivalent emissions rates above, by applying the mathematical expression of the relationship between EPA Method 5G data converted to EPA Method 5H and draft NSC-AQMD protocol data to the base EPA woodstove emissions factor of 6.41 g/kg results in a draft NSC-AQMD protocol emissions factor of 8.43 g/kg. As with emission rates, an increase by 11% to take into account the difference between cold and hot test burn-cycle startups is also appropriate and yields a value of 9.36 g/kg.

Thermal efficiency can be used to provide further equivalency between measured fireplace or masonry heater emissions and woodstove emissions. Since EPA's woodstove NSPS-allowed emissions (ie, 7.5 g/hour) are based, at least in part, on the fact that woodstoves provide utility for home heating, it is a reasonable extension then to factor the measured emissions from any other heating appliances being compared to woodstove emissions with the thermal performance of those appliances. This approach reduces to basing the amount of pollution allowed on the amount of useful heat delivered to the consumer user.

A heating-performance-based factoring system for establishing complete equivalency between the allowed EPA NSPS woodstove emissions limits and measured fireplace and masonry heater emissions should most likely be based on EPA's 63% default thermal efficiency for non-catalytic woodstoves. Under this approach, the ratio between measured fireplace or masonry heater thermal efficiency and 63% would provide a "sliding-scale" factor which would in turn be applied to the measured fireplace or masonry heater emissions factor. With this approach, the passing grade would always become more stringent for fireplaces or masonry heaters that have measured thermal efficiencies of less than 63%. In addition, with this kind of a thermal efficiency-based sliding-scale system, a passing grade would always be more stringent than the equivalent emissions factor corresponding to EPA's NSPS-stipulated 7.5 g/hr emissions rate. As an example of this sliding scale approach, if a fireplace had a measured emissions rate of 20 g/hour and a measured thermal efficiency of 31.5%, it would have an efficiency factored emissions rate of 40 g/hour.

As discussed in the following section, thermal efficiencies are readily measurable using the draft NSC-AQMD protocols.

6. Efficiency Results and Discussion

The thermal efficiency for each test run conducted for this study was measured.

There are two conventions for calculating thermal efficiency. For this study, they have been referred to as "realistic" thermal efficiency and "theoretical" thermal efficiency. Both have been calculated for each test run. The realistic efficiency is, as the name implies, a realistic representation of the actual thermal efficiency obtainable by a solid-fuel-fired heater. The theoretical efficiency can be considered as an index of efficiency and is used to compare the performance of solid-fuel-fired heaters to other types of heaters such as natural gas- and oil-fired heaters. The difference between the two conventions is that in the calculation of realistic thermal efficiency, the latent heat of water vapor (both produced by combustion and by evaporation of fuel moisture) is considered unavailable for heating purposes, whereas in the calculation of theoretical thermal efficiency, the latent heat of water vapor is considered to be available for heating purposes. The realistic thermal efficiency is presented here in this study because for all practical purposes, it is impractical to recover latent heat of moisture vaporization from the combustion gases of solid-fuel-fired appliances.

The overall thermal efficiency for both the realistic and theoretical conventions is the product of two terms: combustion efficiency and heat transfer efficiency. Combustion efficiency provides a measure of chemical energy losses due to the incomplete combustion of the fuel being used. These chemical losses are products of incomplete combustion such as carbon monoxide and, in the case of wood, those volatile and semi-volatile organic compounds that make up creosote and smoke particles. Completely combusted inorganic particles, carbon dioxide, and water created by combustion are products of complete combustion and therefore are not counted as chemical or combustion losses.

Heat transfer efficiency, on the other hand, provides a measure sensible heat (i.e., that heat contained in flue gases and measured by temperature) and, in the case of the theoretical thermal efficiency convention, latent heat of moisture vapor losses out the chimney. As mentioned above, the realistic efficiency convention does not consider the latent heat of water vapor carried out the chimney as recoverable and therefore does not consider latent heat of water out the chimney as lost.

The calculation of combustion efficiency, heat transfer efficiency, and overall thermal efficiency in both the realistic and theoretical conventions were performed using the following equations:

$$\text{Theoretical Combustion Efficiency} = \frac{(\text{DWHHV} - \text{CHHV})}{\text{DWHHV}}$$

$$\text{Realistic Combustion Efficiency} = \frac{(\text{DWLHV} - \text{CLHV} - \text{FMLH})}{(\text{DWLHV} - \text{FMLH})}$$

$$\text{Theoretical Heat Transfer Efficiency} = \frac{(\text{DWHHV} - \text{CHHV} - \text{THL})}{(\text{DWHHV} - \text{CHHV})}$$

$$\text{Realistic Heat Transfer Efficiency} = \frac{(\text{DWLHV}-\text{FMLH}-\text{CLHV}-\text{THL})}{(\text{DWLHV}-\text{FMLH}-\text{CLHV})}$$

$$\text{Overall Theoretical Efficiency} = \frac{(\text{DWHHV}-\text{CHHV}-\text{THL})}{\text{DWHHV}}$$

$$\text{Overall Realistic Efficiency} = \frac{(\text{DWLHV}-\text{FMLH}-\text{CLHV}-\text{THL})}{(\text{DWLHV}-\text{FMLH})}$$

Where,

DWHHV = Dry Wood Higher Heating Value (i.e., energy input rate for theoretical efficiency convention),
DWLHV = Dry Wood Lower Heating Value (i.e., energy input rate for realistic efficiency convention),
FMLH = Fuel Moisture Latent Heat loss rate,
CHHV = Higher Heating Value of Chemical energy loss rate due to the formation of products of incomplete combustion,
CLHV = Lower Heating Value of Chemical energy loss rate due to the formation of products of incomplete combustion, and
THL = Total sensible Heat Loss rate.

A complete compilation of efficiency results along with intermediate parameters used in their calculation for all test runs are provided in Table 9. For illustrative purposes, the average energy loss due to incomplete combustion for woodstoves and fireplaces is shown by each major product of incomplete combustion in Figures 18 and 19. As can be seen, the distribution of chemical energy losses for each product of incomplete combustion is similar for woodstoves and fireplaces with carbon monoxide (CO) responsible for the majority of the chemical energy losses and with methane (CH_4), particles, and non-methane volatile organic compounds (NMVOC) responsible for the remainder.

Figures 20 and 21 illustrate average sensible heat energy losses contained in all of the typical major constituents found in woodstove and fireplace flue-gases. Because there is considerably more dilution air in fireplace flue gases than in woodstove flue gases, the nitrogen, oxygen, and argon constituents associated with air carry a relatively larger share of the sensible heat energy losses than do the flue-gas constituents resulting from combustion process in woodstoves.

As mentioned previously, the primary purpose for presenting thermal efficiency data and their calculation procedures is to document the method for calculating thermal efficiencies with the draft NSC-AQMD protocols. As discussed in Section 5, a reasonable approach to developing a pass/fail particulate emission “grade” following the draft NSC-AQMD method is to index emissions by overall thermal efficiency. To that end, Figure 22 was developed to help illustrate the differences and similarities found in the thermal efficiencies measured by the draft NSC-AQMD protocols for each appliance type and each appliance configuration tested. As can be seen, there is considerable variability among fireplaces and masonry heaters and the woodstove efficiencies are much more uniform and are close to EPA’s default thermal efficiency of 63% assigned to EPA certified non-catalytic woodstoves.

Table 9. Thermal Efficiency Calculations and Results

Test Run Number	Description	Burn Rate (kg/hr, DB)	Fuel Moisture (%, DB)	Dry Flue Flowrate (scfm, ESS Bag analysis)	Dry Flue Flowrate (std. liters/hr)	Dry Flue Flowrate (kg/hr)	Wet Flue Flowrate (scfm, ESS Bag analysis)	Wet Flue Flowrate (std.liters/hr)	Measured Flue Gas % Moisture (WB)	Calculated Flue Gas % Moisture (WB)	Dry Wood HHV Energy Input (KJ/hr)	Fuel Moisture Water Flowrate (kg/hr)
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	1.16	23.87%	9.5	4.5	5.5	10.2	4.8	6.58%	5.14%	24394	0.277
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	3.80	24.25%	22.3	10.5	13.1	25.3	11.9	11.83%	6.78%	79910	0.922
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	1.62	23.71%	11.8	5.6	6.9	12.8	6.0	7.77%	5.70%	34067	0.384
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	1.11	23.14%	8.5	4.0	4.9	9.2	4.3	7.60%	5.46%	23342	0.257
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	0.99	21.31%	7.6	3.6	4.4	8.1	3.8	6.17%	5.53%	20819	0.211
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	4.57	21.55%	23.2	11.0	13.6	ND	ND	ND	ND	96103	0.985
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	1.32	21.68%	8.6	4.1	5.0	9.2	4.4	6.96%	6.44%	27758	0.286
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	0.97	23.41%	7.3	3.4	4.2	8.2	3.9	11.09%	5.35%	20398	0.227
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	4.22	23.41%	19.6	9.2	11.6	22.4	10.6	12.59%	8.48%	88742	0.988
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	0.90	22.47%	7.5	3.5	4.3	8.0	3.8	6.36%	5.07%	18926	0.202
11	Stove - Open - NSC Fuel - 3.4 kg/hr	3.41	21.34%	59.0	27.8	33.6	ND	ND	ND	ND	71709	0.728
12	Stove - Open - NSC Fuel - 3.7 kg/hr	3.66	20.51%	68.7	32.4	39.0	71.3	33.7	3.63%	2.31%	76966	0.751
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	3.23	19.57%	20.0	9.4	11.7	22.3	10.5	10.26%	6.53%	67924	0.632
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	4.12	19.48%	174.6	82.4	98.5	177.7	83.9	1.76%	1.04%	86640	0.803
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	4.12	22.69%	154.0	72.7	86.9	157.6	74.4	2.26%	1.18%	86640	0.935
16	Stove - Open - NSC Fuel - 3.1 kg/hr	3.06	22.24%	64.2	30.3	36.4	66.1	31.2	2.91%	2.09%	64349	0.681
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	2.69	22.44%	17.8	8.4	10.4	19.7	9.3	9.29%	6.16%	56568	0.604
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	2.39	23.00%	21.7	10.2	12.5	23.3	11.0	7.12%	4.61%	50259	0.550
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	1.75	21.97%	11.4	5.4	6.6	12.4	5.9	7.85%	6.35%	36801	0.384
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	2.13	20.91%	12.9	6.1	7.5	14.0	6.6	8.02%	6.84%	44792	0.445
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	6.89	23.33%	87.9	41.5	50.2	93.4	44.1	5.86%	3.32%	144890	1.607
22	FP A - Open - NSC Fuel - 10 kg/hr	10.00	21.99%	164.0	77.4	93.2	169.5	80.0	3.26%	2.66%	210290	2.199
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	4.07	21.39%	89.4	42.2	50.7	93.3	44.0	4.16%	1.97%	85588	0.871
24	FP B - Open - NSC Fuel - 5.9 kg/hr	5.88	22.38%	256.4	121.0	144.6	261.7	123.5	2.00%	1.01%	123651	1.316
25	FP C - Open - NSC Fuel - 7.6 kg/hr	7.58	22.80%	266.8	125.9	150.8	272.4	128.6	2.09%	1.25%	159400	1.728
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	4.89	22.13%	88.7	41.8	50.4	93.2	44.0	4.84%	2.36%	102832	1.082
27	FP D - Open - NSC Fuel - 7.9 kg/hr	7.86	22.44%	113.4	53.5	64.7	120.0	56.6	5.45%	2.95%	165288	1.764
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	8.62	20.64%	91.3	43.1	52.4	100.0	47.2	8.67%	3.88%	181270	1.779

