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**EMISSIONS FROM OUTDOOR WOOD-BURNING
RESIDENTIAL HOT WATER FURNACES**

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ABSTRACT

Modern outdoor residential wood-burning hot water furnaces are freestanding units situated outside the envelope of the structure to be heated. They typically consist of a firebox and water reservoir, assembled in a horizontal configuration. Hot combustion gases flow from the firebox at one end, through channels or tubes in the water reservoir, to the stack. The gases may pass through the water reservoir once to the stack at the end opposite the firebox (one pass) or an additional set of pipes may bring the gases back to the stack located above but isolated from the combustion chamber (double pass). The heated water is pumped through radiators in the dwelling or through a heat exchanger in the HVAC duct in response to the home thermostat. A separate pipe coil in the water reservoir may be used to provide domestic hot water, year round if desired. The furnace draft is controlled by a thermostat monitoring the temperature of the water in the reservoir. Central heating furnaces of all types are exempt from the EPA wood heater (wood stove) standard. In this project, emissions were measured from one single pass and one double pass furnace at average heat outputs of 15,000 and 30,000 Btu/hr while burning typical oak cordwood fuel. One furnace was also tested once at each heat output while fitted with a prototype catalytic unit installed in the combustion chamber. Emissions measured included: EPA Method 5G particulate, semivolatile and condensable organics, 20 target PAH compounds, and carbon monoxide. Emission results are presented in terms of rate per hour, quantity per unit weight of wood burned, and quantity per unit of heat delivered. Delivered efficiencies are also presented. Compared to a wide range of residential heating options, these furnaces' emissions were of the same order as other stick wood burning appliances.

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CONVERSION TABLE

Most quantities in this report are in nonmetric units. Readers more familiar with metric units may use the following values to convert to that system.

Nonmetric	Multiply by	Yields metric
Btu/hr	1.055×10^3	joule (J)
Btu/lb	2.326×10^3	J/kg
Btu/(lb-°F)	4.187×10^3	J/kg-K
degree Fahrenheit (T_F)	$(T_F+459.67)/1.8$	K
cfm	4.719×10^{-4}	m ³ /s
ft	3.048×10^{-1}	m
gpm	6.309×10^{-5}	m ³ /s
lb	4.536×10^{-1}	kg
lb/ft ³	1.602×10	kg/m ³
lb/gal	1.198×10^2	kg/m ³
lb/min	7.560×10^{-3}	kg/s
in. H ₂ O @ 60°F	2.488×10^2	pascal (Pa)

SECTION 1.0 - INTRODUCTION

In the early 1980's, the state of Oregon began developing methods for characterizing source emissions from residential wood combustion units. The developed methods have since blossomed into test methods used to audit and certify wood-burning heaters. From these beginnings, the U.S. Environmental Protection Agency (EPA) has established emission performance standards for residential wood heaters.

The federal regulations established by the EPA in 1988 limit emissions from residential wood heaters, such as wood stoves, pellet-stoves, and factory built fireplace inserts. These regulations, however, do not include all wood-fired heating appliances. For example, central heating furnace/boilers are not covered under the current regulations.

In general, emissions from the combustion of wood in stoves and furnaces contain significant levels of carbon monoxide (CO) and fine particulate matter consisting, in part, of mutagenic polycyclic aromatic hydrocarbons (PAH). If atmospheric conditions are conducive for accumulating smog-like clouds of emissions, the wood smoke could pose a health hazard. With the potential for such a condition under consideration, the EPA established maximum acceptable emissions levels for the certification of most residential wood-fired heaters.

Typically, the modern outdoor residential wood-burning hot water furnace is a freestanding unit situated outside the envelope of the structure to be heated. The unit consists of a closed combustion chamber surrounded by a water tank and vented through a stack. A wood burning fire is contained and controlled in the combustion chamber or fire-box of the furnace. During the combustion process, heat is transferred through the walls of the chamber into the water. The hot water from the furnace tank can then be circulated through radiators or air-handling heat exchangers to transfer heat into a residence. Some central heating furnaces are equipped with additional plumbing to provide domestic hot water.

Most commercial central heating furnaces are supplied with an 8- to 10-foot stack. Typical indoor wood burning stoves have chimneys which extend through the roof of a home to heights of 20 to 30 feet. The relatively low chimney height of the central heating furnace/boiler, compared to the conventional wood stove

installations, creates a greater potential for the localization of objectionable emissions in and around residences. Additionally, concerns have been raised about the manner in which the combustion process is controlled and how the control affects the emissions.

The State of Wisconsin has asked the Control Technology Center of EPA's Air Pollution Prevention and Control Division (APPCD) for assistance in determining whether the need exists to regulate these furnaces. Therefore, the EPA has undertaken the task of evaluating the emissions from the central heating furnaces and the manner in which the combustion is controlled. The objective is to develop baseline emission factors for comparison with other residential heating systems.

Section 2 provides a description of the experimental approach and sampling and analytical methods employed. Steps to ensure project quality are described in Section 3. Data, results and discussion are presented in Section 4. The appendices contain the detailed data.

SECTION 2.0 - PROJECT DESCRIPTION

2.1 EXPERIMENTAL APPROACH

In order to determine whether the need exists to regulate the central heating furnace/boilers, the EPA needs to establish baseline emission factors. The subject investigation was undertaken as a means of "scoping" the performance of typical furnace types under normal operating conditions. The objective of the investigation was to gather emissions data using standard EPA test methods developed for certifying and auditing wood-fired heaters (wood stoves). These results could then be compared to the emission factors established for other gas-, oil, and wood-fired residential heating equipment. There are significant differences in the way these home heating furnaces are designed and operated which produce widely different emission properties and levels. For example, the wood-fired furnaces tested in this project used thermostats to deliver a more constant amount of heat, compared to wood stoves which usually have manual draft controls.

The outdoor residential wood-burning hot water furnaces were tested following EPA Reference Method 28 (M28-40 CFR Part 60, Appendix A). Method 28 is the test method used to certify and audit wood-fired heaters (stick and pellet burning woodstoves). The method specifies fuel preparation, furnace operation, and the reporting of the results. Method 28 requires Method 5G or 5H (CFR Part 60, Appendix A) to determine the concentrations of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and particulate matter (PM) in the emissions.

For the purposes of these tests, some of the fuel preparation procedures under Method 28 were modified in favor of preparing the fuel and operating the furnace as recommended by the manufacturer. Cordwood was used instead of the dimensioned lumber specified for wood heater certification. Method 28A was used to calculate the stack gas dry molecular weight, as required for flow measurements. Method 5G was the primary sampling method used for the test. The sampling method, Method 5G, was modified with the addition of an XAD-2 absorbent trap to collect organics; this modified sampling method will hereafter be referred to as Modified Method 5G (MM5G). The collected MM5G samples were analyzed for total particulate matter (PM), total semivolatile

organics [sometimes referred to as total chromatographable organics (TCO)], condensible organics as measured by gravimetric analysis (GRAV), and polycyclic aromatic hydrocarbons (PAHs). The efficiencies of the units were measured as a secondary objective for reporting emissions relative to the input heating value of the wood and to their heat output from the furnace.

The stack test location and MM5G probe location were selected according to the criteria established by EPA methods for the testing of wood-fired heaters. The emissions sampling system consisted of a dilution tunnel and hood. The hood, or bell, is positioned inches above the stack exit. The released emissions plus dilution air are captured and drawn into the hood and dilution tunnel by an induced draft (ID) fan. A draft differential pressure of <0.005 in H_2O was maintained on the wood-fired furnace as required by Method 28. The MM5G samples were taken from the dilution tunnel duct. The flue gas concentrations as measured by the CEM's were sampled from the chimney. The various protocols for sampling in small ducts as described in EPA Methods 1A, 2C, and 5C (CFR Part 60, Appendix A) were followed. An additional CO monitor was positioned to sample CO concentrations in the dilution tunnel. This allowed the furnace stack flow to be calculated by multiplying the dilution tunnel flowrate by the ratio of dilution tunnel CO to furnace stack CO.

$$\text{Furnace Stack Flow} = \text{dilution tunnel flow} \times \text{CO}_{\text{dilution}} / \text{CO}_{\text{stack}}$$

The MM5G sampling train consisted of a pump which draws gas from the dilution tunnel through a system of filters, an XAD-2 organics trap, a condenser and a gas meter. Sampled gas temperatures were measured, and recorded, throughout the train. Also, the velocity head and temperature in the dilution tunnel were measured at the point of average velocity (as determined by a preliminary velocity and temperature traverse). Sampling rates were controlled to maintain a constant ratio of proportionality between dilution tunnel flow and flow pulled through the probe.

