New York State Energy Research and Development Authority

Environmental, Energy Market, and Health Characterization of Wood-Fired Hydronic Heater Technologies

Final Report

June 2012

No. 12-15

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ENVIRONMENTAL, ENERGY MARKET, AND HEALTH CHARACTERIZATION OF WOOD-FIRED HYDRONIC HEATER TECHNOLOGIES

Final Report

Prepared for the

NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Energy. Innovation. Solutions.

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ABSTRACT

This report describes a comprehensive emission, lifetime cost, energy market, and health characterization program on four wood-fired hydronic heaters (HHs) that span common to advanced technologies. The HHs were variously tested with two species of split logs, hardwood with refuse, and hardwood pellets for their performance in meeting the daily heat load requirements of a typical winter day in upstate New York. An extensive array of pollutants was sampled in batch and real time, including particulate matter (PM), carbon monoxide (CO), volatile organics, semivolatile organics, and greenhouse gases for determination of emission factors. Emissions were expressed in terms of energy input, energy output, and on a temporal basis as available. Significant differences were observed in energy and emission performance from the four units. Tests using a cone calorimeter showed that its emissions were predictive of the full scale units under fully ventilated and air starved conditions. Modeling regional residential space heating scenarios showed that the wood heat market share determined the total PM emissions for the residential sector, and that relatively modest changes in the wood heat market can have substantial impacts on residential and total PM emissions. The rate of turnover and retirement of older, highly emitting units to more efficient, lower-emitting units is critical to avoiding what could be substantial increases in emissions related to residential wood heat over the next 5-10 years. In an assessment of lifetime costs of HHs, fuel costs were shown to have the potential to dominate purchase and installation costs; as a result, market competitiveness is driven by efficiency and access to low cost wood fuel. Emissions toxicity results from animal exposure experiments were inconclusive, as extreme dilution of the combustion gas was necessary to avoid immediate acute toxic effects from the CO that at times exceeded 10,000 parts per million (ppm).

KEY WORDS

Outdoor wood-fired HHs, outdoor wood boilers, pellet burners, heat storage, gasification burners, emissions, particulate matter, energy, levoglucosan, methoxyphenols, polycyclic aromatic hydrocarbons, cone calorimeter, biomass

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ACRONYMS AND ABBREVIATIONS

AAALAC	Association for Assessment and Accreditation of Laboratory Animal Care
AEO	Annual Energy Outlook
RO	Red Oak
ANOVA	Analysis of Variance
APCS	Air Pollution Control System
APS	Aerodynamic Particle Sizer
ASTM	American Society for Testing and Materials
BAL	Bronchoalveolar Lavage
B(a)P	Benzo(a)pyrene
BC	Black Carbon
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
BTU	British Thermal Unit
CEM	Continuous Emission Monitor(Ing
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAS	Data Acquisition System
DL	Detection Limit
dscm	Dry standard cubic meter
EC	Elemental Carbon
EIA	U.S. Energy Information Administration
ELISA	Enzyme-Linked Immunosorbent Assay
ELPI	Electrical Low Pressure Impactor
EMPC	Estimated Maximum Possible Concentration
EPA	U.S. Environmental Protection Agency
EPC	Electronically Programmable Control
ETSAP	Energy Technology Systems Analysis Program
FBS	Fetal Bovine Serum
FE	Total Iron
FGCS	Flue-Gas Cleaning System
FIA	Flow Injection Analysis
FID	Flame Ionization Detector
FIGRA	Fire Growth Rate
GC	Gas Chromatograph(y)
GC/MS	Gas Chromatograph/Mass Spectrometer Gas Chromatography/Mass Spectrometry

GGT	Gamma Glutamyl Transpeptidase
HBSS	Hank’s Balanced Salt Solution
HC	Hydrocarbons
HEPA	High Efficiency Particulate Air
HFID	Heated Flame Ionization Detector
HH	Hydronic Heater
HHV	Higher Heating Value
HIB	40% Hexane, 40% Benzene And 20% Isopropanol
HRGC/HRMS	High Resolution Gas Chromatography/High Resolution Mass Spectrometry
HRR	Heat Release Rate
HWFC	Hot Water Fan Coil
LCOE	Levelized Cost of Energy
LD-1	Lactate Dehydrogenase Isoenzymes
LDH	Lactate Dehydrogenase
LED	Light Emitting Diode
LG	Levoglucosan
LOD	Loss On Drying
LPG	Liquid Petroleum Gas
MAHRE	Maximum Average Heat Rate Emission
MARKAL	MARKet ALlocation
MDL	Method Detection Limit
MIA	Microalbumin
MIP-2	Macrophage Inflammatory Protein -2
MS	Mass Spectrometer
	Mass Spectrometry
Mt	Million Dry Tons
N_2	Nitrogen
N_2O	Nitrous Oxide
NA	Not Analyzed
NAAQS	National Ambient Air Quality Standards
NAG	N-acetyl-β-glucosaminidase
NC	Not Calculated
ND	Non Detect
NDIR	Non-Dispersive Infrared
NEI	National Emissions Inventory
NEMS	National Energy Modeling System(s)
NESCAUM	Northeast States for Coordinated Air Use Management

NH3	Ammonia
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standard and Technology
NM	Not Measured
NMHC	Nonmethane Hydrocarbon(s)
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxide
NPV	Net Present Value
NSPS	New Source Performance Standard(s)
NREL	National Renewable Energy Laboratory
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standards
NTBA	Not To Be Analyzed
NYSERDA	New York State Energy Research and Development Authority
O_2	Oxygen
OAG	Office of the Attorney General
OAQPS	EPA Office of Air Quality Planning and Standards
OC	Organic Carbon
OC/EC	Organic Carbon/Elemental Carbon
OC/TC	Organic Carbon/Total Carbon
ORD	EPA Office of Research and Development
OSHA	Occupational Safety and Health Administration
HH(s)	Outdoor Wood-Fired Boiler(s)
PAH(s)	Polycyclic Aromatic Hydrocarbon(S)
PBT	Persistent Bio-Accumulative Toxic
PC	Process Control
PCDD/F(s)	Polychlorinated Dibenzodioxin(s)/Dibenzofuran(s)
PEL	Permissible Exposure Level
Penh	Enhanced Pause
PID	Proportional Integral Derivative
PJ	Petajoules
PM	Particulate Matter
PM_{10}	Particulate Matter less than or equal to 10 Micrometers in Diameter
$PM_{2.5}$	Particulate Matter less than or equal to 2.5 Micrometers in Diameter
POC	Pollutants of Concern
ppm	Parts Per Million

PQL	Practical Quantification Limit
PSD	Particle Size Distribution
PTFE	Polytetrafluoroethylene
PUF	Polyurethane Foam
QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control
QC	Quality Control
RAPIDS	Regional Air Pollution Inventory Development System
RDV	Relative Deviation
RECS	Residential Energy Consumption Survey
REMPI	Resonance Enhanced Multiphoton Ionization
REMPI-TOFMS	Resonance Enhanced Multiphoton Ionization - Time-Of-Flight Mass Spectrometry
RPD	Relative Percent Deviation
RTP	Research Triangle Park
RWC	Residential Wood Combustion (Consumption)
scfm	Standard Cubic Feet Per Minute
SMPS	Scanning Mobility Particle Sizer
SO_2	Sulfur Dioxide
STDV	Standard Deviation
SVOC(s)	Semivolatile Organic Compound(S)
TC	Total Carbon
TE	Thermal Extraction
TEOM	Tapered Element Oscillating Microbalance
TEQ	Toxic Equivalent
TGA	Thermogravimetric Analysis
THC	Total Hydrocarbon(S)
THR	Total Heat Release
TIC(s)	Tentatively Identified Compound(s)
Tig	Time To Ignition
TK-HSD	Tukey-Kramer Honestly Significant Difference
TNF	Tumor Necrosis Factor
TOFMS	Time-Of-Flight Mass Spectrometry
UDRI	University of Dayton Research Institute
UIBC	Unsaturated Iron Binding Capacity
USDA	U.S. Department of Agriculture
UV	Ultraviolet

VOC(s)	Volatile Organic Compound(S)
WD	Wavelength Dispersive
WP	White Pine
XRF	X-Ray Fluorescence

EXECUTIVE SUMMARY

Wood-fired hydronic heaters (HHs) have proliferated in Northern states during the last decade as oil prices have increased. Some of these units are inefficient and have resulted in numerous complaints to state air quality and health departments because of exceptionally high levels of smoke. Fine particles in wood smoke are primarily composed of organic carbon (OC) and contain numerous toxic compounds, including polycyclic aromatic hydrocarbons (PAHs). Recent reviews of the health literature indicate that wood smoke exposure likely leads to a range of adverse health effects including increases in respiratory symptoms, lung function decreases, increases in asthma symptoms, visits to emergency rooms, and hospitalizations (Naeher et al., 2007; Schreiber and Chinery, 2008). High-efficiency HH units are relatively common in Europe and now are being manufactured in the U.S. by a few companies. The combustion efficiency improvements are due in part to a two-stage combustion chamber design that results in gasification of the fuel and more complete combustion in the second chamber. Despite the high level of environmental concern due to emissions from the older units and the more promising performance of the newer units, little data has been collected to understand emissions and potential human health risks associated with HHs.

A joint project between the U.S. Environmental Protection Agency (EPA) Office for Research and Development (ORD) and the New York State Energy Research and Development Authority (NYSERDA) addressed this data gap by testing four current and emerging technology HHs, which are also referred to as Outdoor HHs, or HHs, and Outdoor Wood-fired Boilers (OWBs). The emissions and energy-efficiency performance of four types of residential wood boiler technologies ranging from the common HH to a high-efficiency pellet heater to a unit with thermal storage were characterized. Measurements included emissions of particulate matter (PM), elemental carbon (EC), carbon monoxide (CO), PAHs, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and polychlorinated dibenzodioxins/dibenzofurans (PCDDs/Fs). This work was complemented by an energy and market impacts analysis of HHs for the State of New York. Lastly, the health effects of HH emissions were evaluated with an exposure study for pulmonary and systemic biomarkers of injury and inflammation. The results of this study are anticipated to be of value to the State of New York in its efforts to develop a high-efficiency biomass heating market of technologies with acceptable emissions performance. It is also anticipated that these results will be of value to EPA as it sets New Source Performance Standards for biomass-fired HHs.

Wood Hydronic Heater Technologies Tested

This project provides a thorough scientific evaluation of the performance of a range of wood boiler technologies. The units tested included a commonly-used Conventional Single Stage HH, a newer Three Stage HH model, a European Two Stage Pellet Burner, and a U.S. Two Stage Downdraft Burner (see Table 1). Each unit was evaluated and tested on the same 24-hour wintertime daily “call for heat” load determined for a typical home (2500 ft^2) in Syracuse, New York.

Table 1. Outdoor Wood-Fired Hydronic Heaters (HHs) Used in this Study.

Unit Model	Conventional, Single Stage HH, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner
Unit #	**1**	**2**	**3**	**4**
Technology	Combustion	Three-stage Combustion	Staged Combustion	Two-stage: Combustion and Gasification with Heat Storage
Fuel	Wood logs	Wood logs	Wood pellets	Wood logs
Heat Capacity, output Btu/hour (kW)	NA	160,000 (46.9)[2]	137,000 (40)[3]	150,000 (44)[4]
Water Capacity gal (liters)	196 (740)	450 (1700)	43 (160)	32 (120)

[1] Not available from the manufacturer

[2] Eight hour stick wood test

[3] Partial load output, based on manufacturer's specifications

[4] Heat rate based on manufacturer claim

The conventional, Single Stage HH uses a natural draft, updraft combustion single-stage combustion process that occurs in a rectangular firebox surrounded by a high capacity water jacket (Figure 1). The hot flue gases are vented through a stainless steel, insulated chimney connected to a rear exhaust outlet. Flue gas movement is by natural convection, assisted with a fan. Heat flow is regulated by the opening and closing of a combustion damper.

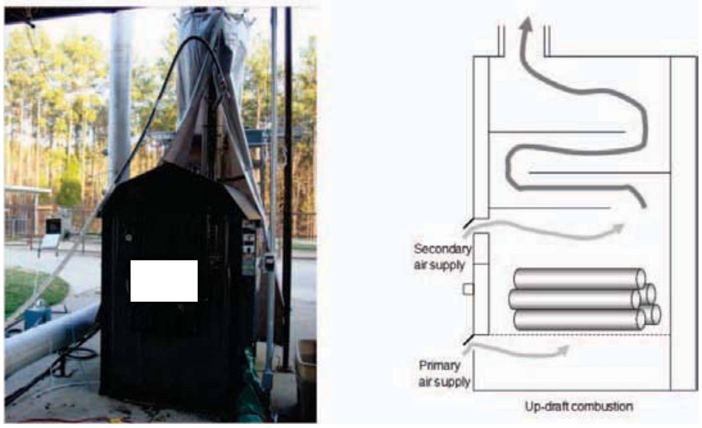


Figure 1. The Conventional, Single Stage HH and Illustration of an Up-Draft Combustion Unit.

The Three Stage HH (46.9 kW, 160,000 BTU/hour, Figure 2) uses a three-stage combustion process in which wood is gasified in the primary combustion firebox, the hot gases are forced downward and mixed with super-heated air starting the secondary combustion. Final combustion occurs in a third, high temperature reaction chamber. Like the conventional, Single Stage HH, the Three Stage HH is regulated by the opening and closing of an air damper.

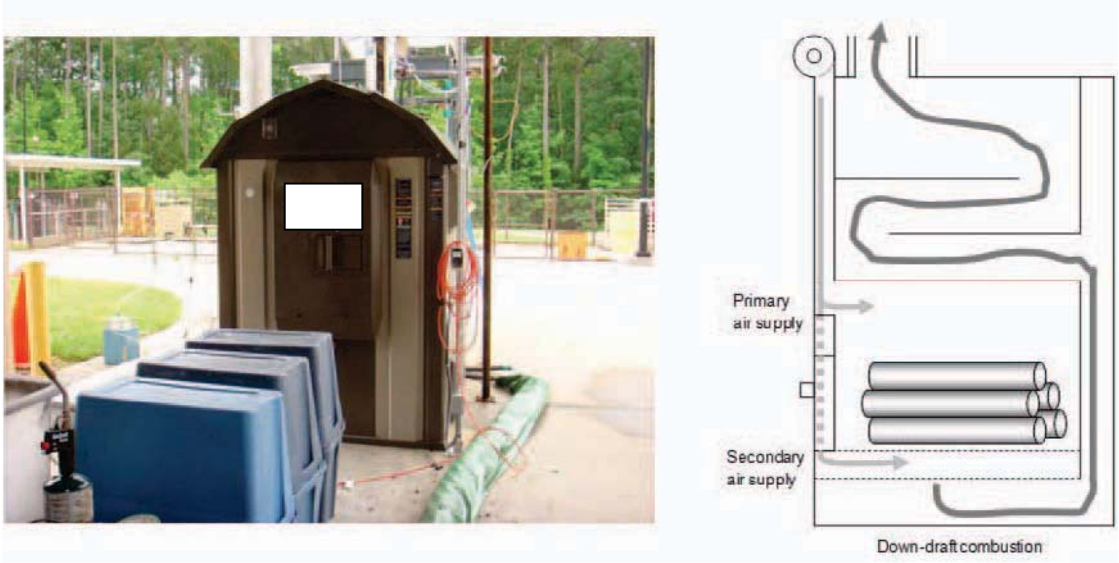
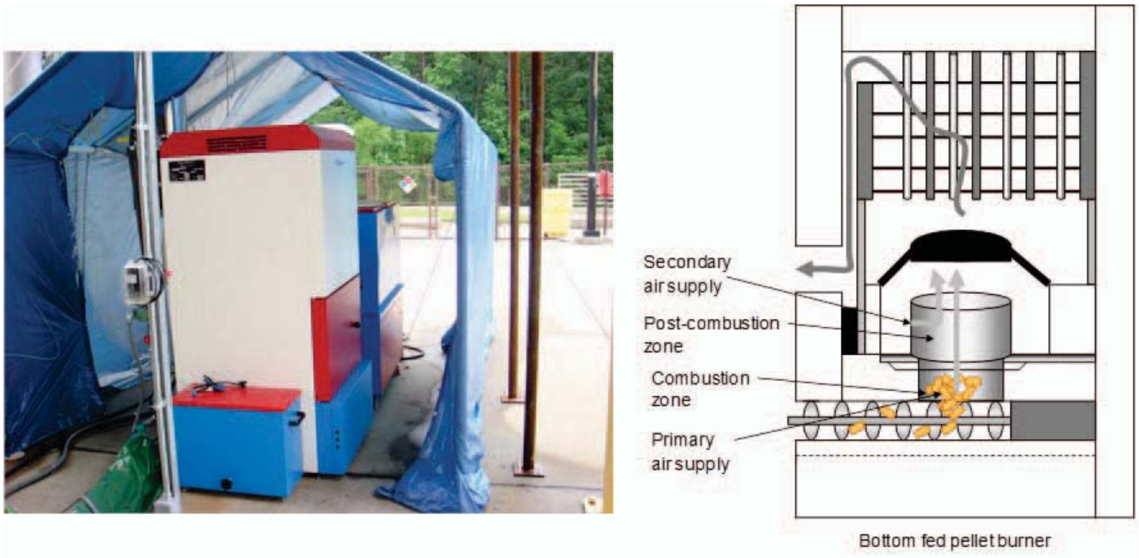


Figure 2. The Three Stage HH Unit and Illustration of a Down-Draft Combustion Unit.

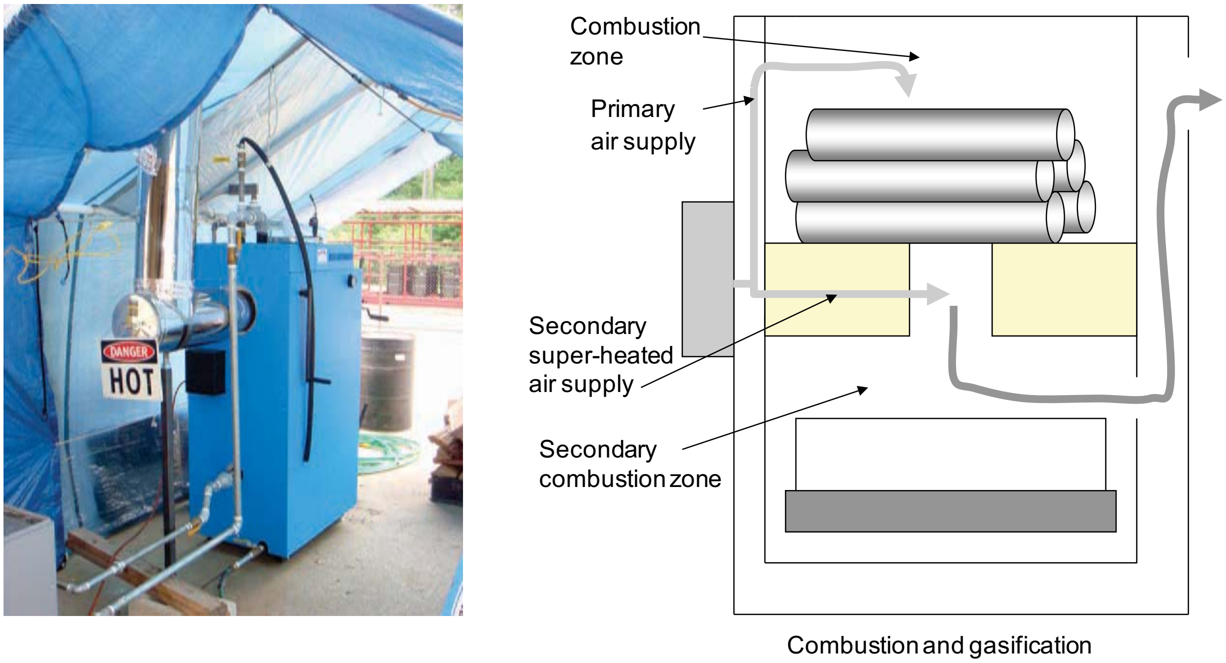
The European Pellet unit (Figure 3) is a commercially available, pellet burning HH rated at 40 kW (137,000 Btu/hour). Combustion occurs on a round burner plate where primary air is supplied. Secondary air is introduced through a ring above the burner plate. Fuel is automatically screw-conveyed from the bottom. Operation of the screw feeder was regulated by a thermostat. During normal operation, the fan modulates based on the measured oxygen level in the exhaust gas, maintaining 8-10% oxygen

The U.S. Two Stage Downdraft Burner (44 kW, 150,000 BTU/hour, Figure 4) is a two-stage heater with both gasification and combustion chambers. Air is added to the firebox continuously while the damper is open and is blown downwards through the wood logs. The gases are forced into a combustion chamber where additional super-heated air is added, resulting in a final combustion of the gases at temperatures higher than 980 °C (1800 °F).



Bottom fed pellet burner

Figure 3. The European Two Stage Pellet Burner and Illustration of a Bottom-Fed Pellet Combustion Unit.



Combustion and gasification

Figure 4. The U.S. Two-Stage, Down-draft Combustion and Gasification Unit Schematic.

FUEL LOADING AND CHARACTERIZATION

The fuel loading protocol was derived from the simulated heat-load demand profile and the type of unit and its capacity. The Conventional, Single Stage HH unit was used to compare emissions for three fuel types including seasoned red oak, unseasoned white pine, and red oak with 4.5% by weight supplementary refuse. The Three Stage HH was tested solely with seasoned red oak. A European Two Stage Pellet Burner and a split-log wood heater (U.S. Two Stage Downdraft Burner) with a simulated heat storage tank were tested under the same heat-load demand profile to characterize and compare their emission signatures. A common fuel type (red oak) was used across all units (hardwood pellets for the European unit) for comparability. The pellets are made out of sawdust from different wood processing industries and consisted of a blend of hardwood (no bark), mostly oak, with a diameter of 6 mm. The ultimate and proximate analyses of the fuels are reported in Table 2. Fuel moisture was determined using a wood moisture meter for three to four measurements on each of eight pieces of split wood chosen randomly from each charge.

Table 2. Fuel Ultimate/Proximate Analysis.

Properties	Fuel		
	Red Oak	Pine	Pellets
Ash	1.46%	0.44%	0.52%
Loss on Drying (LOD)	22.52%	9.68%	7.24%
Volatile Matter	84.23%	88.50%	84.27%
Fixed Carbon	14.31%	11.06%	14.11%
C :Carbon	48.70%	51.72%	50.10%
Cl: Chlorine	38 ppm	36 ppm	44 ppm
H: Hydrogen	5.96%	6.57%	5.86%
N: Nitrogen	<0.5%	<0.5%	<0.5%
S: Sulfur	<0.05%	<0.05%	<0.5%

"<" = below detection limit

HEATING PERFORMANCE

The heat load profile (Figure 5) that was used throughout the testing program is derived from a simulation program for heat demand (Energy-10^{TM}, National Renewable Energy Laboratory [http://www.nrel.gov/buildings/energy10.html?print]) for a 232 m^2 (2500 ft^2) home in Syracuse, New York, using an averaged hour-per-hour heat load for the first two weeks of January averaged over 25 years (Brookhaven National Laboratory). The average daily heat load for the first two weeks in January is about 827 MJ (784,000 BTU) with a maximum heat load of about 40,000 BTU/hr.

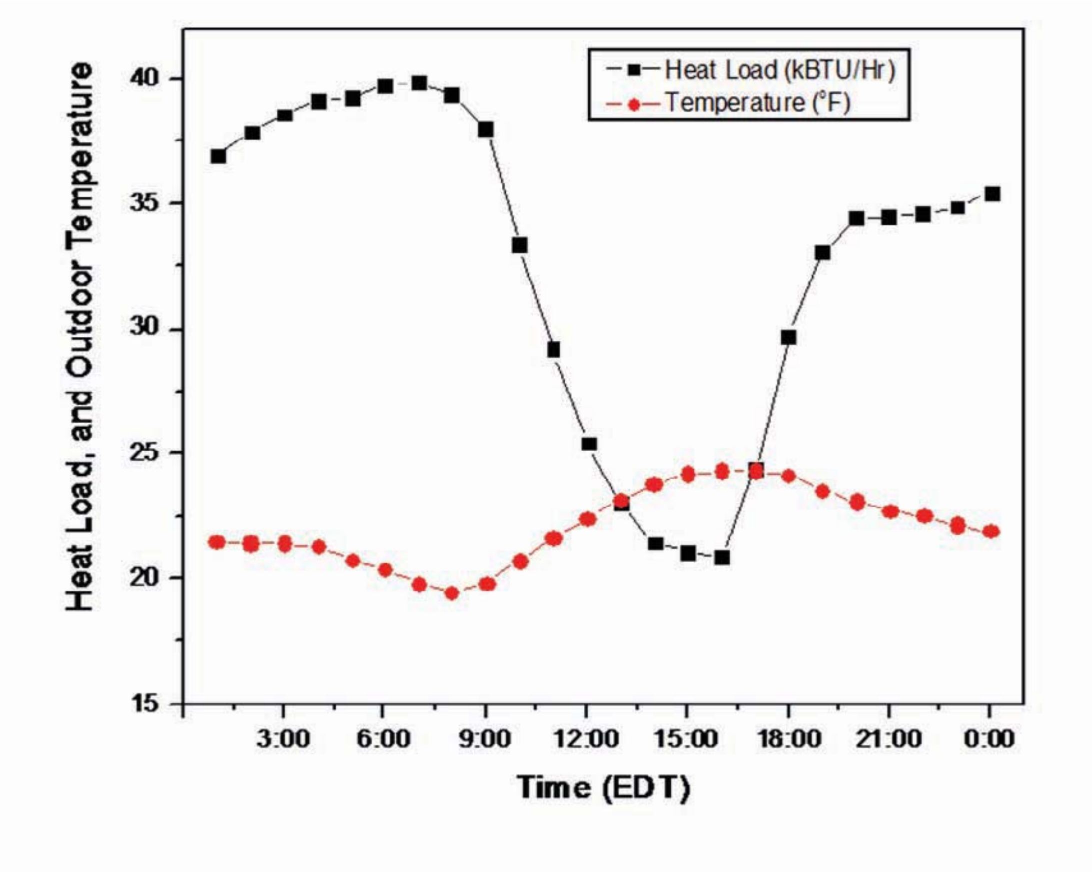


Figure 5. Syracuse, New York Area Heat Load Profile for the First Two Weeks of January.

The heat load demand was simulated by extracting the HH outlet heat with a water/water heat exchanger coupled to the building chilled water supply (Figure 6). The HH units were operated in a mode where hot water was continuously circulated through the water/water heat exchanger and the unit's water jacket. The pre-insulated piping system consists of two 25.4 mm (1 inch) oxygen barrier lines that are insulated with high density urethane insulation. The same piping system was used for all four units tested. The inlet and outlet temperatures of both the chilled water and recirculated hot water were monitored, as well as the chilled water flow rate. The heat load demand control system calculated the change between the chilled water outlet temperature and the chilled water inlet of the heat exchanger and controlled the heat removal by adjusting the chilled water flow rate through the use of a proportional valve.

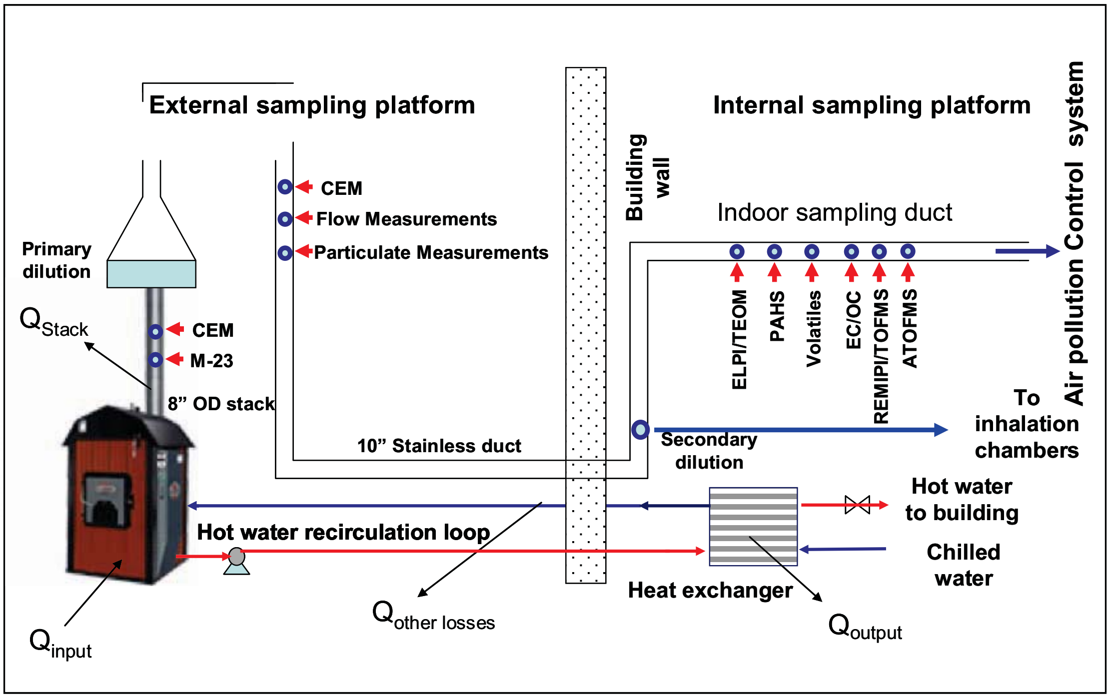


Figure 6. Test System for Wood-Fired Hydronic Heaters.

The units with cyclical damper operation to modulate their heat release resulted in considerable variation of heat transfer and concomitant emissions. When the dampers were closed, combustion became oxygen starved, resulting in incomplete combustion of the fuel and formation of pollutants. Upon damper opening and gas flow through the system, these pollutants are released, resulting in a cyclical increase in pollutant release. The modulating combustion also led to considerable nuisance odor (despite the emissions passing through the laboratory facility's additional air pollution control system (APCS) consisting of an afterburner and scrubber) and threatened to terminate the project.

A typical heat release rate for the Conventional, Single Stage HH unit is shown in Figure 7. The oscillating heat release reflects the cyclical damper opening and closing. Increased heat release is observed during all open damper periods when the fuel combustion rate is enhanced by the air supply. The frequency and duration of the damper openings is a function of the degree to which the unit is oversized for the heat load. The heat release rate is significantly higher than that required for the Syracuse winter load (about 40,000 BTU/hr). The European Pellet unit's moderate cyclical heat release (Figure 8) more closely matches the heat load demand. The U.S. Two Stage Burner unit burns continuously, storing its energy in a thermal storage tank (Figure 9).

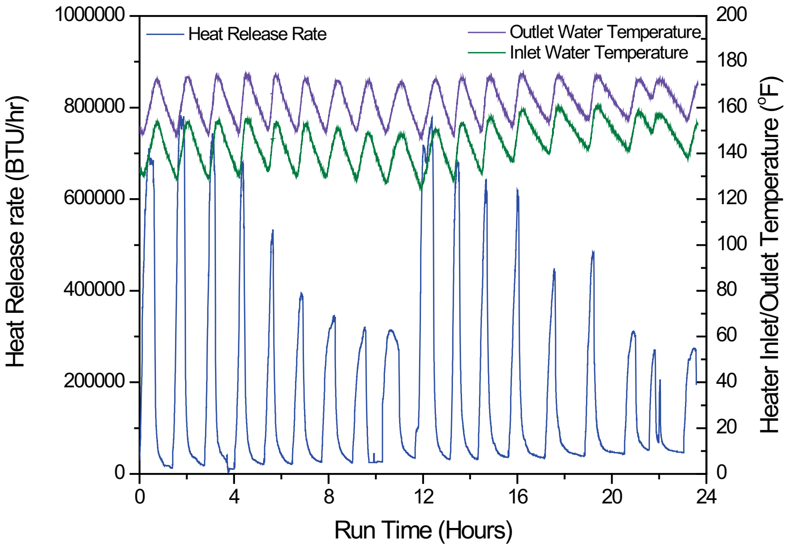


Figure 7. Heat Release Rate and System Water Temperatures for the Conventional, Single Stage HH Unit Firing Red Oak.

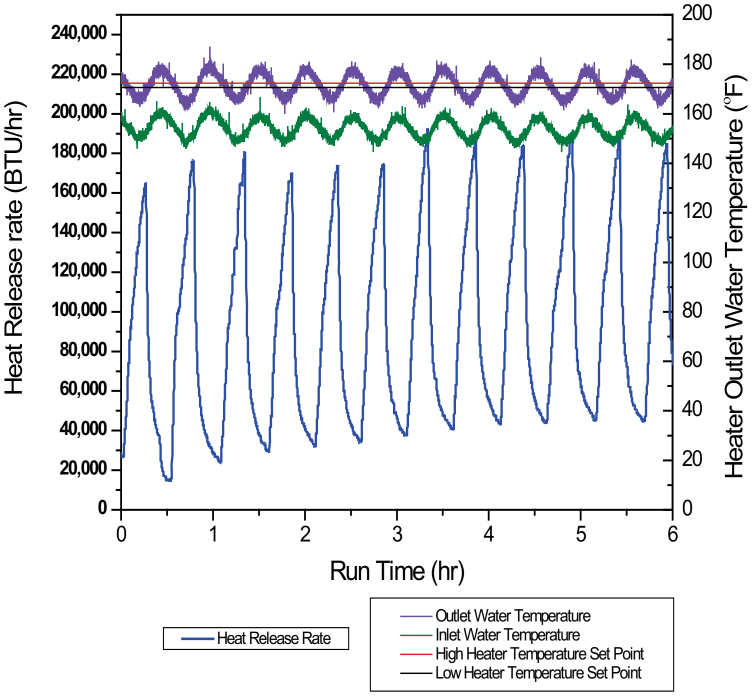


Figure 8. Heat Release Rate and System Water Temperatures for the European Two Stage Pellet Burner Unit.

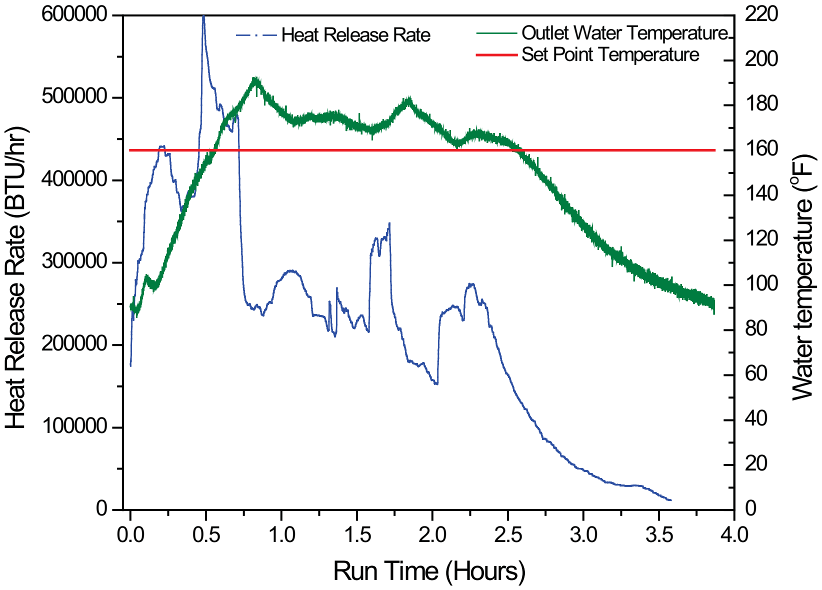


Figure 9. Heat Release Rate from the U.S. Two Stage Downdraft Burner Unit with Thermal Storage.

The performance of HH systems can be evaluated based on their ability to burn the fuel completely (combustion efficiency), the effectiveness of the heat exchanger to transfer the heat generated from the combustion process to the water (boiler efficiency), and the overall generation of useful heat through its transfer to meet the load demand (thermal efficiency). Table 3 summarizes all these efficiencies for all six unit/fuel combinations (boiler efficiency is not presented for cyclical units due to the difficulties inherent in quantifying dynamic measurements). No thermal efficiency can be calculated for the U.S. Two Stage Downdraft Burner unit because measurements of the thermal flows through the water/air heat exchanger were not recorded. The cyclical units had lower efficiencies than the pellet unit and the non-cyclical unit with heat storage. Efficiency improvements can be achieved by reducing the time spent at idle (closed damper) which can be accomplished by proper unit sizing and the use of thermal storage. As the HH's nominal output increases above that of the building's heat load, the amount of time spent at idle is increased (the damper remains closed for a longer time). The work reported here shows that in these closed damper periods energy and emissions performance decreases greatly. In the presence of an external thermal storage system, the low mass/volume ratio of the Two Stage Downdraft Boiler HH system allows it to run at maximum output under relatively steady-state conditions, improving performance. The thermal efficiencies, ranging from 22% to 44% for the conventional, three stage, and pellet systems, compare poorly with oil and natural gas fired residential systems with thermal efficiencies ranging from 86% to 92% and 79% to 90%, respectively (McDonald, 2009).

Table 3. Hydronic Heater Efficiencies.

Units	Thermal Efficiency (%)		Boiler	Combustion
Conventional HH RO	Average	22	NC	74
	STDV	5		3.0
Conventional HH RO + Ref	Average	31	NC	87
	STDV	2.2		3.4
Conventional HH WP	Average	29	NC	82
	STDV	1.8		3.2
Three Stage HH/RO	Average	30	NC	86
	STDV	3.2		1.8
European Pellet/pellets	Average	44	86	98
	STDV	4.1	3.5	0.16
U.S. Downdraft RO	Average	IM	83	90
	STDV		0.71	0.79

NC = Not calculated. IM = Insufficient measurements taken for this calculation

The unit efficiencies can also be viewed through the amount of fuel required to satisfy a given heat load. Figure 10 shows that amount of fuel mass required to supply the 24 hour Syracuse heat load. The European Pellet unit requires significantly less wood mass to meet this demand (the U.S. Two Stage Downdraft unit's wood mass could not be calculated because measurements of the thermal flows through the water/air heat exchanger were not recorded.

EMISSIONS

Carbon Monoxide

A full emissions characterization for each heater unit consisted of, at a minimum, PM (time integrated and real time), total hydrocarbons (THC), PAHs, organic marker compounds, organic carbon/elemental carbon (OC/EC), CO, CO_2, CH_4, N_2O, and PCDD/F. The results of this study are compared with those of EPA's Office of Air Quality Planning and Standards (OAQPS) ongoing validation tests of EPA Method 28 for HH PM and energy efficiency (http://www.vtwoodsmoke.org/pdf/Method28.pdf), particularly for the seasoned red oak fuel since this is the fuel specified in Method 23 OWHH.

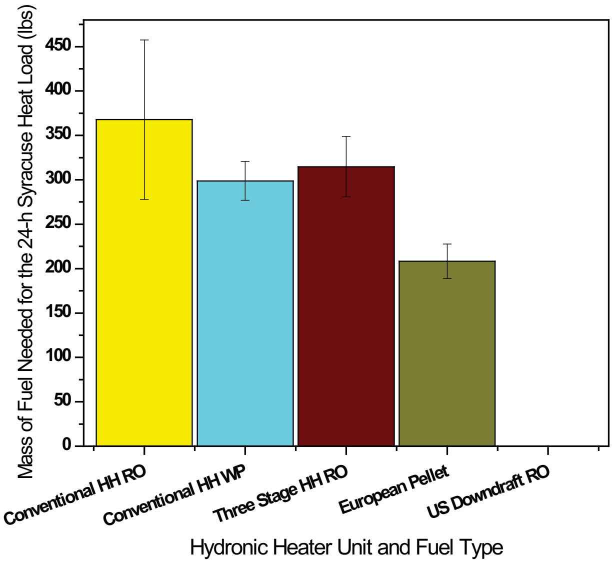


Figure 10. Mass of Fuel Needed for a 24 Hour Syracuse Heat Load. Data are missing for U.S. Downdraft RO.

Temporal emission profiles were more a function of the elapsed time from the last fuel charging than that of the heat load on the unit (Figure 11). The emissions of CH_4, THC, and CO (Figure 12) are consistent with the cyclic nature of the damper openings. These emissions are associated with the damper cycle creating alternately poor and good combustion conditions. Units that cycle the damper opening to regulate the heat production have much higher emissions than the pellet burner and the non-cycling U.S. Downdraft Unit unit. Predictably, lower CO emission factors result from those units that minimize pollutant formation.

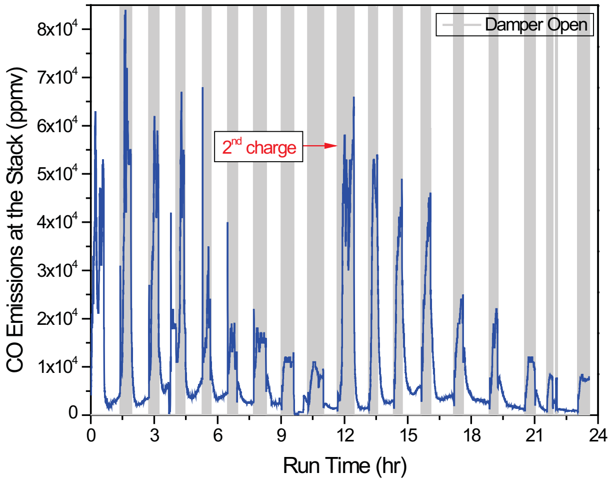


Figure 11. CO Stack Concentration as a Function of Damper Opening and Time of Fuel Charging, Conventional, Single Stage HH unit.

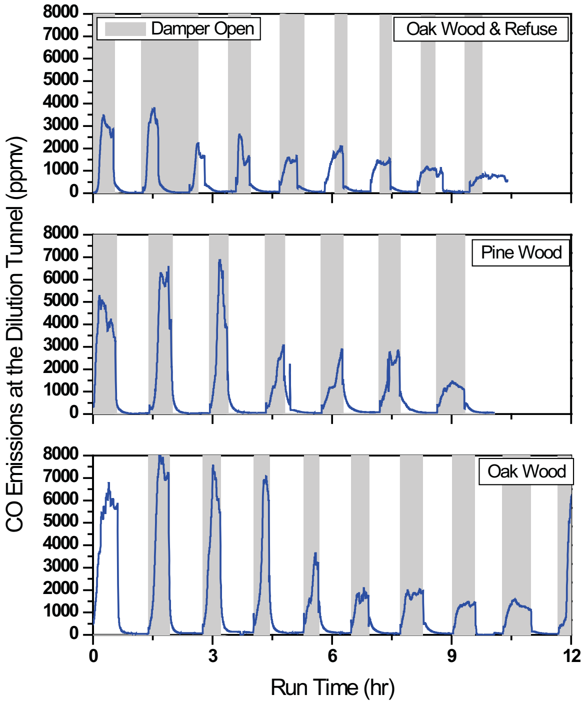


Figure 12. Typical CO Concentration Traces from the Dilution Tunnel for the Conventional, Single Stage HH Unit.

CO emission factors (Figure 13) are complementary to CO_2 emission factors (not shown). The European Pellet Boiler unit has the lowest value at 0.60 g/MJ (1.39 lb/MMBtu). A value of 7.2 g/MJ (16.6 lb/MMBtu) was obtained for the U.S. Downdraft Unit heater while the Conventional, Single Stage HH (average of the three fuels) had the highest value at about 8.9 g/MJ (21 lb/MMBtu) $_{\text{input.}}$ The European Pellet Burner unit is predictably lower in CO emissions as combustion is comparatively steady throughout its 6-hour burn, whereas the other units have variation in their combustion rate. These CO emission factors are orders of magnitude higher than are typically observed in conventional energy sources such as residential oil-fired heaters (< 0.1 lbs CO/MMBtu input, Krajewski et al., 1990).

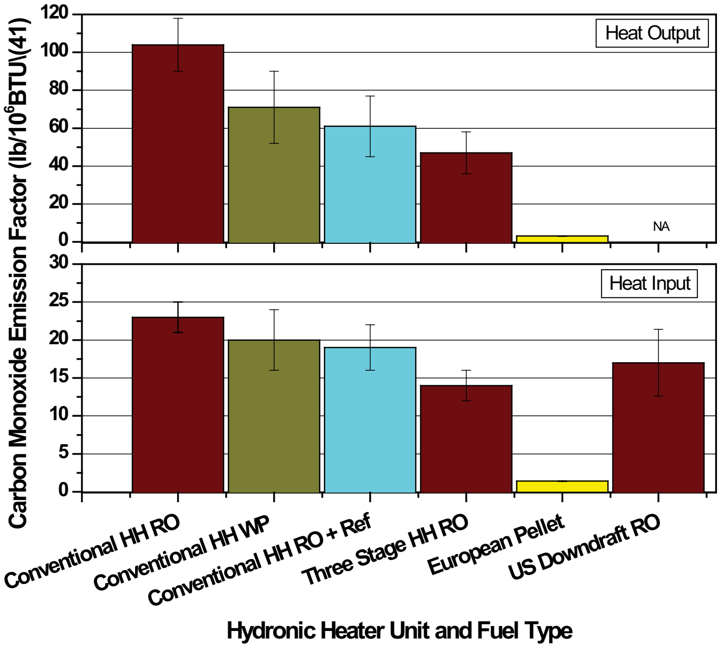


Figure 13. Carbon Monoxide Emission Factors. RO = red oak, WP = white pine, Ref = refuse.

Fine Particle Emissions

Testing showed a wide range of PM emissions depending on both unit and fuel types. Figure 14 compares average daily PM emissions from the four units and different fuels for a typical Syracuse, New York home on a January heating day. These data are analogous to the emissions based on thermal output as the different units attempt to match their thermal outputs to the Syracuse load demand. The Conventional, Single Stage HH burning white pine produced the highest total daily PM emissions [6.3 kg (14 lbs)] and the European Pellet Burner heater with red oak reported the lowest [0.036 kg (0.08 lb)]. Emissions for the Three Stage HH and U.S. Downdraft Unit units were comparable at 0.69 and 0.62 kg/day (1.51 and 1.37 lbs/day), respectively. Again, white pine combustion in the Conventional, Single Stage HH unit produced daily PM emissions that were 40% greater than red oak and 70% greater than red oak plus refuse.

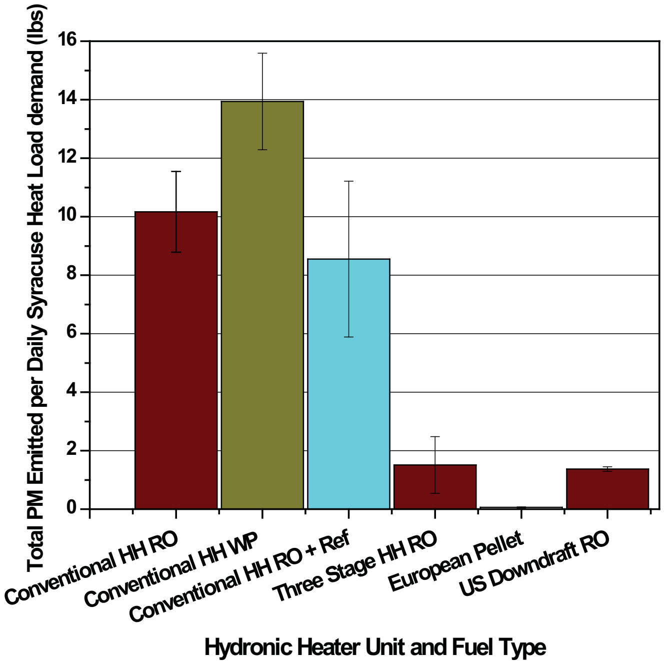


Figure 14. PM Generated per Syracuse Day for All Six Unit/Fuel Combinations. RO = red oak, WP = white pine, Ref = refuse.

For the Conventional, Single Stage HH, the PM emissions on a thermal input basis (see Figure 15) for the three fuels vary between approximately 2.9 and 5.1 lb/MMBTU with the emissions from the red oak and the red oak plus refuse being generally similar (2.9-3.0 lb/MMBTU). The PM emissions almost double, however, when white pine is burned in the same unit. Average emissions on a thermal energy input basis ranged from 0.54 lb/MMBTU for the Three Stage HH, 0.39 lb/MMBTU for the U.S. Downdraft Unit gasifier, and 0.037 lb/10^6 BTU for the European Pellet Burner. Lower PM emissions from these three units reflect the more advanced technologies and generally higher combustion efficiencies compared to the older Conventional, Single Stage HH unit. The Three Stage HH employs a secondary combustion chamber and larger thermal mass. The European Pellet Burner pellet unit uses a consistent uniform fuel and a more steady-state, but still cyclic, fuel feeding approach. The lower emissions from the U.S. Downdraft Unit are likely related to both its two-stage gasifier/combustor and its thermal storage design, where batches of fuel are burned during short, highly intensive, presumably more efficient periods and the extracted heat is stored for future demand. It should be noted, however, that due to our inability to properly measure the thermal flows through the heat storage, the thermal output for the U.S. Downdraft Unit was estimated using the heat loss method (boiler efficiency).

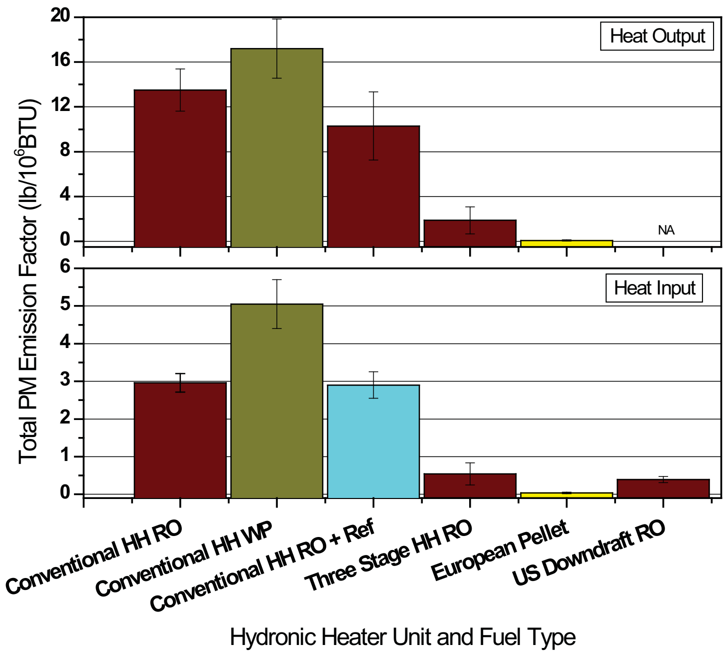


Figure 15. PM Emission Factors for all Six Unit/Fuel Combinations. RO = red oak, WP = white pine, Ref = refuse.

A comparison of PM emission factors determined from the current work with other published HH test data is shown in Figure 16. These data are taken from different studies (OMNI 2009; OMNI 2007, Intertek 2008), and were collected using EPA Method 28 OWHH. The percent rated load calculated from this testing is compared to the emission factor from the Method 28 OWHH report for the burn category that represents the same load. For the Conventional, Single Stage HH and 2300 this was Category II and for the U.S. Downdraft Unit it was Category IV. In the latter case, the maximum rated capacity was used. Also, the pellet emission factor is shown on the plot but there are no Method 28 OWHH data available for the pellet burner. The Other Conventional and Multi-Stage units are included only for comparison purposes. Data are presented in terms of mass of PM emitted per mass of wood burned and only the red oak and hardwood pellet data from this study are included. As shown, the EPA method tends to somewhat under-predict the emissions compared with the current work. This under-prediction is probably due to the differences between the EPA protocol method (e.g., use of cord wood in this project versus crib wood in Method 28 OWHH) and the use of a winter season heat load demand approach used here to characterize emissions. Finally, the PM emission rate for an oil-fired boiler is given for reference at 0.08 g/kg of fuel and cannot be shown on Figure 16.

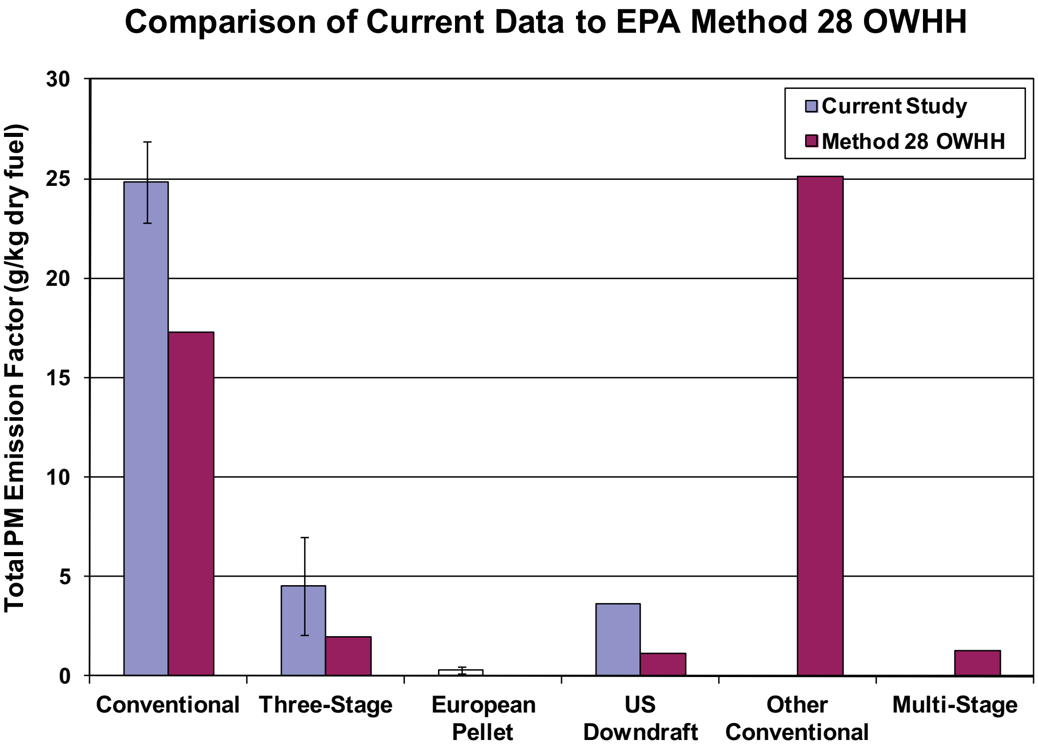


Figure 16. Comparisons of PM Emission Factors to other HH Test Data. Note that residential fuel oil = 0.08 g/kg fuel (Brookhaven National Laboratory).

Particle Composition

The ratio OC/EC was within the range of 20-30 for the Conventional and Three-Stage units regardless of fuel type (Figure 17). This ratio is typically greater than one for biomass combustion sources and less than one for fossil fuel sources. The OC/EC ratio for the European Pellet Burner pellet unit, on the other hand, was much lower indicative of higher combustion efficiency and lower emissions. The OC/EC ratio of the U.S. Downdraft unit, however, was only slightly lower than the Conventional and Three-Stage models indicating somewhat better combustion efficiency. Emission factors for black carbon in the particulate matter less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$) were determined; these are believed to be the first such data for these unit types.

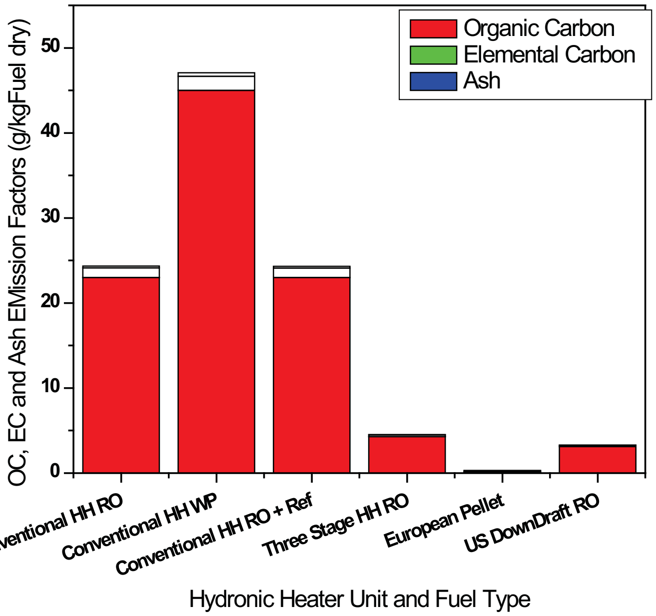


Figure 17. Average Organic Carbon, Elemental Carbon, and Ash for the Six Unit/Fuel Combinations.

Molecular Composition of the Organic Component of PM

Gas chromatography/mass spectrometry (GC/MS) techniques identified and quantified the PM bound semi-volatile organic compounds (SVOCs), which accounted for 9% w/w of the PM emitted from the HH boilers on average. The HH PM comprised 1-5% weight percent levoglucosan, an anhydro-sugar and important molecular marker of cellulose pyrolysis. The levoglucosan compound accounted for approximately 40% of the quantified species. Organic acids and methoxyphenol (lignin pyrolysis products) SVOCs were the compound/functional group classes with the highest average concentrations in the HH PM. These compounds are naturally abundant, also used as atmospheric tracers, and are important to understanding the global SVOC budget.

The PAHs explained between 0.1-4% w/w of the PM mass (Figure 18). All 16 of the original EPA priority PAHs were detected in the HH PM emissions. The older, Conventional, Single Stage HH unit technology emitted PM with higher PAH fractions. In general, the unit/technology type significantly influenced the SVOC emissions produced. Combustion of the white pine fuel using the older unit produced notably high SVOC emissions per unit energy and per unit mass of wood consumed; particle enrichment of SVOCs was also confirmed for this case. Addition of refuse to the seasoned red oak biomass generally resulted in a negligible increase in SVOC emissions per unit energy produced with the saturated hydrocarbons noted as an exception. Use of the pellet boiler generated the lowest SVOC emissions of the HH tested on a mass of fuel burned basis. Nevertheless, the U.S. Downdraft Unit gasifier unit showed the lowest SVOC emissions per unit energy produced. Results show that the phase of the burn cycle can influence the emissions on a compound class basis. These and similar differences are highlighted in the main body of the report.

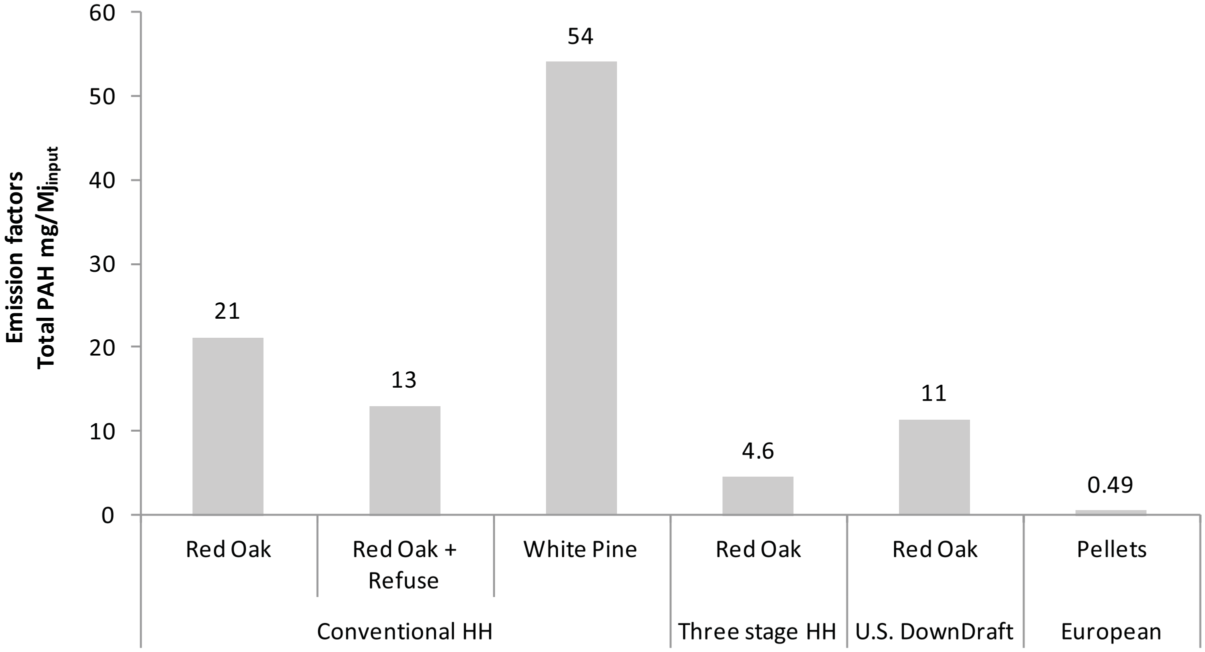


Figure 18. Total PAH Emission Factors.

PCDD/PCDF Emissions

Polychlorinated dibenzodioxin and dibenzofuran (PCDD/F) emissions were sampled and ranged from 0.07 to 2.1 ng toxic equivalents (TEQ)/kg dry fuel input, with the lowest value from the U.S. Downdraft unit and the highest from the Conventional, Single Stage HH with red oak + refuse (see Figure 19). The lowest value, from the U.S. Downdraft unit, may be due to the non-cyclical combustion resulting in consistent combustion and more complete burnout, but the limited data make this speculative. These values are consistent with biomass burn emission factors of 0.91 to 2.26 ng TEQ/kg) (Meyer et al. 2007), woodstove/fireplace values of 0.25 to 2.4 ng TEQ/kg (Gullett et al., 2003), pellet and wood boilers values of 1.8 to 3.5 ng TEQ/kg, and wood stoves and boilers of 0.3 to 45 ng TEQ/kg (Hübner et al, 2005).

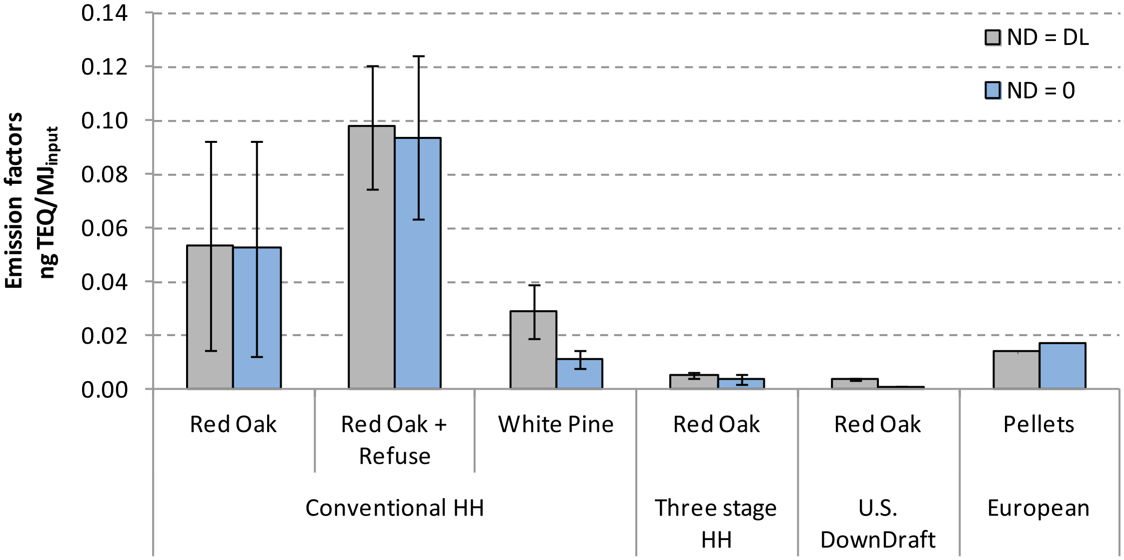


Figure 19. PCDD/PCDF Emissions with Non-Detects = Detection Limit and Zero.

ENERGY AND EMISSIONS IMPACTS OF WOOD HEATING TECHNOLOGIES IN THE HEATING MARKET

An energy systems model termed MARKAL (MARKet ALlocation), with the U.S. EPA's 9-Region database (Loughlin et al., 2011; Shay & Loughlin, 2008), was used to examine the broader energy and emissions impact of HHs. The goals of this analysis were to: (a) identify possible future scenarios for the penetration of HHs and other advanced wood heating systems, (b) place those scenarios in the context of total residential demand for space heating and total residential energy demand, and (c) determine the emissions implications of those scenarios between 2010 and 2030. Because of the unique nature of the market for wood heating devices and wood and pellet fuels, and the non-economic variables that often come into play, modeling this market in a pure cost optimization framework presents a challenge. We therefore used the model in a "what if" scenario framework, rather than in a predictive framework, asking a number of targeted questions, and running the model to assess the impact of certain assumptions regarding total wood heat market size, technology mix, rates of turnover, availability (or not) of advanced and high efficiency units, fuel price and availability, and emissions rates.

A baseline scenario and four alternative scenarios were examined. The baseline scenario models a modestly decreasing market share for wood heat in general, but greater penetration of outdoor HHs over the 2005 through 2015 time period, along with a changeover from existing wood stoves to cleaner wood stoves. The contribution of wood stoves and outdoor HHs to the full market for residential space heating is shown in Figure 20.

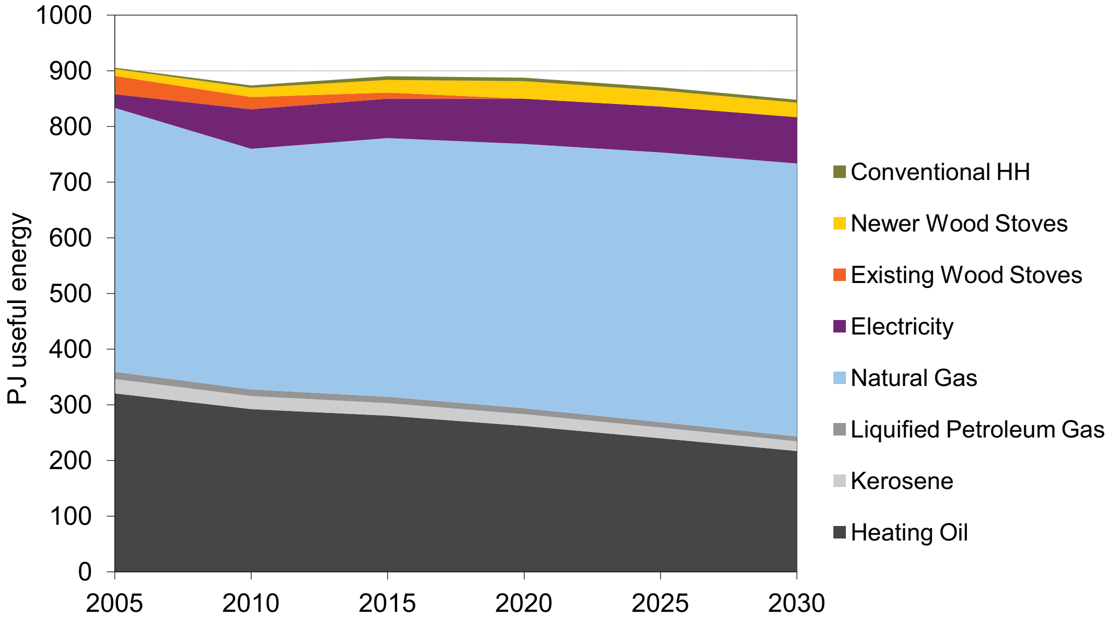


Figure 20. Market for Residential Space Heating for "Baseline" Scenario (PicoJoules of Usable Energy).

In terms of emissions, this scenario was pessimistic in the assumption that cleaner, more efficient outdoor HHs would not be available for the entire modeling horizon. Figure 21 shows the PM emissions trends over time for this scenario for all residential energy use (not just space heating). It becomes clear from this comparison that even though wood heat is a relatively small contributor to meeting total residential energy demand, it can dominate the emissions profile for the residential sector.

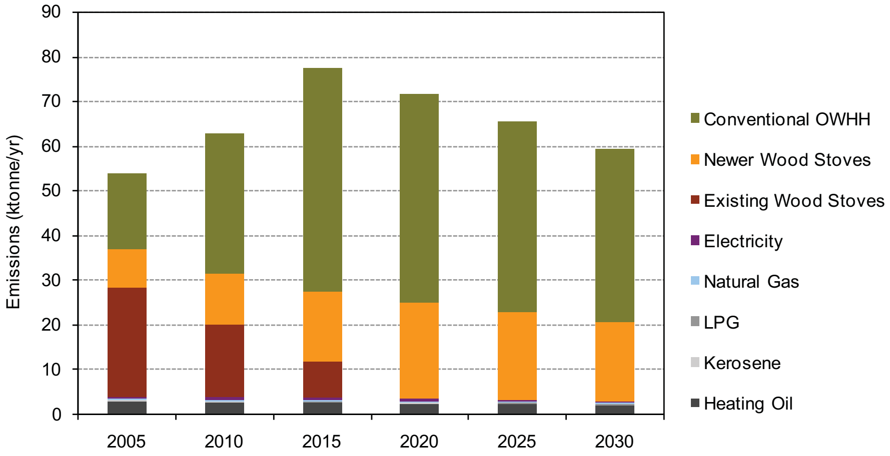


Figure 21. PM Emissions (ktonnes/year) for Total Residential Energy Use for "Baseline" Scenario.

The “baseline” represents only one possible scenario, and not necessarily the most likely. How the market for wood heat, and HH units in particular, will evolve over the next 5-15 years is highly uncertain, and is driven by consumer preferences and behavior that are difficult to capture in a quantitative framework. The role that policy measures will play in terms of the rate of technology turnover, efficiency of new units, and emissions, adds another layer of uncertainty. Figure 22 shows the range of potential emission outcomes for a number of scenarios.

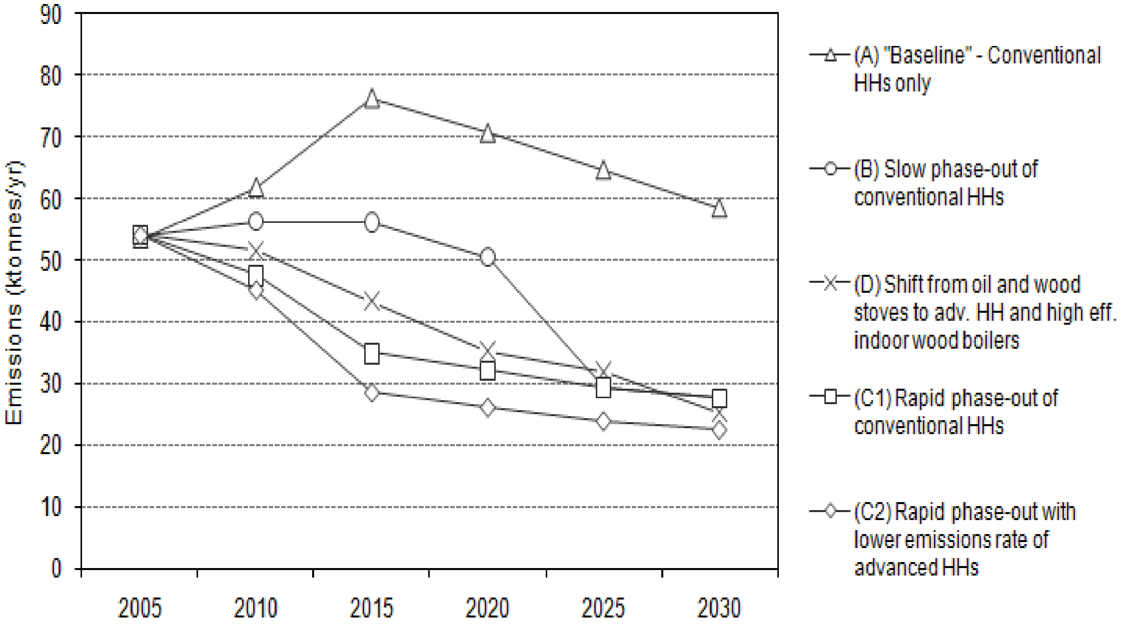


Figure 22. Total Residential PM Emissions “Baseline” and Four Alternative Scenarios (ktonnes/yr)

In contrast to the “baseline” scenario, the “slow phase-out of conventional HH” scenario assumes the same wood heat market share, but now allows for some introduction of advanced HHs. However, this scenario forces the conventional HH units to maintain part of the total HH market at least out to 2020. For 2015, the market for conventional outdoor HH and advanced HH (including higher efficiency outdoor HHs and indoor wood boilers) is split 50/50, but by 2025 there are no conventional outdoor HHs in the market. Two additional scenarios examine what happens under the same wood heat market share, when advanced HHs come into the market more rapidly. Under the scenario, “rapid phase-out of conventional HHs,” new HHs start to enter the market in 2010. Another scenario “rapid phase-out of conventional HHs with lower emissions rate of advanced HHs” looks at the same market split over time, but with lower emissions for the advanced units coming in to the market. This is the most optimistic scenario from the PM standpoint. Finally, “shift from oil to wood heat” illustrates a different scenario both for wood heat in general and for the mix of technologies within the wood heat market. In contrast to the earlier scenarios, this scenario shows a growth in the wood heat market, with a large decline in heating oil, and major shift in the mix of wood heat technologies away from stoves. The key insights from this cross-scenario comparison are: (1) the extent to which wood space heating emissions dominate the total emissions from total residential energy usage, even out to 2030; and (2) the potential for wide variation in future emissions, depending upon the evolution of the technology mix within the market for wood heat, as seen in Figure 22.

Lifetime heating costs of wood boiler technologies in comparison to oil, natural gas, and electricity

Engineering economic techniques were used to compare estimated lifetime costs of alternative technologies, including HHs, automated pellet boilers, high efficiency wood boilers with thermal storage, natural gas and fuel oil boilers, and electric heat pumps. Assumptions for each technology and for fuel prices are listed in Table 4 and Table 5, respectively.

Table 4. Assumed Characteristics of Residential Heating Devices. For the wood devices, nameplate efficiencies are shown in parentheses alongside the observed operational efficiency.

Technology	Tested Efficiency (Rated Efficiency)	Output (BTU/hr)	Base Capital Cost	Scaled Capital Cost
Natural gas boiler	85%	100k	$3,821	$3,821
Fuel oil boiler	85%	100k	$3,821	$3,821
Electric heat pump	173%	36k	$5,164	$11,285
Conventional HH	22% (55%)	250k	$9,800	$9,800
Advanced HH	30% (75%)	160k	$12,500	$12,500
High efficiency wood boiler with thermal storage	80% (87%)	150k	$12,000*	$12,000*
Automated pellet boiler, no thermal storage	44% (87%)	100k	$9,750	$9,750

* The high-efficiency indoor wood boiler cost is assumed to include a supplemental hot water storage tank at a cost of $4,000.

Table 5. Assumed Fuel Prices for the State of New York. National Values are Provided in Parentheses.

Fuel	Price
Fuel wood	$225 / cord
Pellets	$280 / ton
Fuel oil #2	$2.83 / gal ($2.80 / gal)
Natural gas	$1.37 / therm ($1.00 / therm)
Electricity	$0.183 / kwh ($0.109 / kwh)

The engineering economic calculations used here are relatively simple, accounting for capital and fuel costs over the lifetime of the device, but ignoring other costs. Results of the Net Present Value (NPV) calculations are shown below in Table 6.

Table 6. Calculated annual fuel costs and net present value lifetime costs of various residential space heating technologies.

Technology	Annual Fuel Cost	NPV
Automated pellet boiler	$3,900	$64,000
High efficiency indoor wood boiler with hot water storage	$1,300	$30,000
Conventional HH	$4,700	$75,000
Advanced HH	$3,400	$62,000
Electric heat pump	$3,100	$55,000
Natural gas boiler	$1,600	$26,000
Fuel oil boiler	$2,400	$37,000

Under baseline assumptions, natural gas boilers were shown to have the lowest net present value of cost of all of the home heating options that were examined. Natural gas is not available in all parts of the State of New York, however, and many low-density, rural areas do not have access to natural gas distribution systems. It is in these rural areas that HHs are likely to compete with electricity and fuel oil for market share. Of these technologies, HHs were cost-competitive only with the pellet boilers under tested efficiencies and market prices for wood. These results do not imply that wood heat cannot be cost-effective, however. For example, the high efficiency indoor wood boiler with hot water storage had a lifetime cost that was less than all non-natural gas options that were examined.

Sensitivity analysis suggested that there may be situations where HHs *are* cost competitive. Major factors that can contribute to this result are wood price, HH efficiency, and the prices of competing fuels. The sensitivity analysis is summarized in Figure 23.

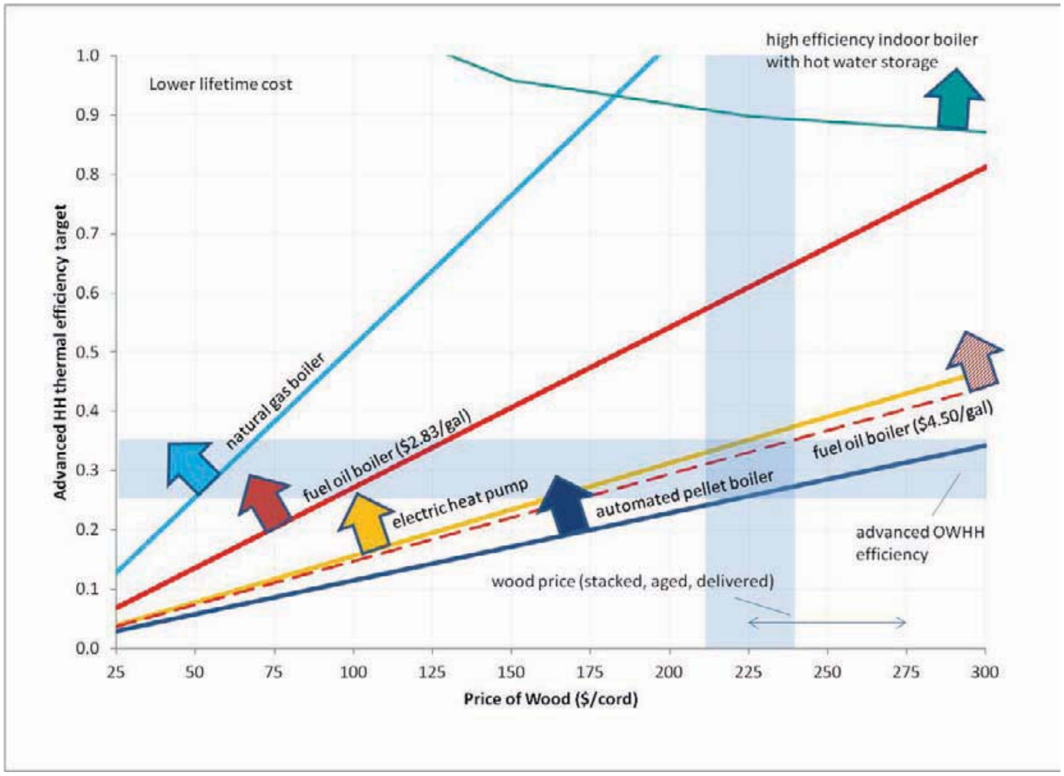


Figure 23. Comparative Technology Costs.

Figure 23 shows the combinations of wood price and thermal efficiency at which an advanced HH becomes cost competitive with other devices. A good starting point for interpreting the graph is the rectangular area created by the intersection of advanced HH efficiencies in the mid-20s to mid-30s and wood prices between $210 and $240, encompassing the baseline assumptions. The rectangle falls below all of the technology-specific lines on the graph except for the automated pellet boiler, indicating that the advanced HH is more costly than those technologies from a Net Present Value (NPV) perspective. Increasing efficiency or lowering the price of wood can result in the advanced HH becoming competitive, however. For example, increasing efficiency to above 35% results in the HH having a lower NPV cost than the electric heat pump (at a wood price of $225). Similarly, a wood price of below approximately $55 per cord is necessary for the NPV cost of the HH to equal that of the natural gas boiler (at an advanced HH efficiency of 30%). It is important to note that decreasing the wood price also has the effect of lowering the NPV cost of the high efficiency indoor wood boiler with storage, and the HH must achieve even higher efficiencies to be cost competitive. The solid and hashed red lines on the graphic indicate that competitiveness with oil is highly dependent on oil price. At a price of $4.50 per gallon, the advanced HH needs only achieve an efficiency of approximately 33% to rival the oil boiler. In contrast, at a fuel oil price of $2.83 per gallon, the HH unit must achieve a thermal efficiency greater than 60%.

As indicated by the figure, a major factor in the engineering economic assessment of HHs is the price for wood fuel. Many rural households have their own wood supply, which they may perceive to be low cost or free, even if the labor costs associated with carrying and splitting the wood are factored in, these homeowners may still perceive HHs as the most cost-effective option. This hints at the importance of difficult-to-quantify factors. Most homeowners may not undertake the analysis carried out here. They also may not go through an explicit process to evaluate the value of their time. They may not be aware of the correlation between wood and oil prices in many markets. Instead, it is likely that those who have chosen to install HHs have been motivated by qualitative perceptions of the technology's cost, perceived environmental benefits, and ability to hedge against increases in fuel prices. Tax credits may also be a highly motivating factor, even if they are far less important than device efficiency and fuel cost in determining lifetime heating costs. These factors cannot easily be quantified within an engineering economic assessment and yet may be the dominant factors in decision-making.

There are additional unmodeled factors that both work for and against the competitiveness of HHs. For example, it is likely that the thermal efficiencies used in this analysis are higher than would be experienced in practice since the units would likely be used during the fall and spring months when loads and efficiencies would be lower. Further, the high emission rates associated with HHs have resulted in some counties and communities to pass ordinances that ban or limit HH use. Space considerations also come into play. Households must have room to store delivered wood fuel, and many residents may find it inconvenient to have to go outside to load wood into the boiler. The high efficiency indoor wood boiler also requires firewood storage. It does, however, address efficiency concerns by storing heat in a large water tank, allowing the unit to operate without cycling. The increased efficiency associated with this configuration is dramatic, and the unit is able to compete well in NPV cost with even the natural gas boiler. Combining hot-water storage with an HH is also an option that may improve thermal efficiency. The high BTU output of many HH units would require a very large storage tank, however, and this option was not examined in our study.

HEALTH CHARACTERIZATION

A health assessment of emissions from three different HHs was conducted to determine if one unit or operating condition was better or worse than another. Adult CD-1 mice were exposed to filtered air, filtered wood smoke or unfiltered wood smoke for four hours per day for one or three consecutive days, then pulmonary and systemic biomarkers of injury and inflammation were assessed. Three days of exposure to either the filtered or whole wood smoke caused statistically significant increases in tumor necrosis factor in lung fluid and creatine kinase in serum. In the second study the only notable change was increased ferritin in the lung after a three-day exposure to whole or filtered wood smoke and smaller increases in creatine kinase in the filtered only group. The third study utilizing the pellet heater resulted in higher numbers of macrophages in the lung 24 hours after a one- and three-day exposure. The results show that none of the exposures caused acute lung injury but were associated with inconsistent increases in inflammatory signaling pathways. Still, the overall emission toxicity results from animal exposure experiments were inconclusive, as extreme dilution of the combustion gas was necessary to avoid immediate acute toxic effects from the carbon monoxide that at times exceeded 10,000 ppm.

CONCLUSIONS:

Comparison testing of four HH units, ranging from common to newer technologies, with different fuel types showed large differences in energy and emission performance. HH units that operated with cyclical damper openings and closings to regulate the supply of heat generally resulted in poorer efficiencies and higher levels of pollutants. The Pellet-fired unit and Two Stage Downdraft unit with heat storage showed greater combustion performance and lower emissions. Use of thermal storage allowed the Two Stage Downdraft HH to run at maximum output under relatively steady-state conditions, improving efficiency performance. For cyclical units, efficiency improvements can likely be achieved by reducing the time spent at idle (closed damper) through proper unit sizing. The thermal efficiencies, ranged from 22% to 44% for the conventional Single Stage HH, Three Stage HH, and European Pellet Burner. These values compare poorly with oil and natural gas fired residential systems with thermal efficiencies ranging from 86% to 92% and 79% to 90%, respectively (McDonald, 2009).

Testing showed a wide range of emissions depending on both unit and fuel types. The Conventional, Single Stage HH burning white pine produced the highest total daily PM emissions [6.3 kg (14 lbs)] and the European Pellet Burner with red oak reported the lowest [0.036 kg (0.08 lb)]. Emissions for the Three Stage HH and U.S. Downdraft Unit units were comparable at 0.69 and 0.62 kg/day (1.51 and 1.37 lbs/day), respectively. CO emissions showed a similar unit to unit trend, with the lowest value from the European Pellet Burner at 0.60 g/MJ (1.39 lb/MMBtu). This value was about 15 times lower than that of the Conventional, Single Stage HH (average of the three fuels). These CO emission factors are orders of magnitude higher than are typically observed in conventional energy sources such as residential oil-fired heaters (< 0.1 lbs CO/MMBtu input, Krajewski et al., 1990).

Market and energy modeling show that while wood heat is a relatively small contributor to meeting total residential energy demand, it is the largest contributor to emissions from the residential energy sector. While different regulatory and technology scenarios for the future can have a significant impact on emissions, pollution from residential wood space heating is likely to dominate the total emissions from total residential energy usage, even out to 2030. Economic calculations for residential heating options, accounting for capital and fuel costs over the lifetime of the device, show that natural gas systems have the lowest net present value cost of all examined home heating options, including HHs. However, natural gas is not available in all parts of the State of New York. In the predominantly rural areas where it is unavailable, HHs are likely to compete with electricity and fuel oil for market share, especially when thermal storage is incorporated. The rate of turnover and retirement of older, highly emitting units to more efficient, lower emitting units is critical to avoid what could be substantial increases in emissions related to residential wood heat over the next 5-10 years.