9050 fuel Btu/lb
6.3% fuel hydrogen content
0.07 g CH4 / g CO
0.07 g NMVOC / g CO

Estimated NMVOC composition: 14.3% C_2-C_6 alkanes, 42.8% < C_4 alkenes, 14.3% CH_2O, 14.3% CH_3CHO and 14.3% other organics

Table 9. (continued) Thermal Efficiency Calculations and Results

Test Run Number	Description	Combustion Water Flowrate (kg/hr)	Average Flue Temperature (K, 8ft)	Average Indoor Temperature (K)	Fuel Moisture Sensible Heat Loss Rate (kJ/hr)	Fuel Moisture Latent Heat Loss Rate (kJ/hr)	Combustion Water Sensible Heat Loss Rate (kJ/hr)	Combustion Water Latent Heat Loss Rate (kJ/hr)	Dry Wood LHV Energy Input (kJ/hr)	Average CO2 (volume %)	CO2 Sensible Heat Loss Rate (kJ/hr)	Average O2 (volume %)
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	0.658	428.7	294.3	73.2	625	174	1486	22908	6.32%	233.6	14.08%
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	2.155	622.9	296.5	600.5	2081	1404	4867	75044	10.50%	2382.4	10.80%
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	0.919	452.4	295.7	118.6	868	284	2075	31992	7.83%	425.6	13.43%
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	0.629	399.5	294.8	52.7	580	129	1422	21921	6.75%	170.5	13.43%
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	0.561	389.8	296.2	38.7	477	103	1268	19551	6.57%	132.1	13.55%
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	2.591	643.8	296.5	684.0	2224	1800	5853	90250	11.10%	2814.1	8.02%
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	0.748	440.1	295.9	81.2	646	212	1690	26068	8.44%	305.0	12.43%
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	0.550	391.5	294.8	43.1	513	104	1242	19156	6.62%	132.1	13.80%
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	2.393	634.3	293.2	673.3	2231	1631	5404	83338	12.56%	2624.1	7.49%
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	0.510	383.3	291.8	36.3	457	92	1153	17774	5.85%	113.1	14.58%
11	Stove - Open - NSC Fuel - 3.4 kg/hr	1.933	467.8	292.9	250.8	1644	666	4367	67342	3.32%	1009.3	18.19%
12	Stove - Open - NSC Fuel - 3.7 kg/hr	2.075	479.4	293.4	275.3	1696	761	4687	72279	2.89%	1094.4	17.83%
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	1.831	573.5	293.7	351.5	1428	1018	4137	63787	9.45%	1622.5	11.47%
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	2.336	432.0	292.6	219.9	1813	640	5276	81363	1.35%	952.8	19.18%
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	2.336	456.8	291.5	304.2	2111	760	5276	81363	1.44%	1076.1	18.93%
16	Stove - Open - NSC Fuel - 3.1 kg/hr	1.735	468.8	292.3	236.7	1537	604	3919	60430	2.64%	881.4	18.03%
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	1.525	580.5	291.2	347.1	1363	877	3445	53123	8.53%	1352.1	12.64%
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	1.355	535.0	294.0	262.4	1242	647	3061	47199	6.28%	993.5	14.39%
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	0.992	491.7	292.0	151.6	868	391	2241	34560	8.40%	570.5	12.72%
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	1.208	539.2	294.8	215.8	1006	585	2728	42064	9.29%	889.8	11.13%
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	3.907	639.8	295.9	1105.0	3631	2686	8824	136066	4.25%	4033.5	16.19%
22	FP A - Open - NSC Fuel - 10 kg/hr	5.670	545.7	294.3	1096.4	4967	2827	12807	197483	3.35%	4201.6	16.95%
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	2.308	469.0	294.5	299.3	1966	793	5212	80376	2.41%	1108.2	18.29%
24	FP B - Open - NSC Fuel - 5.9 kg/hr	3.334	408.0	296.2	288.7	2972	731	7530	116120	1.27%	1047.7	19.21%
25	FP C - Open - NSC Fuel - 7.6 kg/hr	4.298	424.4	293.7	443.8	3904	1104	9708	149692	1.61%	1624.4	19.66%
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	2.773	507.2	296.2	451.4	2444	1157	6262	96569	3.03%	1699.0	17.68%
27	FP D - Open - NSC Fuel - 7.9 kg/hr	4.457	516.3	292.3	781.3	3984	1974	10066	155222	3.91%	2982.1	16.95%
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	4.888	597.8	292.6	1081.4	4019	2971	11039	170231	5.53%	4763.8	14.96%

Table 9. (continued) Thermal Efficiency Calculations and Results

Test Run Number	Description	O2 Sensible Heat Loss Rate (kJ/hr)	Calculated N2 (volume %)	N2 Sensible Heat Loss Rate (kJ/hr)	Calculated Ar (volume %)	Ar Sensible Heat Loss Rate (kJ/hr)	Average CO (volume %)	Average CO (g/hr)	HHV/LHV CO Heat Loss Rate (kJ/hr)	CO Sensible Heat Loss Rate (kJ/hr)	Estimated CH4 (g/hr)	HHV CH4 Heat Loss Rate (kJ/hr)
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	593.2	77.82%	2019	0.93%	17.42	0.86%	159.6	1614	22.82	11.2	621
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	2120.6	77.57%	11623	0.92%	98.85	0.20%	86.5	874	30.53	6.1	336
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	781.6	77.08%	2907	0.92%	25.03	0.74%	171.2	1731	28.61	12.0	666
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	431.3	77.75%	1397	0.93%	12.08	1.15%	190.4	1926	21.15	13.3	740
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	364.6	77.67%	1115	0.93%	9.64	1.28%	189.2	1913	18.78	13.2	736
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	1735.0	79.21%	13199	0.94%	112.09	0.73%	332.3	3360	125.04	23.3	1292
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	496.1	77.45%	1951	0.92%	16.81	0.75%	126.9	1283	19.47	8.9	493
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	363.5	77.46%	1103	0.92%	9.54	1.19%	169.3	1712	17.36	11.9	658
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	1344.1	78.36%	10799	0.93%	91.78	0.66%	253.6	2564	93.63	17.8	986
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	384.9	77.49%	1076	0.92%	9.32	1.16%	169.7	1716	16.46	11.9	660
11	Stove - Open - NSC Fuel - 3.4 kg/hr	5718.1	77.41%	16265	0.92%	139.92	0.16%	184.7	1868	34.48	12.9	718
12	Stove - Open - NSC Fuel - 3.7 kg/hr	6838.4	78.16%	20372	0.93%	175.10	0.19%	257.2	2601	51.09	18.0	1000
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	1771.6	77.71%	8924	0.93%	76.18	0.44%	173.8	1757	52.35	12.2	676
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	15234.3	78.41%	38776	0.93%	334.46	0.12%	425.2	4300	63.06	29.8	1653
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	14930.6	78.58%	40710	0.94%	350.53	0.11%	319.1	3227	56.22	22.3	1241
16	Stove - Open - NSC Fuel - 3.1 kg/hr	6213.2	78.24%	18059	0.93%	155.35	0.16%	198.8	2011	37.45	13.9	773
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	1790.2	77.70%	8229	0.93%	70.23	0.21%	72.1	729	22.47	5.0	280
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	2130.1	78.05%	8349	0.93%	71.47	0.36%	153.2	1549	39.63	10.7	596
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	856.3	77.43%	3607	0.92%	30.97	0.54%	119.9	1212	25.60	8.4	466
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	992.5	78.38%	5065	0.93%	43.34	0.27%	67.3	680	17.65	4.7	262
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	13129.9	78.40%	48916	0.93%	415.52	0.22%	385.1	3894	143.41	27.0	1497
22	FP A - Open - NSC Fuel - 10 kg/hr	19645.5	78.62%	66426	0.94%	568.17	0.14%	460.7	4658	124.45	32.2	1791
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	8696.2	78.16%	24836	0.93%	213.61	0.21%	364.2	3683	67.82	25.5	1416
24	FP B - Open - NSC Fuel - 5.9 kg/hr	19413.8	78.49%	45640	0.93%	394.25	0.10%	481.0	4863	57.09	33.7	1870
25	FP C - Open - NSC Fuel - 7.6 kg/hr	22845.1	77.72%	55040	0.93%	474.96	0.08%	430.4	4352	59.82	30.1	1674
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	9621.6	78.20%	29895	0.93%	256.38	0.16%	286.3	2895	64.70	20.0	1113
27	FP D - Open - NSC Fuel - 7.9 kg/hr	12381.9	78.11%	40568	0.93%	347.79	0.10%	220.0	2224	52.79	15.4	855
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	11365.4	78.45%	44972	0.93%	383.26	0.13%	234.8	2374	77.31	16.4	913