2.2 EXPERIMENTAL SET-UP

The combustion rate of the central heating furnaces investigated is controlled by a thermostat that maintains the temperature of the water within a specified temperature range. When the temperature of the water increases to the upper limit of the range, the temperature switch will stop or slow the combustion air supply into the combustion chamber. The combustion process will be stalled, slowing the amount heat being transferred to the water. During this period of stalled combustion, the temperature in the tank will drop as heat is removed via the water circulated from the tank through the

external space heating heat exchanger. Once the water temperature falls to the lower limit of the temperature range, the temperature switch will allow combustion air to enter the combustion chamber. The combustion process will increase, boosting the heat transfer to the water.

For these scoping tests, two types of furnaces were selected as representative of the industry. One of these furnaces was tested with a pre-production prototype catalyst designed to reduce emissions. The type of furnace is defined by the configuration of the unit. The flue gases exit the combustion chamber by way of a flue that passes through the water tank. In general, a single pass furnace allows the flue gases to pass once through the flue in the water tank before exiting through the chimney. As the hot flue gases pass through the flue, heat is transferred to the water in the tank. In a double pass furnace, flue gases pass through the water tank twice before exiting through the chimney. The second pass of the stack is designed to provide more surface area and more contact time between the hot flue gases and the water in the tank. Representative furnaces of both types were provided to EPA/APPCD for testing.

The double pass furnace tested consists of a plate steel combustion chamber surrounded by a water tank on all sides but one. As shown schematically in Figure 2-1, a door on the exposed surface of the chamber provides the only access to the fire-box for fuel loading and ash removal. Combustion air is supplied to the fire-box by a forced draft fan on the door. The forced draft fan is controlled by the previously mentioned thermostat switch on the front of the unit. A damper on the fan intake was used to adjust the air supplied to the combustion chamber. The flue gases produced during the combustion process exit the fire-box through four flue pipes at the rear of the combustion chamber. The flue pipes extend through the water tank to a chamber at the rear of the unit. In the secondary chamber, flue gases travel upward toward two flue pipes, where they pass back through the water tank to the front of the unit. The upper two flue pipes empty into the chimney where the flue gases exit the furnace. The exterior of the water tank is insulated and covered with exterior metal sheeting. The rear of the water tank is equipped with a pump and plumbing from which the heated water can be circulated. Additional pipe connections and valves are located on the rear of the furnace to fill the water tank. The manufacturer provided the furnace with an air-handling exchanger for heat removal.

Similar to the double pass furnace, the single pass unit shown schematically in Figure 2-2 contains a steel plate fire-box surrounded by a water tank. Several transverse water filled tubes and a water filled transverse baffle provide additional heat transfer surfaces. A door on the front of the unit provides

access to the fire-box. The combustion air is controlled by a thermostat and an electrically controlled damper. The hot gases flow around the tubes and baffle to the rear of the furnace and empty into the chimney. The pump and plumbing for circulating the water are located on the rear of the furnace. The single pass furnace was equipped by the manufacturer with a water cooled heat exchanger for the test.

The furnaces were tested at two conditions. Under the first condition, heat was removed from the furnaces at a rate typical of the average winter heat demands for homes in warmer climate regions (15 to 20 kBtu/h). At the second condition, heat was removed at a higher rate (30 to 40 kBtu/h) to simulate colder climate requirements. The heat extracted from the furnaces during the testing was well below the possible heating output of the furnaces when fully charged. Testing under these conditions caused cycling of the controlled combustion process.

Each furnace was tested twice at each of the test conditions. One of the units, equipped with a prototype removable catalyst, was additionally tested once at the high heat removal rate and once at lower heat removal rate. Blank MM5G samples were also collected for each furnace. The test matrix for this study is shown in Table 2-1.

The project generated sample sets representing 12 tests and three blanks. Each of the test runs spanned the time to burn a full wood charge at a set heat output rate, as defined by the test matrix shown in Table 2-1. Each furnace was connected to an exchanger through which its heated water was circulated. One unit was provided with a forced-air (air-to-air) heat exchanger. The other unit utilized a water-to-water heat exchanger. The heat output rate through the exchanger was determined by measuring the flow rate and the inlet and outlet temperatures of the circulated water. The heat output rate was controlled by regulating the water flow rate being circulated from the furnace and by regulating the flow of the cooling medium across the exchanger. This measurement isolated the deliverable efficiency of the furnace from the deliverable efficiency of the exchanger. The delivered efficiency was defined as the energy removed from the hot water divided by the energy in the wood burned as

TABLE 2-1. TEST MATRIX FOR WOOD-FIRED FURNACE TESTING

Furnace	Test Condition	Test Number
Furnace A Scoping test	High Heat Removal Rate (30 to 40 kBtu/hr)	A-1 ^a , A-2
Furnace A without catalyst	High Heat Removal Rate (30 to 40 kBtu/hr)	A-3, A-4
Furnace A without catalyst	Low Heat Removal Rate (15 to 20 kBtu/hr)	A-5, A-6
Furnace A with catalyst	High Heat Removal Rate (30 to 40 kBtu/hr)	A-7 ^b
Furnace A with catalyst	Low Heat Removal Rate (15 to 20 kBtu/hr)	A-8 ^b

Furnace B	High Heat Removal Rate (30 to 40 kBtu/hr)	B-1, B-2
Furnace B	Low Heat Removal Rate (15 to 20 kBtu/hr)	B-3, B-4
Furnace A without catalyst	Dilution Tunnel Blank	A-9
Furnace A with catalyst	Dilution Tunnel Blank	A-10
Furnace B	Dilution Tunnel Blank	B-5

a Water temperature significantly below manufacturer's recommendation (see text).

b Substantial smoke spillage when draft fan on.

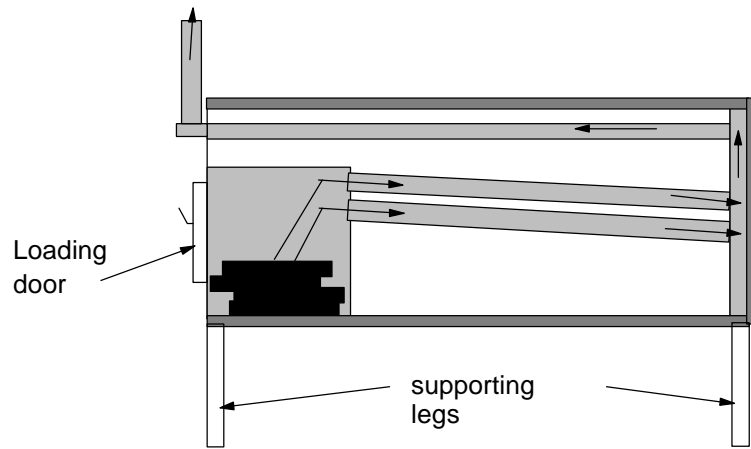


Figure 2-1. Double pass furnace schematic.