1. INTRODUCTION

In states such as New York where solid biomass fuels are readily available, wood-fired HHs (HHs), also termed outdoor wood boilers (HHs) or outdoor wood-fired HHs, have become popular alternatives to, fuel oil, or electrical systems for whole home heating and hot water. A typical outdoor wood-fired heater is essentially a free-standing structure consisting of a firebox surrounded by a water jacket, in which the exhaust gases are vented through a chimney. Typical HHs are designed to cycle from full load to idle, where fuel burns at a low temperature and under oxygen-starved conditions resulting in an average thermal energy efficiency of only 43% (Schreiber and Chinery, 2008). These design features make HHs a unique emission source unlike any other residential wood burning appliances. However, these unique design features can also promote formation of harmful pollutants, resulting in high emissions of particles and unoxidized gaseous compounds (Johnson, 2011). Most of the regulatory (and research) attention regarding HHs has been focused on particulate matter (PM), with recent results reported by the New York State Office of the Attorney General (OAG) Environmental Protection (www.ag.ny.gov) showing that typical HHs emit about four times as much fine PM pollution as conventional wood stoves, about 12 times as much fine particle pollution as U.S. Environmental Protection Agency (EPA)-certified wood stoves, 1000 times more than oil furnaces, and 1800 times more than gas furnaces (Schreiber et al., 2005; Schreiber and Chinery, 2008). HHs can also be 1000 times higher than oil-fired furnaces and 1800 times higher than natural gas-fired furnaces for PM emissions (Schreiber, 2007). Not surprisingly, ambient air studies have shown that most of the fine PM measured in the Adirondacks comes from wood combustion (Miller et al., 2010). Many of the twelve or so states where HHs are most popular suffer from smoke complaints from neighbors of HH systems (NYSOAG, 2005). In response to these complaints, many municipalities are banning new HHs or restricting the use of existing HHs. Despite these bans and restrictions, sales elsewhere are growing fast and are expected to double in next 5-10 years, primarily driven by the higher cost of fossil fuels (Blanchard, 2007).

Preliminary modeling and monitoring indicate air quality PM levels near HHs as high as 8,000 $\mu g/m^3$ with frequent spikes over 1,000 $\mu g/m^3$ (NESCAUM, 2006). These levels can be compared with the current national ambient air quality standards (NAAQS) for PM, which are 15 $\mu g/m^3$ (annual average) and 35 $\mu g/m^3$ (24-hour average) for PM less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$) and 150 $\mu g/m^3$ for PM less than or equal to 10 micrometers in diameter (PM_{10}) (24-hour average). EPA is currently reviewing the NAAQS and considering options to tighten the standards. Fewer results are available for emissions of other pollutants, such as volatile organic compounds (VOCs), particle-bound polycyclic aromatic hydrocarbons (PAHs), and polychlorinated dibenzodioxins and dibenzofurans (PCDDs/Fs). Effects of HHs are purportedly further exacerbated by the short stack height and frequent relatively low stack gas temperatures that do not allow adequate dispersion and can cause significant local air pollution impacts, particularly during atmospheric inversions. The HH combustion chamber design also facilitates the loading and combustion of non-wood materials, such as household waste (e.g., paper, plastic, and packaging). The use of HHs to burn waste is analogous to the use of burn barrels and burn piles, which are known sources of PCDDs/Fs and other persistent bio-accumulative toxic (PBT) emissions (Lemieux et al., 1997).

Wood smoke contains significant quantities of known health-damaging pollutants which may contribute to acute and chronic pulmonary injury, immunosuppression and the development of cancer (reviewed in Naeher et al., 2007). The health impacts of exposure to wood smoke and some individual constituents such as aldehydes and benzene are quite well characterized. Still, comparative toxicity testing using different fuel types, burners, and combustion conditions has not been reported.

In January 2007, EPA's Office of Air Quality Planning and Standards (OAQPS) developed a Phase 1 Voluntary Program to encourage manufacturers to redesign their HHs to be cleaner burning (~70% lower emissions in Phase 1). The emission level for an appliance to qualify under Phase 1 of the Voluntary Program was 2.58×10^{-4} kg/MJ (0.60 lbs/MMBTU) heat input. In addition, a model rule has been developed by Northeast States for Coordinated Air Use Management (NESCAUM) with technical and financial assistance from OAQPS for use by State agencies. The emission levels recommended in the NESCAUM Model Rule are 1.89×10^{-4} kg/MJ (0.44 lbs/MMBTU) heat input for Phase 1 by March 31, 2008, and 1.37×10^{-4} kg/MJ (0.32 lbs/MMBTU) heat output for Phase 2 by March 31, 2010. The Model Rule also includes chimney height requirements and setback requirements (for more information, see www.epa.gov/burnwise and NESCAUM, 2007). The State of New York conducted the dispersion modeling to support the Phase 2 model rule requirements. The model rule has been or is currently being adopted as part of state regulations by several states in the northeast, and the State of New York has just adopted a rule at least as stringent for new units. In October 2008, EPA established the EPA Phase 2 (white tag) Voluntary Program and no longer allows Phase 1 (orange tag) HH models to be qualified. The Phase 2 voluntary emission level matches the Phase 2 emission level in the model rule, i.e., 0.32 lbs/MMBTU heat output. At this time, 23 models have been Phase 2-qualified under the EPA Voluntary Program. These Programs and Rules, as well as associated sampling programs, have focused on total PM emissions and have not included a full emissions characterization and health assessment.

The long-term research plan developed by NYSERDA and the New York Academy of Sciences has identified the characterization of poorly characterized sources - such as HHs - as particularly important. Such characterization data are needed for a better understanding of the atmospheric processes that organic gases and aerosols undergo and for improving (micro-, state-wide (New York), and national) emissions inventories. The work reported here speciates the organic matter in gas- and particle-phase emissions from HHs. Concentrations of biomass combustion markers were measured from the quartz filter catch using gas chromatography/mass spectrometry (GC/MS) methods in the EPA aerosol characterization laboratory (Hays et al., 2002). Due to their toxicity, special emphasis was placed on quantifying the PAHs in the aerosol particles and identifying previously unrecognized trace molecular marker species using a novel 2-dimensional GC/MS heart-cutting technique. Combustion products from the HHs were added to emissions inventories and air quality models for an improved understanding of atmospheric processes and carbonaceous aerosol mass.

With the advent of tighter PM standards, retrofits, and improved designs, new technologies will start to enter and impact upon the market. These recent market entries include gasification units, primarily of European design (Albrecht, 2007), heat storage redesigns (Brady, 2007), add-on catalyst units, pellet burners, and afterburner technologies, either by way of retrofit or incorporation into the original HH design. Nevertheless, it is unclear how well these retrofits and new technologies will satisfy the PM rules and how other pollutants are affected, leaving significant questions as to the energy impact on the State of New York, the market penetration of HH types, and the health impacts on the population.

The combination of the burgeoning HH market, the uncertainty over emissions (particularly non-PM emissions), the minimal health characterization of the HH emissions, and the unknown performance of the retrofit and new technologies leaves considerable questions regarding the environmental, health, energy, and market implications for the State of New York. The goal of this project therefore was to characterize the emissions of the current technology HHs and to provide preliminary comparative information on both the emissions and energy performance of these technologies. This information will aid the State of New York decision-makers in formulating and implementing policies and regulations regarding the use of these appliance heaters.

2. EMISSIONS TESTING

2.1 INTRODUCTION

The goal of this project was to characterize the energy efficiency and emissions of common and recent HH technologies, including those with staged combustion and those using pellet fuels for heating load requirements in upstate New York. This research effort will provide NYSERDA with an energy and emissions performance assessment of current and emerging wood-fired heating appliances.

Two of four units characterized under this study are commercial models that include a very commonly-used unit (a “Conventional, Single Stage HH”) and a newer, “Three Stage HH” model. The characterization consisted of determining input- and output-based emission factors for a broad array of pollutants. The heater units were operated to supply a 24-hour heat demand profile for a typical 232 m^2 (2500 ft^2) house in Syracuse, New York, which is located in the northeastern United States. The fuel loading protocol was derived from the simulated heat-load demand profile and the type of unit and its capacity. The Conventional, Single Stage HH unit was used to compare emissions for five fuel types including seasoned red oak, maple, and ash, as well as unseasoned white pine and red oak with supplementary refuse. The Three Stage HH unit was tested solely with seasoned red oak. A pellet-fueled HH (“European Two Stage Pellet Burner”) and a split-log wood heater (“U.S. Two Stage Downdraft Burner”) with a simulated heat storage tank were tested under the same heat-load demand profile to characterize and compare their emission signatures. A common fuel type (red oak) was used across all units (hardwood pellets for the European Two Stage Pellet Burner unit) for comparability.

A full emissions characterization for each heater unit consisted of, at a minimum, PM (time-integrated and real time), total hydrocarbons (THC), PAHs, organic marker compounds, organic carbon/elemental carbon (OC/EC), carbon monoxide (CO), carbon dioxide (CO_2), CH_4, nitrous oxide (N_2O), and PCDDs/Fs. The results of this study were compared with those of EPA’s Office of Air Quality Planning and Standards’ (OAQPS’) ongoing validation tests of EPA Method 28 for HH PM and energy efficiency (http://www.vtwoodsmoke.org/pdf/Method28.pdf), particularly for the seasoned red oak fuel.

2.2 FACILITY DESCRIPTION

Figure 2-1 depicts the components of the HH test facility located at EPA’s research laboratories in Research Triangle Park, North Carolina. The units were located outside the EPA High Bay facility, allowing testing under ambient conditions. The flue gas was ducted into the facility for ease of sampling and subsequent treatment in the air pollution control systems (APCSs) before being released to the atmosphere. The facility duct work configuration and flows were designed to adhere to American Society for Testing and Materials Method E2515 (ASTM, 2007). The stack from the HH is 0.2 m (8 inches) in diameter and is 2.44 m (8 feet) in length. A conical hood cone is placed above the outlet of the stack to entrain the unit exhaust and ambient air. A canvas shroud (not shown) is hung from the circumference of the dilution cone to further ensure complete collection of emissions without wind gust effects. The cone is connected to a 0.25 m (10 inch) stainless steel duct surrounded by an outdoor sampling platform outfitted with four vertically-oriented 0.076 m (3 inch) ports to support particulate sampling, CEM, and velocity measurements. The outside duct is connected to a horizontal indoor sampling platform set up to accommodate sensitive measurement equipment and other stack measurement methods. The diluted and cooled exhaust gases are transferred into the building and through a 0.25 m (10 inch) diameter and about 12 m (40 ft) long stainless steel duct, with multiple sampling ports. The temperatures within this dilution sampling duct are near ambient. This sampling section is connected to an APCS manifold for treatment prior to release to the atmosphere. The air duct system moved 19.8-20.4 dry standard cubic meters (dscm) (700-720 standard cubic feet per minute [scfm]) of air, which correlates to an approximate dilution ratio of 5-10 to 1 from the HH stack. Flows and pressures are controlled by adjusting the building APCS induction draft fan.

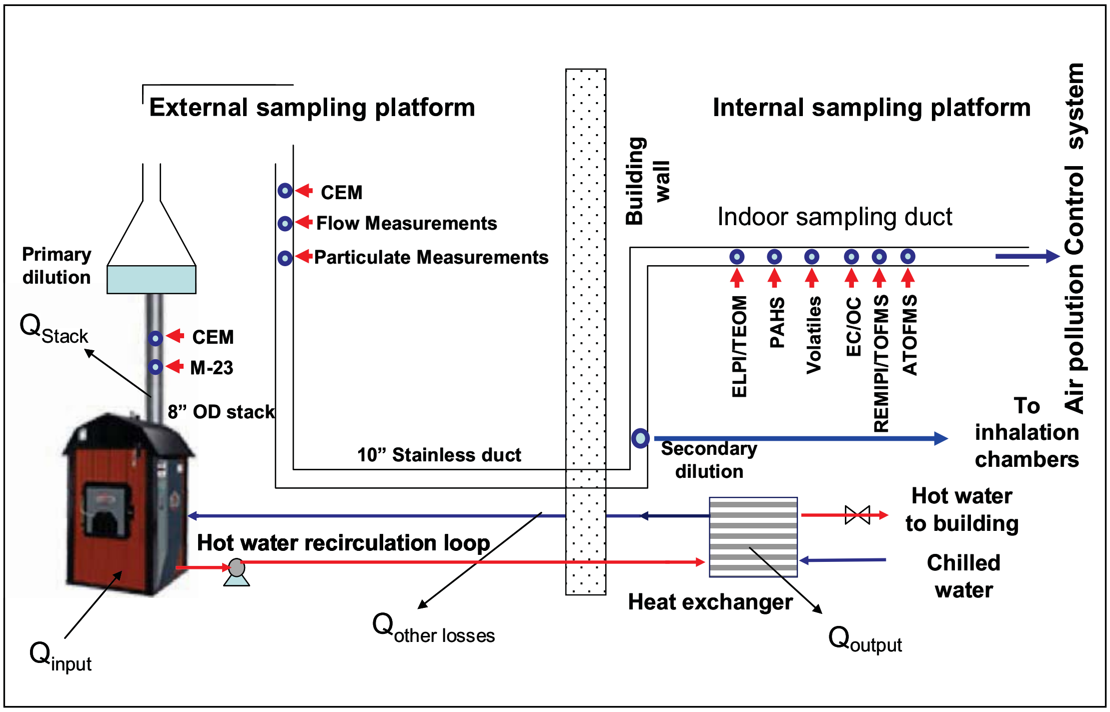


Figure 2-1. Hydronic Heater Test Facility Setup.

2.2.1 Heat Load Profiles

The heat load profile (Figure 2-2) that was used throughout the testing program was derived from a simulation program for heat demand (Energy-10^{TM}, National Renewable Energy Laboratory [http://www.nrel.gov/buildings/energy10.html?print]) for a 232 m^2 (2500 ft^2) home in Syracuse, New York, using an averaged hour-per-hour heat load for the first 2 weeks of January averaged over 25 years (courtesy of Brookhaven National Laboratory). The average daily heat load for the first two weeks in January is about 827 MJ (784,000 British thermal units [BTU]).

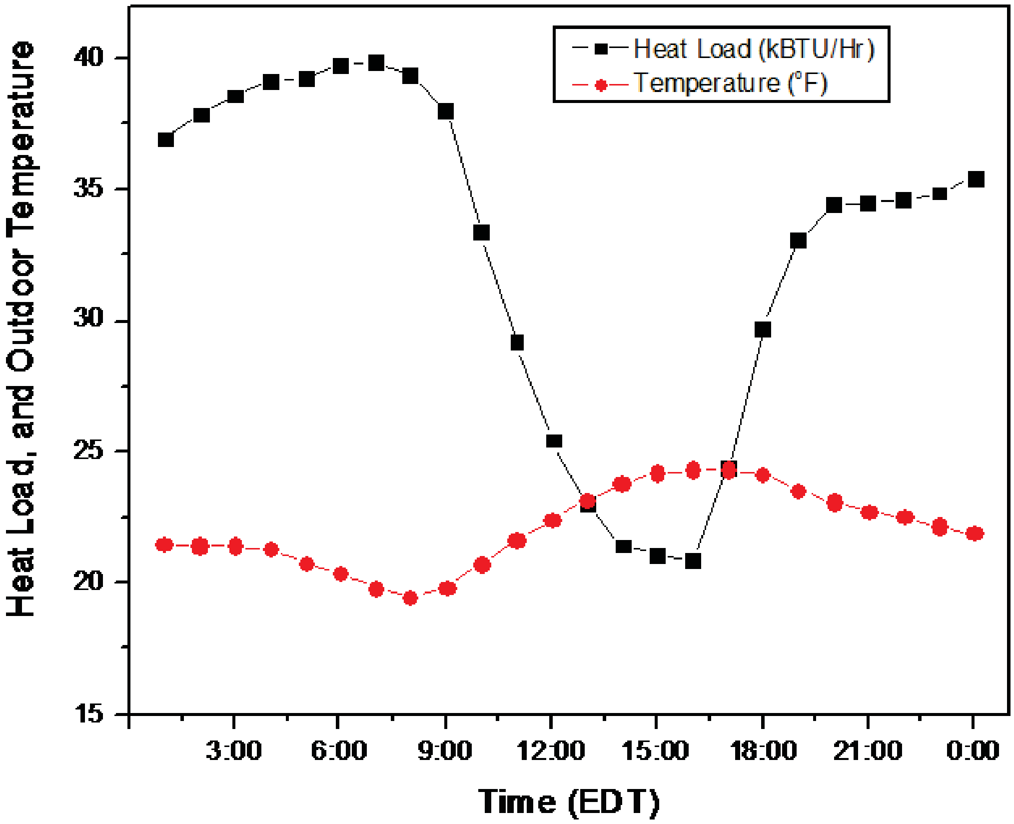


Figure 2-2. Syracuse, New York, Area Heat Load Profile for the First Two Weeks of January.

The heat load demand was simulated by extracting the HH outlet heat with a water/water heat exchanger coupled to the building chilled water supply. The HH units were operated in a mode where hot water was continuously circulated through the water/water heat exchanger and the unit's water jacket. The pre-insulated piping system consists of two 25.4 mm (1 inch) oxygen barrier lines that are insulated with high density urethane insulation. The same piping system was used for all four units tested. The inlet and outlet temperatures of both the chilled water and re-circulated hot water were monitored, as well as the chilled water flow rate. The heat load demand control system calculated the change between the chilled water outlet temperature and the chilled water inlet of the heat exchanger. The system controlled the heat removal by adjusting the chilled water flow rate through the use of the proportional valve. The heat load demand control scheme is described in Figure 2-3.

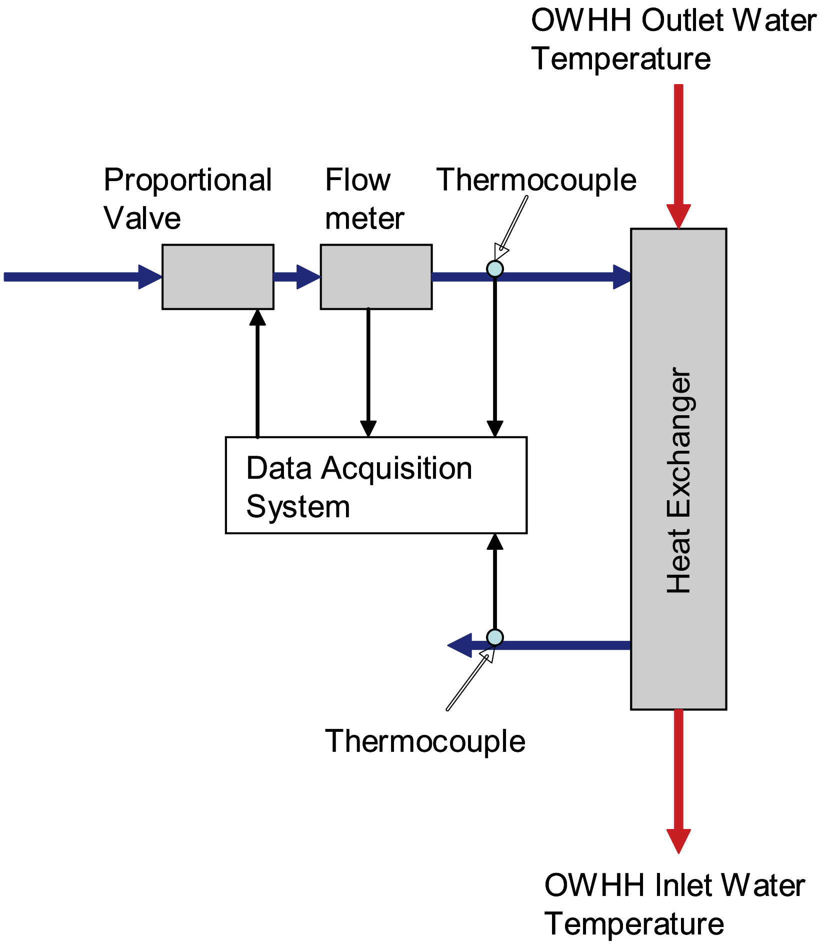


Figure 2-3. Heat Load Demand Control Scheme.

2.3 DESCRIPTION OF HHs AND FUELING PROTOCOLS

2.3.1 The Conventional, Single Stage HH

Four different HHs were used in this study (Table 2-1) representing common and recently-developed technologies. A majority of the work was performed on a historically-common unit, the Conventional, Single Stage HH, designed for updraft combustion, listed for a maximum rating capacity of 264 MJ (250,000 BTU), a total water capacity of 740 L (196 gal), and a heat exchange surface area of 6.87 m^2 (74 ft^2).

Table 2-1. Outdoor Wood-Fired HHs Used in this Study.

Unit Model	**Conventional, Single Stage HH**	**Three Stage HH**	**European Two Stage Pellet Burner**	**U.S. Two Stage Downdraft Burner**
Unit #	**1**	**2**	**3**	**4**
Technology	Combustion	Three-stage Combustion	Combustion	Two-stage: Combustion and Gasification with Heat Storage
Fuel	Wood logs	Wood logs	Wood pellets	Wood logs
Maximum heat rate output BTU/hour (kW)	NA[1]	160,000 (46.9)[2]	137,000 (40)[3]	150,000 (44)
Water Capacity, gal (liters)	196 (740)	450 (1700)	43 (160)	32 (120)

[1] Not available from the manufacturer; [2] Eight hour stick wood test; [3] Partial load output, based on manufacturer's specifications; [4] Heat rate based on manufacturer claim

The Conventional, Single Stage HH uses a natural draft, updraft combustion single-stage combustion process that occurs in a rectangular firebox surrounded by a high capacity water jacket (Figure 2-4). The hot flue gases are vented through a stainless steel insulated chimney connected to a rear exhaust outlet. Flue gas movement is by natural convection, assisted with a fan. The heater is mounted on a skid-based framework for ease of installation. The set-point temperature (76.7 °C ± 5.6 C° (170 °F ± 10 F°)) of the water in the boiler recirculation loop is controlled using a digital temperature controller with a light-emitting diode (LED) display. When the lower temperature limit is reached, the damper opens ("On" Mode), and when the high temperature limit is reached, the damper closes ("OFF" Mode). The heat load demand has a direct effect on the frequency and the duration of each component of the "ON/OFF" cycle.

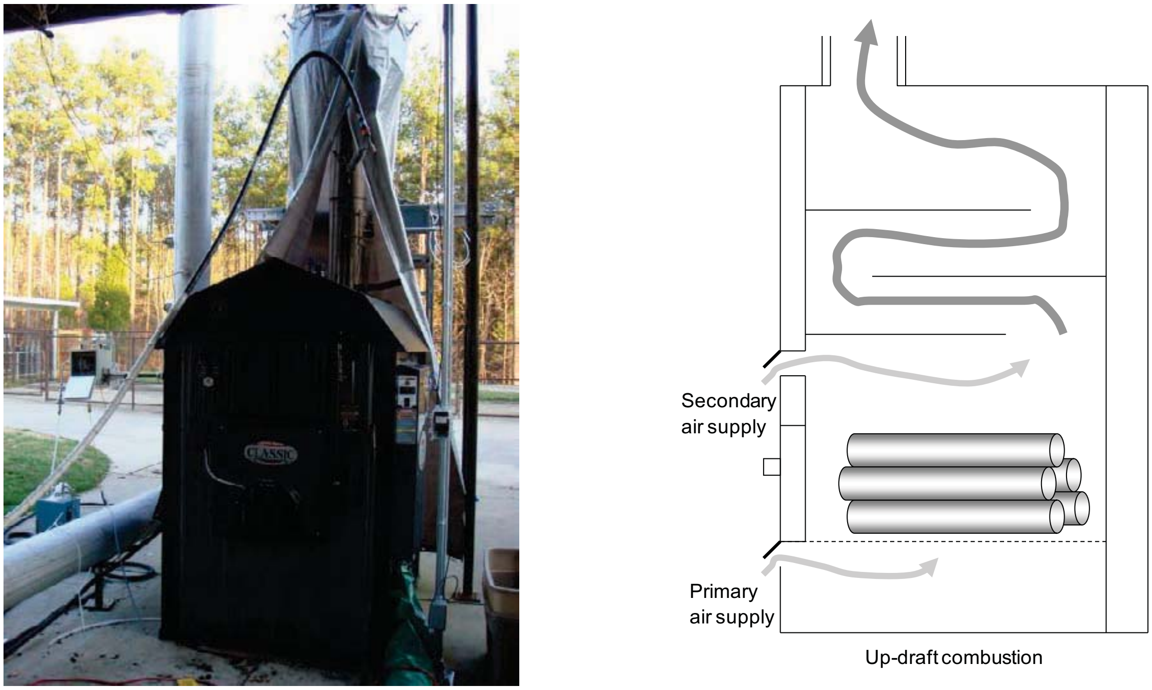


Figure 2-4. Conventional, Single Stage HH Unit and Illustration of an Updraft Combustion Unit.

In each test run the Conventional, Single Stage HH was pre-heated by burning a load of approximately 45 kg (100 lbs) of the tested fuel to establish a bed of hot coals. Thereafter the firebox was filled to capacity with wood logs to start the test, averaging a full charge of 115 kg ± 7 kg (254 lbs ± 15 lbs). For the oak wood and refuse tests, the average charge was 95 kg ± 5 kg (210 lbs ± 11 lbs) of oak wood supplemented with 4.5 kg (10 lb) of household refuse.

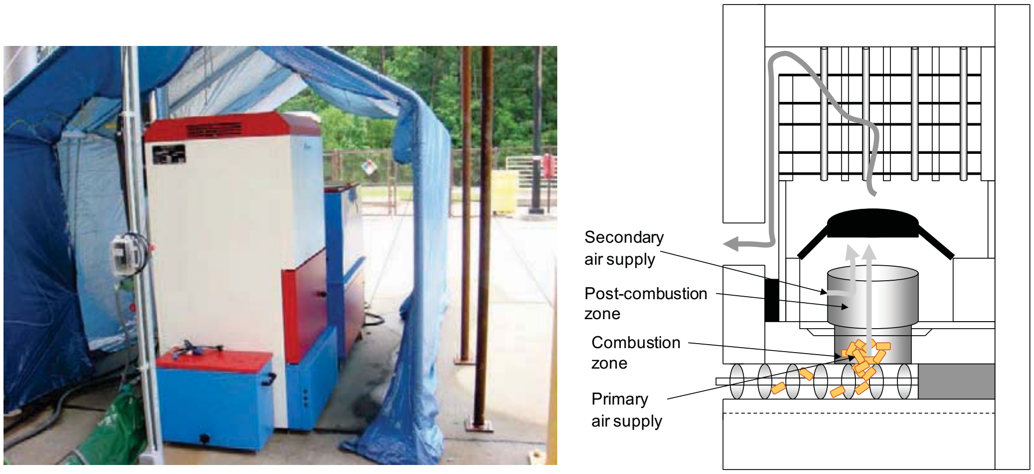
2.3.2 Three Stage HH

The second unit was the manufacturer's newer, high efficiency model, "Three Stage HH", designed for downdraft combustion (Figure 2-5). Its 8-hour generation capacity, based on the EPA output rating, is 160,000 BTU/hour (46.9 kW) and the total water capacity is 1703 L (450 gal). This unit uses a three-stage combustion process. First, the wood is gasified in the primary combustion firebox; then these hot gases are forced downward into a combustor where they are mixed with superheated air starting the secondary combustion process. The final combustion occurs in a reaction chamber where high temperatures increase the quality of the combustion process. The Three Stage HH uses an electronic controller with LED display that controls the temperature of the water in the circulation loop. The set-point temperature for this heater was set at 77 ^{o}C ± 6 C^{o} (170 °F ± 10 F°). When the lower limit is reached, the damper opens ("On" Mode), and when the high temperature limit is reached, the damper closes ("OFF" Mode). The heat load demand has a direct effect on the frequency and the duration of each component of the "ON/OFF" cycle. In each test run the Three Stage HH was pre-heated by burning a load of approximately 45 kg (100 lbs) of red oak a few hours before the test to establish a bed of hot coals. Thereafter the firebox was filled to capacity with logs to start the test, averaging a full charge of 200 lbs ± 2 lbs (91 kg ± 1 kg).

Figure 2-5. Three Stage HH and Illustration of a Down-draft Combustion Unit.

2.3.3 Pellet Heater (European Two Stage Pellet Burner Unit).

The third tested unit ("European Two Stage Pellet Burner" unit) (Figure 2-6) was a commercially available, pellet-burning HH rated at 40 kW (137,000 BTU/hour). Combustion of the fuel occurred on a round burner plate where primary air was supplied. Secondary air was introduced through a ring above the burner plate with fuel automatically screw-conveyed from the bottom. Operation of the screw feeder was regulated by a thermostat. During normal operation, the fans modulate based on the measured oxygen level in the exhaust gas and try to maintain 8-10% oxygen. Ash removal from the combustion chamber and cleaning of the heat exchanger tubes occurs at pre-set intervals.



Bottom fed pellet burner

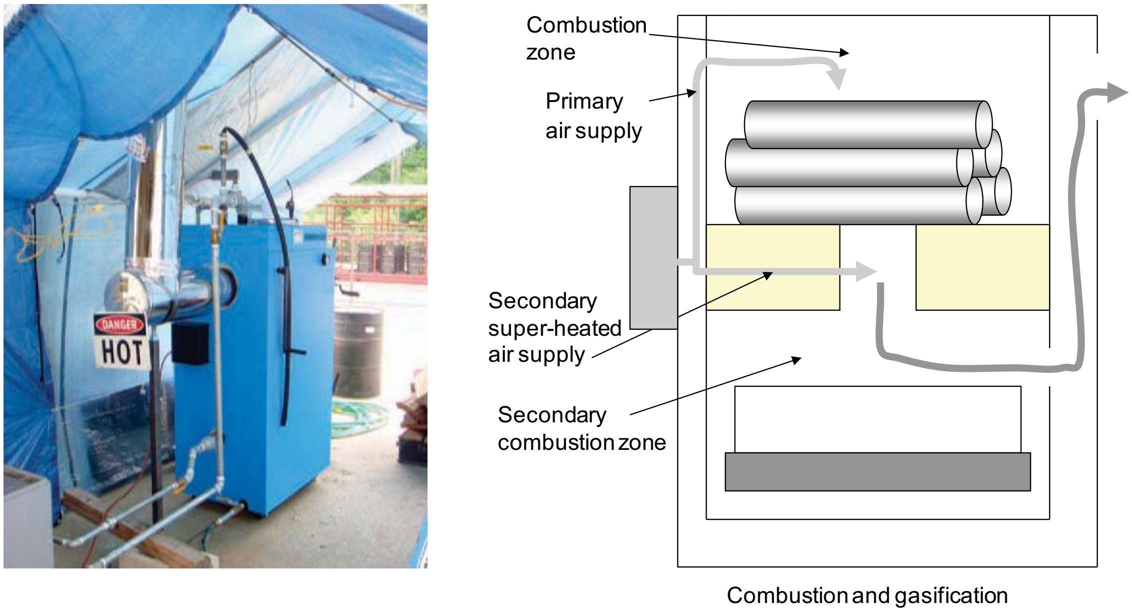
Figure 2-6. European Two Stage Pellet Burner and Illustration of a Bottom-Fed Pellet Combustion Unit.

The HH is fitted with an automatic startup and control unit that regulates the boiler operation according to operator-set parameters based on the fuel type and cleaning cycles. The heater output is controlled according to the difference between the actual and set temperatures of the water exiting the appliance. The unit was operated at 30,000-35,000 BTU/hour, considerably below its optimal firing of 41,000-137,000 BTU/hour, while satisfying the Syracuse profile.

2.3.4 U.S. Two Stage Downdraft Burner Unit.

The U.S. Two Stage Downdraft Burner gasification unit (Figure 2-7) is a two-stage heater with both gasification and combustion chambers. Multiple inlets provide air for ignition, combustion, and gasification. Air is added to the upper combustion zone to initiate combustion afterwhich this door is closed and a variable speed draft fan pulls the primary supply downward through the fuel, intensifying combustion. Finally, secondary superheated air is added to the lower portion of the chamber, finalizing combustion and resulting in a final combustion of the gases at temperatures higher than 980 °C (1800 °F). The temperature of the water jacket in the unit is controlled by an Aquastat draft fan controller. When the temperature of the water jacket is less than the set-point (71 °C (160 °F)), the speed of the draft fan is raised to maximum revolutions, forcing air into the combustion chamber. The fan remains on as long as the boiler is operational. In lieu of a heat storage tank, a 150,000 BTU/hour (29 kW) water-to-air heat exchanger (Hot

Water Fan Coil [HWFC] series) was installed in series with the primary heat exchanger to mimic the heat storage capabilities commonly associated with this unit.



Combustion and gasification

Figure 2-7. U.S. Two Stage Downdraft Burner Unit and a Two-Stage, Downdraft Combustion and Gasification Unit Schematic.

In each test, the unit was pre-heated with approximately 3-4 kg (6-9 lbs) of red oak for about 5 minutes after which the firebox was filled with 28-30 kg (62-66 lbs) split logs in order to start the tests. During the startup, an inner water circulation pump distributed heated water to prevent cold and hot water spots. The unit was operated under a scenario simulating the manufacturer's recommended hot water storage unit (822 gallons/150,000 BTU/hour) through use of the second heat exchanger.

2.4 FUEL CHARACTERISTICS

Two wood types (Figure 2-8) and one hardwood pellet brand were tested in this study. The primary fuel throughout the test program was locally obtained, seasoned, and quarter-split red oak (*Quercus rubra*), a common fuel for the Northeast that is also readily available in North Carolina. Red oak was also co-fired with 4.5% by weight of refuse to simulate situations in which residential waste is co-combusted for ignition or disposal purposes. The weight of this refuse fuel was set at an amount anticipated daily from a household. The refuse composition was derived from an earlier State of New York study (Lemieux, 1997). For these tests 10 lbs (4.5 kg) of waste was added on top of the wood charge. Unseasoned, local, split eastern white pine (*Pinus strobus*) was also used to test situations in the Northeast in which freshly cut and more marginal fuels are combusted. The length of all of the split wood was approximately 16-20 in (40-50 cm). Hardwood pellets were purchased locally in North Carolina from American Wood Fibers, USA (www.awf.com). The pellets are made out of sawdust from different wood processing industries and consisted of a blend of hardwood (no bark), mostly oak, with a diameter of 6 mm. The ultimate and proximate analyses of the fuels are reported in Table 2-2. Fuel moisture was determined using a handheld Delmhorst RDX-1 wood moisture meter for three to four measurements on each of eight pieces of split wood chosen randomly from each charge.

Figure 2-8. Fuels Used in the Study.

Table 2-2. Fuel Ultimate/Proximate Analysis.

Properties	Fuel		
	Red Oak	Pine	Pellets
Ash	1.46%	0.44%	0.52%
Loss on Drying (LOD)	22.52%	9.68%	7.24%
Volatile Matter	84.23%	88.50%	84.27%
Fixed Carbon	14.31%	11.06%	14.11%
C :Carbon	48.70%	51.72%	50.10%
Cl: Chlorine	38 ppm	36 ppm	44 ppm
H: Hydrogen	5.96%	6.57%	5.86%
N: Nitrogen	<0.5%	<0.5%	<0.5%
S: Sulfur	<0.05%	<0.05%	<0.5%
High Heating Value; KJ/Kg (Btu/lb)	19510 (8388)	21574 (9275)	19831 (8526)

2.5 TESTING PROTOCOL

The Conventional, Single Stage HH was tested using three fuel types: seasoned red oak as the baseline fuel, unseasoned white pine, and seasoned red oak with supplementary residential refuse (Table 2-3). Between each new fuel, the unit was “cleaned” by burning out with a hot burn of red oak. The Three Stage HH and U.S. Two Stage Downdraft Burner units were tested only with seasoned red oak. The European Two Stage Pellet Burner used hardwood pellets.

The objective of this testing effort was to characterize emissions over a realistic operating scenario which simulated a homeowner’s firing schedule and heat load demand. The anticipated firing schedule for typical batch-fired operation to meet the winter Syracuse cycle would include early morning and early evening charging.

Table 2-3. Unit/Fuel Test Matrix (all tests were done in triplicate).

Device	Red Oak	White Pine	Red Oak + Refuse*	Wood Pellets
Conventional, Single Stage HH	X	X	X	
Three Stage HH	X			
European Two Stage Pellet Burner				X
U.S. Two Stage Downdraft Burner	X			

* Refuse composition based on NYSERDA Survey (Lemieux et al., 1997).

Testing on the Conventional, Single Stage HH and Three Stage HH units commenced after establishing a suitable bed of coals with approximately 45-57 kg (100-125 lbs) of fuel before the start of a test. After the bed of coals was established, the main fuel charge was added by inserting pre-weighed charges of about 90-115 kg (200-250 lbs) to fill the firebox completely. Before each charging, the total mass of the fuel and the moisture content of a representative batch subsample were measured and recorded. After addition of the initial fuel charge, the Conventional, Single Stage HH and the Three Stage HH heater were allowed to cycle between low (smoldering) and high (flaming) burn, as required to meet the load demand established by the Syracuse heat load profile to the chilled water side of the heat exchanger.

The twice daily charging cycle and the temporally variant Syracuse load demand resulted in unique fuel cycle/load characteristics throughout the 24 hour day. In order to fully characterize emissions under all conditions of fuel cycle history and heat load demand, sampling on the Conventional, Single Stage HH was conducted throughout a 24-hour period. Nevertheless, it became apparent that the cost of 24-hour sampling made continuation of this practice prohibitive. After the red oak test, red oak with refuse, and white pine fuels with the Conventional, Single Stage HH were tested in triplicate, their emissions during the two successive 12-hour charging periods (1800 – 0600 and 0600 – 1800) were reviewed. A plot of ΔCO_2*Time versus cumulative Time (Figure 2-9), expressing the burn rate of the fuel, shows that the two periods were virtually identical despite the different time periods (0600-1800 and 1800-0600), probably due to similar heat demands, 0.346 MMBtu and 0.438 MMBtu, from the daylight hours (0600 – 1800) and nighttime hours (1800 – 0600), respectively. Thereafter, it was deemed sufficient to characterize only a single 12-hour night time load demand in order to approximate the emissions for the two 12-hour periods. The Three Stage HH unit was tested in triplicate for a 12-hour period with red oak. The European Two Stage Pellet Burner operates in an on-demand fuel mode and does not have a 12-hour fuel charge cycle, allowing the complete 24-hour fuel load to be effectively compressed into a six-hour period. The U.S. Two Stage Downdraft Burner unit was recommended for operation with heat storage, typically a high capacity water tank which supplies the heat storage load of the residence throughout the 24 hour period. A 50-gallon heat storage tank (the manufacturer recommends 600 gal) was added to the HH hot water loop; however, this system's limited heat storage capacity and flow restrictions would not allow the unit to maintain stead-state output. Due to limited funding, further efforts with heat storage were simulated, using a 150,000 BTU/hour water/air heat exchanger added in series with the water/water heat exchanger. These two heat exchangers were able to pull heat out of the water at a higher rate than required by the Syracuse load cycle to allow the U.S. Two Stage Downdraft Burner unit to continue combustion over a period of time of about 3.5 hours without overheating and causing a shutdown of the heater. A single full charge of the U.S. Two Stage Downdraft Burner unit was found to supply between 80 and 85% of the 24-hour daily energy load required by the Syracuse load cycle.

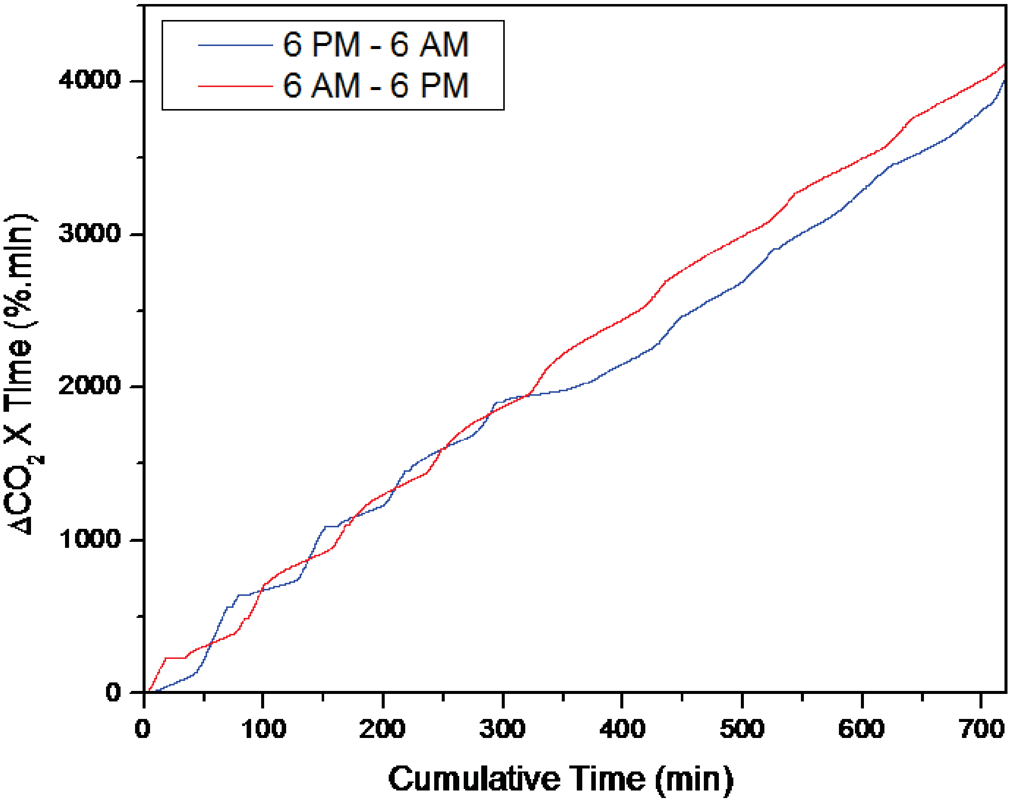


Figure 2-9. Temporal Carbon Dioxide Emissions for Two Successive Wood Charges, Conventional, Single Stage HH Unit.

2.6 SAMPLING AND MEASUREMENT METHOD

Emission sampling was conducted on a suite of pollutants as outlined in Table 2-4, consisting of both continuous measurements and time-integrated sampling to determine key appliance operating parameters as well as gas- and particle-phase emissions. Time-integrated sampling was begun immediately after adding the main fuel charge to the appliance, with continuous monitoring being conducted throughout the entire heat load demand cycle. The continuous measurements included temperature and flow throughout the system, as well as additional temperature measurements conducted in locations such as the stack and dilution tunnel. The frequency of filter change-outs was increased in response to excessive loading on the filters to avoid compromise of isokineticity.

2.6.1 PM Measurements

For the determination of total PM mass emissions on a time-integrated basis, the PM emission measurements adhered to the general procedures outlined in ASTM Method E2515 (ASTM, 2007). The sampling medium for this method consists of two glass fiber filters in series; a 110 mm primary filter for PM measurements followed by a 47-mm backup filter for volatile PM. The 110 mm primary filter was used to reduce the number of sampling train change-outs needed during each test. The PM sampling system draws a metered gas volume from the dilution tunnel through a pre-tarred, non-heated filter. Before each weighing, the balance calibration was checked with a National Institute of Standards and Technology (NIST) certified weight. The filters underwent a 24-hour desiccation before the first tare and gross weighing. The filters are returned to the desiccators for an additional 6 hours before the second weighing. If the 24-hour and 6-hour weighings agree to within 0.5 mg, the filter weight is accepted. The 6-hour desiccation/weighing cycles are repeated until two consecutive weights agree to within 0.5 mg.

For damper-regulated HH units, PM sampling occurred throughout the daily heat demand cycle using two different sampling trains: one train operated with the damper open (high PM loading), while the other one operated with the damper closed (low PM loading).

Table 2-4. Sampling and Analytical Methods.

Pollutant	Method(s)	Duration	Frequency	Sampling Location
Total PM	ASTM Method 2515-07	Integrated run	Up to 8 per cycle	Outdoor sampling platform
PAHs and SVOCs	EPA Method 0010, EPA Method 8270	Integrated run	Up to 4 per cycle	Indoor sampling platform
PCDDs/Fs	EPA Method 23	Integrated run	1 per cycle	Boiler stack
VOCs	EPA TO-15 SUMMA canister	3 min grab sample	Up to 4 per cycle	Indoor sampling platform
OC/EC	National Institute for Occupational Safety and Health (NIOSH) Method 5040	Grab sample	8-12 per cycle	Indoor sampling platform
Oxygen (O_2)	EPA Method 3A	Real time	Continuous	Boiler stack/Indoor sampling platform
CO	EPA Method 10B non-dispersive infrared (NDIR)	Real time	Continuous	Indoor sampling platform
CO_2	EPA Method 3A NDIR	Real time	Continuous	Indoor sampling platform
THC	EPA Method 3C flame ionization detector (FID)	Real time	Continuous	Indoor sampling platform
Aromatics	REMPI-TOFMS	Real time	Continuous	Indoor sampling platform
Particle Loading	Tapering element oscillating microbalance (TEOM)	Real time	Continuous	Indoor sampling platform
Particle Sizing	Electrical low pressure impactor (ELPI)	Real time	Continuous	Indoor sampling platform
N_2O	On-line GC	Grab sample	Multiple per cycle	Indoor sampling platform

REMPI-TOFMS - resonance enhanced multiphoton ionization/ time-of-flight mass spectrometry

2.6.2 Semivolatile (PAH) and Semivolatile Organic Sampling Train

Semivolatile and nonvolatile organic target compounds were sampled via EPA Method 0010 using a Modified Method 5 sampling train (http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/0010.pdf). The sampling techniques that were used in this test program were based on stack sampling applications.

The EPA Method 0010 sampling train consisted of a heated probe, heated box containing a cyclone and a filter, water-cooled condenser, water-cooled XAD-2 cartridge, impinger train for water determination, leak-free vacuum line, vacuum pump, and a dry gas and orifice meter with flow control valves and vacuum gauge. Sampling was conducted in the horizontal dilution tunnel at near ambient temperatures. Temperatures were measured and recorded in the heated box (set at 125 °C (257 °F)), at the impinger train outlet, at the XAD-2 cartridge outlet (maintained to be below ambient temperature), and at the inlet and outlet of the dry gas meter. Leak checks are conducted at the beginning and end of each sample run. Prior to sampling, all glassware, the probe, glass wool, and aluminum foil are cleaned following the Method 0010 cleaning procedure. The XAD-2 resin was spiked with pre-sampling PAH surrogates: naphthalene-d_8, acenaphthene-d_{10}, phenanthrene-d_{10}, chrysene-d_{12}, and perylene-d_{12}.

PAH sampling from the dilution duct at the indoor sampling platform throughout the 24-hour heat demand cycle used two different sampling trains: one train operated with the damper open (high PM loading), while the other one operated with the damper closed (low PM loading). The sampling temperature was near ambient due to the substantial dilution. One single low-loading train was used throughout the target running cycle, for all periods when the damper was closed. Up to four high-loading trains were operated for a maximum of 3-hours each when the damper was open over the entire running cycle.

2.6.3 Polychlorinated Dibenzodioxins and Polychlorinated Dibenzofurans (PCDDs/Fs)

EPA Method 23A (http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/0023a.pdf) was used to sample for polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDDs/Fs). This method is similar to EPA Method 0010 for semivolatile compounds and the same sampling train can be modified to sample for nonvolatile compounds. The modifications include pre-spiking the XAD-2 resin with carbon-13-labeled PCDD/F pre-sampling surrogates. The train consists mainly of a heated probe, heated box containing a cyclone and a filter, water-cooled condenser, water-cooled XAD-2 cartridge, impinger train for water determination, leak-free vacuum line, vacuum pump, and a dry gas and orifice meter with flow control valves and vacuum gauge. Temperatures were measured and recorded in the heated box (set at 125 °C (257 °F)), at the impinger train outlet, at the XAD-2 cartridge outlet (maintained to be below ambient temperature), and at the inlet and outlet of the dry gas meter. Leak checks are conducted at the beginning and end of each sample run. Prior to sampling, all glassware, the probe, glass wool, and aluminum foil are cleaned following the EPA Method 23 cleaning procedures.

Due to expectations of relatively low PCDD/F concentrations in the flue gas and the need to collect sufficient sample to exceed the method detection limits (MDLs), only one sample for PCDD/F was taken over the entire burning cycle. Filters were changed for the Method 23 samples during the test to minimize clogging of the sampling train, while using the same XAD-2 sorbent trap through the test cycle. Isokineticity was maintained during sampling when the damper was open; however, isokineticity was not maintained when the damper was closed due to the extremely low flow in the stack.

2.6.4 **Volatile Organic Sampling Train**

Volatile Organics were sampled via EPA Method TO-15 (http://www.epa.gov/ttnamti1/files/ambient/airtox/to-15r.pdf). A maximum of four samples were drawn from the dilution duct at the indoor sampling platform when the damper was open during the heat demand cycle. Isokineticity was not necessary for these samples because of the expected very short duration of the sampling (3 min). VOC loss to the walls of the dilution duct was expected to be minimal due to the high dilution rate and the near ambient temperatures.

2.6.5 **Organic Carbon/Elemental Carbon OC/EC Sampling**

National Institute for Occupational Safety and Health (NIOSH) Method 5040 (http://www.cdc.gov/niosh/docs/2003-154/pdfs/5040f3.pdf) was used for organic OC/EC analyses. The first step in the OC/EC sampling involves filter preparation. The 47 mm quartz filters are pre-ashed by placing them in an oven at 900 °C (1652 °F) overnight to remove any residual carbon present. Samples are collected directly from the chambers onto the pre-ashed quartz filters using an unheated stainless-steel probe, filter housing, and metered sampling pump. A properly loaded filter has a grey appearance. Black sample appearance indicates that the filter loading is too heavy and the filter should be changed. A maximum of eight grab samples were drawn in the dilution tunnel when the damper was open. Isokineticity was not possible, nor warranted, for these samples because of the very short duration (30 s) of the sampling.

In order to characterize the PM emission factors, it was necessary to analyze filter samples not only for OC and EC but also for inorganic ash content or fraction. X-ray fluorescence (XRF) analysis was performed using the quartz-fiber filters that had previously been used for PM mass analysis. A 47 mm punch of the

110 mm collection filter was made in order to fit within the XRF instrumentation. The XRF output values in kilocounts per second (kcps) were background-corrected using a blank quartz-fiber filter. The spectra were interpreted as the oxide of the element, consistent with combustion product analyses, and the elemental concentration was determined. A balance of the element concentrations with carbon fully characterizes the species composition in the sample.

2.6.6 Extraction and Analysis of Organics on PM

A select set of 100 mm glass fiber filters was solvent-extracted and analyzed by GC/MS to determine the organic chemical composition of the samples collected using the method developed by Hays and others (Hays et al., 2002 and references therein). Eighteen of these filter samples were extracted and analyzed between September14 and September 23, 2009. In the interest of experimental replication, an additional 18 samples were extracted on January 19, 2010, and chromatographed shortly thereafter. Several different target compound listings were analyzed and reported for the GC/MS part of the study: neutrals (e.g., polycyclic aromatic hydrocarbons (PAH) and *n*-alkanes), methoxyphenols, organic acids, and other polar organic compounds that required further derivatization. Extract derivatization was required for the organic acid and anhydro-sugar target compounds prior to injection. A Gerstel TDS 2 Thermal Extraction Unit coupled with an Agilent 6890 GC equipped with a low resolution 5973 mass selective detector (GC/MS) was used to perform all of the analytical work. The MS was operated in the full scan mode. The above experimental setup allowed for excellent peak shape to be realized for typically poorly responding polar and neutral organic components.

Samples were extracted using ultrasonication in a tertiary solvent system comprising 40% hexane, 40% benzene and 20% isopropanol (HIB) solution. Punches of 1.5 cm^2 (between 2-5, depending on load) of each filter were placed inside a 7-mL amber vial. Next, 3.0 mL of HIB solution was placed into each amber vial and 15-45 µL of internal standard solution was added, depending on the filter weight. Samples were sonicated for 45 minutes, concentrated to 400 µL, and then transferred to a 2 mL injection vial with glass insert. Samples containing high particle loads were allowed to settle for 1 hour, and a 1 mL aliquot of the 3 mL extract was concentrated. All sample contents were concentrated to a final volume of 300 µL and stored for thermal extraction (TE)/GC/MS analysis. A final volume of 300 µL for the extracts ensured that the HIB solvent mixture remained at a similar starting ratio for solubility concerns. No filtration step was performed to ensure low background. The 300 µL extract was analyzed for neutral organic compounds and also for methoxyphenols. After multiple injections, 45 µL of the extract was allowed to react for at least 1 hour with 45 µL of methylating reagent (diazomethane) and 10 µL of methanol for organic acid derivatization. Finally, a 10 µL aliquot of the sample extract was mixed with 50 µL of silylating reagent and heated for 30 minutes at 70 °C (158 °F) prior to injection for anhydro-sugars and related polar organic compounds.

Multi-level calibrations were performed for each target compound except for the methoxyphenols and those compounds analyzed following silylation. A mid-level check standard was prepared and analyzed as a continuing calibration check for the methoxyphenols. A freshly prepared anhydro-sugar standard was used for daily calibration due to a response fluctuation noticed for certain compounds. The ^{13}C-galactosan internal standard had previously been determined to be viable (after sylilation) only over a 7-hour reaction time. The sylilation reaction for ^{13}C-galactosan appeared to break down after this time period relative to other compounds, causing low recovery to occur for all associated target compounds and for matrix spike compounds when spikes were analyzed after seven hours. All samples therefore had to be analyzed inside this time constraint. While this process limited the number of samples that could be analyzed per day, good-to-fair matrix spike recoveries were achieved for most compounds under these conditions. Relative response factors at each of the lowest calibration levels were dropped when the overall relative percent deviation (RPD) was greater than 30%. Only a few cases existed that had the RPD% greater than 30% with most below 10% RPD.

Quality Assurance and Quality Control (QA/QC). Proper QA/QC was critical for defining sample quality. Individual compound concentrations were bracketed by a laboratory blank and a matrix spike. Each laboratory blank revealed the background level while the matrix spike demonstrated method effectiveness. Overall, blanks showed low background interferences and spike recoveries were within acceptable limits. All exceptions are noted in the raw data. Mid-level calibration checks were analyzed and reported every 10 samples except for the silylation compounds that were calibrated daily. The data were reported in ppm units (µg/g). Replicated GC/MS injections were performed on greater than 10% of all the samples. Excellent agreement was determined (in most cases) by comparing individual components in all classes of compounds. In addition, Red Oak sample 22 was extracted a second time to determine the efficiency of extraction of the microextraction technique described. Greater than 95% extraction efficiency was realized in each of the four reported target classes.

MDL data were used to give greater meaning to the submitted data set. An estimated detection level below the practical quantification limit (PQL) was chosen in most cases as the level that was replicated seven times in accordance to SW 846 guidelines for determination of MDLs. The standard deviation (STDV) between the values determined from this process was multiplied times 3.14 (Student's t chart values for seven repetitions) to determine each MDL.

The neutral and organic acid calibration curves had a few components listed that are not present in the standard but were quantified along with the other target analytes. Quantitative values for these components are estimates and use relative response factors from closely eluting similar compounds. The qualitative identifications for these components are determined through fragmentation library matching and also by their retention behavior. In general, a very close approximation can be made for estimated values such as alkanes because of the similar response noticed in the calibration curve for components that were present in the standard.

Target analyte validity was determined by isotopic ratio and relative retention times. Because the GC was equipped with electronically programmable control (EPC), retention times did not shift much through the analysis period. This retention time stability was critical for the predictability of target analyte components.

Tentatively identified compounds (TICs) were added to the final report and can be found on the individual worksheets in the neutral data. One sample from each HH condition was selected to have TICs worked up because it is likely that the associated samples had similar TIC evolution. Quantitative values for the TICs are estimated values based solely on the closest internal standard response but were worked up anyway to give the viewer a feel for the relative concentration of these components.

Special considerations had to be made for the first eluting internal standard in several of the red oak sample organic acid listings due to co-elution with 1,2,3-trimethoxybenzene (ion at mass 77). Integration was performed to only take the portion of the main target ion at mass 77 that had secondary and tertiary ions (masses 99 and 105) as markers to help define where to integrate. In addition, some of the phthalic acid internal standard concentrations were quite low but still present. This low value affected the sensitivity for the corresponding non-deuterated homologs.

A compensation factor was used to correct the levoglucosan data reported with the first set of 18 samples. A freshly prepared levoglucosan standard revealed that the levoglucosan standard that is normally used for calibration was incorrect and very low, causing the reported data to be about 409% too high. This error was determined to be consistent and backed up by a third party standard, so a factor was developed to compensate exactly for the error. This factor was formed by direct comparison of the two standards and yields a real-time comparison factor for the most accurate results. The latter 18 samples used the correct and recently-prepared levoglucosan standard for quantification. After the earlier data were corrected, both sets of data had levoglucosan values that were comparable and seemingly quite realistic.

2.6.7 Continuous Emissions Sampling

Continuous measurements of criteria gas phase pollutants were performed in the stack and in the dilution tunnel, with toxic aromatic pollutant concentrations and PM number and size monitored in the dilution tunnel only. Also, in certain tests, CH_4 and N_2O were also continuously measured in the dilution tunnel. The following sections describe the continuous measurements conducted during the program.

Criteria Pollutants Measurements. Several primary gaseous flue gas constituents were analyzed continuously using a CEM system that includes monitors for CO, CO_2, oxygen (O_2), and THC. The analog signal outputs of the analyzers were connected to a computer-based data acquisition system (DAS). The DAS uses a process control (PC) and an IOtech® analog-to-digital converter (IOtech® Personal DAQ 55/56 (Cleveland, Ohio)). Sample gases were extracted for CEM analysis through a fixed stainless-steel probe at each location. The sample gases were transported in Teflon polytetrafluoroethylene (PTFE) tubing, through a Hankison dryer and a particulate filter, and on to the CEM system. The sample gas is then split so that a portion of the flow passes through a Drierite canister for further drying before going to the individual analyzers for O_2, CO_2, and CO analysis. The other portion of the sample goes directly to the nitrogen oxide (NO_X) analyzer as Drierite is a NO_X-absorbing material. The analog outputs of the analyzers are connected to a DAS for monitoring and recording with a sampling frequency set to 30 seconds.

N_2O Analyzer. Nitrous oxide (N_2O) concentrations were determined using a modified GC equipped with an electron capture detector (Ryan et al., 1993). This system is equipped with a two-position 10 port valve that enables sample back-flushing to eliminate unneeded later-eluting components that are not desired (including likely moisture). A slip stream of the post-combustion gas stream was pulled through a fixed 1 mL sample loop via a small vacuum pump. N_2O concentration ranges between 300 and 800 ppb can be sampled successfully using this technique (Ryan et al., 1993).

CH_4 Analyzer. CH_4 was measured using a J.U.M. Engineering Model 109A CEM that features a dual detector/dual electrometer design to provide three continuous, simultaneous signals of:

- THCs
- Methane/Only
- Nonmethane Hydrocarbons (NMHC)

The analyzer is a compact 48 cm (19 in) rack-mounted analysis system using the flame ionization detector (FID) principle. The sample pump, the sample filter and all pressure and flow-regulating components are built in a modular design which allows easy maintenance. This unit was rented and was used only on a single experiment (the single stage Conventional heater with red oak wood) due to cost.

O_2 Analyzer. Two O_2 analyzers were used at the stack and at the outdoor dilution tunnel sampling platform location. Both analyzers are Beckman Model 755 oxygen analyzers. The analyzer operates by utilizing the paramagnetic property of oxygen and adheres to EPA Method 3A. Other gases present in significant concentration in the stack effluent do not exhibit this property. A three-point calibration was performed prior to the testing sequence using an oxygen-free standard gas (typically high purity nitrogen [N_2]), a suitable span gas at or near the upper range limit, and a mid-range concentration gas to check the linearity of each analyzer The measurement range of the two analyzers is 0 to 25%.

CO and CO_2 Analyzers. Two CO monitors were used at the stack and at the indoor tunnel sampling platform location. The CO analyzers are a Thermo Electron Model 48 gas filter correlation CO analyzer and a Rosemount 880A analyzer, respectively. A California Analytical ZRH CO_2 analyzer was used at the stack location. The analyzers operate by directing identical infrared beams through an optical sample cell and a sealed optical reference cell. A detector located at the opposite end of the cells continuously measures the difference in the amount of infrared energy absorbed within each cell. This difference is a measure of the concentration of the component of interest in the sample. The CO_2 analyzer adheres to EPA Method 3A principles, the CO analyzer adheres to EPA Method 10A. A three-point calibration was performed prior to the testing sequence using an oxygen-free standard gas (typically high purity N_2), a suitable span gas at or near the upper range limit, and a mid-range concentration gas to check the linearity of each analyzer. A calibration is accomplished with a high purity N_2 gas and a known concentration sample of the span gas.

Total Hydrocarbon (THC) Analyzer. Total unburned hydrocarbons (HC) were measured at the indoor tunnel sampling platform location using a California Analytical Instrument Model 300M-heated-FID (HFID). The analyzer utilizes the principle of FID to determine the THC within a gaseous sample. A gaseous sample becomes ionized in the flame and the electrostatic field causes the charged particles to migrate. The migration creates a small current. This current is measured by the amplifier and is directly proportional to the HC concentration in the sample. The sampling adhered to EPA Method 3C.

Aromatic Organic Pollutants. The resonance enhanced multiphoton ionization - time-of-flight mass spectrometry (REMPI-TOFMS) instrument was applied as a CEM for aromatic organic air pollutants at moderate to high concentrations (mid-ppt to ppm level or higher). The REMPI technique consists of the laser-induced ionization of the molecule of interest using a two-step resonant process. A first ultraviolet photon is absorbed and the subsequent absorption of a second ultraviolet photon brings the internal energy of the molecule above its ionization energy to form a molecular ion. The spectral “fingerprint” of a specific molecule/ion can be obtained by changing the wavelength of the laser, which is, in general, unique for each target compound of interest. The created ions are extracted into a TOFMS. The ion extraction optics and relatively long field-free drift tube separate the masses up to a mass resolution of 1:1000, which is more than sufficient for the mass discrimination of carbon isotopes in aromatic molecules, for example. The combination of REMPI and TOFMS makes it possible to measure trace gas concentrations at high sensitivity, selectivity and virtually in real time, much faster than conventional GC/MS techniques.

REMPI, as used in this application, is a soft ionization technique. Therefore, no significant fragmentation takes place and a mass spectrum consists of a single peak at the mass of the compound. To further improve selectivity with the flow, the gases are introduced through a pulsed valve with a small opening diameter, as pulses. The following adiabatic expansion into vacuum creates a supersonic in which rotational and vibrational cooling of the molecules takes place. Hence, the population in the electronic ground state that was initially spread over a large number of (ro-) vibrational states is transferred into only the lowest (ro-) vibrational states. This cooling results in more discernible spectra, enhancing the selectivity. Since the ion signal is proportional to the population of the initial state, transitions starting from this smaller set of populated states appear stronger than in the case where the population is spread over a larger number of initial states.

The experimental setup is shown in Figure 2-10. The experimental setup consists of a pulsed Nd:YAG-OPO laser system with frequency doublers that provide ultraviolet (UV) laser energy pulses, of approximately 2 mJ/pulses, at a 10 Hz repetition rate. The pulsed valve provides the adiabatic expansion of the gas. The laser beam intersects with the gas in a region of expansion where no additional cooling takes place but where the density is still high. The ions are extracted from the ionization region using specially-designed ion extraction optics (Kaesdorf design) that compensates for the presence of the gated valve near the ion optics and compensates for the supersonic velocity of the compounds in the expansion. Following the extraction, the ions fly through a field-free region in order to produce a mass separation. An ion reflector is used to compensate for the different initial velocities of the compounds. A multi-channel plate is used as the ion detector. All signals are transferred to a computer for visualization and data storage.

Benzene, toluene, ethylbenzene, xylenes, styrene, and gaseous PAHs are among the non-exclusive list of compounds that were targeted for measurement with the REMPI.

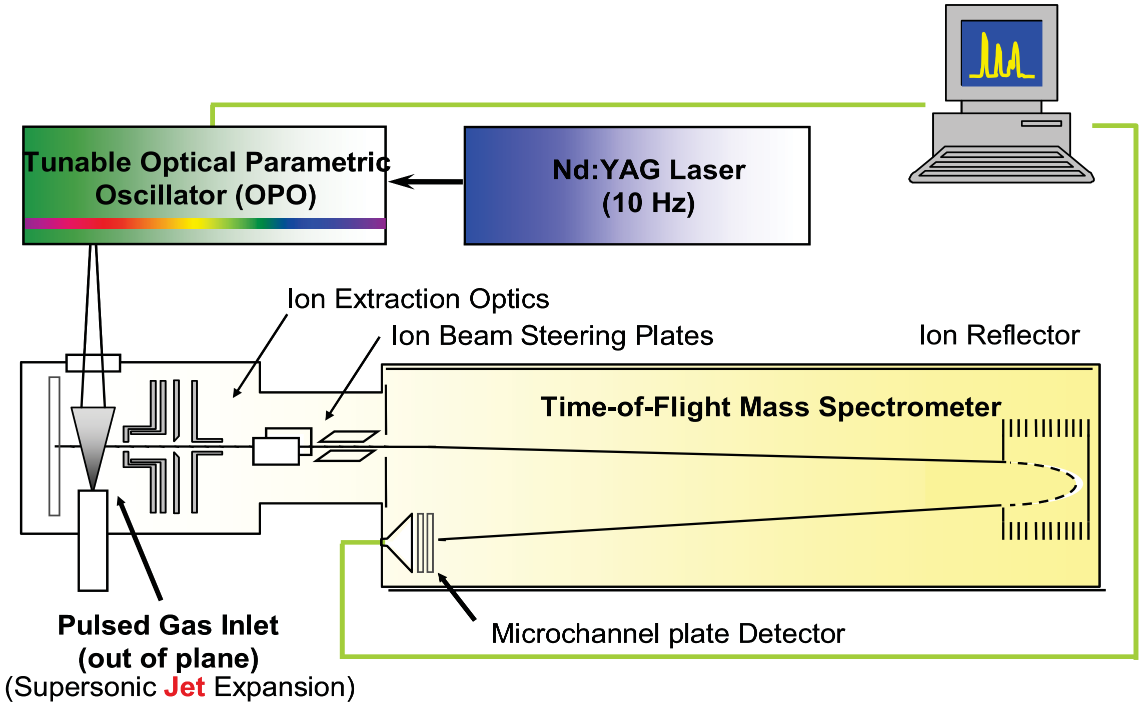


Figure 2-10. Experimental Setup of the REMPI Instrument.

2.6.8 Particle Size Distribution (PSD)

A Dekati electrical low-pressure impactor (ELPI) was used to provide real-time particle number concentrations and size distributions. The ELPI generates a particle size distribution (PSD) by first charging the particles with a unipolar diode charger, which charges the particles based on geometrical diameter, before the particle enters a cascade impactor. The charged particles impact the stages on the impactor based upon their inertia, i.e., their aerodynamic diameter. A multi-channel electrometer measures the charge of the particles as they land on each of the stages giving current values for each stage, in f-Amps. These current values are then converted to number of particles on each stage and, if the density of the particle is known, the mass of the particles on each of the stages can also be found.

The differential number distribution, dN/dlog (Dp), is determined from the current distribution by dividing the current for each channel by a conversion factor. This conversion factor was calculated by the manufacturer from the charger efficiency for the midpoint diameter of each impaction stage. The stage midpoint diameter is the average of the cut-points of the stage of interest and the stage above. These midpoint diameters are determined for both the Stokes diameters. The particle number is then normalized by dividing by the logarithmic width of the stage in terms of Stokes diameter.

Daily QC checks on the ELPI were performed by zeroing the electrometer using a flush of high-efficiency particulate air (HEPA)-purified air and by monitoring the current profiles of the ELPI while it samples room air and HEPA purified room air. Because of the heavy loading, the impaction stages were cleaned before each test.

2.6.9 Particulate Loading with the Tapered-Element Oscillating Microbalance (TEOM)

The R&P Series 1400a Ambient Particulate Monitor uses tapered-element oscillating microbalance (TEOM) technology to measure PM mass concentrations continuously. The Series 1400a monitor is a gravimetric instrument that draws the sample through a filter at a constant flow rate, continuously weighing the filter and calculating near real-time (10 minute) mass concentrations of particles less than 10 µm. The sample first passes through a PM_{10} inlet, then enters the mass transducer where the flow passes through a filter made of Teflon PTFE-coated borosilicate glass fiber. This filter is weighed every 2 seconds. The difference between the filter's current weight and initial weight gives the total mass of collected PM. The tapered elements at the heart of the mass detection system are a hollow tube, clamped on one end, and free to oscillate at the other. The tapered element oscillates precisely at its natural frequency. The tapered element is in essence a hollow cantilever beam with an associated spring rate and mass. As in any spring-mass system, if additional mass is added, the frequency of the oscillation decreases. For this study, the TEOM is used as a (near) real-time instrument to follow the PM loads through the 24-hour heat demand load cycle. EPA has designated the R&P TEOM Series 1400a PM_{10} Monitors as an equivalent method for the determination of 24-hour average PM_{10} concentrations in ambient air. Previous scoping tests had confirmed the good agreement between TEOM measured mass concentrations and EPA Method 5 measurements.

2.7 EFFICIENCY CALCULATIONS

Three different efficiencies were evaluated to assess the performance of different parts of the HH system. These efficiencies are described below.

2.7.1 Combustion Efficiency.

Combustion efficiency is used to evaluate the ability of the HH unit to burn the fuel completely. Combustion efficiency is a measure of the completeness of carbon oxidation and was calculated by measurement of CO_2 divided by CO_2 + CO +THC and evaluated throughout each run.

2.7.2 Boiler Efficiency

Boiler efficiency is used to determine the effectiveness of the heat exchanger to transfer the heat generated from the combustion process to the water. Boiler efficiency takes into account the energy lost in the flue gas through sensible and latent losses as well as from unburned or partially burned fuel. Sensible losses are those associated with temperature changes such as raising the combustion air from ambient temperature to the flue gas temperature. Latent losses relate to the energy required for phase changes including evaporation of wood moisture. Boiler efficiency is calculated using the "Heat Loss Method" that consists of subtracting the flue gas heat losses from the higher heating value (HHV) of the fuel burned. The calculation does not account for radiation/convection losses from the heater jacket and transfer lines and the effectiveness of the external heat exchanger. The energy losses in the system include sensible heat losses from the stack, latent heat loss due to hydrogen conversion to steam, heat loss due to moisture in the fuel and air, and heat losses from incomplete combustion resulting in formation of CO rather than CO_2, as indicated below:

$$n_{combustion} = 100 - \frac{Q_{stack}}{Q_{input}} * 100$$

$$Q_{stack} = Q_{dg} + Q_{wm} + Q_{lh} + Q_{CO}$$

where :

Q_{dg} = the sensible heat losses from the flue gas
Q_{wm} = the heat losses due to moisture in the fuel
Q_{lh} = the heat loss due to latent heat from burning hydrogen
Q_{CO} = the heat loss from the formation of CO.

2.7.3 Thermal Efficiency

Thermal efficiency is used to determine the overall ability of the system to generate useful heat by transferring it to meet the load demand (thermal efficiency). Thermal efficiency in this project was defined as the heat delivered to the water/water heat exchanger (heat output) in Figure 2-1 divided by the calculated energy input of the fuel (HHV).

2.8 EMISSION CALCULATIONS

The conventional extractive sampling techniques are based on established EPA Methods, or their modified versions, adapted to this particular HH source. The data obtained from conventional extractive methods were considered "reference" data and used to evaluate the data obtained from the continuous measurement techniques.

For each test run, emission factors for the target pollutants were reported in terms of mass of fuel burned, energy input, and energy output.

The mass emission for a set burn time t, M_x for each target compound is calculated in the dilution tunnel as follows:

$$M_x = \sum_t \left(C_{x,t} - C_{x,a}\right) \cdot V_t$$

where

$C_{x,t}$ is the concentration (mass/volume) of the target compound x, sampled at time t
V_t is the volumetric flow rate (volume/time) in the dilution tunnel at time t.
$C_{x,a}$ is the ambient concentration (mass/volume) of the target compound x

The mass of fuel burned, M_f was calculated indirectly by adding the carbon emitted by the fuel and converting this value to mass of fuel using the fuel carbon composition determined by an ultimate/proximate analysis. The equation used to determine the mass of fuel burned is:

$$M_f = \sum_t \sum_i \left(M_{i,t} - M_{i,a}\right) \cdot C_{i,t}$$

$M_{i,t}$ and $M_{i,a}$ are the sum of the carbon fractions in the criteria pollutants (i = CO, CO_2, and THC) and the corresponding mass of carbon in the dilution air, respectively, emitted during a burn time t.

$C_{i,t}$ is the fraction of the carbon in the fuel (dry basis), determined using an independent fuel ultimate/proximate analysis

Emission factors were calculated and reported in three units:

1. Emissions per unit of mass of fuel burned

The emission factor per mass burned × $EF_{m,x}$ is calculated as:

$$EF_{m,x} = \frac{M_x}{M_f}$$

2. Emissions per unit of energy input

The emission factor per energy input $EF_{Input,x}$ is defined as the mass of pollutant (x) per fuel energy generated by the HH unit. This emission factor is calculated as follows:

$$EF_{Input,x} = {}^{EF_{m,x}}\!\Big/_{HHV_f}$$

HHV_f is the high heating value of the fuel

3. Emissions per unit of energy output

The emission factor per energy output is defined as the mass of pollutant (x) discharged per useful room heat produced by an HH unit. This emission factor is calculated as follows:

$$EF_{output,x} = EF_{Input,x} \cdot \eta_t$$

where η_t is the thermal efficiency of the heater defined as:

$$\eta_t = \frac{Q_o}{Q_i}$$

where Q_o is the useful output heat calculated using the inlet and outlet temperatures of the cooling water loop used to simulate the heat load demand, and Q_i is the energy input to the heater during the burn time and defined as:

$$Q_i = M_f \cdot HHV_f$$

Calculation of temporal emission factors:

The temporal emission factors were calculated for a complete cycle defined as the lapse time between two successive damper opening times. This cycle will include the emission carryover when the damper is closed. These temporal emission factors better characterize the overall emission factors over time.

Calculation of dilution ratio:

Dilution ratio was based on the concentration of CO_2 between the stack and the dilution tunnel and calculated as follows:

$$\varphi = \frac{CO_{2_{ambient}} - CO_{2_{stack}}}{CO_{2_{ambient}} - CO_{2_{Dilution}}}$$

If φ is less than 1,

$$CO_{Stack} = CO_{Dilution}$$

If φ is greater than 1, then

$$CO_{Stack} = CO_{dilution} \cdot \varphi$$

Dilution ratios are unit-specific and can vary considerably with time, especially for units that are damper-modulated (see Figure 2-11). Pollutant concentrations were determined in the dilution tunnel where the flow rate remains relatively constant. The corresponding concentrations in the stack are higher by the factor of the dilution ratio.

2.9 EMISSION RESULTS

2.9.1 Overview

Six HH unit type-fuel combinations were tested in triplicate over a five-month period using the Syracuse January heat load profile. The test matrix of Table 2-3 resulted in the following measurements on the Conventional, Single Stage HH unit burning split red oak (Table 2-5), white pine (Table 2-6), and red oak with refuse (Table 2-7); on the Three Stage HH unit with red oak (Table 2-8); on the European Two Stage Pellet Burner unit with hardwood pellets (Table 2-9); and on the U.S. Two Stage Downdraft Burner unit with red oak (Table 2-10).

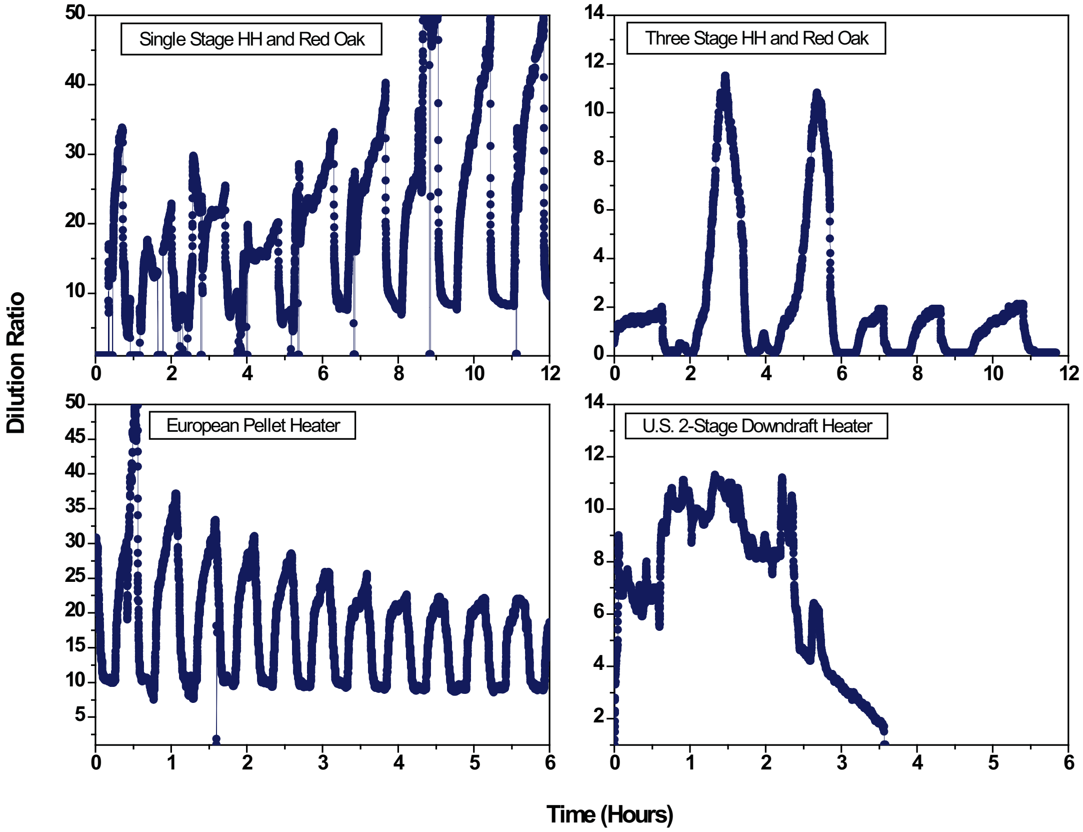


Figure 2-11. Representative Dilution Ratios for the Tested Units.

Table 2-5. Test Details and Emission Sampling Performed on the Conventional, Single Stage HH Firing Red Oak.

	Red Oak		
	03/18-19/2009	**03/24-25/2009**	**03/25-26/2009**
Test Duration	22.74 h	23.08 h	23.06 h
Number of damper openings	17	18	18
Fuel load per 12 h	105 +117 kg	110 +116 kg	129 +112 kg
BTU Input (MMBTU)$^{\&}$	2.53	3.74	3.75
Fuel Moisture (%)	27 ± 6	26 ± 9	30 ± 8
N_2O	B (~@30 min)	B (~@30 min)	B (~@30 min)
O_2	✓	✓	✓
CO	✓	✓	✓
CO_2	✓	✓	✓
CH_4		✓	✓
THC	✓	✓	✓
Jet REMPI	✓	NM	NM
PAH	5	5	5
PCDD/F	1	1	1
VOC	4	NM	NM
TEOM	✓	✓	✓
PM	B	B	B
ELPI	✓	✓	✓

✓ – continuously sampled

B – batch samples

– number of measurements

NM – not measured

& - Higher heating value

Table 2-6. Test Details and Emission Sampling Performed for the Conventional, Single Stage HH Firing White Pine.

	White Pine		
	04/20-21/2009	**04/21-22/2009**	**04/22-23/2009**
Test Duration	11.54 h	9.68 h	9.46 h
Number of Damper Openings	9	9	9
Fuel load	106 kg	116 kg	120 kg
BTU Input (MMBTU)[&]	1.37	1.17	1.07
Fuel Moisture (%)	37 ± 4	36 ± 9	34 ± 7
N_2O	B (~@30 min)	B (~@30 min)	B (~@30 min)
O_2	✓	✓	✓
CO	✓	✓	✓
CO_2	✓	✓	✓
THC	✓	NM	NM
Jet REMPI	✓	NM	NM
PAH	4	4	4
PCDD/F	1	1	1
TEOM	✓	✓	✓
PM	B	B	B
ELPI	✓	✓	✓

✓ - continuously sampled

B – batch samples

\# - number of measurements

NM – not measured

& - Higher heating value

Table 2-7. Test Details and Emission Sampling Performed for the Conventional, Single Stage HH Firing Red Oak + Refuse.

	Red Oak + refuse		
	04/27-28/2009	**04/28-29/2009**	**04/29-30/2009**
Test Duration	9.36 h	9.67 h	12 h
Number of Damper Openings	8	8	8
Fuel Load, Logs	91 kg	99 kg	95 kg
Fuel Load, Refuse	4.5 kg	4.5 kg	4.5 kg
BTU Input (MMBTU)&	1.14	1.10	Not available
Fuel Moisture (%)	40 ± 9	38 ± 7	37 ± 8
N_2O	B (~@30 min)	B (~@7.2 min)	B (~@7.2 min)-
O_2	✓	✓	✓
CO	✓	✓	✓
CO_2	✓	✓	✓
THC	✓	✓	✓
JetREMPI	NM	✓	NM
PAH	4	4	4
PCDD/F		1	1
TEOM	✓	✓	✓
PM	B	B	B
ELPI	✓	✓	✓

✓ - continuously sampled,

B – batch samples

- number of measurements

& - the heat content of the refuse was assumed to be equal to the heat content of Red Oak; Higher heating value

NM – not measured

Table 2-8. Test Details and Emission Sampling Performed for the Three Stage HH Firing Red Oak.

	Red Oak		
	05/11-12/2009	**05/12-13/2009**	**05/13-14/2009**
Test Duration	11.77 h	11.56 h	9.69 h
Number of Damper Openings	6	6	6
Fuel Load	91 kg	91 kg	92 kg
BTU Input (MMBTU)[&]	1.19	1.29	1.21
Fuel Moisture (%)	30 ± 6	25 ± 5	26 ± 5
N_2O	B (~@7.2min)	No	no
O_2	✓	✓	✓
CO	✓	✓	✓
CO_2	✓	✓	✓
THC	✓	✓	✓
Jet REMPI	NM	✓	NM
PAH	2	2	2
PCDD/F	1	1	1
TEOM	✓	✓	✓
PM	B	B	B
ELPI	✓	✓	✓

✓ - continuously sampled,
B – batch samples
- number of
measurements NM – not
measured
& - Higher heating value

Table 2-9. Test Details and Emission Sampling Performed for the European Two Stage Pellet Burner Firing Hardwood Pellets.

	Wood Pellets		
	06/10/2009	**06/11/2009**	**06/12/2009**
Test Duration	5.63 h	5.33 h	5.79 h
Number of Cycles	10	12	10
Fuel Load	NM		
Fuel Moisture (%)	7.24		
BTU Input (MMBTU)$^{\&}$	0.46	0.38	0.38
N_2O	B (~@7.2min)	No	no
O_2	✓	✓	✓
CO	✓	✓	✓
CO_2	✓	✓	✓
THC	✓	✓	✓
JetREMPI	✓	✓	✓
PAH	1	1-NTBA	1-NTBA
PCDD/F	1 cumulative sample for all three runs		
TEOM	✓	✓	✓
PM	B	B	B
ELPI	✓	✓	✓

✓ - continuously sampled

NTBA – not to be analyzed (lack of $s)

B – batch samples

- number of measurements

NM – not measured

& - Higher heating value

Table 2-10. Test Details and Emission Sampling Performed for the U.S. Two Stage Downdraft Burner Unit Firing Red Oak.

	Red Oak		
	07/08/2009	**07/09/2009**	**07/10/2009**
Test Duration	3.55 h	3.58 h	3.58 h
Number of Damper Openings	Always Open	Always Open	Always Open
Fuel Load	33 kg	31 kg	33 kg
BTU Input (MMBTU)[&]	0.53	0.47	0.72
N_2O	No	B (~@7.2min)-	No
O_2	✓	✓	✓
CO	✓	✓	✓
CO_2	✓	✓	✓
THC	NM	✓	✓
Jet REMPI	NM	NM	✓
PAH	NM	NM	✓
PCDD/F	1	1	1
VOC	NM	NM	3
TEOM	✓	✓	✓
PM	B	B	B
ELPI	✓	✓	✓

✓ - continuously sampled

B – batch samples

- number of measurements

NM – not measured

& - Higher heating value

2.9.2 Energy

Syracuse Heat load Demand Cycle Simulation. The ability of the heat transfer control system to match the Syracuse heat load profile is shown in Figure 2-12 for a representative run of the Conventional, Single Stage HH unit burning red oak. The system provided a good match between the required and supplied heat load cycles. The actual cycle underestimates the Syracuse heat load demand cycle by 4%, with a correlation coefficient of 0.96.