Table 9. (continued) Thermal Efficiency Calculations and Results

Test Run Number	Description	LHV CH4 Heat Loss Rate (kJ/hr)	Estimated CH4 (volume %)	CH4 Sensible Heat Loss Rate (kJ./hr)	Estimated NMVOC (g/hr)	HHV NMVOC Heat Loss Rate (kJ/hr)	LHV NMVOC Heat Loss Rate (kJ/hr)	Estimated NMVOC (volume %)	NMVOC Sensible Heat Loss Rate (kJ./hr)	Average Dry Flue Gas MW (g/mol)	Particulate mass flowrate (g/hr)	HHV Particulate Heat Loss Rate (kJ/hr)
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	559	0.11%	3.79	11.2	466	437	0.04%	2.40	29.35	7.2	263
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	303	0.02%	5.58	6.1	252	237	0.01%	3.72	29.87	12.9	471
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	600	0.09%	4.81	12.0	499	468	0.03%	3.07	29.56	4.7	170
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	667	0.14%	3.46	13.3	556	521	0.05%	2.17	29.40	9.7	354
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	663	0.16%	3.06	13.2	552	518	0.05%	1.91	29.38	12.5	456
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	1164	0.09%	23.07	23.3	970	909	0.03%	15.44	29.86	26.0	947
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	445	0.09%	3.26	8.9	370	347	0.03%	2.07	29.62	3.1	113
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	593	0.15%	2.83	11.9	494	463	0.05%	1.77	29.39	12.0	438
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	889	0.08%	17.18	17.8	740	694	0.03%	11.46	30.07	12.9	469
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	595	0.14%	2.67	11.9	495	464	0.05%	1.66	29.30	11.0	400
11	Stove - Open - NSC Fuel - 3.4 kg/hr	647	0.02%	5.84	12.9	539	505	0.01%	3.74	29.01	23.4	853
12	Stove - Open - NSC Fuel - 3.7 kg/hr	901	0.02%	8.70	18.0	750	704	0.01%	5.60	28.93	28.1	1026
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	609	0.05%	9.34	12.2	507	475	0.02%	6.16	29.73	5.3	194
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	1490	0.02%	10.48	29.8	1241	1164	0.01%	6.64	28.73	51.9	1895
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	1118	0.01%	9.46	22.3	931	873	0.00%	6.04	28.74	47.6	1738
16	Stove - Open - NSC Fuel - 3.1 kg/hr	697	0.02%	6.34	13.9	580	544	0.01%	4.07	28.89	17.4	635
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	253	0.03%	4.02	5.0	210	197	0.01%	2.65	29.63	3.2	115
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	537	0.04%	6.94	10.7	447	419	0.02%	4.54	29.34	7.3	265
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	420	0.07%	4.39	8.4	350	328	0.02%	2.83	29.62	1.5	55
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	236	0.03%	3.10	4.7	196	184	0.01%	2.03	29.69	2.7	99
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	1349	0.03%	26.41	27.0	1124	1054	0.01%	17.65	29.08	21.7	792
22	FP A - Open - NSC Fuel - 10 kg/hr	1614	0.02%	21.91	32.2	1344	1261	0.01%	14.36	28.96	41.7	1522
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	1276	0.03%	11.50	25.5	1063	997	0.01%	7.38	28.87	46.9	1710
24	FP B - Open - NSC Fuel - 5.9 kg/hr	1685	0.01%	9.39	33.7	1403	1316	0.00%	5.91	28.72	65.2	2380
25	FP C - Open - NSC Fuel - 7.6 kg/hr	1508	0.01%	9.91	30.1	1256	1178	0.00%	6.26	28.80	70.4	2568
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	1003	0.02%	11.19	20.0	835	783	0.01%	7.27	28.94	20.4	743
27	FP D - Open - NSC Fuel - 7.9 kg/hr	771	0.01%	9.15	15.4	642	602	0.00%	5.95	29.05	23.9	871
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	823	0.02%	13.94	16.4	685	642	0.01%	9.24	29.23	12.0	436

Table 9. (continued)   Thermal Efficiency Calculations and Results

Test Run Number	Description	LHV Particulate Heat Loss Rate (kJ/hr)	Particulate Sensible Heat Loss Rate (kJ/hr)	Total HHV[1] Combustion Heat Loss Rate (kJ/hr)	Total LHV[2] Combustion Heat Loss Rate (kJ/hr)	Theoretical[1] Combustion Efficiency	Realistic[2] Combustion Efficiency	Dry Gas[3] Sensible Heat Loss Rate (kJ/hr)	Total[4] Sensible Heat Loss Rate (kJ/hr)	Theoretical[1] Heat Transfer Efficiency	Realistic[2] Heat Transfer Efficiency	Theoretical[1] Overall Efficiency	Realistic[2] Overall Efficiency
1	Stove - Closed - EPA Fuel - 1.2 kg/hr	262	1.41	2963	2871	87.9%	87.1%	2894	5252	65.6%	72.9%	57.7%	63.5%
2	Stove - Closed - EPA Fuel - 3.8 kg/hr	469	6.15	1934	1883	97.6%	97.4%	16271	25223	58.7%	64.5%	57.3%	62.8%
3	Stove - Closed - EPA Fuel - 1.6 kg/hr	169	1.06	3065	2968	91.0%	90.5%	4177	7521	66.2%	73.3%	60.3%	66.3%
4	Stove - Closed - EPA Fuel - 1.1 kg/hr	353	1.48	3576	3467	84.7%	83.8%	2039	4223	68.5%	76.4%	58.0%	64.0%
5	Stove - Closed - EPA Fuel - 1.0 kg/hr	455	1.71	3657	3548	82.4%	81.4%	1647	3533	69.3%	77.2%	57.1%	62.9%
6	Stove - Closed - EPA Fuel - 4.6 kg/hr	944	13.16	6570	6378	93.2%	92.8%	18037	28598	59.0%	65.0%	55.0%	60.3%
7	Stove - Closed - EPA Fuel - 1.3 kg/hr	113	0.65	2259	2187	91.9%	91.4%	2794	5425	69.6%	76.7%	63.9%	70.1%
8	Stove - Closed - EPA Fuel - 1.0 kg/hr	436	1.69	3302	3205	83.8%	82.8%	1632	3534	69.1%	77.1%	57.9%	63.9%
9	Stove - Closed - EPA Fuel - 4.2 kg/hr	467	6.40	4759	4614	94.6%	94.3%	14987	24927	61.2%	67.4%	57.9%	63.6%
10	Stove - Closed - EPA Fuel - 0.9 kg/hr	398	1.46	3272	3174	82.7%	81.7%	1606	3343	68.4%	76.4%	56.5%	62.4%
11	Stove - Open - NSC Fuel - 3.4 kg/hr	849	5.96	3978	3870	94.5%	94.1%	23182	30110	46.7%	51.3%	44.1%	48.3%
12	Stove - Open - NSC Fuel - 3.7 kg/hr	1022	7.63	5377	5227	93.0%	92.6%	28553	35972	40.8%	45.0%	38.0%	41.6%
13	Stove - Closed - NSC Fuel - 3.2 kg/hr	193	2.17	3133	3034	95.4%	95.1%	12464	19399	61.5%	67.3%	58.6%	64.0%
14	36" ZC - Open - NSC Fuel - 4.1 kg/hr	1887	10.56	9089	8841	89.5%	88.9%	55389	63338	9.2%	10.4%	8.2%	9.3%
15	36" ZC - Closed - NSC Fuel - 4.1 kg/hr	1731	11.49	7137	6949	91.8%	91.2%	57151	65603	8.2%	9.3%	7.5%	8.5%
16	Stove - Open - NSC Fuel - 3.1 kg/hr	633	4.48	3999	3884	93.8%	93.4%	25361	31658	38.5%	42.4%	36.1%	39.6%
17	Stove - Closed - NSC Fuel - 2.7 kg/hr	115	1.33	1335	1294	97.6%	97.5%	11472	17505	59.6%	65.3%	58.2%	63.7%
18	Stove - Closed - NSC Fuel - 2.4 kg/hr	264	2.55	2857	2769	94.3%	94.0%	11598	16810	55.5%	61.1%	52.3%	57.4%
19	Stove - Closed - EPA Fuel - 1.8 kg/hr	55	0.44	2083	2015	94.3%	94.0%	5098	8750	65.8%	72.4%	62.1%	68.0%
20	Stove - Closed - EPA Fuel - 2.1 kg/hr	98	0.96	1236	1198	97.2%	97.1%	7015	11549	64.9%	71.0%	63.1%	69.0%
21	FP A - Closed - NSC Fuel - 6.9 kg/hr	789	10.89	7307	7086	95.0%	94.6%	66693	82938	30.7%	33.8%	29.1%	32.0%
22	FP A - Open - NSC Fuel - 10 kg/hr	1516	15.31	9316	9050	95.6%	95.3%	91018	112715	35.1%	38.6%	33.5%	36.8%
23	FP B - Closed - NSC Fuel - 4.1 kg/hr	1704	11.93	7873	7660	90.8%	90.2%	34952	43224	35.1%	38.9%	31.9%	35.1%
24	FP B - Open - NSC Fuel - 5.9 kg/hr	2371	10.64	10517	10236	91.5%	91.0%	66579	78102	21.7%	24.1%	19.8%	21.9%
25	FP C - Open - NSC Fuel - 7.6 kg/hr	2558	13.42	9850	9597	93.8%	93.4%	80074	95233	27.2%	30.1%	25.5%	28.1%
26	FP C - Closed - NSC Fuel - 4.9 kg/hr	740	6.27	5587	5422	94.6%	94.2%	41561	51876	37.7%	41.5%	35.7%	39.1%
27	FP D - Open - NSC Fuel - 7.9 kg/hr	867	7.80	4592	4465	97.2%	97.0%	56356	73161	45.7%	50.2%	44.5%	48.7%
28	FP D - Closed - NSC Fuel - 8.6 kg/hr	435	5.33	4408	4273	97.6%	97.4%	61590	80700	45.9%	50.2%	44.7%	48.9%