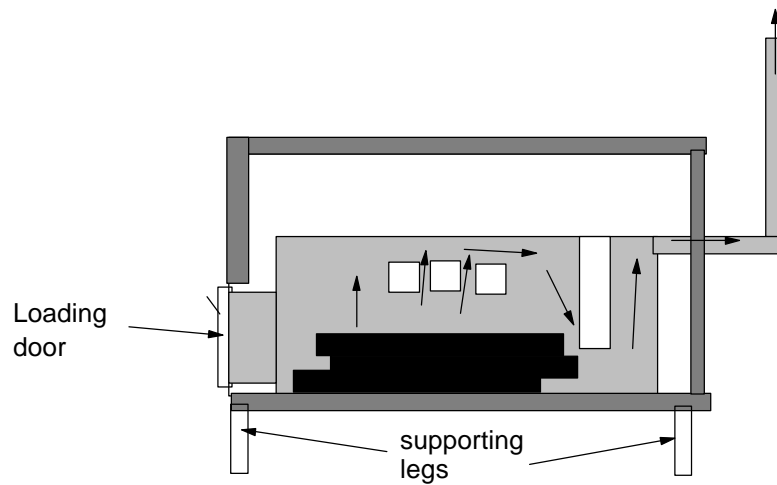
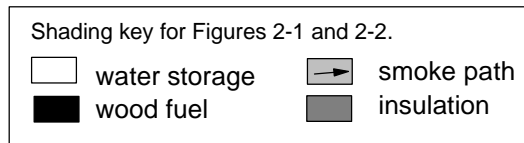


Figure 2-2. Single pass furnace schematic.



determined using the lower heating value (see Sample A, Table 2-2). Specifically:

Delivered efficiency = $100 \times \sum \text{energy removed}_t / \text{energy input}$ (1)
where:

Energy removed_t = (water_t/60) x density_t x (T₂ - T₁) x [(t+1) - t]
x specific heat_t

water_t = corrected water flow, gpm

density_t = corrected water density, lb/gal

T₂ = temperature of water leaving furnace

T₁ = temperature of water entering furnace

t+1 = time at end of recording interval, sec.

t = time at start of recording interval, sec.

specific heat = 1 Btu/(lb-°F)

and:

Energy input = (wood weight_{start} - wood weight_{end}) x lower heating value/(1 + wood moisture content)

wood weight, lb

lower heating value, Btu/lb dry

moisture content, %

The furnaces were tested at separate wood stove testing facilities. Both facilities are designed specifically for Method 5 dilution tunnel sampling and should, therefore, have produced similar quality results. The Method 5G facility specifications are restrictive enough to ensure that there were no substantial differences in the dilution tunnel arrangement. The testing at both facilities adhered to the guidance provided by the Quality Assurance Project Plan (QAPP) developed under the EPA Work Assignment entitled "Emissions from Wood-Fired Residential Central Heating Furnaces." A representative from EPA/APPCD's Technical Services Branch audited both facilities during testing to determine any deviations from the QAPP.

The unsplit, mixed hardwood used for the two scoping tests on Furnace A was supplied by Furnace A's manufacturer. The red oak fuel used at both test facilities for all other tests came from the same seasoned lot of cordwood. Samples of the red oak fuel were sent to Commercial Testing and Engineering for an ultimate and proximate Analysis. The results of the analysis are shown in Table 2-2. The results from Sample B reflect the analysis of a wood chip taken from the surface of a typical piece of test fuel at one facility. The analysis of Sample A reflects the results from core samples taken from a number of pieces of typical test fuel at the other facility.

2.3 EXPERIMENTAL AND SAMPLING PROCEDURES

Each furnace was installed per manufacturers' installation instructions at its respective test facility upon an electronic weighing scale as shown in Figure 2-3. The manufacturers also provided the testing facilities with instructions on loading and operating the furnace. Once installed and visually inspected, the furnaces were pre-burned and checked with the assistance of representatives from the manufacturers.

TABLE 2-2. PROXIMATE AND ULTIMATE ANALYSIS FOR RED OAK

SAMPLE A					
PROXIMATE ANALYSIS			ULTIMATE ANALYSIS		
	<u>As</u> <u>Received</u>	<u>Dry</u> <u>Basis</u>		<u>As</u> <u>Received</u>	<u>Dry</u> <u>Basis</u>
% Moisture	21.98	xxxxxx	% Moisture	21.98	xxxxxx
% Ash	0.27	0.35	% Carbon	39.09	50.10
% Volatile	69.03	88.48	% Hydrogen	4.89	6.27
% Fixed Carbon	<u>8.72</u>	<u>11.17</u>	% Nitrogen	0.18	0.23
Total	100.00	100.00	% Sulfur	0.02	0.03
			% Ash	0.27	0.35
Btu/lb	6295	8069	% Oxygen	<u>33.57</u>	<u>43.02</u>
% Sulfur	0.02	0.03	Total	100.00	100.00
MAF Btu		8097			

SAMPLE B					
PROXIMATE ANALYSIS			ULTIMATE ANALYSIS		
	<u>As</u> <u>Received</u>	<u>Dry</u> <u>Basis</u>		<u>As</u> <u>Received</u>	<u>Dry</u> <u>Basis</u>
% Moisture	9.29	xxxxxx	% Moisture	9.29	xxxxxx
% Ash	0.77	0.85	% Carbon	45.21	49.84
% Volatile	79.26	87.38	% Hydrogen	5.60	6.17
% Fixed Carbon	<u>10.68</u>	<u>11.77</u>	% Nitrogen	0.27	0.30
Total	100.00	100.00	% Sulfur	0.02	0.02
			% Ash	0.77	0.85
Btu/lb	7680	8467	% Oxygen	<u>38.84</u>	<u>42.82</u>
% Sulfur	0.02	0.02	Total	100.00	100.00
MAF Btu		8540			

As noted above, the fuel burned during all the tests, except the two scoping tests on Furnace A, was seasoned, cut and split cordwood purchased from the same source. For all tests, a test charge of 7 lbs of wood/ft³ of useful combustion chamber volume was selected from the cordwood. For Furnace A, each piece was

weighed and measured in three locations for moisture content. The weighted average of the moisture content was determined for the combined test charge. For Furnace B, moisture measurements were averaged without weighting. As specified by the test method, the average moisture content of the test fuel was between 15- and 25-percent moisture dry basis.

Prior to the testing, the furnace was pre-loaded with a warm-up charge consisting of 40 to 80 lb of cordwood similar to the test fuel charge. The pre-load was to be sufficient enough