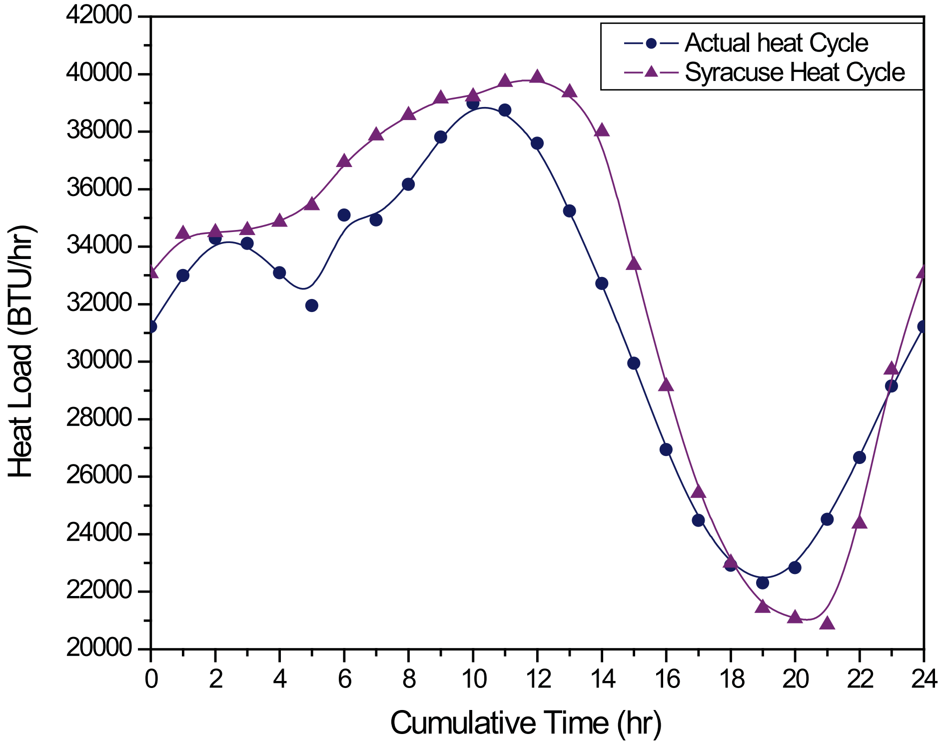


Figure 2-12. Actual 24-Hour Heat Supply Cycle versus the Required Syracuse Heat Load Cycle (Conventional, Single Stage HH, Red Oak, 6 PM to 6 PM Period).

Temporal Heat Generation Rate. The heat generation rate is commonly known to be dependent on parameters such as the fuel charge mass and moisture, the weight of the existing hot coal bed, and the frequency and period of damper openings and closings. The temporal heat generation rates for all trials of the six unit/fuel combinations are shown in Figures 2-13 through 2-18 along with the heater inlet and outlet water temperatures. These figures highlight the operating characteristics and reproducibility of the units.

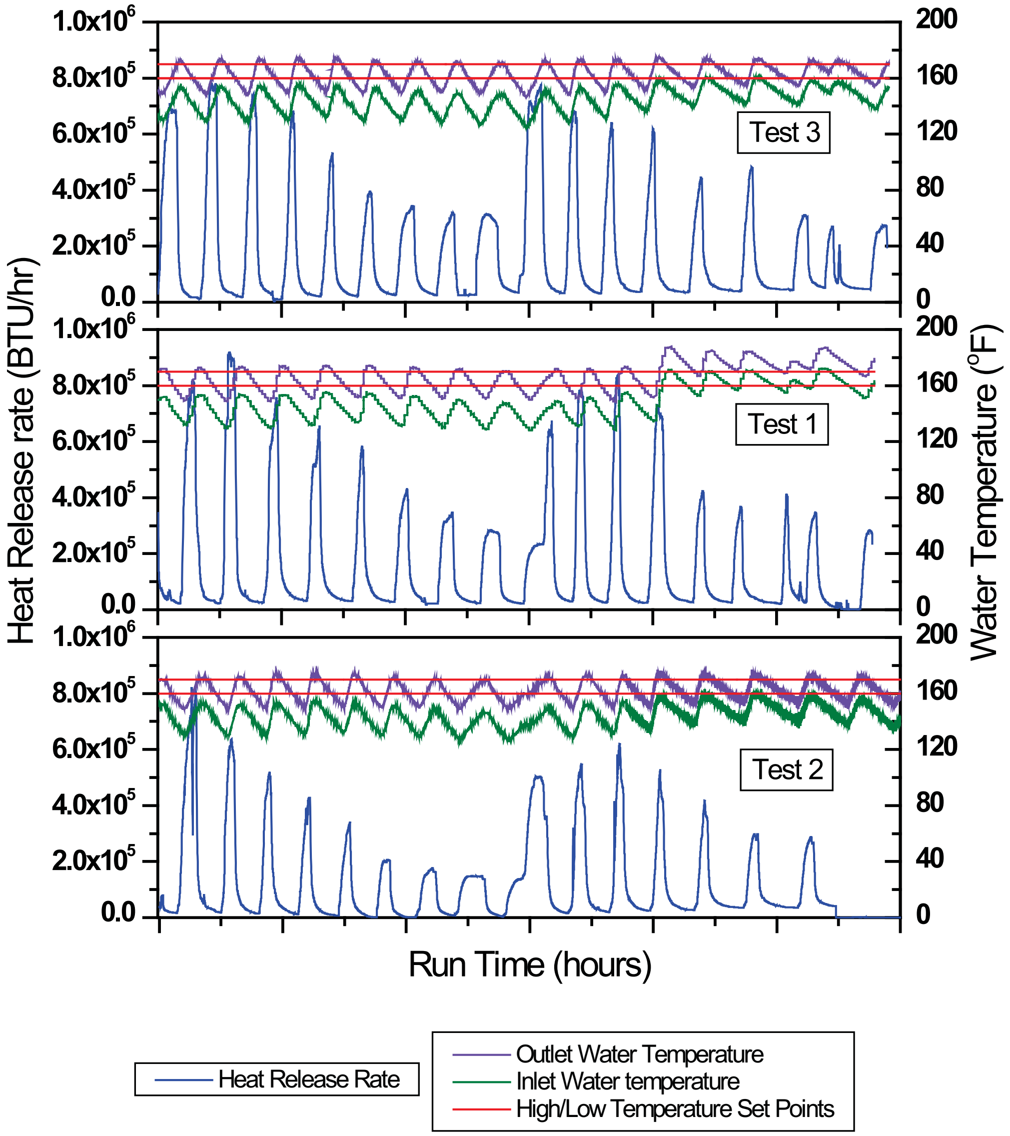


Figure 2-13. Conventional, Single Stage HH Heat Generation Rate and Inlet/Outlet Water Temperatures Burning Red Oak.

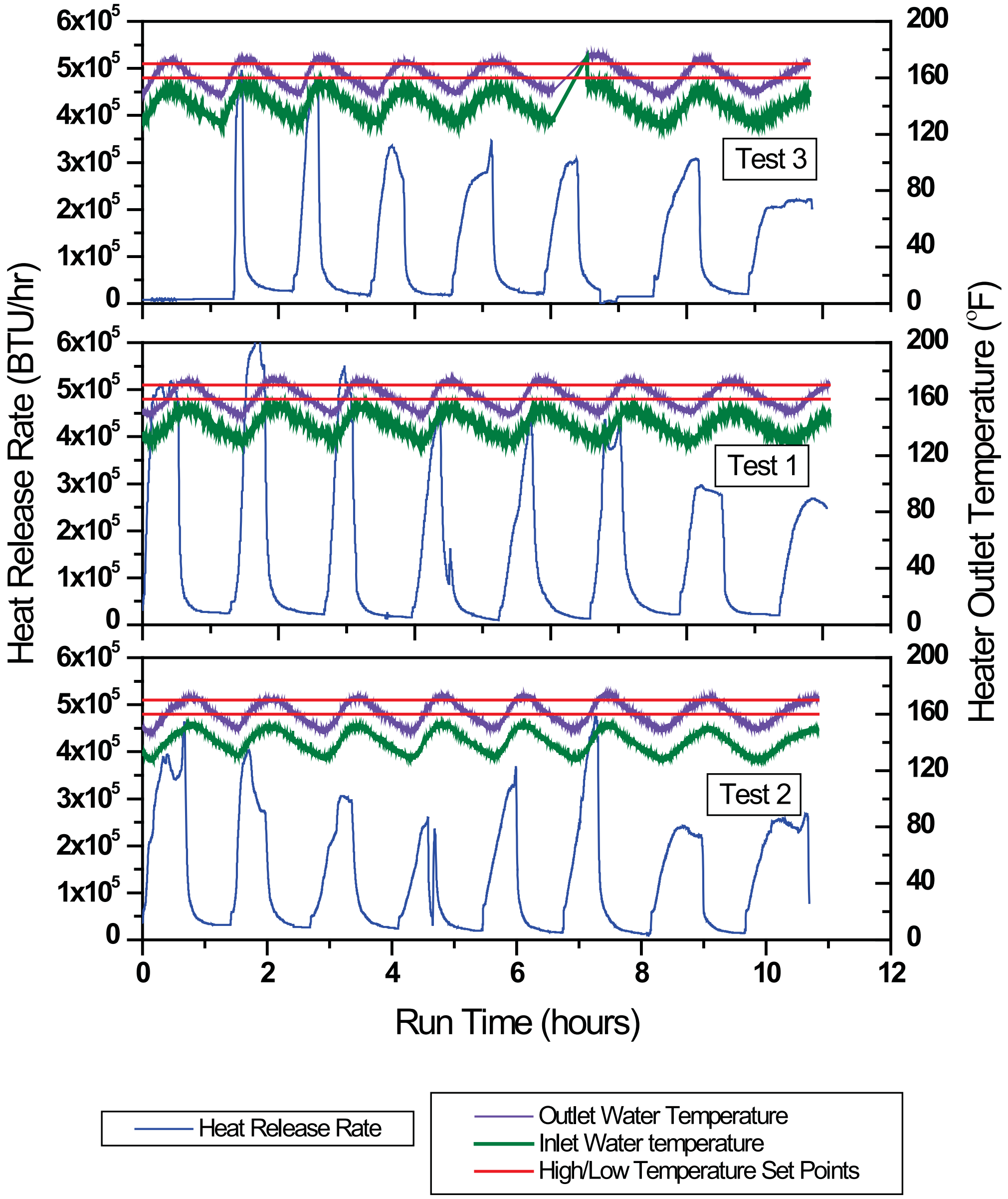


Figure 2-14. Conventional, Single Stage HH Heat Generation Rate and Inlet/Outlet Water Temperatures Burning Red Oak and Refuse.

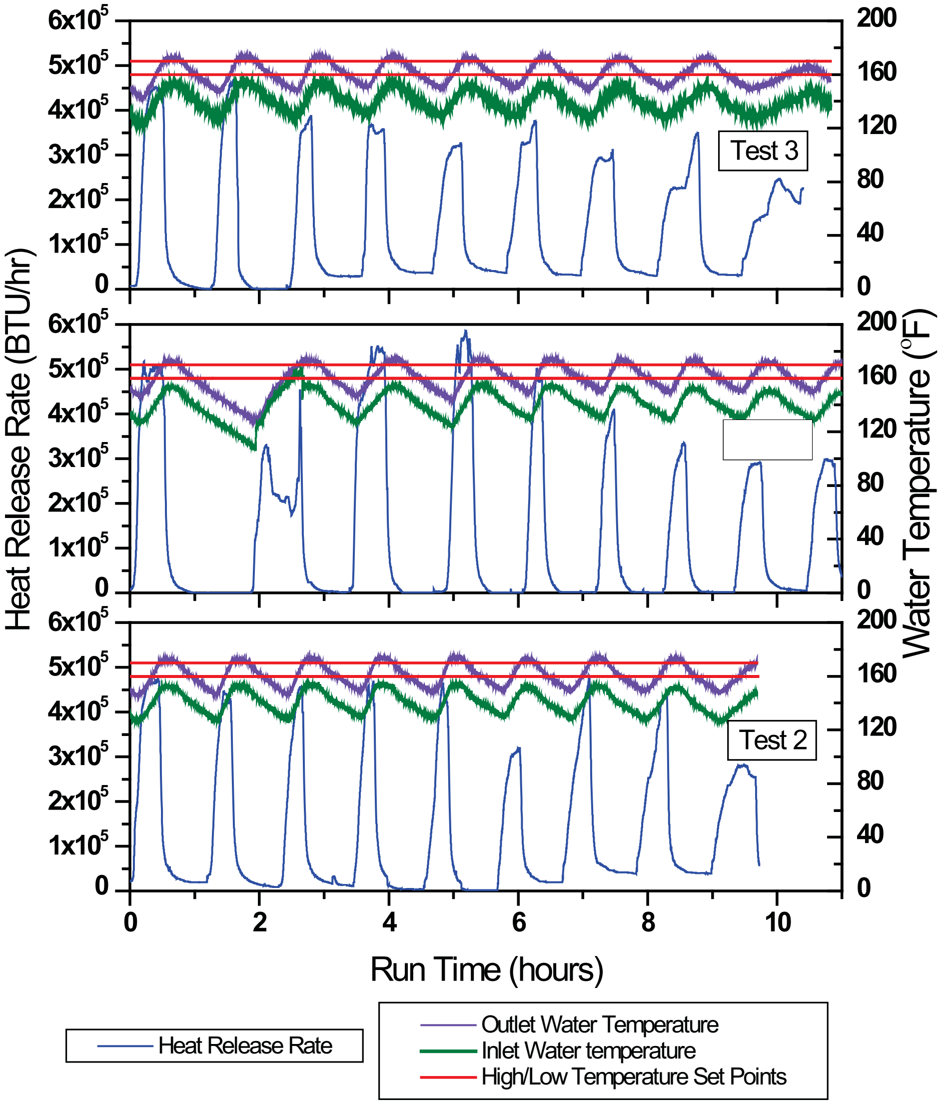


Figure 2-15. Conventional, Single Stage HH Heat Generation Rate and Inlet/Outlet Water Temperatures Burning White Pine.

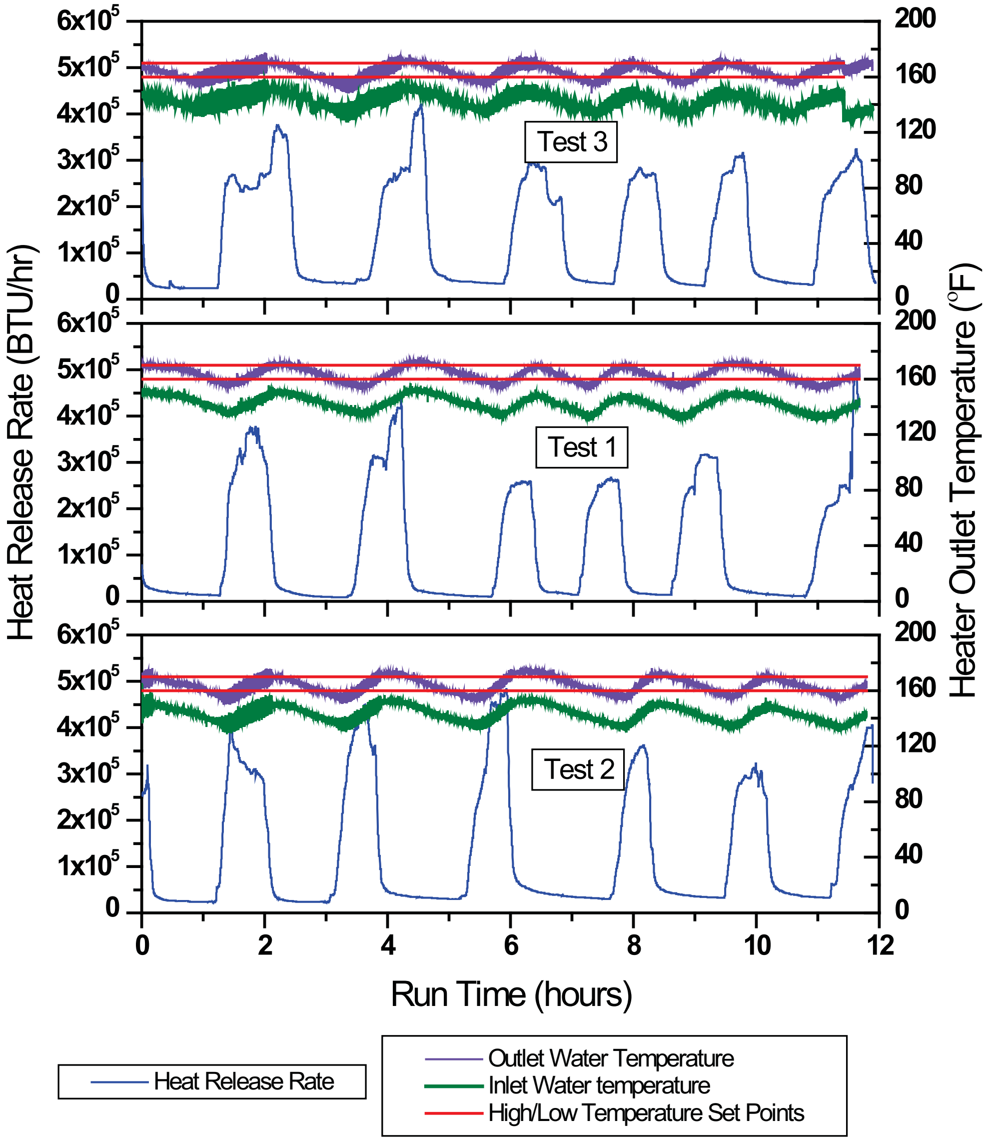


Figure 2-16. Three Stage HH Heat Generation Rate and Inlet/Outlet Water Temperatures Burning Red Oak.

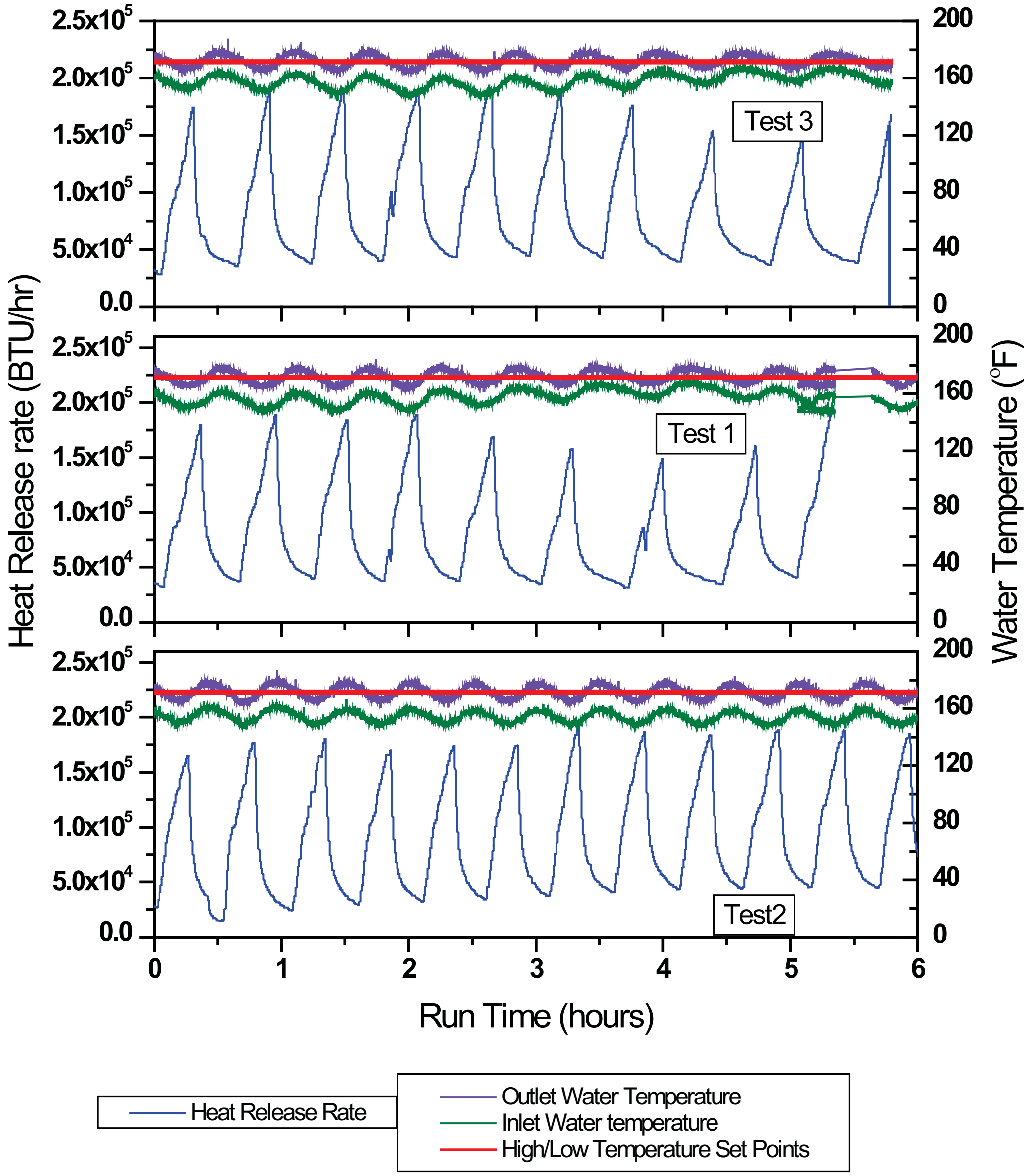


Figure 2-17. European Two Stage Pellet Burner Heat Generation Rate and Inlet/Outlet Water Temperatures Burning Hardwood Pellets.

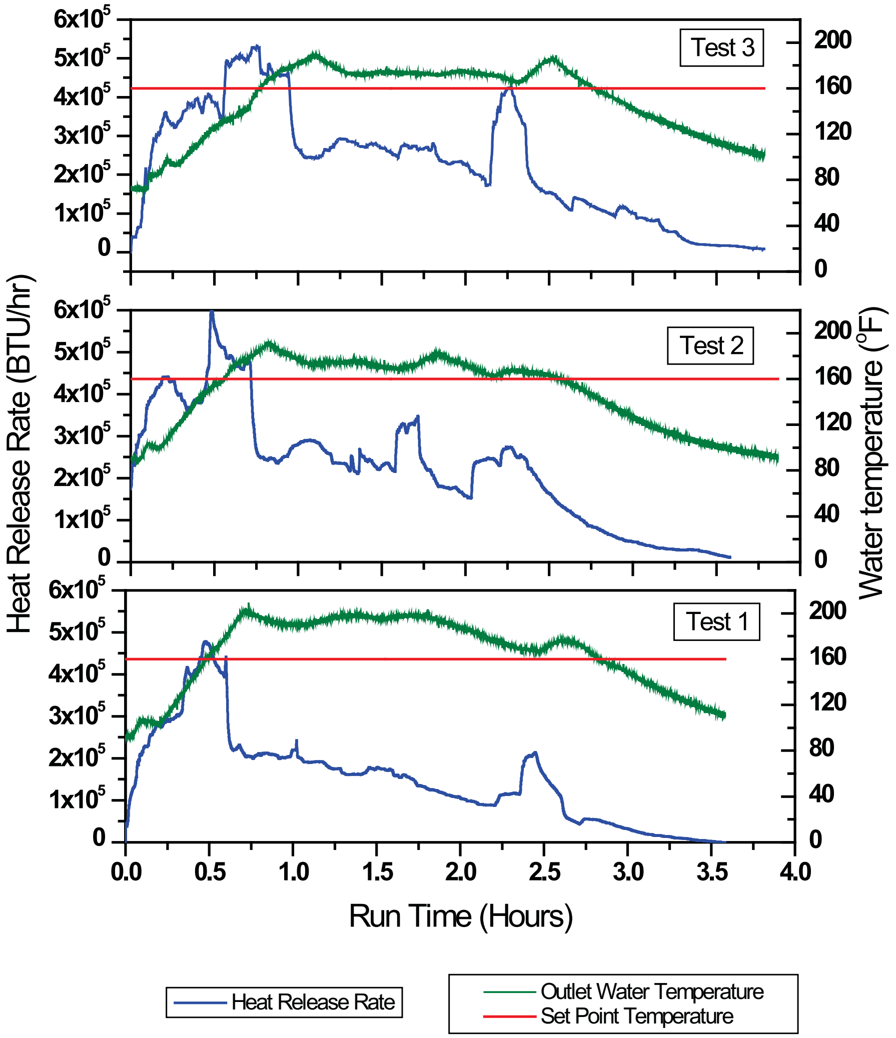


Figure 2-18. U.S. Two Stage Downdraft Burner Heat Generation Rate and Inlet/Outlet Water Temperatures Burning Red Oak.

Conventional, Single Stage HH Unit. This unit exhibited characteristic cyclical operation (Figures 2-13 through 2-15), with heat generation peaks when the damper is open, resulting in increased combustion, and heat generation minimums when the damper is closed, decreasing combustion. The maximum heat generation rate occurs when the fuel is initially charged in the unit and decreases with time as the fuel charge is consumed. The cyclical period between two damper openings is about 80 minutes, with an open damper period of about one third of the cycle, and a damper closed period of about two thirds of the cycle. This results in a 6- to 8-fold range in its heat generation rate between damper openings and closings.

The heat exchanger used to simulate the Syracuse heat load demand resulted in an average of 10 C° ± 2 C° (18 F° ± 3 F°) drop between the heat exchanger water inlet and outlet (load side). The Conventional, Single Stage HH unit comes with an adjustable water temperature controller (aquastat) that opens and closes the firebox damper to regulate the combustion air and control the rate of burning. The high/low temperature set points for the aquastat were set for all the tests at 77 °C/71 °C (170 °F/160 °F). For all the burns, the maximum water outlet temperature was found to be 80 °C ± 0.5 C° (176 °F ± 0.7 F°), while the minimum water outlet temperature was about 62 °C ± 4.0 C° (143 °F ± 7.2 F°). The large variation between the low set point and the actual minimum water outlet temperature ($\Delta T = 9$ C°) (17 F°) is dependent on the duration of time when the damper is closed. The longer this duration, the cooler the HH structure becomes, lowering the water inlet temperature, resulting in higher convective/radiation heat losses.

Three Stage HH Hydronic Heater Unit. The Three Stage HH unit exhibits the same characteristic cyclical operation (Figure 2-16) as the Conventional, Single Stage HH unit, with maximum heat generation rate when the fuel is charged. The peak heat generation rate generally declines with time, although less rapidly than with the Conventional, Single Stage HH unit. The period between successive damper openings for the Three Stage HH heater is greater than for the Conventional, Single Stage HH. A single cycle time of 120 min is comprised of an open damper period (about 51 min) and a closed damper period (67 minutes). This higher opening/closing cycling period is due to the higher water capacity of the Three Stage HH heater (1700 L or 450 gal) compared to the water capacity of the Conventional, Single Stage HH (740 L or 196 gal).

The heat exchanger resulted in an average of 11.4 °C ±0.1 C° (20.5 °F ± 0.1 F°) drop between the heat exchanger water inlet and outlet (load side). Similar to the Conventional, Single Stage HH unit, the Three Stage HH unit comes with an adjustable water temperature controller (aquastat) that opens and closes the damper to regulate the air entering the firebox and control the rate of burning. The high/low temperature set points for the aquastat were set for all the tests at 77 °C/71 °C (170 °F/160 °F). For all the burns, the maximum water outlet temperature was found to be 80.3 °C ± 0.5 C° (177 °F ± 0.8 F°), while the minimum water outlet temperature was about 65.5 °C ± 1.1 C° (150 °F ± 1.9 F°), The small variation observed between the low set point and the actual minimum outlet water temperature (5.5 °C (10 F°)) suggests that the Three Stage HH responds more quickly to the aquastat regulator than does the Conventional, Single Stage HH unit (9 °C (17 °F)).

European Two Stage Pellet Burner. The European Two Stage Pellet Burner unit exhibited atypical cyclical heat generation rates (Figure 2-17) due to changes in the unit's control system to accommodate the low heat demand from the Syracuse profile that was below the minimum operating range of the European Two Stage Pellet Burner unit. The heat exchanger used in this study extracted 8.8-10.3 kW (30,000-35,000 BTU/hour), which is lower than the manufacturer's normal operating range of 12.0-40.1 kW (41,000-137,000 BTU/hour). In order to satisfy this low heat load demand, the European Two Stage Pellet Burner controller was programmed to follow a modulation sequence (see Table 2-11) that put the unit into a "stop heating mode" when the target output water temperature (in this case, 80 °C (176 °F)) overshot the unit output modulation range (target temp +3 C°, +5.4 F°). In this mode, the exhaust fan continues to run but the fuel feeding and the combustion air fans are stopped, resulting in a sub-optimal burning condition in the combustion chamber until the residual fuel is burned out. When the outlet water temperature is below the set target temperature of 80 °C (176 °F), a call for heat (unit power at 100% capacity) is activated. As the outlet water temperature rises over the target temperature, the fuel feed and combustion air fan speed are reduced in tandem from 100% to 30% in 1% increments until the boiler reaches 83 °C (181 °F). The result is that the fuel feeding overshoots the demand. The period between fuel feedings is about 35 minutes, with the unit in the "stop heating mode" for an average of 16 minutes and in the "heating mode" for about 19 minutes.

Table 2-11. European Two Stage Pellet Burner Unit Modulation Sequence.

Unit operating condition	Temp., °C (°F)
Call for heat (Maximum fuel feed rate)	<80 (176)
Modulated reduction of fuel feed and combustion air. Fuel feed rate reduced from 100% to 30% in 1% increments as temperature rises over target	80-83 (176-181)
Stop heating mode	>83 (181)

The heat exchanger produced an average temperature drop of 8.7 C° ±1.2 C° (15.8 F° ± 2.2 F°) between the inlet and outlet water. For all three European Two Stage Pellet Burner tests, the maximum water outlet temperature was 85.4 °C ± 0.1 C° (186 °F ± 2.0 F°), while the minimum water outlet temperature was about 71.2 °C ± 0.6 C° (160 °F ± 1.1 F°). The relatively high difference between the target temperature for the call for heat and the minimum temperature recorded is due to the rapid cooling of the unit when it is in "stop heating mode."

U.S. Two Stage Downdraft Burner Heater Unit. The U.S. Two Stage Downdraft Burner unit was operated without damper cycling (Figure 2-18). The forced draft fan was left on throughout the test, varying between high or low speed to maintain the set-point temperature, as all of its surplus heat production goes into heat storage. In our system, the water/water heat exchanger transfers about 10.3 kW (35,000 BTU/hour), depending on the requirements of the Syracuse cycle. The additional water/air heat exchanger (model HWFC 150) adds an additional heat load demand up to 43 kW (147,250 BTU/hour). The net effect of these two load demands is a rapid drop in unit outlet water temperature when the fuel is near depletion. In application, the U.S. Two Stage Downdraft Burner units commonly are used as primary heating systems to offset the amount of gas, fuel oil, or electricity. If the unit is out of wood and the temperature drops below a predetermined temperature set by the installer, then the backup fossil fuel system will start automatically.

Under the testing protocol, the heat generation rate was calculated from the start of the heating process until the time when the unit output failed to match the instantaneous load requirements of the Syracuse home. The point at which the unit output failed to match the instantaneous load requirements of the Syracuse home occurred at about 2.5 hours, corresponding to the time when the unit could no longer generate heat and its water output temperature was dropping. The fully charged U.S. Two Stage Downdraft Burner unit supplied about 88% of the 230 kW·h (784,000 BTU/day) Syracuse winter heat load and so was operated with a single fuel charge to represent a full day's heating for emissions testing. This 24 h charging cycle would result in substantial cooling of the unit between charges and so each new test was started cold using only a 5 kg (11 lb) pre-charge to establish a bed of coals. All three of the U.S. Two Stage Downdraft Burner trials exhibited an initial peak in heat generation rate about 30 min after charging; the rise and the fall in the heat generation rates corresponded presumably to high and low firing rate operations of the unit, respectively. The firing rate for the U.S. Two Stage Downdraft Burner unit is controlled using a proportional integral derivative (PID) temperature controller with 4-20 mA interface to a Nimbus variable speed fan. The three trials also exhibit brief (about 10 min) peaks in heat generation rate about 1.5 to 2.5 h after the initial charge. The second peak observed is probably due to a call for a high firing rate when the temperature of the water jacket is below the set-point temperature. This situation occurs when the heat generation rate after about 2.5 hours is low due to a lack of fuel in the combustion chamber. The average heat generation rate for the first 2.5 hours is equal to 81 kW (277,000 BTU/hour, STDV = 43,500 BTU/hour) that is well above the manufacturer's reported heat generation rate of 44 kW (150,000 BTU/hour) for this unit. For the three burns, the steady state outlet temperature was equal to 80 °C ± 5 C° (176 °F ± 9 F°), higher than the set point temperature of 71 °C (160 °F). The unit was operated in a downdraft/gasification mode from the start of the burn, as reflected in the flue gas temperatures that average, for all three burns, 173 °C (343 °F), values that are well within the manufacturer flue gas specifications of 138 °C- 204 °C (280 °F – 400 °F).

2.9.3 Heat Generation Rate

The maximum heat generation rate for these units is a function of their heat transfer characteristics and design capacity and occurs, for damper-modulated units, when the damper is open. The actual heat generation rate during these tests is dependent on the heat load profile, in this case defined by the Syracuse winter load demand. For units that operate with a damper, the Syracuse load demand is satisfied by modulation of the damper opening and closing. Maximum fuel combustion occurs during open damper conditions; this condition is interrupted by the closing of the damper. For the pellet unit, the fuel feed rate or frequency is varied to meet the load demand. The U.S. Two Stage Downdraft Burner unit, operating with heat storage, is not modulated by a damper or fuel feeder setting. Any of its heat generated in excess of that required by the instantaneous Syracuse load is stored in a hot water storage tank. The ratio of the maximum heat generation rate to the actual heat generation rate provides a measure of the degree of oversize of the unit for the Syracuse load.

The actual heat generation rate includes heat generated during both the open and closed damper operation periods over the whole duration of the test. The maximum heat generation rate accounts for heat generation and elapsed time only when the damper is open. These heat generation rate values are calculated from the HHV and the mass burn rate of the fuel, where the latter is calculated from a carbon emission summation (CO_2, CO, and HC) and the carbon content of the fuel. The closer the actual heat generation rate is to the maximum heat generation rate, the more appropriately sized the unit is for the heat load. Comparing the actual heat generation rate to the Syracuse heat load provides a measure of efficiency where higher efficiencies are achieved when the actual and maximum heat generation rates are the same and as close as possible to the heat load.

Actual Heat Generation Rate. The average actual heat generation rate for five of the six unit/fuel combinations that operate with cyclical opening and closing of a damper are shown in Table 2-12 and Figure 2-19. These rates are dependent on the heat load, unit design, and fuel type.

Table 2-12. Heat Generation Rates for the Six Unit/Fuel Combinations.

Heater/Fuel Units	Heat Generation Rate				
		Actual		Maximum	
		BTU/hour	kW	BTU/hour	kW
Conventional, Single Stage HH/Red Oak	Average	160,000	46	310,000	92
	STDV	24,000	7.1	94,000	28
Conventional, Single Stage HH/Red Oak and refuse	Average	110,000	32	210,000	61
	STDV	12,000	3.6	33,000	9.8
Conventional, Single Stage HH/White Pine	Average	120,000	35	240,000	71
	STDV	3,800	1.1	15,000	4.4
Three Stage HH/Red Oak	Average	110,000	33	220,000	64
	STDV	12,000	3.5	13,000	3.8
European Two Stage Pellet Burner/pellets	Average	73,000	22	87,000	25
	STDV	6,700	2.0	6,600	1.9
U.S. Two Stage Downdraft Burner/ Red Oak	Average	Not measured.		210,000	62
	STDV			46,000	13

STDV – standard deviation

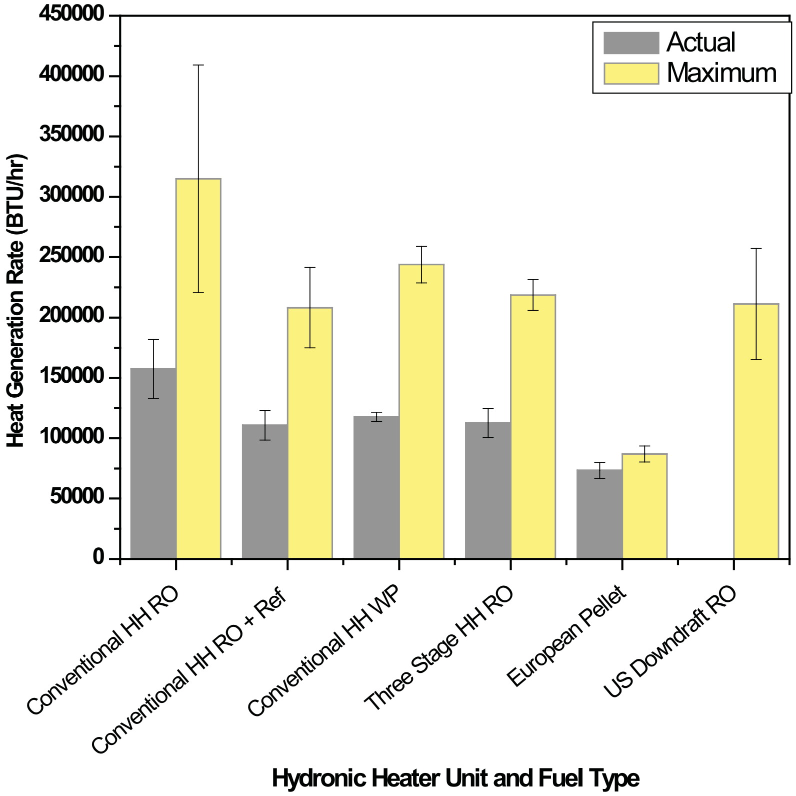


Figure 2-19. Actual and Maximum Heat Generation Rate (Average Syracuse Heat Load = 32,700 BTU/Hour).

For the three fuel types, the single charge, 12 h, actual heat generation rate for the Conventional, Single Stage HH unit ranged, from 32 to 46 kW (109,000 to 157,000 BTU/hour, with a high value 45% above the lowest value). The Three Stage HH unit was in the same range, at 33 kW. The European Two Stage Pellet Burner unit had the lowest actual heat generation rate, at 22 kW (75,100 BTU/hour). The U.S. Two Stage Downdraft Burner unit operates without damper closings and so its actual heat generation rate is the same as its maximum heat generation rate and is reported in the next section.

Maximum Heat Generation Rate. The run-average maximum heat generation rate can be considered the unit's heat generation capacity, and the ratio of this value to the value of the actual heat generation rate can be used to determine if the unit is sized properly for a specific heat load demand.

The average maximum heat generation rates for all six unit/fuel combinations are shown in Figure 2-19 and Table 2-12. The 0 to 12 hours (single fuel charge) average maximum heat generation rate for the Conventional, Single Stage HH unit ranged from 92 kW to 71 kW (314,000 BTU/hour to 242,000 BTU/hour), a 30% increase above the lower value. For all three fuels and their replicates, the average Conventional, Single Stage HH maximum heat generation rate was 75 kW (256,000 BTU/hour). The maximum heat generation rate for the Three Stage HH unit with red oak was a bit lower than the Conventional, Single Stage HH unit at 64 kW (218,000 BTU/hour). The 6-hr maximum heat generation rate for the European Two Stage Pellet Burner unit was 25 kW (87,000 BTU/hour), while the maximum heat generation rate for the U.S. Two Stage Downdraft Burner heater was 62 kW (212,000 BTU/hour).

The ratio of the maximum heat generation rate to the actual heat generation rate for the Conventional, Single Stage HH and Three Stage HH units is about 2/1, suggesting that these units are more than sufficient to satisfy the heat load demand of the Syracuse cycle. The European Two Stage Pellet Burner unit ratio was about 1.14/1, the excess above 1 showing the excess heat supplied due to a minimal effect of the modulation of the fuel/air controls in satisfying the Syracuse heat load demand cycle. This ratio was not calculated for the U.S. Two Stage Downdraft Burner unit since the heater was operated with damper open and full load during the tests and so its maximum and actual heat generation rates are equivalent.

Heat Generation Rate Summary. HHs that are sized or operated to minimize damper closing times will eliminate this idle condition and are therefore better suited to meet the load demands. Minimization of the closed damper periods will reduce heat loss and duration of suboptimal combustion conditions. The European Two Stage Pellet Burner unit was operated so the ratio of its open damper to actual heat generation rate was about 1.14/1, suggesting that it was operating at about 14% higher capacity than the Syracuse load demanded and that its program would allow. The Conventional, Single Stage HH and Three Stage HH had a rate ratio of about 2, suggesting that in the conditions during our testing they were twice the size necessary to meet the demand of the Syracuse load. The U.S. Two Stage Downdraft Burner heat storage unit stored all of its effective heat and so had no excess capacity.

2.9.4 Hydronic Heater Efficiency

The performance of HH systems can be evaluated for the ability of the unit to burn the fuel completely (combustion efficiency), the effectiveness of the heat exchanger to transfer the heat generated from the combustion process to the water (boiler efficiency), and the overall ability of the system to generate useful heat by transferring it to meet the load demand (thermal efficiency). Table 2-13 summarizes all these efficiencies for all six unit/fuel combinations.

Table 2-13. Hydronic Heater Efficiencies.

Units	Thermal Efficiency		Boiler Efficiency	Combustion Efficiency
	%			
Conventional, Single Stage HH/Red Oak	Average	22	NC	74
	STDV	5		3.0
Conventional, Single Stage HH/Red Oak and Refuse	Average	31	NC	87
	STDV	2.2		3.4
Conventional, Single Stage HH/White Pine	Average	29	NC	82
	STDV	1.8		3.2
Three Stage HH/Red Oak	Average	30	NC	86
	STDV	3.2		1.8
European Two Stage Pellet Burner/Pellets	Average	44	86	98
	STDV	4.1	3.5	0.16
U.S. Two Stage Downdraft Burner Red Oak	Average	NM	83	90
	STDV	NM	0.71	0.79

NM – not measured

NC – not calculated; cyclical units make this calculations unreliable

STDV – standard deviation

Thermal Efficiency. Thermal efficiency or "system efficiency" is defined here for the overall system as the sensible heat delivered to the load side of the water/water heat exchanger outlet divided by the HHV of the fuel burned during the same time period. The efficiency of heat delivery is a function of the unit design and its heat transfer and insulation characteristics as well as the fuel combustion efficiency. Potential heat losses for these units may occur due to incomplete fuel combustion (CO and HC levels in the emissions), heat losses (sensible and latent) out the stack, and insufficient insulation of the transfer lines between the heater and the external heat exchanger used to simulate the heat load demand. Heat Losses are also exacerbated by the cyclical operation of the heater that results in high excess air when the damper is open (higher sensible heat loss though the stack), suboptimal combustion efficiency when the damper is closed, inefficient heat transfer (from the combustion gases to the water jacket), and radiation/convection heat loss due to cooling of the unit.

Average thermal efficiencies for five of the six unit/fuel combinations operating under a cyclical mode are shown in Figure 2-20. The Conventional, Single Stage HH unit averaged a thermal efficiency of 22% for all nine runs, the Three Stage HH averaged 30% for three runs, and the European Two Stage Pellet Burner averaged 44% for three runs. Thermal efficiencies are not available for the U.S. Two Stage Downdraft Burner unit because measurements of the thermal flows through the water/air heat exchanger were not recorded. These thermal efficiencies, ranging from 22% to 44%, can be compared with oil and natural gas fired residential systems with thermal efficiencies ranging from 86% to 92% and 79% to 90%, respectively (McDonald 2009).

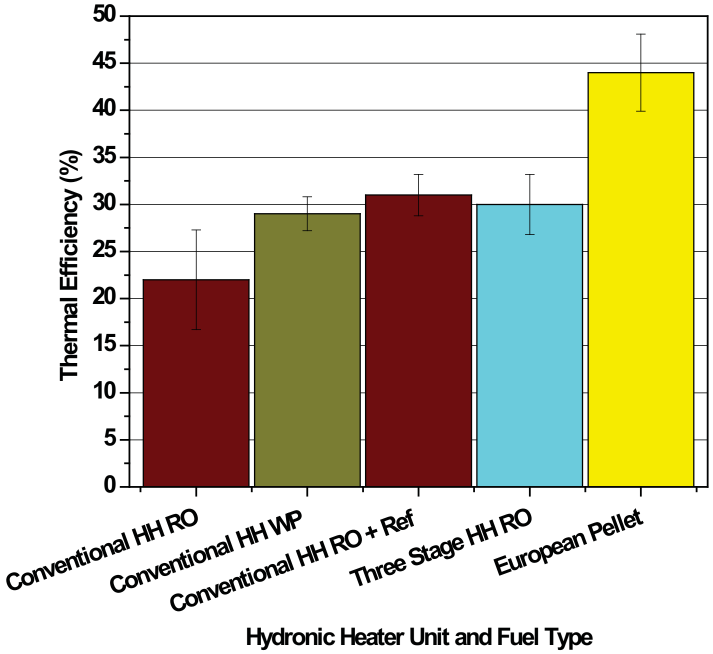


Figure 2-20. Average Thermal Efficiencies of Cyclic Hydronic Heaters.

The relatively low thermal efficiencies for the Conventional, Single Stage HH and Three Stage HH units are due to their damper cycling (open and closed). This cycling is necessitated by the excess of heat generated compared to the heat demand required by the Syracuse cycle. During closed damper periods, cooling of the unit's structure occurred, resulting in standby losses from the water jacket and heater casing. The open damper periods resulted in excessive generation of heat, which overwhelmed the heat load demand required by the Syracuse load and increased the sensible heat losses at the stack.

The European Two Stage Pellet Burner unit's thermal efficiency may also be hindered by the standby heat losses. These losses occurred during the unit's automatic "stop heating mode" which avoided overheating of the unit. In this mode the exhaust fan continues to run, increasing the convective losses of the water jacket.

Boiler Efficiency. Boiler efficiency was calculated using the "Heat Loss Method": subtracting the flue gas heat losses from the HHV of the fuel burned. The "Heat Loss Method" does not account for radiation/convection losses from the heater jacket and transfer lines and the effectiveness of the external heat exchanger. Boiler efficiencies were calculated for both the European Two Stage Pellet Burner and U.S. Two Stage Downdraft Burner heaters. Boiler efficiencies were not calculated for the Conventional, Single Stage HH and the Three Stage HH units because their cyclic mode of operation made accurate measurement of stack flow rates difficult and unreliable. The average boiler efficiencies for the U.S. Two Stage Downdraft Burner heaters and the European Two Stage Pellet Burner heaters are shown in Figure 2-21. The European Two Stage Pellet Burner heater averaged a boiler fficiency of 86% for the three runs, and the U.S. Two Stage Downdraft Burner averaged 80% for the three runs. Boiler efficiency was calculated for the U.S. Two Stage Downdraft Burner unit from the start of the heating process until the unit's output failed to match the unit set point temperature. For our system this occurred after 2 to 2.5 hours. For this unit, no cycling of the process was allowed, and the heat load demand required that the unit operate at full power during the whole time of testing. The boiler efficiency for the European Two Stage Pellet Burner heater was averaged over the whole testing cycle.

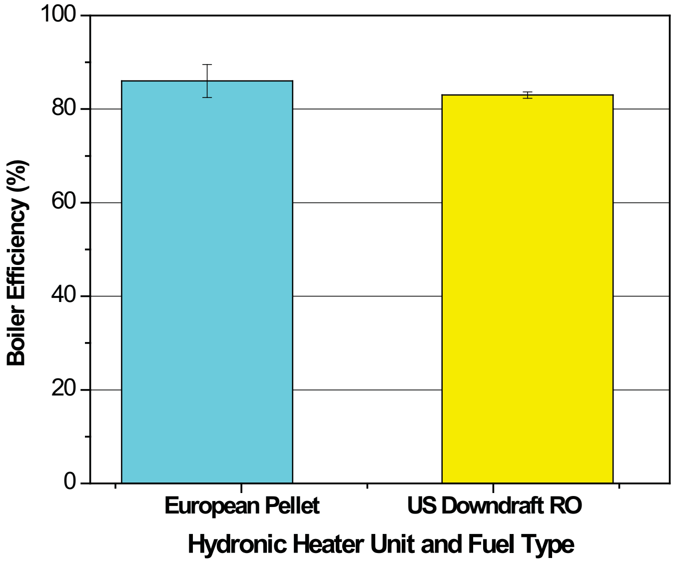


Figure 2-21. Average Boiler Efficiency of the European Two Stage Pellet Burner and U.S. Two Stage Downdraft Burner Heaters.

Stack temperature is another parameter used to determine the boiler efficiency and reflects the heat generated by the heater and not transferred to the water jacket. Typical flue gas temperatures in the stack are shown in Figure 2-22 for the Conventional, Single Stage HH unit and Figure 2-23 for the Three Stage HH, European Two Stage Pellet Burner, and U.S. Two Stage Downdraft Burner. The relatively high stack temperatures observed for the Conventional, Single Stage HH heater, and, to a lesser extent, for the Three Stage HH heater, demonstrate the high sensible heat losses (dry and water vapor) leaving the heaters due to the high energy output of these two units when the damper is open. For the European Two Stage Pellet Burner heater, the flue gas temperatures were lower, showing better and more effective heat removal by the unit water jacket and lower heat losses up the stack. For the U.S. Two Stage Downdraft Burner heater, the stack temperatures observed are within the manufacturer's specifications.

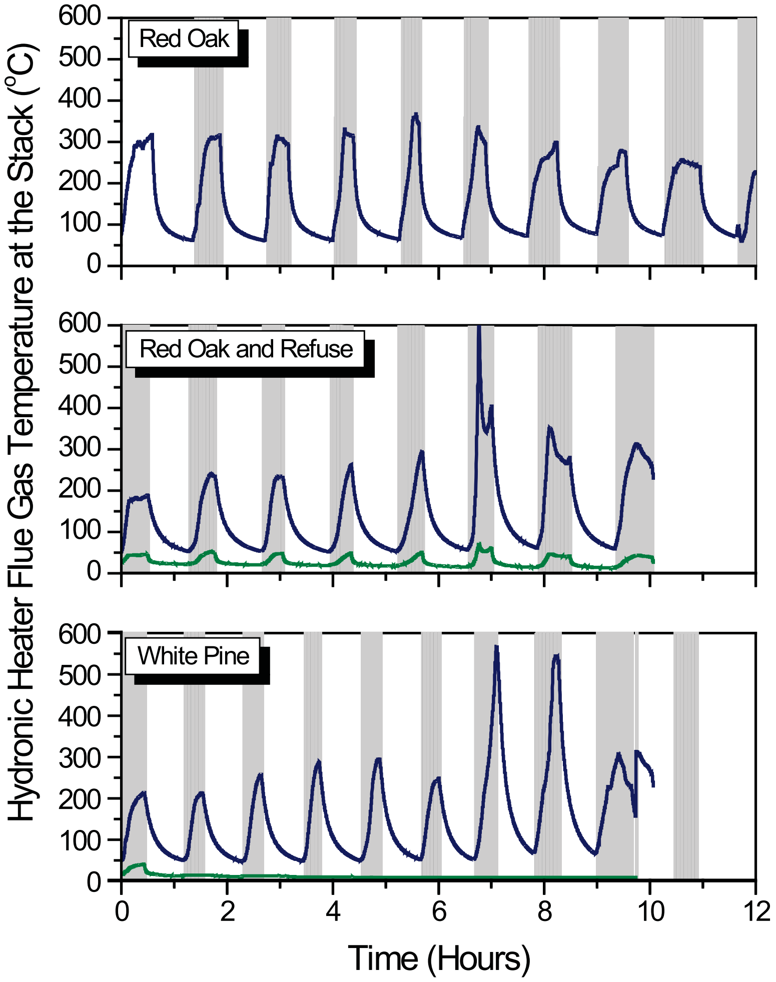


Figure 2-22. Typical Stack and Duct Temperatures for the Conventional, Single Stage HH Unit.

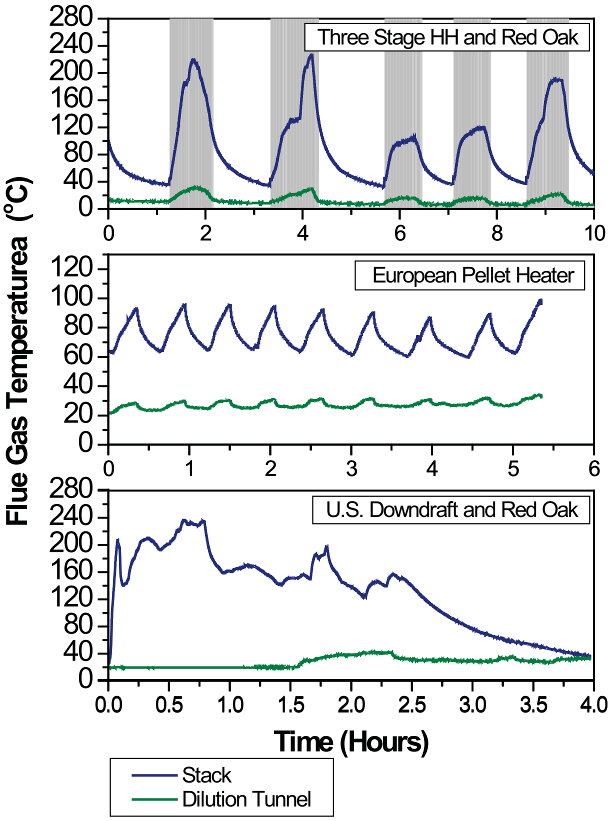


Figure 2-23. Typical Stack and Duct Temperatures for the Three Stage HH, European Two Stage Pellet Burner, and U.S. Two Stage Downdraft Burner Units.

Combustion Efficiency. Combustion efficiency was calculated by measurement of CO_2 divided by CO_2 + CO + THC and evaluated for each unit (Figure 2-24). The Conventional, Single Stage HH unit averaged a combustion efficiency of 81% for all nine runs, the Three Stage HH averaged 87% for three runs, the European Two Stage Pellet Burner averaged 98% for three runs, and the U.S. Two Stage Downdraft Burner 91% for three runs. The Conventional, Single Stage HH and the Three Stage HH units showed lower combustion efficiencies than the European Two Stage Pellet Burner unit, probably due to the design of the first two units that accommodate a large span of heat load demand through a cycling process ("ON" and "OFF" mode of damper operation) rather than through fuel feed modulation and heat storage. When the damper is closed, the reduced airflow causes smoldering and poor combustion, lowering combustion efficiency. For the European Two Stage Pellet Burner heater, the cycling process seems to have little or no detrimental effect on the combustion efficiency. The European Two Stage Pellet Burner regulates fuel feed without stopping air flow, probably not creating the fuel rich environment experienced with damper closure. The U.S. Two Stage Downdraft Burner unit was operated without cycling, resulting in better combustion efficiency than the Conventional, Single Stage HH and the Three Stage HH burning the same type of wood.

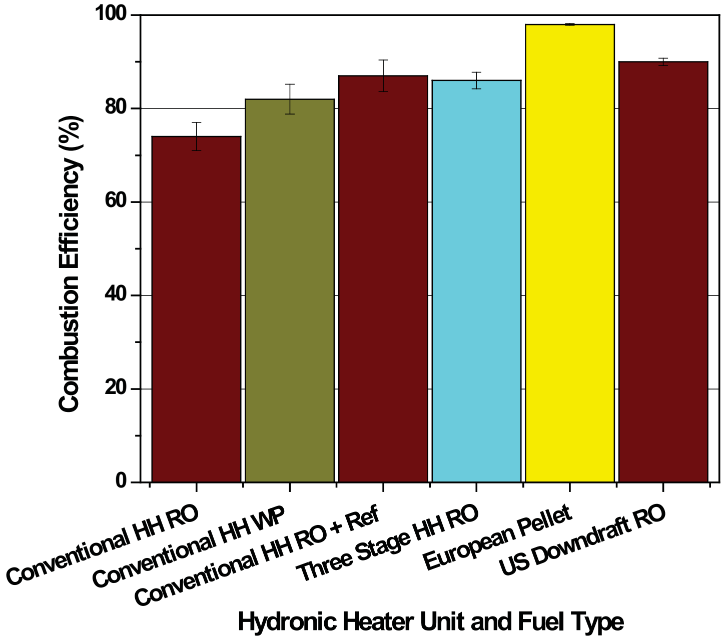


Figure 2-24. Average Combustion Efficiencies for Tested Heaters.

2.9.5 Carbon Emissions

Temporal Carbon Emissions. Temporal carbon emissions are reported in Figures 2-25 through 2-30 for the six unit/fuel combinations. The proportion of carbon emitted from CO, CO_2, and THC is shown as a function of run time. For the units equipped with an air flow damper, emissions are present and measurable only when the damper is open and air is flowing through the unit and out the stack. Predictably, the majority of carbon is emitted as CO_2. For the Conventional, Single Stage HH (Figures 2-25 to 2-27) and Three Stage HH (Figure 2-28) damper units, there is about a 20% absolute variation in the CO_2 proportion during each damper open cycle, reflecting fluctuations in combustion efficiency. CO typically exceeds THC, and both exhibit some variation throughout each damper open cycle. The magnitude of the CO and THC traces in these figures represent energy lost due to incomplete oxidation. In many cases this loss amounts to over 20% of the carbon. The most complete conversion to CO_2 and the steadiest emissions are observed with the European Two Stage Pellet Burner, Figure 2-29. The U.S. Two Stage Downdraft Burner unit (Figure 2-30), which operates with a modulated draft fan, exhibits relatively steady carbon emissions, especially after the initial hour of charging.

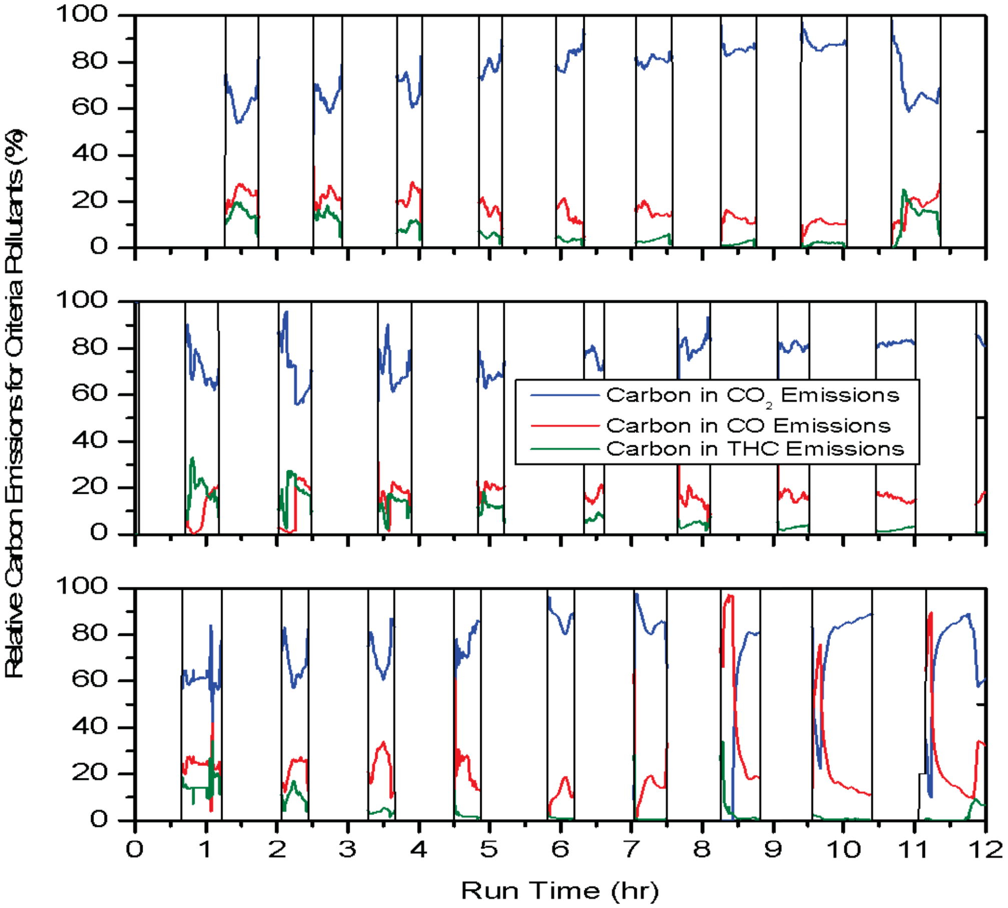


Figure 2-25. Relative Carbon Emissions for Criteria Pollutants (Conventional, Single Stage HH All Tests, Red Oak, Damper Open).

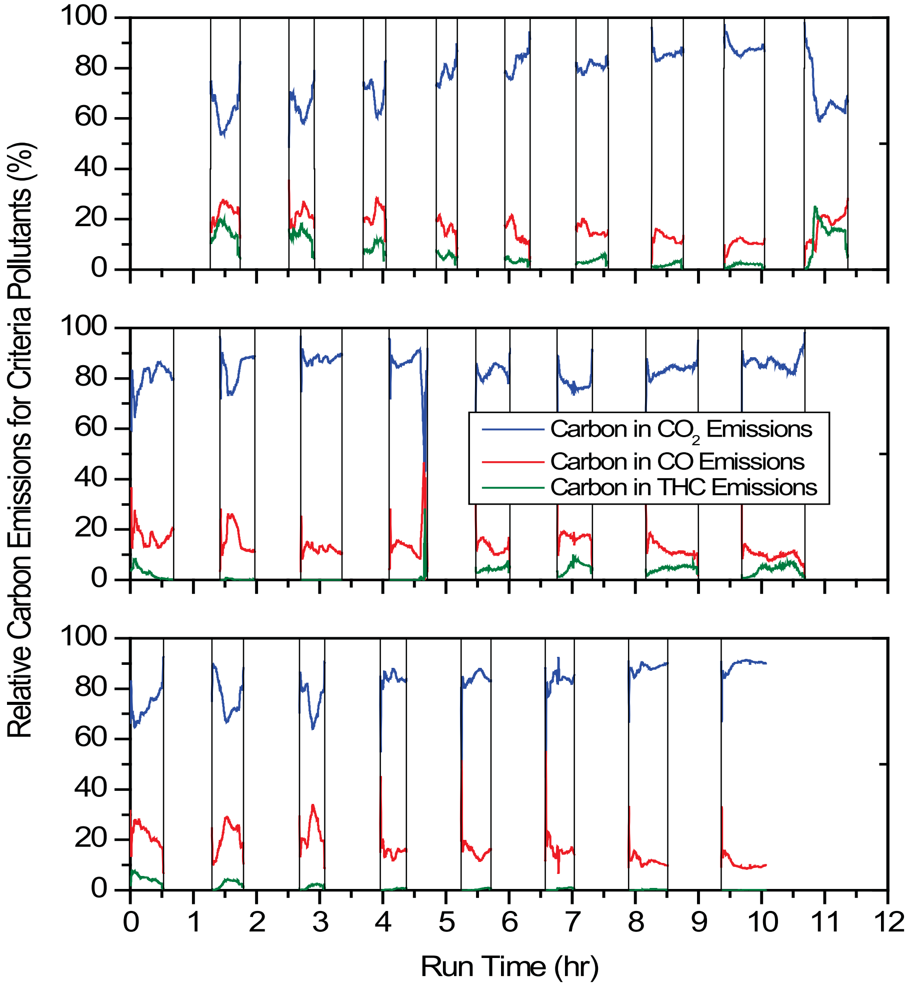


Figure 2-26. Relative Carbon Emissions for Criteria Pollutants (Conventional, Single Stage HH All Tests, Red Oak + Refuse, Damper Open).

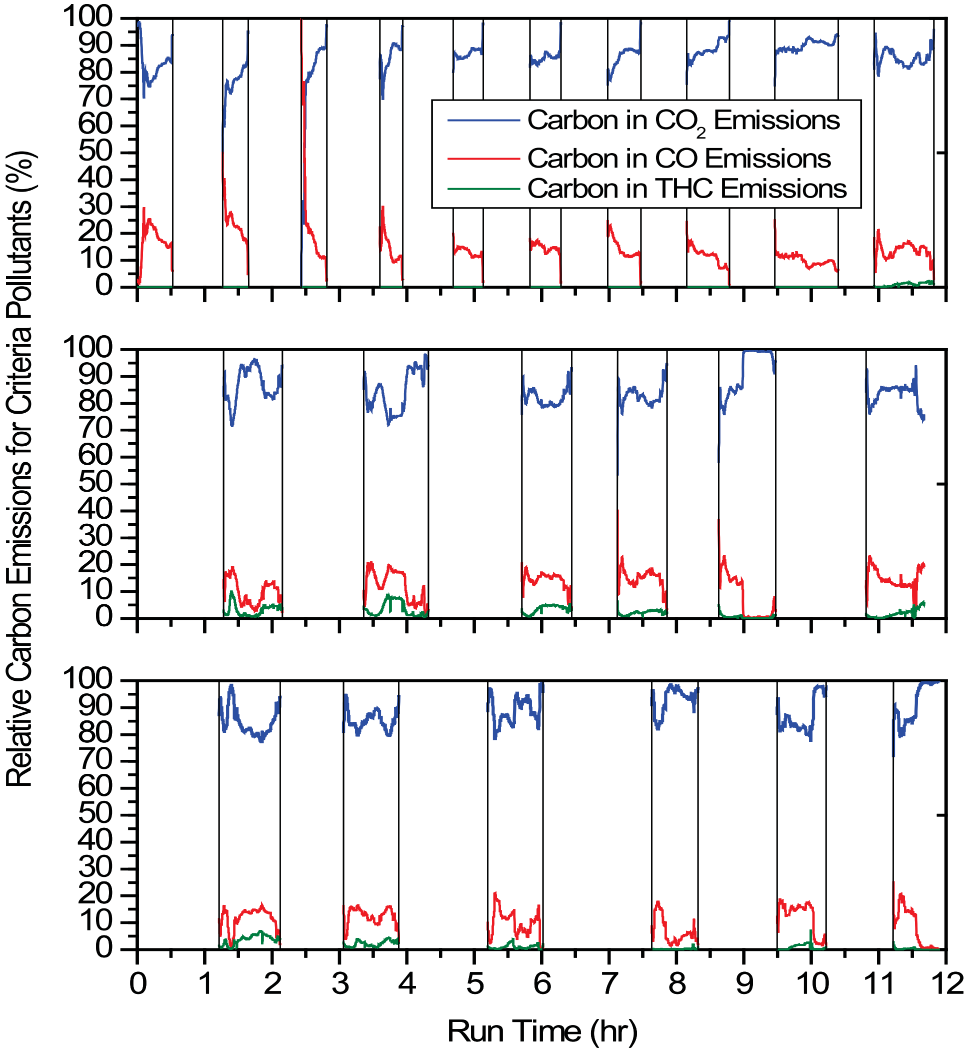


Figure 2-27. Relative Carbon Emissions for Criteria Pollutants (Conventional, Single Stage HH All Tests, Pine Wood, Damper Open).

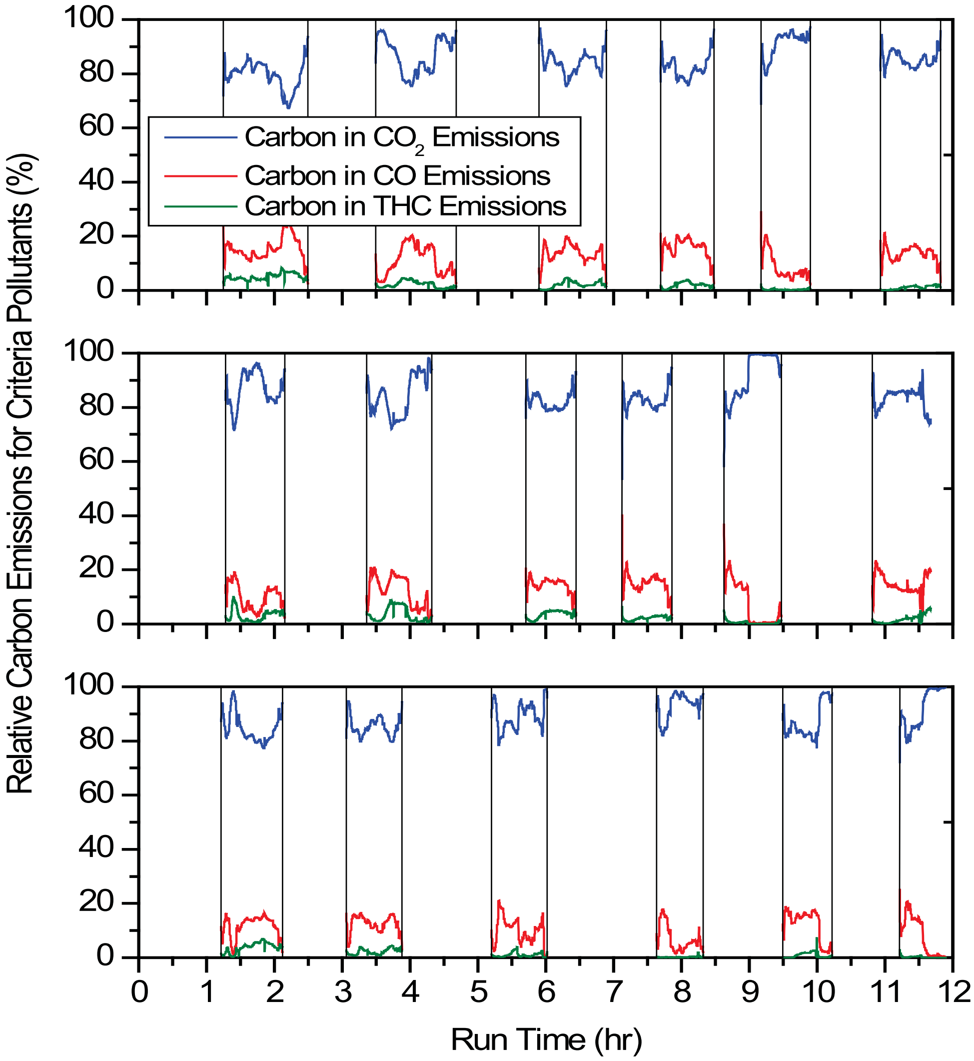


Figure 2-28. Relative Carbon Emissions for Criteria Pollutants (Three Stage HH, All Tests, Red Oak, Damper Open).

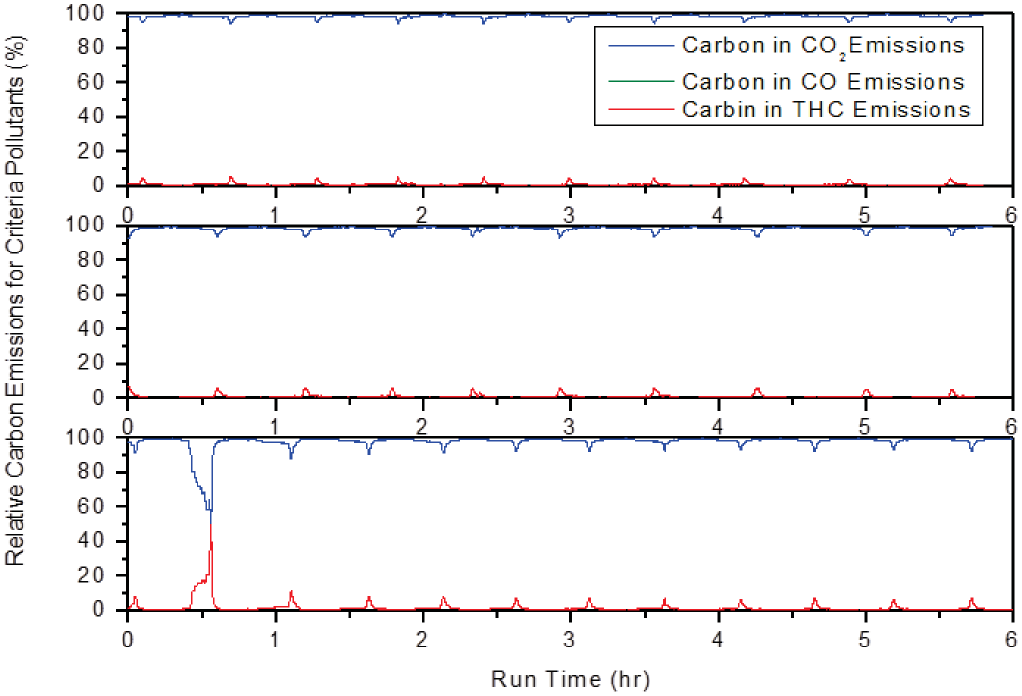


Figure 2-29. Relative Carbon Emissions for Criteria Pollutants (European Two Stage Pellet Burner). CO level is too low to be seen.

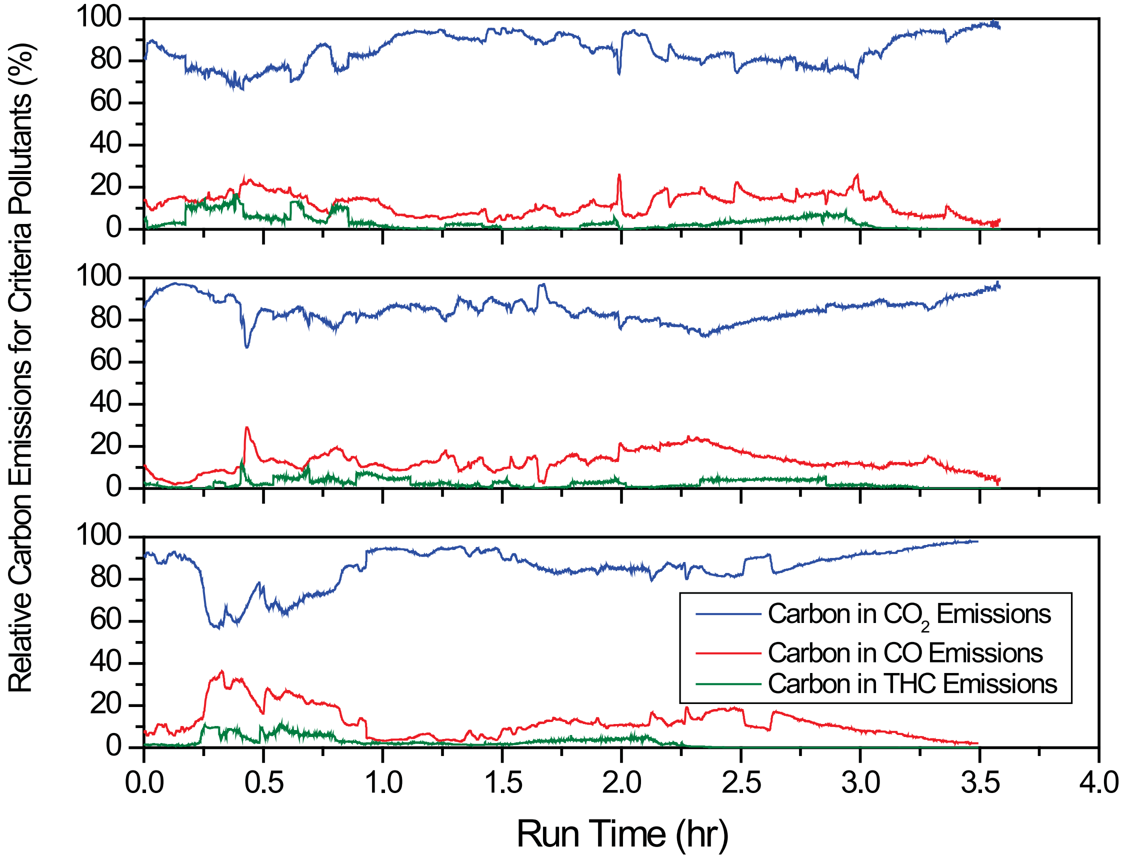


Figure 2-30. Relative Carbon Emissions for Criteria Pollutants (U.S. Two Stage Downdraft Burner Heater, Oak Wood, 3 Cycles).

The Conventional, Single Stage HH unit shows an initial dip in the CO_2 proportion when the damper opens and, inversely, a spike in the CO and THC proportions due to the initial fuel-rich condition in the chamber during the off-cycle smoldering period. Slight improvement in CO_2 proportion is observed throughout the run cycle, indicating improved combustion. Emissions for the Three Stage HH unit also show fluctuation during damper open periods, but there is little apparent rise throughout the overall test period. These initial temporary dips at the onset of the opening of the damper resulted in relatively low combustion efficiencies when compared to non-cyclic systems (European Two Stage Pellet Burner and U.S. Two Stage Downdraft Burner).

CO concentration profiles in the dilution tunnel from typical runs of the three fuels on the Conventional, Single Stage HH are exhibited in Figure 2-31. The initial concentration peaks at 7,000- 8000 ppm for the red oak and the white pine and about 4,000 ppm for the red oak and refuse. The CO concentration decreases two- to three-fold from its peak, indicating an apparent improvement in the combustion efficiency after the second damper opening. Figure 2-32 shows the CO concentration profiles for all three tests on the Three Stage HH unit. Typical concentrations during the open damper periods are 1,000 – 4,000 ppm. The European Two Stage Pellet Burner, Figure 2-33, has a distinctive CO concentration profile, with short duration spikes at the onset of pellet feeding. The U.S. Two Stage Downdraft Burner unit operates without cyclic damper openings and shows an average peak CO concentration of about 4,000-7,000 ppm at the dilution tunnel (Figure 2-34).

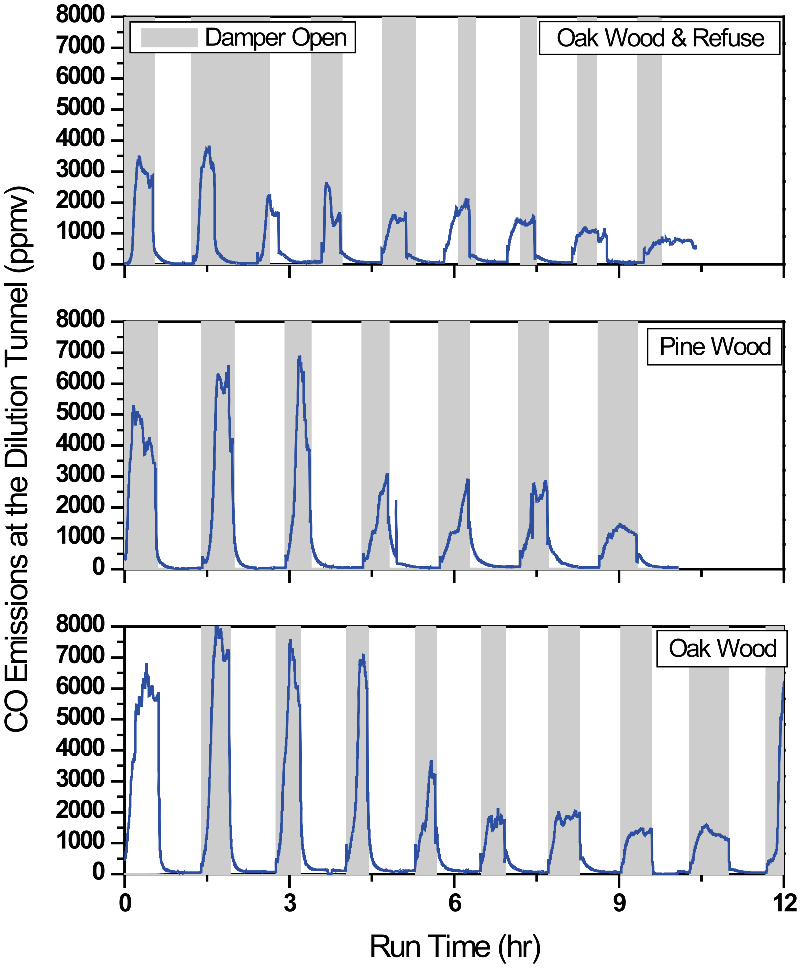


Figure 2-31. Typical Conventional, Single Stage HH Heater CO Concentration Trace (Three Fuels).

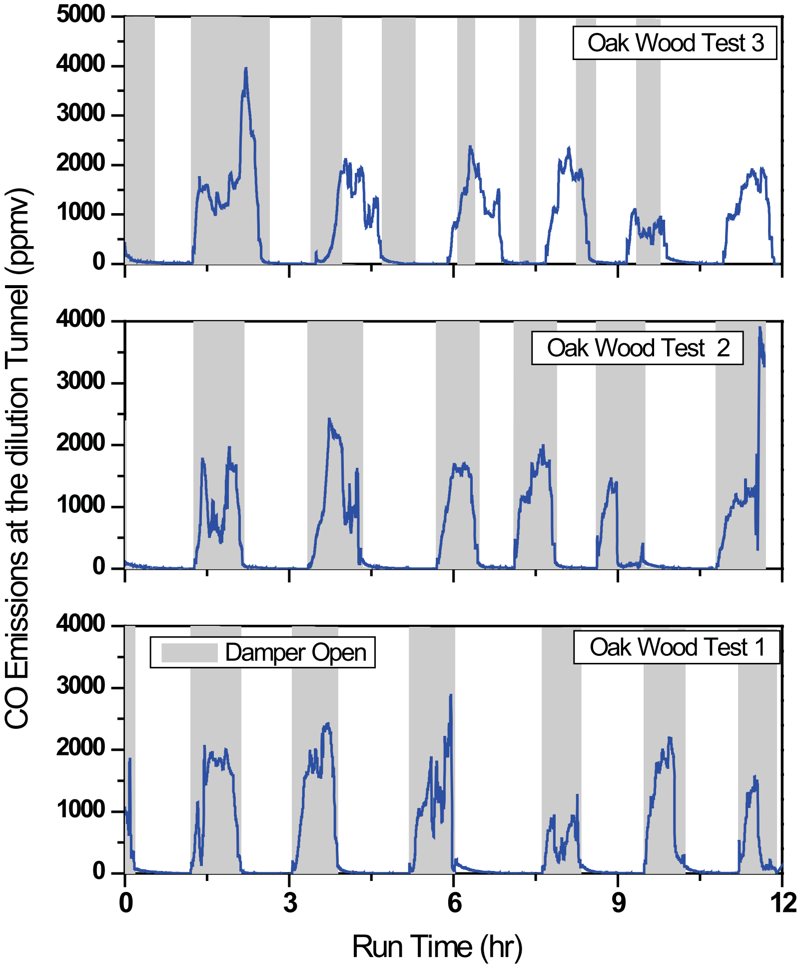


Figure 2-32. Three Stage HH Heater CO Concentration Trace (Triplicates).

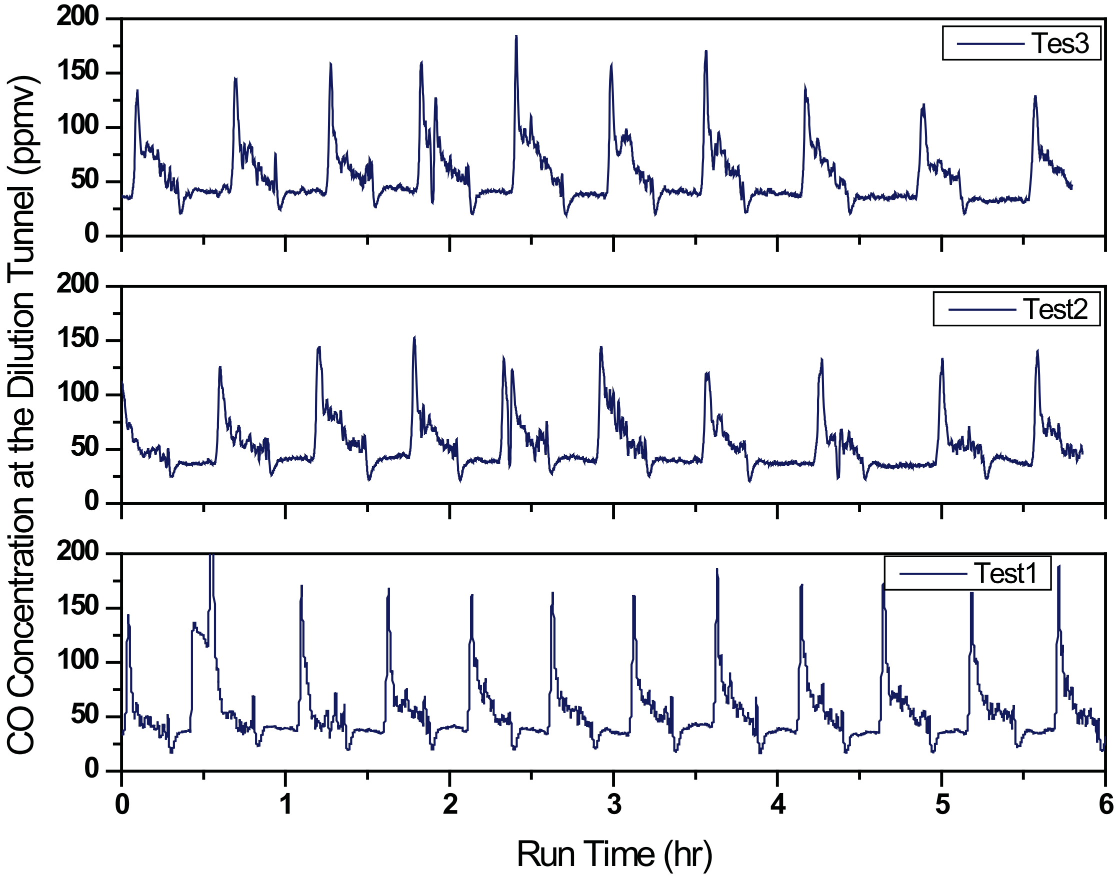


Figure 2-33. European Two Stage Pellet Burner Heater CO Concentration Trace (Triplicates).