[1] Assumes full HHV available but not utilized

[2] Assumes: LHV - without fuel moisture latent heat available

[3] Includes Particles

[4] Includes latent heat of fuel moisture and combustion water

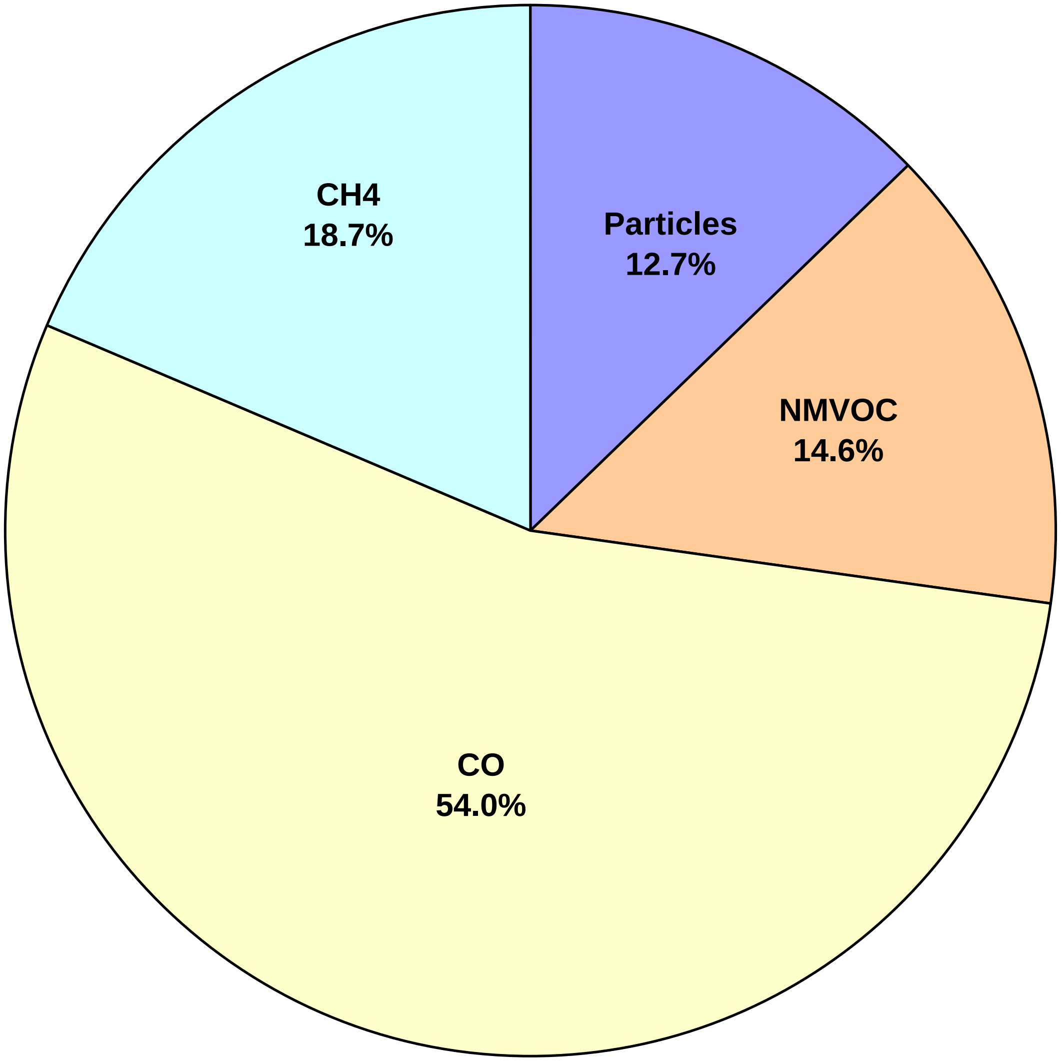

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Figure 18. Woodstove Energy Loss Due to Incomplete Combustion, (percent by chemical compound).

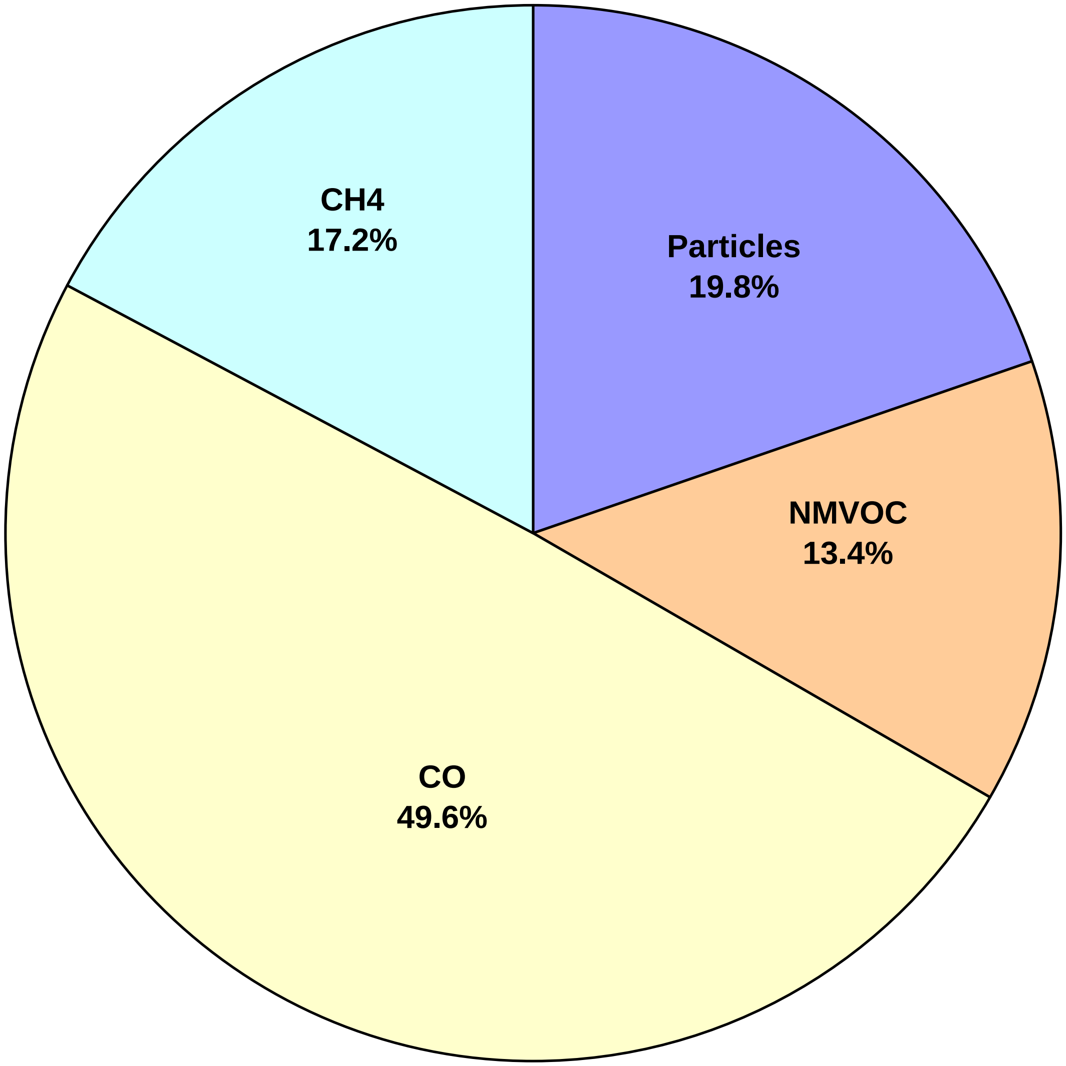

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Figure 19. Fireplace Energy Loss Due to Incomplete Combustion, (percent by chemical compound)

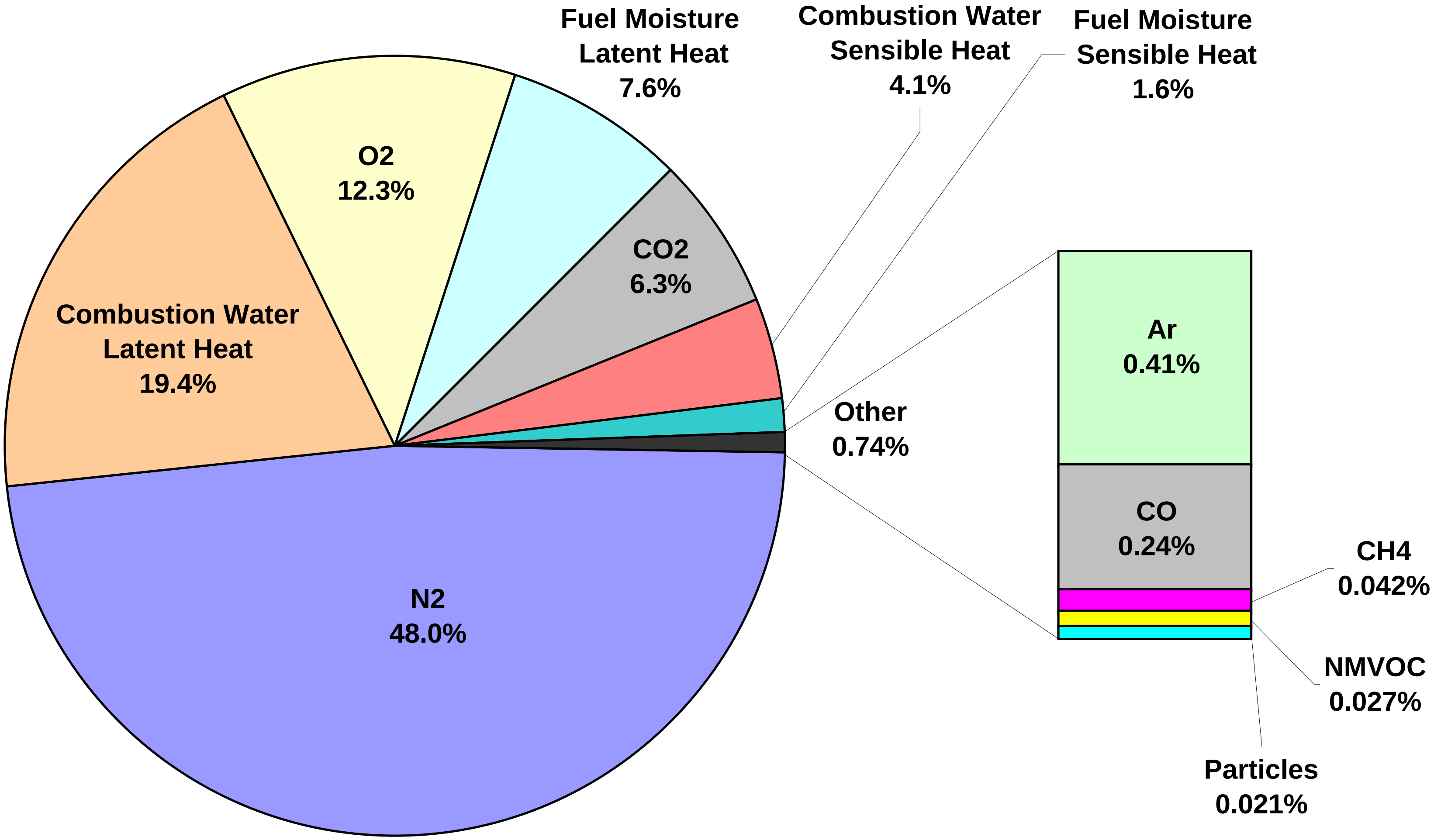

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Figure 20. Woodstove Heat Transfer Loss,
(percent by chemical compound)