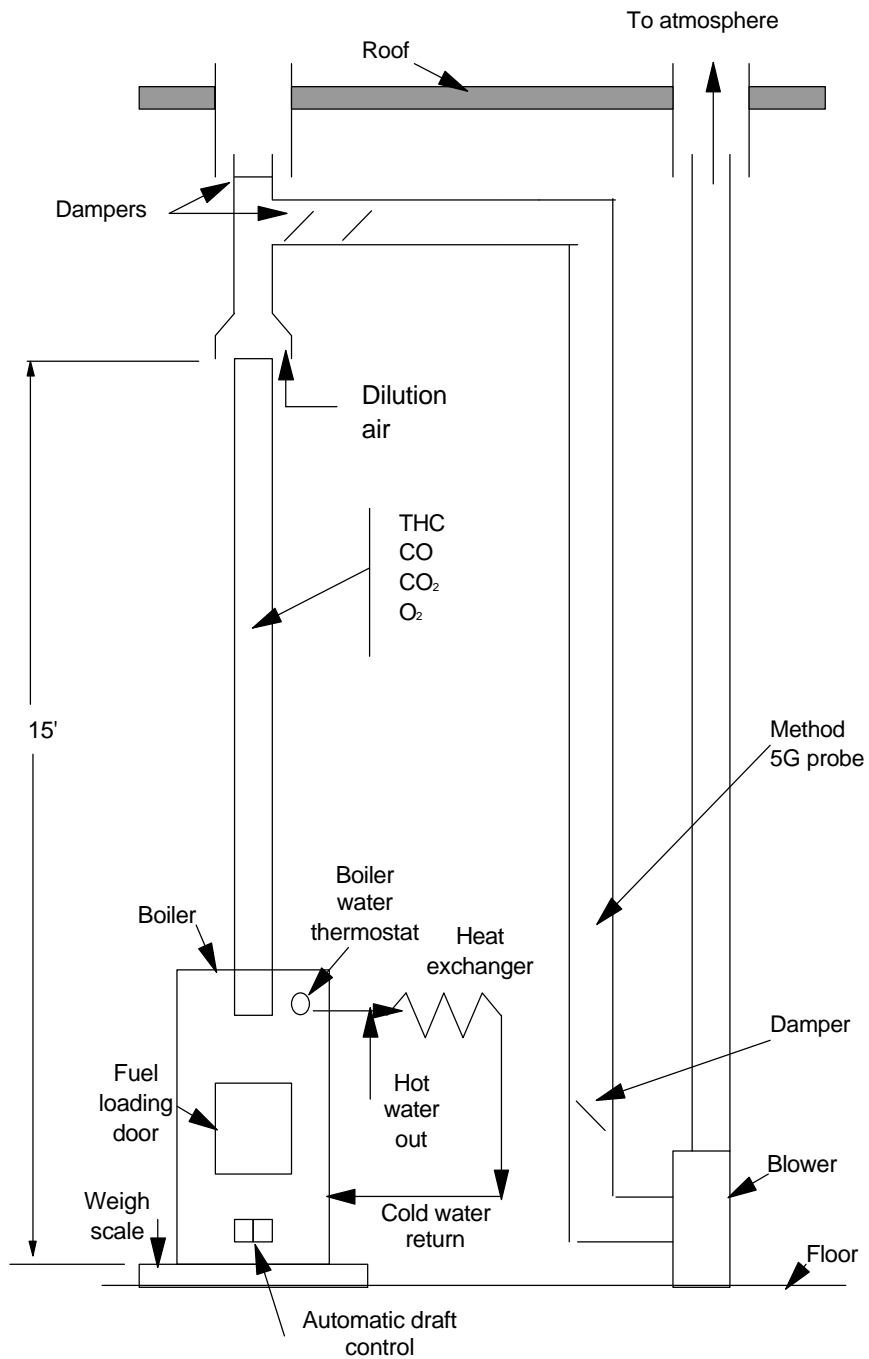


Figure 2-3. Typical furnace test setup.

to raise the water temperature in the tank to the operating temperature of ~180 °F. At least one hour before the sampling was to begin, the heat removal rate and the furnace were adjusted to the test conditions. During the pre-burn period the continuous emissions monitors (CEMs) were calibrated to appropriate zero and span values. After the two-point calibration, the CEMs were set to sample. Also during this time, the MM5G sampling train was assembled and checked for leakage. Upon passing the leak check as specified by the test methods, the sampling trains were set to sample.

Once the pre-load fuel had been reduced to hot coals, the MM5G sampling pumps and CEM pumps were started. The furnace was stoked to its specified fuel charge. The initial scale readings were recorded along with the process temperatures, flue gas concentrations, and ambient temperature and humidity. The critical parameters were continually monitored and recorded at regular intervals throughout the test. During the test, the systems were continually monitored. The water flow rate was adjusted during the test, as needed, to maintain the desired heat removal rate. The furnace's built-in temperature controlling thermostat continually measured the temperature in the water tank and adjusted the combustion process to suit the heat removal rate.

The sampling was ceased when the entire test fuel charge had been expended as measured by the weight. A post-test, leak check of the MM5G sampling train and verification of the CEM's zero and span calibration values were conducted. The MM5G sample filters were recovered by returning the filters to their labeled petri dishes and returning them to a desiccator. The XAD-2 absorbent trap was sealed and stored in a freezer. The probe and glassware were triple rinsed with acetone into a clean, tare weighed pan and placed into a fume hood for reduction. The sample fractions and XAD-2 were stored for later semivolatile, polycyclic aromatic hydrocarbon (PAH), and condensible organic analyses. These terms are described in more detail below.

2.4 ANALYSIS

Upon recovery of sample at the conclusion of a test, the filters and the pan from the probe rinse were transferred to a desiccator. After a minimum of 24 hours in a desiccator, the filters and pan rinse were weighed. The collected particulate matter was calculated as the difference between the filter and pan final weight and the tare weight. The total particulate matter was calculated as the sum of all the values from each of the components for each test.

The collected particulate and organics from the filters, pan rinses, and XAD-2 canisters were then extracted with methylene chloride and reduced to a volume of 5mL. This reduced sample was used to measure the organic composition of the particulate.

The condensible fraction represents compounds with boiling points greater than 300°C. A 1 mL aliquot was removed from the 5mL extract solution. The aliquot was added to prepared and tared micrograv pans. The pan weights were measured and repeated at 24-hour intervals until a 1-percent or less relative difference was recorded between consecutive weighings. Between weighings, the pans were stored in a desiccator over activated carbon and silica gel. The net weight of the reduced aliquot was calculated by subtracting the tare weight. The net weight was multiplied by five to obtain the total extracted condensible organics sampled.

A second 1mL aliquot was removed from the extracted solvent solution for total chromatographable organic (TCO) analysis. TCO compounds are defined as semivolatile organics with boiling points between 100 and 300°C. The TCO determinations were measured with a gas chromatograph. The aliquot was sealed in a glass autosampler vial. The samples were injected into a fused-silica capillary column heated to a final temperature of 250°C. The column was connected to a flame ionization detector (FID) that produced a response approximately proportional to the weight of organic material present in the sample. The analyzer then used algorithms to calculate and validate data. The TCO program summed together all valid data from duplicate runs of each sample. The TCO program then used storage parameters to calculate TCO mass per sample and statistical information about the replicate results.

The polycyclic aromatic hydrocarbons were analyzed using a mass spectrometer (MS). The MS was tuned for better resolution around a list of target analytes. The target analytes are listed in Table 2-3.

TABLE 2-3. PAH Target Analyte List [number in () refers to Figures 4-2 and 4-3].

Naphthalene (1)	Chrysene (11)
2-methyl naphthalene (2)	Benzo(a)anthracene (12)
Acenaphthylene (3)	Benzo(b)fluoranthene (13)
Acenaphthene (4)	7,12-Dimethylbenz(a)anthracene (14)
Dibenzofuran (5)	Benzo(k)fluoranthene (15)
Fluorene (6)	Benzo(a)pyrene (16)
Phenanthrene (7)	3-methyl cholanthrene (17)
Anthracene (8)	Indeno(1,2,3-cd)pyrene (18)

Naphthalene (1)	Chrysene (11)
Fluoranthene (9)	Dibenz(a,h)anthracene (19)
Pyrene (10)	Benzo(ghi)perylene (20)

SECTION 3.0 - QUALITY ASSURANCE AND QUALITY CONTROL

3.1 PREPARATION OF SAMPLING MEDIA

All MM5G sampling glassware was acetone rinsed, scrubbed with a nylon brush if necessary, and left under a fume hood for 24 hours prior to assembling the sampling trains. The quartz fiber filters were desiccated for a minimum of 24 hours. An average tare weight was recorded for each filter after three consecutive weight measurements. The filter casings were then assembled and sealed with aluminum foil until the final assembly.

The XAD-2 canister and resin were cleaned prior to assembling. Impurities were extracted from the resin by sequentially pumping toluene and dichloromethane through the media. The solvents were then removed from the resin by evaporation with a stream of nitrogen. The XAD canister was baked in an oven for 24 hours to remove impurities. Once cleaned, the canister was filled with the XAD-2 resin and sealed. The sealed containers were refrigerated until the final assembly in the sample trains.

When all the components for the sampling train were ready for assembling, the components were visually inspected and assembled. Once the sampling train was assembled, a vacuum leak check was performed on the system. The assembly was accepted if less than 0.02 ft³/min, or approximately two-percent of the normal sampling rate, could be pulled through the sampling train while the probe was capped or plugged. If the sampling train did not pass the leak check, it was disassembled, reassembled, and checked again until the leakage was reduced to the acceptable level. The sampling train was also checked for leaks at the completion of the test. If the sampling train did not pass the post-test leak check, the test was disregarded.

The MM5G dry gas meters have been calibrated semi-annually against a spirometer. Temperature and pressure measurements are taken before and after the meter, so as to convert the measured dry gas volume flow rates to standard pressure and temperature.

3.2 MEASUREMENTS

All thermocouples used for measuring temperatures were calibrated at the end of the test period. The thermocouples were calibrated at two points, in freezing water and in boiling water. All of the thermocouples measured the two calibration standards

to within 1F°. The results of the calibration are reported in Appendix A.

The continuous emission monitors (CEMs) used to measure the gas concentrations in the stack and dilution tunnel were zeroed and spanned prior to and following each test. The CEMs were calibrated to two values. First, the CEMs were calibrated to zero with nitrogen. The other value for the calibration, the instrument span, was measured against bottled gases of known concentrations. At one facility, a three-point calibration was conducted prior to testing. The other facility performed a five point calibration at the completion of all the tests. The daily zero and span calibration checks are reported with the test information data. The post-test calibrations are reported in Appendix B.