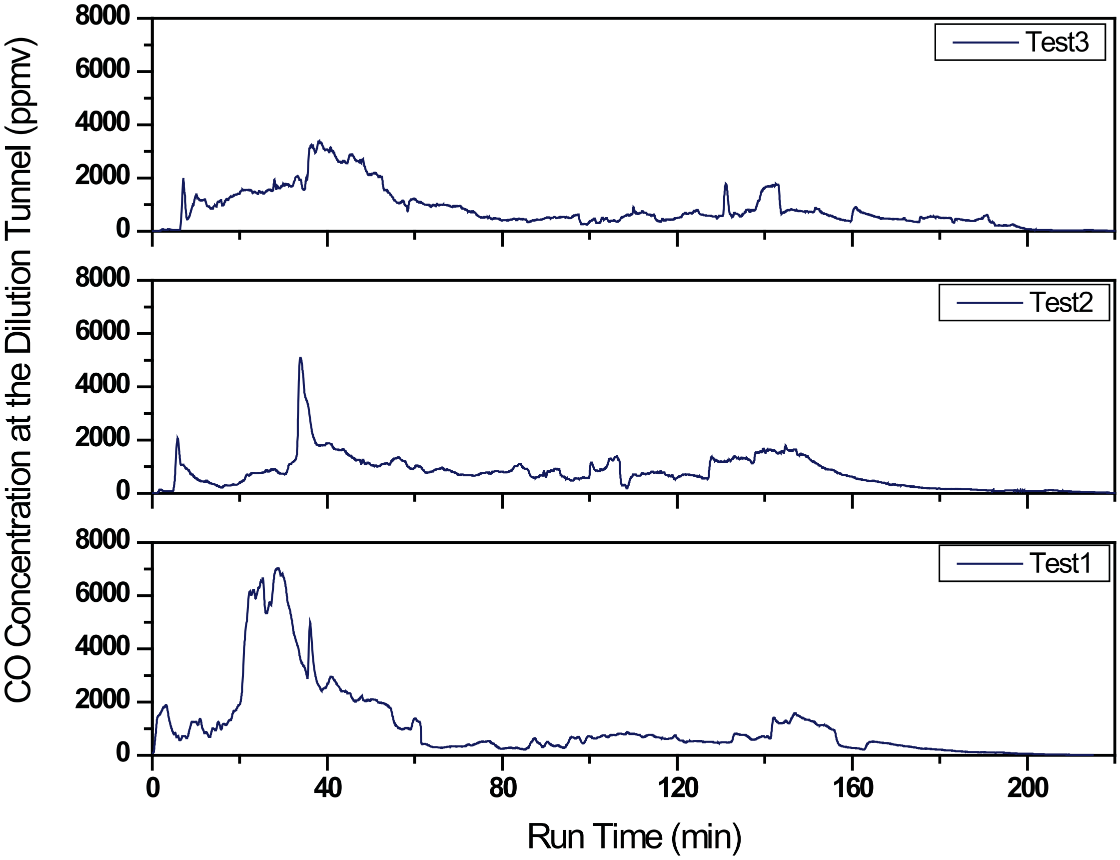


Figure 2-34. U.S. Two Stage Downdraft Burner Heater CO Concentration Trace (Triplicates).

THC concentration profiles at the dilution tunnel from the three fuels on the Conventional, Single Stage HH follow the same trend as the CO emissions (Figure 2-35). The initial concentration peaks at 5,000-7,000 ppm for the red oak with a sharp decline over the burn time. Figure 2-36 shows the THC concentration profiles for representative tests on the Three Stage HH unit. Typical concentrations during the open damper periods are 1,000 – 4,000 ppm and about one order of magnitude lower in average compared to the THC emissions from the Conventional, Single Stage HH unit. The European Two Stage Pellet Burner, Figure 2-37, shows a similar distinctive THC concentration profile from the CO profile of the Conventional, Single Stage HH and the Three Stage HH heaters, with short duration spikes at the onset of pellet feeding. The U.S. Two Stage Downdraft Burner unit shows peak concentrations during the first hour of burning before decreasing dramatically with time, as seen earlier with the CO emissions (Figure 2-38).

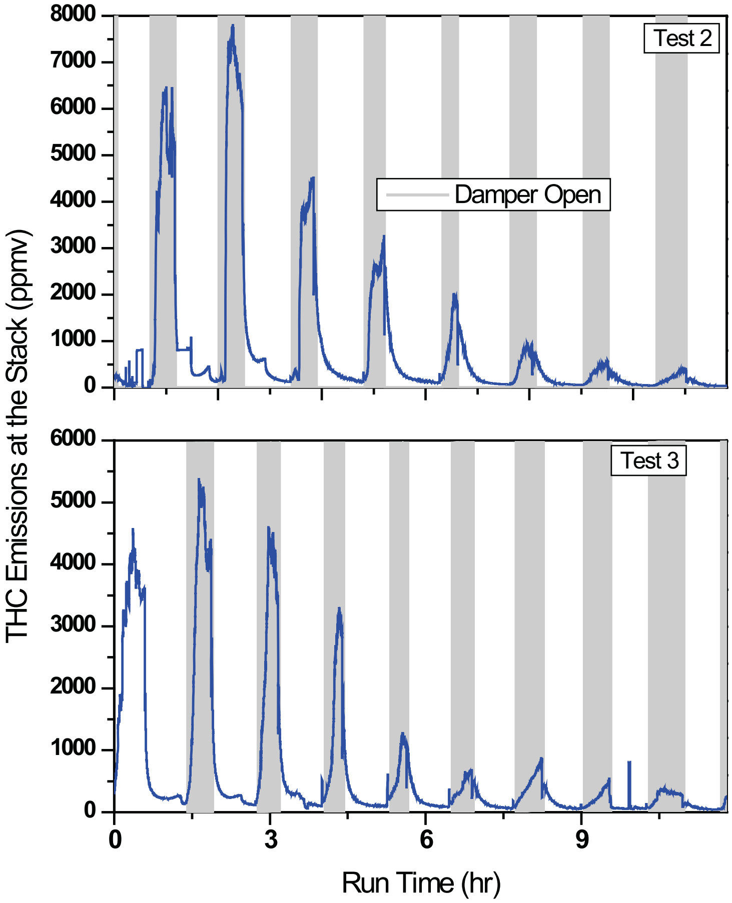


Figure 2-35. Typical Conventional, Single Stage HH Heater THC Concentration Trace (Red Oak).

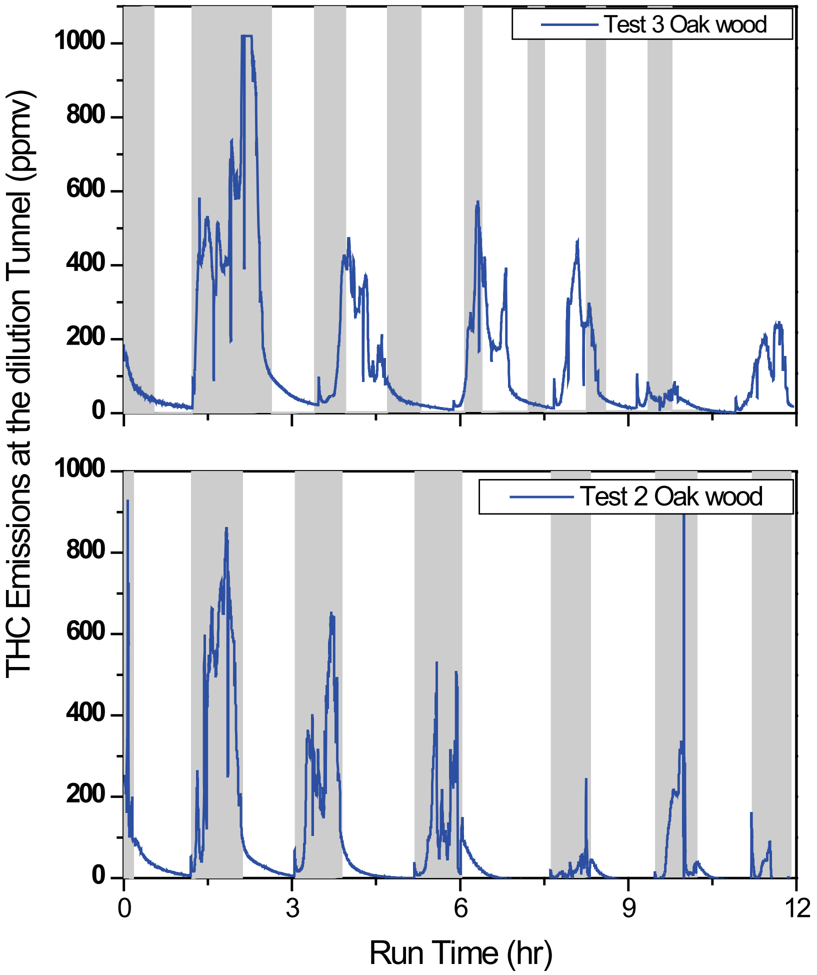


Figure 2-36. Three Stage HH Heater Typical THC Concentration Trace.

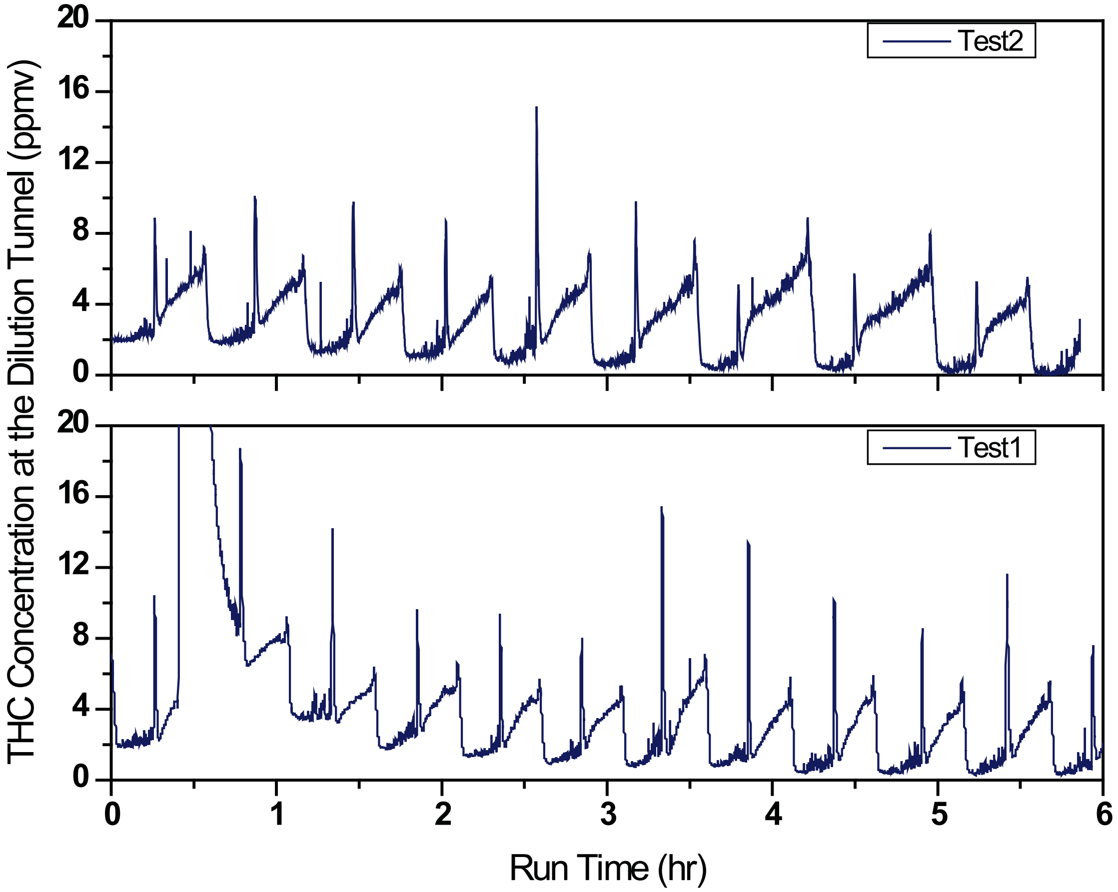


Figure 2-37. European Two Stage Pellet Burner Heater THC Concentration Trace (Duplicates).

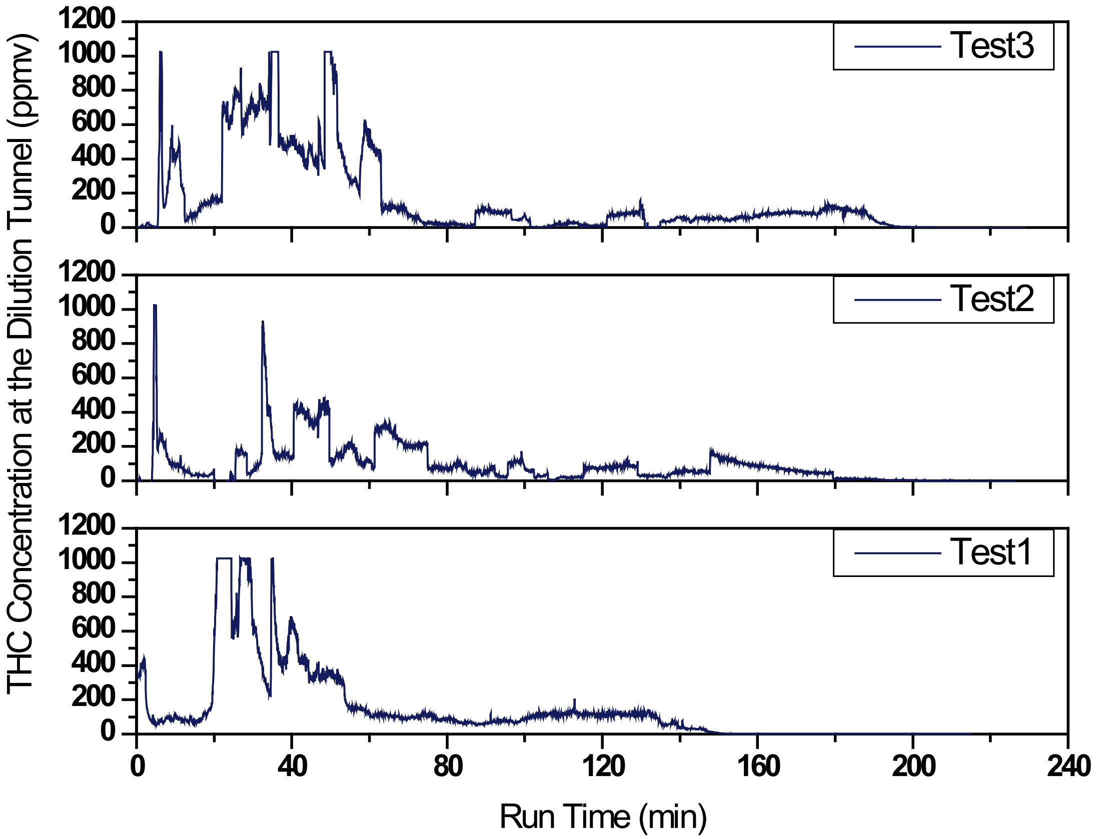


Figure 2-38. U.S. Two Stage Downdraft Burner THC Concentration Trace.

2.9.6 Carbon Dioxide

Average CO_2 emission factors for the six unit/fuel combinations are shown in Figure 2-39 and Table 2-14. Emission factors range from a low of about 72 g/MJ (170 lb/MMBtu $_{input}$) for the Conventional, Single Stage HH (average of the three fuels), 78 g/MJ (180 lb/MMBtu $_{input}$) for the U.S. Two Stage Downdraft Burner heater, to a high of about 210 lb/MMBtu$_{input}$ for the European Two Stage Pellet Burner heater. Variation in these results is due to combustion quality (the extent of complete C oxidation to CO_2) and fuel composition differences, especially with the hardwood pellets.

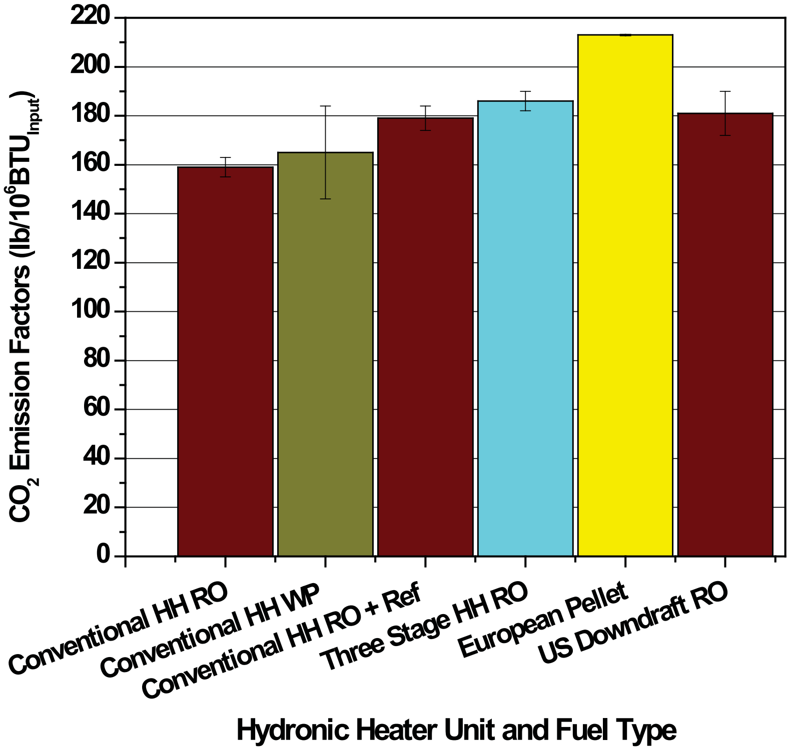


Figure 2-39. Carbon Dioxide Emission Factors.

Table 2-14. Carbon Dioxide Emission Factors.

CO_2 Emission Factors				
Heater/Fuel		**g/kg $_{Dry\ Fuel}$**	**g/MJ (lb/MMBTU) $_{input}$**	**g/MJ (lb/MMBTU)$_{output}$**
Conventional, Single Stage HH/Red Oak	Average	1330	68.4 (159)	314 (730)
	STDV	33.5	1.72 (4.0)	59.8 (139)
Conventional, Single Stage HH/White Pine	Average	1530	71.0 (165)	245 (570)
	STDV	176	8.14 (19.0)	18.1 (42.2)
Conventional, Single Stage HH/Red Oak and refuse	Average	1500	76.9 (179)	245 (569)
	STDV	41.5	2.13 (4.95)	21.3 (49.6)
Three Stage HH/Red Oak	Average	1560	80.0 (186)	269 (626)
	STDV	37.0	1.90 (4.41)	27.0 (62.9)
European Two Stage Pellet Burner/pellets	Average	1820	91.6 (213)	208 (483)
	STDV	1.47	0.07 (0.172)	19.5 (45.5)
U.S. Two Stage Downdraft Burner/Red Oak[1]	Average	1520	77.7 (181)	93.5 (218)
	STDV	77.0	3.95 (9.18)	4.86 (11.3)

[1] based on boiler efficiency

STDV – standard deviation

2.9.7 Carbon Monoxide

As expected, CO emission factors (Figure 2-40, Table 2-15) are complementary to CO_2 emission factors. The European Two Stage Pellet Burner unit has the lowest value at 0.60 g/MJ (1.39 lb/MMBtu)$_{input}$, 7.2g/MJ (16.6 lb/MMBtu)$_{input}$ for the U.S. Two Stage Downdraft Burner heater, to a high of about 8.9 g/MJ (21 lb/MMBtu) $_{input}$ for the Conventional, Single Stage HH (average of the three fuels). The European Two Stage Pellet Burner unit is predictably lower in CO emissions as combustion is comparatively steady throughout its 6 h burn, whereas the other units have variation in their combustion rates. CO levels are of interest due to their health effects and impact on National Ambient Air Quality Standards (NAAQS). These HH CO emission factors are orders of magnitude higher than those commonly noted (Krajewski et al., 1990) for residential oil-fired units (< 0.1 lbs/MMBtu)$_{input}$.

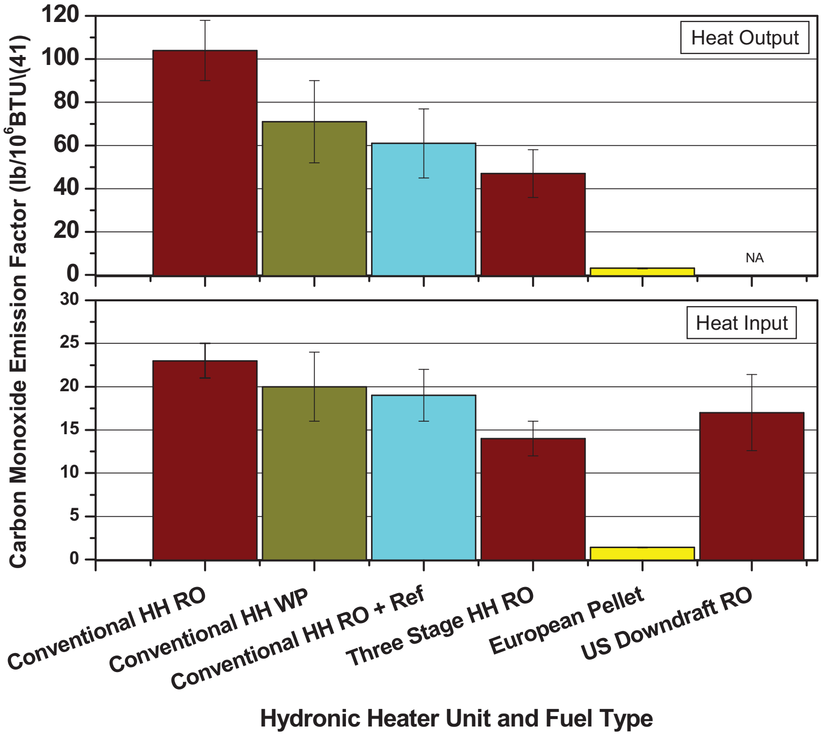


Figure 2-40. Carbon Monoxide Emission Factors.

Table 2-15. Carbon Monoxide Emission Factors.

CO Emission Factors				
Heater/Fuel		**g/kg $_{\text{Dry Fuel}}$**	**g/MJ (lb/MMBTU) $_{\text{input}}$**	**g/MJ (lb/MMBTU)$_{\text{output}}$**
Conventional, Single Stage HH/Red Oak	Average	193	9.87 (23.0)	44.9 (104)
	STDV	17	0.871 (2.03)	5.87 (13.6)
Conventional, Single Stage HH/White Pine	Average	189	8.76 (20.4)	30.6 (71.2)
	STDV	39	1.79 (4.15)	8.02 (18.6)
Conventional, Single Stage HH/Red Oak and refuse	Average	158	8.09 (18.8)	26.0 (60.6)
	STDV	25.3	1.30 (3.01)	6.83 (15.9)
Three Stage HH/Red Oak	Average	117	6.0 (14.0)	(20.3 (47.3)
	STDV	17.4	0.892 (2.08)	4.67 (10.9)
European Two Stage Pellet Burner/pellets	Average	8.3	0.6 (1.39)	1.35 (3.15)
	STDV	3.4	0.0205 (0.0478)	0.0814 (0.189)
U.S. Two Stage Downdraft Burner/Red Oak[1]	Average	140	7.16 (16.6)	8.61 (20.0)
	STDV	37	1.89 (4.39)	2.28 (5.29)[1]

STDV – standard deviation

[1] based on boiler efficiency

2.9.8 Total Unburned Hydrocarbons

Total hydrocarbon (THC) emission factors are presented in Figure 2-41 and in Table 2-16, showing that the pellet burner had the lowest THC emission factor. Average THC varied between 0.67-2.8 g/MJ (1.6-6.5 lb/MMBtu)$_{input}$ for the Conventional, Single Stage HH unit (only one single white pine test was measured for THC). The Three Stage HH, European Two Stage Pellet Burner, and U.S. Two Stage Downdraft Burner units averaged 0.77 g/MJ (1.8 lb/MMBtu), 0.03 g/MJ (0.05 lb/MMBtu, and 0.72 g/MJ (1.7 lb/MMBtu), respectively. These factors predictably mimic those of CO (Figure 2-40), indicating that both CO and THCs are produced with less efficient combustion conditions.

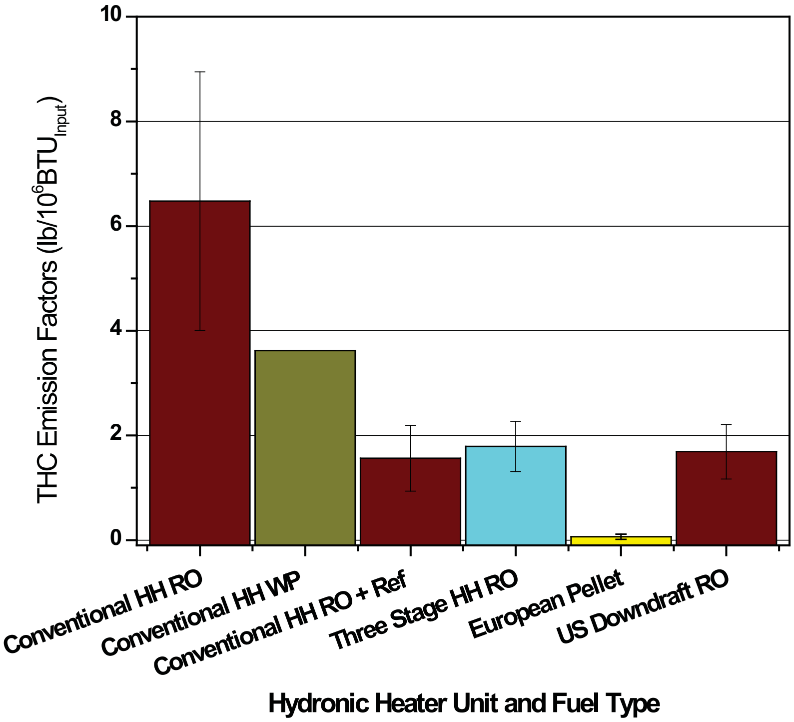


Figure 2-41. Total Hydrocarbons Emission Factors.

Table 2-16. Total Hydrocarbon Emission Factors.

THC Emission Factors				
Heater/Fuel		**g/kg $_{\text{Dry Fuel}}$**	**g/MJ (lb/MMBTU) $_{\text{input}}$**	**g/MJ (lb/MMBTU) $_{\text{output}}$**
Conventional, Single Stage HH/Red Oak	Average	54.3	2.78 (6.48)	13.46 (31.31)
	STDV	20.7	1.06 (2.47)	6.95 (16.2)
Conventional, Single Stage HH/Red Oak and refuse	Average	13.2	0.673 (1.57)	2.18 (5.08)
	STDV	5.41	0.271 (0.631)	1.00 (2.32)
Conventional, Single Stage HH/White Pine	Average*	33.6	1.55 (3.62)	5.70 (13.3)
Three Stage HH/Red Oak	Average	15.0	0.770 (1.791)	2.59 (6.02)
	STDV	4.01	0.206 (0.478)	0.728 (1.693)
European Two Stage Pellet Burner/pellets	Average	0.554	0.028 (0.065)	0.062 (0.144)
	STDV	0.445	0.0225 (0.0522)	0.0465 (0.108)
U.S. Two Stage Downdraft Burner/Red Oak	Average	14.2	0.726 (1.70)	8.61 (2.02)
	STDV	4.34	0.222 (0.517)	0.258 (0.600)

STDV – standard deviation, *Only a single test run was measured.

2.9.9 Methane

A dual methane/THC analyzer was used to determine simultaneous concentrations of the two compounds. The results for one run (red oak in the Conventional, Single Stage HH heater) are shown in Figure 2-42, where the methane concentration is about one order of magnitude lower than the total unburned hydrocarbons (THC). The THC and methane concentration traces mimic each other with a decline over time as the combustion inside the heater improves. Additional tests were not possible due tofunding limitations.

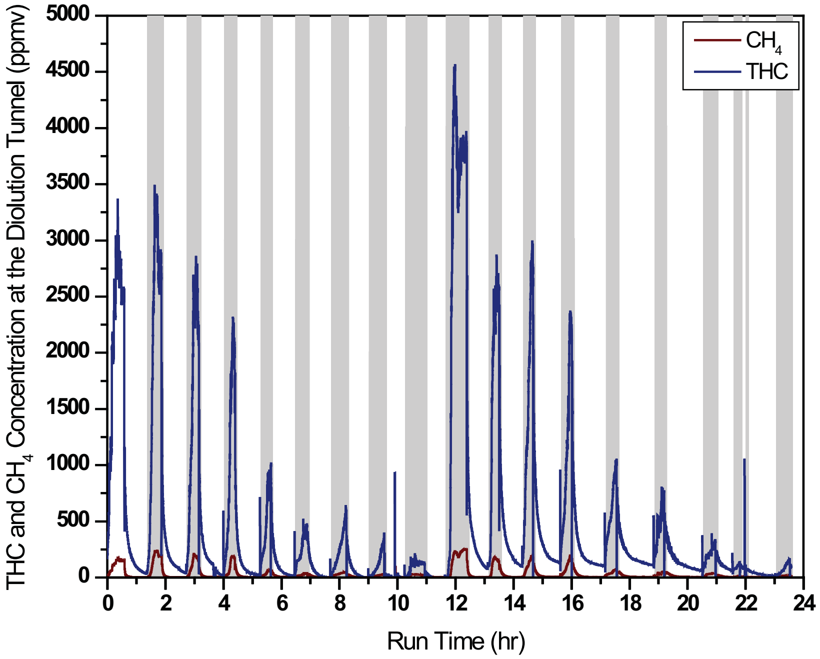


Figure 2-42. Conventional, Single Stage HH Total Unburned Hydrocarbons/Methane Concentration Traces.

2.9.10 Particulate Matter

PM Mass Emissions. Average total PM emissions on both heat input and heat output basis are shown in Figure 2-43 and Table 2-17. As these data indicate, there is a wide range of PM emissions depending on both appliance and fuel types. For the Conventional, Single Stage HH, the PM emissions on a thermal input basis for the three fuels vary between approximately 2.9 and 5.1 lb/MMBTU with the emissions from the red oak and the red oak plus refuse being generally similar (2.9-3.0 lb/MMBTU). The PM emissions almost double, however, when white pine is burned in the same unit. On a thermal output basis the emissions for the Conventional, Single Stage HH unit ranged from approximately 10.3 lb/MMBTU for oak plus refuse to 17.2 lb/MM BTU for white pine. Higher emissions for soft wood (e.g., white pine) combustion in residential wood combustion (RWC) appliances is typical and have been discussed previously (Kinsey et al., 2009).

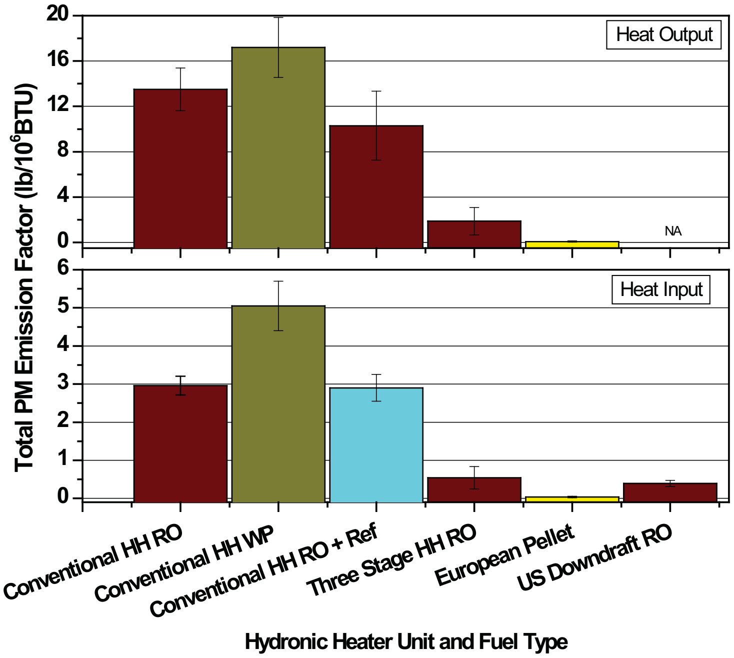


Figure 2-43. PM Emission Factors for All Six Unit/Fuel Combinations.

Table 2-17. PM Emission Factors.

PM Emission Factors				
Heater/Fuel		**g/kg fuel dry**	**g/MJ (lb/MMBTU) input**	**g/MJ (lb/MMBTU) Output**
Conventional, Single Stage HH/Red Oak	Average	24.8	1.27 (2.96)	5.79 (13.5)
	STDV	2.05	0.105 (0.244)	0.813 (1.89)
Conventional, Single Stage HH/White Pine	Average	46.9	2.17 (5.05)	7.40 (17.2)
	STDV	6.02	0.279 (0.649)	1.14 (2.65)
Conventional, Single Stage HH/Red Oak and refuse	Average	24.3	1.25 (2.90)	4.43 (10.3)
	STDV	2.96	0.151 (0.352)	1.31 (3.04)
Three Stage HH/Red Oak	Average	4.55	0.233 (0.542)	0.808 (1.88)
	STDV	2.47	0.126 (0.294)	0.520 (1.21)
European Two Stage Pellet Burner/pellets	Average	0.31	0.0159 (0.0370)	0.0366 (0.085)
	STDV	0.18	0.00925 (0.0215)	0.0245 (0.057)
U.S. Two Stage Downdraft Burner/Red Oak	Average	3.30	0.169 (0.393)	0.173 (0.410)[1]
	STDV	0.68	0.035 (0.0814)	0.083 (0.192)

[1] based on boiler efficiency

STDV – standard deviation

For the other three appliances, only one fuel type was tested due to financial constraints. The Three Stage HH and U.S. Two Stage Downdraft Burner gasifier appliances burned red oak cordwood and the European Two Stage Pellet Burner unit burned hardwood pellets. Average emissions on a thermal energy input basis for these units ranged from 0.54 lb/MM BTU for the Three Stage HH, 0.39 lb/MM BTU for the U.S. Two Stage Downdraft Burner gasifier, and 0.037 lb/MM BTU for the European Two Stage Pellet Burner heater. On a thermal output basis, the PM emission for the Three Stage HH ranged from 1.9 lb/MM BTU to 0.085 lb/MM BTU for the European Two Stage Pellet Burner heater. Lower PM emissions from these three units reflect the more advanced technologies and generally higher combustion efficiencies compared to the older Conventional, Single Stage HH appliance discussed above. The Three Stage HH employs a secondary combustion chamber and larger thermal mass. The European Two Stage Pellet Burner unit uses a consistent uniform fuel and a more steady-state, but still cyclic, fuel feeding approach. The lower emissions from the U.S. Two Stage Downdraft Burner unit are probably related to both its two-stage gasifier/combustor and its thermal storage design, where batches of fuel are burned during short, highly intensive, presumably more efficient, periods and the extracted heat is stored for future demand. Due to our inability to properly measure the thermal flows through the heat storage, the thermal output for the U.S. Two Stage Downdraft Burner unit was estimated using the heat loss method (boiler efficiency).

Figure 2-44 compares average daily PM emissions from the four units and different fuels for a typical Syracuse, New York, home on a January heating day. These data are analogous to the emissions based on thermal output (Figure 2-43) as the different units attempt to match their thermal outputs to the Syracuse load demand. The Conventional, Single Stage HH burning white pine produced the highest total daily PM emissions (6.3 kg (14 lbs)) and the European Two Stage Pellet Burner heater the lowest (0.036 kg (0.08 lb)). Emissions for the Three Stage HH and U.S. Two Stage Downdraft Burner units were comparable at 0.69 and 0.62 kg/day (1.51 and 1.37 lbs/day), respectively. Again, white pine combustion in the Conventional, Single Stage HH unit produced daily PM emissions that were 40% greater than red oak and 70% greater than red oak plus refuse.

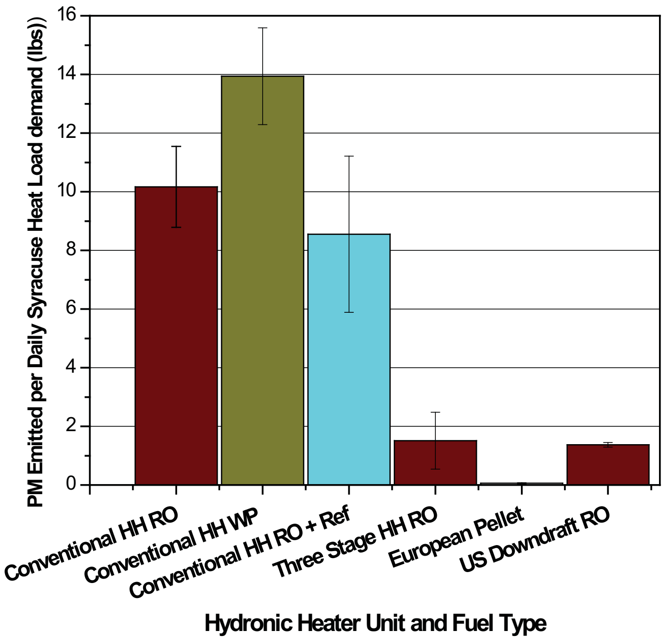


Figure 2-44. Daily Total PM Emission per Syracuse Heat Load Demand. Ro = red oak, WP = white pine, Ref = refuse.

A comparison of PM emission factors determined from the current work to other published HH test data is shown in Figure 2-45. These data are taken from different studies (OMNI, 2009; OMNI, 2007, Intertek, 2008), and were collected using EPA Method 28 OWHH. To develop the plot in Figure 2-45, the percent rated load calculated from this testing is compared to the emission factor from the Method 28 OWHH report for the burn category which represents that same load. For the Conventional, Single Stage HH and Three Stage HH this was Category II and for the U.S. Two Stage Downdraft Burner unit it was Category IV. In the latter case, the maximum rated capacity was used. Also, the pellet emission factor is shown on the plot but there are no Method 28 OWHH data available for the pellet burner. The other unit types are just there for comparison purposes. Data are presented in terms of mass of PM emitted per mass of wood burned. For comparison purposes, only the red oak and hardwood pellet data from this study are included. As shown in Figure 2-45, the EPA method tends to somewhat under-predict the emissions from the Conventional, Single Stage HH and Three Stage HH units. Nevertheless, where comparison data exist, the agreement is somewhat remarkable considering the differences between the EPA protocol method (e.g., use of cord wood here versus crib wood in Method 28) and the more "real world" approach used here to characterize emissions. As a further comparison, the total PM emissions factor for a residential oil-fired boiler is 0.08 g/kg fuel and cannot be shown on Figure 2-45.

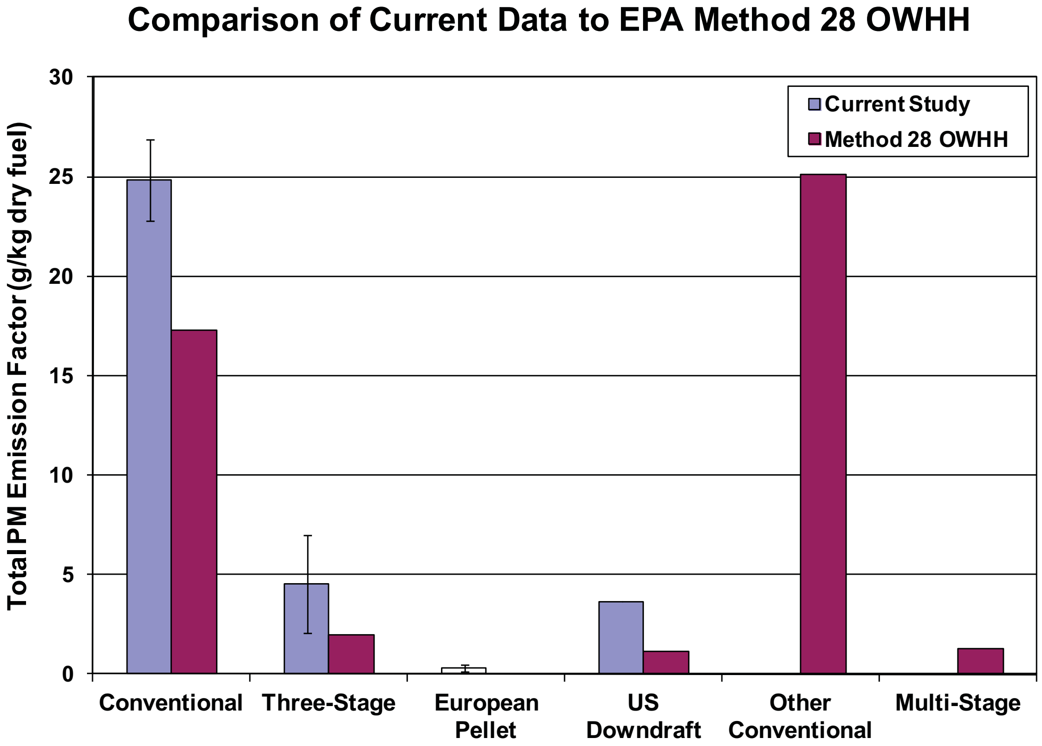


Figure 2-45. Comparisons of PM Emission Factors to Other HH Test Data. Note that residential fuel oil = 0.08 g/kg fuel (Brookhaven National Laboratory).

2.9.11 Particle Number Emissions

Particle number concentrations as well as particle size distributions (PSDs) were measured continuously, inside the dilution tunnel, using an ELPI during each experiment. Figure 2-46 presents these number concentrations for the various unit and fuel combinations tested, integrated over the test cycles, and normalized for heat input. Note that these data have not been corrected for dilution in the tunnel that varied from test to test but was generally about 10:1. Therefore, the values shown in Figure 2-46 would need to be multiplied by this value in order to correct the emission factors for dilution.

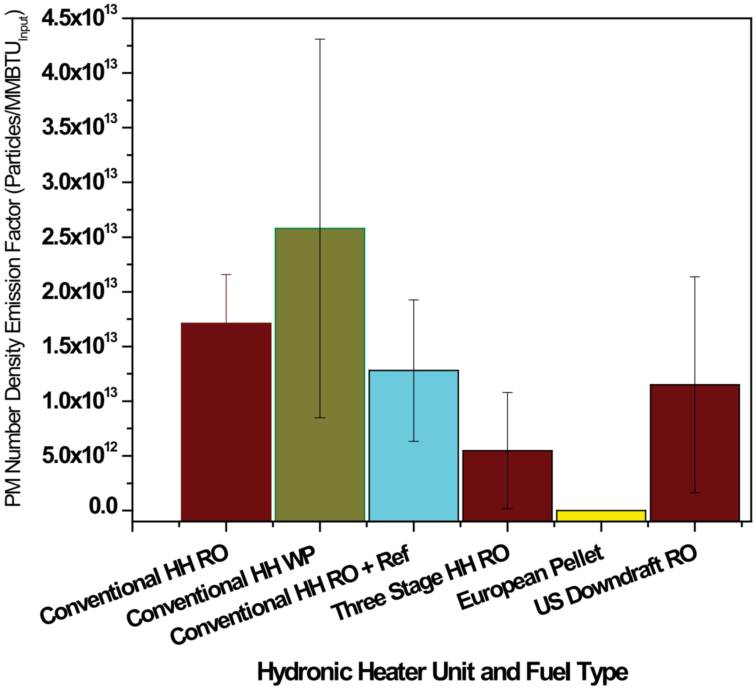


Figure 2-46. Total PM Number Emission Factors for All Six Unit/Fuel Combinations.

As can be observed in Figure 2-46, the particle number emissions range from a high of ~ $2.6\text{x}10^{13}$ particles/MM BTU for the Conventional, Single Stage HH burning white pine to a low of ~ $4.0\text{x}10^{12}$ particles/MM BTU for the European Two Stage Pellet Burner. Still, note the higher amount of variability evident during replicate tests of the U.S. Two Stage Downdraft Burner unit. For the three fuels burned in the Conventional, Single Stage HH unit, the trend in the particle number emissions is similar to the PM mass emissions discussed above with pine combustion having the highest value and the oak plus refuse having the lowest.

2.9.11.1 Temporal Particle Number Density

Due to the cyclic damper operation of several of the units, the PM number emissions were also both cyclic and highly variable. The exception was the U.S. Two Stage Downdraft Burner gasifier where a single high burn condition (consistent with its thermal storage design) was tested. Number concentrations versus time are presented in Figures 2-47, 2-48, and 2-49 for the three fuels burned in the Conventional, Single Stage HH unit and in Figures 2-50, 2-51, and 2-52 for the Three Stage HH, European Two Stage Pellet Burner, and U.S. Two Stage Downdraft Burner units, respectively. Two temporal data sets are presented for each unit representing the range in emissions measured in the dilution tunnel. Note that these number concentrations have not been corrected for dilution and are at least one order of magnitude lower than the concentrations measured in the stack.

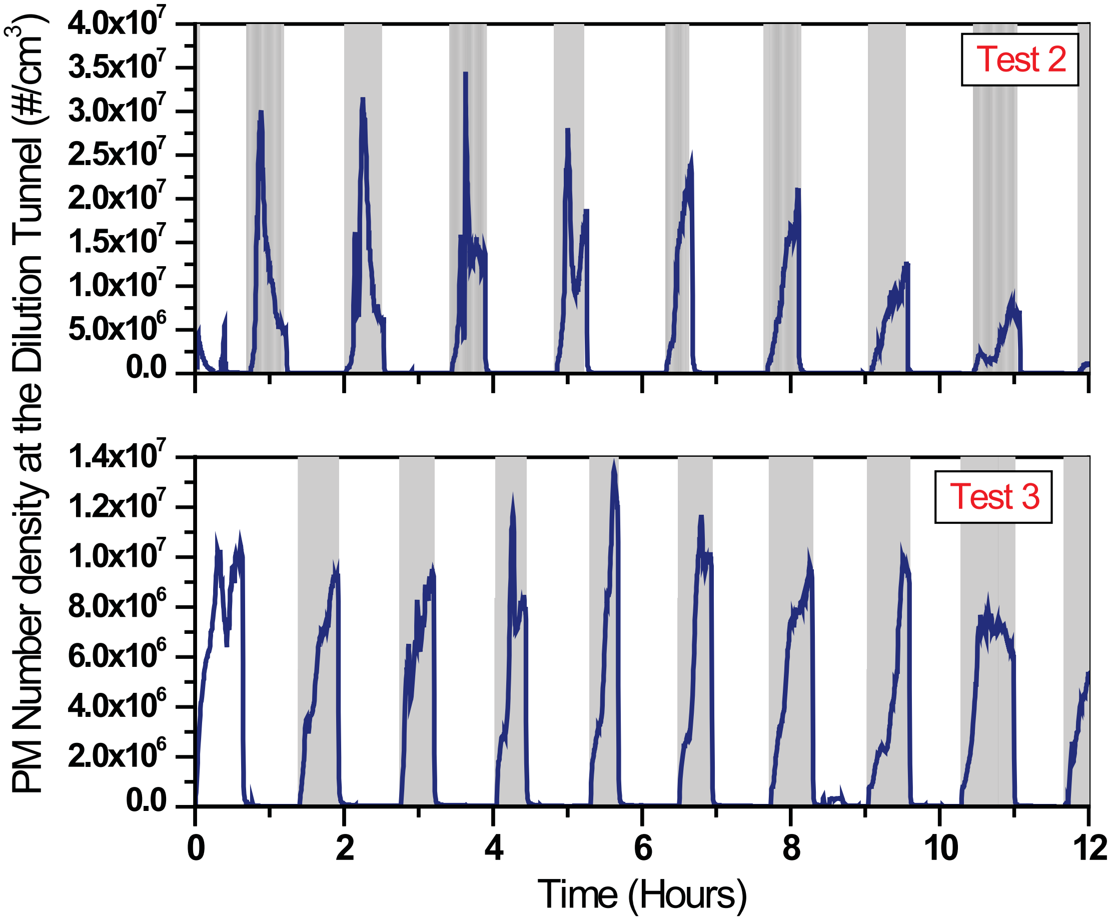


Figure 2-47. Conventional, Single Stage HH Temporal PM Number Density and Concentration in the Dilution Tunnel (Red Oak).

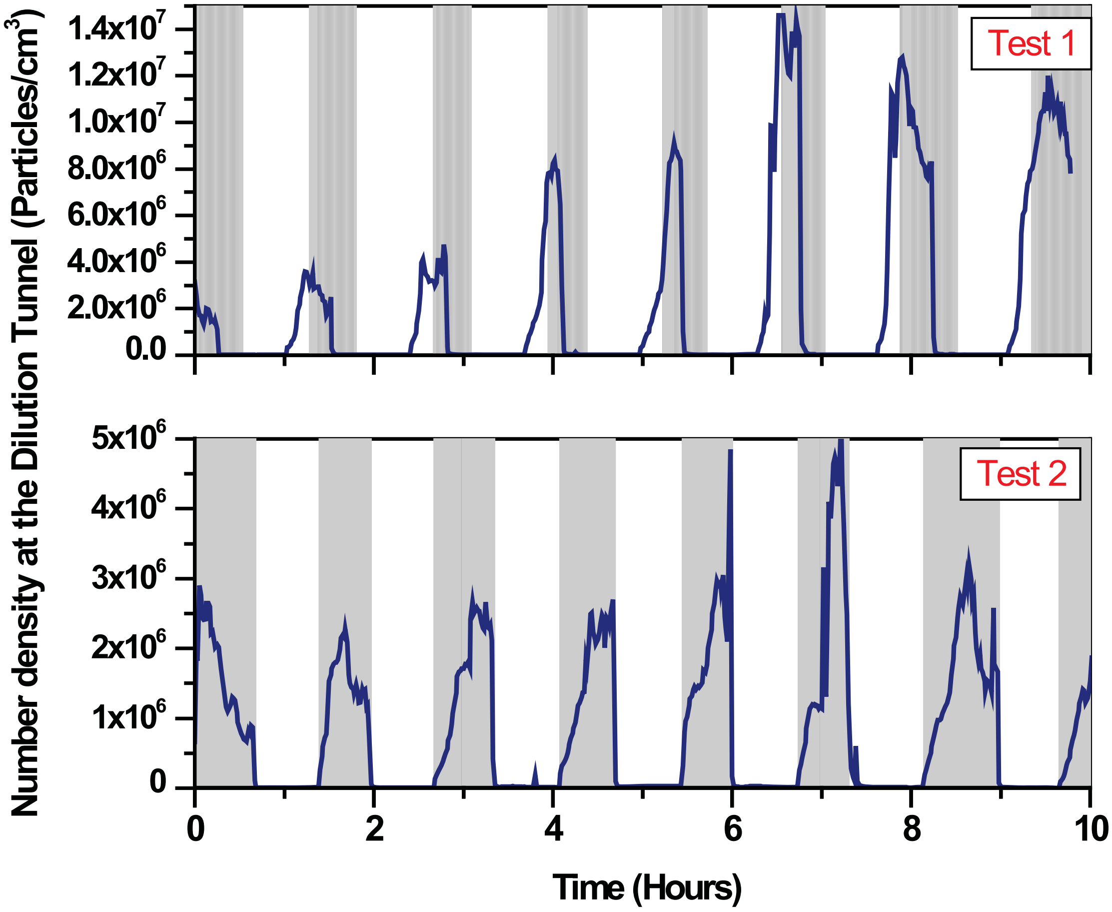


Figure 2-48. Conventional, Single Stage HH Temporal PM Number Density and Concentration in the Dilution Tunnel (Oak + Refuse).

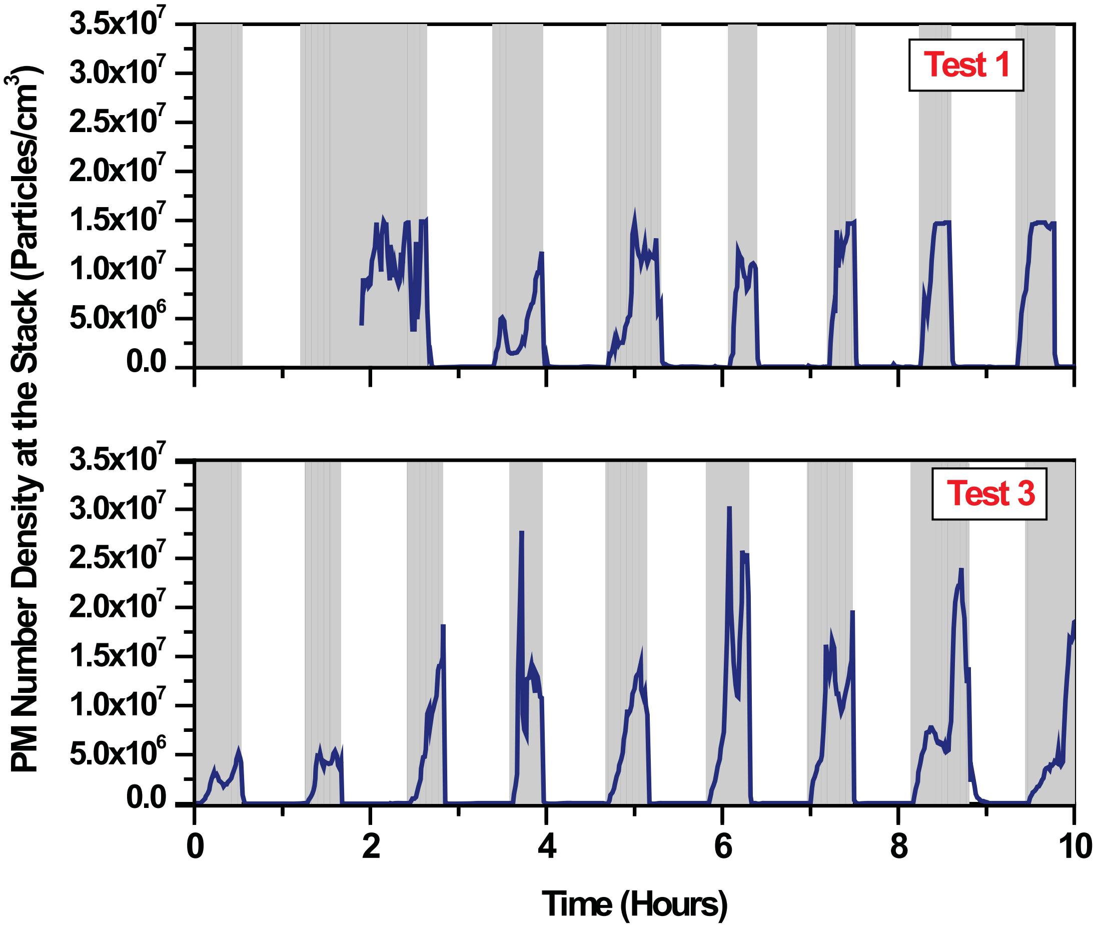


Figure 2-49. Conventional, Single Stage HH Temporal Concentration in the Dilution Tunnel (White Pine).

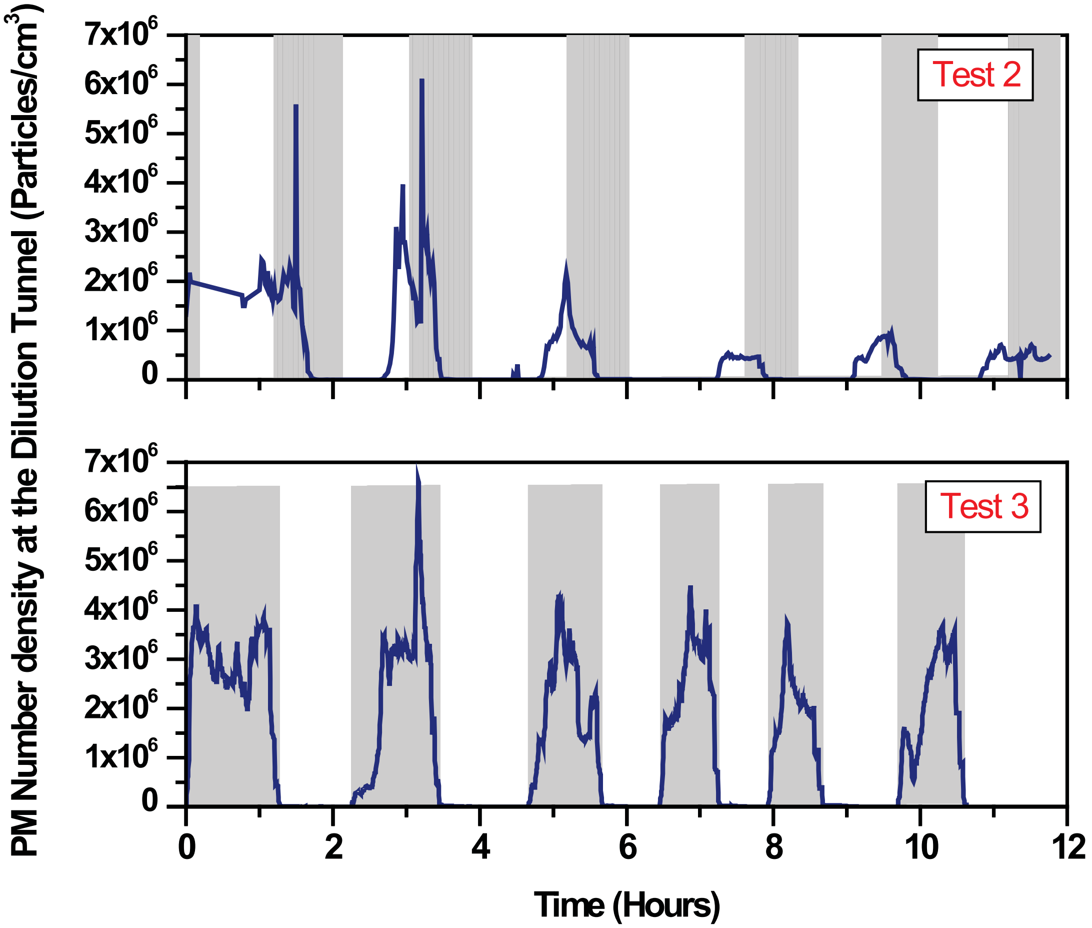


Figure 2-50. Three Stage HH Temporal PM Number Density and Concentration in the Dilution Tunnel (Red Oak).

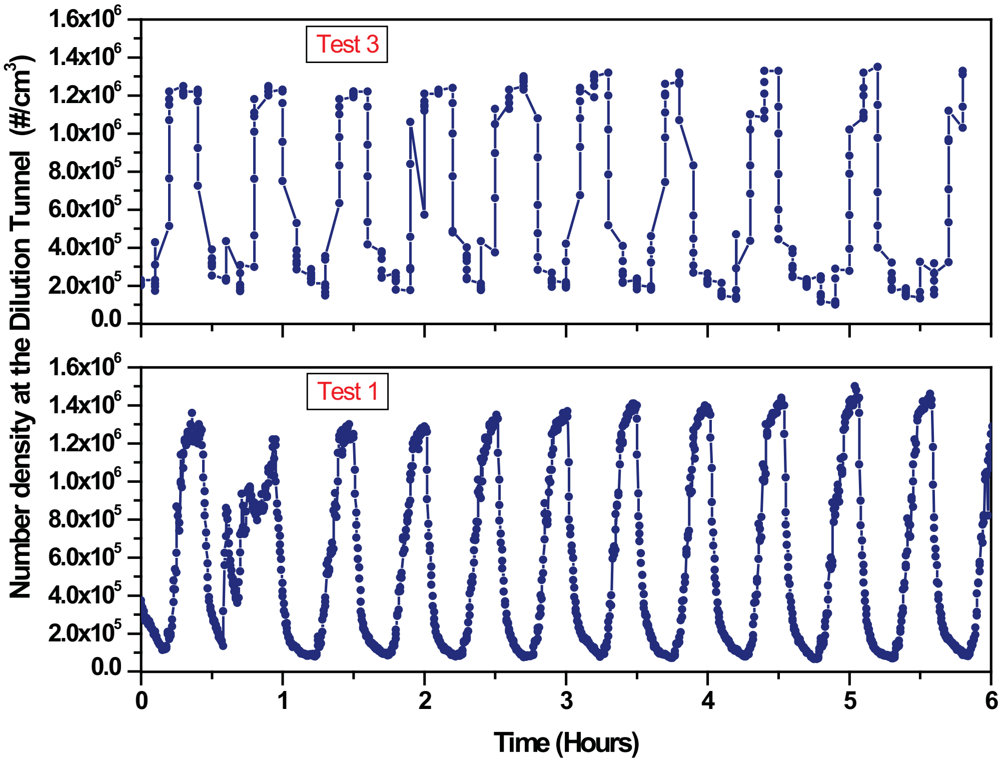


Figure 2-51. European Two Stage Pellet Burner Temporal PM Number Density and Concentration in the Dilution Tunnel (Wood Pellets).

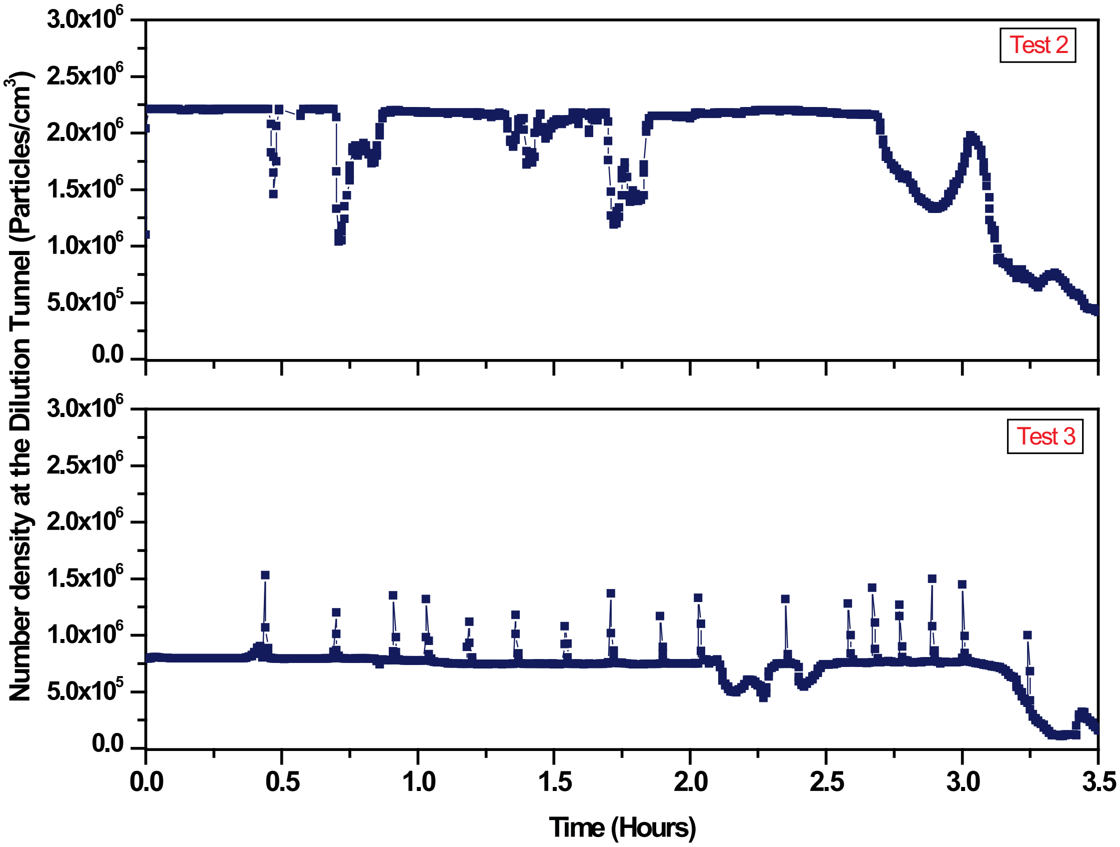


Figure 2-52. U.S. Two Stage Downdraft Burner Temporal Particulate Number Density in the Dilution Tunnel (Red Oak).

The particle number distributions shown in Figures 2-47, 2-48, and 2-49 indicate periods of very high number concentrations (>3.0 x 10^7 particles/cm^3) followed by periods with almost no emissions corresponding to damper openings and closings, respectively, for the three fuels burned in the Conventional, Single Stage HH. The maxima in the PM number concentration for each damper opening do not always decrease with time as was seen to be the case with PM mass. For PM mass, the maximum emissions for each damper cycle tended to decrease with time as the fuel charge was consumed. Also, depending on fuel type, the number concentration at the end of the fuel charge might be as high as, or even higher than, at the beginning. Some of these observations might be explained by corresponding changes in the PSDs discussed below.

Figure 2-49, which presents data for the Conventional, Single Stage HH burning white pine, also illustrates the large variability in number emissions from replicate charges during otherwise identical experiments. In this case, the trend in the number concentrations appears to be different for the two replicate runs. In the first test, the peaks are much more consistent for each damper open period. In the second test, the spikes are more variable with significantly higher number concentrations indicated. The reasons for these differences are not immediately apparent from the data collected, but may be due to subtle differences in the way the units are loaded and the fuel charges consumed.

Although a similar cyclic pattern was also observed for the Three Stage HH and European Two Stage Pellet Burner appliances, different trends were evident. Figures 2-50 and 2-51 indicate significantly lower PM number concentrations for the Three Stage HH and European Two Stage Pellet Burner, respectively, compared to the Conventional, Single Stage HH. For the Three Stage HH (Figure 2-50), there is some indication that the PM number concentrations tend to decrease with time as the fuel charge is consumed. The peaks also tend to be somewhat flatter, indicating less variability in the combustion process, possibly related to its two stage design where the secondary chamber helps to reduce and dampen emissions. The Three Stage HH required only six damper openings over 12 hours to meet the Syracuse demand compared to nine or 10 damper cycles for the Conventional, Single Stage HH, probably related to the higher thermal mass and efficiency associated with the Three Stage HH. In the case of the European Two Stage Pellet Burner unit (Figure 2-51), the PM number emission profile produces a very uniform repeatable pattern related to the consistent manner that fuel pellets are periodically fed into the combustion chamber. Still, this on/off operating cycle of the pellet feeder was established by the manufacturer when the unit was set up. The European Two Stage Pellet Burner was programmed to follow a modulation sequence that put the unit into a “stop heating mode” whenever the target output water temperature, in this case 80 °C (176 °F), overshot the unit output modulation range (target temp + 3 C°). In this mode, the exhaust fan continues to run but the fuel feeding and the combustion air fans are stopped. According to the manufacturer, this mode of operation is not typical of the appliance’s normal operation. The unit typically operates at a higher heat load or with heat storage, but in this test the unit was programmed to directly meet the Syracuse cycle heat load without heat storage. Finally, Figure 2-52 presents PM number concentration profiles for the U.S. Two Stage Downdraft Burner gasification unit. Recall that for this unit each test involves gasification and combustion of a single wood charge to simulate the heat generation and thermal storage inherent in the design of this particular appliance. The data suggest that the PM number concentrations are generally relatively constant throughout the burn with only few variations from time to time throughout the run. This unit benefits from a design that uses intense combustion to minimize emissions and thermal storage to minimize the number of combustion cycles needed to meet a specific load. The duration of its single 3.5 hour operating cycle is comparable to the sum of seven, 30 min cycles characteristic of the Three Stage HH operation.

2.9.12 Particle Size Distributions

Number PSDs, based on one minute “snapshots” taken five minutes into the damper open cycle, are shown in Figures 2-53, 2-54, and 2-55 for the three fuels used in the Conventional, Single Stage HH (red oak, white pine, and red oak plus refuse, respectively). Figures 2-56, 2-57, and 2-58 present similar data for the Three Stage HH (red oak), European Two Stage Pellet Burner unit, and U.S. Two Stage Downdraft Burner gasifier (red oak), respectively. In these figures, PSDs are shown for each damper open cycle throughout each test period. The ELPI data present number PSDs over the size range of 30 nm to 3 um. Also recall that these PSDs have not been corrected for dilution in the tunnel which varied but was about a factor of 10:1. Thus, the PSDs provided should reflect the gas-to-particle conversion process associated with dilution of the stack gases by a factor of 10.

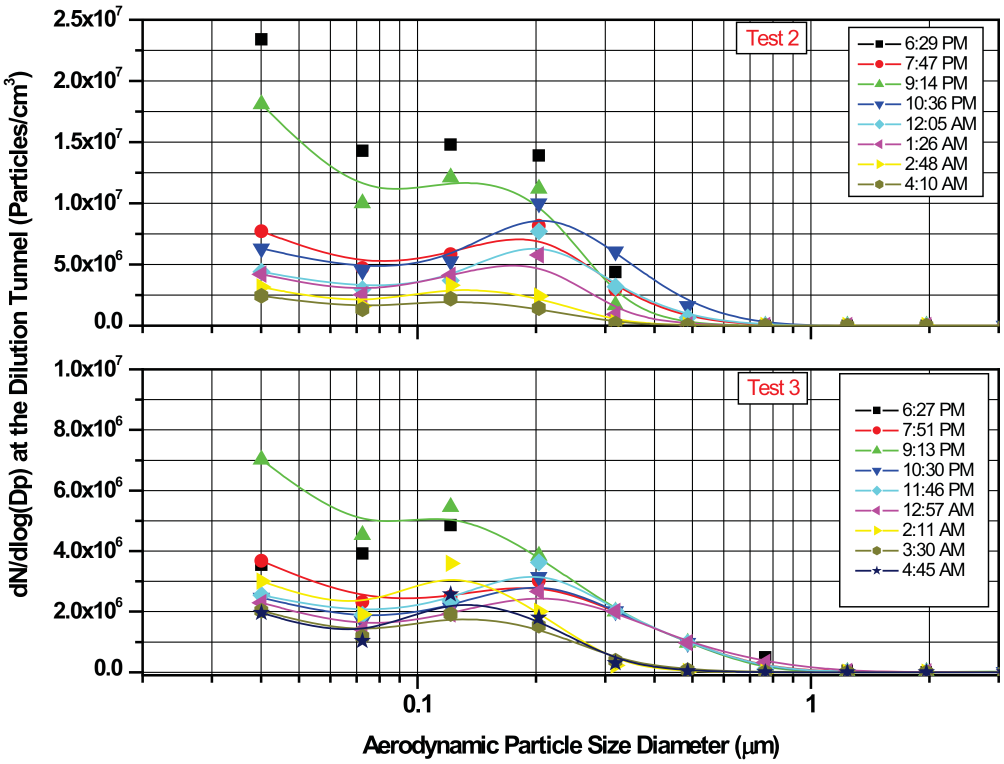


Figure 2-53. Conventional, Single Stage HH Particulate Density and Size Distribution (Snapshot of 1 min, 5 min into Damper Open, Red Oak).

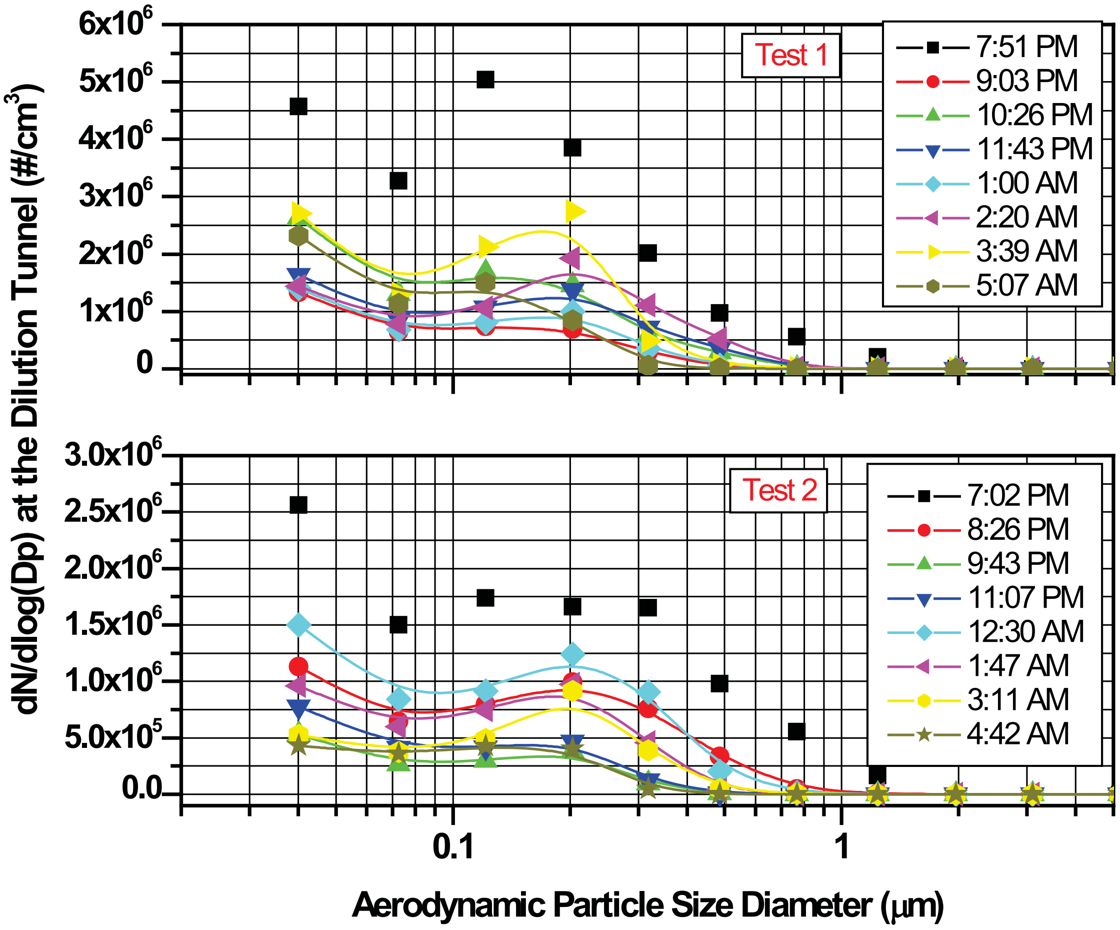


Figure 2-54. Conventional, Single Stage HH Particulate Density and Size Distribution (Snapshot of 1 min, 5 min into Damper Open, Red Oak + Refuse).

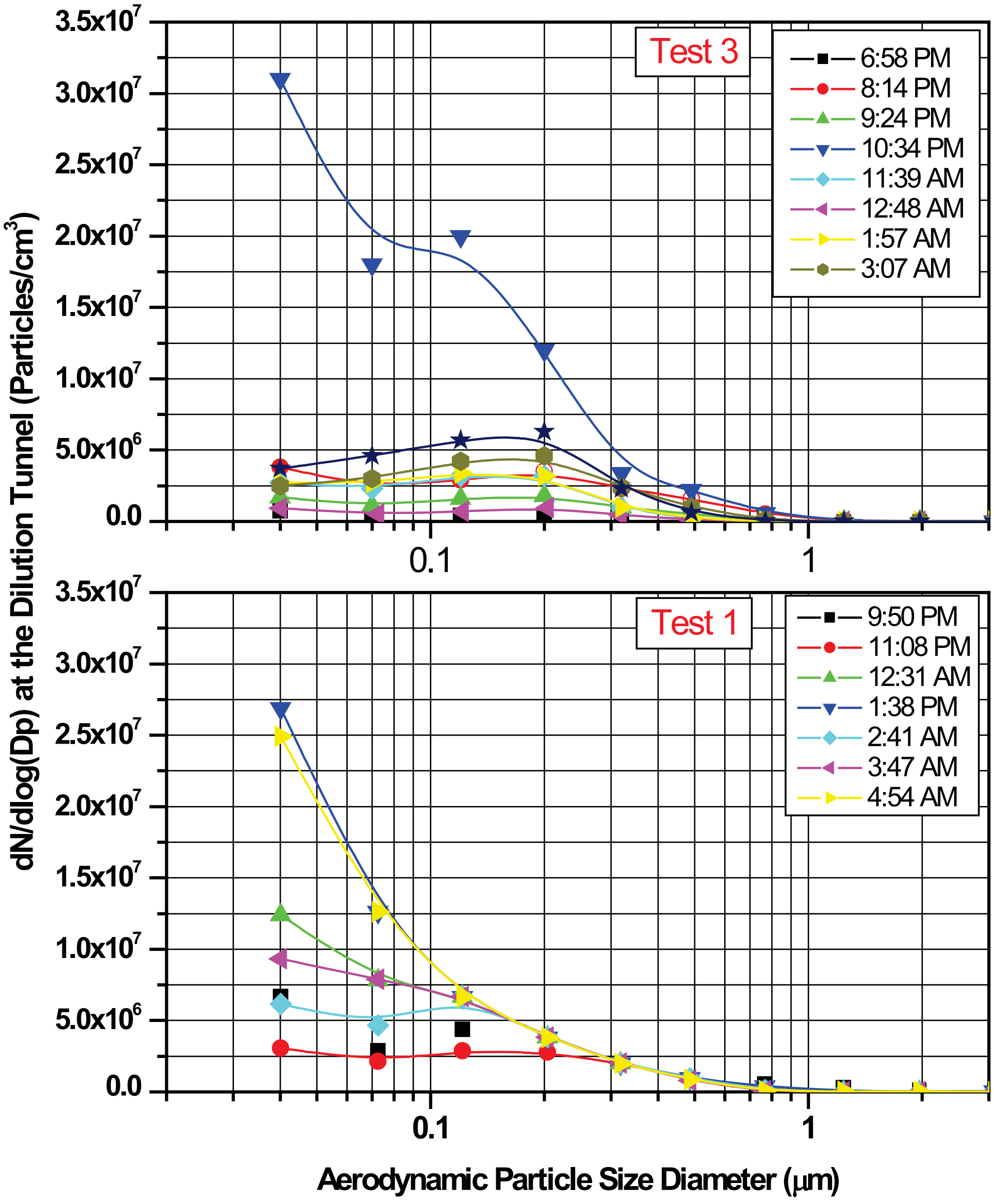


Figure 2-55. Conventional, Single Stage HH Particulate Density and Size Distribution (Snapshot of 1 min, 5 min into Damper Open, White Pine).

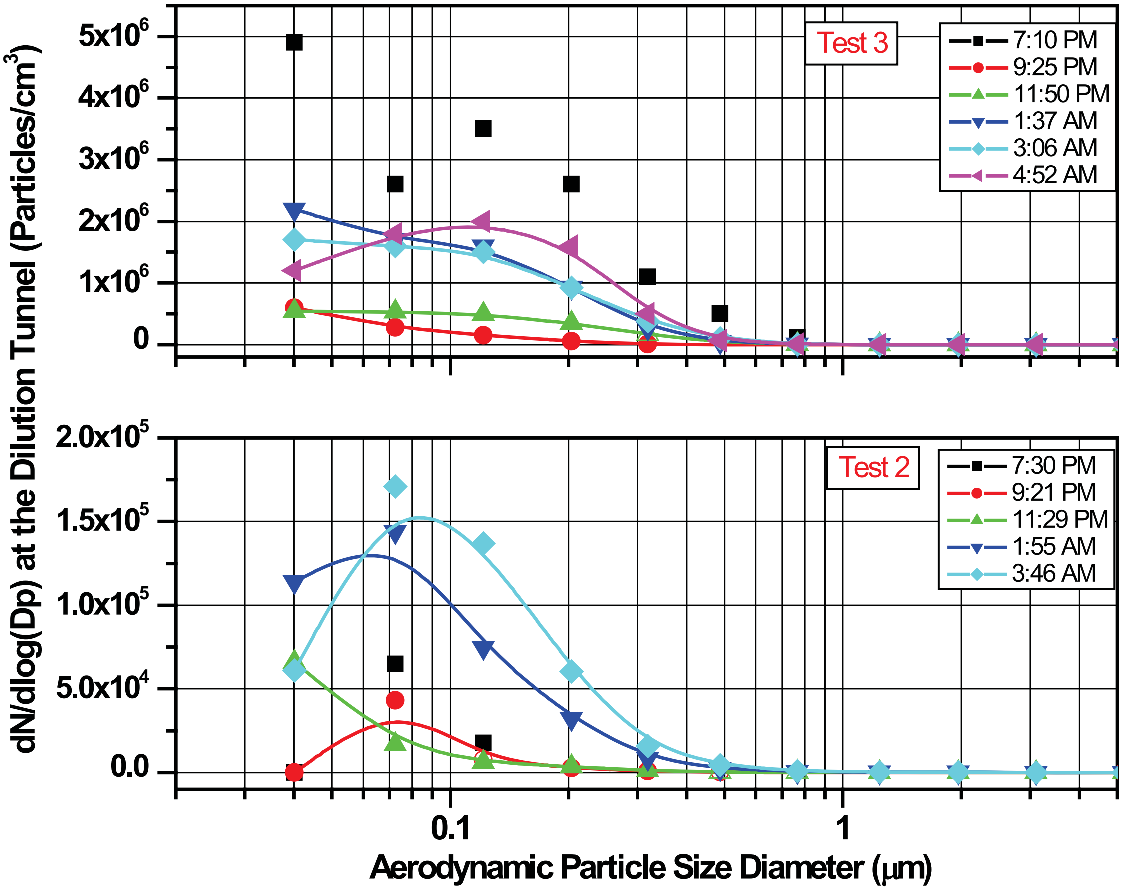


Figure 2-56. Three Stage HH Particulate Density and Size Distribution (Snapshot of 1 min, 5 min into Damper Open, Red Oak).

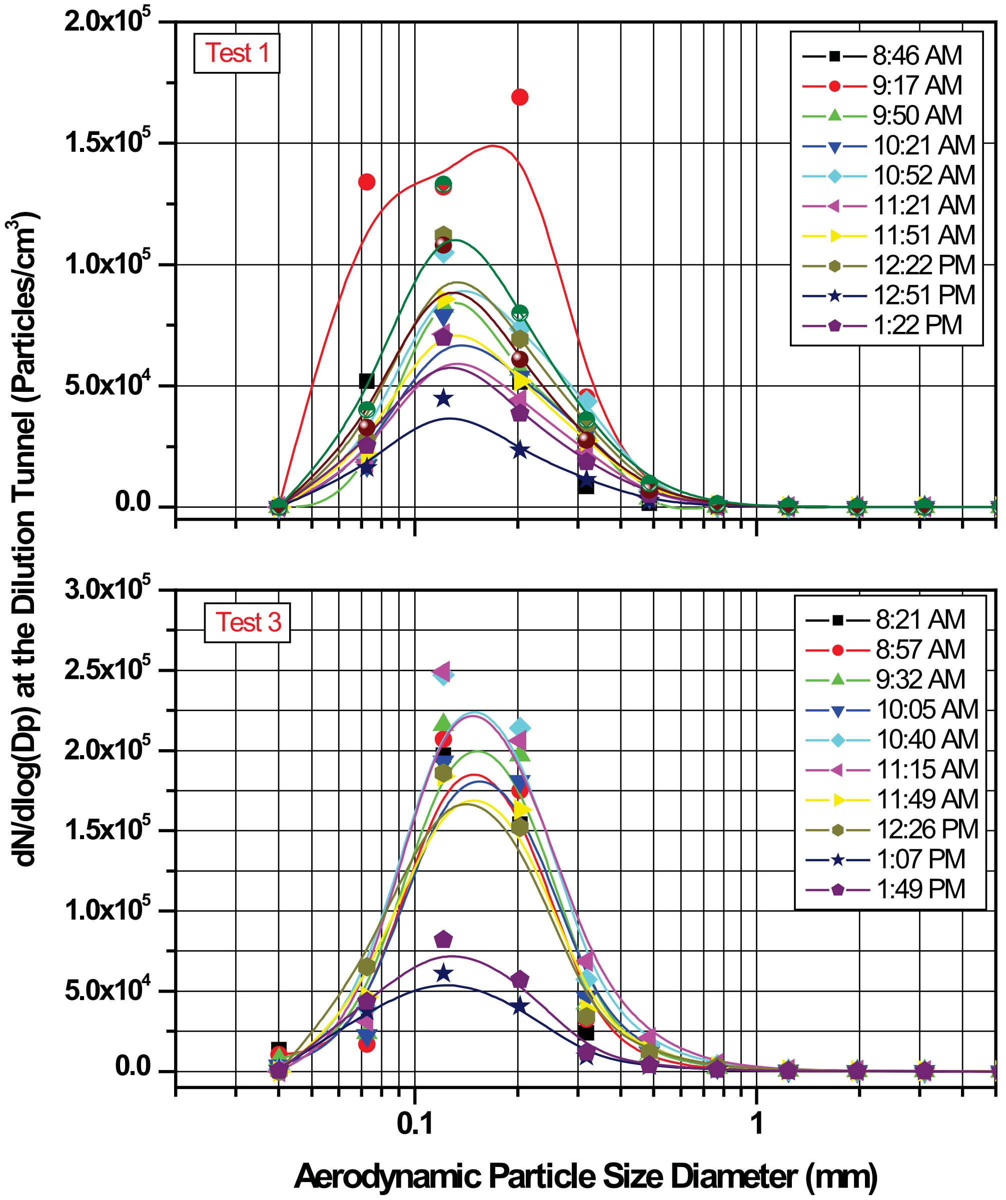


Figure 2-57. European Two Stage Pellet Burner Particulate Density and Size Distribution (Snapshot of 1 min, 5 min into Damper Open, Wood Pellets).