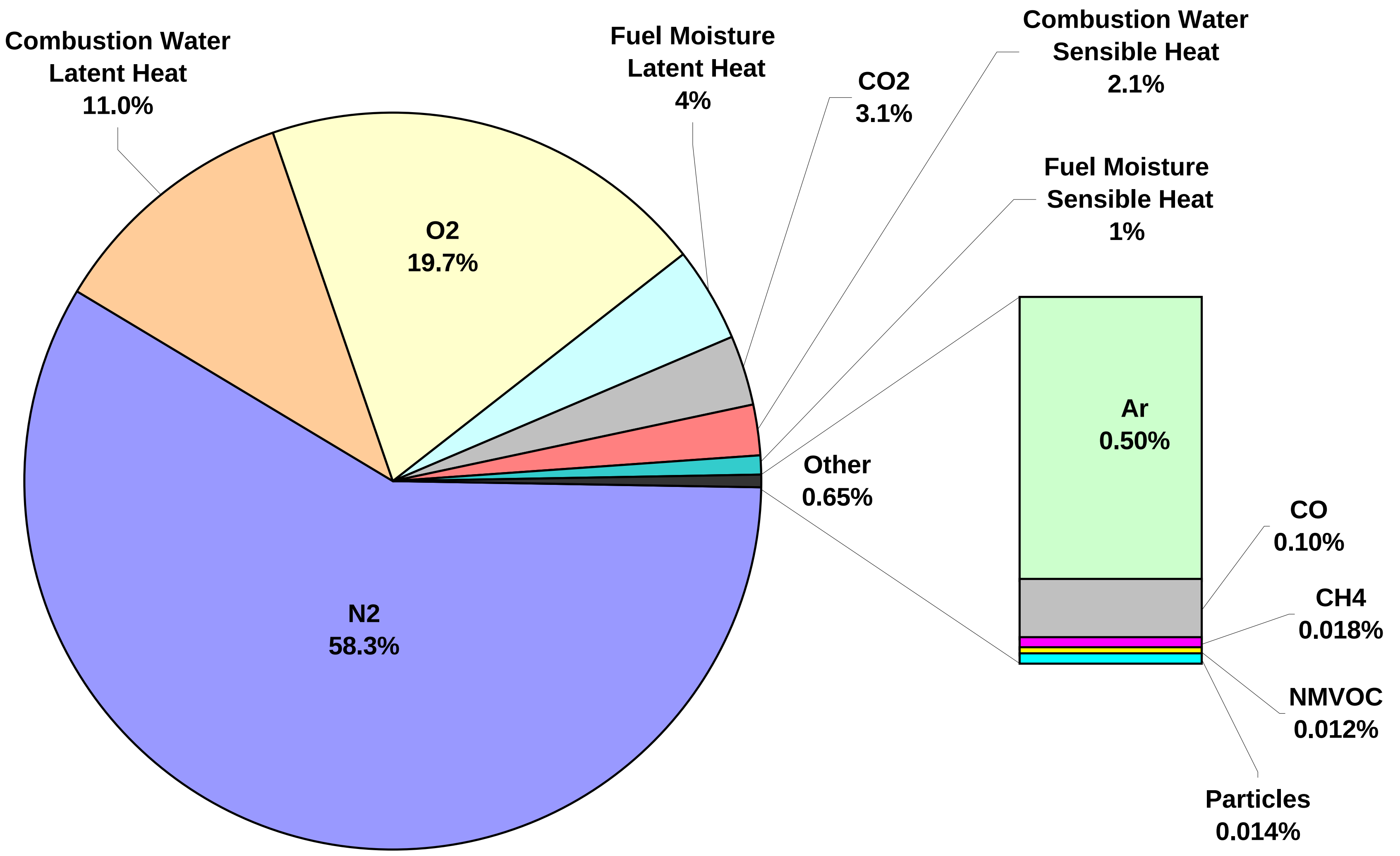

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Figure 21. Fireplace Heat Transfer Loss,
(percent by chemical compound)

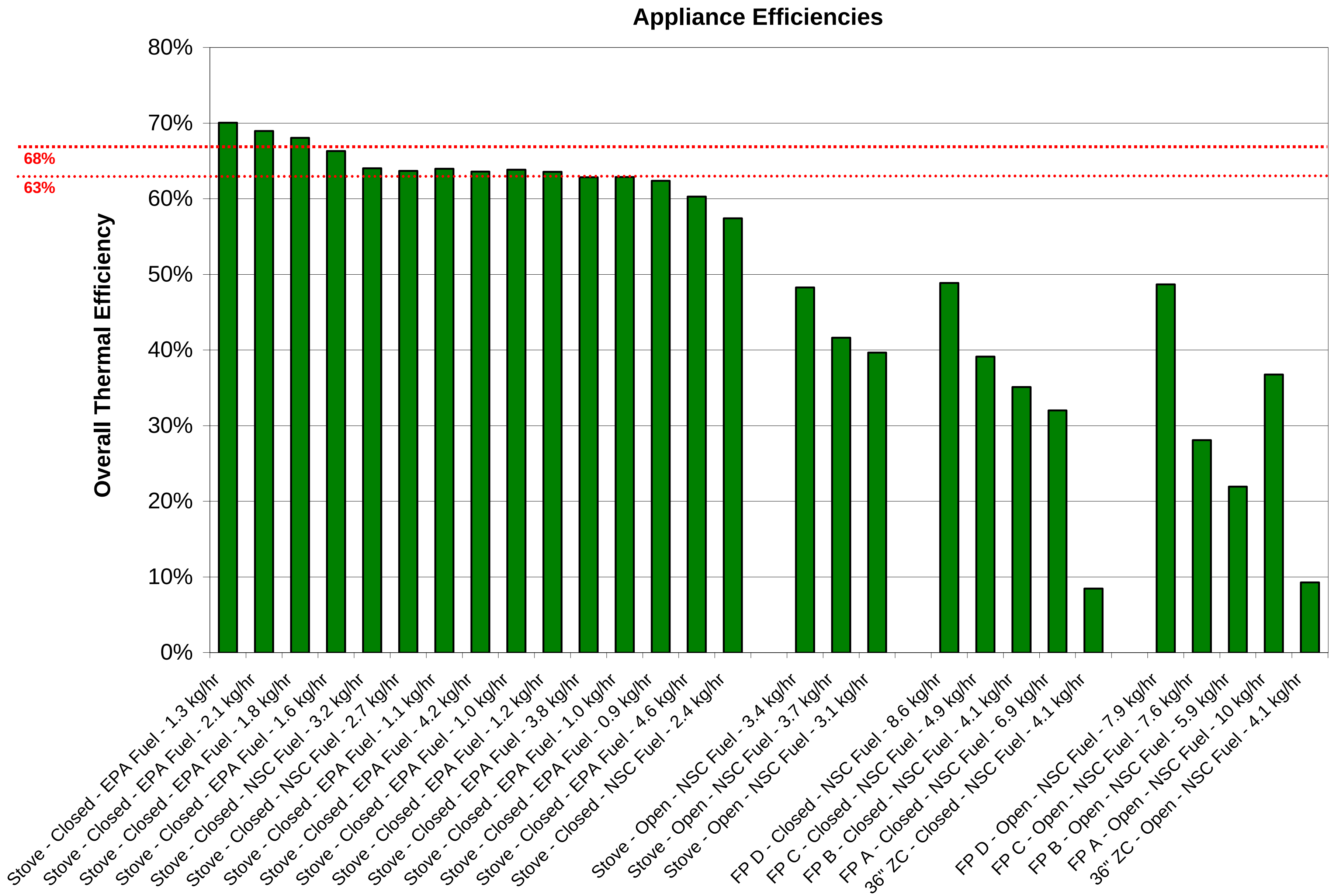

Figure 22. Appliance Thermal Efficiency Grouped by Appliance Type and Door Position Status.

68% EPA AP-42 certified non-catalytic woodstove efficiency
63% default certified non-catalytic woodstove efficiency - 40CFR 60.536(i)(3)
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7. Summary and Conclusions

The key objective of the study was met. Particulate emissions factors and rates measured using the draft NSC-AQMD protocols are related with statistical confidence to those produced by using the U.S. EPA woodstove reference Methods 5G and 5H for sampling fireplace and masonry heater emissions. In addition, a statistically significant relationship was also found between measured emissions factors and rates resulting from fueling the tested woodstove according to EPA's Method 28-specified fueling procedures and those resulting from fueling the tested woodstove according to the fueling procedures contained in the draft NSC-AQMD protocols.

The inherent differences between fireplace and woodstove fueling procedures, operating protocols, and flue-gas composition received detailed evaluations. Comparison of the results among the emissions sampling methods used and between the replicate sampling conducted for each method demonstrated the efficacy of the draft NSC-AQMD protocols. Recommendations on approaches for the development of an emission standard either in terms of emission factors or emission rates based on woodstove equivalency were made. And finally, the efficacy of using the draft NSC-AQMD protocols procedure for measuring fireplace and masonry heater thermal efficiency was documented. It was found that not only is thermal efficiency a useful performance evaluation tool for making comparisons between all fuel burning appliances but, where emissions comparisons are to be made between appliance types, it can be taken into consideration by the development of a thermal-efficiency-factored emissions standard.

Appendix A

Maximum Achievable Control Technology (MACT) Analysis of Fireplace Burn Rates, Carbon Monoxide Emissions, and Particulate Emissions Data Compiled from A Comprehensive Survey of Available Literature

Evaluation of The Northern Sonoma County Wood-Burning
Fireplace and Masonry Heater Emissions Testing Protocols

November 30, 2000

Introduction

A comprehensive literature review was conducted to establish the range and distribution of fireplace burn rates, fireplace carbon monoxide emissions, and fireplace particulate emissions (references 1-20). The compiled data base represents a large “cross section” of fireplace types and fireplace usage characteristics. Compiled data are from tests conducted over the last 32 years and include: Tests conducted on masonry and zero clearance fireplaces of various sizes; tests conducted using various sizes and styles of hearth grates; tests conducted without grates; tests conducted using different chimney heights and types; tests conducted with hot and cold starts; and tests conducted with a variety of cordwood and dimensional lumber fuel types.

To analyze these data, tabulations and plots of cumulative distributions were made. Means, standard deviations, and the values corresponding to the lowest 12% of burn rates and the best 12% of carbon monoxide and particulate emissions performances were calculated. The best 12% of fireplace emissions performances were calculated to illustrate what the Maximum Achievable Control Technology (Section 112 (d)(3) of the Clean Air Act Amendments of 1990 (MACT)) threshold would be if a U.S. Environmental Protection Agency MACT approach was applied to fireplaces.

Fireplace Burn Rates

Fireplace burn rates in units of dry kilograms of wood per hour (dry kg/hr), were compiled from 377 tests on 177 fireplace models. The mean burn rate was 5.6 dry kg/hr, the standard deviation was 3.2 dry kg/hr and the value corresponding to the lowest 12% was 2.9 dry kg/hr. The results are compiled in Table A-1 and plotted in Figure A-1.

Carbon Monoxide Emissions

Both carbon monoxide emissions rates (g/hr) and emissions factors (g/dry kg) were compiled. The emissions rate data are based on 269 tests on 70 fireplace models. The mean was 279 g/hr, the standard deviation was 41 g/hr, and the best performing 12% value was 130 g/hr. These results are compiled in Table A-2 and plotted in Figure A-2.