The volume flow rate of the water circulated from the tank of the furnace was measured with either a rotameter (Furnace A) or a totalizing flow meter (Furnace B). The meters were calibrated by weighing the water collected in a container over a set flowrate and timed interval. The total volume of water as determined from the weight was then compared to the measured volume flow as measured by the meter. The results from the water meter calibrations are reported in Appendix C.

The method used to determine the average moisture content of the fuel differed between the two facilities. One facility determined the average moisture content of the fuel in a manner consistent with Method 28. Each individual piece of test fuel was weighed and measured for moisture content. The weight and moisture content of the individual pieces of test fuel ranged from 1.5 to 5 lbs and 10- to 35-percent respectively. The moisture content value used in the calculations was determined as the average measured moisture content. Because the test fuel used was not dimensioned lumber as per Method 28, the other facility determined the moisture content of the fuel as a weighted average. Each individual piece was weighed and measured for moisture content. The total weight and moisture weight was determined. The resulting weighted average was determined as the fraction of total moisture per total dry weight of the fuel charge. Both laboratories used the Delmhorst electric conductivity instrument to measure the moisture content of the individual pieces of wood. This instrument provides a direct reading of the moisture content on a dry wood basis.

The fuel charges were also loaded differently at the two facilities. This investigation was undertaken to determine baseline emission factors for these furnaces at normal operating conditions. The furnaces were therefore loaded in a manner recommended by the respective manufacturers. One facility loaded the test fuel into the firebox in a latticed fashion. Each layer of fuel was turned perpendicular to the preceding layer. The

other facility loaded fuel into the firebox in a more compact stack of parallel layers.

3.3 DATA QUALITY INDICATOR GOALS

Despite their differences, both facilities were able to remain (with minor exceptions) within the guidelines of the technical objectives and data quality indicator goals established in the Quality Assurance Project Plan. The EPA audited the test procedures and equipment at each of the testing facilities. Through the Technical Systems Audit (TSA), the EPA identified all procedural modifications and differences. The EPA concluded that "The TSA did not identify any major problems associated with the implementation of the QAPP ... The quality of data generated is expected to satisfy the project's technical objectives."

The manufacturer of Furnace A recommended a water reservoir set point (temperature at which the draft is turned off) of 160 °F. Scoping Test A-1 set point was incorrectly set at 120 °F. Average water outlet temperature for test A-1 was 124 °F. The set point for the remaining tests on Furnace A was 160 °F; the water outlet temperature for these tests ranged from 156 to 172 °F. Average Furnace B water reservoir outlet temperature ranged from 180 - 182 °F for the four tests. Although the QAPP was written with the concept of requiring a set point temperature ≥ 180 °F, this requirement was abandoned for the tests on Furnace A in favor of the manufacturer's recommendation. Manufacturer of furnace B recommended a set point of 180 °F as being typical of field operation.

Scoping Tests A-1 and A-2 on Furnace A burned mixed hardwood fuel. All the remaining tests on Furnace A, and all tests on furnace B, used seasoned red oak fuel from the same source.

The data quality indicator goals from the QAPP are identified in Table 3-1. It should be noted that due to the length of these tests, and the fact that tests were not intended as certification tests, the DQI goals for O₂, CO₂, and CO measurements were relaxed from the standards of Method 5H to the less stringent standards set forth in Methods 3A and Method 10.

TABLE 3-1. PRECISION, ACCURACY, AND COMPLETENESS OBJECTIVES

Measurement Method or Parameter	Reference	Experimental Conditions	Precision Standard Deviation	Accuracy	Completeness
Velocity-Pitot/ Manometer	EPA-2	Stack	10%	None	100%
Moisture-Condenser	EPA-4	Stack	5%	None	100%
Moisture-Wet Bulb/ Dry Bulb Thermocouple		Ambient	±5%	None	100%
Moisture-Condenser	EPA-4	Dilution Tunnel	±5%	None	100%
Stack Temperature		Stack	±5%		100%
Boiler Water Temperature (In & Out)		Furnace	±5%		100%
Stove Surface Temperature	EPA-28	External Surface	±5%	±1°F	100%
Stove Combustion Temperature	EPA-28	Firebox	±5%	±1°F	100%
O ₂ -Paramagnetic Monitor	44FR58625	Stack	±10%	±10% Bias	100%
CO/CO ₂ -Nondispersive Infrared Monitor	44FR58625	Stack	±2%	±5% Bias	100%
CO-NDIR		Dilution Tunnel	—	—	—
THC-FID	44FR58625	Stack	±10%	±10% Bias	100%
Particulate Emissions	EPA-MM5,5G	Dilution Tunnel	±10% RPD ^a	±15%	100%
Total Chromatographic Organics	EPA-MM5G	Dilution Tunnel	±10% RPD ^a	±25%	100%
Semivolatile Organics	EPA-MM5G	Dilution Tunnel	±10%	±20%	100%
Test Fuel Weight Electronic Weight Scale	EPA-28	—	±5%	±0.5	100%
Test Fuel Moisture Electrical Resistance	EPA-28	—	±5%	±3% Bias	100%
Test Fuel Moisture ASTM		—	—	—	—

^a Relative Percent Difference

SECTION 4.0 - DATA, RESULTS AND DISCUSSION

4.1 GENERAL DISCUSSION

The two furnaces were tested at separate wood stove testing facilities following prescribed EPA test methods. One of the laboratories is EPA-accredited for certification testing wood heaters. The test methods provided sufficient controls to ensure that the testing results were comparable. The test methods did, however, allow for some flexibility in the equipment and means in which the data were collected.

Both facilities were equipped with similar dilution tunnel arrangements. The position of the dilution tunnel "bell" relative to the stack is set so that the negative pressure in the tunnel does not affect the stack pressure. The Method 28 criteria require that, with the tunnel turned on, the effect on stack pressure must be <0.005 in. of H_2O . The negative pressures maintained in the dilution tunnel pull the stack emissions into it along with ambient (dilution) air. A greater or lesser amount of excess air may have been pulled into the dilution tunnel depending upon the stack flow, so that the total tunnel volumetric flow remains relatively constant. The sampling rate was related to the volume flow rate within the dilution tunnel. The resulting calculation yielded a value of total measured emissions independent of the quantity of the excess air.

At one of the testing facilities, the dilution tunnel flow rate was sized for normal wood stove testing which easily accommodates stack flows in the 10 - 30 cfm range. During preliminary firing of Furnace A, it was found that with the draft setting at its maximum, a significant fraction of the stack emissions were not captured by the tunnel. However, during actual testing, the draft setting was reduced per the manufacturer's direction to a nearly closed position, limiting air flow into the furnace. Under these reduced draft flow conditions, all stack emissions were captured during tests of the standard furnace. When testing Furnace A with the prototype catalyst (tests A-7 and A-8), the draft setting was closed down, again at the manufacturer's direction. However, when the draft was on, significant emissions escaped the furnace and were not captured by the tunnel. The draft was on for a small fraction of the total test period. The effect on the measured emissions cannot be quantified; the final emission numbers presented in

this report may be under estimated by as much as 20% for tests A-7 and A-8.

Another variance between the testing facilities was the manner in which the data were recorded. One facility utilized a data acquisition system (DAS) to record, at one minute intervals, the temperatures, the CEM measured gas concentrations, and the weight of the remaining fuel. The other facility manually recorded the same information at ten-minute intervals. During the ten minute intervals, significant excursions in the measured gas concentrations may have occurred without being recorded. The data were averaged over the duration of the test to minimize the affects the excursions might have on the resulting data. In addition, the difference in the manner in which this portion of the data was recorded did not affect the MM5G particulate measurements.

Scoping tests A-1 and A-2 with Furnace A were conducted as preliminary runs to evaluate the test methods and collect data to predict heat load maintenance operations, and filter and XAD-2 loadings. Both of these scoping tests were run using a different fuel (mixed hardwoods) than the remaining tests. In addition, Scoping Test A-1 was run at the incorrect water reservoir temperature set point. The results from scoping tests A-1 and A-2, and from the two tests with the preproduction prototype catalyst (tests A-7 and A-8) are presented separately from the other tabulated test results.