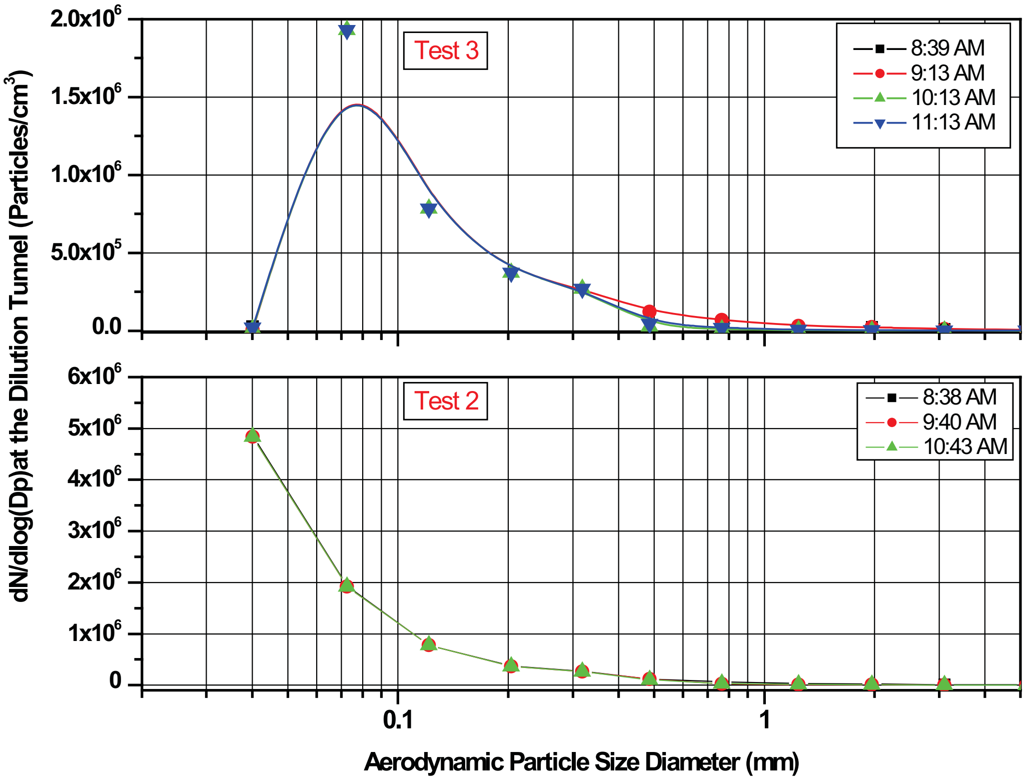


Figure 2-58. U.S. Two Stage Downdraft Burner Particulate Density and Size Distribution (Snapshot of 1 min, 5 min into Damper Open, Red Oak).

For the Conventional, Single Stage HH (Figure 2-53, 2-54, and 2-55), the PSDs all tend to be bimodal, with well established accumulation modes between 100 and 300 nm and evidence of predominant nuclei modes indicated by increasing concentrations for particles less than 30 nm. The accumulation modes are likely comprised of an evolving aerosol, formed within the combustors, and comprised of soot, ash, and condensing organics. In contrast, the nuclei modes are likely the result of nucleating organics that form much closer to the sampling location. These emissions are characterized by very large amounts of unburned organic carbon that tend to nucleate preferentially as the cooling emissions become highly supersaturated. For the Conventional, Single Stage HH, the PSDs determined during the various damper openings are highly variable, consistent with the variable number concentrations, and likely related to differences within the combustor during each damper cycle.

For the Three Stage HH (Figure 2-56), the PSDs appear to be somewhat similar to those generated by the Conventional, Single Stage HH except with respect to the lower number concentrations and the related shift in the accumulation mode toward smaller sizes (70-150 nm). Coagulation processes are directly related to number concentrations, and increases in particle number densities, as seen for the Conventional, Single Stage HH, are expected to result in larger particle diameters. The Three Stage HH PSDs show less evidence of large nuclei modes, consistent with lower relative organic emissions, lower partial pressures, and preferential heterogeneous condensation on existing particles rather than homogeneous condensation to form nuclei. This behavior is consistent with the increased efficiency and lower emissions of the Three Stage HH compared to the Conventional, Single Stage HH.

For the European Two Stage Pellet Burner (Figure 2-57), the PSDs exhibit a well-established accumulation mode between 100 and 200 nm with no evidence of a nuclei mode. Further, the PSDs for this unit are relatively similar over time. These features are consistent with the more controllable operation of the pellet unit and the uniform pellet fuel used. For this unit, organic carbon emissions are significantly reduced.

Finally, PSDs measured from the U.S. Two Stage Downdraft Burner gasification unit (Figure 2-58) suggest a single evolving mode. For the replicate tests, this mode varied from less than 30 to 80 nm. Both sets of PSDs also suggest the presence of a 200 nm accumulation mode. Nevertheless, evolution of this single mode is not entirely clear. Differences in the two data sets suggest modest differences in nucleation between the replicate tests, perhaps due to slight differences in temperature profiles, dilution, or combustor parameters. One set of PSDs (80 nm) suggests a slightly older aerosol. Still, the differences are small considering the coagulation rates of aerosol in this nanometer size range.

For comparison between units, Figure 2-59 presents selected test-averaged PSDs on similar scales. Only red oak data, or hardwood pellets in the case of the European Two Stage Pellet Burner unit, are included. The first two units (Conventional, Single Stage HH and Three Stage HH) exhibit characteristic bimodal PSDs with median particle diameters of 150 and 120 nm, respectively. The major difference between the two units is the particle number concentration which is almost an order of magnitude lower for the Three Stage HH, reflecting the addition of a secondary combustion chamber to the traditional Conventional, Single Stage HH design. The European Two Stage Pellet Burner unit and U.S. Two Stage Downdraft Burner gasifier, on the other hand, both show single mode PSDs with median particle diameters of 187 and 84 nm, respectively, indicative of the different combustion technologies used in these two units.

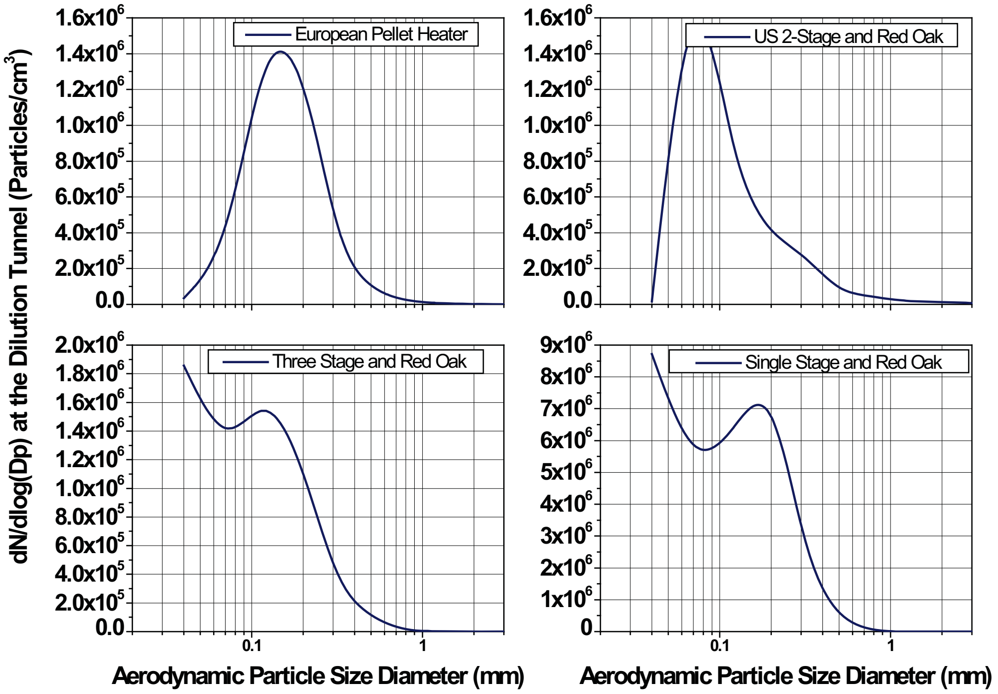


Figure 2-59. Average Across One Day's Test PM Size Distribution for All the Heaters.

2.9.13 Elemental Carbon, Organic Carbon, and Inorganic Ash

Organic carbon (OC) and elemental carbon (EC) concentrations and their emission factors were determined from the thermal optical analysis of the OC/EC ratio in combination with the PM mass emission factor. Direct calculation of the OC and EC concentrations was not possible from the filter samples, as the rapid loading of PM on the filter required short sampling times and did not allow accurate determination of the sample volume. The portion of the PM comprised of inorganic PM was determined using XRF on single samples from each unit. Quartz fiber filters from each unit/fuel type were analyzed for the mass of inorganic PM; the remainder of the PM was organic, with an OC/EC ratio determined with the thermal optical method. Multiple filter samples were taken for every unit in order to determine the organic and elemental carbon ratio throughout the duration of each run.

The average values of the OC/EC ratios for each six unit/fuel combinations are shown in Table 2-18. The average values ranged from about 0.84 to 27, with the lowest value achieved by the European Two Stage Pellet Burner unit and the highest value achieved by the Conventional, Single Stage HH unit burning white pine. OC/EC ratios much greater than unity are typical for biomass fuel such as wood logs because, in general, large amounts of organic compounds exist in the exhaust. The low value for the European Two

Stage Pellet Burner unit suggests that possibly the organic fraction is the result of the combined low content of semivolatile organics in the wood pellets and the high combustion efficiency of the European Two Stage Pellet Burner unit. The carbonaceous fraction of the PM emitted represents more than 99% of the total PM emitted and is independent of the fuel/unit combination.

Table 2-18. Range and Average OC/EC Ratios and the Inorganic Portion of the PM for the Six Unit/Fuel Combinations.

OC/EC Results					
Heater/Fuel	**Samples Collected**	**High OC/EC**	**Low OC/EC**	**Average OC/EC**	**Inorganic Ash (%)**
Conventional, Single Stage HH/Red Oak	23	83.2	9.6	20.34	0.86
Conventional, Single Stage HH/White Pine	12	40.4	12	27.20	0.88
Conventional, Single Stage HH/Red Oak and Refuse	12	52.4	10.2	20.84	0.86
Three Stage HH/Red Oak	12	43	8.3	23.01	0.93
European Two Stage Pellet Burner/Pellets	12	21	0.2	0.84	0.33
U.S. Two Stage Downdraft Burner/Red Oak	9	54.7	11.4	20.27	0.92

The ranges of OC/EC ratios for all the unit/fuel combinations and the average value of each range, which are plotted with the PM emission factor in Figure 2-60, facilitate consideration of unit-specific impact on emitted mass of OC and EC. The relative OC and EC emissions can be weighted by the PM emission factor. The results suggest that the OC/EC fraction for the fuel logs is mostly dependent on the type of fuel burned and is less dependent on the type of heater utilized. The OC/EC fraction does not follow the same trend as the PM emission factor, which is dependent on both the fuel type and type of unit. Although the average OC/EC ratios were found to be comparable between burn cycles, a wide range of OC/EC ratios is observed within the burning cycle, particularly for the Conventional, Single Stage HH unit burning red oak which varied from an OC/EC ratio of 10:1 up to a ratio of 83:1 (Figure 2-61). These large deviations observed within the burning cycle, or between different burn cycles, may be due to the difficulties encountered in sampling for OC/EC in this type of cyclic combustion process.

The OC, EC, and inorganic ash PM emission factors are shown in Table 2-19 and Figure 2-62. Due to the high carbon content of the PM emitted, most of the emissions are OC and EC, with a negligible amount of inorganic PM. From this figure, it is clear that the OC is the dominant species in the emissions from nearly all of the HH and fuel combinations tested, barring the European Two Stage Pellet Burner. The white pine, the only softwood tested, had twice the OC and EC emission factors of the red oak in the same unit (Conventional, Single Stage HH). Red oak burns showed OC and EC emission factors varying up to threefold depending on the unit. For the European Two Stage Pellet Burner, the EC is slightly greater than the OC fraction. However, in all instances, as seen in Figure 2-62, the inorganic ash fraction represents an extremely low portion of the overall emissions. The insignificant proportion of inorganic ash in the emissions minimized any concerns regarding the use of single samples to determine inorganic ash concentration.

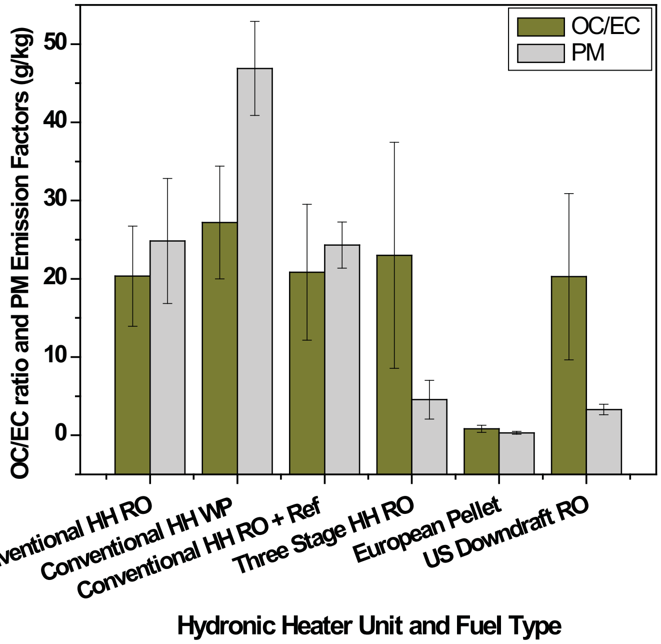


Figure 2-60. OC/EC Ratio and PM Emission Factors for All Six Unit /Fuel Combinations.

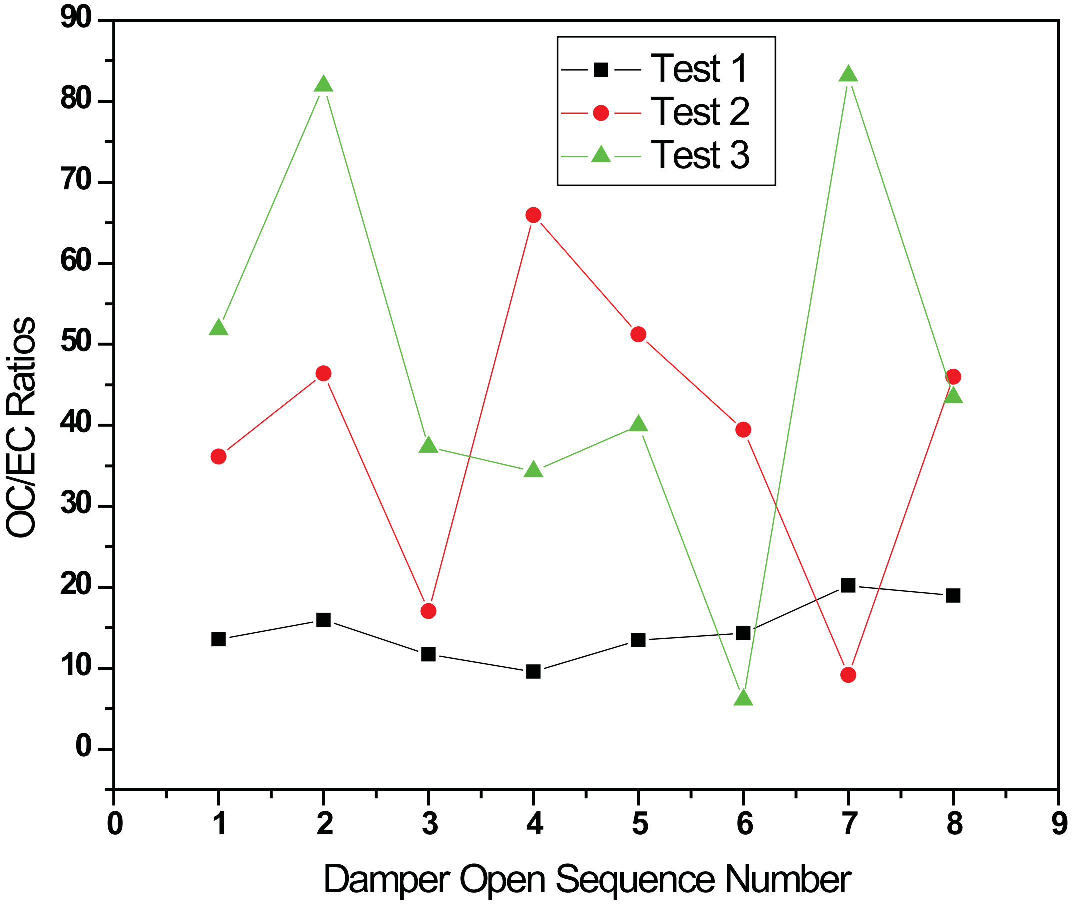


Figure 2-61. Temporal OC/EC Ratios for the Conventional, Single Stage HH Unit Burning Red Oak.

Table 2-19. EC, OC, and Inorganic PM Emission Factors.

PM Emission Factors									
Heater/Fuel	g/kg			g/MJ (lb/MMBTU) Input			g/MJ (lb/MMBTU) Output		
	OC	EC	Inorganic PM	OC	EC	Inorganic PM	OC	EC	Inorganic PM
Conventional, Single Stage HH/ Red Oak	23	1.15	0.21	1.2 (2.8)	0.060 (0.14)	0.011 (0.025)	5.6 (13)	0.27 (0.63)	0.052 (0.12)
Conventional, Single Stage HH/ White Pine	45	1.65	0.41	2.06 (4.8)	0.077 (0.18)	0.019 (0.045)	6.9 (16)	0.26 (0.60)	0.064 (0.15)
Conventional, Single Stage HH/ Red Oak and refuse	23	1.1	0.21	1.2 (2.7)	0.056 (0.13)	0.011 (0.025)	4.3 (10)	0.20 (0.47)	0.038 (0.088)
Three Stage HH/ Red Oak	4.3	0.19	0.04	0.22 (0.51)	0.0096 (0.022)	0.0022 (0.0050)	0.77 (1.8)	0.033 (0.078)	0.0075 (0.018)
European Two Stage Pellet Burner/ Pellets	0.14	0.17	0.001	0.0086 (0.017)	0.0085 (0.020)	0.000052 (0.00012)	0.017 (0.039)	0.019 (0.046)	0.00012 (0.00028)
U.S. Two Stage Downdraft Burner/ Red Oak	3.12	0.15	0.03	0.16 (0.37)	0.0079 (0.018)	0.0016 (0.0036)	0.12 (0.39)	0.0082 (0.019)	0.0016 (0.0038)

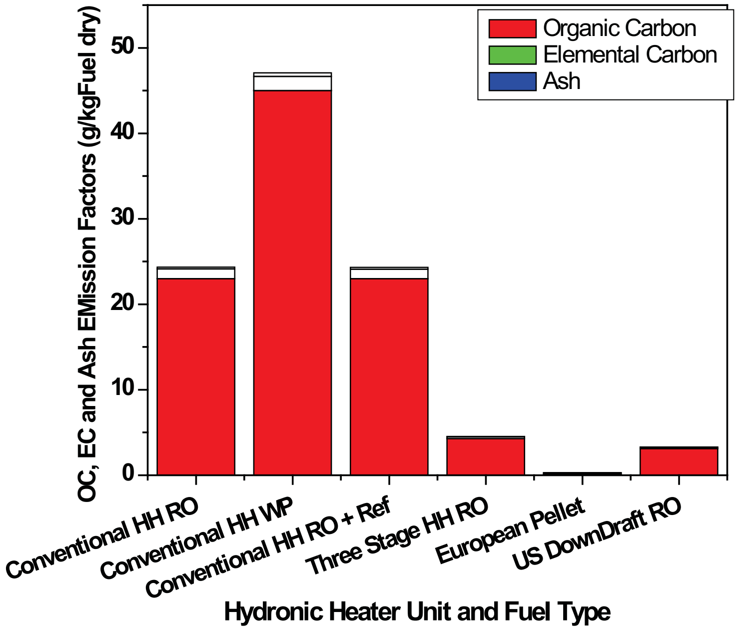


Figure 2-62. OC, EC, and Inorganic PM Emission Factors for All Six Unit /Fuel Combinations.

2.9.14 PM Organics and Marker Compounds

Gas Chromatography/Mass Spectrometry (GC/MS). In the present study, GC/MS techniques were used to identify and quantify individual semivolatile organic compounds (SVOCs) in the PM emissions collected from the four HHs. A total of six different HH-fuel combinations were selected for organic matter speciation, including the Conventional HH burning red oak wood, white pine wood, and red oak wood with supplementary refuse, the more efficient Three Stage HH heater burning red oak wood, the pellet unit burning wood pellets, and the Alternative Fuel Boiler appliance burning red oak wood. Each test included the analysis of three phases classified as a beginning (first two hours of the test cycle), middle, and end (roughly the last 2 hr) of the test cycle. A replicate analysis was performed for each HH-fuel combination. A total of 138 compounds from the PAH, normal (*n*)-, branched (*b*)-, and cyclic (*c*) alkane, organic acid, methoxyphenol, sterol, and anhydro-sugar compound classes were targeted for analysis. Roughly 100 of these target analytes were detected and quantified for the HH study. The emission factor results for these compounds (denoted as "X") in units of µg X/g PM, µg X/MBTU$_{in}$, and µg X/MBTU$_{out}$ are provided in Attachment A. The hopane and sterane molecular markers typically assigned to motor vehicle sources were below detection limits for the present study and thus not reported.

The identified and quantified SVOCs account for 9% w/w of the PM emitted from the HH on average. The HH PM comprised 1-5 wt % of the anhydro-sugar levoglucosan, a molecular maker of cellulose pyrolysis. Organic acids—including *n*-alkanoic, *n*-dialkanoic, aromatic, and resin acids—and the methoxyphenols (lignin pyrolysis products) were the compound/functional group classes with the highest average concentrations in the HH PM. The PAH explained between 0.1-4% w/w of the PM mass, with the Conventional, Single Stage HH boiler showing the most significant PAH fraction in the HH PM.

Test phase-composited GC/MS concentration data (µg X/g PM; log transformed; color-coded by compound class) for all the speciated organic compounds in the PM (zeroes are omitted) are plotted for each HH test in Figure 2-63. The figure shows that the mass concentrations of individual compounds in the HH PM span as much as five orders of magnitude (note values are log-transformed). When considering this entire GC/MS constrained chemical space, results from a Tukey-Kramer Honestly Significant Difference test (TK-HSD) show that (i) the European Two Stage Pellet Burner-Pellets experiment was significantly different (lower) from all other tests, and (ii) Conventional, Single Stage HH-White Pine (WP) was significantly different from Three Stage HH-RO, U.S. Two Stage Downdraft Burner-Red Oak (RO), and Conventional, Single Stage HH-RO.

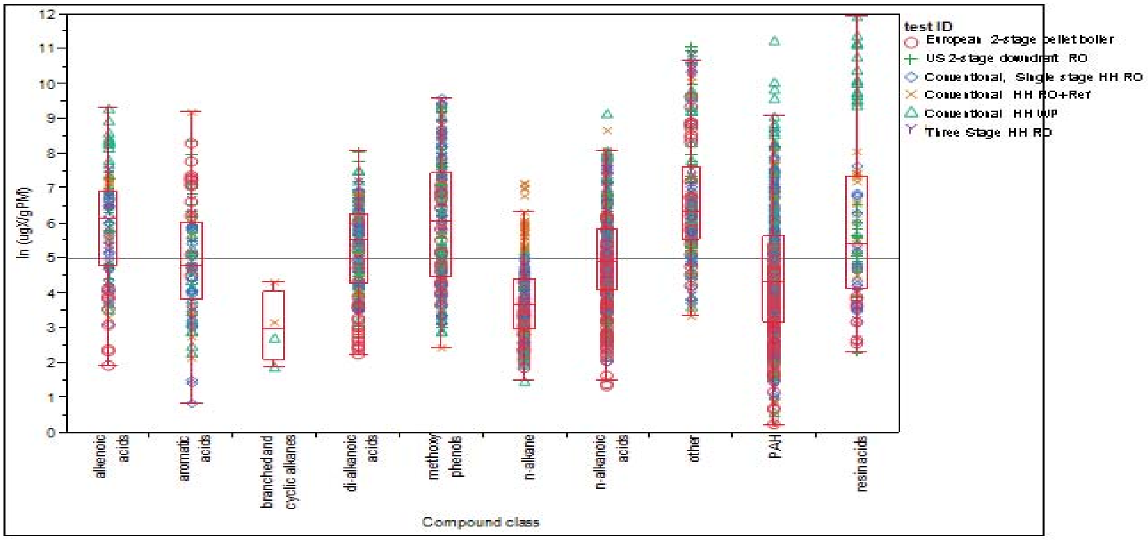


Figure 2-63. Box Plots of Organic Pollutant Levels in PM Organized by HH Test. (Box plots indicate the 25th and 75th percentiles and the median. The whiskers indicate the upper and lower quartiles ± 1.5 times the inter-quartile range.)

For each HH/fuel type experiment, box plots of test phase-composited organic pollutant levels in the HH PM are provided in Figure 2-64, panels A-D. Each panel represents a compound class (*n*-alkane, PAHs, methoxyphenols, and organic acids) and is color-coded by test phase. Test pair means for each compound class were compared using the TK-HSD. Results were placed in Table 2-20, which lists the compound classes that exhibit a significant difference between test set pairs. For example, the emissions of the organic acid and PAH compound classes from the European Two Stage Pellet Burner-Pellets test were significantly lower than for all other HH combustion tests. The Conventional, Single Stage HH-WP test, on the other hand, showed significantly higher PAH and organic acid levels in PM than all other tests. The *n*-alkanes in the PM emissions were the most narrowly distributed with regard to concentration, were significantly higher for the Conventional, Single Stage HH RO + R tests, but appear relatively erratic between HH tests. The TK-HSD model indicated no significant difference among the HH tests for the anhydro-sugars and methoxyphenols in the PM. The TK-HSD conclusions for the anhydro-sugars and methoxyphenol class were consistent even after further dividing the Figure 2-64 concentration data by phase.

Figure 2-65 depicts the organic pollutant levels in the HH PM organized by compound class. The analysis of variance (ANOVA) model confirms significant differences ($p < 0.0001$) among the compound class emission levels using the composited log transformed concentration values for all organic compounds and tests (omitting zero values). Results from a TK-HSD test verified that the anhydro-sugars in PM, which are dominated by levoglucosan, are significantly higher than all other organic compound classes. The mass of individual PAHs in the HH PM were significantly lower than the mass due to organic acids, alkanes, and methoxyphenols.

Figure 2-66A shows the concentration of individual *n*-alkane compounds in the HH PM. The plot is a composite of the results (log-transformed values) from all tests and is color-coded by boiler type but disregards the fuel type burned. Of the compound classes studied, the *n*-alkane levels in PM were the most narrowly distributed. Combined, the *n*-, *b*-, and cyclic-alkanes accounted for the lowest proportion (< 1% w/w/) of the total identified fraction for each boiler/fuel combination. A selected subset (*n*-C_{18} thru *n*-C_{26}) of these compounds showed significant positive correlation (Pearson-product moment correlation of $r \geq 0.7$ with $p \leq 0.0002$) with one another. In each case, the *n*-C_{18} through *n*-C_{24} *n*-alkanoic acid positively correlated to its corresponding *n*-alkane. Only for the C_{18} pair was the relationship considered insignificant ($p = 0.2$). Both *n*-alkanes and *n*-alkanoic acids are contained in vegetative waxesand are likely removed intact via distillation from the surface of vegetation during the fire.

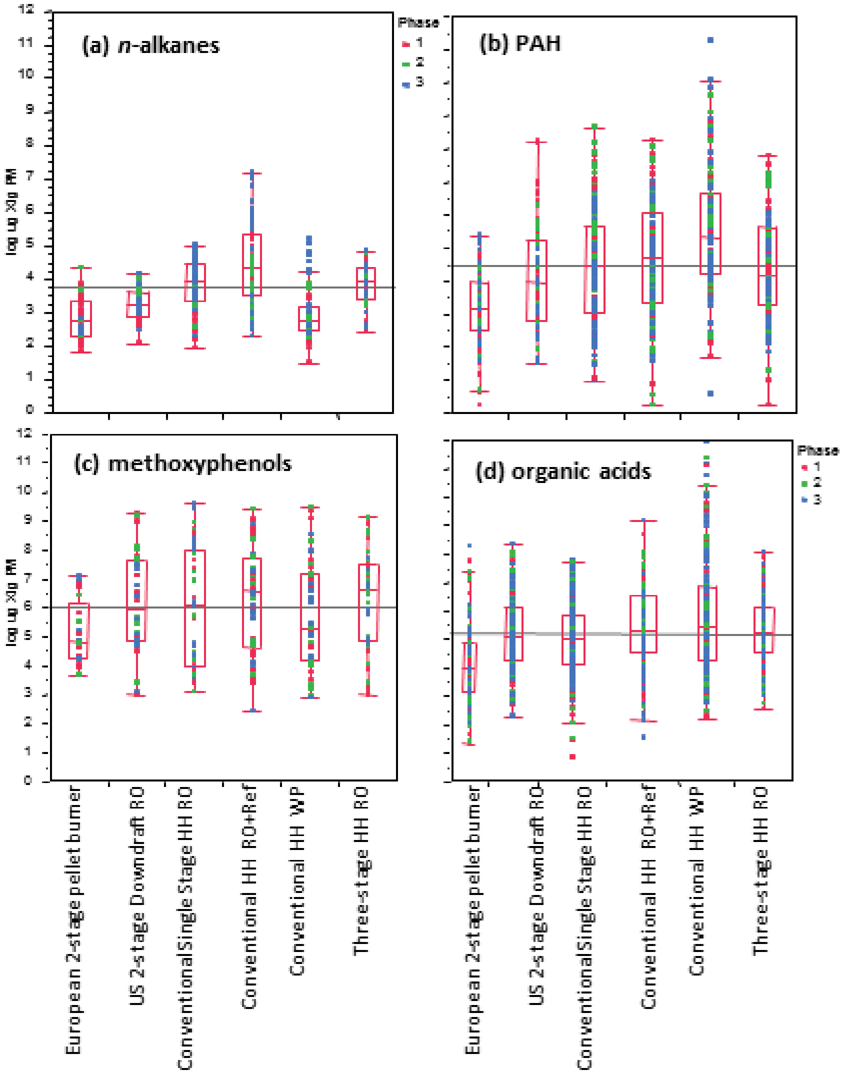


Figure 2-64 A-D. Box Plots of Test Phase-Composited Organic Pollutant Levels in the HH PM for Each Boiler/Fuel Type Experiment. Each panel represents a different compound class (*n*-alkanes, PAHs, methoxyphenols, and *n*-alkanoic acids) and is color-coded by test phase.

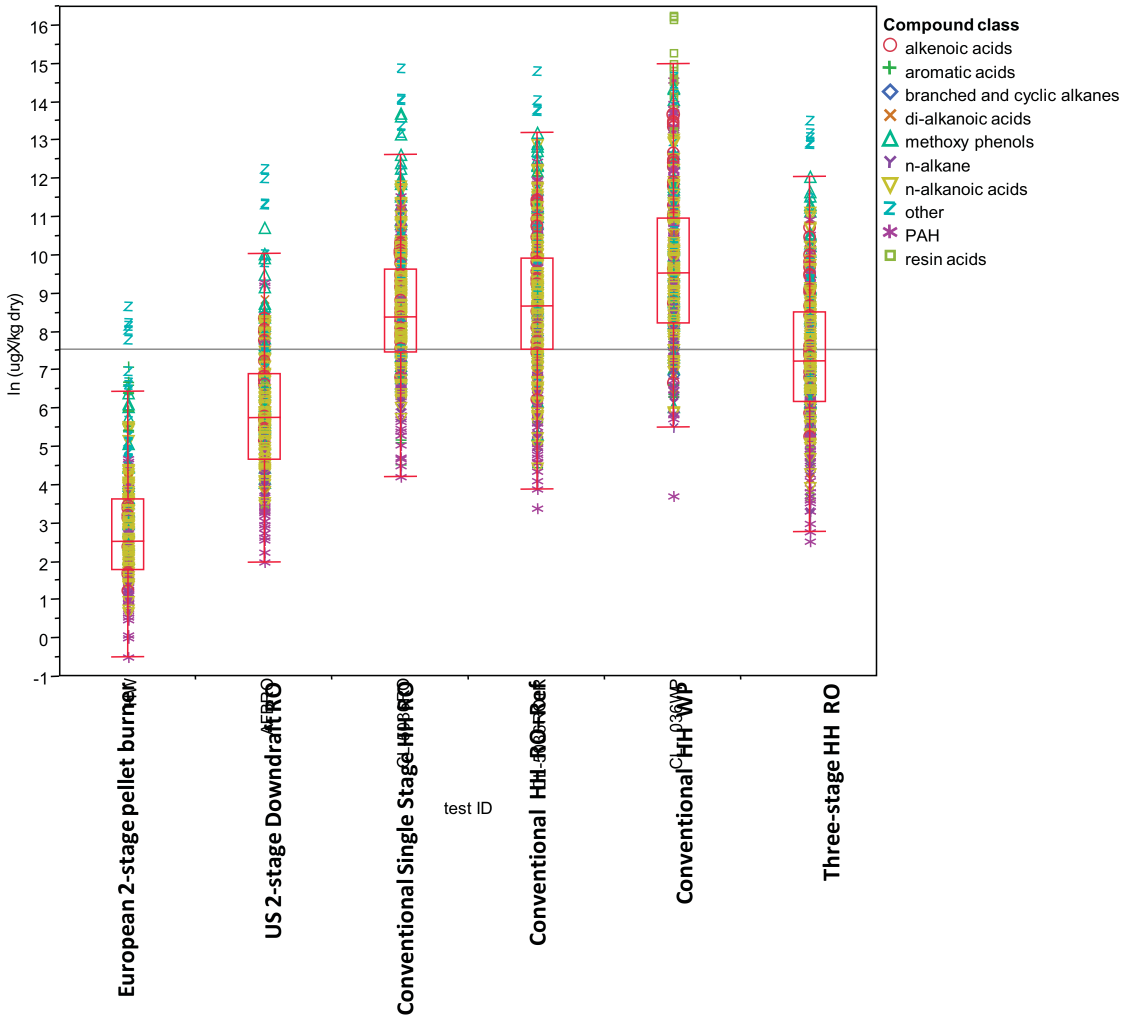


Figure 2-65. Box Plots of Organic Pollutant Levels in PM Organized by Compound Class. **(Box plots indicate the 25th and 75th percentiles and the median. The whiskers indicate the upper and lower quartiles ± 1.5 times the inter-quartile range.)**

Figure 2-66B is identical to Figure 2-66A but shows the concentration of individual PAH compounds in the HH PM. PAH compounds are important to study because of their known toxicity and potential use in source apportionment models. The PAH explain a relatively small fraction of the PM mass (0.1-4% w/w). The Conventional, Single Stage HH-WP boiler/fuel combination showed the highest enrichment of PAHs in the PM. Retene (methylisopropyphenanthrene) was found for all fuel/boiler combinations but was highest for the Conventional, Single Stage HH-WP test and is often treated as a major marker of conifer (pine wood) combustion. The individual PAH compounds detected as a part of this study are positively correlated to one another with no exceptions. Just 13 of 162 possible PAH compound pairs were insignificantly correlated ($p > 0.05$). Pairwise correlation among PAHs and *n*-alkanes were generally insignificant or negative. PAHs are thermodynamically stable soot precursors that may form from simpler molecules through various reaction mechanisms. Levoglucosan (LG), which is thermally-degraded cellulose, also showed weak positive correlation to select PAH with p values greater than 0.2, likely reflecting their different formation mechanisms.

Figure 2-66C shows the concentration of individual organic acids in the HH PM. The *n*-alkanoic acids exhibit a strong even number predominance with a $C_{MAX} = 16$ (hexanedecanoic acid). Di-alkanoic acids were commonly present in the HH PM. The benzene dicarboxylic acid isomers were the most predominant aromatic acids detected. Alkenoic and resin acids were present for all boiler/fuel combinations but were highest for the Conventional, Single Stage HH-WP test owing to the high resin content of the pine wood. Generally, the aromatic acids correlate weakly with those of the other acid sub-groups. From the individual *n*-alkanoic (17) and di-alkanoic acids (n = 7), 276 pairs could be formed. Of these pairs, 232 showed positive correlations. Hexanoic acid and decanedioic acid appeared least correlated with the other acid compounds within these two classes. The resin acids were strongly correlated ($r > 0.8$; $p < 0.0001$) to each other and to the alkenoic acids as well.

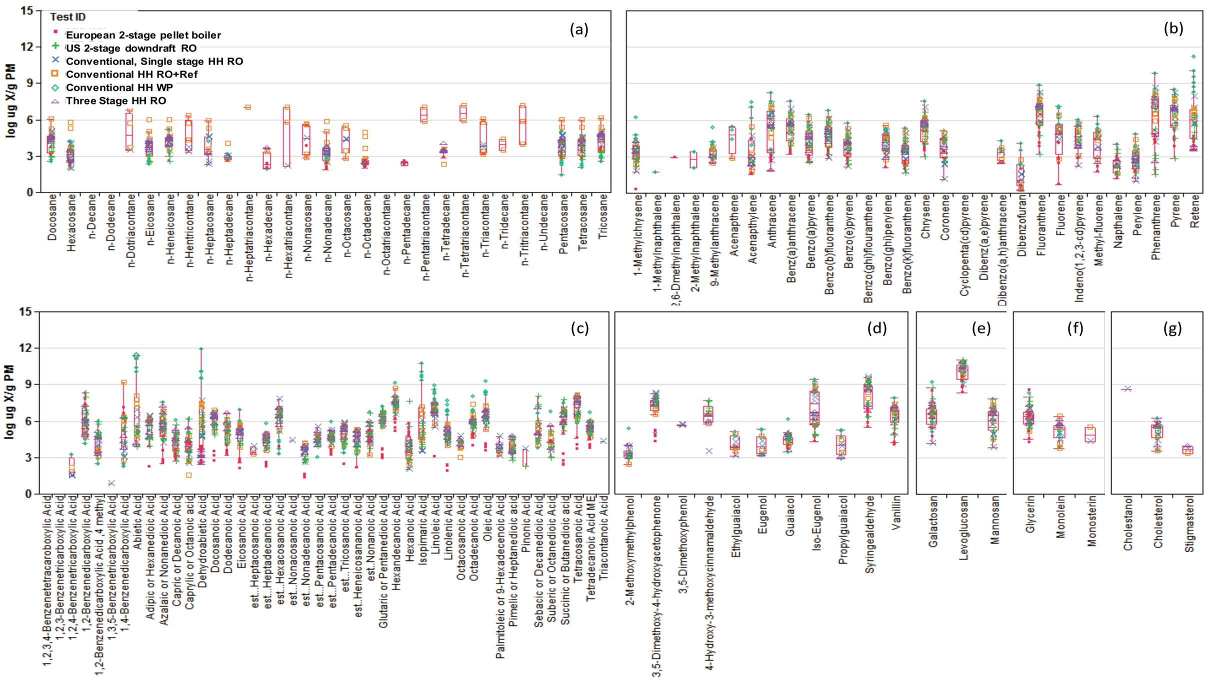


Figure 2-66 A-G. Log-transformed Concentrations (µg/g PM) of Individual Organic Compounds Coded (Color and Symbol) by Test. Panels are separated by compound class: (a) *n*-alkanes; (b) PAHs; (c) organic acids; (d) methoxyphenols; (e) anhydro-sugars; (f) other; and (g) sterols. Data shown are emblematic of an HH composite emissions profile.

Attachment A reports the mass of methoxyphenols in the HH PM and emission factors for this compound group. Methoxyphenols are pyrolysis products of lignin and thus expected in the HH emissions. With the exception of the Conventional, Single Stage HH-WP test, syringaldehyde was the most concentrated methoxyphenol compound in the PM. Syringols are regularly released from the combustion of hardwood species following thermal breakdown of sinapyl alcohol in lignin. This thermal breakdown explains its predominance in the HH experiments burning red oak wood fuel. In contrast, guaiacol from thermal breakdown of coniferyl alcohol in the pine wood lignin, is consistently higher in the PM from the Conventional, Single Stage HH-WP test. The methoxyphenols—similar to many of the compounds being discussed currently—are semivolatile. Hence, they are subject to transfer loss, etc., during solvent extraction and concentration steps, which may bias the concentration levels being reported. Nevertheless, the micro-extraction technique practiced for these samples and further described in the experimental section seeks to limit these losses by reducing the volume of nitrogen required for concentration and by limiting the number of transfer steps prior to GC/MS analysis.

Of all the individual molecules examined using GC/MS, LG has received the most attention lately, likely due to its high abundance in biomass burning aerosols and to its use as a tracer in source apportionment research. As implied, of all the compounds detected by GC/MS, LG consistently showed the highest concentration in the HH aerosols. Minor anhydro-sugars—mannosan and galactosan—are also detected in the HH PM but at substantially lower concentrations. This wide span of anhydro-sugar concentrations in the HH aerosols can be observed in Figure 2-66. The proportions of these compounds in the biomass burning emissions directly reflect the glucose, mannose, and galactose sugar concentrations in the plant hemicellulose and cellulose. The LG, mannose, and galactose concentration values reported here are in excellent agreement with those compiled in Ma et al. (2010) for biomass combustion.

2.9.15 Nitrous Oxide

Nitrous oxide (N_2O) is considered an important non-CO_2 greenhouse gas, and little information is known about its emission levels. The average values of the N_2O emission factors for each of the six unit/fuel combinations are shown in Table 2-21 and Figure 2-67. The highest N_2O emissions are observed for non-cyclic European Two Stage Pellet Burner and U.S. Two Stage Downdraft Burner units with respectively 6.25E-03 g/MJ $(1.45\text{E-02 lb/MMBTU})_{\text{Input}}$, and the lowest for the Conventional, Single Stage HH burning white pine with an average value of 2.94E-04 g/MJ $(6.85\text{E-04 lb/MMBTU})_{\text{Input}}$). The N_2O emissions may be dependent on both the combustion conditions as well as the type of fuel used during the burning process.

Table 2-20. Tukey-Kramer Honest Significant Difference Test Results for Comparisons of Phase-Composited HH Test Pairs Using Compound Class Means. Significant Differences (α = 0.05) in the HH testing are listed by compound class.

Test	Conventional, Single Stage HH-RO+Refuse	Conventional, Single Stage HH-RO	Three Stage HH-RO	U.S. Two Stage Downdraft Burner-RO	Conventional, Single Stage HH-WP	European Two Stage Pellet Burner-Pellets
Conventional, Single Stage RO+R		*n*-alkanes	*n*-alkanes	*n*-alkanes	*n*-alkanes, organic acids, PAHs	*n*-alkanes, organic acids, PAHs
Conventional, Single Stage HH-RO	*n*-alkanes			*n*-alkanes	*n*-alkanes, organic acids, PAHs	*n*-alkanes, organic acids, PAHs
Three Stage HH-RO	*n*-alkanes			*n*-alkanes	organic acids, PAHs	*n*-alkanes, organic acids, PAHs
U.S. Two Stage Downdraft Burner-RO	*n*-alkanes	*n*-alkanes	n-alkanes		organic acids, PAHs	organic acids, PAHs
Conventional, Single Stage HH-WP	*n*-alkanes, organic acids, PAHs	*n*-alkanes, organic acids, PAHs	n-alkanes, organic acids, PAHs	organic acids, PAHs		organic acids, PAHs
European Two Stage Pellet Burner-Pellets	*n*-alkanes, organic acids, PAHs	*n*-alkanes, organic acids, PAHs	n-alkanes, organic acids, PAHs	organic acids, PAHs	organic acids, PAHs	

Table 2-21. N_2O Emission Factors.

N_2O Emission Factors				
Unit/Fuel		**g/kg $_{\text{Dry fuel}}$**	**g/MJ (lb/MMBTU) $_{\text{input}}$**	**g/MJ (lb/MMBTU) $_{\text{Output}}$**
Conventional, Single Stage HH/ RO	Average	3.66E-03	1.94E-03 (4.51E-03)	8.48E-03 (1.97E-02)
	STDV	4.80E-0.3	3.15E-04 (7.33E-04)	2.25E-03 (5.22E-03)
Conventional, Single Stage HH/ WP	Average	6.35E-03	2.94E-04 (6.85E-04)	1.12E-03 (2.60E-03)
	STDV	1.76E-03	8.14E-05 (1.89E-04	3.33E-04 (7.75E-04)
Conventional, Single Stage HH/ RO & Refuse	Average	1.82E-02	9.33E-04 (2.17E-03)	3.26E-03 (7.58E-03)
	STDV	5.66E-03	2.90E-04 (6.74E-04)	1.11E-03 (2.58E-03)
European Two Stage Pellet Burner/ Pellets	Average	1.24E-01	6.25E-03 (1.45E-02)	1.49E-02 (3.47E-02)
U.S. Two Stage Downdraft Burner/ RO	Average	5.96E-02	3.06E-03 (7.11E-03)	4.22E-03 (9.82E-03)

STDV – standard deviation

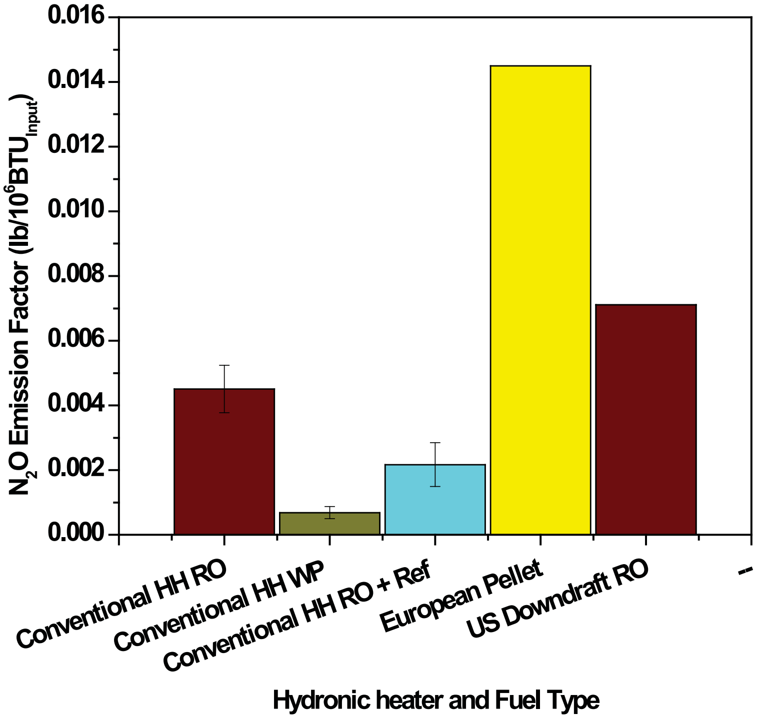
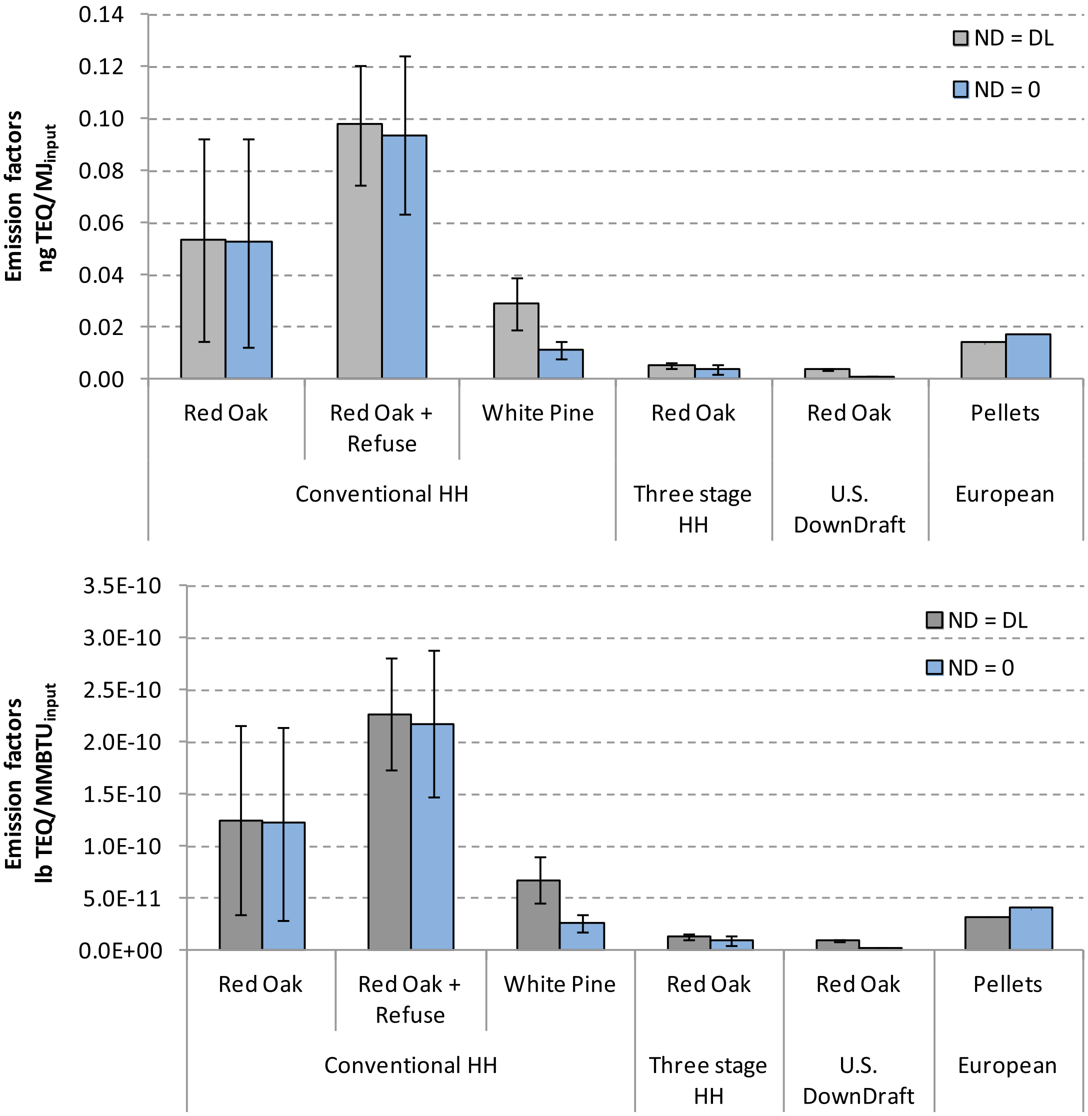


Figure 2-67. Nitrous Oxide Emission Factors.

2.9.16 PCDD/PCDF

Gas samples were extracted directly from the stack for determination of PCDD/PCDF emissions. PCDD/PCDF emission factors (presented in Figure 2-68) ranged from 0.07 to 2.1 ng toxic equivalent (TEQ)/kg dry fuel input, with the lowest value from the U.S. Two Stage Downdraft Burner unit and the highest from the Conventional, Single Stage HH with red oak + refuse (these values are presented with non-detect (ND) congeners equivalent to the detection limit (DL) value, or ND = DL). The lowest value, from the U.S. Two Stage Downdraft Burner unit, may be due to the non-cyclic combustion resulting in consistent combustion and more complete burnout, but the limited data make this assessment speculative. These values are consistent with biomass burn emission factors of 0.91 to 2.26 ng TEQ/kg) (Meyer et al., 2007), woodstove/fireplace values of 0.25 to 2.4 ng TEQ/kg (Gullett et al., 2003), pellet and wood boiler values of 1.8 to 3.5 ng TEQ/kg, and wood stoves and boilers of 0.3 to 45 ng TEQ/kg (Hübner et al., 2005). These emission factors also compare well with 11 values from woodstoves and fireplaces compiled in an EPA dataset (Pechan, 2006) that averaged 1.2 E-10 lb TEQ/MMBTU$_{input}$.



(Non-Detects - ND, at Detection Limit - DL, Zero - 0)

Figure 2-68. PCDD/PCDF TEQ Emission Factors and Standard Deviation Range of Data.

Of the 17 TEF-weighted congeners, between 0 and 11 congeners were non-detected over the course of the 15 unit/fuel tests, despite sampling directly from the stack, without dilution. Table 2-22 also shows the PCDD/PCDF emission factor for the case when the non-detect congeners were treated as zeros. The average ratio of the TEQ with ND = 0 and TEQ with ND = DL is 0.70, suggesting that the missing congeners did not significantly affect the overall TEQ determination. The lowest ratios, 0.39 and 0.29, were determined for white pine and the U.S. Two Stage Downdraft Burner unit with red oak, respectively, likely due to their relatively low emission levels in combination with the small sample volume size.

Table 2-22. PCDD/PCDF Emission Factors (ND = DL; ND = 0 within Parentheses).

Unit	Fuel	Number of Samples	ng TEQ/kg_{input}	ng TEQ/MJ_{input}	lb TEQ/$MMBTU_{input}$
Conventional, Single Stage HH	Red oak	3	1.1 (1.0)	0.054 (0.053)	1.3E-10 (1.2E-10)
	STDV		0.76 (0.78)	0.039 (0.040)	9.0E-11 (9.3E-11)
Conventional, Single Stage HH	Red oak + refuse	2	1.9 (1.8)	0.098 (0.093)	2.3E-10 (2.2E-10)
	RDV		0.45 (0.59)	0.023 (0.030)	5.3E-11 (7.1E-11)
Conventional, Single Stage HH	Pine	3	0.63 (0.24)	0.029 (0.011)	6.8E-11 (2.6E-11)
	STDV		0.21 (0.077)	0.0097 (0.0036)	2.3E-11 (8.3E-12)
Three Stage HH	Red oak	3	0.11 (0.079)	0.0056 (0.0041)	1.3E-11 (9.4E-12)
	STDV		0.022 (0.036)	0.0011 (0.0018)	2.6E-12 (4.2E-12)
U.S. Two Stage Downdraft Burner	Red oak	3	0.080 (0.023)	0.0041 (0.0012)	9.5E-12 (2.7E-12)
	STDV		0.0077 (0.0087)	0.00039 (0.00044)	9.2E-13 (1.0E-12)
European Two Stage Pellet Burner#	Red oak	1	0.28 (0.25)	0.014 (0.012)	3.3E-11 (2.9E-11)

STDV - standard deviation

RDV - relative deviation (only two tests)

- STDV not applicable (only one test)

Despite some wide ranges in emission factors from the limited testing, both device and fuel type appear to play a role in determining PCDD/PCDF emissions. For all fuel types, the Conventional, Single Stage HH unit had higher emissions than the other three units. The previous results for other emissions suggest that combustion quality also plays a role in determining the PCDD/PCDF emission levels, consistent with current theory on PCDD/PCDF formation mechanisms. Among the Conventional, Single Stage HH results, the addition of refuse likely increased emissions over that of red oak alone and the red oak + refuse values were distinctly higher than the values from the white pine.

The contribution of the five mass percent refuse toward the PCDD/PCDF TEQ in the red oak + refuse emission factor can be calculated using the red oak-only emission factor. The refuse would have to have an emission factor of 19 ng TEQ/kg refuse to reach the red oak + refuse emission factor. This value is consistent with earlier determinations (Lemieux, 1997; Gullett et al., 2001) using this same approximate refuse composition that resulted in an average baseline value of 79 ng toxic equivalency (TEQ)/kg burned and a range of 9 to 148 ng TEQ/kg waste burned when combusted in a barrel. An emission factor for this work’s refuse on the lower end of those observed from the barrel burn studies is consistent with the absence of potentially catalytic metals in the added refuse and an improved combustion environment in the presence of 95% by mass wood. Further, these historic barrel burn values will be even lower when normalized to the basis of initial refuse mass used in this work, rather than mass burned, and thus, closer to the value of 19 ng TEQ/kg refuse determined here.

Table 2-23. PCDD/PCDF Emission Factors (ND = DL, ND = 0 within Parentheses).

Unit	Fuel	Number of Samples	ng TEQ/kg$_{input}$	ng TEQ/MJ$_{input}$	lb TEQ/MMBTU$_{input}$
Conventional, Single Stage HH	Red oak	3	1.1 (1.0)	0.054 (0.053)	1.3E-10 (1.2E-10)
	STDV		0.76 (0.78)	0.039 (0.040)	9.0E-11 (9.3E-11)
Conventional, Single Stage HH	Red oak + refuse	2	1.9 (1.8)	0.098 (0.093)	2.3E-10 (2.2E-10)
	RDV		0.45 (0.59)	0.023 (0.030)	5.3E-11 (7.1E-11)
Conventional, Single Stage HH	Pine	3	0.63 (0.24)	0.029 (0.011)	6.8E-11 (2.6E-11)
	STDV		0.21 (0.077)	0.0097 (0.0036)	2.3E-11 (8.3E-12)
Three Stage HH	Red oak	3	0.11 (0.079)	0.0056 (0.0041)	1.3E-11 (9.4E-12)
	STDV		0.022 (0.036)	0.0011 (0.0018)	2.6E-12 (4.2E-12)
U.S. Two Stage Downdraft Burner	Red oak	3	0.080 (0.023)	0.0041 (0.0012)	9.5E-12 (2.7E-12)
	STDV		0.0077 (0.0087)	0.00039 (0.00044)	9.2E-13 (1.0E-12)
European Two Stage Pellet Burner[#]	Red oak	1	0.28 (0.25)	0.014 (0.012)	3.3E-11 (2.9E-11)

STDV - standard deviation

RDV - relative deviation (only two tests)

- STDV not applicable (only one test)

PCDD/PCDF Total (tetra- to octa-chlorinated) emission factors are also reported, as they are sometimes used as a regulatory measure. These values ranged from about 9E-09 to 0.2E-09 lb/MMBTU of fuel input (Figure 2-69). Despite the ~45-fold range in emission factors, the relative STDV for the average emission factor of the units was less than 0.3. These Total values averaged about 40 times higher than their respective TEQ values. This ratio is quite lower than other values (ca. 100) from open biomass combustion (Gullett et al., 2008).

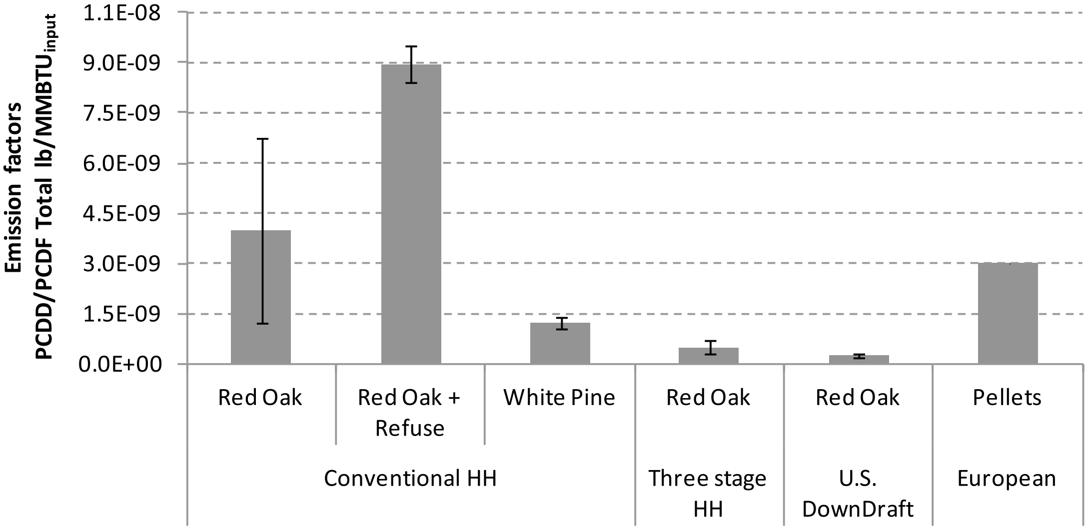


Figure 2-69. PCDD/PCDF Total Emission Factors and Standard Deviation (STDV) Range of Data.

2.9.17 Polycyclic Aromatic Hydrocarbons (PAHs)

Total PAH emission factors, as determined by extractive Method 0010, are shown in Figure 2-70 for all six unit/fuel combinations. These samples were drawn from the dilution duct and their emission factors are scaled by fuel energy input. The white pine fuel on the Conventional, Single Stage HH consistently had the highest PAH emissions, while the European Two Stage Pellet Burner unit with hardwood pellets had the lowest. PAH levels seem to be a clear function of fuel type (compare white pine with red oak on the Conventional, Single Stage HH) and unit type (compare red oak on the Conventional, Single Stage HH, Three Stage HH, and U.S. Two Stage Downdraft Burner units).

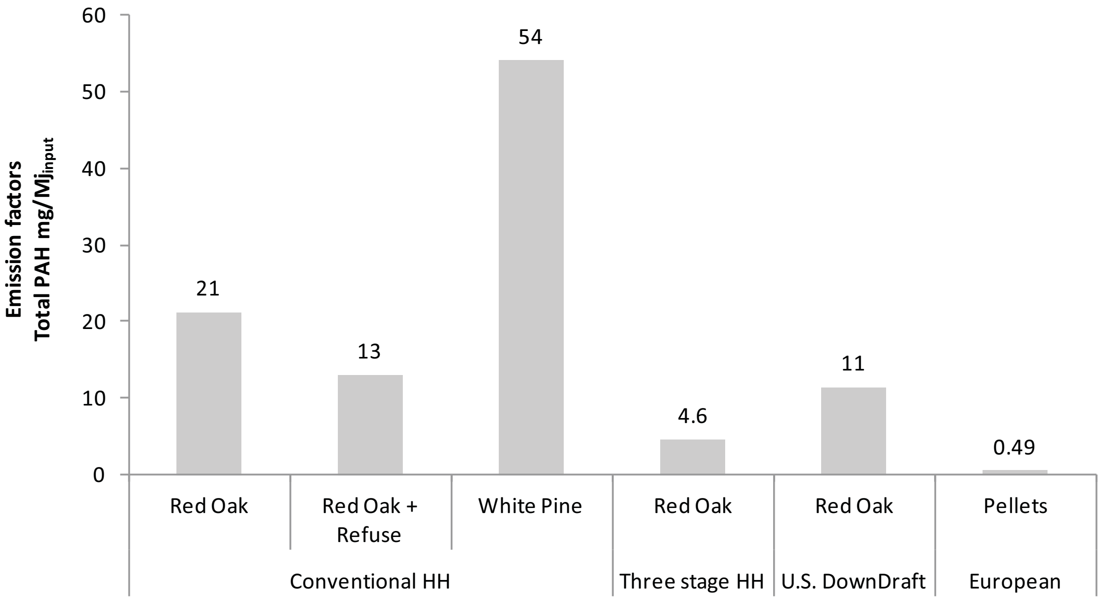


Figure 2-70. Total PAH Emission Factors.

Individual PAH emission factors for all six unit/fuel combinations are shown in Figure 2-71 and Table 2-24. As with Total PAHs, the white pine fuel had some of the highest levels, most notably with naphthalene, acenaphthylene, and phenanthrene. Naphthalene was the highest PAH for all unit/fuel combinations and varied 50-fold among the units. The European Two Stage Pellet Burner had the lowest emission factor. Compiled emission factors for naphthalene from 12 woodstoves and fireplaces in an EPA dataset (Pechan, 2006; Houck et al., 2001; EPA, 1996) averaged 4.3 mg/MJ$_{input}$ (0.10 lb/MMBTU$_{input}$), flanking the naphthalene emission factors for the six unit/fuel combinations in Table 2-24.

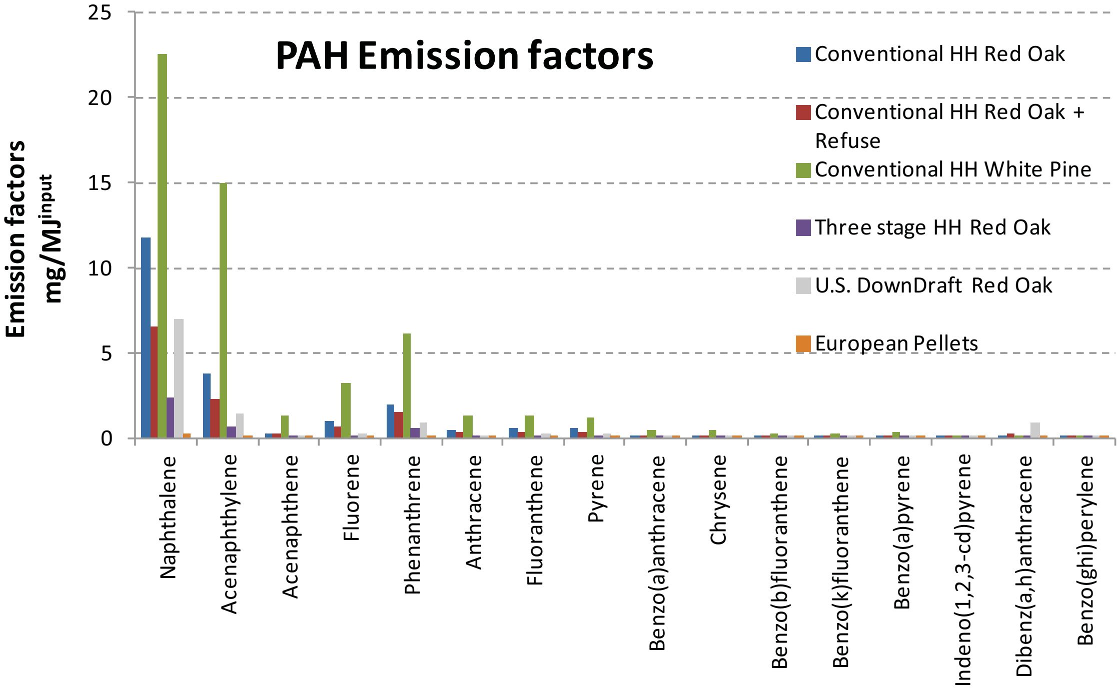


Figure 2-71. Total PAH Emission Factors Determined by Method 0010.

Table 2-24. Individual PAH Emission Factors Determined by Method 0010.

	Conventional, Single Stage HH			Three Stage HH	U.S. Two Stage Downdraft Burner	European Two Stage Pellet Burner
	Red Oak mg/MJinput	Red Oak + Refuse mg/MJinput	White Pine mg/MJinput	Red Oak mg/MJinput	Red Oak mg/MJinput	Pellets mg/MJinput
Naphthalene	12	6.6	22	2.4	6.9	0.23
Acenaphthylene	3.7	2.3	15	0.67	1.40	0.058
Acenaphthene	0.27	0.23	1.3	0.07	0.092	0.0035
Fluorene	0.96	0.70	3.2	0.18	0.28	0.013
Phenanthrene	2.0	1.5	6.1	0.58	0.86	0.074
Anthracene	0.46	0.33	1.3	0.10	0.17	0.012
Fluoranthene	0.60	0.34	1.3	0.13	0.28	0.041
Pyrene	0.62	0.32	1.2	0.10	0.26	0.043
Benzo(a)anthracene	0.18	0.093	0.45	0.027	0.072	0.0049
Chrysene	0.17	0.093	0.42	0.029	0.077	0.0047
Benzo(b)fluoranthene	0.09	0.055	0.24	0.019	0.037	0.0035
Benzo(k)fluoranthene	0.13	0.047	0.28	0.007	0.043	0.0014
Benzo(a)pyrene	0.16	0.076	0.36	0.021	0.049	0.0031
Indeno(1,2,3-cd)pyrene	0.065	0.041	0.15	0.011	0.023	0.0027
Dibenz(a,h)anthracene	$0.0070^{\#}$	$0.29^{\#}$	$0.040^{\#}$	$0.19^{\#}$	$0.85^{\#}$	0.00021
Benzo(ghi)perylene	0.093	0.046	0.15	0.0090	0.025	0.0025

Detection limit values.

2.9.18 Volatile Organic Compunds (VOCs)

Sampling for VOCs was conducted on the three units that burned red oak using the EPA TO-15 SUMMA canister method (http://www.epa.gov/region9/qa/pdfs/aircrf.pdf). SUMMA canisters were filled from the sampling duct over a period of about 3 min. Table 2-25 and Figure 2-72 show differences in some VOC emission factor values from the three units despite use of the same fuel, red oak. This difference is particularly noticeable for the U.S. Two Stage Downdraft Burner concentrations of propylene and styrene which are considerably lower than the Conventional, Single Stage HH and Three Stage HH units. The benzene values from the Conventional, Single Stage HH (22-37 mg/MJ) are similar to those determined on cord wood (32 and 91 mg/MJ) using an older, up-draught boiler (Johansson et al., 2004). Benzene emission factors from 12 woodstoves and fireplaces compiled in an EPA dataset (Pechan, 2006; EPA, 1996, Li and Rosenthal, 2005) averaged 36 mg/MJ$_{input}$ (0.08 lb/MMBTU$_{input}$), consistent with Table 2-26 results.

Table 2-25. Select VOCs from Red Oak Combustion in Three HHs, SUMMA Canister Analysis, Fuel Input Basis.

	Conventional, Single Stage HH		Three Stage HH		U.S. Two Stage Downdraft Burner	
Emission	**mg/MJ**	**lb/MMBTU**	**mg/MJ**	**lb/MMBTU**	**mg/MJ**	**lb/MMBTU**
1,2,4-Trimethylbenzene	0.53	1.2E-03	0.056	1.3E-04	0.033	7.6E-05
1,3,5-Trimethylbenzene	0.17	3.9E-04	0.014	3.2E-05	0.011	2.5E-05
Acetylene	33	7.7E-02	35	8.1E-02	54	1.3e-01
Benzene	37	8.5E-02	22	5.0E-02	23	5.4E-02
Ethylbenzene	1.9	4.4E-03	0.71	1.7E-03	0.56	1.3E-03
m,p-Xylene	2.6	6.0E-03	0.45	1.0E-03	0.35	8.1E-04
o-Xylene	1.0	2.4E-03	0.22	5.1E-04	0.16	3.7E-04
Toluene	5.9	1.4E-02	5.0	1.2E-02	4.6	1.1E-02
Propylene	68	1.6E-01	29	6.7E-02	0.015	5.2E-02
Styrene	8.4	2.0E-02	1.2	2.7E-03	0.051	3.7E-03

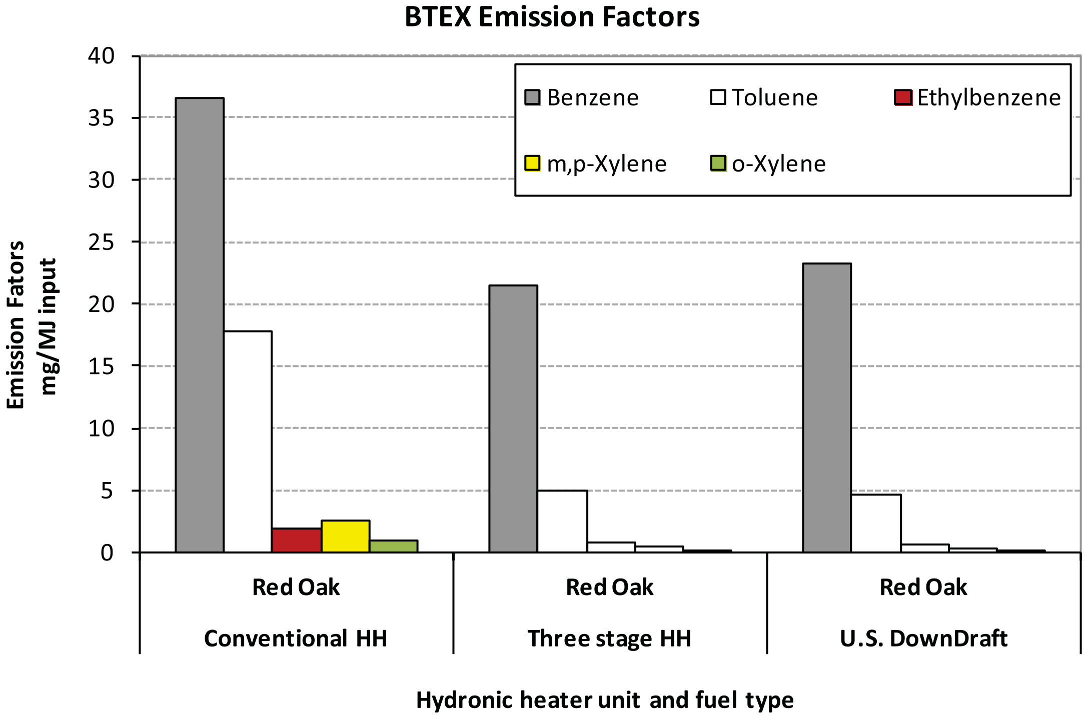


Figure 2-72. Emission Factors for Benzene, Toluene, Ethylbenzene, and Xylene (BTEX) Compounds Based on SUMMA Canister Measurements from the Dilution Duct.

2.9.19 <u>REMPI-TOFMS Measurements</u>

On-line measurements of aromatics were taken using REMPI-TOFMS on selected unit/fuel combinations. Figures 2-73 through 2-77 show the time-resolved concentrations of selected aromatics for the Conventional, Single Stage HH (red oak and red oak + refuse), Three Stage HH, European Two Stage Pellet Burner, and U.S. Two Stage Downdraft Burner units, respectively. Concentrations for benzene, naphthalene, and mass 178 (likely phenanthrene and anthracene) show familiar, characteristic responses to the damper openings and fuel history as observed previously. Emissions peak during damper openings (Conventional, Single Stage HH and Three Stage HH), fuel feeding (European Two Stage Pellet Burner), and maximum combustion rate (U.S. Two Stage Downdraft Burner).

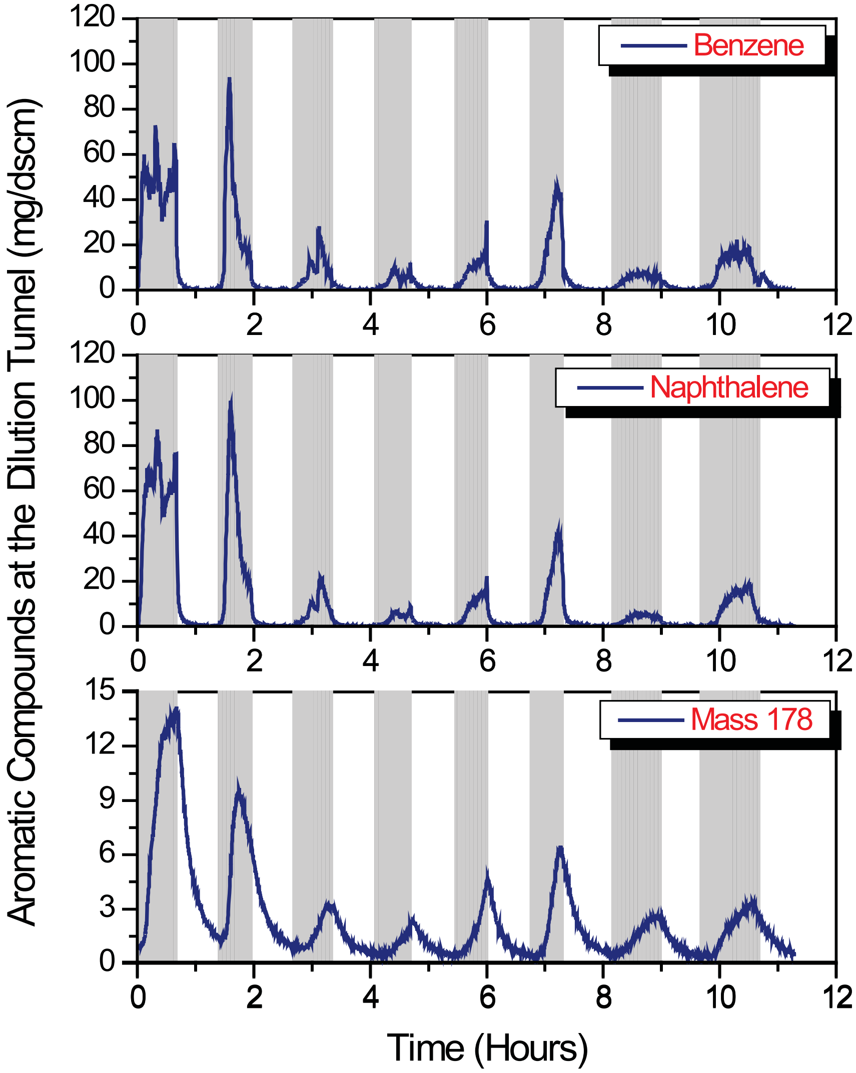


Figure 2-74. REMPI-TOFMS Measurements on the Conventional, Single Stage HH Unit with Red Oak + Refuse (a single fuel charge over 12 h).

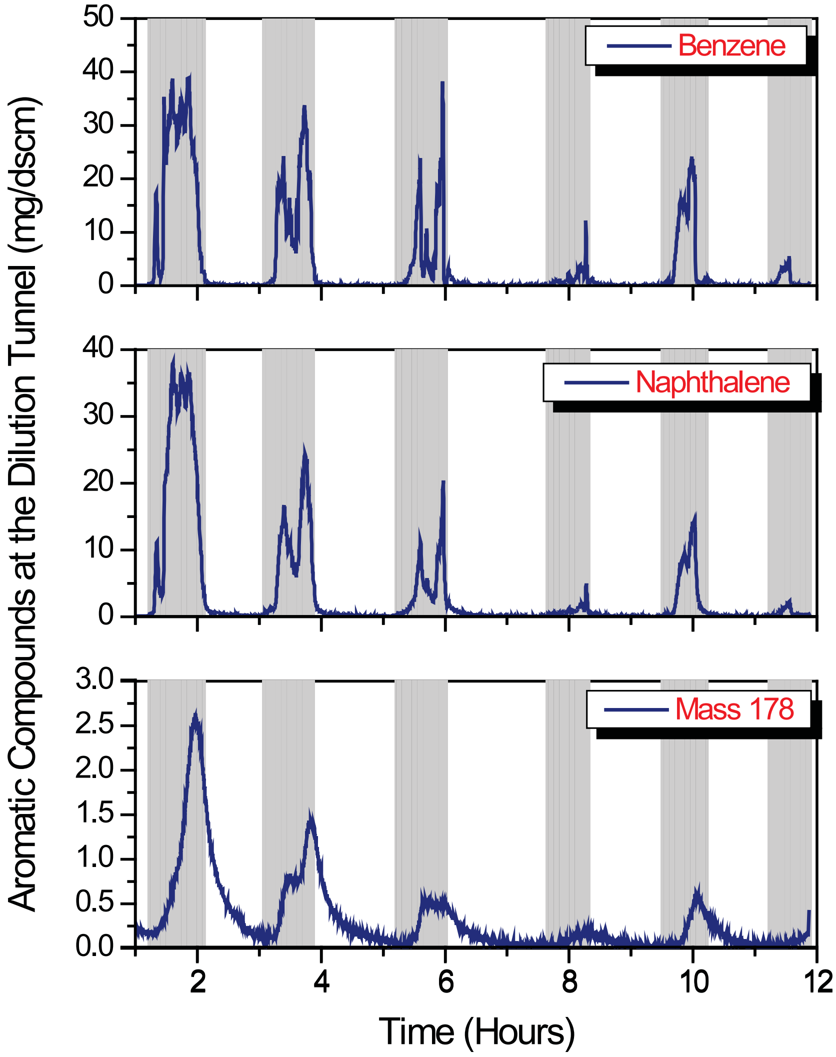


Figure 2-75. REMPI-TOFMS Measurements on the Three Stage HH unit with Red Oak (a single fuel charge over 12 h).

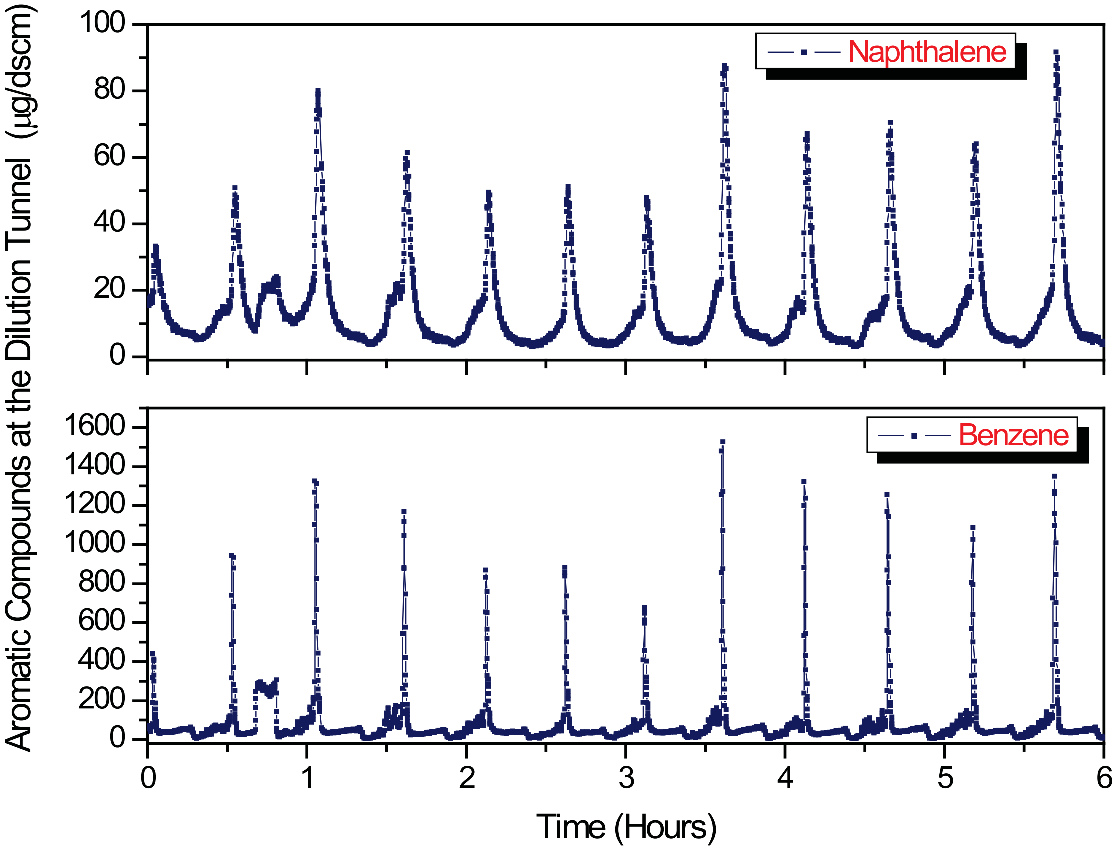


Figure 2-76. REMPI-TOFMS Measurements on the European Two Stage Pellet Burner Unit with Hardwood Pellets (on-demand pellet feeding over 6 h).

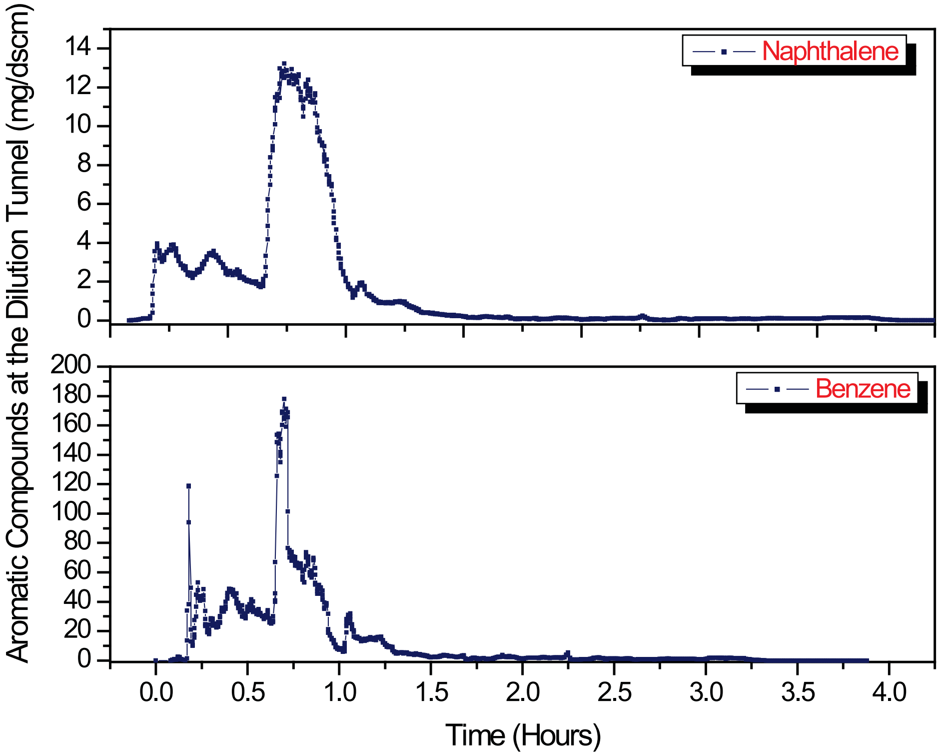


Figure 2-77. REMPI-TOFMS Measurements on the U.S. Two Stage Downdraft Burner Unit with Red Oak (a single fuel charge over 4h).