The emission factor data are based on 277 tests on 70 fireplace models. The mean was 64 g/dry kg, the standard deviation was 41 g/dry kg, and the best performing 12% value was 22 g/dry kg. The results are compiled in Table A-3 and plotted in Figure A-3. For comparison purposes, the carbon monoxide emissions factor value, based on much more limited data published by the U.S. Environmental Protection Agency in AP-42, is 126 g/dry kg (Reference 21).

Particulate Emissions

As with carbon monoxide, both particulate emissions rates (g/hr) and emission factors (g/dry kg) were compiled. Because there have been a number of test methods used to measure particulate emissions, all of the results were converted to Method 5H equivalent values. Conversion of emissions data generated by using the Automated Woodstove Emission Sampler (AWES), the Virginia Polytechnic Institute (VPI) sampler, and EPA's Method 5G dilution sampling system (including other Method 5G-like dilution tunnel sampling approaches) to Method 5H equivalent values was conducted with equations developed for the U.S. Environmental Protection Agency (Reference 22). Data collected with the Emission Sampling System (ESS), developed for the Washington state certification program (see Reference 18), and for the draft Northern Sonoma County Protocols (Reference 20) were converted to Method 5H equivalent values using the relationships developed from conducting simultaneous Method 5H and the ESS testing of fireplace emissions (Reference 20).

Historical data generated with a Method 5 sampling system were converted to Method 5H equivalents by calculating the relationship between emissions values obtained with a Method 5H sampling system and emissions values generated by the same sampling system but with the additional particulate matter that is collected on the back-half filter removed from the total emissions "catch". As a note, the key physical difference between a Method 5H sampling system and a Method 5 sampling system is that the Method 5 sampling system does not have a second filter in the sample gas stream after the impinger train (ie, "back-half filter") but the Method 5H does. The relationship between data generated by Method 5H sampling systems and data generated by Method 5 sampling systems and converted in this fashion is shown in Table A-4 and Figure A-4.

The particulate emissions rate data are based on 357 tests on 111 fireplace models. The mean emissions rate was 50 g/hr, the standard deviation was 35 g/hr, and the best performing12% value was 20 g/hr. These results are compiled in Table A-5 and plotted in Figure A-5.

Particulate emissions factor data are based on 388 tests on 112 fireplace models. The mean was 12 g/dry kg, the standard deviation was 12 g/dry kg, and the best performing 12% value was 3.5 g/dry kg. These results are compiled in Table A-6 and plotted in Figure A-6. For comparison purposes, the EPA AP-42 particulate emissions factor value, based on much more limited data is 17.3 g/dry kg (Reference 21).

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Appendix A:

Table A-1. Distribution of Fireplace Burn Rates (dry kg/hr)

Comments	Maximum Value of Interval (dry kg/hr)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
	1	3	1%	3
Mean-SD	2.4	25	7%	22
12% (MACT)	2.9	46	12%	21
	4	133	35%	87
	5	207	55%	74
Mean	5.6	229	61%	22
	6	244	65%	15
	7	285	75%	41
	8	311	82%	26
Mean + SD	8.7	325	86%	14
	10	344	91%	19
	11	358	95%	14
	12	366	97%	8
	15	373	99%	7
	20	376	99%	3
	25	377	100%	1
	30	378	100%	1

Number of models=177
Number of tests=377
SD= Standard Deviation= 3.2 dry kg/hr

Table A-2. Distribution of Fireplace Carbon Monoxide Emissions Rates (g/hr)

Comments	Maximum Value of Interval (g/hr)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
	20	7	3%	7
	40	8	3%	1
	60	12	4%	4
	80	17	6%	5
	100	21	8%	4
	120	27	10%	6
12% (MACT)	130	33	12%	6
	160	51	19%	18
	180	64	24%	13
	200	85	32%	21
	220	101	38%	16
Mean-SD	238.5	118	44%	17
	260	130	48%	12
Mean	279.1	154	57%	24
	300	177	66%	23
Mean + SD	319.8	196	73%	19
	340	206	77%	10
	360	211	78%	5
	380	221	82%	10
	400	226	84%	5
	420	232	86%	6
	440	237	88%	5
	460	241	90%	4
	480	245	91%	4
	500	246	91%	1
	550	250	93%	4
	600	252	94%	2
	650	260	97%	8
	700	263	98%	3
	750	264	98%	1
	800	266	99%	2
	850	267	99%	1
	900	268	100%	1
	1020	269	100%	1

Number of models=70
Number of tests=269
SD= Standard Deviation= 40.7 g/hr

Table A-3. Distribution of Fireplace Carbon Monoxide Emissions Factors (g/dry kg)

Comments	Maximum Value of Interval (g/dry kg)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
	10	16	6%	16
12% (MACT)	22	34	12%	18
Mean-SD	23.4	42	15%	8
	30	59	21%	17
	40	73	26%	14
	50	112	40%	39
	60	135	49%	23
Mean	64.1	150	54%	15
	70	160	58%	25
	80	192	69%	32
	90	221	80%	29
	100	236	85%	15
Mean + SD	104.7	240	87%	4
	110	246	89%	10
	120	257	93%	11
	130	262	95%	5
	140	266	96%	4
	150	270	97%	4
	175	272	98%	2
	200	274	99%	2
	225	275	99%	1
	250	275	99%	0
	275	276	100%	1
	300	277	100%	1

Number of models=70
Number of tests=277
SD= Standard Deviation= 40.7 g/dry kg

Table A-4. Method 5H vs Method 5 Emission Rates

Method 5H Emission Rate (g/hr)	"Method 5" Emission Rate (g/hr)
18.0	15.5
19.6	17.2
18.2	16.3
24.7	22.2
16.8	15.7
15.4	12.9
36.4	32.3
29.9	25.5
29.6	27.1
32.1	25.4
23.5	21.5
22.0	18.1
35.7	31.4
33.0	26.8
15.6	13.5
15.5	13.3
16.9	16.3
15.9	15.1
7.3	7.2
7.0	6.8
Avg. 21.7	Avg. 19.0

Method 5H = 1.1898(Method 5) - 0.9374, R^2 = 0.9815, n=20

Back filter included in Method 5H calculations but not in Method 5 Calculations

Table A-5. Distribution of Fireplace Particulate Matter Emissions Rates (g/hr, EPA 5H equivalents)

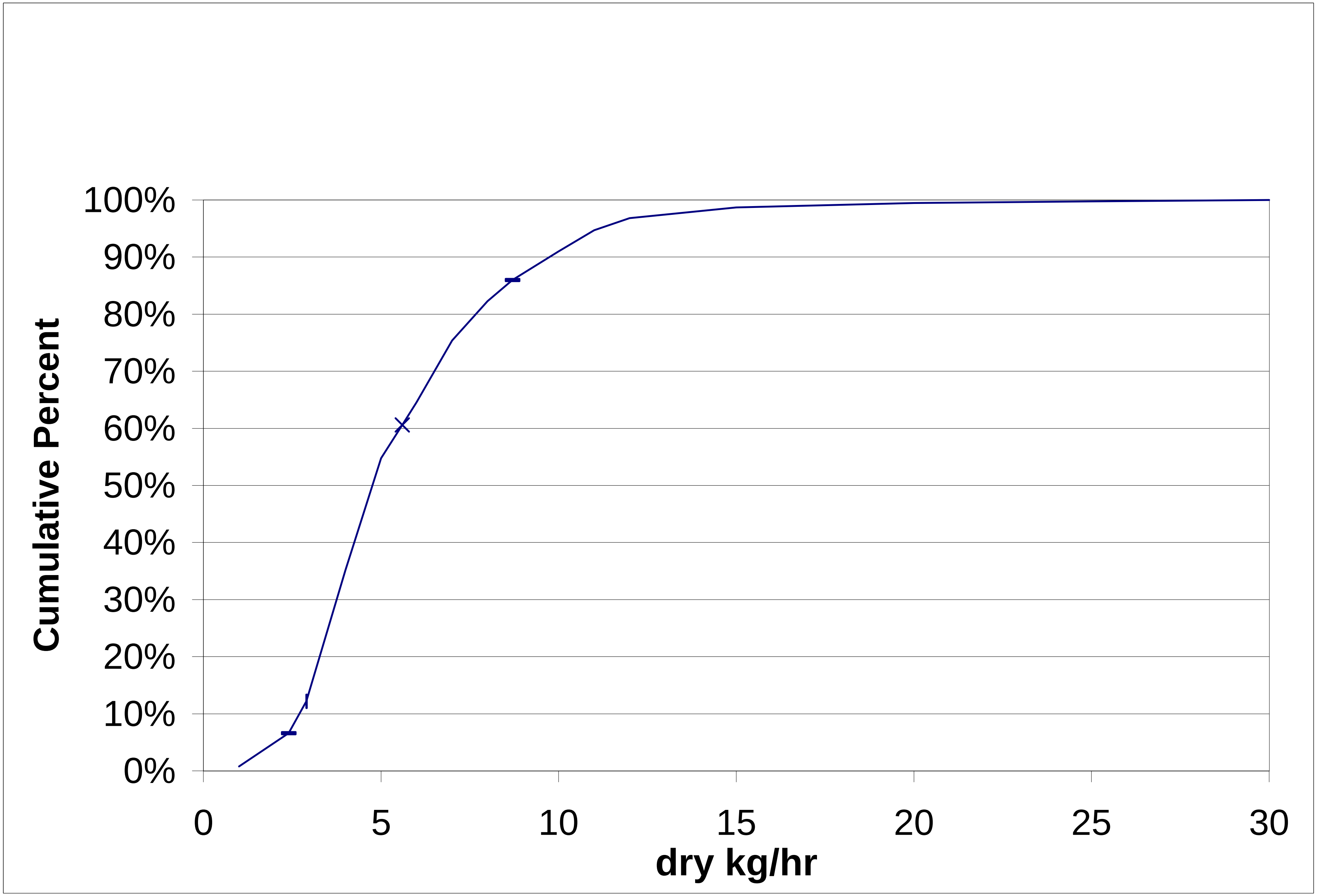
Comments	Maximum Value of Interval (g/hr)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
	5	2	1%	2
	10	8	2%	6
Mean-SD	14.4	29	8%	21
12% (MACT)	20	44	12%	15
	25	71	20%	27
	30	108	30%	37
	35	138	39%	30
	40	172	48%	34
Mean	49.7	233	65%	61
	55	255	71%	22
	60	271	76%	16
	65	280	78%	9
	70	293	82%	13
	75	297	83%	4
Mean + SD	85	313	88%	16
	90	322	90%	9
	95	325	91%	3
	100	330	92%	5
	105	332	93%	2
	110	336	94%	4
	115	339	95%	3
	120	341	96%	2
	125	343	96%	2
	140	345	97%	2
	160	347	97%	2
	180	352	99%	5
	210	355	99%	3
	255	357	100%	2