4.2 CALCULATED RESULTS

The MM5G sampling train was used to calculate the total particulate matter (PM) in the emissions. The total PM was divided by the sampling time to calculate the average emissions in grams per hour. The burn rate of the fuel was determined from the dry weight of the initial fuel charge and the sampling time. The input fuel energy was determined from the dry charge weight and the dry basis heating value of the wood as determined by the ultimate and proximate analyses. The ratio of particulate weight to dry fuel weight was determined from the average PM emission rate and the burn rate. The total PM was then compared to the total input heat; the result was a calculation of milligrams of particulate matter per Btu of input heat. This value was also converted to milligrams of PM per megajoule (MJ) of input heat. The total PM was also compared to the furnace output in units of milligram per Btu of output heat. The MM5G particulate results for the comparable tests on both furnaces are presented in Table 4-1a. The organics results in the samples, measured as GRAV, TCO, and PAH fractions, are reported in Table 4-2a. The PAH results shown in Table 4-2a are based on the target compounds listed in Table 2-3. The gas concentrations shown in Table 4-3a are reported as averages over the duration of the tests.

4.3 EVALUATION OF RESULTS

The first two tests on Furnace A (scoping tests A-1 and A-2) were performed as an evaluation of the test methods. As previously stated, the test methods were developed for the testing and certification of wood stoves and had to be modified for testing the central heating furnaces. These two initial scoping tests were therefore used for methods evaluation and development. These data, reported separately in Tables 4-1b through 4-3b, indicate that the developmental tests results, even with different, somewhat higher moisture cordwood as fuel, are consistent with the other tests. Note also that scoping test A-1 was run at a lower water temperature set point (120° F compared to 160° F for all the rest of Furnace A tests). The results from the prototype catalyst tests on Furnace A are also presented in Tables 4-1b through 4-3b.

In all test cases, the furnaces delivered heat at an efficiency of about 50 percent, plus or minus 10 percent, of the input heating value of the wood. This measurement reflects the combustion of the fuel and transfer of the heat to the water in the tank to be circulated. This does not account for the efficiency of the heat exchanging device or electrical energy required for the draft fan, the draft damper or the thermostats.

As noted previously one furnace (Furnace A) was supplied by the manufacturer with a water-air heat exchanger to simulate the home heat demand. Furnace B's manufacturer provided a water-water heat exchanger for this purpose. Appendices D and E, respectively, show that this had a significant effect on the draft on/off cycle times. Furnace A's cycle was quite variable. Typically, it cycled on for about 120 min. At the higher burn rate, it then cycled off for about 60 min. At the lower burnrate it cycled off for about 80 min. Furnace B exhibited a typical on cycle of 8 minutes, followed by 30 and 60 min. off cycles at higher and lower burn rates, respectively.

The MM5G data were analyzed to see if a relationship existed between the measured emissions, in grams per MJ heat input rate, and the average burn rate, in dry kilograms of fuel burned per hour. The relationships are illustrated in Figure 4-1. The particulate matter emission factor does not show a clear trend as a function of the burn rate. At a glance, the organic measurements do not show any trend, either. For a given furnace configuration, the emission factors derived from Figure 4-1 appear to be relatively constant across the burn rate range studied. Furnace A with the prototype catalyst showed higher levels of TCO and PAH emissions, especially at the lower burn rate. This may have been due to cracking of the larger organic molecules as they passed through the catalyst but not complete oxidation due to a lack of excess air.

The difference in the catalyst versus noncatalyst results from Furnace A can be explained in two possible ways. The

catalyst could have greatly changed the combustion process and therefore, the emissions composition. For example, it was noted that the furnace operated much differently with the catalyst installed. The heat was transferred to the furnace's water tank at a much higher rate with the catalyst. Also, the excess oxygen level fell to nearly zero when the draft was on (see runs TTCD-1 and 2 in Appendix D). But when the temperature in the tank reached the maximum of the set range, the thermostat would stall the combustion. During the periods of stalled combustion, the temperatures at the catalyst were not sufficient for the catalyst to be effective. The overall process resulted in the furnace cycling "on and off" more frequently.

Another possible explanation for the difference in catalyst versus noncatalyst results was the timely manner in which the samples were analyzed. All samples for all tests were measured for total particulate within 24 to 36 hours after the tests. The separate components were then stored for analytical analysis. The samples were then extracted within 30 days after the measurements for total particulate. The extracted samples were then stored in a freezer until all the tests were completed. The non-catalyst samples were stored for nearly 6 months while the catalyst samples were stored for 45 days. The non-catalyst samples were analyzed well outside the test method specified hold times. Based on experience on a number of prior projects, however, it is believed that the without catalyst PAH data were not severely compromised by this delay.

Furnace A results for the low heat output without catalyst runs (tests A-5 and A-6) and both tests with the catalyst in place (tests A-7 and A-8) are suspect because the weigh scale showed periods of weight gain near the end of each test (see Appendix D, Run TTD-1A, for example). These tests were continued until the scale reached zero as specified in the method. The reasons for the weight increases are not known; possibilities include a shift in the plumbing to the heat exchanger which placed more weight on the scale or moisture condensation in the furnace-stack system (although the latter seems highly unlikely). The plastic plumbing looped from the back of the furnace, across the laboratory floor, and then up to the heat exchanger mounted on an 8 ft high shelf. It is very possible that the piping was bumped or changed position due to thermal stresses during the suspect tests. The data from these tests are consistent with the other results so they are included in the tables, but should be treated with caution, especially the values calculated on a emission per hour basis. The values calculated on an emissions per unit weight of fuel and per unit heat value are less likely to have been affected by the weigh scale anomaly. These anomalies occurred late in each test during the final phase of the charcoal burn when very little particulate was being generated.

The laboratory which tested Furnace A was equipped with two CO monitors in the stack, one calibrated over a 0-5000 ppm range, the other over a 0-5% range. A third CO monitor, calibrated over a 0-2000 ppm range analyzed samples from the dilution tunnel. At some point during all tests on Furnace A, the stack low range instrument and the dilution tunnel CO monitor experienced CO concentrations exceeding their respective high limits. Under this condition, the instruments are effectively pegged and the readings are useless. Therefore, the Furnace A CEM data in Appendix D include the minute readings on these two monitors but no average is shown since it would be incorrect.

Two basic furnace designs (single and double pass boiler heat exchanger) were chosen for these tests to see if this impacted emissions. Table 4-4 presents the particulate and PAH emission factor data and efficiency aggregated by furnace and operating mode. Furnace A with the prototype catalyst showed markedly higher PAH emissions compared to the standard Furnace A. Furnace B showed much less variability in operation and emissions data compared to Furnace A. Whether this is due to (1) furnace design, (2) the way the fuel was loaded, and/or (3) the differences in the draft on/off cycles cannot be determined without further tests; more than likely, all three variables exerted significant influences.

Table 4-5 lists the emission results for various residential combustion devices. Furnace A test results (the next to last line in Table 4-5) are the average of the four tests (A-3 through A-6) shown in Table 4-1a. The test results from Furnace B (the last line in Table 4-5) are included as an average from all four tests (B-1 through B-4). Note that all particulate emission values have been converted to the EPA Method 5H equivalents. The levels of PAHs in the emissions are comparable to EPA-certified wood stoves. The data presented in Table 4-5 were originally generated by different researchers using a variety of sampling and analytical methodologies. A number of assumptions had to be made to "normalize" the data for comparison. Consequently, only order of magnitude differences should be considered significant. Readers are encouraged to review the reference cited in the footnote for a more thorough understanding of the data.

Figures 4-2 and 4-3 present results for the individual PAH compounds for each test on Furnaces A and B, respectively. In testing Furnace B, dual MM5G sampling trains were used and the PAH results from each train are presented separately in Figure 4-3 to illustrate the excellent precision achieved. The target compounds are listed in order in Table 2-3.

These tests were designed to provide Wisconsin DNR with a first look at emissions from residential wood burning furnaces. The differences in fuel load configuration and draft on/off cycling time make it difficult to discern any significant

difference between the results from the two furnaces. If further emissions testing is conducted, it should be designed to verify the measured results and further investigate the effects of variations in furnace design (including the draft on/off cycle time) and operating protocol.