Integrated measurements from the REMPI-TOFMS were compared with the filter/XAD- method 0010 for naphthalene (Table 2-26) and SUMMA canister samples for benzene (Table 2-27). Between the two methods, naphthalene emission factors vary up to about tenfold, and benzene values vary fourfold (only one pair of data to compare), always with the REMPI-TOFMS values higher than the comparison measurement. The two methods report closer naphthalene values from the European Two Stage Pellet Burner and U.S. Two Stage Downdraft Burner units when the concentrations are lower.

Table 2-26. Comparison of Naphthalene Emission Factors Determined by REMPI-TOFMS and Filter/XAD- Method 0010.

Unit	Date	Fuel	JetREMPI Naphthalene		Filter/XAD- Method 0010 Naphthalene	
			mg/MJ	lb/MMBTU	mg/MJ	lb/MMBTU
Conventional, Single Stage HH	03/24-25/2009	Red oak	131	0.31	NA	NA
Conventional, Single Stage HH	03/25-26/2009	Red oak	138	0.32	13	0.029
Conventional, Single Stage HH	04/28/2009	Red oak + refuse	80	0.19	6.9	0.016
Conventional, Single Stage HH	04/20-21/2009	Pine	NM	NM	34	0.079
Three Stage HH	05/12/2009	Red oak	27	0.062	2.9	0.0068
European Two Stage Pellet Burner	06/10/2009	Red oak	0.12	0.00027	0.21	0.00048
U.S. Two Stage Downdraft Burner	07/10/2009	Red oak	10	0.024	6.9	0.016

NM – Not measured. NA – Not Analyzed.

Table 2-27. Comparison of Benzene Emission Factors Determined by REMPI-TOFMS and SUMMA Canister/Gas Chromatography.

Unit	Date	Fuel	JetREMPI Benzene		SUMMA Canister Benzene	
			mg/MJ	lb/MMBTU	mg/MJ	lb/MMBTU
Conventional, Single Stage HH	03/18-19/2009	Red oak	NM	NM	37	0.085
Conventional, Single Stage HH	03/24-25/2009	Red oak	97	0.23	NM	NM
Conventional, Single Stage HH	03/25-26/2009	Red oak	99	0.23	NM	NM
Conventional, Single Stage HH	04/28/2009	Red oak + refuse	74	0.17	NM	NM
Conventional, Single Stage HH	04/20-21/2009	Pine	NM	NM	NM	NM
Three Stage HH	05/12/2009	Red oak	32	0.074	NM	NM
Three Stage HH	05/13/2009	Red oak	NM	NM	22	0.05
European Two Stage Pellet Burner	06/10/2009	Red oak	0.68	0.0016	NM	NM
U.S. Two Stage Downdraft Burner	07/10/2009	Red oak	99	0.23	23	0.05

NM – Not measured

The higher emission factors obtained from REMPI-TOFMS may be due to several factors. First, the REMPI-TOFMS was calibrated prior to sampling against a standard mix of 14 compounds at 100 ppb each, concentrations much lower than observed from these units. If the instrument responds non-linearly to the high field concentrations, this non-linear response would explain the higher REMPI-TOFMS values. However, past results have shown linearity for over four (4) orders of magnitude in concentration (Oser et al., 1998). A second factor relates to the difficulty in ensuring simultaneous sampling from the methods during widely variant concentrations caused by the opening and closing of dampers. The variant concentrations could be a factor on the cyclic units where, in fact, the higher differences were observed (naphthalene, Table 2-26). This point is illustrated in Figure 2-78 in which the REMPI-measured benzene concentration from the relatively "stable" U.S. Two Stage Downdraft Burner unit is compared against the SUMMA canister sampling time. Even a slight asynchronizaton of the sampling periods could induce significant variation in concentration. For the damper units with greater fluctuations in concentration, this phenomenon would be further exacerbated. Lastly, the SUMMA canisters "sample" or fill non-linearly with time, their fill rate dropping as the pressure increases. This non-linear fill would bias their concentration toward the beginning of the canister fill, whereas the REMPI-TOFMS value is a 3-min average of sampling/measurements with a frequency of 0.1 s^{-1}.

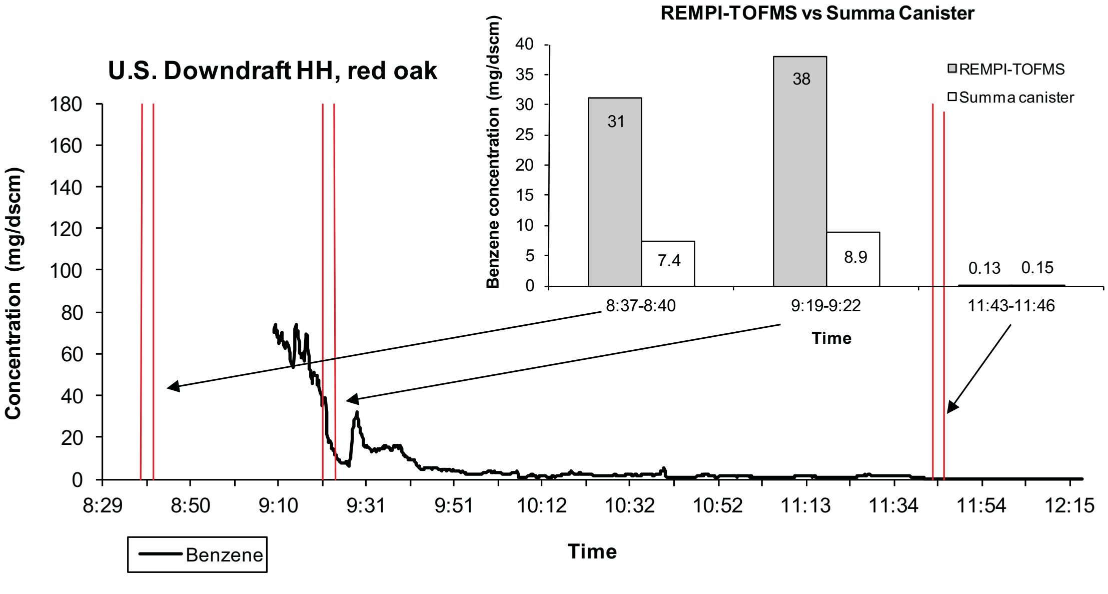


Figure 2-78. Typical REMPI-TOFMS Concentration Trace of Benzene from the U.S. Two Stage Downdraft Burner Unit. Inset: Comparison of REMPI-TOFMS and SUMMA Canister Concentrations.

2.10 CONCLUSIONS

Four HH units representing various technologies and fuels were tested under conditions representative of homeowner operation with a Syracuse winter heat load demand. The units with cyclic damper operation resulted in considerable nuisance odor despite the emissions passing through a downstream APCS consisting of an afterburner and scrubber. When the dampers were closed, combustion became oxygen-starved, resulting in incomplete combustion of the fuel and formation of pollutants. Upon damper opening and gas flow through the system, these pollutants are released, resulting in a cyclic increase in pollutant release.

The heat release rate also reflects the cyclic damper frequency, increasing during open damper, enhanced combustion periods. The frequency and duration of the damper openings is a function of the degree to which the unit is oversized for the heat load. This damper opening also impacts the thermal efficiency of the unit, which ranges between 22% and 31% for the Conventional, Single Stage HH and Three Stage HH units. The European Two Stage Pellet Burner unit had a thermal efficiency of 44%. Its cyclic heat release more closely matches the heat load demand. Comparative measurements for the non-cycling U.S. Two Stage Downdraft Burner unit were not made and no thermal efficiency can be determined.

PM mass emissions were highest for the two units with cyclic damper operation, the Conventional, Single Stage HH and the Three Stage HH. The U.S. Two Stage Downdraft Burner unit, operated with simulated heat storage, also burned cord wood but did not cycle its combustion air, resulting in overall improved combustion and lower PM emissions. The European Two Stage Pellet Burner had the lowest PM emissions, likely due to its ability to maintain relatively stable combustion compared to the other units.

Three fuels on the Conventional, Single Stage HH resulted in distinctive PM emissions, with the white pine having the highest total PM mass emissions followed by red oak and oak with refuse. This sequence is consistent with prior National Risk Management Research Laboratory (NRMRL) testing of wood stoves and fireplaces where the burning of softwood had higher emissions. For red oak fuel, our PM results are generally higher than those generated by EPA Method 28 HH except for the European Two Stage Pellet Burner unit.

The Conventional, Single Stage HH had the highest particle number emissions per heat input emissions with the European Two Stage Pellet Burner having the lowest number emissions of the four units tested.

With regard to PSD, the first two units produced a bimodal PSD, with one mode centered at < 30 nm and the second around 150-200 nm.The modes differ only in the number of particles contained in the emissions, in contrast to the European Two Stage Pellet Burner and U.S. Two Stage Downdraft Burner Econoburn that exhibited a single mode PSD. The U.S. Two Stage Downdraft Burner unit produced generally smaller particles than the European Two Stage Pellet Burner.

The ratio of OC/EC was within the range of 20-30 for the first two units regardless of fuel type. The OC/EC ratio for the European Two Stage Pellet Burner unit, on the other hand, was much lower, indicative of higher combustion efficiency and lower emissions. The OC/EC ratio of the U.S. Two Stage Downdraft Burner unit, however, was only slightly lower than that of the first two units indicating somewhat better combustion efficiency.

The emission profiles were more a function of the time from the last fuel charging than the heat load on the unit. Emission factors vary significantly throughout the fuel burn cycle. The emissions of CH_4, THC, and CO are consistent with the cyclic nature of the damper openings. These emissions are associated with the damper cycle creating alternately poor and good combustion conditions. Units that cycle the damper opening to regulate the heat production have much higher emissions than the pellet burner and the non-cycling U.S. Two Stage Downdraft Burner unit. Predictably, higher CO_2 emission factors result from those units that minimize pollutant formation, such as the European Two Stage Pellet Burner. The European Two Stage Pellet Burner shows a curious cyclic CO spike; the U.S. Two Stage Downdraft Burner unit has a single high peak.

3. CONE CALORIMETER

3.1 EXECUTIVE SUMMARY

In an attempt to help fill an existing information gap on emissions data from outdoor wood-fired HHs and to develop a viable method to characterize and quantify emissions from HHs, a study was conducted by the University of Dayton Research Institute (UDRI) in collaboration with EPA at Research Triangle Park (RTP), North Carolina. The study entailed a laboratory-scale study using the cone calorimeter test facility at UDRI to compare with a simulated field study using the HH test facility at EPA. The cone calorimeter is a fire testing instrument which quantitatively measures the inherent flammability of material through the use of oxygen consumption calorimetry. The cone calorimeter is widely used to obtain data for models that predict fire behavior. UDRI has modified this instrument to extend its use to obtain samples to characterize for emissions. The study provides quantitative emissions data on CO/CO_2, PM, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins/furans (PCDDs/Fs), and other pollutants of concern (POC) from combustion of wood/fuel commonly used in HHs. The emissions data/emission factors for four types of wood (red oak, ash wood, sugar maple and pine) and wood pellets are presented in this study. The emission factors obtained using the cone calorimeter for the various samples are compared to the emission factors data provided by EPA using the HH test facility. This comparison will determine the usefulness of the cone calorimeter data for predicting full scale performance.

The study shows that the cone calorimeter system can be used to obtain emission factors to compare different samples and to predict some emission factors from HHs. The cone tests show that pine has the highest emission factors for most of the emissions characterized. The emission factors from the cone tests when compared to the HH Conventional, Single Stage HH predict the PM trend but fail to predict the trends for CO/CO_2, PCDDs/Fs and PAHs. The magnitude of the emission factors from cone tests when compared to HHs are similar for CO_2 and PCDDs/Fs but are up to two orders of magnitude lower than others. The differences are attributed to the two different combustion conditions, i.e., the well-ventilated condition in the cone tests versus the oxygen-starved conditions in HHs. If the cone calorimeter is to be used as a viable tool to obtain representative emission factors, we recommend that a range of conditions (i.e., from well-ventilated to oxygen-starved) be investigated.

3.2 INTRODUCTION

The study was designed to characterize and quantify toxic air emissions from HHs to be able to determine the impact of pollutants of concern such as CO/CO_2, PM, PAHs, PCDDs/Fs and others. The objective of several national and international programs similar to the Canadian/U.S. Binational Toxics Strategy is to identify the sources of these pollutants of concern and reduce or eliminate their release to the environment (U.S. EPA, 2011). An EPA study has shown that diffuse sources like backyard barrel burning of waste can make significant contributions to overall PCDD/F emissions (Gullett et al., 2001). The conclusions of NESCAUM report and other wood combustion literature suggest that HHs can be a significant source of PAHs, PCDDs/Fs, mercury (Hg) and other persistent bioaccumulative toxic (PBT) emissions. HHs are designed to operate intermittently and burn wood at a low temperature under oxygen-starved conditions. These design features promote formation of harmful pollutants, as inefficient smoldering conditions can result in high emissions of particles and unoxidized gaseous compounds leading to the formation of particle-bound PAHs and PCDDs/Fs. Therefore, HHs are a unique emission source unlike any other residential wood-burning appliances. The results given in a report by Schreiber et al. show that HH emissions are 10 to 20 times higher than certified indoor wood stoves (Schreiber et al., 2005). Also, the HH combustion chamber design facilitates the loading and combustion of non-wood materials, such as household waste (e.g., paper, plastic, and packaging). The use of HHs to burn trash is analogous to the use of burn barrels and burn piles, which are known sources of dioxins and other PBT emissions. Emission inventory data generated by the Regional Air Pollutant Inventory Development System (RAPIDS) shows that residential wood combustion contributes to 46% of the benzo(a)pyrene (B[a]P) emissions in the states. This inventory does not contain any PCDD/F emission data from wood-burning furnaces, but we know from other studies in the literature that wood burning can lead to significant emissions of these pollutants. Therefore, the main objective of this project was to eliminate this information gap and provide reliable emission data on CO/CO_2, PM, PAHs and PCDDs/Fs from HHs.

To accomplish the project objectives, woods/fuels that are commonly used in HHs were selected. These woods were burned using the Cone Calorimeter Test Facility at UDRI. The CO/CO_2, PM, PAH, and PCDD/F emissions were characterized and quantified using established protocols/equipment to determine their emission factors.

3.3 EMISSIONS TESTING – CONE CALORIMETER

3.3.1 Apparatus Description

A cone calorimeter housed at UDRI was modified and used to characterize emissions from combustion of various wood samples. The cone calorimeter is a fire testing instrument that quantitatively measures the inherent flammability of material through the use of oxygen consumption calorimetry, and is a standard technique (ASTM E1354-07) under ASTM E-1354/ISO 5660. This instrument was designed primarily as a fire safety engineering tool, but has found great utility as a scientific tool for understanding fire performance in relation to regulatory pass/fail tests. In effect, the cone calorimeter mimics a well-ventilated forced combustion scenario of an object being exposed to a constant heat source and constant ventilation (Figure 3-1). This scenario represents many real world fire scenarios where an object or material is a flame and radiates heat to other objects which, in turn, catch fire. The cone calorimeter therefore serves as a very useful fire safety engineering tool by looking at the heat release rates of a material under these forced conditions.

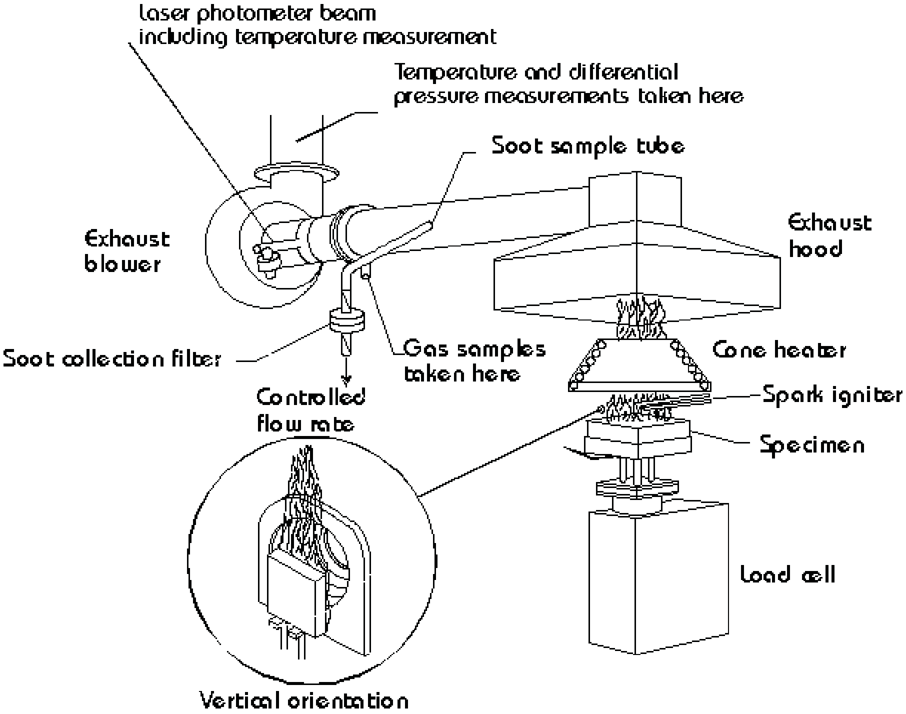


Figure 3-1. Cone Calorimeter Schematic Diagram.

By studying the various parameters measured by the cone calorimeter, one can correlate the cone calorimeter measurements with other tests or bring understanding of how a material behaves when exposed to various fire scenarios. Work on comparing cone calorimeter tests to other tests has included full-scale flammability tests (Bundy and Ohlemiller, 2004), bench-scale tests like UL-94 or limiting oxygen index (Bundy and Ohlemiller, 2004; Costa et al., 1995; Weil et al., 1992; Schartel and Braun, 2003; Morgan and Bundy, 2007), automotive-material flame spread tests (Spearpoint et al., 2005), wire and cable flame spread tests (Cogen et al., 2004) and other types of fire tests/scenarios (Petrella, 1994; Schartel et al., 2005; Filipczak et al., 2005; Babrauskas and Peacock, 1992). A schematic of the cone calorimeter basic setup is shown in Figure 3-1.

Several measurements are obtained from the cone calorimeter. The cone calorimeter at UDRI is equipped with a laser for smoke measurements (laser photometer beam in Figure 3-1), an oxygen sensor (paramagnetic) for measuring oxygen consumption, and a load cell for measuring mass loss as the sample pyrolyzes during heat exposure. The instrument at UDRI also has a CO/CO_2 (infrared-based) detection system, allowing for the measurement of CO/CO_2 production as a function of time during sample combustion. From these parts of the instrument, various measurements collected during each test can reveal scientific information about material flammability performance. For the purposes of understanding the flammability behavior of wood samples, only some of the parameters will be discussed in this chapter, including the following:

- Time to ignition (Tig): Measured in seconds, this is the time to sustained ignition of the sample. Interpretation of this measurement assumes that earlier times to ignition mean that the sample is easier to ignite under a particular heat flux.
- Heat Release Rate (HRR): The rate of heat release, in units of kW/m^2, as measured by oxygen consumption calorimetry.
- Peak Heat Release Rate (Peak HRR): The maximum value of the heat release rate during the combustion of the sample. The higher the peak HRR, the more likely that flame will self-propagate on the sample in the absence of an external flame or ignition source. Also, the higher the peak HRR, the more likely that the burning object can cause nearby objects to ignite.
- Time to Peak HRR: The time to maximum heat release rate. This value roughly correlates to the time required for a material to reach its peak heat output, which would, in turn, sustain flame propagation or lead to additional flame spread. Delays in time to peak HRR are inferred to mean that flame spread will be slower in that particular sample, and earlier time to peak HRR is inferred to mean that the flame spread will be rapid across the sample surface once it has ignited.
- Time to Peak HRR minus Time to Ignition (Time to Peak HRR – Tig): This parameter is the time in seconds required for the peak HRR to occur after ignition rather than at the start of the test (the previous measurement). This parameter can be meaningful in understanding how fast the sample reaches its maximum energy release after ignition, which can suggest how fast the fire grows if the sample itself catches fire.
- Average Heat Release Rate (Avg HRR): The average value of heat release rate over the entire heat release rate curve for the material during combustion of the sample.
- Starting Mass, Total Mass Lost, Weight % Lost. These measurements are taken from the load cell of the cone calorimeter at the beginning and end of the experiment to see how much total material from the sample was pyrolyzed/burned away during the experiment.

- Total Heat Release (THR): THR is measured in units of MJ/m^2 and is basically the area under the heat release rate curve, from time to ignition to time to flameout, representing the total heat released from the sample during burning. The higher the THR, the higher the energy content of the tested sample. THR can be correlated roughly to the fuel load of a material in a fire and is often affected by polymer chemical structure.
- Total Smoke Release: Total smoke release is the total amount of smoke generated by the sample during burning in the cone calorimeter from time to ignition through time to flameout. The higher the value, the more smoke generated, either due to incomplete combustion of the sample or due to polymer chemical structure.
- Maximum Average Heat Rate Emission (MAHRE): MAHRE is a fire safety engineering parameter (Duggan et al., 2004), and is the maximum value of the average heat rate emission, defined as the cumulative heat release (THR) from t=0 to time t divided by time t. The MAHRE can best be thought of as an ignition modified rate of heat emission parameter, which can be useful to rank materials in terms of ability to support flame spread to other objects.
- Fire Growth Rate (FIGRA): FIGRA is another fire safety engineering parameter, determined by dividing the peak HRR by the time to peak HRR, giving units of kW/m^2 per second. The FIGRA represents the rate of fire growth for a material once exposed to heat, and higher FIGRA suggests faster flame spread and possible ignition of nearby objects.
- CO/CO_2 Yields: This parameter is the total measured amounts of CO/CO_2 measured during testing, pre-ignition and post-ignition. The yields are in units of kg gas (CO, CO_2) per kg sample.

3.3.2 Sampling Train

The total sampling train was designed and constructed to collect the total exhaust gas emitted from the combustion of samples in a standard cone calorimeter (Figures 3-2 and 3-3). Sampling the total exhaust reduces the amount of sample that has to be burned to characterize and quantify emissions. The exhaust duct on the Cone Calorimeter (Dual Cone) from Fire Testing Technology Limited, United Kingdom, was modified to enable connecting of the total sampling train. The exhaust hood above the combustion zone is connected to the sampling exhaust duct (110 mm in diameter) with a cooling jacket (not used for these experiments). The sampling exhaust duct is connected to a stainless steel filter holder 24” width x 10” height x 1” depth. The filter holder holds three 8” x 10” filters. The filter holder is connected to a glass coiled condenser to cool the hot gas flowing before it enters a glass cartridge containing four polyurethane foam (PUF) cartridges of 4” diameter x 2” height meant to capture semivolatile organics. The PUFs are retained by a fritted disc, made of Teflon PTFE inside the cartridge. The gas exiting the PUF is passed through an impinger containing silica gel to capture moisture. The impinger is connected to a vacuum pump and the gas exiting the pump is directed to the cone calorimeter exhaust system through a wire reinforced vacuum tube.

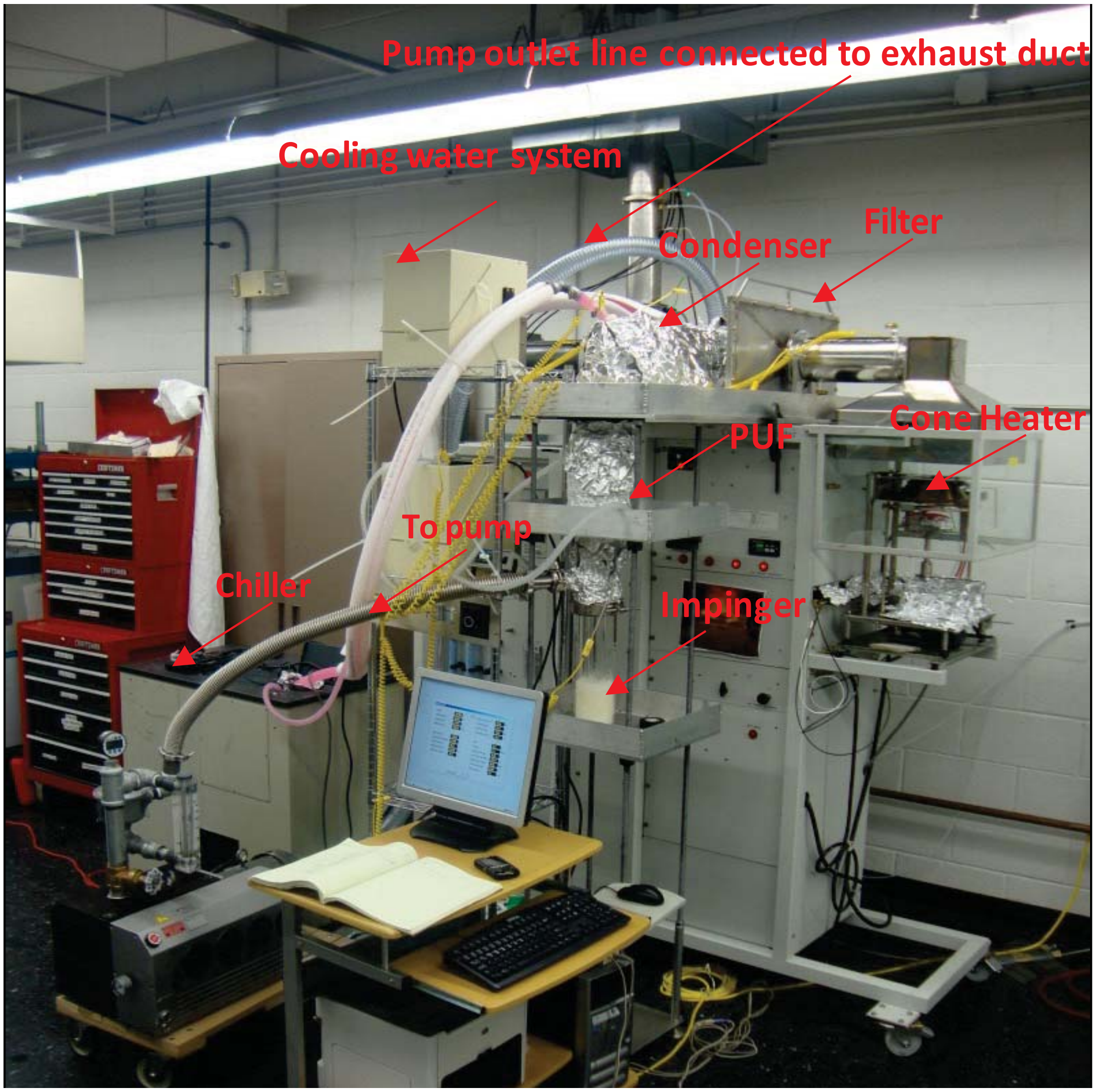


Figure 3-2. Total Sampling Train Coupled with UDRI Cone Calorimeter.

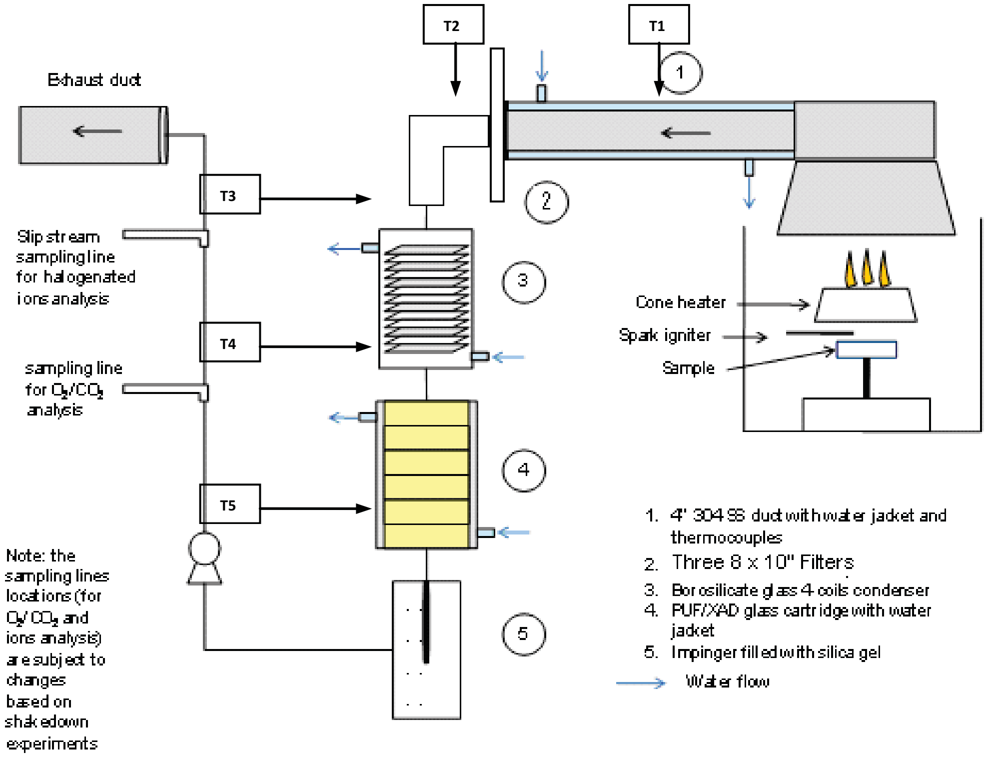


Figure 3-3. Schematic of Total Sampling Train.

At the beginning of each sampling period, after assembling the sampling train, the system is checked for leaks. Once all leaks are repaired the air flow is set to 15 L/second by turning the vacuum pump on and using a gate valve to control the air flow. All the wood samples tested were exposed to a constant heat flux of 50 kW/m^2 by setting the cone temperature to ~760 °C which was verified with the cone calorimeter heat flux gauge. Once the cone reaches its set temperature, the cone calorimeter ignition spark is turned on and samples are placed in the sample holder at the center of the cone heater and ignited. Once the samples ignite, they are allowed to burn until no flames and smoke are detectable. During sampling, the gas temperature inside the sampling train is constantly monitored at eight different positions (Figure 3-3). The first two thermocouples are placed inside the stainless steel duct at 5 cm (2 inches) and 25 cm (10 inches) from the exhaust hood above the cone to monitor the gas temperature entering the duct (T1) and entering the filter holder (T2). The third thermocouple (T3) is placed at the outlet of the filter holder (or the entrance of the condenser). The fourth thermocouple (T4) is positioned at the inlet of the PUF cartridge and the fifth thermocouple (T5) is placed to monitor the gas temperature exiting the PUF cartridge. The cold bath temperatures are adjusted to maintain the PUF cartridge exit gas temperatures (T5) at ~20-25 °C. However, the average gas temperatures exiting the PUFs were ~30 °C for all experiments (temperature data given in appendix). The other thermocouples are used to monitor the water bath temperatures for the stainless steel duct water jacket, the condenser, and the glass cartridge water jacket. All thermocouples used are 1/8'' sheath diameter, grounded, type K thermocouple probes from Omega Engineering, Stamford, Connecticut. During sampling, the pressure drop inside the sampling train and the flow through the sampling train are constantly monitored by a digital gauge manometer placed at the pump inlet and using a differential flow meter on the cone calorimeter exhaust system, respectively. When the soot particles start to build up on the glass filter and decrease the gas flowing through it, the flow is adjusted by opening the gate valve situated at the inlet of the pump. Post sampling, the sampling train is disassembled; the condensate from the condenser is recovered to a pre-cleaned container for analysis, and the various components of the train are covered with hexane rinsed foil and transported to the recovery laboratory. In the recovery laboratory, the filters and PUFs are removed, the filters are weighed to determine their PM loading and the entire sampling train (from the hood and duct work above the cone/combustion zone) up to the inlet of the impinger is rinsed with three solvents (methanol, methylene chloride and toluene, respectively) to recover condensed material for analysis. All solvent rinses, condensate, PUFs and filters are stored in pre-cleaned amber glass containers with Teflon PTFE-lined caps. The solvent levels are marked and the appropriate labels and chain of custody documents are filled out and the samples are refrigerated until they are shipped to a certified analytical laboratory for extraction and analysis using high- resolution GC / high-resolution MS (HRGC/HRMS). The glass fiber filter and PUF adsorbents are combined with the solvent rinses, extracted and analyzed for organic pollutants using standard EPA methods. The analytical methods used to quantify involved the use of isotope dilution and internal standard procedures. Post sample recovery with the three solvents (i.e., after the last rinse with toluene), the metal duct, fume hood and filter holder are rinsed with methylene chloride and covered with hexane-rinsed foil until the next experiment; the glassware is rinsed with Sparkleen soap solution/deionized water and baked at 475 °C for eight hours in a Barnstead Thermolyne Pyro-Clean Trace Oven for baking glassware. After baking, the glassware is rinsed with methylene chloride and covered with hexane-rinsed aluminum foil. A field blank was performed to check for carryover and memory effects.

All fluorescent lights in the laboratory, as well as in the fume hood, were covered with clear ultraviolet (UV)-absorbing filters supplied by UV Process Supply, Chicago, Illinois. The three solvents used are toluene (Envisolv, 34413) and methanol (Pestanal, 34485) purchased from Sigma-Aldrich, Milwaukee, Wisconsin, and methylene chloride (Pestisolv, PS 724) purchased from Spectrum Chemicals. The 150 mm glass-microfiber filters without binder were purchased from Whatman, USA, and the indicator silica gel was from Sigma-Aldrich. The PUFs were purchased from Tisch Environmental. The PUFs and the filters were cleaned by the analytical laboratory (Analytical Perspectives and EPA) in Soxhlet extractors with methylene chloride for 16 hours and the PUFs were spiked with the necessary surrogates and shipped to UDRI in pre-cleaned air-tight containers to use for sampling.

Prior to taking the sampling train from the recovery laboratory to the cone test facility, the pre-spiked and cleaned PUFs are placed in the glass cartridge, the filters are weighed and placed in the filter holder and the glass cartridge and filter holder are sealed with hexane-rinsed aluminum foil and transported to the cone calorimeter laboratory with all other glassware and components also wrapped in hexane-rinsed aluminum foil. Also, the wood samples to be tested were weighed and placed in a hexane-rinsed aluminum sample holder and were covered with hexane-rinsed aluminum foil.

3.3.3 Samples Tested

The initial mass of each type of wood burned for the cone calorimeter total sampling train experiments is given in Table 3-1 and Figures 3-4 through 3-8 show the five types of samples tested. The wood samples used for cone testing were from the same batch/stock of wood used for the HH testing. The samples were cut to ~4 x 4 inch pieces and were ~1-inch in thickness to comply with the standard ASTM cone testing procedure. Pellets were filled to 1-inch in thickness in an aluminum metal sample holder to be comparable to other woods. The wood samples were wrapped in aluminum foil on the back side of the sample, and placed upon a metal sample holder which had insulating mineral wool on the surface to prevent heat from the burning sample penetrating into the load cell that the sample holder sat on top of (see Figure 3-1).

Table 3-1. UDRI – Total Mass Burned per Sample.

Type of Wood Burned	Total Mass Burned per Sample (g)
Ash	175.3
Sugar Maple	178.6
Pine	130.6
Red Oak	156.9
Wood Pellets	173.8

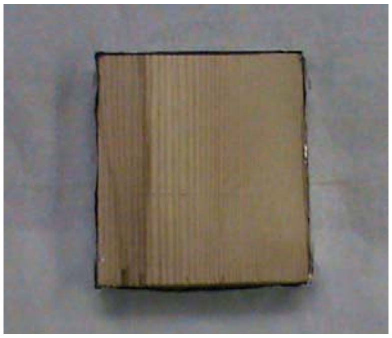


Figure 3-4. Ash Wood.

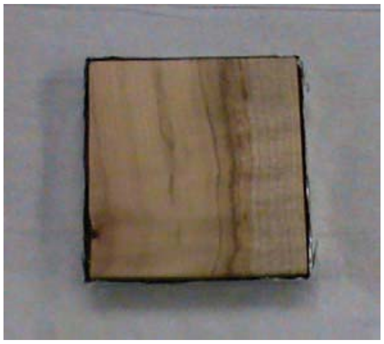


Figure 3-5. Sugar Maple.

Figure 3-6. Pine Wood.

Figure 3-7. Red Oak.

Figure 3-8. Wood Pellets.

Prior to sampling, analyses were performed to determine the composition of the different types of wood and the results are shown in Table 3-2.

Table 3-2. UDRI – Analyses of Wood Samples.

Type of Wood	C, wt%	Cl, ppm	S, wt%	Ash, wt%	Moisture, wt%
Ash	51.20	0.3	<0.05	0.75	9.00
Sugar Maple	50.03	1	<0.05	1.10	9.00
Pine	51.72	36	<0.05	0.44	9.68
Red Oak	48.70	38	<0.05	1.46	22.52
Pellets	50.10	44	<0.50	0.52	7.24

Note: Pine Wood, Red Oak and Pellets data obtained from EPA

3.4 RESULTS

The results from the experiments performed using the standard cone calorimeter (without the total sampling train) to obtain data on heat release, smoke and CO/CO_2 emission factors from all of the wood samples are shown in Tables 3-3 through 3-5. Tables 3-6 through 3-9 present data on PM, PAHs, PCDDs/Fs and chlorobenzene/chlorobutadiene emission factors for different types of wood from experiments conducted using the cone calorimeter and the total sampling train. The emissions results (with the exception of smoke and CO/ CO_2 tests that involved replicate burns / experiments) are from experiments that involved burning one piece of wood of each type (i.e., no replicate burns or experiments). The cone calorimeter is an instrument that is known to have a relatively high reproducibility and any differences in results from experiments are likely to result from the sample-to-sample variation for each piece of wood burned. Therefore, the statistical differences from the experiments using the cone calorimeter are likely to be the same as from the replicate burns of a similar wood using the same HH. Tables 3-10 through 3-13 present results provided to UDRI by EPA, NC, from experiments conducted using the HH test facility to obtain CO/CO_2, PM, PCDD/F and PAH emission factors. All emission factors reported have been calculated based on the mass of fuel before combustion. The data from the HH represent four HHs: a Conventional, Single Stage HH; a Three Stage HH; a European Two Stage Pellet Burner; and a U.S. Two Stage Downdraft Burner. The Conventional, Single Stage HH uses a single-stage combustion process while the Three Stage HH, U.S. Two Stage Downdraft Burner, and European Two Stage Pellet Burner use advanced combustion processes for improved combustion efficiency. Tables 3-14 through 3-19 compare UDRI cone data to HH data provided by EPA. The data are compared to assess the extent to which the cone calorimeter can be used to predict emission factors from HHs since the cone calorimeter may provide a cost effective alternate tool to full-scale HH studies if future work necessitates comparison and prediction of emission factors from other woods.

3.4.1 UDRI – Cone Calorimeter

Table 3-3. UDRI – Heat Release Data.

Sample Description	#	Time to Ignition (s)	Peak HRR (kW/m^2)	Time to Peak HRR (s)	Time to Peak HRR – Tig (s)	Average HRR (kW/m^2)	Total Heat Release (MJ/m^2)	Avg. Effective Heat of Comb. (MJ/kg)	MAHRE (kW/m^2)	FIGRA
Ash	1	34	220	58	24	123	162.1	11.33	125	3.79
	2	36	249	58	22	135	161.4	11.41	134	4.29
	3	48	260	66	18	130	162.2	11.22	131	3.94
STDV		8	21	5	3	6	0.4	0.10	5	0.25
Average Data		39	243	61	21	130	161.9	11.32	130	4.01
Pine	1	5	295	29	24	118	165.7	16.67	198	10.17
	2	18	263	38	20	110	136.1	13.79	146	6.93
	3	7	260	34	27	124	165.1	16.55	168	7.64
STDV		7	19	5	4	7	16.9	1.63	26	1.70
Average Data		10	273	34	24	117	155.6	15.67	170	8.24
Sugar Maple	1	36	252	55	19	133	170.8	11.98	140	4.58
	2	30	254	59	29	108	166.9	11.67	141	4.30
	3	32	275	63	31	128	164.2	11.60	144	4.37
STDEV		3	13	4	6	14	3.3	0.20	2	0.15
Average Data		33	260	59	26	123	167.3	11.75	142	4.42

Sample Description	#	Time to Ignition (s)	Peak HRR (kW/m^2)	Time to Peak HRR (s)	Time to Peak HRR – Tig (s)	Average HRR (kW/m^2)	Total Heat Release (MJ/m^2)	Avg. Effective Heat of Comb. (MJ/kg)	MAHRE (kW/m^2)	FIGRA
Red Oak	1	28	236	47	19	110	160.0	11.80	130	5.02
	2	34	223	58	24	111	161.6	11.62	125	3.85
	3	28	218	50	22	111	167.1	12.12	122	4.35
STDV		3	9	6	3	1	3.7	0.25	4	0.59
Average Data		30	226	52	22	111	162.9	11.85	126	4.41
Wood Pellets	1	52	485	612	560	229	163.9	12.37	230	0.79
	2	52	461	636	584	223	165.5	12.44	226	0.72
	3	56	341	697	641	210	164.9	12.52	208	0.49
STDV		2	77	44	42	10	0.8	0.08	12	0.16
Average Data		53	429	648	595	221	164.8	12.44	221	0.67

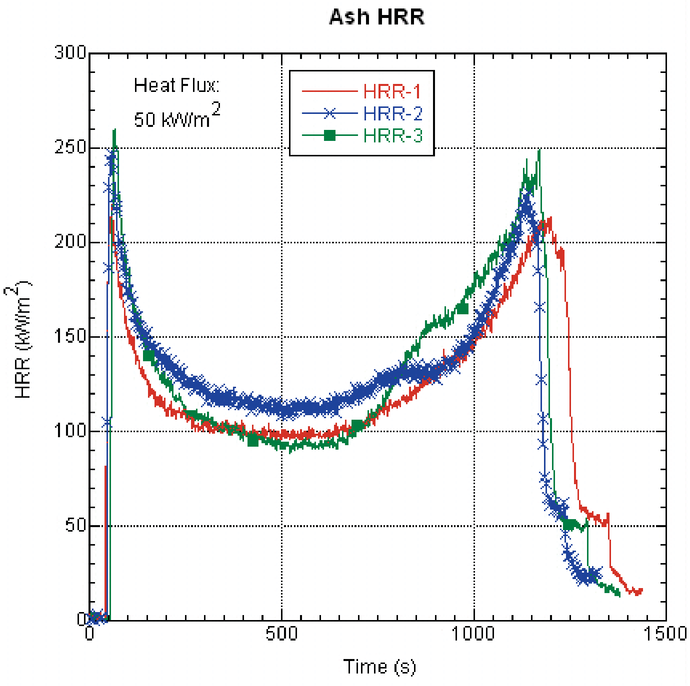


Figure 3-9. HEAT RELEASE RATE for Ash Wood Sample.

Figure 3-10. Final Char for Ash Wood Sample.

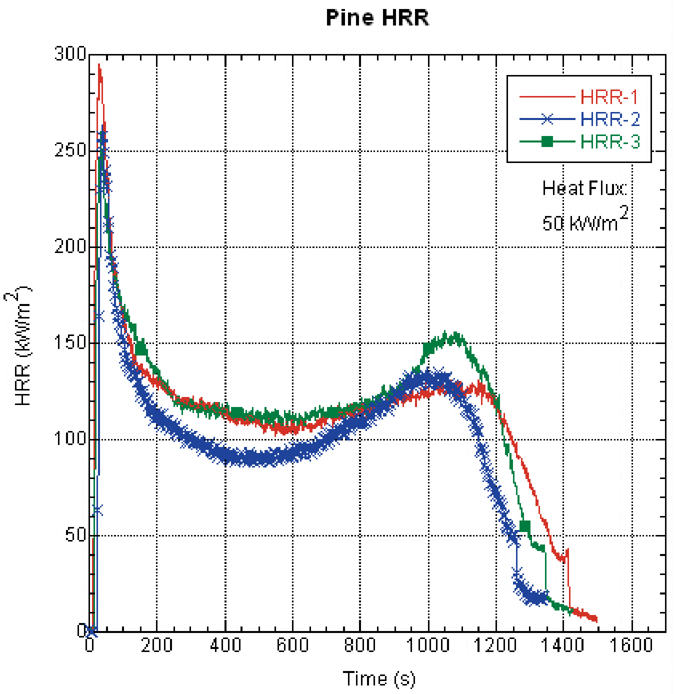


Figure 3-11. HEAT RELEASE RATE for Pine Wood Sample.

Figure 3-12. Final Char for Pine Wood Sample.

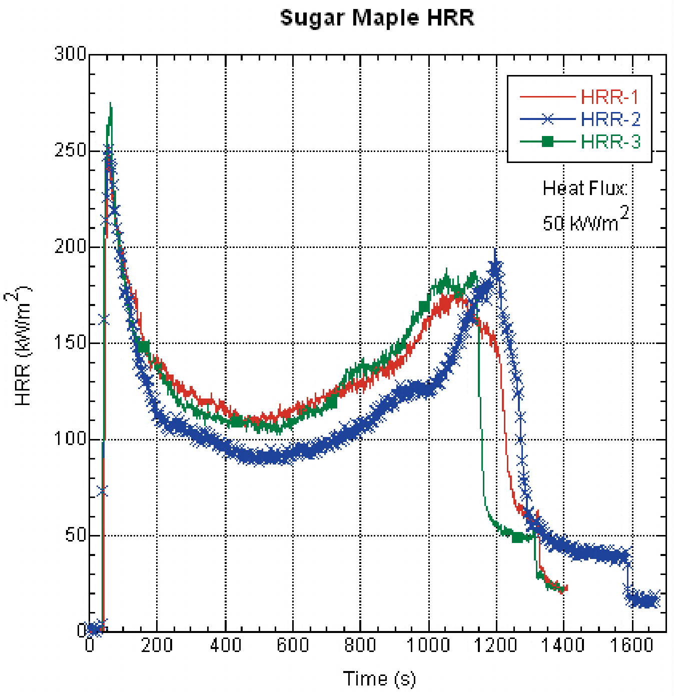


Figure 3-13. HEAT RELEASE RATE for Sugar Maple Wood Sample.

Figure 3-14. Final Char for Sugar Maple Wood Sample.

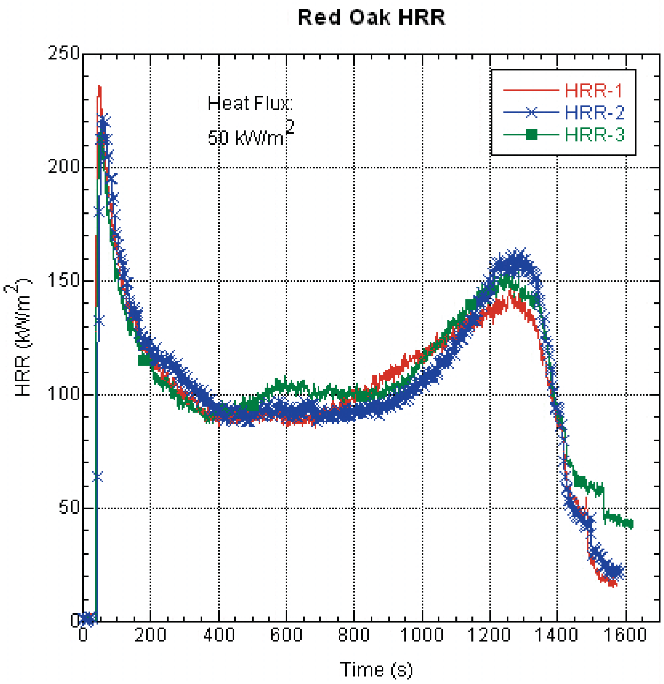


Figure 3-15. HEAT RELEASE RATE for Red Oak Wood Sample.

Figure 3-16. Final Char for Red Oak Wood Sample.

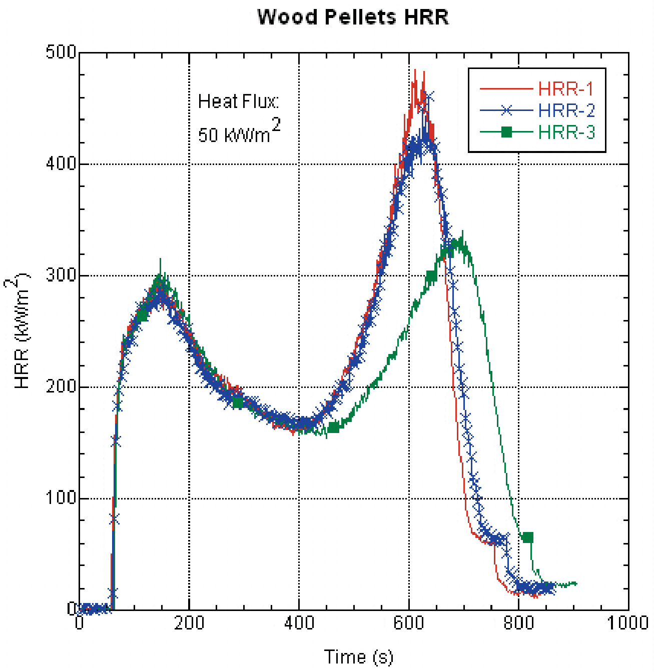


Figure 3-17. HEAT RELEASE RATE for Wood Pellets Sample.

Figure 3-18. Final Char for Wood Pellets Sample.

Table 3-4. UDRI – Smoke Release.

Sample Description	#	Sample Thickness (mm)	Starting Mass (g)	Total Mass Loss (g)	Weight % Lost (%)	Total Smoke Release (m^2/m^2)
Ash Wood	1	24.4	163.3	126.9	77.7	507
	2	24.1	162.7	125.1	76.9	634
	3	23.3	163.8	125.6	76.7	642
STDEV		0.55	0.6	0.9	0.6	75
Average Data		23.9	163.3	125.9	77.1	594
Pine Wood	1	25.6	104.8	87.8	83.7	2623
	2	25.3	106.1	86.6	81.6	690
	3	25.6	106.2	88.7	83.5	2614
STDEV		0.17	0.8	1.1	1.2	1113
Average Data		25.5	105.7	87.7	83.0	1976
Sugar Maple Wood	1	24.6	153.8	122.1	79.4	383
	2	25.4	158.2	125.9	79.6	222
	3	25.6	162.4	124.6	76.7	376
STDEV		0.49	4.3	1.9	1.6	91
Average Data		25.2	158.2	124.2	78.6	327
Red Oak Wood	1	25.0	149.4	116.5	78.0	111
	2	24.7	149.6	116.5	77.9	72
	3	24.7	148.6	115.6	77.8	149
STDEV		0.16	0.5	0.5	0.1	39

Sample Description	#	Sample Thickness (mm)	Starting Mass (g)	Total Mass Loss (g)	Weight % Lost (%)	Total Smoke Release (m^2/m^2)
Average Data		24.8	149.2	116.2	77.9	111
Wood Pellets	1	29.7	169.2	132.5	78.3	431
	2	29.7	169.4	133.0	78.5	459
	3	29.7	169.1	131.6	77.8	517
STDEV		0.00	0.2	0.7	0.3	44
Average Data		29.7	169.2	132.4	78.2	469

Table 3-5. UDRI – CO/CO_2 Emission Factors.

Sample Description	#	CO Yield (kg/kg)		CO_2 Yield (kg/kg)	
		Pre- Ignition	Post- Ignition	Pre- Ignition	Post- Ignition
Ash	1	0.004	0.007	0.870	1.22
	2	0.003	0.007	0.590	1.19
	3	0.009	0.007	0.570	1.20
STDEV		0.003	0.000	0.168	0.02
Average Data		0.006	0.007	0.677	1.20
Pine	1	0.000	0.015	0.000	1.58
	2	0.000	0.009	0.590	1.42
	3	0.000	0.014	-	1.57
STDEV		0.000	0.003	-	0.09
Average Data		0.000	0.013	-	1.52
Sugar Maple	1	0.004	0.006	0.610	1.26
	2	0.001	0.009	0.550	1.27
	3	0.002	0.007	0.660	1.20
STDEV		0.001	0.001	0.055	0.04
Average Data		0.002	0.007	0.607	1.24
Red Oak	1	0.003	0.006	0.610	1.28
	2	0.003	0.006	1.040	1.29
	3	0.002	0.008	0.740	1.30
STDEV		0.001	0.001	0.221	0.01
Average Data		0.003	0.007	0.797	1.29

Sample Description	#	CO Yield (kg/kg)		CO_2 Yield (kg/kg)	
		Pre- Ignition	Post- Ignition	Pre- Ignition	Post- Ignition
Wood Pellets	1	0.001	0.006	0.410	1.24
	2	0.001	0.006	0.450	1.24
	3	0.003	0.006	0.390	1.23
STDEV		0.001	0.000	0.031	0.01
Average Data		0.001	0.006	0.417	1.24

Table 3-6. UDRI – Particulate Mass (PM) Emission Factors.

Type of Wood	PM, g/kg Fuel In
Ash	5.6
Sugar Maple	5.5
Pine	29.5
Red Oak	2.1
Wood Pellets	5.6

Table 3-7. UDRI – PCDD/F Emission Factors.

Analyte	Ash g/kg fuel in	Sugar Maple g/kg fuel in	Pine g/kg fuel in	Red Oak g/kg fuel in	Pellets g/kg fuel in
(ND[1]=0, EMPC[2]=EMPC)					
2,3,7,8-TCDD	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.27E-12
1,2,3,7,8-PeCDD	6.50E-11	2.02E-11	0.00E+00	0.00E+00	0.00E+00
1,2,3,4,7,8-HxCDD	6.67E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1,2,3,6,7,8-HxCDD	7.47E-10	1.01E-10	0.00E+00	6.95E-11	4.54E-11
1,2,3,7,8,9-HxCDD	2.41E-10	4.13E-11	0.00E+00	0.00E+00	4.52E-11
1,2,3,4,6,7,8-HpCDD	1.85E-09	3.31E-10	6.28E-10	2.70E-10	2.36E-10
OCDD	1.21E-09	4.31E-10	2.21E-09	5.19E-10	5.46E-10
2,3,7,8-TCDF	9.01E-11	1.85E-10	2.15E-10	1.13E-10	1.12E-10
1,2,3,7,8-PeCDF	1.13E-10	2.52E-10	3.32E-10	1.41E-10	1.39E-10
2,3,4,7,8-PeCDF	3.18E-10	4.01E-10	4.64E-10	2.30E-10	0.00E+00
1,2,3,4,7,8-HxCDF	2.88E-10	1.61E-10	2.19E-10	1.36E-10	8.40E-11
1,2,3,6,7,8-HxCDF	1.29E-10	1.55E-10	2.07E-10	1.11E-10	8.05E-11
2,3,4,6,7,8-HxCDF	7.59E-11	1.62E-10	2.61E-10	1.10E-10	7.94E-11
1,2,3,7,8,9-HxCDF	0.00E+00	0.00E+00	2.37E-10	0.00E+00	9.66E-11
1,2,3,4,6,7,8-HpCDF	1.80E-10	1.72E-10	2.33E-10	1.52E-10	1.20E-10
1,2,3,4,7,8,9-HpCDF	4.20E-11	8.06E-11	0.00E+00	7.14E-11	5.22E-11
OCDF	1.40E-10	7.95E-11	4.18E-10	1.10E-10	1.17E-10
TCDDs	6.62E-10	2.75E-09	1.61E-09	1.33E-09	6.56E-10

Analyte	**Ash g/kg fuel in**	**Sugar Maple g/kg fuel in**	**Pine g/kg fuel in**	**Red Oak g/kg fuel in**	**Pellets g/kg fuel in**
(ND[1]=0, EMPC[2]=EMPC)					
PeCDDs	8.84E-10	2.44E-10	1.49E-10	1.75E-10	5.57E-11
HxCDDs	2.46E-09	3.17E-10	0.00E+00	2.08E-10	2.12E-10
HpCDDs	2.65E-09	5.16E-10	9.26E-10	1.81E-10	2.36E-10
OCDD	1.21E-09	4.31E-10	2.21E-09	5.19E-10	5.46E-10
TCDFs	4.35E-09	9.01E-09	8.42E-09	4.85E-09	5.67E-09
PeCDFs	2.71E-09	4.29E-09	5.12E-09	2.60E-09	2.04E-09
HxCDFs	1.29E-09	1.49E-09	1.19E-09	1.07E-09	5.75E-10
HpCDFs	2.22E-10	2.53E-10	4.85E-10	3.23E-10	1.85E-10
OCDF	1.40E-10	7.95E-11	4.18E-10	1.10E-10	1.17E-10
Total PCDD/Fs (ND=0; EMPC=0)	1.66E-08	1.93E-08	2.01E-08	1.13E-08	1.03E-08
Total PCDD/Fs (ND=0; EMPC=EMPC)	1.84E-08	2.03E-08	2.55E-08	1.39E-08	1.18E-08
Total PCDD/Fs (2378-X ND=DL[3]; EMPC=EMPC)	1.85E-08	2.04E-08	2.64E-08	1.40E-08	1.18E-08
WHO-2005 TEQ (ND=0; EMPC=0)	3.26E-10	2.27E-10	2.17E-10	1.14E-10	4.58E-11

Analyte	Ash g/kg fuel in	Sugar Maple g/kg fuel in	Pine g/kg fuel in	Red Oak g/kg fuel in	Pellets g/kg fuel in
(ND[1]=0, EMPC[2]=EMPC)					
WHO-2005 TEQ (ND=0; EMPC=EMPC)	3.49E-10	2.35E-10	2.73E-10	1.33E-10	6.67E-11
WHO-2005 TEQ (ND=DL; EMPC=EMPC)	3.71E-10	2.52E-10	5.05E-10	1.99E-10	9.84E-11

[1] ND = Non-Detect

[2] EMPC = Estimated Maximum Possible Concentration

[3] Detection Limit

Table 3-8. UDRI – PAH Emission Factors.

Analyte	Ash g/kg fuel in	Sugar Maple g/kg fuel in	Pine g/kg fuel in	Red Oak g/kg fuel in	Pellets g/kg fuel in
Naphthalene	1.18E-03	2.36E-04	1.49E-03	2.31E-04	4.14E-04
Acenaphthylene	1.83E-03	8.34E-04	3.00E-02	3.68E-04	1.16E-03
Acenaphthene	1.06E-04	2.64E-05	4.40E-04	1.29E-05	2.94E-05
Fluorene	3.01E-04	1.35E-04	4.97E-03	7.71E-05	1.69E-04
Phenanthrene	1.07E-03	5.35E-04	4.33E-03	2.73E-04	8.40E-04
Anthracene	1.67E-04	9.29E-05	2.41E-03	3.63E-05	1.35E-04
Fluoranthene	6.39E-04	3.38E-04	1.75E-03	1.41E-04	5.17E-04
Pyrene	1.44E-04	6.22E-05	1.60E-04	5.88E-05	1.28E-04
Benzo(a)Anthracene	8.50E-05	4.46E-05	1.70E-03	1.80E-05	6.67E-05
Chrysene	1.03E-04	4.64E-05	1.74E-03	1.99E-05	6.96E-05
Benzo(b)Fluoranthene	2.13E-04	9.57E-05	4.21E-03	3.73E-05	1.46E-04
Benzo(k)Fluoranthene	9.41E-05	3.99E-05	2.22E-03	1.58E-05	7.54E-05
Benzo(a)Pyrene	1.06E-04	9.35E-05	2.26E-03	3.27E-05	1.37E-04
Indeno(1,2,3-cd)Pyrene	1.29E-04	7.45E-05	2.77E-03	3.28E-05	1.39E-04
Dibenzo(a,h)Anthracene	1.56E-05	6.89E-06	6.00E-04	4.86E-06	1.08E-05
Benzo(ghi)Perylene	1.67E-04	7.39E-05	3.89E-03	4.12E-05	1.71E-04
Total 16 EPA PAHs	6.35E-03	2.74E-03	6.50E-02	1.40E-03	4.21E-03
2-Methylnaphthalene	1.71E-04	4.56E-05	6.82E-04	4.68E-05	6.21E-05
Benzo(e)Pyrene	9.41E-05	4.71E-05	1.58E-03	1.88E-05	8.34E-05
Perylene	3.87E-05	4.10E-05	1.23E-03	2.13E-05	7.08E-05

Table 3-9. UDRI – Chlorobenzenes/Chlorobutadiene Emission Factors.

Analyte	Ash g/kg fuel in	Pine g/kg fuel in	Red Oak g/kg fuel in	Pellets g/kg fuel in
1,2,3,5-Tetrachlorobenzene	1.64E-07	4.28E-08	1.71E-07	3.62E-08
1,2,4,5-Tetrachlorobenzene	1.52E-07	4.84E-08	1.37E-07	3.88E-08
1,2,3,4-Tetrachlorobenzene	5.42E-07	1.56E-07	4.60E-07	1.22E-07
Pentachlorobenzene	1.03E-06	7.89E-07	4.24E-07	6.56E-07
Hexachlorobenzene	3.57E-07	4.77E-07	3.07E-07	2.88E-07
Total (Tetra to Hexa) Clbz	2.25E-06	1.51E-06	1.50E-06	1.14E-06
Hexachlorobutadiene	7.93E-09	0.00E+00	1.12E-08	1.81E-08

3.4.2 EPA – Outdoor Wood Fired Hydronic Heaters

Tables 3-10 through 3-13 show the average emission factors and the corresponding STDVs are shown in parentheses.

Table 3-10. EPA – CO/CO$_2$ Emission Factors.

HH Unit	Fuel	CO, g/kg Fuel In	CO$_2$, g/kg Fuel In
Conventional, Single Stage HH	Red Oak (24 H) Av.	194 (±20)	1330 (±29)
	White Pine (12 H) Av.	190 (±38)	1529 (±177)
	Ash (12H) Av.	205 (±22)	1556 (±34)
Three Stage HH	Red Oak (12 H) Av.	117 (±17)	1560 (±37)
European Two Stage Pellet Burner	Hardwood pellets (6 H) Av.	8 (±3)	1817 (±2)
U.S. Two Stage Downdraft Burner	Red Oak (3.5 H) Av.	127 (±60)	1537 (±136)

Table 3-11. EPA – PM Emission Factors.

HH Unit	Fuel	PM, g/kg Fuel In
Conventional, Single Stage HH	Red Oak (24 h) Av.	23.92 (±0.86)
	White Pine (12 h) Av.	46.42 (±6.95)
	Ash (12 h)	28.48
Three Stage HH	Red Oak (12 h) Av.	4.48 (±2.47)
European Two Stage Pellet Burner	Hardwood pellets (6 h) Av.	1.70 (±1.11)
U.S. Two Stage Downdraft Burner	Red Oak (3.5 h) Av.	2.96 (±0.83)

Table 3-12. EPA – PCDD/F Emission Factors.

HH Unit	Fuel	WHO2005-TEQ-PCDD/PCDF, g/kg Fuel In (Std Dev)	Total-PCDD/PCDF, g/kg Fuel In (Std Dev)
Conventional, Single Stage HH	Red Oak (24 H) Av.	1.05E-09 (±7.58E-10)	3.30E-08 (±2.26E-08)
	White Pine (12 H) Av.	6.27E-10 (±2.10E-10)	1.14E-08 (±1.62E-09)
	Ash (12H) Av.	3.81E-10 (±5.33E-11)	1.34E-08 (±4.06E-09)
Three Stage HH	Red Oak (12 H) Av.	1.10E-10 (±2.15E-11)	4.24E-09 (±1.47E-09)
European Two Stage Pellet Burner	Hardwood pellets (6 H) Av.	2.80E-10	2.58E-08
U.S. Two Stage Downdraft Burner	Red Oak (3.5 H) Av.	7.95E-11 (±7.69E-12)	2.05E-09 (±5.98E-10)

Table 3-13. EPA – PAH Emission Factors.

Analyte	HH Unit					
	Conventional, Single Stage HH			Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner
	Fuel, g/kg fuel in					
	Red Oak	Pine	Ash	Red Oak	Wood Pellets	Red Oak
Naphthalene	2.47E-01	7.37E-01	1.70E+00	5.69E-02	4.13E-03	1.35E-01
Acenaphthylene	7.25E-02	3.35E-01	3.62E-01	1.18E-02	9.39E-04	2.73E-02
Acenaphthene	5.03E-03	2.77E-02	2.67E-02	1.09E-03	2.75E-02	1.80E-03
Fluorene	1.67E-02	6.21E-02	8.59E-02	2.92E-03	4.50E-02	5.41E-03
Phenanthrene	3.66E-02	1.27E-01	2.14E-01	1.03E-02	1.46E-03	1.68E-02
Anthracene	8.69E-03	2.65E-02	5.18E-02	1.83E-03	2.70E-04	3.31E-03
Fluoranthene	1.08E-02	2.75E-02	8.97E-02	2.13E-03	6.76E-04	5.41E-03
Pyrene	1.15E-02	2.57E-02	8.45E-02	1.75E-03	6.76E-04	5.11E-03
Benzo(a)anthracene	3.40E-03	1.03E-02	3.02E-02	1.02E-02	1.84E-04	1.41E-03
Chrysene	3.39E-03	9.32E-03	2.75E-02	7.46E-03	1.24E-04	1.50E-03
Benzo(b)fluoranthene	2.46E-03	3.15E-02	9.22E-02	1.06E-02	7.76E-02	7.21E-04
Benzo(k)fluoranthene	3.55E-03	1.85E-02	2.24E-02	5.14E-03	3.75E-02	8.41E-04
Benzo(a)pyrene	3.65E-03	3.70E-02	2.75E-02	1.18E-02	8.76E-02	9.62E-04
Indeno(1,2,3-cd)pyrene	8.23E-03	2.44E-02	2.54E-03	8.37E-03	6.26E-02	4.51E-04
Dibenz(a,h)anthracene	6.06E-03	1.25E-02	3.68E-03	9.63E-03	3.50E-02	1.66E-02
Benzo(ghi)perylene	8.33E-03	2.53E-02	1.46E-02	8.64E-03	6.26E-02	4.81E-04
Total 16 EPA PAHs	4.48E-01	1.54E+00	2.83E+00	1.61E-01	4.44E-01	2.23E-01

3.4.3 EPA – HH DATA versus UDRI-CONE CALORIMETER DATA

Table 3-14. EPA versus UDRI – CO_2 Emission Factors.

Fuel	EPA				UDRI
	g / kg fuel in				
	Conventional, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner	Cone Calorimeter
Red Oak	1330 (±29)	1560 (±37)	-	1537 (±136)	2087
Pine	1529 (±177)	-	-	-	-
Ash	1556 (±34)	-	-	-	1880
Wood Pellets	-	-	1817 (±2)	-	1653

Table 3-15. EPA versus UDRI – CO Emission Factors.

Fuel	EPA				UDRI
	g / kg fuel in				
	Conventional, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner	Cone Calorimeter
Red Oak	194 (±20)	117 (±17)	-	127 (±60)	9
Pine	190 (±38)	-	-	-	13
Ash	205 (±22)	-	-	-	13
Wood Pellets	-	-	8 (±3)	-	7

Table 3-16. EPA versus UDRI – PM Emission Factors.

Fuel	EPA				UDRI
	g / kg fuel in				
	Conventional, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner	Cone Calorimeter
Red Oak	23.92 (±0.86)	4.48 (±2.47)	-	2.96 (±0.83)	2.1
Pine	46.42 (±6.95)	-	-	-	29.5
Ash	28.48	-	-	-	5.6
Wood Pellets	-	-	1.70 (±1.11)	-	5.6

Table 3-17. EPA versus UDRI – Total PCDD/F Emission Factors.

Fuel	EPA				UDRI
	g / kg fuel in				
	Conventional, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner	Cone Calorimeter
Red Oak	3.30E-08 (±2.26E-08)	4.24E-09 (±1.47E-09)	-	2.05E-09 (±5.98E-10)	1.39E-08
Pine	1.14E-08 (±1.62E-09)	-	-	-	2.55E-08
Ash	1.34E-08 (±4.06E-09)	-	-	-	1.84E-08
Wood Pellets	-	-	2.58E-08	-	1.18E-08

Table 3-18. EPA versus UDRI – WHO-2005-TEQ-PCDD/F Emission Factors.

Fuel	EPA				UDRI
	g / kg fuel in				
	Conventional, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner	Cone Calorimeter
Red Oak	1.05E-09 (±7.58E-10)	1.10E-10 (±2.15E-11)	-	7.95E-11 (±7.69E-12)	1.33E-10
Pine	6.27E-10 (±2.10E-10)	-	-	-	2.73E-10
Ash	3.81E-10 (±5.33E-11)	-	-	-	3.49E-10
Wood Pellets	-	-	2.80E-10	-	6.67E-11

Table 3-19. EPA versus UDRI – PAH (16 EPA) Emission Factors.

Fuel	EPA				UDRI
	g / kg fuel in				
	Conventional, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner	Cone Calorimeter
Red Oak	4.48E-01	1.61E-01	-	2.23E-01	1.40E-03
Pine	1.54E+00	-	-	-	6.50E-02
Ash	2.83E+00	-	-	-	6.35E-03
Wood Pellets	-	-	4.44E-01	-	4.21E-03

3.5 DISCUSSION AND CONCLUSIONS

3.5.1 Heat Release and Smoke

Table 3-3 provides heat release and other data on flammability, and Table 3-4 provides smoke data for the different wood samples burned. A two-peak heat release behavior is observed for the samples, which is typical for thermally thick charring samples (Figures 3-9, 3-11, 3-13, 3-15, and 3-17). The ash, pine, sugar maple, and red oak all show this behavior, with the first peak of heat release (occurring at ignition) being of highest value. The ash sample (Figure 3-9) may be an exception to this, with its first and second peak of HRR almost of equivalent values. The wood pellet samples also show a two-peak behavior, but for this sample it is the second peak of HRR (the one occurring shortly before extinguishing of the sample) which shows the higher value. Reproducibility for the flammability behavior is reasonable for all of the wood samples, although one of the wood pellet flammability runs gave a noticeable difference in burning behavior (Figure 3-17). Some discrepancies in smoke release values were noted for the pine sample – with some large differences in time to ignition noted as well for one sample in the set. While the char yields match for all samples in the set, the one sample with longer time to ignition has much lower total smoke and a lower effective heat of combustion, and the reason for this is not clear at this time. The ash, sugar maple, and red oak samples are similar to one another in heat release behavior, but do have some notable differences in smoke release value. Pine also has some similarities in heat release behavior, but does ignite much sooner than the other wood samples and with the one outlier, gives off much more smoke and has a higher effective heat of combustion. Since pine is known to contain more volatile organic compounds (tars, resins), the higher smoke and effective heat of combustion may be reasonable results for burning this particular wood. The wood pellet samples are obviously different from the other wood samples. While they have a total heat release similar to the other wood samples, they have very different flammability behavior. Time to ignition is delayed, but peak HRR is much higher as is average HRR. Further, the heat release rate curve shape is different, possibly due more to the geometry of the sample (pellets with lots of surface area rather than a solid piece) than the composition of the pellet itself. Interestingly, the wood pellet sample has a MAHRE value equal to that of a plastic sample burned at the UDRI facility, meaning its fire risk for heat release growth is the same as that seen with a plastic sample. Still, it takes ~170 g of wood pellets to equal the fire risk of 10 g of plastic so the MAHRE number comparison is not an exact comparison for the fire risk of the two products. Instead, it suggests that there is a reason why wood pellets are used as fuel over full pieces of wood - they burn with a lot of energy released making them more efficient per pound as a fuel source from an energy density perspective.

3.5.2 CO/CO_2 Emission Factors

The CO_2 emission factors from the cone calorimeter (Table 3-5) show that pine wood has the highest post-ignition CO_2 emission factor of all the woods. Red oak has the next highest and the other woods tested have comparable post-ignition CO_2 emission factors. Also, when the total CO_2 emission factors (i.e., the sum of pre-ignition and post-ignition) are compared for the different samples, red oak appears to have the highest CO_2 emission factor (excluding pine for which the data for the pre-ignition CO_2 emission factor have not been reported here due to the high uncertainty in the measured value). The total CO_2 emission factors from the cone calorimeter are slightly higher than most of the HHs except for the European Two Stage Pellet Burner where wood pellets were burned. When compared, the CO_2 emission factors from Conventional, Single Stage HH are ~85% of ash and ~65% of red oak and from the Three Stage HH and U.S. Two Stage Downdraft Burner are ~70% of red oak emission factors from the cone calorimeter. The CO_2 emission factors from the cone calorimeter are ~90% of the European Two Stage Pellet Burner for wood pellets. Although the trend observed for total CO_2 emission factors from HHs for different types of wood is different from the trend observed in the cone calorimeter, the emission factors for CO_2 are of the same order of magnitude.

The post ignition CO emission factors from the cone calorimeter experiments (Table 3-5) show pine has the highest emission factor. Nevertheless, the total CO emission factors (sum of pre-ignition and post-ignition) show that pine and ash have similar emission factors while the other woods have similar emission factors. With the exception of the European Two Stage Pellet Burner (where CO emission factors are comparable), the total CO emission factors from the cone calorimeter are an order of magnitude less than the HHs. The higher CO_2 and lower CO emission factors from the cone tests compared to the HHs are likely due to the well-ventilated combustion exposure conditions in the cone tests.

3.5.3 PM Emission Factors

The PM emission factors from cone data show that pine wood has an emission factor higher than all the woods tested and red oak has the lowest (Table 3-6). Also, the smoke data (Table 3-4) show a trend similar to the PM trend observed. This trend appears to relate to the carbon content of the wood (Table 3-2), i.e., the sample with the higher carbon content gives more PM and smoke. As mentioned when discussing the smoke data, the higher PM emissions from pine are likely due to its higher volatile organics content consisting of tars that would contribute to PAH emissions that are precursors to soot as well as due to its higher carbon content. Chlorine and sulfur are both known to increase PM yields during combustion of various fuels. Therefore, the higher chlorine and sulfur content in the wood pellets may have contributed to the higher PM yields despite the lower carbon content than ash. The PM emission factors from

Conventional, Single Stage HH (Table 3-11) show a trend similar to the observations from the cone calorimeter. The PM emission factors from the cone calorimeter are lower when compared to Conventional, Single Stage HH (by a factor of ~1.5 for Pine, 5 for ash and 11 for Red Oak), within experimental uncertainty comparable to Three Stage HH and U.S. Two Stage Downdraft Burner, and are higher than from European Two Stage Pellet Burner (by a factor of ~3). The reason PM emission factors for the different woods from Conventional, Single Stage HH vary by different orders of magnitude when compared to the corresponding wood data from the cone could be that the differences in composition of the woods appear to affect the PM yields differently under the two different combustion conditions in the cone and HH.

The higher PM emission factors seen for the Conventional, Single Stage HH are due to the oxygen-starved combustion conditions as opposed to the well-ventilated combustion conditions used in the cone calorimeter. Except for Conventional, Single Stage HH, the PM emission factors from the cone calorimeter are more comparable in magnitude to the other three HHs with improved combustion efficiency technologies.

3.5.4 PCDD/F Emission Factors

The total PCDD/F emission factors from the cone calorimeter experiments shown in Table 3-7 indicate that pine has the highest and the pellets have the lowest (by a factor of 2) PCDD/F emission factors. Based on the WHO-2005 TEQ emission factors from cone tests, ash has the highest and pellets have the lowest emission factors. Nevertheless, these differences observed between the different wood samples could be within experimental uncertainty and show no definitive trend in the emission factors. Also, the results show no direct correlation between the chlorine content of the samples (Table 3-2) and the PCDD/F emission factors, and are likely due to the low chlorine content in the samples or due to confounding effects from other parameters/products of combustion. Given the experimental uncertainty, the PCDD/F data from the cone calorimeter (at ND=0, EMPC=EMPC) when compared to the HH PCDD/F data (Table 3-17) are similar in magnitude and within a factor of 3.

3.5.5 PAH and Semivolatile Emission Factors

Table 3-8 shows the PAH emission factors for the 16 EPA PAHs and the other PAHs quantified for the different wood samples tested using the cone calorimeter. Pine has the highest total PAH and red oak has the least. The higher PAH emissions from pine are likely due to its higher volatile organic content consisting of tars as mentioned before when discussing smoke and PM yields from pine. PAHs are known to be the nascent precursors of soot. Therefore, a higher presence of PAHs could lead to higher PM yields from combustion. The PAH trend from cone tests follows the same smoke/PM trends and indicates higher amounts of soot in the presence of higher amounts of PAHs. When compared to the cone calorimeter experiments, the PAH emission factors from the HHs are about two orders of magnitude higher and do not follow the same trend. In the cone calorimeter, prior tests with the total sampling train have shown some losses of pre-sampling surrogates lighter than anthracene/phenanthrene from breakthrough due to the high gas flow/sampling velocities. However, almost all the other PAHs from the cone calorimeter when compared to the HH PAHs are also about two orders of magnitude less. Therefore, the lower PAH yields are likely due to the better-ventilated combustion conditions used in the cone tests than in the HHs.

The chlorobenzenes (tetra- through hexa-) and chlorobutadiene emission factors from cone tests quantified (at ND=0, EMPC=EMPC) in Table 3-9 show that all the different samples tested with the exception of hexachlorobutadiene emissions from pine are of the same order of magnitude. Similar to PCDD/F observations, no direct correlation is observed between the chlorine content and the chlorobenzenes/chlorobutadiene emission factors.

3.5.6 Conclusions

The study provides emission factors for five different types of wood samples using a cone calorimeter modified to sample emissions and allows us to compare emission factors for similar compounds/products of interest obtained using HHs.

The cone calorimeter study shows that of all of the wood samples tested, pine wood has the highest emission factors for most of the emissions characterized (CO/CO_2, smoke/PM, total PCDD/F, PAH).

The smoke/PM emissions from cone data appear to correlate with the initial composition of the samples. No direct correlation is observed between the chlorine content and the trend in chlorinated compounds characterized, most likely due to the low chlorine content in the samples or due to confounding effects from other parameters/products of combustion.

The trends for the emission factors from the HH Conventional, Single Stage HH when compared to the cone calorimeter show within experimental uncertainty a similar trend for PM, a different trend for CO_2 and PAH, and no discernible trend to compare for PCDD/F and CO emission factors.

The magnitude of the emission factors from the cone calorimeter when compared to the HHs are similar for CO_2 and PCDD/F, up to an order of magnitude lower than CO and PM, and two orders of magnitude lower than PAHs.

The lower emission factors from cone experiments for CO, PM and PAH could be attributed to the differences in combustion conditions (well-ventilated in cone versus oxygen-starved in HHs). The differences are least when compared to the HHs with advanced combustion technologies (European Two Stage Pellet Burner, U.S. Two Stage Downdraft Burner and Three Stage HH).

Although the same stock of wood was used for both the cone tests and HH tests, it is noteworthy that emission factors (and their trends) from combustion of biomass such as wood could be affected due to sample-to-sample variations in composition. These variations could be effects from moisture, or changes in the composition of bark in the quartered logs burned in the HHs as opposed to smaller wood pieces cut and burned in the cone experiments. If the ambient conditions of the wood logs had high levels of impurities they could deposit/absorb onto the bark. Therefore, some of the smaller differences observed between the cone tests and the HH may not be significant.

The two systems compared provide different combustion scenarios from well-ventilated combustion in the cone calorimeter to oxygen-starved conditions in an HH and provide us valuable data on the emission factors from different types of woods. The cone tests provide emission factors to compare different types of wood in a simpler/economical way in a laboratory setting while the HH provides emission factors closer to real-world conditions. The study indicates that emission factors generated under a range of conditions (from oxygen-starved to well-ventilated conditions) using the cone calorimeter would likely be more appropriate to compare emission factors and trends observed from HHs. If studies are conducted over a range of conditions, the cone calorimeter could then be used as a tool to predict emission factors from biomass combustion in real world conditions/HHs and also the emission factors generated could then be used to guide/optimize the design and operation of HHs.

3.6 SECTION 3 APPENDIX

3.6.1 Composition Analyses

Moisture, Carbon, Ash Analyses. Two wooden block samples referenced as “Ash Wood” and “Sugar Maple” was submitted for analysis at a UDRI laboratory to determine moisture content, ash content, and elemental composition.

Small cylindrical sections 1/8” in diameter and 1/8” tall were taken from each sample for thermogravimetric analysis (TGA). The TGA analysis monitors the sample weight as a function of temperature and was used to determine the moisture and ash content. Sample pieces were heated from 50 °C to 700 °C in air. A set of vapor sensors attached to the exit port of the TGA instrument was also used to examine the types of vapor being driven off as the sample materials break down. The sensors include a Figaro organic vapor sensor and a CO_2 sensor. The TGA curve for the ash wood is shown in Figure 3-19. The curve shows a transition that begins almost immediately and then levels off at around 150 °C. This transition is associated with the loss of moisture. A large transition associated with the decomposition of the sample begins around 260 °C and continues out to about 425 °C where the weight stabilizes. The remaining weight after the moisture loss transition is 91%, which correlates to a moisture content of 9%. The remaining weight at 600 °C is 0.75%, which represents the ash content. The vapor sensor response curves are shown in Figure 3-20. The organic vapor sensor shows a response in the 50 °C to 150 °C region associated with the loss of moisture. This loss of moisture is followed by a response beginning at around 175 °C that is associated with the breakdown of the wood. The CO_2 sensor begins to respond around 225 °C. This response is associated with the combustion of the wood.

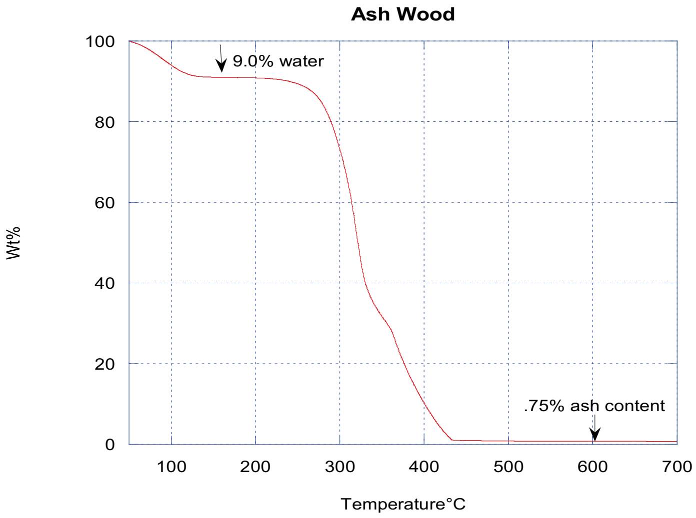


Figure 3-19. TGA Curve of Ash Wood Sample.

The TGA curve of the sugar maple sample is shown in Figure 3-21. The TGA curve is similar to the curve of the ash wood. Again, the moisture content is 9.0%. The ash content for the sugar maple is slightly higher at 1.1%. The decomposition appears to be complete at a slightly lower temperature (around 375 °C). The vapor sensor responses are shown in Figure 3-22. In this sample, the response of a water vapor sensor is also included. This sensor shows a response in the temperature range associated with the loss of moisture. The organic vapor sensor response and CO_2 sensor responses are similar to those of the ash wood.

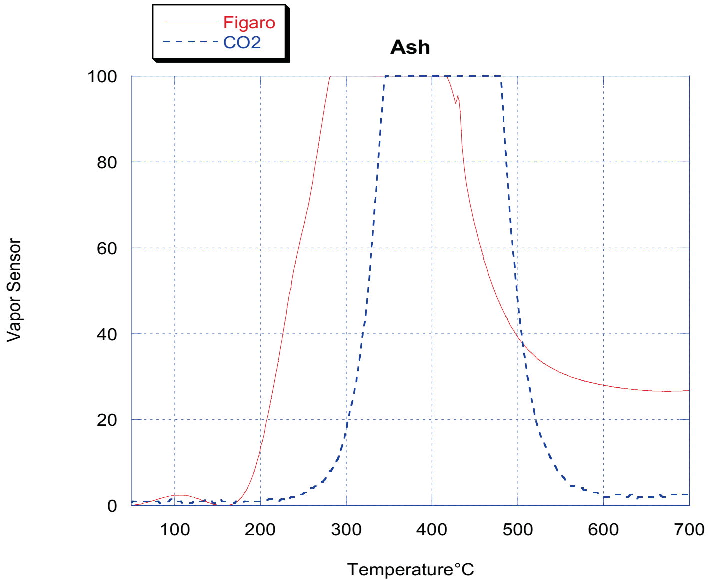


Figure 3-20. Vapor Sensor Response Curves of Ash Wood Sample.