Number of models=111
Number of tests=357
SD= Standard Deviation= 35.3 g/hr

Table A-6. Distribution of Fireplace Particulate Matter Emissions Factors (g/dry kg, EPA 5H equivalents)

Comments	Maximum Value of Interval (g/dry kg)	Cumulative Number of Data Points	Cumulative Percentage	Number of Data Points in Interval
Mean-SD	.3	0	0	0
	1.2	8	2	8
12% (MACT)	3.5	46	12	46
	4	58	15	50
	6	104	27	46
	8	148	38	44
	10	198	51	50
Mean	11.8	235	61	37
	14	275	71	40
	16	304	78	29
	18	328	85	24
	20	346	89	18
Mean + SD	23.4	361	93	15
	25	366	94	20
	30	378	97	12
	35	381	98	3
	45	383	99	2
	50	385	99	2
	55	385	99	0
	60	385	99	0
	65	386	99	1
	80	387	100	1
	170	388	100	1

Number of models=112
Number of tests=388
SD= Standard Deviation= 11.6 g/dry kg



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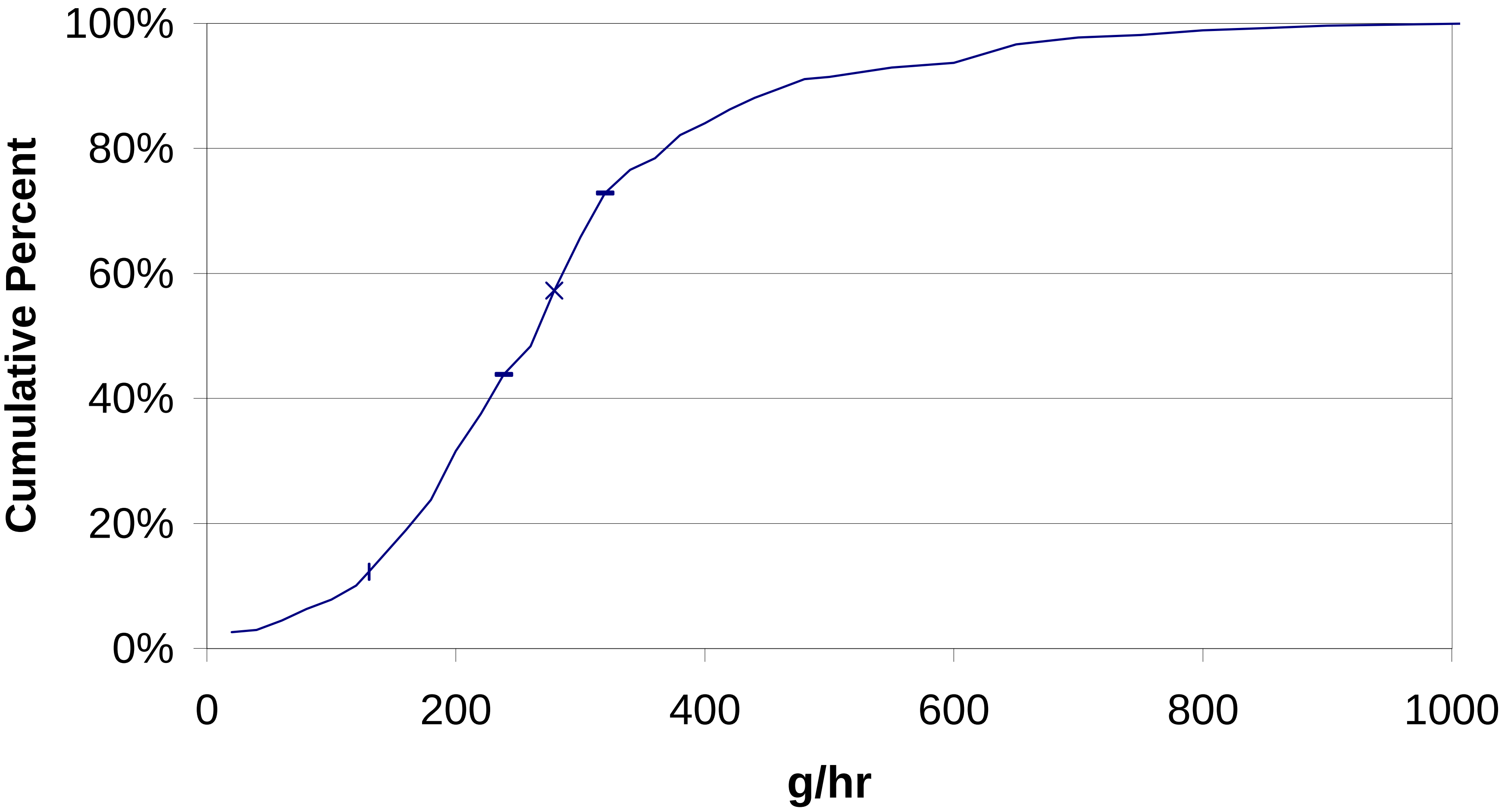
Sheet2 Chart 1

Figure A-1. Cumulative Fireplace Burn Rate Distribution. (x=mean, - mean +- S.D., ◇=12% value)



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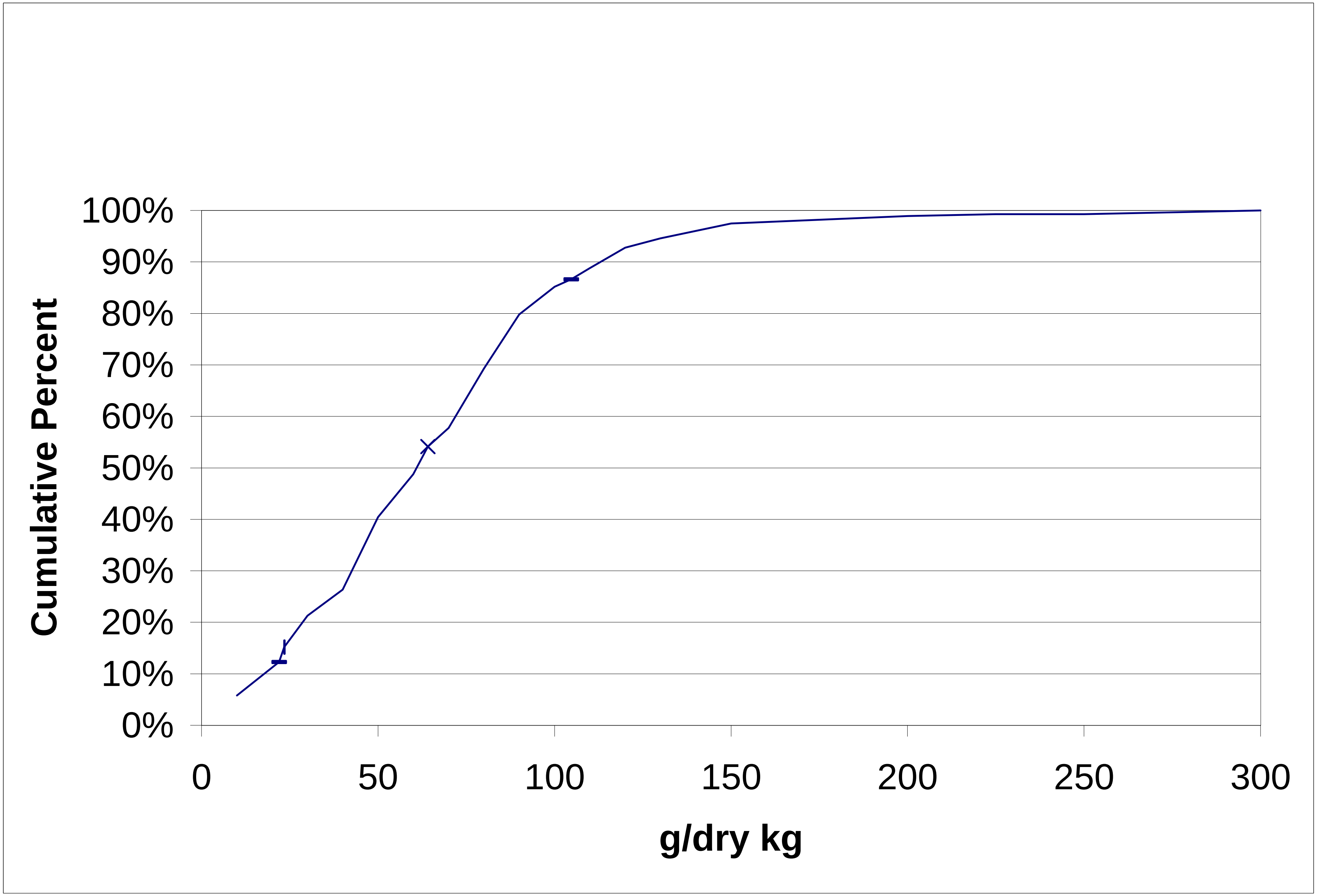
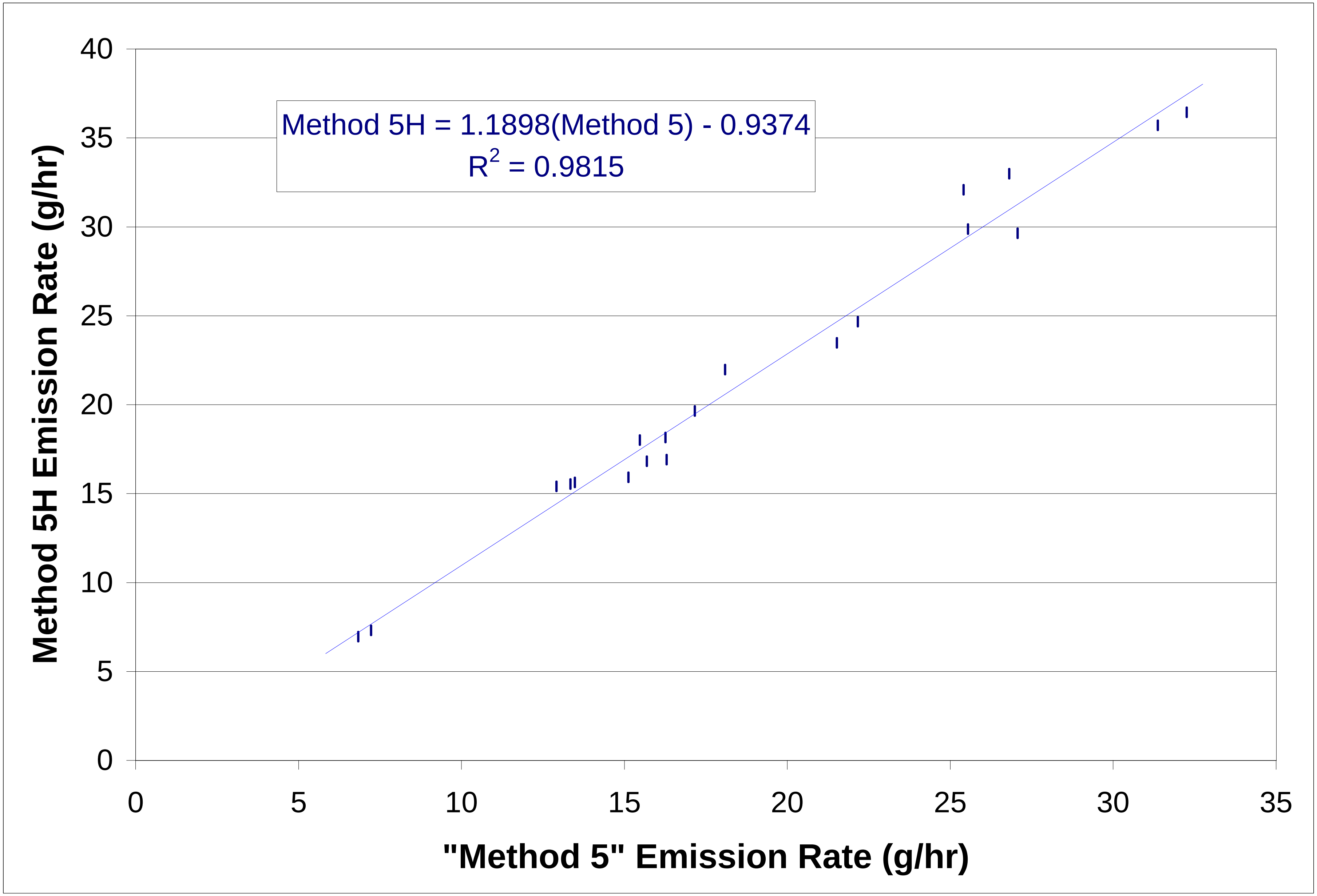
Sheet2 Chart 7