TABLE 4-1a. SUMMARY OF TEST RESULTS - FURNACES A AND B COMPARATIVE DATA.

Furnace/Test/ Condition	Wood Load (wet lbs)	Coal Bed (lbs)	Moisture (% dry basis)	Average Burnrate (dry kg/hr)	Average Delivered Efficiency (%)	Particulate, EPA Method 5G				
						g/hr	g/kg of dry fuel	mg/Btu output	mg/MJ output	mg/MJ input
Furnace A/A-3/high heat removal	87.0	21.3	23.9	5.86	38.8	143.2	24.5	3.55	3361	1305
Furnace A/A-4/high heat removal	81.2	12.0	22.1	4.11	53.4	61.0	14.8	1.56	1482	791
Furnace A/A-5/low heat removal ^a	80.5	30.0	21.8	2.42	46.4	38.5	15.9	1.93	1829	849
Furnace A/A-6/low heat removal ^a	83.0	18.5	20.4	2.81	42.4	48.6	17.3	2.30	2177	924
Furnace B/B-1/high heat removal	133.0	29.5	23.7	3.36	50.5	36.5	10.8	1.21	1145	579
Furnace B/B-2/high heat removal	136.9	29.5	23.7	2.84	57.1	37.6	13.3	1.31	1238	707
Furnace B/B-3/low heat removal	125.3	28.0	24.7	1.51	55.4	14.3	9.5	0.96	911	505
Furnace B/B-4/low heat removal	139.5	28.0	23.6	1.68	55.1	15.5	9.2	0.94	892	491

a. Weigh scale data suspect; per hour data therefore suspect. Per kg and per heat unit data not as likely to have been affected.

TABLE 4-1b. SUMMARY OF TEST RESULTS - FURNACE A SCOPING AND PROTOTYPE CATALYST DATA.

Furnace/Test/ Condition	Wood Load (wet lbs)	Coal Bed (lbs)	Moisture (% dry basis)	Average Burnrate (dry kg/hr)	Average Delivered Efficiency (%)	Particulate, EPA Method 5G				
						g/hr	g/kg of dry fuel	mg/Btu output	mg/MJ output	mg/MJ input
Furnace A/scoping test A-1/high heat removal	82.5	NA ^a	29.0	4.14	58.9	35.1	8.5	0.81	767	452
Furnace A/scoping test A-2/ high heat removal	83.5	NA	25.1	3.95	58.2	49.9	12.6	1.22	1158	674
Furnace A/with catalyst test A-7/ high heat removal ^b	84.0	NA	21.7	4.73	47.6	53.8	11.4	1.35	1276	583
Furnace A/with catalyst test A-8/ low heat removal ^b	87.5	NA	18.9	2.49	54.4	37.8	15.2	1.58	1492	812

a. Data not available for these tests.

b. Weigh scale data suspect; per hour data therefore suspect. Per kg and per heat unit data not as likely to have been affected.

TABLE 4-2a. ORGANIC EMISSIONS SUMMARY - FURNACES A AND B COMPARATIVE DATA.

Furnace/Test/ Condition	Gravimetric Analysis		Total Chromatographable Organics		Polycyclic Aromatic Hydrocarbons	
	g/h	mg/MJ in	g/h	mg/MJ in	g/h	mg/MJ in
Furnace A/A-3/high heat removal	90.5	823	3.75	34.2	2.80	25.5
Furnace A/A-4/high heat removal	42.0	546	2.84	36.8	0.890	11.6
Furnace A/A-5/low heat removal ^a	27.1	597	8.31	183	0.594	13.1
Furnace A/A-6/low heat removal ^a	33.3	632	4.53	85.9	0.641	12.2
Furnace B/B-1/high heat removal	23.2	370	3.83	61.0	1.09	17.5
Furnace B/B-2/high heat removal	21.6	407	5.40	102	0.893	16.8
Furnace B/B-3/low heat removal	9.41	329	3.00	105	0.356	12.5
Furnace B/B-4/low heat removal	10.0	319	2.33	74.1	0.557	17.7

- a. Weigh scale data suspect; per hour data therefore suspect. Per heat unit data not as likely to have been affected.

TABLE 4-2b. ORGANIC EMISSIONS SUMMARY - FURNACE A SCOPING AND PROTOTYPE CATALYST DATA.

Furnace/Test/ Condition	Gravimetric Analysis		Total Chromatographable Organics		Polycyclic Aromatic Hydrocarbons	
	g/h	mg/MJ in	g/h	mg/MJ in	g/h	mg/MJ in
Furnace A/scoping test A-1/high heat removal	24.9	321	1.57	20.3	0.543	7.00
Furnace A/scoping test A-2/high heat removal	28.1	380	5.93	80.1	0.435	5.88
Furnace Awith catalyst A-7/ high heat removal ^a	20.7	234	26.7	301	2.58	29.1
Furnace A/with catalyst A-8/ low heat removal ^a	54.6	1170	42.8	917	2.68	57.4

- a. Weigh scale data suspect; per hour data therefore suspect. Per heat unit data not as likely to have been affected.

TABLE 4-3a. GAS CONCENTRATIONS - FURNACES A AND B COMPARATIVE DATA.

Furnace/Test/Condition	O ₂ %	CO ₂ %	CO %	THC ppm
Furnace A/A-3/high heat removal	9.70	10.42	2.44	Na ^a
Furnace A/A-4/high heat removal	9.55	10.30	1.79	Na
Furnace A/A-5/low heat removal	11.01	8.82	1.46	Na
Furnace A/A-6/low heat removal	9.92	9.61	1.75	Na
Furnace B/B-1/high heat removal	15.76	4.01	0.93	Na
Furnace B/B-2/high heat removal	16.09	3.71	0.78	Na
Furnace B/B-3/low heat removal	15.40	4.68	1.27	Na
Furnace B/B-4/low heat removal	15.38	4.63	1.10	Na

a. Hydrocarbon analyzer not available for these tests.

TABLE 4-3b. GAS CONCENTRATIONS - FURNACE A SCOPING AND PROTOTYPE CATALYST DATA.

Furnace/Test/Condition	O ₂ %	CO ₂ %	CO %	THC ppm
Furnace A/scoping test A-1/high heat removal	14.27	6.38	1.15	1057
Furnace A/scoping test A-2/high heat removal	15.59	5.16	0.62	1640
Furnace A/with catalyst A-7/high heat removal	11.08	9.39	1.37	2533
Furnace A/with catalyst A-8/low heat removal	13.52	7.32	0.95	1358

TABLE 4-4. COMPARATIVE DATA AGGREGATED BY OPERATING MODE AND FURNACE [RANGE IN ()].

Operating Mode	Furnace		Parameter
	A	B	
High Heat removal	19.6 (14.8-24.5) 0.347(0.216-0.478) 45.6 (38.8-53.4)	12.0 (10.8-13.3) 0.319 (0.315-0.324) 53.8 (50.5-57.1)	M5G Particulates, g/kg PAH, g/kg Delivered Efficiency, %
Low Heat removal	16.6 (15.9-17.3) 0.236 (0.228-0.245) 44.4 (42.4-46.4)	9.35 (9.2-9.5) 0.283 (0.235-0.332) 55.2 (55.1-55.4)	M5G Particulates, g/kg PAH, g/kg Delivered Efficiency, %

TABLE 4-5. OVERALL COMPARISON OF RESIDENTIAL WOOD, OIL, AND GAS COMBUSTION EMISSIONS^a

Combustion Device	M5H Particulate, mg/MJ input	PAHs, mg/MJ input	Mutagenicity, krev/MJ input ^b
Natural gas furnace			
Conventional	0.44	0.000124	0.007 ^c
High Efficiency	0.43	0.000028	ND ^{c,d}
Oil Furnace			
Retention head	3.2	-- ^e	6
Conventional	15.1	--	20
Conventional wood stove	786	40	600
Certified wood stove			
Non-catalytic	383	28	100
Catalytic	425	24	--
Pellet (certified)	110	0.082	--
Pellet (exempt)	176	0.014	--
Fireplace	907	41	--
Wood furnace			
Cordwood-Swedish lab tests			
Intermittent firing	1862	--	
Continuous firing	182	15.3	148 ^f
Chips (dry)	45.3	<0.02	0.48 ^f
<i>U.S. EPA lab tests (this report)</i>			
<i>Furnace A^g</i>	<i>1048</i>	<i>15.6</i>	--
<i>Furnace B</i>	<i>681</i>	<i>16.1</i>	--

a = All data except that in *italics* taken from: McCrillis, R.C., "Review and Analysis of Emissions Data for Residential Wood-Fired Central Furnaces," In Proceedings of the 88th Annual Meeting of the AWMA, Air & Waste Management Association, San Antonio, TX, June 1995, Paper No. 95-RP137.04.

b = Microsuspension assay, TA98+S9 unless otherwise noted.

c = Ames plate incorporation assay, TA98+S9.

d = ND means not detected.
e = No data available for this parameter.
f = Ames plate incorporation assay, TA100+S9.
g = Only includes comparison data.