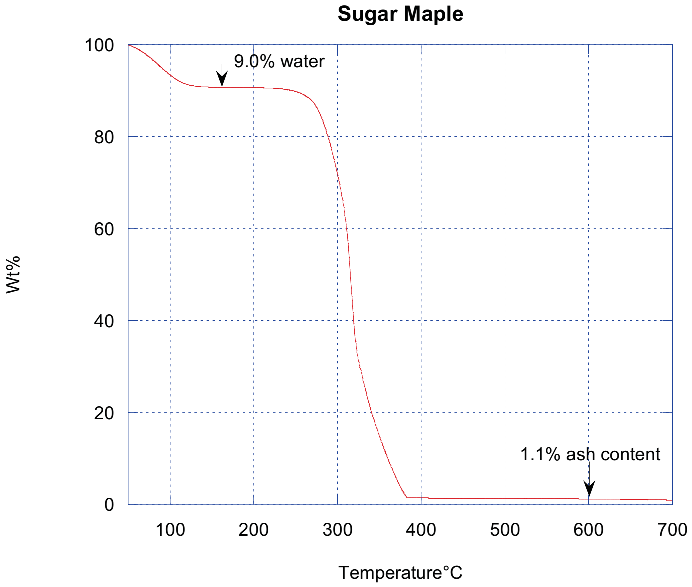


Figure 3-21. TGA Curve of Sugar Maple Sample.

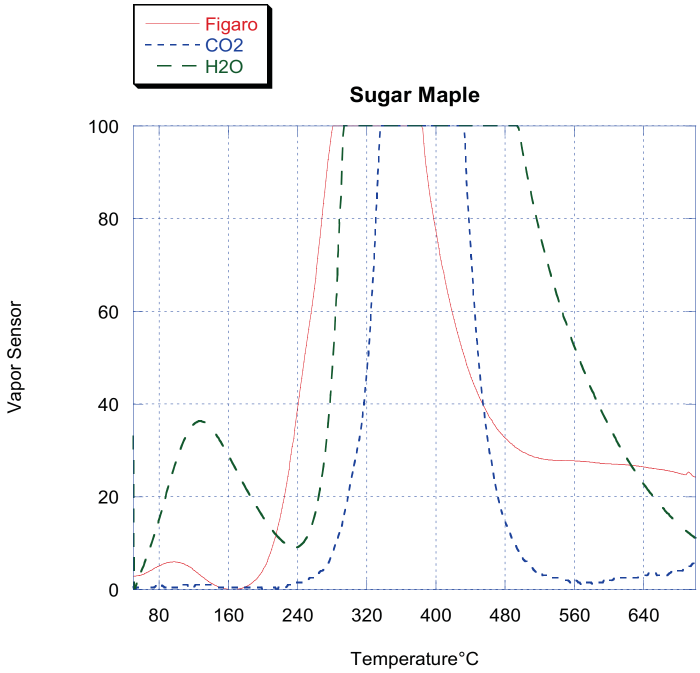
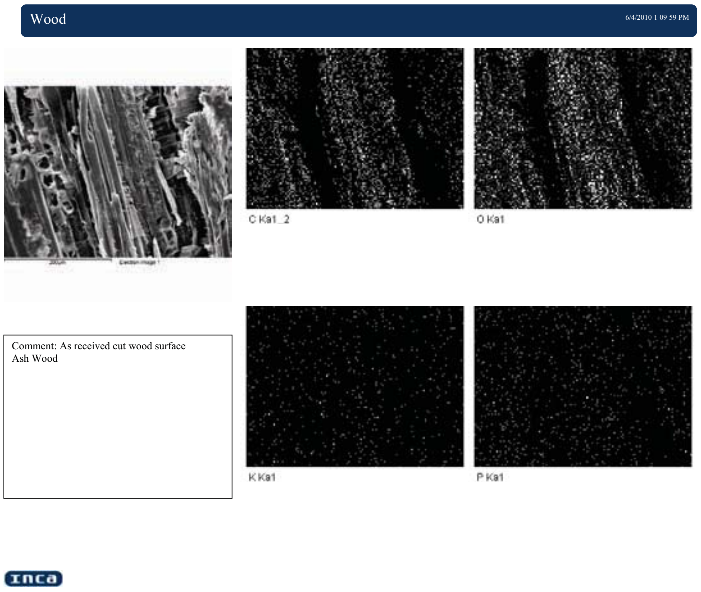


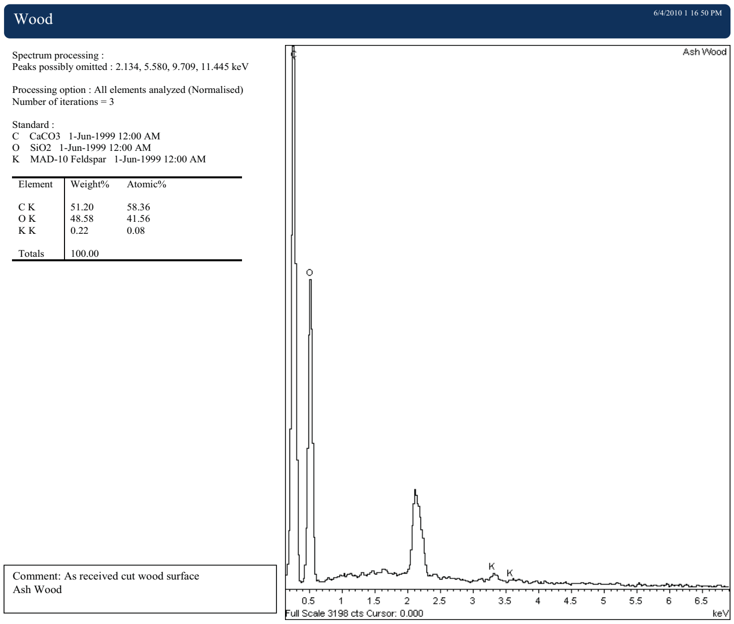
Figure 3-22. Vapor Sensor Response Curves of Sugar Maple Sample.

Samples of each material were also analyzed for elemental composition. Figure 3-23 shows an image and elemental map of an examined area of the ash wood sample. The analysis shows the material to be composed primarily of carbon and oxygen with trace amounts of potassium and phosphorus. The spectra and semi-quantitative analysis results are shown in Figure 3-24. An image and elemental map of the sugar maple sample are shown in Figure 3-25. The spectra and semi-quantitative analysis results are shown in Figure 3-26. Again, the analysis shows mostly carbon and oxygen, with trace amounts of potassium and phosphorus.



Comment: As received cut wood surface
Ash Wood

Figure 3-23. Image and Elemental Map of Examined Area of Ash Wood Sample.



Wood

6/4/2010 1 16 50 PM

Spectrum processing :
Peaks possibly omitted : 2.134, 5.580, 9.709, 11.445 keV

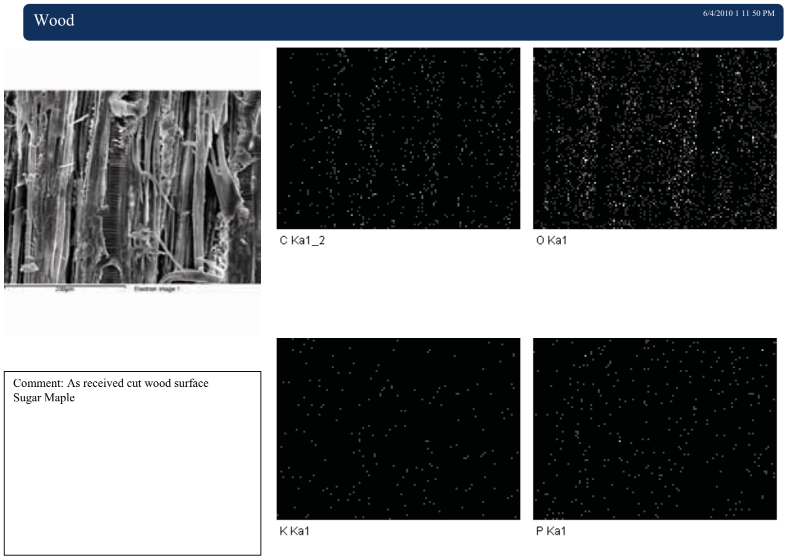
Processing option : All elements analyzed (Normalised)
Number of iterations = 3

Standard :
C CaCO3 1-Jun-1999 12:00 AM
O SiO2 1-Jun-1999 12:00 AM
K MAD-10 Feldspar 1-Jun-1999 12:00 AM

Element	Weight%	Atomic%
C K	51.20	58.36
O K	48.58	41.56
K K	0.22	0.08
Totals	100.00	

Comment: As received cut wood surface
Ash Wood

Figure 3-24. Spectra and Semi-Quantitative Analysis of Examined Area Shown in Figure 3-23.

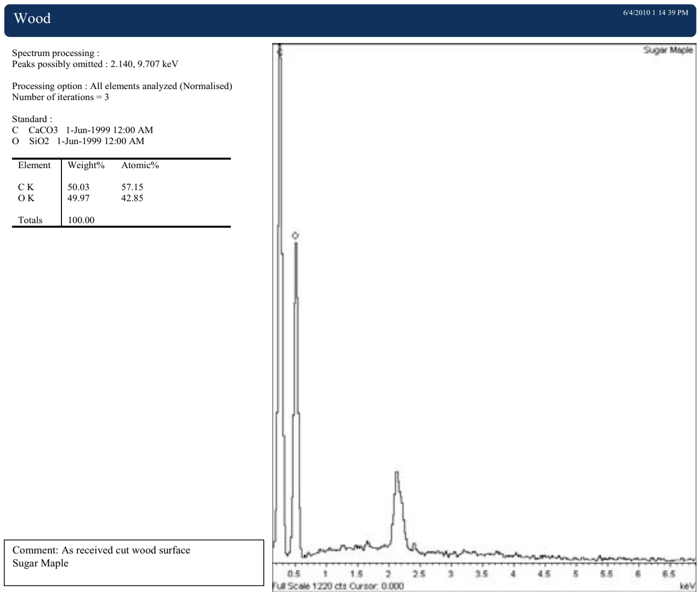


Wood

6/4/2010 1 11 50 PM

Comment: As received cut wood surface
Sugar Maple

Figure 3-25. Image and Elemental Map of Examined Area of Sugar Maple Sample.


Wood

6/4/2010 1 14 39 PM

Spectrum processing :
Peaks possibly omitted : 2.140, 9.707 keV

Processing option : All elements analyzed (Normalised)
Number of iterations = 3

Standard :
C CaCO3 1-Jun-1999 12:00 AM
O SiO2 1-Jun-1999 12:00 AM

Element	Weight%	Atomic%
C K	50.03	57.15
O K	49.97	42.85
Totals	100.00	

Comment: As received cut wood surface
Sugar Maple

Figure 3-26. Spectra and Semi-Quantitative Analysis of Examined Area Shown in Figure 3-25.

Sulfur Analysis. The two submitted wood samples (ash wood and sugar maple) were examined by XRF to determine the sulfur content. The two samples were examined along with a HC standard that contained 0.5% sulfur. The XRF spectrum of the 0.5% standard is shown in Figure 3-27. Figures 3-28 and 3-29 show the XRF spectra of the ash wood and sugar maple samples, respectively.

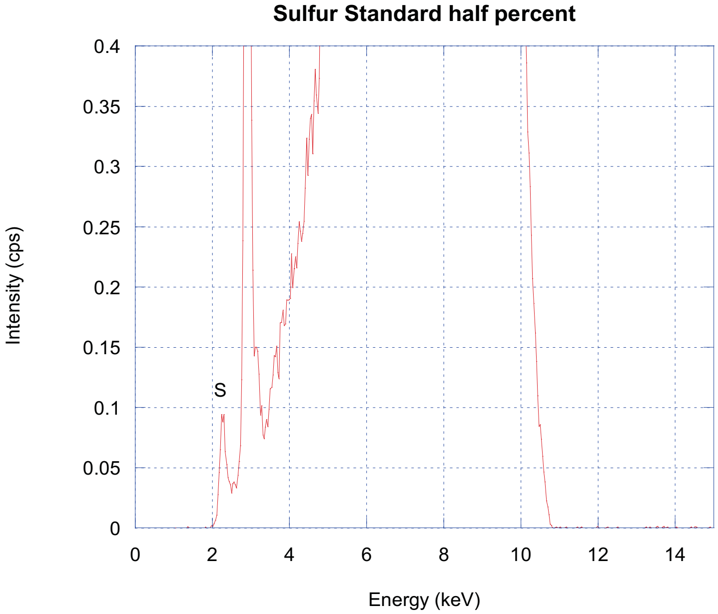


Figure 3-27. XRF Spectrum of 0.5% Sulfur Standard.

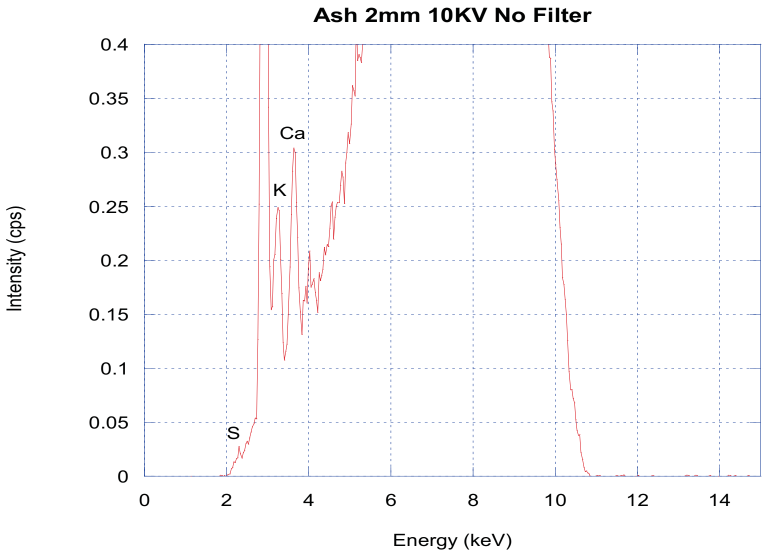


Figure 3-28. XRF Spectrum of Ash Wood Sample.

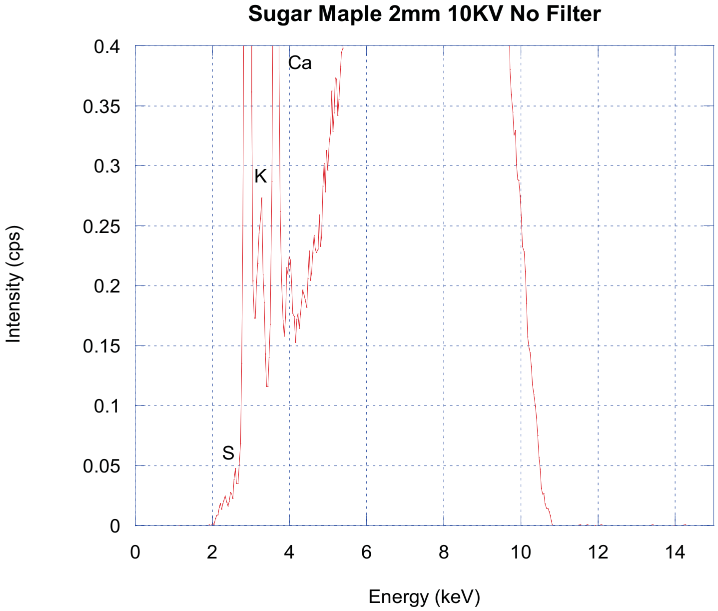


Figure 3-29. XRF Spectrum of Sugar Maple Sample.

The spectra of the two wood samples show no detectable peaks for sulfur compared to the 0.5% standard. The peak on the standard spectrum was integrated to determine the area under the peak. The same start and stop parameters were used to integrate the sulfur peaks on the two wood sample spectra. Table 3-20 shows the results of the peak integration. The table shows the peak intensity area of 0.42. The two sulfur peaks show intensity areas of essentially zero. Based on the response of the sulfur in the sulfur standard, a peak produced by a concentration of one tenth the standard amount (0.05%) should produce a peak with an area of 0.04. Since both wood spectra sulfur peak areas fall below this level, sulfur levels in the two wood samples should be less than 0.05% (500 ppm).

Table 3-20. UDRI – Areas from Integration of Sulfur Peaks in Wood and Standard Samples.

Sulfur Standard		**10 kV**		**2mm Aperture**		**No Filter**			
Z	Line	Start	Stop	Sum	Bkgrd	Left	Center	Right	Intensity
S	Kα	59	76	0.77	0.36	0.75	0.42	0.09	0.42
Ash Wood									
Z	Line								
S	Kα	59	76	0.32	0.33	0.30	-0.01	-0.32	0.00
Sugar Maple									
Z	Line								
S	Kα	59	76	0.31	0.36	0.28	-0.06	-0.39	0.00

Chlorine Analysis. Sample pieces were cut from the submitted blocks of ash wood and sugar maple. The weights of the cut pieces were 9.03 grams for the ash wood and 8.20 grams for the sugar maple. The pieces were ashed by placing them in glass beakers and heating them on a hot plate at the maximum temperature for approximately five hours. The ashing process was conducted to convert the chlorine in the wood to water-soluble chlorides. Sample solutions were prepared by adding thirty grams of deionized water to the ash and holding the solutions at room temperature overnight to maximize the chloride extraction into the water. The solutions were then filtered to produce clear solutions. These solutions were then analyzed by flow injection analysis (FIA) to determine the chloride content in the solutions. FIA is a colorimetric method that mixes a solution with a color reagent (mercuric thiocyanate) that reacts with the chloride ions in solution to produce a characteristic color that absorbs at 480 nm. The intensity of this color is directly proportional to the chloride ion concentration. Solutions of 0, 1, 2, 5, and 10 ppm chloride were used as calibration standards. The results of the FIA are shown in Figure 3-30.

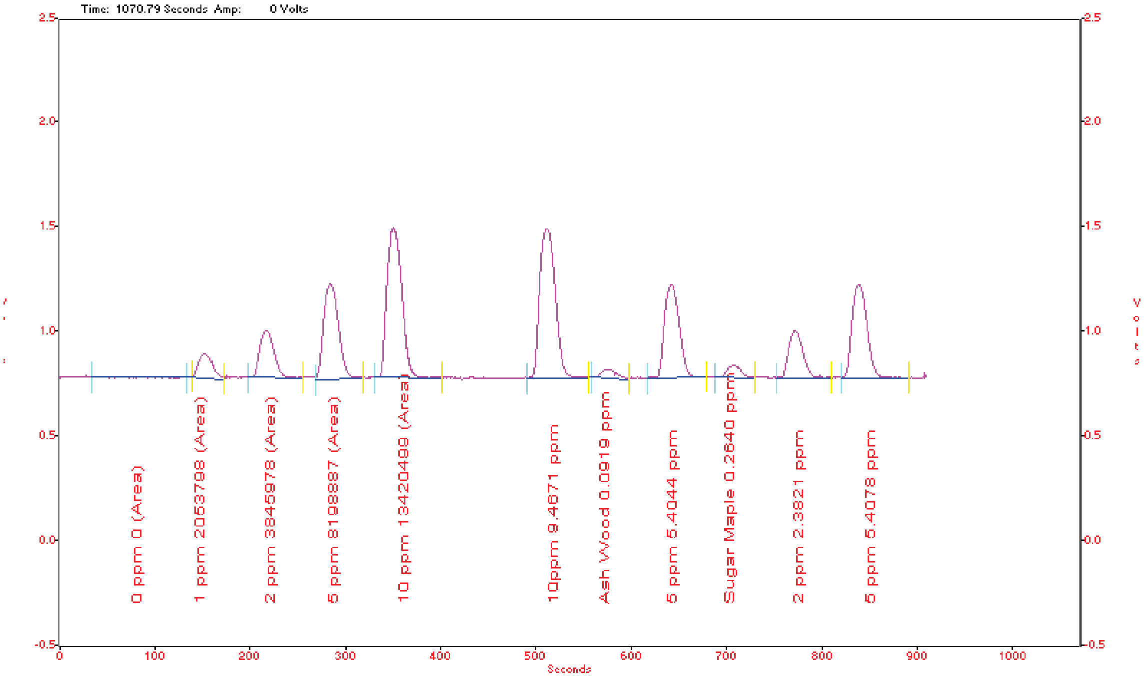


Figure 3-30. Flow Injection Analysis Results for Ash Wood and Sugar Maple Samples.

The results show a chloride concentration of 0.1 ppm for the ash wood solution and 0.26 ppm for the sugar maple sample. These solution concentrations result in chloride weights of 0.003 µg in the ash wood sample and 0.008 µg for the sugar maple sample in the thirty-gram test solutions. By dividing these weights by the weights of the original samples, the results show the chlorine amount in the original samples to be approximately 0.3 ppm for the ash wood and 1.0 ppm for the sugar maple sample.

3.6.2 Experimental Conditions

3.6.2.1 Ambient Conditions

Table 3-21. UDRI – Ambient Conditions during Cone Testing.

Ambient Conditions	Sample				
	Ash	Sugar Maple	Pine	Red Oak	Pellets
Temperature, °C	26	24	25	23	24
Relative Humidity, %	40	41	43	44.5	38
Pressure, mbar	989	987	985	990	990

Sampling Temperatures

Tables 3-22 through 3-26 provide temperature measurements at different locations in the total sampling train during the experiments.

Table 3-22. UDRI – Temperature Data during Sampling for Ash.

Time, min	Ash				
	Thermocouple Temperatures, °C				
	T1	T2	T3	T4	T5
0	46	53	43	18	15
2	99	133	77	31	24
4	99	133	77	33	25
6	106	133	79	33	26
8	107	136	81	35	27
10	116	140	82	36	27
12	114	142	84	37	28
14	139	161	87	37	28
16	144	192	89	37	28
18	248	235	91	37	28
20	185	182	83	36	28

Table 3-23. UDRI – Temperature Data during Sampling for Sugar Maple.

Time, min	Sugar Maple				
	Thermocouple Temperatures, °C				
	T1	T2	T3	T4	T5
0	76	79	63	23	17
2	136	109	91	36	27
4	106	130	89	34	28
6	106	130	91	35	29
8	105	130	93	35	29
10	103	130	92	36	29
12	104	130	96	38	30
14	111	138	97	37	31
16	123	145	101	40	33
18	139	158	106	42	34
20	118	150	103	45	29
22	96	113	89	42	32
24	93	111	89	41	35
26	94	105	83	38	30

Table 3-24. UDRI – Temperature Data during Sampling for Pine.

Time, min	Pine				
	Thermocouple Temperatures, °C				
	T1	T2	T3	T4	T5
0	110	130	82	24	21
2	112	142	80	33	26
4	112	138	91	32	29
6	122	145	90	33	30
8	137	144	75	32	26
10	141	154	92	36	27
12	150	154	84	31	27
16	157	167	88	34	28
18	163	162	79	31	27
20	165	165	83	35	31
24	151	141	72	35	27

Table 3-25. UDRI – Temperature Data during Sampling for Red Oak.

Time, min	Red Oak				
	Thermocouple Temperatures, °C				
	T1	T2	T3	T4	T5
2	86	120	84	28	26
4	87	118	79	30	28
6	87	116	86	35	26
8	86	116	88	35	28
10	89	118	87	35	28
12	88	121	91	38	31
14	92	128	92	40	32
16	100	134	96	40	33
18	105	137	99	41	34
20	107	123	103	44	35
22	94	106	97	43	34
24	87	83	87	41	32

Table 3-26. UDRI – Temperature Data during Sampling for Pellets.

Time, min	Pellets				
	Thermocouple Temperatures, °C				
	T1	T2	T3	T4	T5
0	70	72	58	22	15
3	158	199	128	46	36
5	152	191	127	47	37
7	159	188	127	47	38
9	186	212	132	47	37
11	200	221	141	48	36
13	135	101	133	47	34

4. EVALUATION OF PULMONARY FUNCTION AND CELLULAR AND BIOCHEMICAL INDICES IN MICE AFTER EXPOSURE TO INHALED FILTERED AND UNFILTERED WOOD SMOKE FROM THREE DIFFERENT HYDRONIC HEATERS

4.1 INTRODUCTION

Exposure to anthropogenic emissions such as vehicle exhaust, oil combustion, or wood smoke is known to cause dose-dependent increases in acute lung injury and systemic toxicity. These effects include increased inflammatory cells and lactate dehydrogenase levels in lung fluid and increased fibrinogen and pro-inflammatory cytokines in the blood. Residential wood combustion is now recognized as a major particle source in many countries and has elevated concerns about negative health effects associated with wood smoke exposure. The combustion appliances in use today provide highly variable combustion conditions, resulting in large variations in the physicochemical characteristics of the emitted particles. These differences in physicochemical properties are likely to influence the biological effects induced by the wood smoke particles.

We have previously reported that exposure to up to 2 mg m^{-3} of diesel exhaust causes a small degree of pulmonary inflammation (pro-inflammatory cytokines, neutrophil numbers), increases susceptibility to influenza virus infection and enhances allergic sensitization to experimental allergens in inbred Balb/C mice (Gowdy et al., 2008; Stevens et al., 2008, 2009). We have also demonstrated that oropharyngeal aspiration of size-fractionated particles obtained from a number of different cities or from specific locations have differential abilities to induce pulmonary inflammation and cardiovascular responses in CD-1 outbred mice (Gilmour et al., 2007; Cho et al., 2009).

The purpose of this study was to assess potential cardiopulmonary toxicity of wood smoke emissions from three different wood-fired HHs and to determine if one appliance had more harmful emissions than another. In addition, the test results were compared between whole wood smoke, filtered wood smoke which contained just the gas and vapor phases without particles and clean air controls. The appliances tested were a conventional, single stage HH (Conventional, Single Stage HH); a newer generation model with multiple stages (Three Stage HH), which uses gasification technology with a larger capacity than Conventional, Single Stage HH; and the European Two Stage Pellet Burner heater (pellet), which also uses gasification with automatic feeding of fuel. During the performance testing of each of the HHs, the automated opening and closing of the air supply dampers resulted in massive cyclic excursions in PM and noxious concentrations of CO and other combustion components that could reach toxic levels. At this time, the decision was made to conduct inhalation tests on the more stable post-test smoldering emissions where the damper would not open and close. A target concentration of 2 mg m^{-3} was established with the caveat that CO would not rise over 50 ppm, which is the Occupational Safety and Health Administration (OSHA) permissible exposure level (PEL) for an eight-hour work day. Mice were exposed for four hours per day for one or three days and were assessed for systemic and pulmonary toxicity immediately and after a further four and 24 hours. While the original experimental design was intended to provide comparison of the relative effects of particulate and gaseous emissions from the different heaters during normal operation, due to the unexpected operational issues noted above, the study design actually adopted can provide this comparison solely for the smoldering emission phase and, therefore, the results should not be interpreted as providing information on any health effects that may result from the heater emissions during their normal operation. The exposures conducted during the smoldering phase were potentially different from the exposures that may have occurred during the firing and burning phases, because the organic emissions were likely to be greater in these initial phases.

4.2 MATERIALS AND METHODS

4.2.1 Animals

Pathogen- free CD-1 female mice, 8-10 weeks old, weighing 20-24 g, were purchased from Charles River (Raleigh, North Carolina). All of the animals were housed in an Association for Assessment and Accreditation of Laboratory Animal Care (AAALAC) International -approved animal facilities with HEPA air filters and received access to food and water *ad libitum*. The studies were conducted after approval by the laboratory's Institutional Animal Care and Welfare Committee.

4.2.2 Wood Smoke Exposure

Three different wood-fired HHs were used to characterize chemical properties and animal toxicities of wood smoke:

1. Conventional, Single Stage HH
2. Three Stage HH, which uses gasification technology with a larger capacity than Conventional, Single Stage HH
3. European Two Stage Pellet Burner heater (pellet), which also uses gasification with automatic feeding of fuel.

Seasoned red oak was used for the first two HHs with one-time feeding for a 12-hour combustion cycle, and wood pellets were used for the pellet heater with an automatic feeder, controlled according to the temperature. Animals were exposed separately to each of the three different wood smoke conditions for four hours per day for three days.

1. HEPA-filtered clean air (control)
2. Particle-filtered wood smoke (HEPA-filtered)
3. Whole wood smoke (unfiltered).

The heater emissions were directed to two of the three stainless steel 1 m^3 Hazelton inhalation exposure chambers (model 1000), housed in an isolated animal exposure room (Figure 4-1). Because the CO level was found to be extremely high (up to 8000 ppm) even in the diluted heater exhaust at the active burning stage during a test run with Conventional, Single Stage HH, the animal exposures were conducted during the end of the combustion cycle where the CO level was much reduced (lower than 2000 ppm stack emission). The CO level in the inhalation chamber was continuously monitored, and the heater emission was diluted to maintain the CO level in the chamber below 50 ppm, the OSHA PEL threshold limit value[1].Target particle concentration in the unfiltered chambers was 2000 $\mu g/m^3$. However, the actual PM level was lower because of the high dilution rate to keep the CO at adequately safe levels. All three chambers were operated at the same flow rate (424 L/min), which resulted in 25.4 air exchanges per hour.

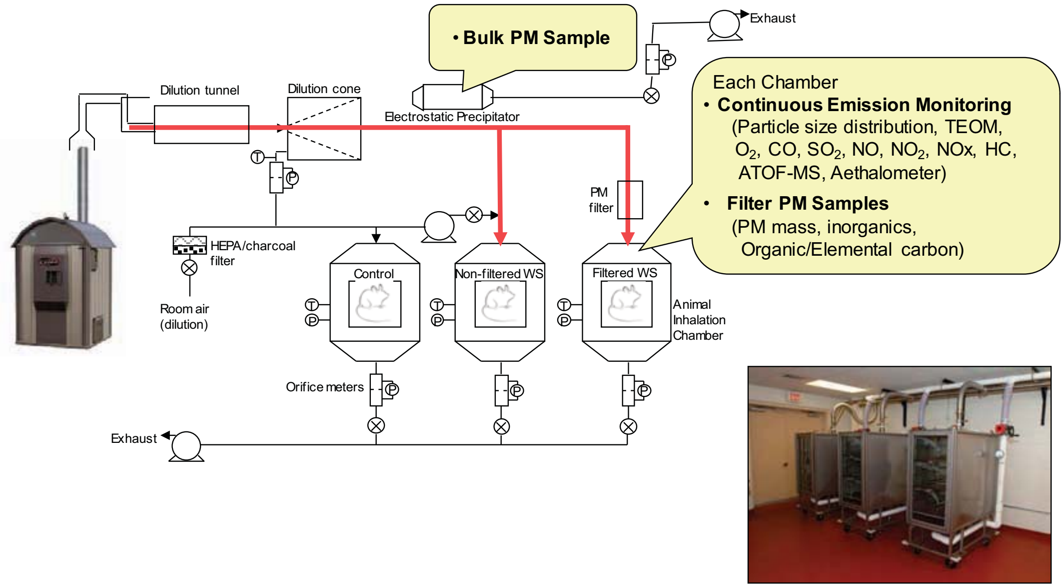


Figure 4-1. Wood Smoke Exposure System and Monitoring Assessment.

4.2.3 <u>Emission Monitoring</u>

A time-integrated 4 h filter sample (14.1 L/min) was collected from all three chambers once daily and analyzed gravimetrically to determine particle concentrations, and the results were compared with data from direct-reading instruments. Two or more PTFE filter samples were collected daily from the unfiltered

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[1] http://www.osha.gov/SLTC/healthguidelines/carbonmonoxide/recognition.html

chamber for analysis of the inorganic elemental components of particles, and the filters were analyzed by a wavelength dispersive (WD) Philips PW2404 XRF spectrometer (Panalytical, Natick, Massachusetts). In addition, quartz filter samples were collected from the unfiltered chamber to determine OC/EC partitioning of the collected particles by a thermal-optical carbon analyzer with transmittance-based pyrolysis correction (model 107A, Sunset Laboratory, Inc., Tigard, Oregon) based on NIOSH Method 5040, NIOSH Manual of Analytical Methods, http://www.cdc.gov/niosh/nmam/).

The same air stream divided by a manifold was directed to an optical-sensing direct-reading black carbon (BC) analyzer, the aethalometer (AE21, Magee Scientific Company, Berkeley, California). BC data measured while the filter samples were collected were compared with EC data. CEMs were used to measure chamber concentration of PM by TEOM (TSI Inc., St Paul, Minnesota), oxygen (O_2) (Beckman, La Habra, California), CO (Thermo Electron Corp, Waltham, Massachusetts), nitric oxide (NO) (Thermo Electron Corp, Waltham, Massachusetts), nitrogen dioxide (NO_2) (Thermo Electron Corp, Waltham, Massachusetts), and sulfur dioxide (SO_2) (Thermo Electron Corp, Waltham, Massachusetts). Samples were extracted through fixed stainless steel probes in the exposure chambers. Gas samples were passed through a particulate filter prior to the individual gas analyzers. PSDs were characterized using a scanning mobility particle sizer (SMPS) (TSI Inc., St. Paul, Minnesota) and aerodynamic particle sizer (APS) (TSI Inc., St. Paul, Minnesota). Average concentrations (and STDVs) for the CEM measurements from both PM chambers are presented in Table 4-1. Chamber temperatures, relative humidity, and noise were also monitored and maintained within acceptable ranges.

4.2.4 Experimental Design

For each heating device, the mice were randomly separated into three groups of 36. Animals were exposed to air, filtered, and unfiltered woodstove smoke. Eighteen mice in each group were exposed four hours per day for three days and an additional 18 mice per group were added on day 3 (used for day 1 time points). Six mice from each group were euthanized at 0-hours, 4-hours, and 24-hours post-exposure. One hour before the 4-hour and 24-hour time points, pulmonary responses to aerosolized methacholine were monitored.

4.2.5 Pulmonary Function Measurements

Pulmonary function changes in response to increasing concentrations of inhaled methacholine were measured in mice using a 12-chamber whole-body plethysmograph system (Buxco Electronics, Troy, New York) one hour before the 4-hour and 24-hour time points. Pressure signals were analyzed with BioSystem XA software (SFT3812, version 2.0.2.4, Buxco Electronics) to derive whole-body flow parameters that were used to calculate enhanced pause (Penh). Penh was used as an index of airflow obstruction, which has been correlated with changes in airway resistance. After measuring baseline parameters for seven minutes, an aerosol of saline or methacholine in increasing concentrations (6.25, 12.5, and 25 mg/mL) was nebulized through an inlet of the chamber and mice were exposed for 10 minutes to each concentration. The recorded Penh values were averaged during the baseline periods and the 10-minute methacholine challenges to obtain mean values for each event and these mean values were represented as change from the mean during the baseline period to the mean during each methacholine challenge.

4.2.6 Necropsy

Mice from each treatment group were euthanized with a 1:10 dilution of euthasol and weighed. The blood was obtained by cardiac puncture (0.5 mL collected in a microfuge tube containing 17 µL of 4% sodium citrate and the remainder placed in serum separator tubes). The trachea was exposed, cannulated, and secured with suture thread. The left mainstem bronchus was isolated and clamped with a microhemostat. To obtain the bronchoalveolar lavage, the right lung lobes were lavaged three times with a single volume of warmed Hank's balanced salt solution (HBSS) (Invitrogen, Grand Island, New York) (35 mL/kg). The resulting lavage was centrifuged (717 g, 15 min, 4 °C) and 150 µL was stored at 4 °C or -80 °C for cytokine measurement. The cell pellets were re-suspended in 1 mL of RPMI 1640 (GIBCO, Carlsbad, California) containing 2.5% fetal bovine serum (FBS) (GIBCO, Carlsbad, California). Total cell counts in the lavage fluid of each mouse were obtained with a Coulter Counter (Beckman Dickson). Each sample (200 µL) was centrifuged in duplicate onto slides using a Cytospin (Shandon, Pittsburgh, Pennsylvania) and subsequently stained with Diff Quick solution (American Scientific, McGraw Park, Pennsylvania) for cell differentiation determination with at least 200 cells counted from each slide.

4.2.7 Bronchoalveolar Lavage (BAL)Biochemistry

Lactate dehydrogenase (LDH) and total protein were modified for use on a Konelab 30 clinical chemistry analyzer (Thermo Clinical Lab systems Espoo, Finland). Activity for LDH was determined using a commercially available kit from Thermo DMA Corp. (Cincinnati, Ohio). Total protein concentrations were determined with the Coomassie plus protein Reagent (Pierce Chemical, Rockford, Illinois) with a standard curve prepared with bovine serum albumin from Sigma-Aldrich (St. Louis, Missouri). Ferritin, gamma glutamyl transpeptidase (GGT), microalbumin (MIA), N-acetyl-β-glucosaminidase (NAG), total iron (FE), and unsaturated iron binding capacity (UIBC) were also measured as previously described (Cho et al., 2009).

4.2.8 Cytokine Measurements

Macrophage inflammatory protein-2 (MIP-2), IL-6, IL-1beta, and TNFα concentrations in bronchoalveolar lavage (BAL) were measured by enzyme-linked immunosorbent assay (ELISA) with commercially available paired antibodies per manufacturer's instructions (Pharmingen, Franklin Lakes, New Jersey).

4.2.9 Statistical Analysis of Inflammatory, Biochemical, and Immune Endpoints

The data were analyzed using a three-way ANOVA model. The three independent variables were exposure, duration of exposure, and time post-exposure. Pair-wise comparisons were performed as subtests of the overall ANOVA. In cases where the usual ANOVA requisites of homoscedasticity and normality were violated, the data were transformed and the usual analysis was carried out on the transformed values. If the transformation did not adequately address the ANOVA conditions, a distribution-free method of analysis was employed. The level of statistical significance was set at 0.05. No adjustment was made for multiple comparisons. We recognize this will tend to increase the Type I error; however, it will maintain a reasonable Type II error.

4.3 RESULTS

4.3.1 Wood Smoke Exposures

In the first study using the Conventional, Single Stage HH, the 2 mg m^{-3} target concentration was achieved (Table 4.1). Only ~1 mg m^{-3} could be achieved for the Three Stage HH and European Two Stage Pellet Burner under similar CO constraints (Tables 4.2 and 4.3).

Table 4-1. Exposure Summary for Conventional, Single Stage HH.

Conventional, Single Stage HH				
	Units	**Air**	**Filtered Wood Smoke**	**Unfiltered Wood Smoke**
PM Concentration (TEOM)	mg/m^3	NM	0.06 ± 0.001	1.84 ± 0.005
PM Concentration (filter)	mg/m^3	0.18 ± 0.02	0.002 ± 0.08	2.61 ± 0.14
PM Number Concentration	$\#/cm^3$	7.30E+04	1.2e5 ± 3.6E4	3.6e5 ± 7.4E4
CO	ppm	NM	54.0 ± 0.002	53.6 ± 0.03
Oxygen (O_2)	%	NM	20.3 ± 0.005	20.3 ± 0.007
Nitrogen Oxide (NO)	ppm	NM	<1	<1
Nitrogen Dioxide (NO_2)	ppm	NM	<1	<1
Sulfur Dioxide (SO_2)	ppm	NM	<1	<1
BC Concentration	μg/m3	0.13 ± 0.05	0.35 ± 0.06	46.88 ± 6.65
OC/TC	wt. ratio	1.0	1.0	0.93 ± 0.01
EC/TC	wt. ratio	0	0	0.07 ± 0.01

*Values given as mean value plus/minus standard error.

NM = Not measured.

Table 4-2. Exposure Summary for Three Stage HH.

Three Stage HH				
	Units	**Air**	**Filtered Wood Smoke**	**Unfiltered Wood Smoke**
PM Concentration (TEOM)	mg/m^3	NM	0.02 ± 0.003*	0.84 ± 0.003
PM Concentration (filter)	mg/m^3	8.6E-3 ± 8.8E-3	7.3E-3 ± 0.02	0.86 ± 0.09
PM Number Concentration	#/cm^3	2.2E5 ± 8.7E4	3.8E5 ± 2.2E5	2.4E5 ± 3.3E4
Carbon Monoxide (CO)	ppm	NM	45.3 ± 0.109	42.3 ± 0.134
Oxygen (O_2)	%	NM	20.4 ± 0.003	20.4 ± 0.003
Nitrogen Oxide (NO)	ppm	NM	<1	<1
Nitrogen Dioxide (NO_2)	ppm	NM	<1	<1
Sulfur Dioxide (SO_2)	ppm	NM	<1	<1
BC Concentration	µg/m3	0.15**	0.11**	48.35 ± 8.97
OC/TC	wt. ratio	1.0	0.99 ± 0.002	0.94 ± 0.002
EC/TC	wt. ratio	0	0.0038 ± 0.0023	0.0615 ± 0.0028

*Values given as mean value plus/minus standard error.

**Only one measurement taken.

NM = Not measured.

Table 4-3. Exposure Summary for the European Two Stage Pellet Burner.

European Two Stage Pellet Burner				
	Units	**Air**	**Filtered Wood Smoke**	**Unfiltered Wood Smoke**
PM Concentration (TEOM)	mg/m^3	NM	0.25±0.003	0.42±0.002
PM Concentration (filter)	mg/m^3	0.03 ± 0.01	0.02 ± 0.02	0.96 ± 0.33
PM Number Concentration	#/cm^3	1.4E5 ± 1.2E4	1.3E5 ± 2.5E4	3.3E5 ± 3.7E4
Carbon Monoxide (CO)	ppm	NM	40.1 ± 0.156	33.5 ± 0.165
Oxygen (O_2)	%	NM	21.0 ± 0.002	21.0 ± 0.003
Nitrogen Oxide (NO)	ppm	NM	<1	<1
Nitrogen Dioxide (NO_2)	ppm	NM	<1	<1
Sulfur Dioxide (SO_2)	ppm	NM	<1	<1
BC Concentration	µg/m3	0.08 ± 0.02	0.98 ± 0.87	245.19 ± 63.98
BC/PM	ratio			
OC/TC	wt. ratio	0.93 ± 0.04	0.99 ± 0.002	0.4 ± 0.07
EC/TC	wt. ratio	0.079 ± 0.048	0.010 ± 0.002	0.598 ± 0.079

Conventional, Single Stage HH. Figure 4-2 shows the four-hour exposure profile for Conventional, Single Stage HH on the third day of exposure. The PM concentrations as measured by TEOM ranged between 1.4 and 3.1 mg m^{-3} with the CO levels kept below 50 ppm. Virtually no PM was detected by the TEOM in the filtered wood smoke. Table 4-1 shows the mean values for exposure conditions for all three days. The average mass by filter was 2.612 mg m^{-3} while the TEOM values were 1.84 mg m^{-3}. The mean CO level was 53.6 while other emission gases were negligible. The BC measurement by aethalometry was 46.88 µg m^{-3} in the whole smoke and 0.35 µg m^{-3} in the filtered chamber. Finally, the OC/TC ratio was 0.93 in the whole smoke with the corollary EC/TC ratio being 0.07. Figure 4-3 shows the particle number count to be approximately 4x10^5/cc with the size distribution of the whole smoke to be approximately 110 nm with far fewer particles being detected in the filtered chamber or in the clean air controls.

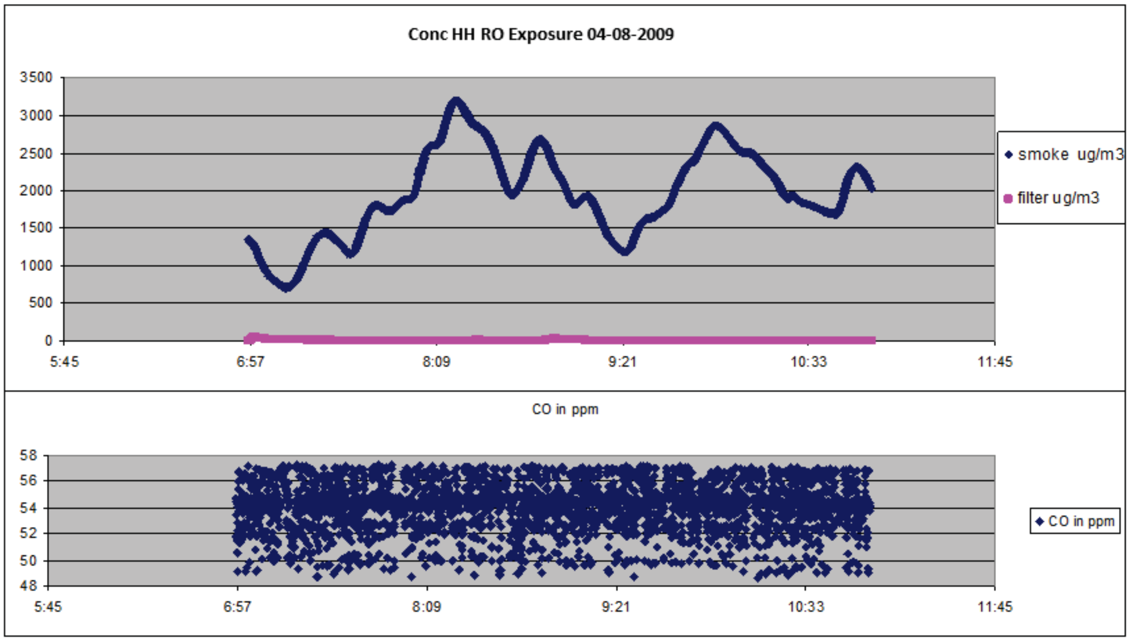


Figure 4-2. Exposure Profile of Day 3 of Conventional, Single Stage HH. Top Panel is Concentration of PM by TEOM in Filtered and Non-Filtered Chamber. Bottom Panel Shows CO Concentrations.

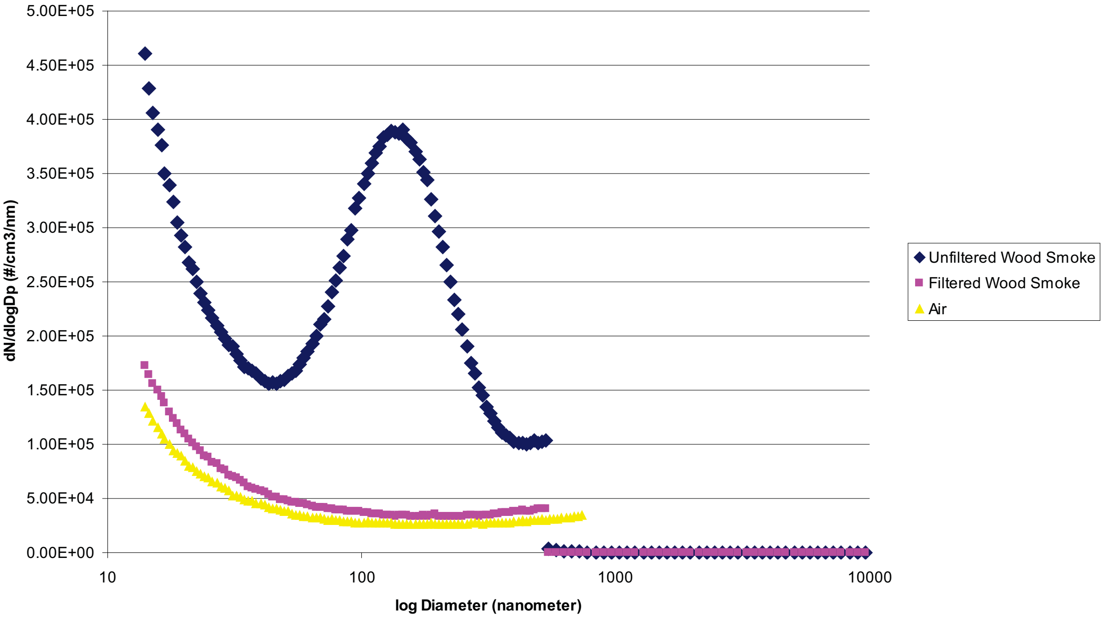


Figure 4-3. Particle Size of Day 3 of Conventional, Single Stage HH in Air, Filtered and Non-Filtered Chamber.

To evaluate the effect of wood smoke exposures for one and three days, the cellular profile of BAL fluid at 0-hour, 4-hours, and 24-hours post-exposure was assessed. There were virtually no statistically significant differences between the whole or filtered wood smoke compared to the air-exposed animals for either the one- or three-day exposure period or for any of the assessed time points except for the results stated below. Immediately following the third day of exposure, an increase in TNF-α in the lung fluid was detected for both the whole wood smoke and filtered wood smoke samples (p=0.01, Figure 4-4). In addition, animals assessed at this time point also had increased levels of creatine kinase in the blood compared to air controls (Figure 4-5). No other differences were noted in either the hematology or blood serum measurements (Appendix 1d-e). There were no differences in pulmonary responsiveness to methacholine aerosol in any of the groups or time points (data not shown).

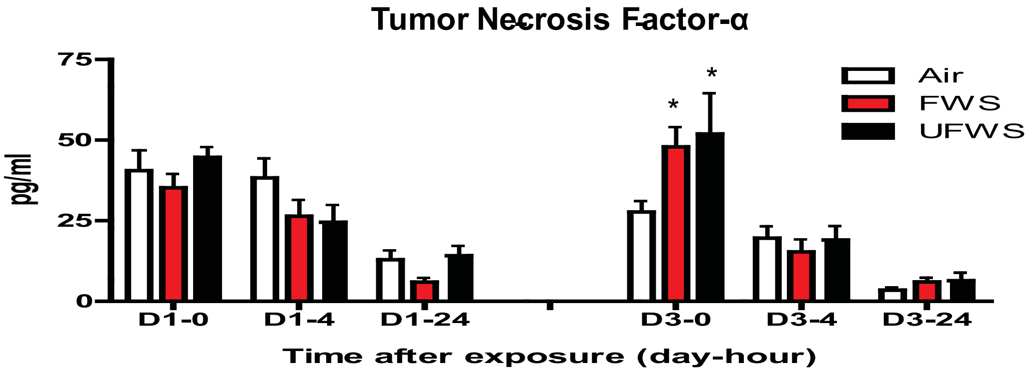


Figure 4-4. TNF-α Levels in BAL Fluid of Mice Exposed to Clean Air, Whole or Filtered Wood Smoke for One or Three Days. N=6 per Time Point (0-hour, 4-hours, and 24-hours), *Indicates Significance Over Air Controls.

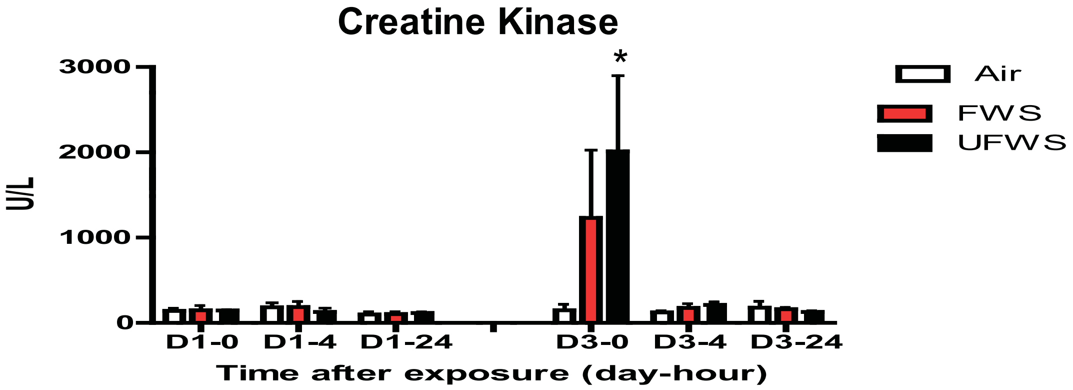


Figure 4-5. Creatine Kinase Levels in Serum of Mice Exposed to Clean Air, Whole or Filtered Wood Smoke for One or Three Days. N=6 per Time Point, (0-hour, 4-hours, and 24-hours), *Indicates Significance Over Air Controls.

Three Stage HH. Figure 4-6 shows the four-hour exposure profile for Three Stage HH on the third day of exposure. The PM concentrations as measured by TEOM ranged between 0.5 and 1.5 mg m^{-3} with the CO levels largely kept below 50 ppm. Virtually no PM was detected by the TEOM in the filtered wood smoke. Table 4-2 shows the mean values for exposure conditions for all three days. The average mass by filter was 0.86 mg m^{-3} while the TEOM values were 0.84 mg m^{-3}. The mean CO level was 42.3 while other emission gases were negligible. The BC measurement by aethalometry was 48 µg m^{-3} in the whole smoke and 0.11 µg m^{-3} in the filtered chamber although only one measurement was obtained for this latter result. Finally the OC/TC ratio was 0.94 in the whole smoke with the corollary EC/TC ratio being 0.06. Figure 4-7 shows the particle number count to be approximately $2x10^5$/cc with the size distribution of the whole smoke to be approximately 110 nm with far fewer particles being detected in the filtered chamber or the clean air controls.

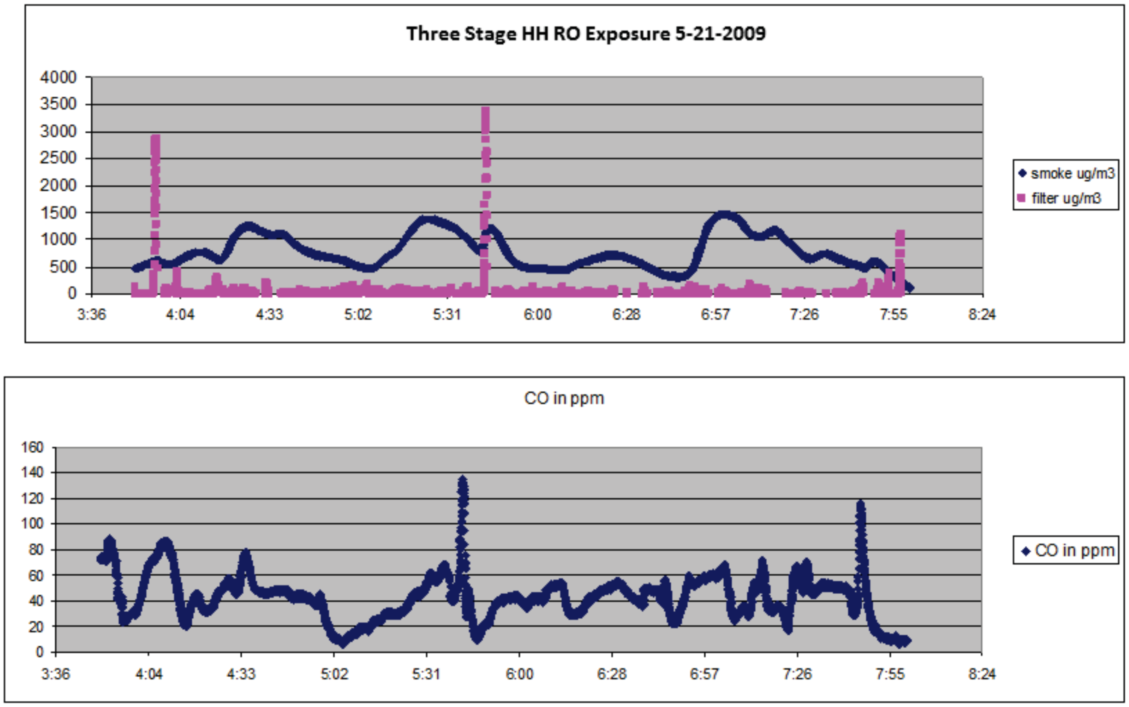


Figure 4-6. Exposure Profile of Day Three of Three Stage HH. Top Panel is Concentration of PM by TEOM in Filtered and Non-Filtered Chamber. Bottom Panel is CO Concentrations.

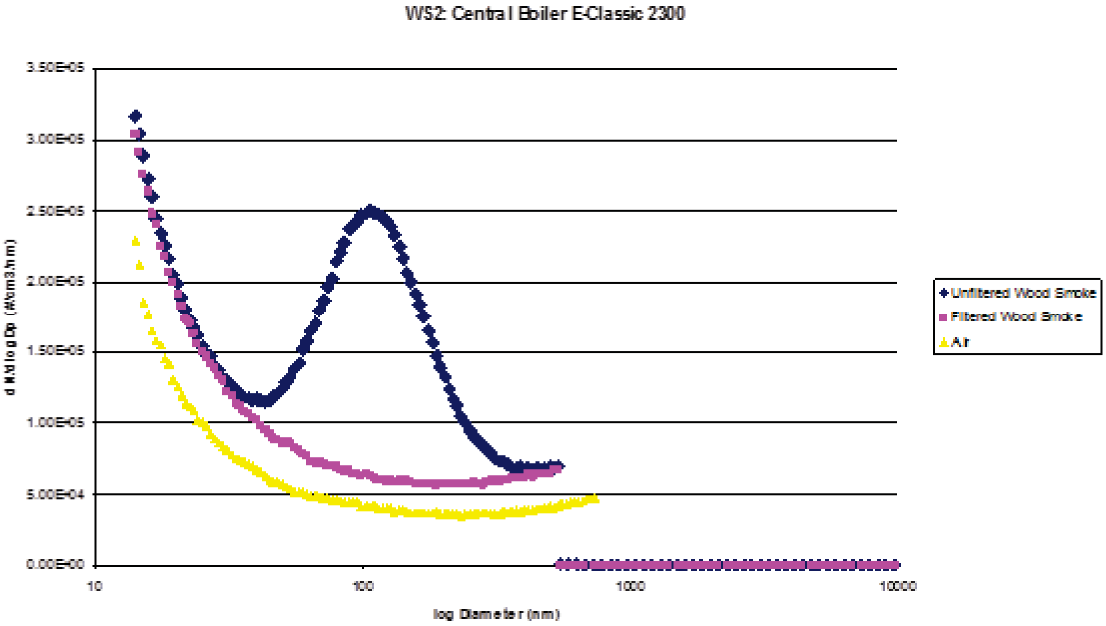


Figure 4-7. Particle Size of Day 3 of Three Stage HH in Air, Filtered and Non-Filtered Chamber.

To evaluate the effect of wood smoke exposures for one and three days, the cellular profile of BAL fluid at 0-hours, 4-hours, and 24-hours post-exposure was assessed. Mice exposed to the whole or filtered wood smoke produced in the Three Stage HH had no statistically significant differences in lung cell populations, lung biochemistry or cytokines (Appendix 2a-c) between either the whole or filtered wood smoke compared to the air-exposed animals for either the one- or three-day exposure period or for any of the assessed time points except for results stated below. Twenty-four hours after the third day of exposure, lung fluid levels of ferritin were increased in both the whole smoke and filtered smoke compared to air controls (Figure 4-8). In addition, animals assessed four hours after one or three filtered wood smoke exposures had slight non-significant increases in creatine kinase in the blood compared to air controls (Figure 4-9). Because of clotting issues, hematology data were not available for this study and no other differences were noted in the blood serum measurements (Appendix 2d). There were no differences in pulmonary responsiveness to methacholine aerosol in any of the groups or time points (data not shown).

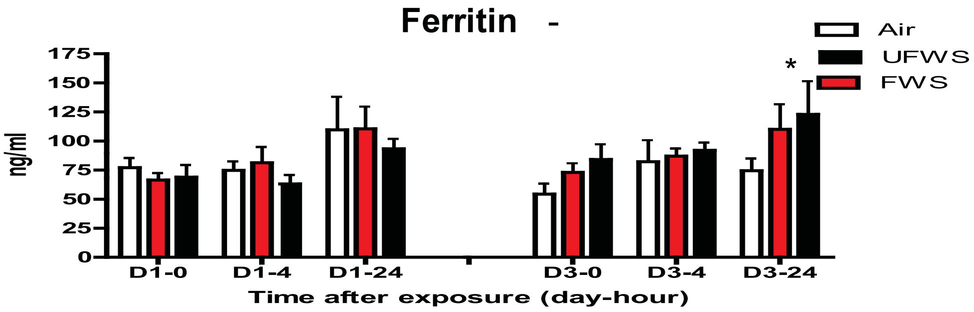


Figure 4-8. Ferritin Levels in BAL Fluid of Mice Exposed to Clean Air, Whole or Filtered Wood Smoke for One or Three Days. N=6 per Time Point (0-hours, 4-hours, and 24-hours), *Indicates Significance Over Air Controls.

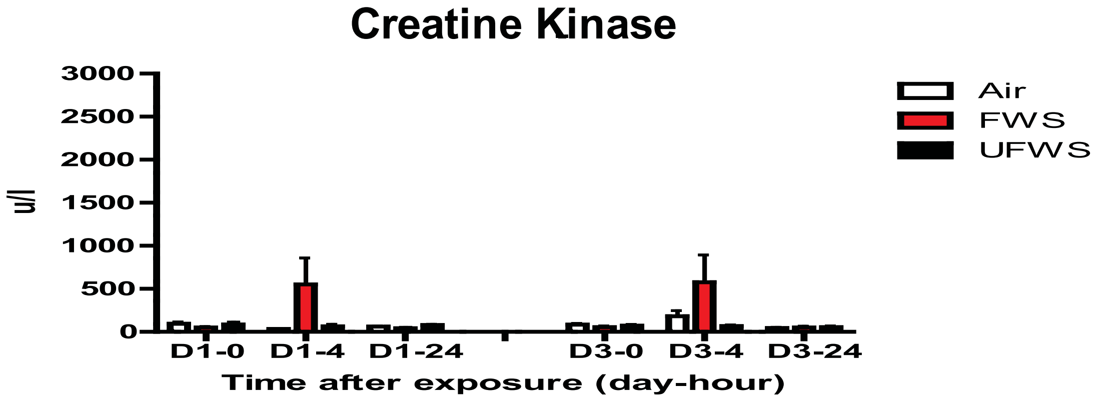


Figure 4-9. Creatine Kinase Levels in Serum of Mice Exposed to Clean Air, Whole or Filtered Wood Smoke for One or Three Days. N=6 per Time Point (0-hour, 4-hours, and 24-hours). *Indicates Significance Over Air Controls.

European Two Stage Pellet Burner Heater. Figure 4-10 shows the four-hour exposure profile for the European Two Stage Pellet Burner heater on the third day of exposure. The PM concentrations as measured by TEOM ranged between 0.2 and 2.0 mg m^{-3} with the CO levels largely kept below 50 ppm. Virtually no PM was detected by the TEOM in the filtered wood smoke. Table 4-3 shows the mean values for exposure conditions for all three days. The average mass by filter was 0.96 mg m^{-3} while the TEOM values were 0.42 mg m^{-3}. The mean CO level was 33.5 while other emission gases were negligible. The BC measurement by aethalometry was 245µg m^{-3} in the whole smoke, and 0.98 µg m^{-3} in the filtered chamber. Finally, the OC/TC ratio was 0.4 in the whole smoke with the corollary EC/TC ratio being 0.6, in contrast to the filtered wood smoke and air controls which had OC/TC ratios of 0.99 and 0.93, respectively, and the corollary EC/TC ratio of 0.08 and 0.01, respectively. Figure 4-11 shows the particle number count to be approximately $4x10^5$/cc with the size distribution of the whole smoke to be approximately 110 nm with far fewer particles being detected in the filtered chamber or the clean air controls.

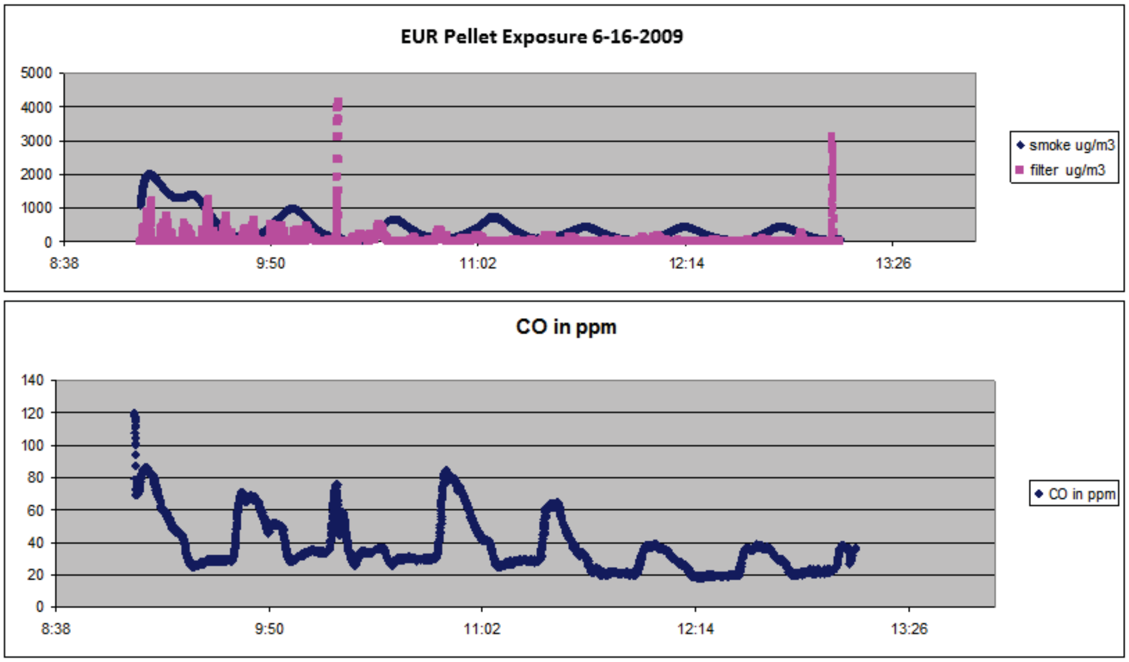


Figure 4-10. Exposure Profile of Day 3 of the European Two Stage Pellet Burner Heater. Top Panel is Concentration of PM by TEOM in Filtered and Non-Filtered Chamber. Bottom panel shows CO concentrations.

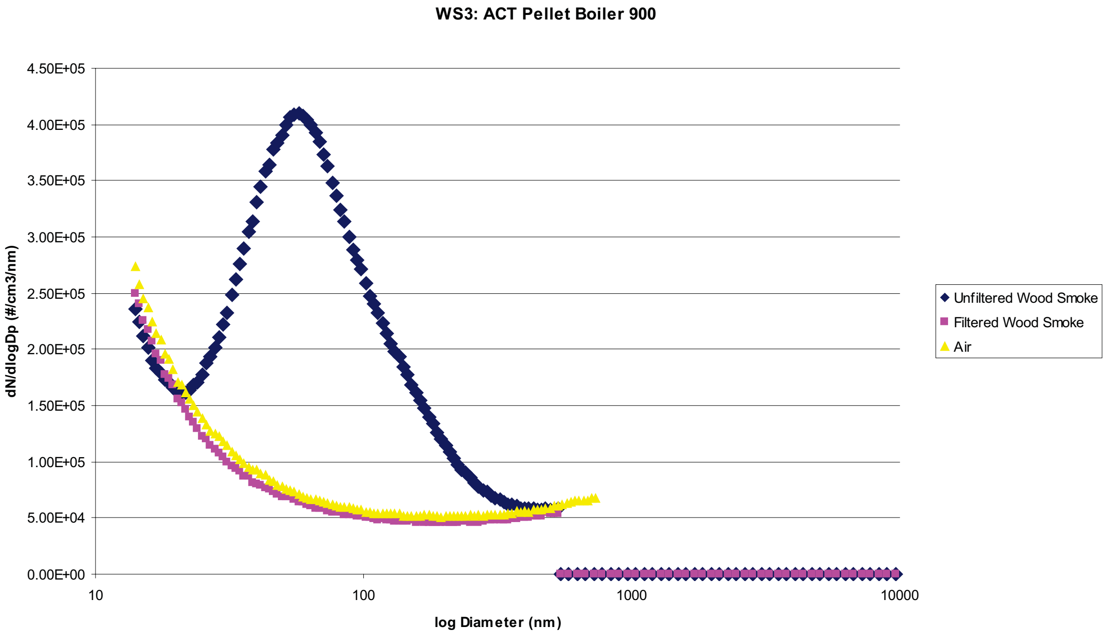


Figure 4-11. Particle Size of Day 3 of European Two Stage Pellet Burner Heater in Air, Filtered and Non-Filtered Chamber.

To evaluate the effect of wood smoke exposures for one and three days, the cellular profile of BAL fluid at 0-hours, 4-hours, and 24-hours post-exposure was assessed. Mice exposed to the whole or filtered wood smoke produced in the European Two Stage Pellet Burner had an increased number of alveolar macrophages in the lung washes 24 hours after the third exposure to either whole or filtered wood smoke (Figure 4-12). This finding was significant, however, only with the unfiltered wood smoke at the 1-day exposure and with the filtered emission of the three-day exposure. No other differences in cell type lung biochemistry or cytokine levels were noted (Appendix 3a-c). As in the last experiment, clotting issues affected the ability to obtain reliable hematology results. In the serum, however, some non-significant increases in lactate dehydrogenase isoenzymes (LD-1) were noted 24 hours after one or three exposures to the filtered wood smoke (Figure 4-13). No other parameters were notably different (Appendix 3d). There were no differences in pulmonary responsiveness to methacholine aerosol in any of the groups or time points (data not shown).

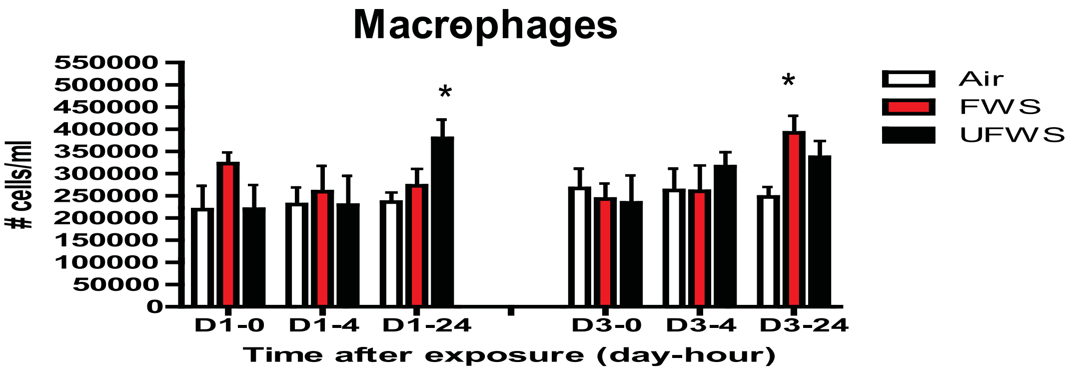


Figure 4-12. Number of Alveolar Macrophages in the BAL Fluid of Mice Exposed to Clean Air, Whole or Filtered Wood Smoke for One or Three Days. N=6 per Time Point, (0-hour, 4-hours, and 24-hours). *Indicates Significance Over Air Controls.

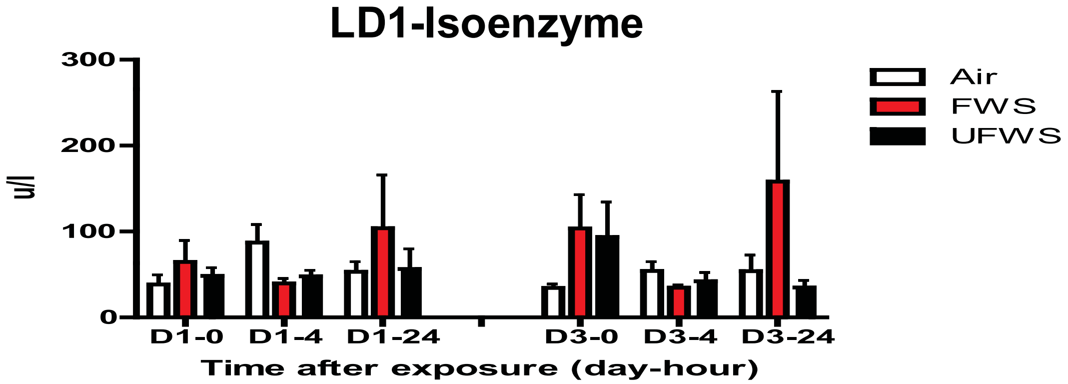


Figure 4-13. Lactate Dehydrogenase Isoenzymes Levels in Serum of Mice Exposed to Clean Air, Whole or Filtered Wood Smoke for One or Three Days. N=6 per Time Point. (0-hour, 4-hours, and 24-hours).

4.4 DISCUSSION

Wood-burning stoves, fireplaces, as well as wildland and agricultural fires, emit significant amounts of health-damaging pollutants, including complex particulates, carbon monoxide and oxides of nitrogen (Naeher et al., 2007). The purpose of this study was to provide pilot toxicological data on emissions from three distinct wood burning HHs whose performance was being tested as part of a larger cooperative agreement between NYSERDA and EPA. For the first two heaters, the same fuel could be used to provide a direct comparison. For the third (pellet) heater, however, the fuel was necessarily different and therefore would not provide any comparison other than the comparison achieved by maintaining a similar airborne particle concentration. A target average particle concentration of 2 mg m^{-3} was established for all three heaters with the caveat that CO would not rise over the OSHA-permissible level of 50 ppm for an 8-hour work day. Early testing showed that during normal operation the automated opening and closing of the air supply dampers resulted in massive cyclic excursions in PM and noxious gases that exceeded toxic levels. The decision was therefore made to conduct inhalation tests on the more stable post-test smoldering emissions where the damper would not open and close. In addition to examining systemic and pulmonary changes in mice immediately and four and 24 hours after a single exposure or three daily exposures, the exposure emissions were also filtered to determine whether any health effects were caused by the gas phase components of the wood smoke.

In terms of a fuel comparison, the red oak emitted more OC than EC. The wood pellets produced a more even distribution of OC/EC. Changing from the Conventional, Single Stage HH to the Three Stage HH did not change the ratio of EC to TC under smoldering combustion conditions. No direct comparisons could be made between the first unit and the other two units because the target concentration of 2 mg m^{-3} was achieved only in the first test. Exposure to both the whole emissions and the filtered atmosphere from the first test resulted in elevated TNF-α levels in the BAL fluid immediately following the third inhalation exposure. These exposure conditions also increased levels of creatine kinase in the serum. The data show that moderate exposures to filtered or whole wood smoke under the specific conditions of this study for one- or three-day periods did not result in any consistent overt pulmonary or systemic toxic effects. Increases in pulmonary TNF-α, neutrophils and a systemic indicator such as creatine kinase do, however, suggest that under some circumstances these exposures can cause inflammation, immune signaling and systemic toxicity in a fashion similar to, for example, cigarette smoke, although comparisons need to made based on duration and extent of exposure.

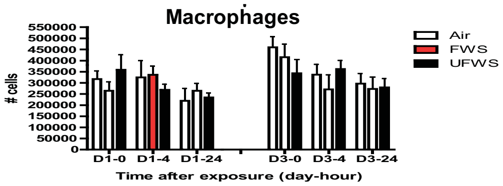
Comparisons could be made between exposure to emissions from the second and third heaters because the particle concentration was approximately the same (0.86 versus 0.96 mg m^{-3} for Three Stage HH and European Two Stage Pellet Burner heater, respectively). In these studies, however, only ferritin levels were seen to increase in Three Stage HH while the total number of alveolar macrophages was increased with the pellet heater exposure responses to an inhaled pollutant and are not regarded as being adverse. Again, the effects seemed to occur for both the unfiltered and filtered emissions, suggesting these effects were elicited primarily by the gas phase components. Taken together, the data show that moderate exposures to filtered or whole wood smoke for one- or three-day periods did not result in any overt pulmonary or systemic toxic effects and are in line with other studies that report only modest effects with even higher exposure concentrations (reviewed in Naeher et al., 2007). The direct comparison of the heaters was thwarted to some extent by achieving the target concentration only in the first HH that was tested. Furthermore, testing of the actual dynamic conditions during normal operation of the heaters was not performed because of the possibility of created cyclic asphyxiating conditions that would have overcome any meaningful assessment of particle-based toxicity.

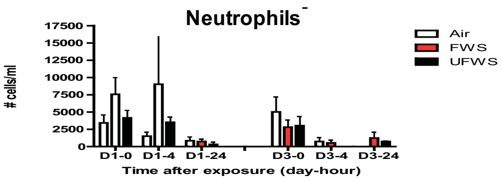
4.5 SUMMARY

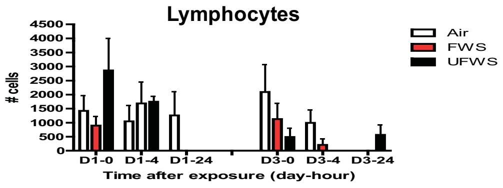
The goal of this study was to conduct a health assessment of emissions from three different wood-fired HHs and to determine if one unit was better or worse than another. Adult CD-1 mice were exposed to filtered air, filtered wood smoke or unfiltered wood smoke for four hours per day for one or three consecutive days, then pulmonary and systemic biomarkers of injury and inflammation were assessed. Three different wood-fired HHs were used to investigate chemical properties and toxicities of wood smoke: a popular, conventional model (Conventional, Single Stage HH); a newer generation model with multiple stages (Three Stage HH), and an imported pellet system (European Two Stage Pellet Burner) heater. Seasoned red oak was used for all of the units except for the pellet heater which used hardwood pellets. Initial studies showed that normal functioning of the heaters resulted in large swings in concentrations and thus the decision was made to perform inhalation studies at the end (smoldering phase) of a test cycle in order to control the exposure concentrations. A target concentration of 2 mg m^{-3} was achieved for the Conventional, Single Stage HH but only ~1 mg m^{-3} could be achieved for the Three Stage HH and European Two Stage Pellet Burner under similar carbon monoxide (CO) constraints (maximum of 50 ppm). The red oak emitted more OC than EC compared to the wood pellet heater that emitted comparable levels of EC and OC, and changing from the Conventional, Single Stage HH to Three Stage HH did not change the ratio of EC to total carbon (TC) at smoldering combustion conditions. In the Conventional, Single Stage HH study, three days of exposure to either the filtered or whole wood smoke caused statistically significant increases in tumor necrosis factor (TNF)-α in lung fluid and creatine kinase in serum. In the second study on the Three Stage HH, the only notable change was increased ferritin in the lung after a three-day exposure to whole or filtered wood smoke and smaller non-significant increases in creatine kinase in the filtered-only group. The European Two Stage Pellet Burner study utilizing the pellet heater resulted in higher numbers of macrophages in the lung 24 hours after a one- and three-day exposure. The results show that none of the exposures caused acute lung injury but some were associated with small and inconsistent increases in inflammatory signaling pathways (cells with one exposure, TNF-α in another, no change in a third) in the lung and enzyme concentrations in the blood. Nevertheless, the overall emission toxicity results from animal exposure experiments were inconclusive, as extreme dilution of the combustion gas was necessary to avoid immediate acute toxic effects from the carbon monoxide that at times exceeded 10,000 ppm.

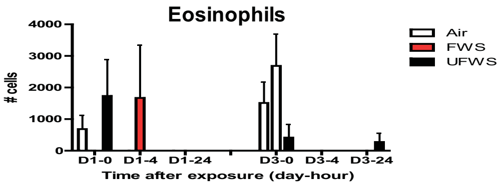
4.6 SECTION 4 APPENDICES

4.6.1 Appendix 1a: Conventional, Single Stage HH Cells in Bronchoalveolar Lavage Fluid

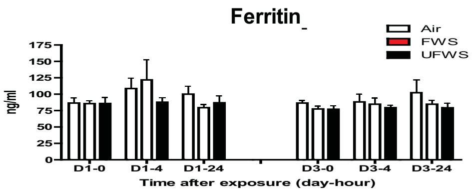


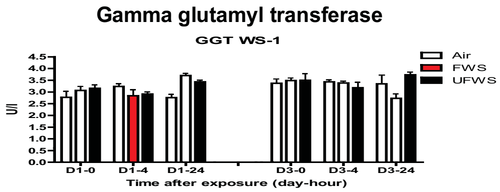


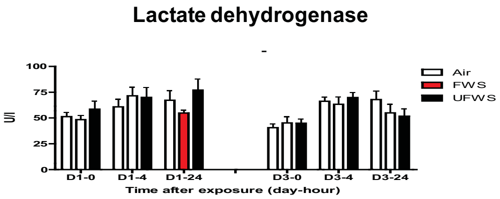


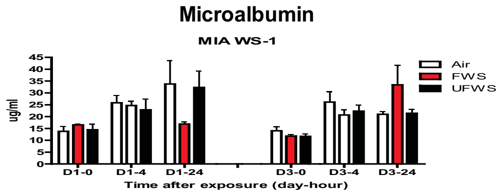


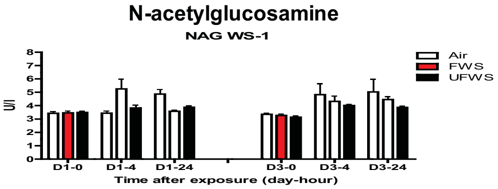
4.6.2 Appendix 1b. Conventional, Single Stage HH BAL Biochemistry

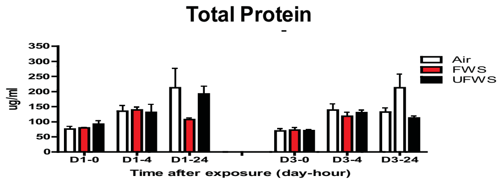

Ferritin


Gamma glutamyl transferase

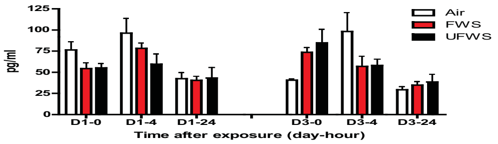

Lactate dehydrogenase

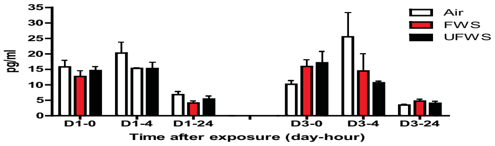

Microalbumin


N-acetylglucosamine


Total Protein

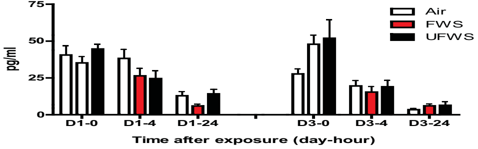
4.6.3 Appendix 1c: Conventional, Single Stage HH BAL Cytokines


Interleukin-6


Macrophage inflammatory protein-2

Interleukin-1β

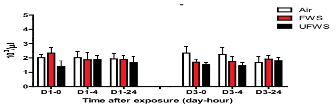
N < 4


Tumor Necrosis Factor-α

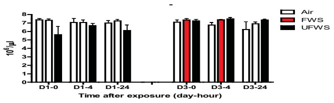
(Circled figure also expanded upon in text.)