Figure A-2. Cumulative Fireplace Carbon Monoxide Emissions Rate Distribution.
(x=mean, - mean +- S.D., ◇= 12% value)



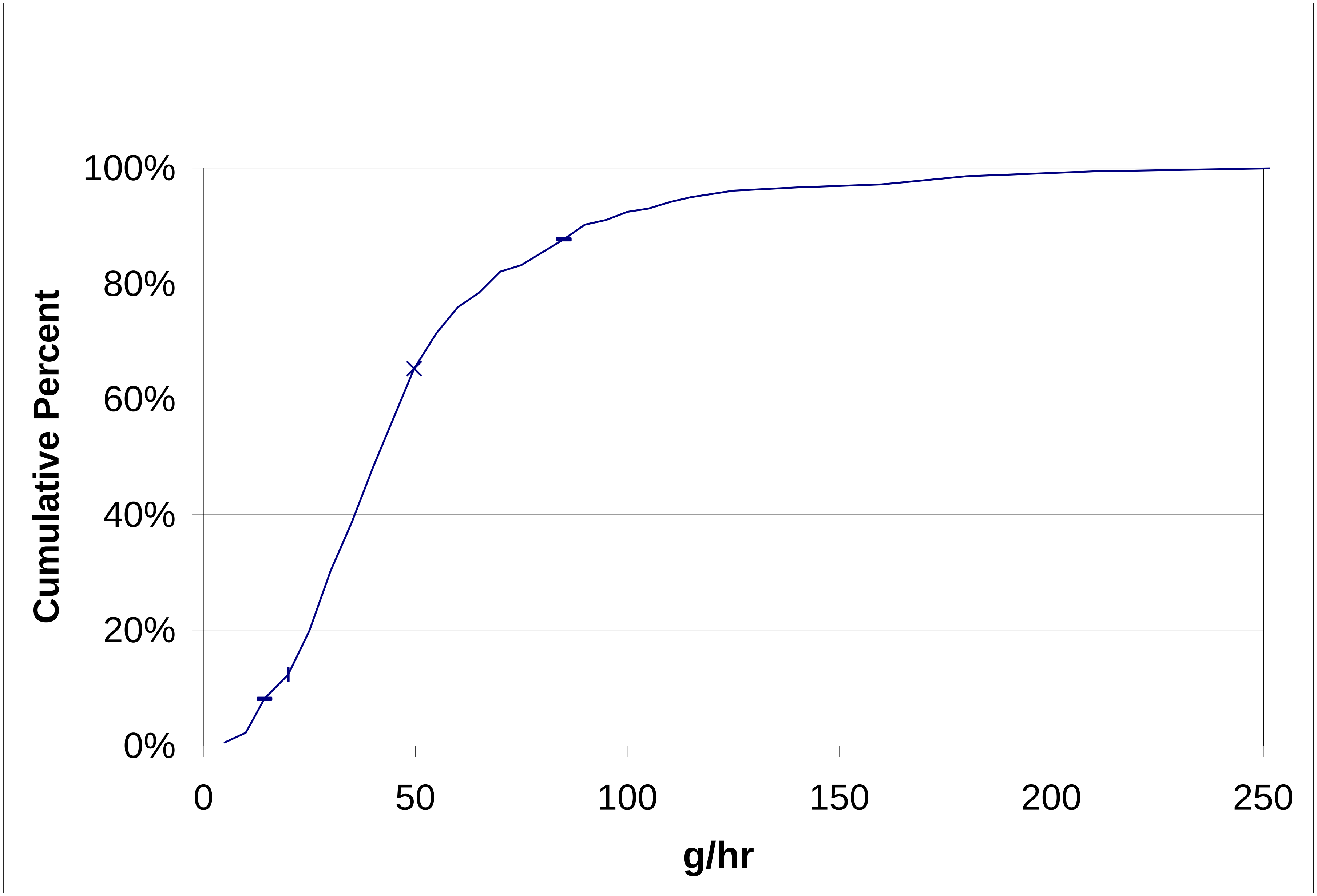
12/15/2000
Sheet2 Chart 9

Figure A-3. Cumulative Fireplace Carbon Monoxide Emissions Factor Distribution
(x=mean, - mean+- S.D., ◇= 12% value)



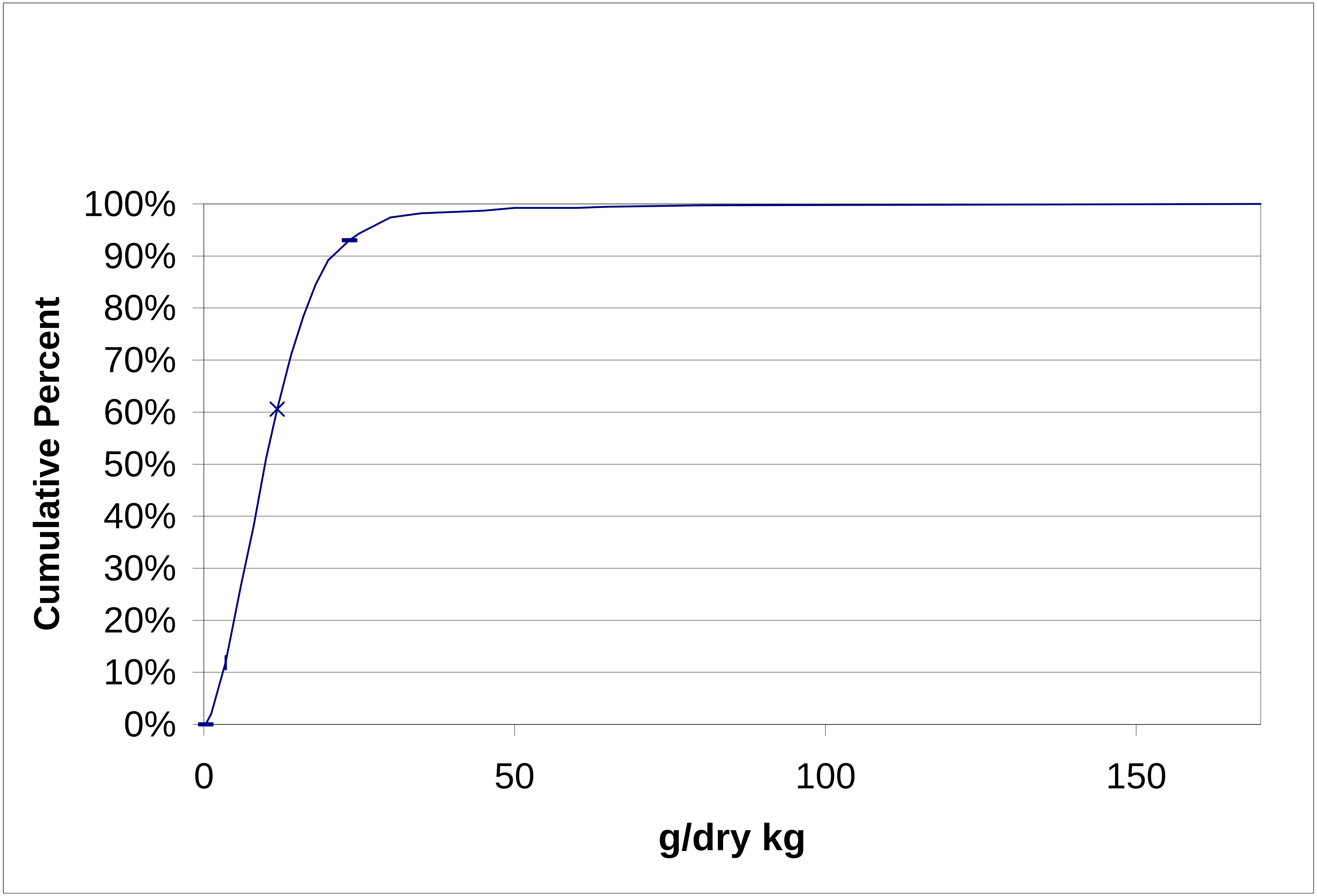
12/15/2000
Chart Chart 1

Figure A-4. Relationship between Fireplace Particulate Emissions Rates Determined by EPA Method 5H and Method 5.
(back-half filter included in EPA Method 5H but not in Method 5)



12/15/2000
Sheet2 Chart 3

Figure A-5. Cumulative Fireplace Particulate Emissions Rate Distribution
(x=mean, - mean+ - S.D., ◇= 12% value)



12/15/2000
Sheet2 Chart 5

Figure A-6. Cumulative Fireplace Particulate Emissions Factor Distribution
(x=mean, - mean +- S.D., ◇= 12% value)