Figure 4-2.

Idempotent

Figure 4-3.

Idempotent

SECTION 5 - CONCLUSIONS

There were several data quality problems with tests of Furnace A, all of which, although significant, are thought to be small enough to not bias the results for Furnace A sufficiently to cause an order of magnitude error. Tests of Furnace B had no reported data quality problems. All tests of Furnace B particulate matter emissions were in the range of 36.5 to 37.6 g/hr (high heat removal rate - tests B-1 and B-2) and 14.3 to 15.5 g/hr (low heat removal rate - tests B-3 and B-4) as shown in Table 4-1a. Particulate matter emissions from Furnace A appear consistently higher but, within the limits of these tests, experimental error, and considering the testing problems previously discussed that may have compromised the data quality for Furnace A, a direct comparison of Furnace A and Furnace B emissions is without adequate foundation and therefore is not meaningful. However, from inspection of Table 4-5, it is evident that all wood-burning home heating combustion equipment, including wood stoves, boilers, and fireplaces, has much higher particulate matter emissions than gas-fired or oil-fired home heating furnaces.

Appendix A - Thermocouple Calibration Data

FURNACE A THERMOCOUPLE CALIBRATIONS

DATE: July 10, 1995
 NAME: Joseph Valenti and Russell Logan
 TEST: Emissions from wood-fired residential heating furnace

DATA ACQUISITION	BOILING WATER °F	ICE WATER °F	AMBIENT °F	% DIFFERENCE
Fire Box	211.4	32.4	68.3	0.56
Stove Exit	212.6	32.4	68.3	0.11
Stack	212.8	32.4	68.0	0.22
Dilution	211.7	32.4	68.3	0.39
Ambient	212.6	32.4	69.1	0.11
Water In	210.7	32.4	67.4	0.94
Water Out	210.7	32.4	68.0	0.94

METER BOX

Dilution	213	31	67	1.11
Filter	213	32	68	0.56
Inlet	211	32	68	0.56
Condenser	213	31	68	1.11
Temp Out	212	32	67	0.00

FURNACE B THERMOCOUPLE CALIBRATIONS

DATE: April 13,1995

TEST: Emissions from wood-fired residential heating furnace

Thermocouple Number	BOILING WATER °F	ICE WATER °F	% DIFFERENCE
1-Flue Gas	211	32	0.56
2-Room Temperature	211	32	0.56
3-Dry Bulb-Tunnel	211	32	0.56
4-Wet Bulb-Tunnel	211	32	0.56
5-Unit Top	211	32	0.56
6-Unit Back	211	32	0.56
7-Unit Right Side	211	32	0.56
8-Unit Left Side	211	32	0.56
9-Unit Bottom	211	32	0.56
10-Catalyst Downstream	211	32	0.56
11-Catalyst Center	211	32	0.56
12-(not used)	211	32	0.56
13-(not used)	211	32	0.56
14-(not used)	211	32	0.56
15-(not used)	211	32	0.56
16-(not used)	211	32	0.56
17-DGM in	211	32	0.56
18-DGM out	211	32	0.56
19-Filter	211	32	0.56
20-DGM in	211	32	0.56
21-DGM out	211	32	0.56
22-Filter (2)	211	32	0.56

Appendix B - CEM Calibration Data

FURNACE A CEM CALIBRATIONS

DATE: July 10, 1995
 NAME: Joseph Valenti and Russell Logan

TEST: Emissions from wood-fired residential heating furnace

CEM ANALYZER	ZERO	SPAN	ACTUAL	% CALIBRATION ERROR
CO high	0 ppm	39307 ppm	39400 ppm	0.186
CO low	0 ppm	3760 ppm	3760 ppm	0
CO dilution	0 ppm	2004 ppm	2060 ppm	2.8
O2	0.06 %	9.61 %	9.7 %	0.36
CO2	0.02 %	6.4 %	6.0 %	1.48

SYSTEM BIAS	ZERO	SPAN	ACTUAL	% SYSTEM BIAS
CO high	0 ppm	10132 ppm	10060 ppm	0.144
CO low	0 ppm	2093 ppm	2060 ppm	0.66
CO dilution	0 ppm	467 ppm	465 ppm	0.1
O2	0.04 %	15.01 %	15 %	0.04
CO2	0.02 %	15 %	15 %	0

AMBIENT	
CO high	61 ppm
CO low	0 ppm
CO dilution	2 ppm
O2	20.66 %
CO2	0.05 %

FURNACE B CEM CALIBRATIONS

DATE: June 28,1995

TEST: Emissions from wood-fired residential heating furnace

CEM ANALYZER	ZERO	SPAN	ACTUAL	% CALIBRATION ERROR
CO	0 %	9.99 %	9.99 %	0
O2	0 %	24.5 %	24.50 %	0
CO2	0 %	20.93 %	20.93 %	0

CAL GAS #1	ACTUAL	SHOULD BE	% SYSTEM BIAS
CO	0.93 %	0.987 %	5.78
O2	10.2 %	10.05 %	1.49
CO2	9.43 %	9.99 %	5.61

CAL GAS #2	ACTUAL	SHOULD BE	% SYSTEM BIAS
CO	2.27 %	2.36 %	3.81
O2	5.69 %	5.55 %	2.52
CO2	5.58 %	5.88 %	5.10

CAL GAS #3	ACTUAL	SHOULD BE	% SYSTEM BIAS
CO	7.68 %	7.94 %	3.27
O2	17.58 %	17.53 %	0.29
CO2	19.05 %	19.89 %	4.22

AVERAGE		% SYSTEM BIAS
CO		4.29
O2		1.43
CO2		4.98

Appendix C - Water Meter Calibration Data

Furnace A water meter flow calibration.

DATE: July 10, 1995

NAME: Joseph Valenti and Russell Logan

TEST: Emissions from wood-fired residential heating furnace

water density: at 68°F= 8.3317 lb/gal, at 150°F = 8.1818 lb/gal

water temp. during calibration = 150°F

	ROTAMETER	FLOW	FLOW	%	Calibration
TRIAL	reading, gpm	lb/min meas.	gpm calc.	difference	factor
1	4.60	39.50	4.83	4.72	1.04951
2	4.50	39.56	4.84	6.93	1.07447
3	4.30	37.68	4.61	6.63	1.07101
4	4.50	38.60	4.72	4.62	1.04839
5	6.20	51.24	6.26	1.00	1.01010
6	6.10	51.33	6.27	2.77	1.02847
7	6.20	51.40	6.28	1.31	1.01326
				Average	1.04217

Furnace B water meter flow calibration.

Test laboratory water meter calibration.

Water temperature not recorded.

Calculated Gallons	Observed Weight	Assumed Density	Observed Gallons	Calibrati Factor
18.29	152.3	8.326955	20.31	0.90032
29.67	247.1	8.328278	32.59	0.91032
30.52	254.2	8.328965	33.54	0.90995
32.13	267.6	8.328665	35.46	0.90606
			Average	0.90666

Appendix D - CEM Run Data

Appendix E - Method 5G Meter Box Data

Appendix F - Method 5G Summary Data

Appendix G - Organic Analyses Data Sheets.