4.6.4 Appendix 1d: Conventional, Single Stage HH Whole Blood

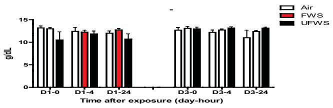
White Blood Cells



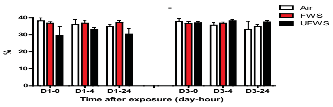
Red Blood Cells



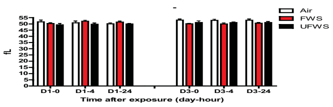
Hemoglobin



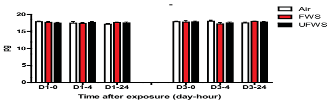
Hematocrit



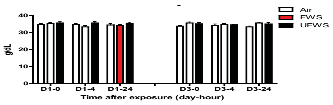
Mean corpuscular volume



Mean corpuscular hemoglobin



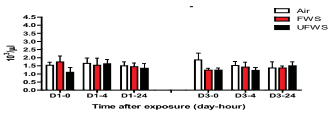
Mean corpuscular hemoglobin concentration



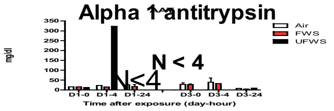
Platelet

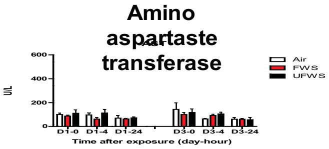
N < 4

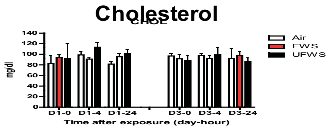
Lymphocytes

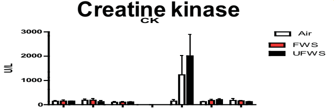


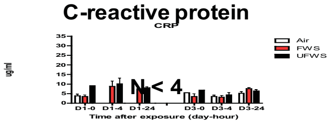
4.6.5 Appendix 1e: Conventional, Single Stage HH Blood Serum

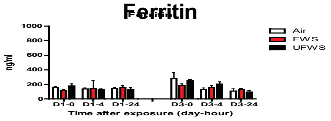


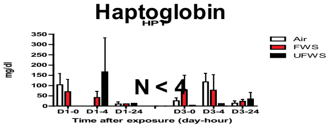


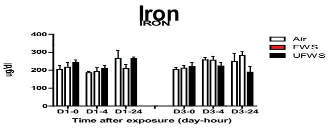


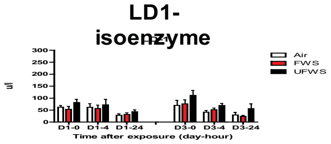


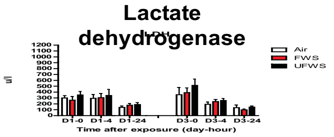


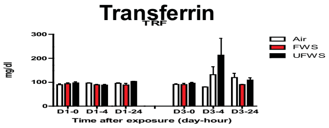


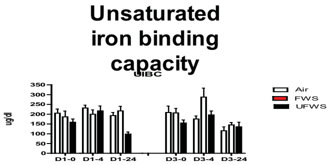












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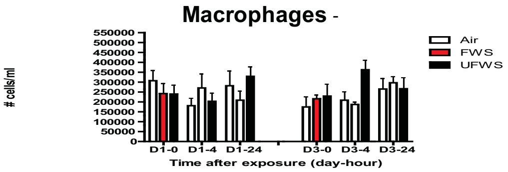
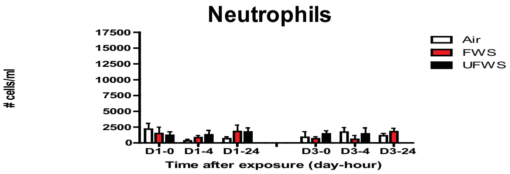
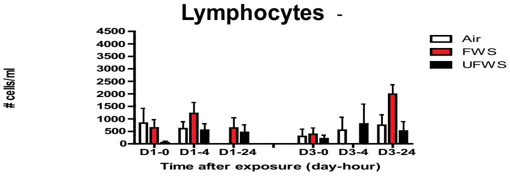
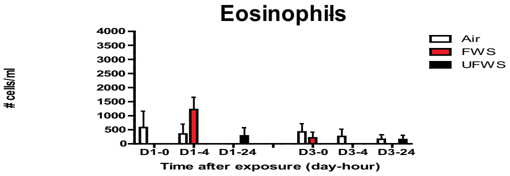
4.6.6 Appendix 2a: Three Stage HH Cells in Chronchoalveolar Lavage Fluid

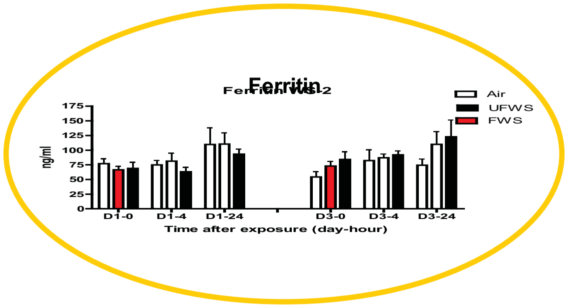


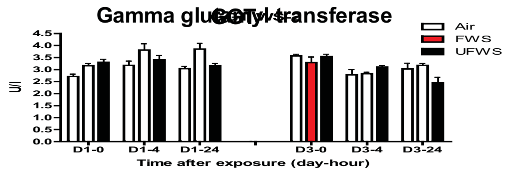


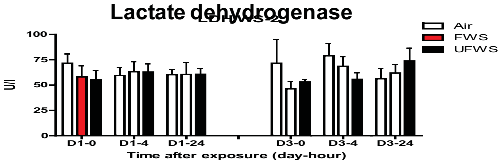


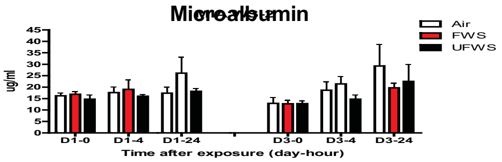


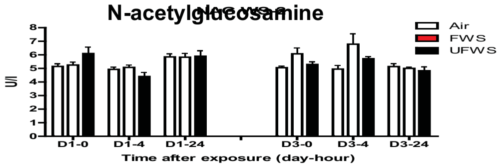
4.6.7 Appendix 2b: Three Stage HH BAL Biochemistry

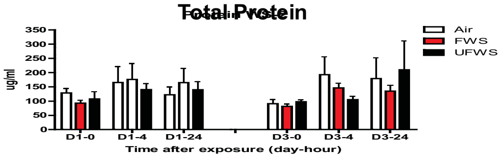












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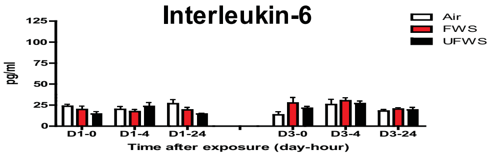
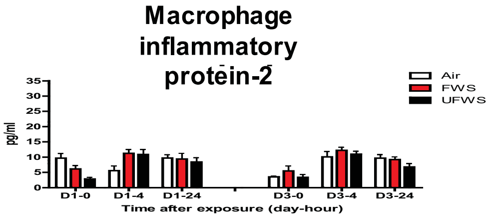
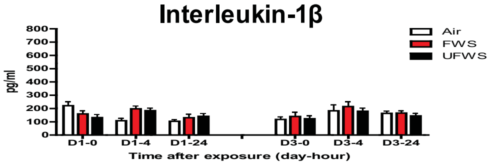
4.6.8 Appendix 2c: Three Stage HH BAL Cytokines


Interleukin-6


Macrophage inflammatory protein-2


Interleukin-1β

Tumor Necrosis Factor-α

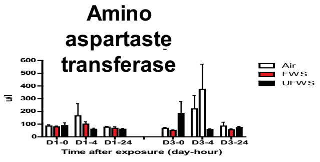
N < 4

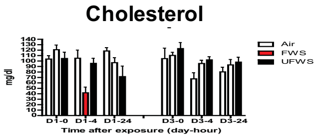
4.6.9 Appendix 2d: Three Stage HH Blood Serum

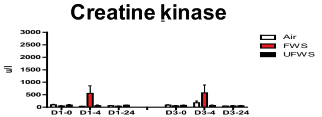
Alpha 1 antitrypsin

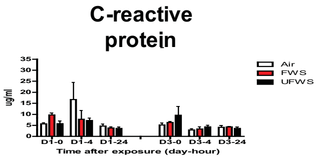
N < 4

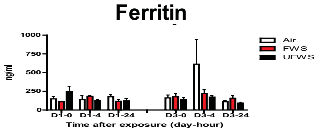
me a er ex ure a -


Amino aspartaste transferase


Cholesterol

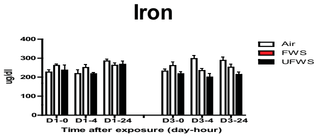

Creatine kinase

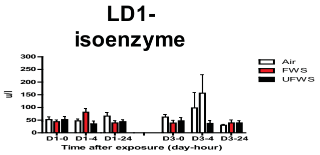

C-reactive protein

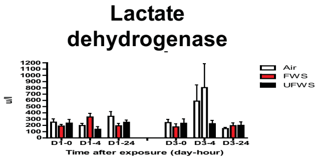

Ferritin

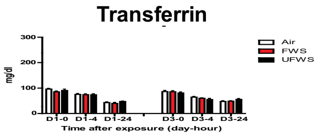
Haptoglobin

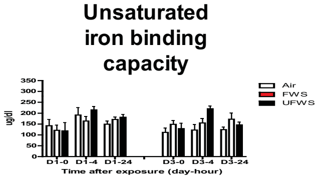
N < 4


Iron


LD1-isoenzyme


Lactate dehydrogenase


Transferrin


Unsaturated iron binding capacity

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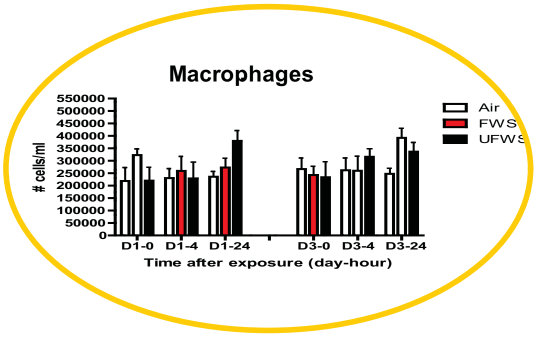
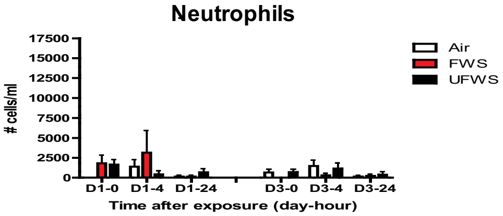
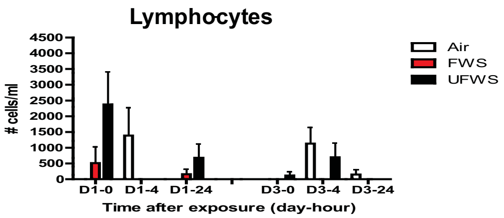
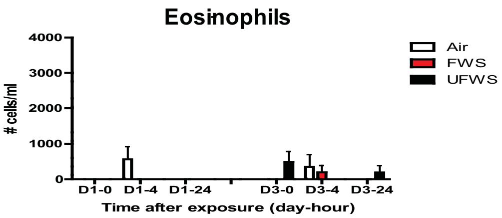
4.6.10 Appendix 3a: European Two Stage Pellet Burner Cells in Bronchoalveolar Lavage Fluid









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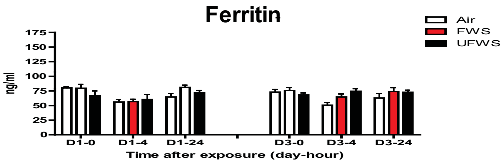
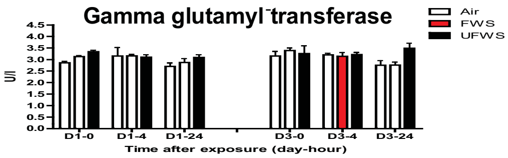
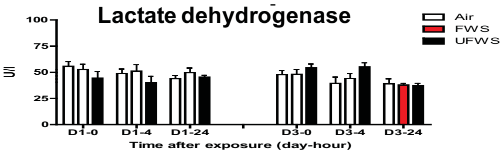
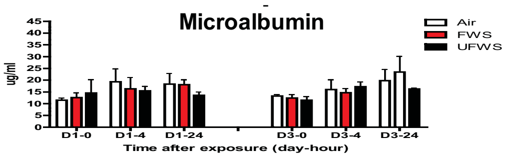
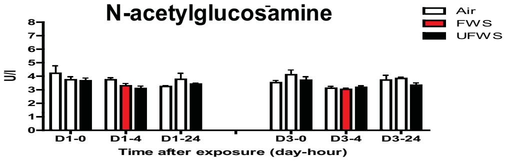
4.6.11 Appendix 3b: European Two Stage Pellet Burner Heater BAL Biochemistry





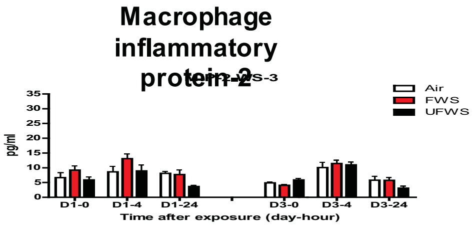


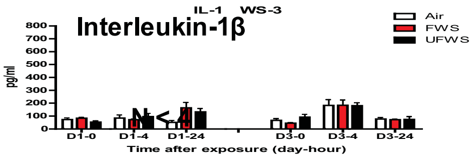


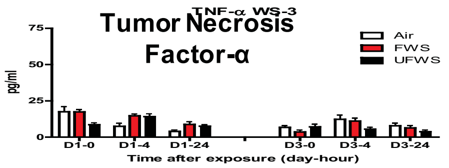


4.6.12 Appendix 3c: European Two Stage Pellet Burner Heater BAL Cytokines

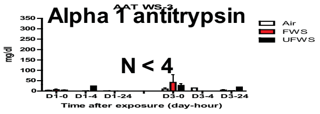

Interleukin-6

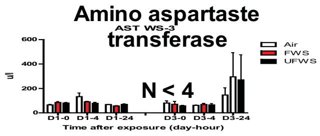

Macrophage inflammatory protein-2

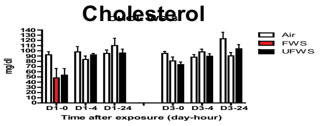

Interleukin-1β

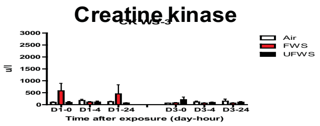

Tumor Necrosis Factor-α

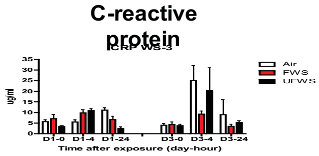
4.6.13 Appendix 3d: European Two Stage Pellet Burner Heater Blood Serum

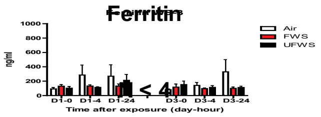


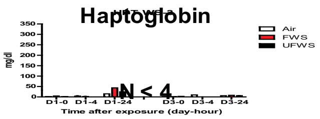


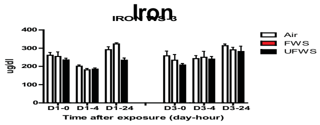


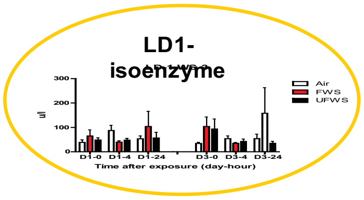


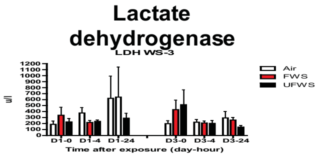


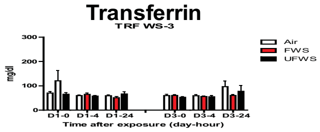


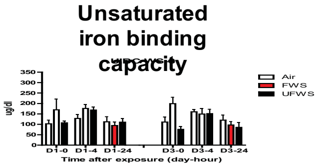












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5. MARKET ALLOCATION (MARKAL) ENERGY SYSTEMS MODELING OF ALTERNATIVE HH MARKET PENETRATION SCENARIOS

5.1 INTRODUCTION

The companion chapter, *"An Engineering Economic Assessment of HHs in the State of New York"*, provides an engineering-economic assessment of outdoor wood HHs as well as higher efficiency indoor wood/pellet boilers and gasifiers. The sensitivity analyses highlight trade-offs and breakeven points under a number of different market considerations, but also emphasize the number of non-economic factors that may drive decisions to purchase and use HHs. The purpose of this current chapter is to: (a) identify possible future scenarios for the penetration of HHs and other advanced wood heating systems, (b) place those scenarios in the context of total residential demand for space heating and total residential energy demand, and (c) determine the aggregate emissions implications of those scenarios between 2010 and 2030. This analysis derives energy and emissions scenarios from an aggregate perspective, both in terms of the geographic scale (e.g., the Mid-Atlantic Region including the States of New York, New Jersey and Pennsylvania), and total residential end-use energy demand. Analyzing HHs from this broader energy systems perspective can provide insights regarding the impacts of fuel displacement (for space heating and, to a more limited extent, for water heating), fuel wood demand and supply, technology improvements, and technology turnover (natural and policy-induced) over the modeling time horizon.

5.1.1 MARKAL Modeling of Energy Systems

The modeling framework used for this analysis is the MARKet ALlocation (MARKAL) energy systems model.[2] MARKAL is a widely-used optimization modeling framework (Loulou et al., 2004) that can be applied to energy systems on different geographic scales (global, national, regional, or metropolitan) to look at broad energy system trends or analyze the role of particular energy technology sectors (Johnson et

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[2] The MARKAL model generator is maintained by and available free of charge from the Energy Technology Systems Analysis Program (ETSAP), an international consortium (see http://www.iea-etsap.org/web/Markal.asp). Still, the licenses for the modeling language (e.g. GAMS) and solvers (e.g. CPLEX) must be purchased. As discussed later, the database of input parameters that is used with the MARKAL modeling platform for this analysis has been developed by the U.S. EPA’s Office of Research and Development and is available free of charge.

al., 2006; DeCarolis et al., 2007; Yeh et al., 2008).[3] Users of MARKAL supply the databases that describe the energy system of interest. Required modeling inputs include energy resource supplies (e.g., crude oil, coal, natural gas, biomass, solar, wind, and uranium), demand for end-use energy services (e.g., petajoules (PJ) of space heating, lumens of lighting, vehicle miles traveled, etc.), and characterization of the cost and performance of the technologies that convert primary energy resources into usable forms of energy (e.g., heating oil, gasoline, electricity). Taking these inputs, MARKAL solves for the least-cost system-wide solution for the full energy system. In other words, given the primary energy resources and the portfolio of existing and possible future energy technologies, MARKAL finds the optimal technology and fuel mix to meet end-use energy demands.

The EPA's Office of Research and Development has developed two MARKAL databases of the U.S. energy system: the EPA U.S. National Model (EPAUSNM) and the EPA U.S. 9-region Model (EPAUS9r) (Shay et al., 2006; Shay and Loughlin, 2008). For this analysis, the EPAUS9r MARKAL database was used to capture regional differences in fuel, biomass and electricity prices; technology performance, availability and existing capacity; and differences in end-use demand for energy services. Both databases have undergone external peer review and are publicly available via the EPA's online portal.[4] The regions in the EPAUS9r model correspond to the U.S. Census Divisions, shown in Figure 5-1. For this analysis, the region of interest is the Middle-Atlantic Census Division, which includes the States of New York, New Jersey, and Pennsylvania. All results will be presented for the Middle-Atlantic region, unless otherwise specified.

5.1.2 Overview of Scenario Approach

Because MARKAL solves in an optimization framework, the results cannot be considered projections or forecasts of future technology penetrations. Instead, the results show the optimal cost solution for the entire energy system given the resources, demands, and technologies that are provided. When choosing the mix of technologies, the model will move aggressively toward the most efficient technologies and will not reflect many of the other consumer preferences and perceptions that come into play when actual purchasing decisions are made.

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[3] Loulou et al. (2004) provide general documentation of the MARKAL model. Some sector-specific MARKAL applications include the electric sector (Johnson et al., 2006), nuclear power (DeCarolis, 2007) and light duty vehicles (Yeh et al., 2008).

[4] Contact lenox.carol@epa.gov for instructions on accessing EPA's Environmental Science Connector project for the MARKAL databases.

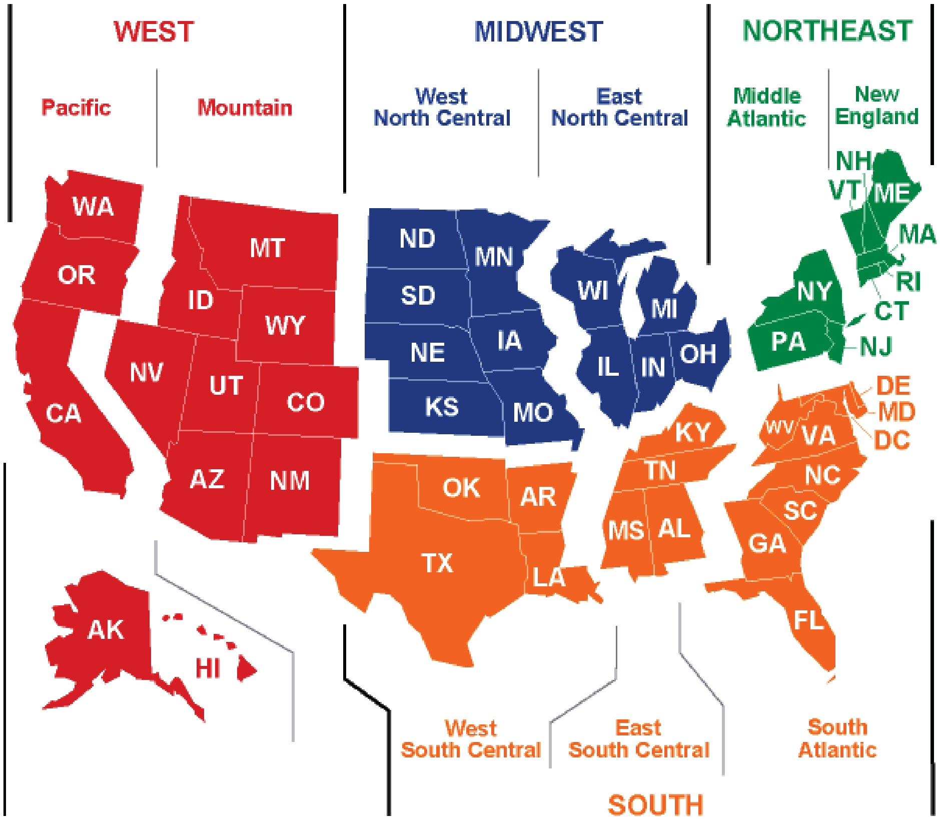

Figure 5-1. Map of U.S. Census Divisions (U.S. Energy Information Administration [EIA] 2000).

For this analysis, as will be shown in more detail below, the low efficiencies and relatively high capital costs of some of the wood heat technologies meant that many of the technologies of interest, in particular, the HHs, would not enter the market under the optimal MARKAL model solution, even when provided with a “free” supply of fuel wood. Given free wood supplies, the model would still choose other wood heating units, such as wood stoves, over the HHs. Therefore, in order to explore a broader range of possible futures for the penetration of a range of wood heat technology types, it was necessary to construct scenarios that force specific mixes of technology into the model. These forced scenarios were done in order to (a) assess how to displace other technologies and fuels for space heating and hot water, and (b) assess how to determine the net emissions impacts.

Having briefly discussed the MARKAL modeling framework, we will first review in more detail the data in the EPAUS9r base model and then discuss specific modifications and updates done for this current analysis. We will then show the results of a set of scenarios.

5.2 DATA

The EPAUS9r database was used as a basis for this analysis (Shay and Loughlin, 2008). Several modifications were made to represent a broader range of existing and new wood heat technologies, as a well as a more detailed representation of the regional fuel wood and pellet resources. The following section will describe the relevant EPAUS9r data and modifications, including: residential energy demand, space heating technology characteristics, wood/pellet resources, emission factors, and constraints that were created to model different wood heat scenarios.

5.2.1 Residential Energy Demand and Base Year Fuel Shares

Residential energy end-use demand encompasses a range of different energy services, including space heating and cooling, water heating, lighting, refrigeration and freezing, and miscellaneous electric power devices. Table 5-1 highlights a number of trends in residential energy demand for the Mid-Atlantic (the States of New York, New Jersey and Pennsylvania) region. These trends in residential space heating and cooling energy demands are based on data from the U.S. Energy Information Administration's (EIA) 2008 Annual Energy Outlook (AEO) (EIA, 2008), using the National Energy Modeling Systems (NEMS). Residential space heating, the largest energy end-use demand in this region, shows a decrease of 6% between 2005 and 2030, reflecting improvements in insulation and building shells over time, as projected by the EIA's 2008 AEO (AEO08) (EIA, 2008). In contrast, the space cooling demand, albeit lower than the heating demand, shows an increase of 30% over the same time period. The growth in demand for air conditioning outpaces the increase in both regional population and number of households, because the market for air conditioners is not yet saturated (i.e., not all households that "need" air conditioning actually have air conditioning). In contrast, the market for space heating is generally saturated for existing homes, with new purchases being driven by replacement of older units or installation of units in new construction.

Table 5-1. Trends in Residential End-Use Energy Demand (Mid-Atlantic).

Demand	Unit	2005	2030	2005-2030 Difference	
Space Heating	PJ	906	848	-58	-6%
Water Heating	PJ	153	149	-4	-3%
Space Cooling	PJ	189	245	56	30%
Refrigeration	M units	19	21	2	13%
Freezing	M units	5	5	0	1%
Lighting	B lumens	76	94	19	25%
Other Appliances: Electricity	PJ	277	380	103	37%
Other Appliances: Natural gas	PJ	42	43	1	2%

Source: EPAUS9r database. Note that these are aggregate end-use demands for all "energy services," such as heating, cooling, freezing, lighting and do not represent specific technologies. Units are as follow: PJ of heating and cooling provided or direct electricity/natural use, millions of units (M units) for refrigerators and freezers, and billions of lumens (B lumens) of lighting.

Within EPAUS9r, projections of energy end-use demand can be modified to reflect different assumptions regarding population growth and number of new households and assumptions regarding changes in heating and cooling degree days. For these scenarios, U.S. census population projections were used. The heating and cooling degree days that were used to derive space heating and cooling demands are based on data that reflect recent warming trends – ten year (1997-2006) averages in heating and cooling degree days by region. Still, future climate change and warming trends that will continue to reduce the number of heating days and increase the number of cooling days in this region are not reflected in this ten-year average. It is therefore likely that the future space cooling needs are underestimated, and that future space heating needs may decline more than the 6% shown in Table 5-1.

While total regional demand (current and projected) for residential space heating was derived from the 2008 Annual Energy Outlook (AEO08), space heating demand is then allocated to different fuel and equipment combinations, in order to represent the existing stock of residential space heating equipment. This allocation was done based upon the Residential Energy Consumption Survey (RECS) of 2005.[5] As seen in Figure 5-2, wood was identified as a main heating fuel for 300,000 housing units, approximately 2% of homes in the Mid-Atlantic. The 2% share of wood heat in homes is also consistent with New York State-specific data from the American Community Survey (Figure 5-3). Whereas the RECS provides additional detail on the equipment type for other heating fuels (e.g., central warm-air furnace, steam or hot

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[5] All 2005 and other RECS survey year data are provided at www.eia.doe.gov/emeu/recs/

water system, etc.), wood was divided only into wood stoves and “other equipment.” Moreover, for the survey, there were not enough responses for reporting “other equipment” that would include non-stove wood heat technologies such as indoor wood furnaces and HHs. As a result, the RECS allocates all of the 300,000 wood users to wood stoves.

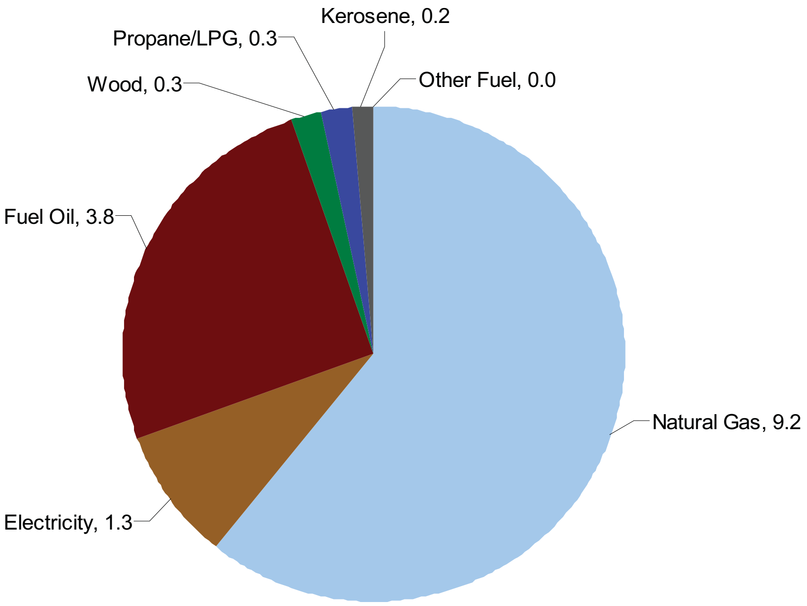

Figure 5-2. Main Heating Fuel for the Mid-Atlantic (Millions of Housing Units).

Source: 2005 Residential Energy Consumption Survey: Preliminary Housing Characteristic Table (HC11.4). http://www.eia.gov/emeu/recs/recs2005/hc2005_tables/hc4spaceheating/pdf/tablehc11.4.pdf

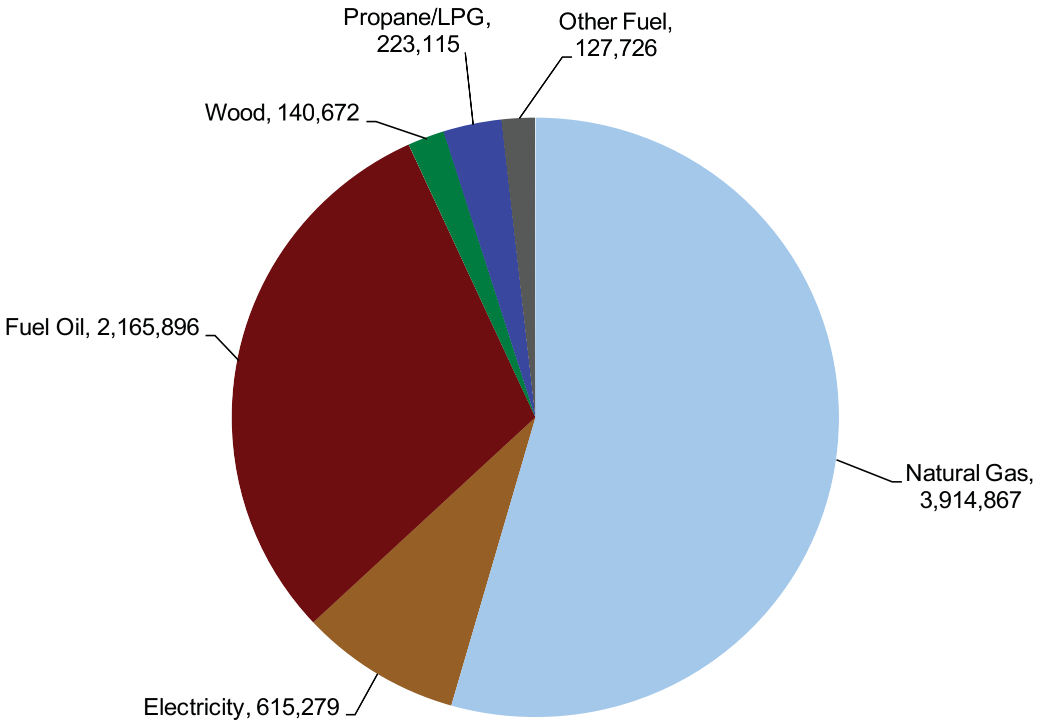

Figure 5-3. Main Heating Fuel for the State of New York (Number of Housing Units).

Source: State of New York (2011) [*http://www.nyserda.org/publications/1995_2009_patterns_trends_rpt.pdf*](http://www.nyserda.org/publications/1995_2009_patterns_trends_rpt.pdf)

Actual numbers on HHs in operation in the states/regions are typically based on sales figures, which rely on data and reporting from the manufacturers and dealers and may represent sales of units in one state for use in another state. As a base assumption, 6% of total wood heat activity in the Mid-Atlantic, or roughly 18,000 households, were assumed to use HHs in 2005. This figure reflects some of the estimates of cumulative sales of HHs in the State of New York of approximately 9,000 units sold through 2005 (Schreiber and Chinery, 2008; Burkhard, 2009a). Another 9,000 units are assumed to be in use in New Jersey and Pennsylvania combined, with the majority of those units used in Pennsylvania. This is on the lower range of estimates for HHs sold since 1990. Estimates for 2006 (NESCAUM, 2006) suggest higher numbers of HHs, with 13,200 in New York, 11,800 in Pennsylvania, and 200 in New Jersey, which would put the Mid-Atlantic total at 25,200. However, given that annual sales for New York State alone were estimated at over 2,000 units per year, the numbers for 2005 could have been 4,000-5,000 below the 2006 estimates. Moreover, some of the units from the reported sales may not have actually been installed and in operation. Nonetheless, the 18,000 estimate is likely to be low, and therefore emissions results presented later may also be lower for the 2005 base year.

5.2.2 Technology characteristics

The EPAUS9r database characterizes the cost and performance of multiple residential space heating technologies, including both existing and future year technologies, within the following technology/fuel categories: radiant (electric, natural gas, heating oil), furnace (natural gas, kerosene, liquid petroleum gas (LPG), heating oil), and heat pump (electric, geothermal, natural gas). Table 5-2 provides the range of costs, efficiencies, start years, lifetime and hurdle rates (which simulates a required pay-back period to recoup equipment/installation cost) for each fuel and technology type combination. The numbers for the fossil fuel units are unmodified from the EPAUS9r database, and are derived from data from the EIA. Although the range of prices, efficiencies and hurdle rates are relatively broad, often these factors compensate for each other. To give an example, a natural gas furnace may have a high capital cost but also have a high efficiency that makes it competitive with the cheaper units. The model may choose optimal solutions in terms of initial capital cost and annual fuel expenditures within each category of fuel. The hurdle rate can play into this calculation as well, with higher hurdle rates providing a relative disincentive to high capital cost units. For simplicity, these are set at 18% for all wood heat for this analysis.

In the case of the wood units, the capital costs generally fell within the range of the costs for the fossil fuel units. The wood unit efficiencies, however, were all at the very low end of the scale when looking at the thermal efficiencies of the units. The wood heat units were assumed to have an average operating lifetime of 15 years. This average operating lifetime may be a conservative estimate of how long the units may actually stay in operation.

Table 5-2. Residential Heating Device Characteristics.

Technology	Installed Cost (M$/PJ)	Efficiency Range	Start Year	Lifetime (Years)	Hurdle Rate
Fossil fuel units					
Natural gas	3.43-18.06	0.78-0.96	2000	30	18-28%
Fuel oil	4.24-12.54	0.81-0.95	2000	30	18-24%
Electricity	3.43-14.61	2.11-3.19[6]	2000	15-30	18-28%
Kerosene	4.24-8.40	0.81-0.95	2000	30	18-24%
LPG		0.78-0.96	2000	30	18-24%
Wood units		Typical efficiency (tested thermal efficiencies[7])			
Conventional HH	3.75	0.55 (0.21)	2000	15	18%
Advanced HH	8.38	0.75 (0.27)	2005	15	18%
H.E. indoor boiler	8.62	0.87 (0.80)	2010	15	18%
Pellet boiler	10.77	0.87 (0.40)	2015	15	18%
New wood stoves	3.19	0.68	2005	15	18%

This analysis focuses on the provision of thermal energy – primarily for space heating, but also provision of hot water – and the role of wood and pellet fuels in providing thermal energy. For application of this model, HH are treated as primary heating devices for residential space heating, while residential water heating is treated as an ancillary application. As a result, application of this model is subject to the same capacity factor and seasonal usage as if it were used solely for space heating, meaning that the model does not reflect owners' utilization of wood boilers for water heating during the space cooling season.

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[6] The efficiency for electric units is not directly comparable to PJ (output) / PJ (input) for other fuels.

[7] Note that the thermal efficiencies used in this application of the MARKAL model differ slightly (by 0.01-0.04) from those reported in earlier chapters. The MARKAL runs were completed concurrently with the analysis of the emissions results and therefore used preliminary numbers. Still, the efficiencies fall well within the range of uncertainty of the reported efficiency. For additional detail on how changes in efficiencies affect market penetration and relative competiveness of different space heating technologies, see the previous economic analysis chapter.

5.2.3 Fuel Prices and Supply

The supplies and prices of natural gas, fuel oil, kerosene and electricity are captured in detail in the base EPAUS9r MARKAL database, from the extraction and importation of crude oil and natural gas, to the refining of finished petroleum products and production of electricity at the regional level, to the delivery/transmission to different end-use sectors (residential, industrial, etc.). The model also includes a detailed supply database of cost and availability of biomass feedstocks (Walsh, 2008) for the production of liquid transportation fuels and for use in electric power generation, including logging residues and primary mill residues.

The biomass supply and cost estimates in the base EPAUS9r database do not include fuel wood supplies for residential heating purposes. For the purposes of this analysis, we therefore constructed new wood resource supplies reflecting the price and upper limit on availability of three residential wood categories: (a) marketed fuel wood, (b) privately collected fuel wood, and (3) wood pellets (see Table 5-3). Note that these categories do not capture other potential fuels such as waste, corn, wood pallets, etc. Table 5-3 summarizes the cost and availability for these three categories.

Table 5-3. Summary of Fuel Wood and Wood Pellet Supply Assumptions.

Fuel Category	Cost	Availability	
		2010	2030
Marketed fuel wood	$200/cord	3.9 million dry tons (Mt)	4.4 Mt
Privately collected fuel wood	$0/cord	3.9-7.8 Mt	4.4-8.9 Mt
Wood pellets	$280/ton	3.9-7.8 Mt	4.4-8.9 Mt

In terms of the prices of wood, households that have access to fuel wood on their private lands may perceive that supply as free when estimating their energy savings from avoiding the use of fossil fuels such as heating oil or natural gas. For simplicity and transparency of analysis, we set the price at zero for privately-collected fuel wood. There is a value of time component and opportunity cost associated with cutting, collecting, seasoning, and splitting wood that is not captured when pricing private fuel wood as zero. At the same time, one cannot discount the personal preferences driving the purchase and use of wood boilers. “Most people who heat with wood like heating with wood. They see the ritual of moving firewood not as a chore that needs to get done any more than they see the ritual of preparing the evening meal a chore. Cutting, stacking and hauling firewood can be a wholesome and rewarding part of living in a cold climate."[8]

The price for marketed fuel wood can vary substantially – a cord of wood will depend on the type of wood, location, size of purchase, quality of wood and seasoning, and whether the price includes delivery and stacking.[9] We used the default price of $200/cord used in the EIA's Heating Fuel Comparison Calculator[10].

For pellets, we utilized the fuel price reports from the State of Vermont.[11] When the input data were being collected for the MARKAL scenario runs, the reported pellet price was $280/ton. Nevertheless, the reported prices have fallen by 5-10%. In addition, other estimates suggest that pellet prices are lower, with bulk residential retail pellets costing around $180/ton, with delivery ranging between $25 -$40/ton within 100 miles of the plant, giving an estimated bulk delivered price of $220/ton to the homeowner (New England Wood Pellet, 2011). The engineering economic assessment chapter explores in greater detail the sensitivity of wood pellet heating units to pellet (and other fuel) prices, with pellet prices ranging from $180/ton to $400/ton.

In terms of fuel wood availability, the following approach was used. The U.S. Department of Agriculture (USDA) forest service reports changes in fuel wood use over time (Haynes, 2003). While residential fuel heat is the primary use of fuel wood, other potentially competing uses include industrial heat and power and electric power production. Residential use fell from approximately 44.3 million dry tons (Mt) in 1986 to 32.3 Mt in 2000, but is projected to increase again reaching 44.1 Mt by 2050. We used these figures for the baseline availability of marketed fuel wood, taking a simple linear interpolation of the growth between 2000 and 2050. Because these numbers were for the national level, we then regionally allocated total residential fuel wood based on the regional share of demand for wood heat and therefore demand for wood supplies. Approximately 300,000 households in the Mid-Atlantic census division were using wood heat as their main heating fuel, compared to 2.9 million households in the U.S.[12] The Mid-Atlantic represented 11% of national residential wood heating capacity. Therefore, allocating the estimated 35 Mt in 2010 and 40 Mt in 2030 to the Mid-Atlantic gives a regional availability of 3.9 Mt in 2010 and up to 4.4 in 2030. Given the uncertainty in this estimate, the scenarios also looked at impacts of higher availability, up to 7.8 Mt in 2010 and 8.9 Mt in 2030.

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[8] Source: www.revisionenergy.com/pdfs/woodboilernews.pdf

[9] Source: www.hearth.com/econtent/index.php/fuels/viewfirewood/

[10] Source: EIA, 2010. Heating Fuel Comparison Calculator version: HEAT-CALC-Vsn-D_1-09.xls.

[11] Source: Multiple monthly fuel price reports from publicservice.vermont.gov/pub/fuel-price-report/

[12] Source: www.eia.doe.gov/emeu/recs/

Another source for estimating total wood utilization is the Residential Wood Consumption (RWC) Tool, which reports quantities of wood burned by equipment type, as seen in Table 5-4. The RWC tool shows lower quantities of wood consumption, with approximately 2.7 Mt utilized in the Mid-Atlantic Census Division. Because of the interest in exploring a range of future scenarios for wood heat, the higher estimates were used, in order to avoid having wood availability constrain the range of results. As a caveat, however, these wood supplies should be interpreted as optimistic.

Table 5-4. Tons Burned by Technology for Mid-Atlantic (1000 tons).

Equipment Type	Amount burned (1000 tons)	Share (%)
Fireplaces and fire logs	401	15
Woodstove fireplace inserts-non-certified	377	14
Woodstove fireplace inserts-catalytic	65	2
Woodstove fireplace inserts-non-catalytic	25	1
Woodstove freestanding-non-certified	950	36
Woodstove freestanding-catalytic	168	6
Woodstove freestanding-non-catalytic	65	2
Woodstove pellet-fired	257	10
Indoor cordwood furnace	158	6
Outdoor HH	160	6
Total	2,628	100%

These estimates reflect projected trends in the use of marketed fuel wood and do not capture the potential supply of wood available for personal use on private lands. Therefore, for these scenarios, the quantity of "free" wood available was also varied from approximately 4 Mt in 2010 to 8 Mt per year. As noted earlier, both the perceived cost and total availability of wood collected by owners is highly uncertain. Similarly, the supply of pellets was simply assumed to be at the same level as both the market fuel wood and privately collected fuel wood. Again, the focus of the scenarios was on the equipment characteristics, rather than an assessment of the potential wood and pellet availability, and these levels were therefore set so as not to constrain technology choice.

5.2.4 Emission Factors

EPAUS9r includes emission factors for all sectors in the energy system for CO_2, CO, nitrogen oxide (NO_X), PM less than or equal to 2.5 micrometers ($PM_{2.5}$), PM less than or equal to 10 micrometers (PM_{10}), sulfur dioxide (SO_2) and volatile organic compounds (VOCs). Emission factors for the non-wood residential emissions in EPAUS9r are incorporated using the emission rates per unit (PJ) of fuel input. These factors were developed by matching the EPA's 2005 National Emissions Inventory (NEI) [13] to the EIA's AEO08 energy consumption by sector and fuel for 2005. The PM emission factors for natural gas, fuel oil, kerosene, and LPG were used without further modification, as listed in Table 5-5. These emission factors are constant for all equipment types using each of those fuels. Therefore, emission differences between different equipment types using fossil fuels are not captured. In addition, these factors are constant over all future model years, meaning that emission reductions from fossil fuel units come from efficiency improvements.

For this analysis, we will primarily focus on how scaling up wood heat and, in particular, increasing utilization of HHs, can affect total regional PM emissions. For the wood heat units, emissions were linked directly to the units themselves as ktonnes/PJ output, rather than to the fuel wood or pellet supply as PJ of fuel input. In the MARKAL modeling framework, this approach facilitates identification of emissions by individual wood heat technologies, as opposed to general emission factors for wood heat. For the conventional HH, advanced HH, high efficiency boiler with thermal storage, and pellet boiler, these emission factors were taken from the emissions testing carried out by EPA. For the Conventional, Single Stage HH unit, the emissions factors for Red Oak were used for consistency with the emission factors from the Three Stage HH unit and U.S. 2-stage downdraft Burner unit with thermal storage, which were tested using only red oak, as opposed to white pine or red oak mixed with refuse.

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[13] Source: http://www.epa.gov/ttn/chief/trends/trends06/nationaltier1upto2007basedon2005v1.xls

Table 5-5. Residential Sector PM Emission Factors.

Technology	ktonnes/ PJinput	ktonnes/ PJoutput	Source
Fossil fuels			
Natural gas	1.86E-04		2005NEI/AEO08
Fuel oil	6.28E-03		2005NEI/AEO08
Kerosene	3.42E-03		2005NEI/AEO08
LPG	3.42E-03		2005NEI/AEO08
Electricity	Allocated from total electric power generation based on residential share of electricity demand.		
Wood units			
Conventional HH		5.93E+00	Tested – Conventional, Single Stage HH
Advanced HH		8.80E-01	Tested – Three Stage HH
H.E. indoor boiler with thermal storage		1.50E-01	Tested – U.S. Two Stage Downdraft Burner (Econoburn)
Pellet boiler		2.10E-01	Tested – Advanced Climate Technologies (European Two Stage Pellet Burner)
Newer wood stoves		6.80E-01	Kroetz and Friedland (2008)
Older wood stoves		7.30E-01	2005NEI/AEO08

The technology breakdown for wood units captures only a subset of current and newer technologies. For example, pellet stoves are not specified separately from wood stoves. Additionally, there are technologies such as high-efficiency indoor wood chip-fired boilers now entering the U.S. market, the costs of which are comparable to the pellet-fired boilers. Additionally, for fuel, the general breakdown was for cordwood and pellets, but did not capture wood chip, the prices of which are highly variable and range from about $40/ton in bulk delivery to very low prices if one has their own wood supply and a chipper.

5.2.5 Model Constraints

The model defines the existing stock of heating equipment in the model base year, based on data from the AEO08 and 2005 RECS. The model then meets future space heating demands by choosing the technologies that most cost-effectively serve that demand given their relative cost, efficiency, availability, and input fuel prices. In order to reflect base year fuel splits more accurately, as well as lags in fuel switching and technology turnover, there are constraints in the model that are relaxed over time. This relaxation follows the logic that households will likely have a tendency to continue to use the same fuels that they currently use, all else being equal, when purchasing new equipment. Therefore, while the initial model period is tightly constrained to reflect existing fuel splits, the model has increasing flexibility to choose new fuels and equipment over time, as shown in Table 5-6.

Table 5-6. Base and Future Year Fuel Share Constraints for Mid-Atlantic.

Fuel	2005	2030
Heating Oil	35%	26%
Electricity	3%	2%
LPG	1%	1%
Natural Gas	52%	38%
Wood	5%	4%
Kerosene	3%	2%
Constrained	100%	72%
Unconstrained	0%	28%

For some of the scenarios, we used these constraints to force in specific scenarios, such as a growth in the market for wood and further decline in the market for heating oil. In addition, several new constraints were created in order to model trends or policies that would favor/disfavor specific mixes of wood heating technologies. These trends represent the “levers” in the MARKAL model to project particular wood heat scenarios of interest and include: (a) HH share of the total wood heat market, (b) split between conventional and advanced HH, (c) high efficiency boilers/gasifiers share of the wood heat market, and (d) wood stoves share of the market. These scenarios were utilized to examine a number of alternative scenarios, as described in the following section.

5.3 SCENARIOS

The following section outlines the results of a set of scenarios that were run for this analysis using the MARKAL EPAUS9r model and database. Because of the unique nature of the market for wood heating devices and wood and pellet fuels and the non-economic variables that often come into play, modeling this market in a pure cost optimization framework presents a challenge. As noted above, in the absence of constraints on the market shares for wood heat technologies, the model would tend toward the nearly exclusive use of new wood stoves (Scenario F, in Section 5.5). Therefore, we have used the model in a "what if" scenario framework, asking a number of targeted questions and running the model to assess the impact of certain assumptions regarding total wood heat market size, technology mix, rates of turnover, availability (or lack of availability) of advanced and high efficiency units, fuel price and availability, and emission rates.

We will first walk through the "baseline" scenario, which represents a bounding scenario of high growth in the HH market, coupled with no introduction of advanced HHs, and no penetration of high efficiency indoor wood or pellet boilers. An additional four scenarios, representing different storylines, will then be presented and discussed, in order to assess the impacts of different wood heat market configurations into the future. We will then compare the results of these five scenarios. In this type of analysis, given the high levels of uncertainty, there is more value in looking at the differences and similarities across scenarios, rather than the results of a single scenario. Finally, we will highlight some of the insights that can be provided from the optimization framework, again recognizing that these are not projections.

As noted above, the MARKAL model runs from 2000 to 2050. We will be presenting the results from 2005 to 2030, to capture the relevant time frame. In addition, unless otherwise noted, all results presented will be at the scale of the Mid-Atlantic Census Division, which includes New York, New Jersey and Pennsylvania.

5.3.1 "Baseline" HH Growth Scenario (Scenario A)

For our baseline scenario, a simplified market mix is assumed, which is pessimistic from the standpoint of emission impacts. This scenario projects little change in the total wood heat market share relative to other fuels, but a growing market for HHs. For this baseline run, cleaner and more efficient boiler units are not available. In 2005, the market for wood heat is divided broadly across existing and newer wood stoves.[14]

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[14] "Existing wood stoves" broadly represent non EPA-certified freestanding woodstoves, fireplace inserts, and fireplaces, whereas "newer wood stoves" represent EPA-certified, catalytic and non-catalytic freestanding woodstoves and fireplace inserts.

Based on the burn rates by appliance category from the 2005 Residential Wood Combustion Tool (v7), outdoor HHs account for approximately 6% of total tons of firewood/fire logs burned in the Mid-Atlantic Census Division. Translating this share of total tons of wood burned into a market share of actual PJ of space heating provided would require information on the average thermal efficiency of each category of residential wood combustion. For simplicity, we assume a 5% share of HH in 2005, and a doubling of the market share to 10% of total wood heat by 2010, and 17% for 2015 and beyond. Because the HH units do not enter the market in a straight optimization model run, we constrained the model to force in the HH market shares as a lower limit.

Figure 5-5 shows the results of these input assumptions regarding HHs and the market shares for other technologies and fuels. The wood heat share of total residential space heating is small and decreases slightly, from approximately 5% (2005) to 4% (2030). In terms of fossil fuels, this scenario and later scenarios showed a trend of decreasing market share for heating oil, a slight decline in the already small shares of LPG and kerosene, and a move toward natural gas and secondarily to electricity. A result of note is an uptake in the use of electricity (primarily radiant, given that electric heat pumps are not well suited to colder northern areas of the U.S.). Under scenarios of much higher total wood heat demand, electricity, along with fuel oil, is displaced substantially by that growth in wood heat.

Within the market for wood heat, newer and more efficient wood stoves displace older wood stoves, as seen in Figure 5-5. The low efficiency of the HH units in terms of the heat delivered to the home, as specified in these model runs, means that the model will not choose these units under a system-wide optimal solution. Instead, the model results show that the market for wood heat is dominated by wood stoves, while HH units enter the market only to the extent that they are forced in by the lower limit. Because stoves were not the focus of this analysis, there was no separation made between wood stoves and pellet stoves in the technology characterization.

Given that one of the potential limitations on the expansion of a wood heat market is the cost and availability of purchased fuel wood, privately collected wood, and wood pellets, we compare the total demand for wood and pellets with the available supply that was specified as an input to the model. Figure 5-6 shows that while the model utilizes all of the “free” privately collected wood available, it uses only a fraction of the purchased fuel wood and none of the wood pellets. However, as noted above, wood pellets were modeled here only for use in pellet boilers, and the low use of wood pellets reflects the characteristics of the pellet boilers, rather than pellet heat in general.

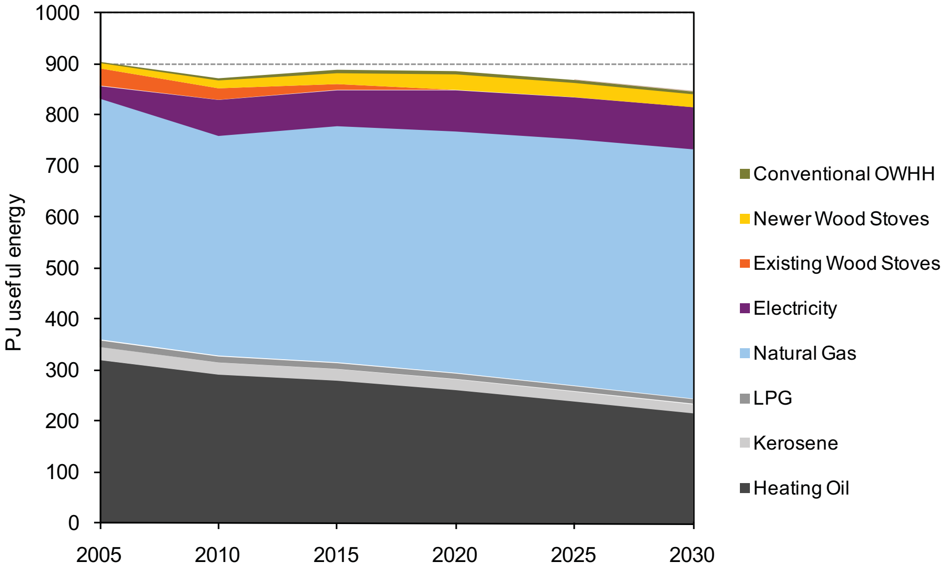

Figure 5-4. Market for Mid-Atlantic Residential Space Heating Based on a Baseline HH Scenario (PJ of Usable Energy, shown as cumulative for all categories).

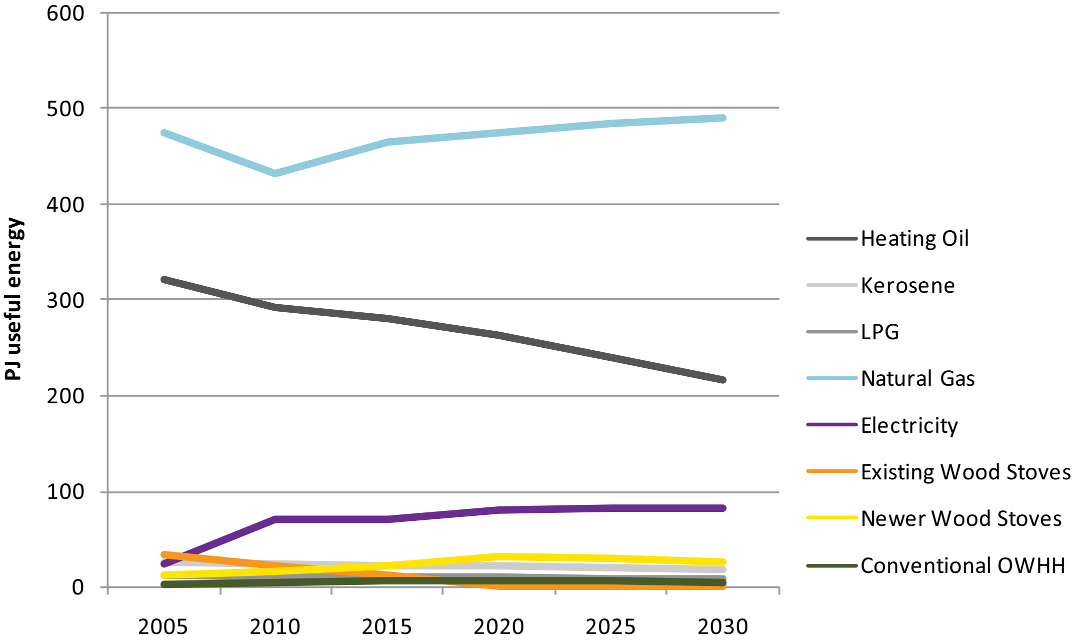

Figure 5-5. Trends in Mid-Atlantic Residential Space Heating Based on Baseline HH Scenario (PJ of Usable Energy, shown as line trends for each category).

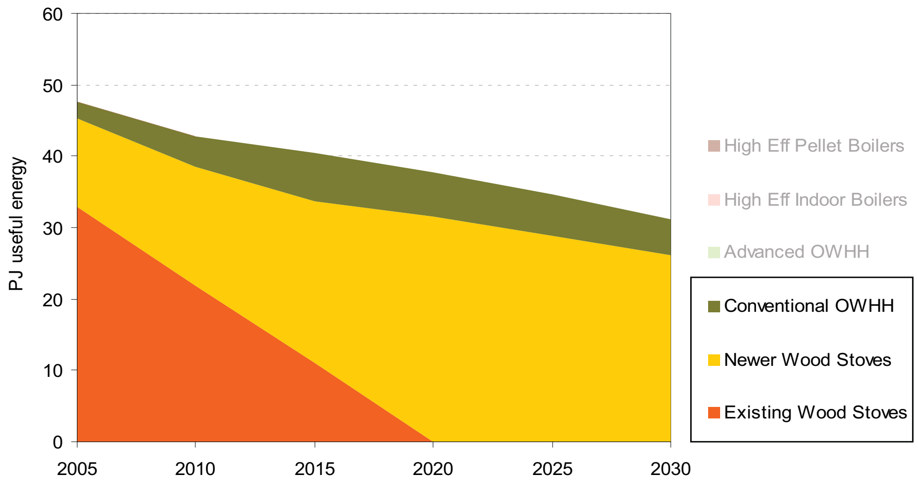

Figure 5-6. Mid-Atlantic Market Share for Wood Heat Devices Only (PJ of useful energy, shown as cumulative).

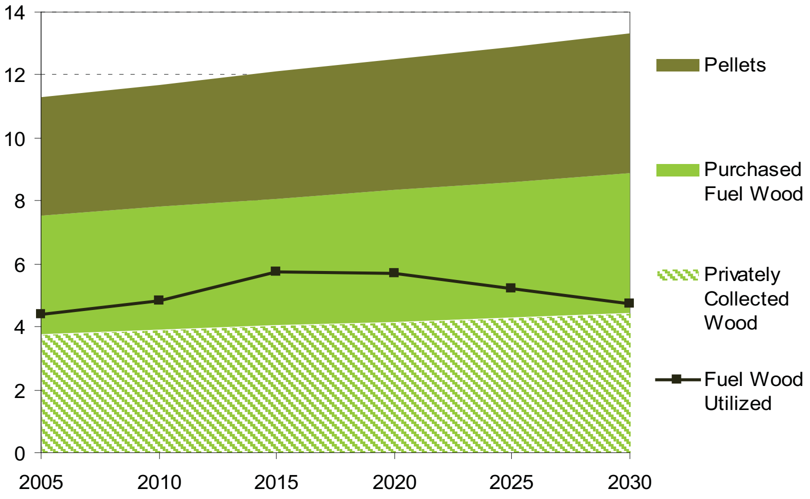

Figure 5-7. Comparison of Wood/Pellet Usage and Total Availability (Mt).

Although the market for wood heat and HHs is a small component of the total residential space heating market, as Figure 5-8 shows, the emissions from these sources dominate the total residential regional emissions profile for PM. Of particular interest is the peak of emissions from 2015 through 2020. This result points to large potential emission increases under a relatively conservative scenario (Figure 5-6) in which the wood heat market is actually falling but the HH market share of that wood heat market grows at a moderate rate (from 10% of the wood heat market in 2010 to at least 17% of the market in 2015).

Table 5-7 presents the same emission trends as shown in Figure 5-8 but shows the percent contribution from each source category. Note as well that these are PM emissions for total residential energy use, not just emissions related to space heating. In addition, the PM emissions from electric power production in this region have been allocated to the residential sector based on its share of electricity demand.

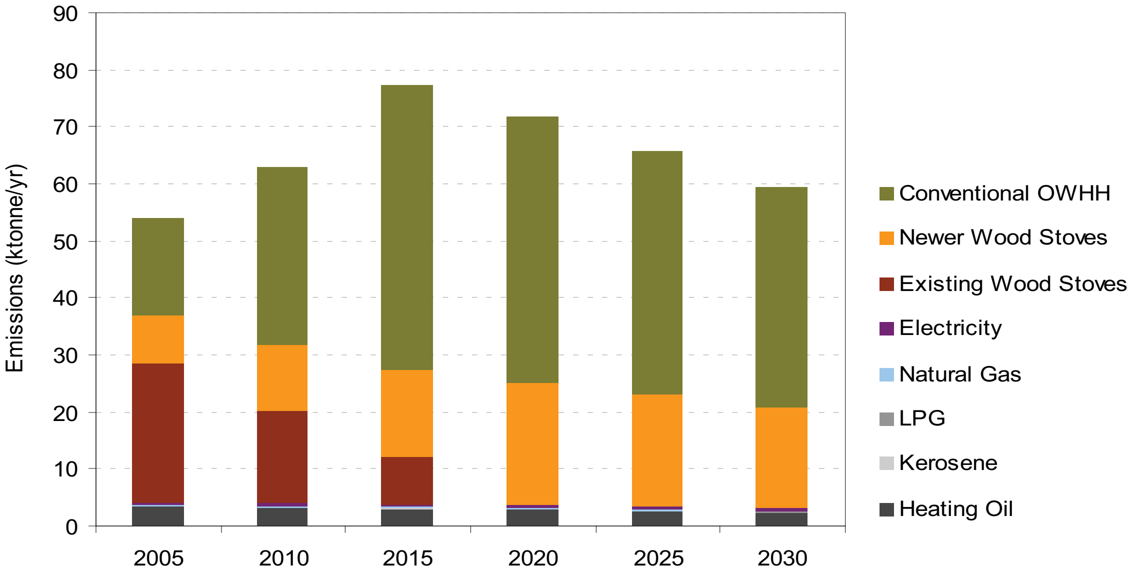

Figure 5-8. PM Emissions (ktonnes) for Total Mid-Atlantic Residential Energy Use. Natural gas, liquid petroleum gas and kerosene emissions do not appear at this scale given their lower emission rates or smaller market share.

Table 5-7. PM Emissions (ktonnes) for Total Mid-Atlantic Residential Energy Use.

	2005		2010		2015		2030	
	Ktonnes	%	ktonnes	%	ktonnes	%	ktonnes	%
Wood	50.04	92.6%	58.87	93.7%	73.48	95.0%	56.26	94.7%
Heating Oil	3.36	6.2%	3.08	4.9%	2.97	3.8%	2.33	3.9%
Natural Gas	0.18	0.3%	0.17	0.3%	0.18	0.2%	0.18	0.3%
Kerosene	0.13	0.2%	0.12	0.2%	0.11	0.1%	0.08	0.1%
LPG	0.11	0.2%	0.10	0.2%	0.09	0.1%	0.07	0.1%
Electricity	0.21	0.4%	0.49	0.8%	0.51	0.7%	0.49	0.8%
Total	54.03		62.83		77.34		59.41	
HH	17.11		31.19		49.89		38.59	
% of Wood	34%		53%		68%		69%	
% of Total	32%		50%		65%		65%	

5.3.2 Four Alternative Scenarios

We now examine a set of alternative wood heat market scenarios (summarized in Table 5-8) that were run in order to assess the relative impact on emissions, fossil fuel displacement, and fuel use, among other factors. Additional scenarios were evaluated in the model and are briefly discussed at the end of this chapter. Figure 5-9 presents the different market configurations, while Figure 5-10 highlights the emissions implications of those scenarios. Because the market share of other fuels (natural gas, heating oil) did not change across these four scenarios, Figure 5-9 only presents the relative market share for wood heat devices. Still, in order to show the total emissions contribution of wood heat relative to fossil fuels, all residential space heating fuels are included in Figure 5-10.

Table 5-8. Summary of Baseline and Four Alternative Scenarios.

Scenario	Description
A: Baseline	Modestly decreasing market share for wood heat Greater share of conventional HHs over the 2005 through 2015 time period Changeover from existing wood stoves to cleaner wood stoves Cleaner, more efficient HHs not be available
B: Slow phase-out of conventional HHs	Same wood heat market share Introduction of advanced HHs Conventional HH units must maintain part of the total HH market at least out to 2020
C1: Rapid phase out of conventional HHs	Scenarios C1/C2 again assume same wood heat share Advanced HHs to come into the market at pace determined by model optimization Result is that advanced HHs enter the market in 2010 and conventional HHs disappear from the market by 2015
C2: Rapid phase out of conventional HHs with lower emission factors for advanced HHs	Same market share result as C1, lower emission factors for advanced units
D: Shift from oil to wood heat	Model constraints force a shift away from heating oil Growth in wood stove utilization capped Results show a growth in the wood heat market and major shift in the mix of technologies toward high efficiency indoor boilers, and large share of advanced HHs

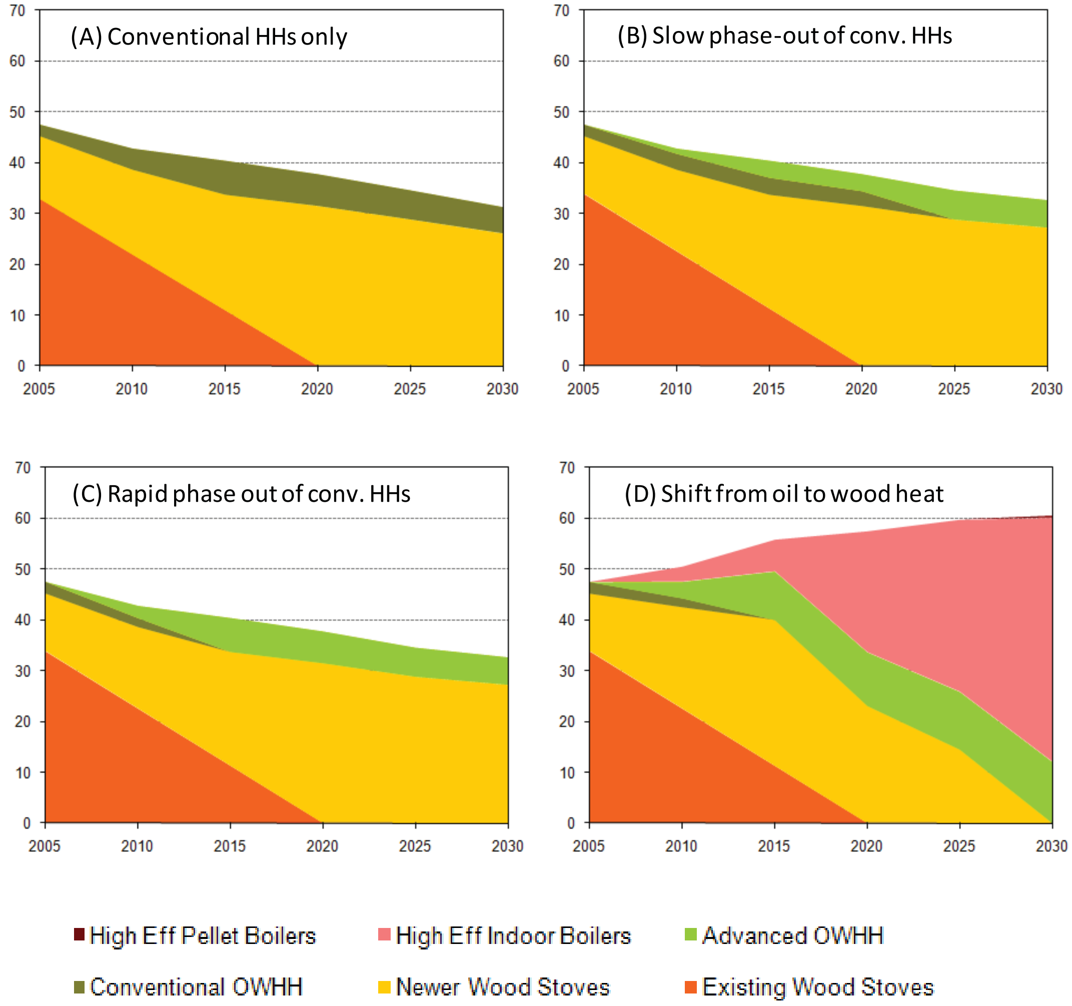

Figure 5-9. Four Alternative Market Scenarios (PJ Usable Energy). Note that the market share is the same for C1 and C2, the difference between the two scenarios being the emission rate applied to the advanced HHs. High efficiency pellet boilers do not appear in these four scenarios.

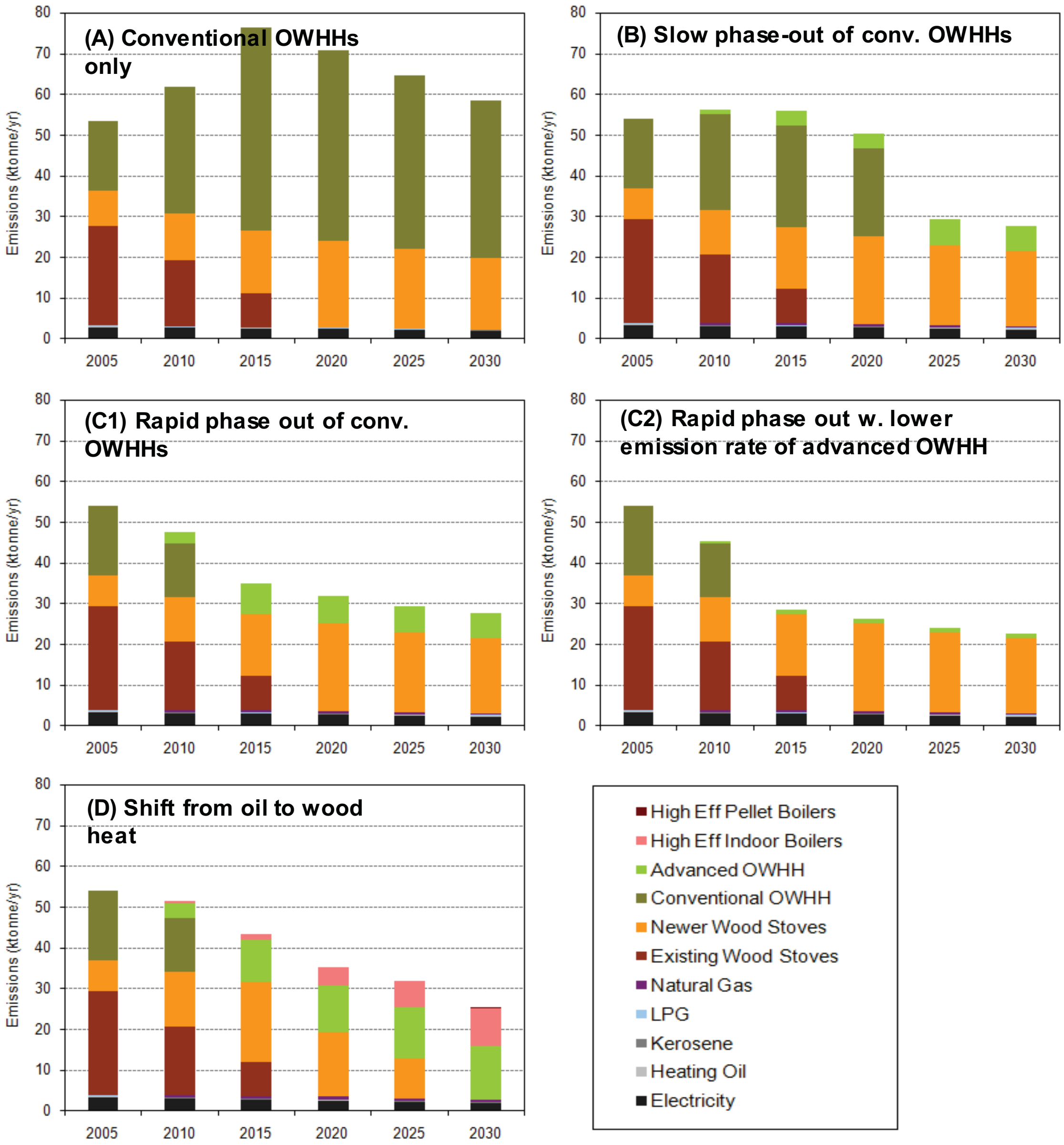

Figure 5-10. Total Mid-Atlantic Residential PM Emissions (ktonnes/yr) for Four Alternative Market Scenarios. Note that high efficiency pellet boiler did not appear in these scenarios.

Scenario A represents the baseline scenario shown above in Figure 5-6, with a modestly decreasing market share for wood heat in general (out of total residential space heating demand), but greater penetration of conventional HHs over the 2005 through 2015 time period and a changeover from existing wood stoves to cleaner wood stoves. This scenario was pessimistic in the assumption that cleaner more efficient HHs would not be available for the entire modeling horizon.

Scenario B assumes the same wood heat market share but now allows for the introduction of advanced HHs. However, Scenario B forces the conventional HH units to maintain part of the total HH market at least out to 2020. For 2015, the market for conventional HH and advanced HH is split 50/50, but by 2025 there are no conventional HHs in the market.

Scenarios C1 and C2 (shown in Figure 5-8) again assume the same wood heat market share, but allow advanced HHs to come into the market as quickly as the model decides. The difference between C1 and C2 is the use of lower emission factors for the advanced HHs in Scenario C2. The technology mix for C1 and C2 is the same, shown as "C" in Figure 5-9. Under this scenario, new HHs begin to enter the market in 2010. Interestingly, the conventional HHs now completely disappear from the market after 2015, indicating that in an optimization modeling framework, the model actually prefers to no longer operate the conventional HHs given their low efficiencies, despite the fact that the initial capital cost has already been incurred and they were still within their usable lifetime. Instead, the model prefers to invest in the higher efficiency advanced HHs.

Scenario D illustrates a different scenario both for wood heat in general and for the mix of technologies within the wood heat market. This scenario uses model constraints to force a shift away from heating oil by exogenously defining upper bounds on its market share for each model period (specified in Table 5-9). The bounds are gradually ratcheted down, resulting in a greater use of wood heat (again, Table 5-9). This scenario also places a cap on the growth in wood stove utilization to simulate a shift away from smaller wood stoves which function primarily as room heaters to larger capacity boilers/gasifiers that provide more distributed heating to the whole home. In contrast to the Scenarios A-C, this scenario shows a growth in the wood heat market and a major shift in the mix of technologies.

Figure 5-10 shows the related emissions for these four market scenarios. For scenarios A, B, C1, and D, the emission factors were the same (as shown in Table 5-5). Again, the only exception is Scenario C2, where the only change was to lower the emissions for the advanced HHs to meet a 0.32 lbs/MMBtu output limit.

One of the motivations for using an energy systems model was to determine the impact of fossil fuel displacement and understand overall residential emissions implications from changes in the wood heat portion of the residential space heating market. In terms of the changes in the emissions from fossil fuel devices, Figure 5-10 shows that these change relatively little from one run to another.

Table 5-9. Changes in Mid-Atlantic Residential Space Heating Fuel Split for Scenario D: Shift from Oil to Wood Heat (PJ Usable Energy).

Fuel	2005	2010	2015	2020	2025	2030
Heating Oil	321	284	264	238	208	178
Kerosene	26	24	23	21	19	18
LPG	13	12	11	11	10	9
Natural Gas	474	433	466	479	491	500
Electricity	25	71	71	81	82	83
Wood	48	53	60	66	71	75

In this context, Scenario D provides an interesting snapshot in which the heating oil usage is reduced substantially – 45% decrease in delivered energy in 2030 from the 2005 base year (Table 5-9). Yet the relative changes in PM emissions from heating oil are not significant when compared to emissions from wood heat, as shown in Figure 5-10 (D). Even major displacements in fossil fuels will not greatly affect residential emissions from those fuels, but the emissions of the additional wood heat will generate major impacts on overall PM emissions.

5.3.3 Summary Comparison of Scenarios

How the market for wood heat, and wood boilers in particular, will evolve over the next 5-15 years is highly uncertain, and in many cases is driven by consumer preferences, which are difficult to capture in a quantitative framework, and regulations and restrictions at different scales –local, state, federal – that affect the types of boilers and HHs that are available to the public. The role that policy measures will play in terms of the rate of technology turnover, efficiency of new units, and emissions rates, adds another critical layer of uncertainty. What the MARKAL scenario analysis aims to provide is a range in terms of how the market could evolve over time and what that evolution means for emissions. Figure 5-11 illustrates the diversity of possible outcomes for how a limited set of factors could play out over the 2005-2030 time period.

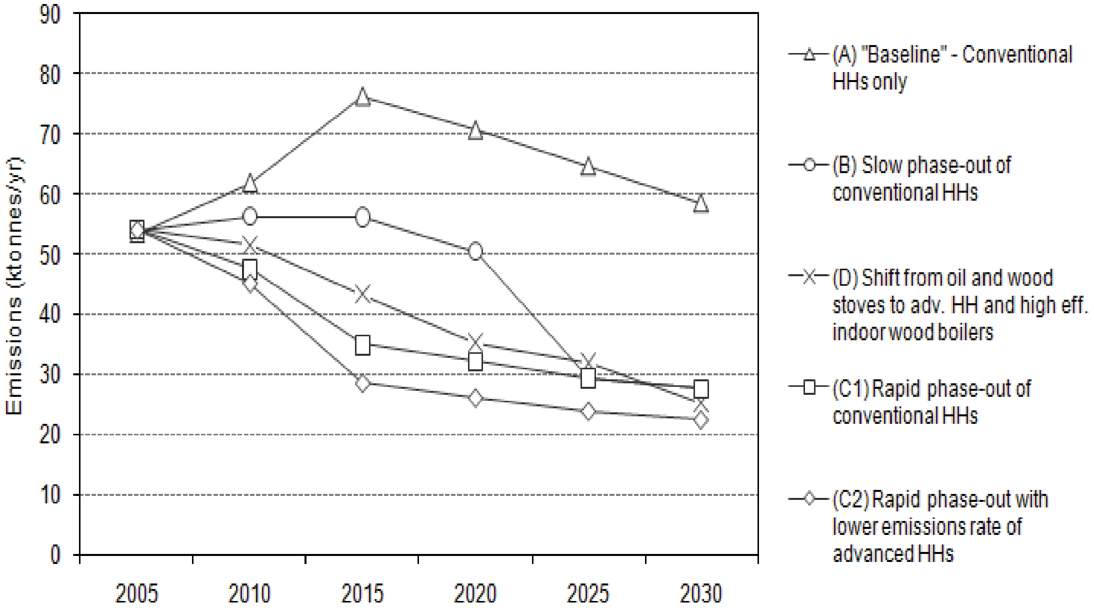

Figure 5-11. Comparison of Total Mid-Atlantic Residential PM Emissions Across Scenarios (ktonnes). Note that C1 and C2 reflect same wood heat market shares, but lower emissions factors (EFs) for advanced HHs.

Looking at Figure 5-11, the 2015 and 2020 time periods are of particular interest. Depending upon the wood heat market share and mix of technologies, the residential PM emissions could either increase by a third or fall to half of the 2005 emissions – a major uncertainty for residential PM and total PM for the Middle-Atlantic region. While the "baseline" run (Scenario A) is highly pessimistic across the entire time horizon, the rapid phase-out of conventional HHs (Scenario C1) coupled with more stringent emissions rates (Scenario C2) can have a significant and positive impact on emissions outcomes. One of the limitations in exploring these medium term dynamics in greater detail is that the EPAUS9r MARKAL model runs at five-year time increments. Understanding the year-to-year dynamics for the wood heat market will be important to determine how emissions will play out and whether there will be a strong peaking of emissions well above current emissions levels, or whether emissions will decline and, if so, at what rate. One of the key factors seems to be how rapidly the new units are introduced and available, and how quickly the older highly emitting units are pulled out of service. This result is clearly intuitive, but by tracking turnover of stock and new equipment for wood heat, as well as the displacement or increased use of other fuels/equipment, MARKAL is able to illustrate a range of potential outcomes for all residential sector emissions and how those change over time.

Table 5-10 provides a snapshot of 2030 PM emissions for scenarios A-D and some additional scenarios (E-I) that were analyzed (briefly described below). The key insights from this comparison are: (1) the extent to which wood space-heating emissions dominate the total emissions from total residential energy usage, even out to 2030; and (2) the potential for wide variation in future emissions, depending upon the evolution of the technology mix within the market for wood heat (between 22.6 and 63.1 ktonnes PM per year). Comparing Figure 5-11, above, and Table 5-9, below, the longer-term picture (2025-2030) appears to be much more optimistic than the potential medium-term emissions profile (2015-2020) in terms of overall residential emissions.

Table 5-10. 2030 PM Emissions for Total Mid-Atlantic Residential Energy Use (ktonnes/year).

	Main Scenarios A-D					Additional Scenarios (E-I)				
Fuel	**A**	**B**	**C1**	**C2**	**D**	**E**	**F**	**G**	**H**	**I**
	All units in ktonnes/year, except were shown as share of total emissions									
Wood/Pellets	56.3	24.4	24.4	19.4	22.4	26.9	60.0	31.2	28.4	57.6
Heating Oil	2.3	2.3	2.3	2.3	2.0	2.3	2.3	2.3	2.0	2.3
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Kerosene	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
LPG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Electricity	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
TOTAL	59.4	27.6	27.6	22.6	25.2	30.0	63.1	34.3	31.1	60.7
Wood / Total Emissions	95%	89%	89%	86%	89%	90%	95%	91%	91%	95%

5.4 DISCUSSION

5.4.1 Market Share and Emissions Implications

These scenarios explored a range of potential market trends for residential wood heat in an effort to evaluate the emissions implications of those scenarios. The results show that relatively modest changes in the market for residential wood heat can have major implications for PM emissions. Across scenarios, wood heat was the primary contributor to PM emissions out to the 2030 time period as shown in Table 5-10. In light of this result, it is important to highlight the contrast between useful energy provided, in the total residential energy picture, and the emissions implications. As shown in Figure 5-5, wood heat supports only a fraction of the annual residential energy demands. Indeed, except where fuels like heating oil were explicitly forced to lower market shares (Scenario D), the market for the major residential fuels – natural gas, heating oil, and electricity – and their emissions were affected very little by changes in the assumptions regarding wood heating technologies or wood prices. In other words, our modeling showed that the market for wood heat did not "move" the broader residential energy market, but it did drive the emissions trends from the residential sector.

The range of possible emissions scenarios is broad and is dependent on how the wood heat market plays out over the next few years and, even more importantly, the mix of technologies within the wood heat market. Indeed, it is difficult to estimate exactly how much wood is currently serving as a primary heating fuel, what types of units are in operation, and where those units are. Even for our baseline scenario, our modeling work may be underestimating the base year HH market share and the extent to which the HH will enter into and stay in operation. First, we have chosen relatively conservative lifetimes, and the units may stay in operation for substantially longer time periods. Second, consumer purchasing preferences that may drive decisions to use wood heat and HHs are not reflected here. Therefore, the emissions peaks that are seen may be higher and, in the absence of policy measures that force early turnover or removal of higher emitting HH units, these emissions peaks could extend farther into future years.

5.4.2 **Insights From an Optimization Framework.**

As described earlier, the MARKAL model is an optimization model that chooses the mix of technologies and fuels that lowers the total cost of the entire energy system. The results presented above reflect a combination of optimization scenarios (i.e., the model was given substantial flexibility in the choice of fuel and equipment/technology mix) as well as scenarios with strict constraints built in to simulate alternative possible futures for wood heat. While an optimization framework will not provide projections due to other behavioral factors that drive decision making in the real world, we can draw some insights from how the model would optimize the system.

First, these scenarios provide a slightly different perspective to the idea that HHs are a cost-effective form of space heating when owners have access to their own “free” wood supplies. Although “free” wood supplies are renewable, they are also finite resources in terms of their annual availability.[15] Therefore, from an optimization standpoint, those resources would be best employed in units with relatively high efficiencies. When allowed to choose (i.e., no modeling constraints to force market penetration of HH or

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[15] The term "finite" refers to the fact that there are upper limits on available fuel wood either because of the actual resource availability (i.e., how much biomass is available to collect) or the ability to collect that resource (i.e., how many cords a household can realistically buy or collect and store).

other types of wood boilers), the MARKAL model would provide wood heat entirely with newer wood stoves, given their relatively good efficiency and relatively low capital cost per unit of capacity. Important differences in terms of how well a wood stove compares with a larger boiler or gasifier unit for the quality of heat within the home are not captured. Still, these unconstrained model runs (in particular, Scenario F) showed higher total wood usage – both “free” privately-collected wood as well as purchased wood – because the model was allowed to optimize the wood heat market.

Second, one of the motivations for using a full energy systems model (such as MARKAL) to assess the market for wood heat technologies is to look at the displacement of other fuels in the residential sector, and even to see if displacement of those fuels, such as heating oil, has any impact on the broader energy system within the region. The idea is that if enough heating oil were displaced in the residential sector, prices could fall due to this lower demand, and changes in other sectors, industrial or commercial, may respond to these lower prices with increased consumption of heating oil. However, as discussed earlier, there was a limited impact of wood heat technologies on the broader market for residential fuels and electricity. Across the runs, there was no discernible impact on any other sectors within the energy system.

Third, an optimization model can look at how different fuels and equipment can meet multiple end uses, such as both residential space heating and residential hot water. The role of HHs in providing water heating was also briefly investigated in these scenarios. Still, it was unclear how to determine the relative amount of hot water provided, compared to the space heating output. In terms of the market share for wood heating options, the addition of hot water did not substantially affect the results. In general, energy use for water heating is only a fraction of the energy use required for space heating. In the Mid-Atlantic region, water heating represents approximately 20-30% of the fuel used for space heating. Water heating may be critical to the extent that the addition of hot water storage may substantially improve the efficiency of wood heat units due to improved cycling. Therefore, hot water storage and provision of hot water may substantially improve both the competitiveness of those units as well as the emissions performance. This consideration was not explored in detail with the MARKAL scenarios but may provide an interesting direction for future research.

5.5 SECTION 5 APPENDIX

5.5.1 Additional Supporting Scenarios

The section below briefly outlines a number of additional "what-if" scenarios. The scenarios are presented as the following. First, what is the general question that the scenario is meant to address? Second, what are the inputs in terms of assumptions (e.g., efficiency) or constraints (e.g., a 30% market share by 2030)? Third, what was the MARKAL result, based on the input assumptions and constraints? The market share trends and PM emissions for each scenario are then shown in Figure 5-12 and Figure 5-13.

Many of these scenarios provided a wider range of flexibility to the model for optimization, including for the 2005 time period. Because of the increased model flexibility for the full 2000-2050 time period, there may also be some differences in the 2005 market split for wood heating devices. These scenarios were meant to explore some of the potential sensitivities in the model, but they are not to be construed as a full sensitivity analysis. The model runtime for the EPAUS9r MARKAL model (45 minutes, excluding time to change assumptions/constraints) made a full sensitivity analysis infeasible. For a more detailed assessment of sensitivities regarding fuel prices, technology performance and other factors, please reference the engineering economic assessment in Chapter 6.

5.5.2 Scenario E: Advanced HHs and 30% x 2030 Penetration of High Efficiency Boilers

Question: "What happens when more efficient wood and pellet boilers/gasifiers enter the market more aggressively?"

Inputs: The total HH market share is the same as for Scenarios A-C. Conventional HHs are forced to stay as 75% of market in 2010, but can drop off after that point. High efficiency wood and pellet units may come in starting in 2010 and have to ramp up to at least 30% of the wood heat market share by 2030.

Results: As opposed to the Scenario A-C, where the market share gradually declines, here the wood market does not fall quite as much and even picks back up in the later model period. Although the 30 x 30 constraint is meant to push either high efficiency indoor units or pellet boilers into the market, the model chooses the former over the latter for the entire model horizon.

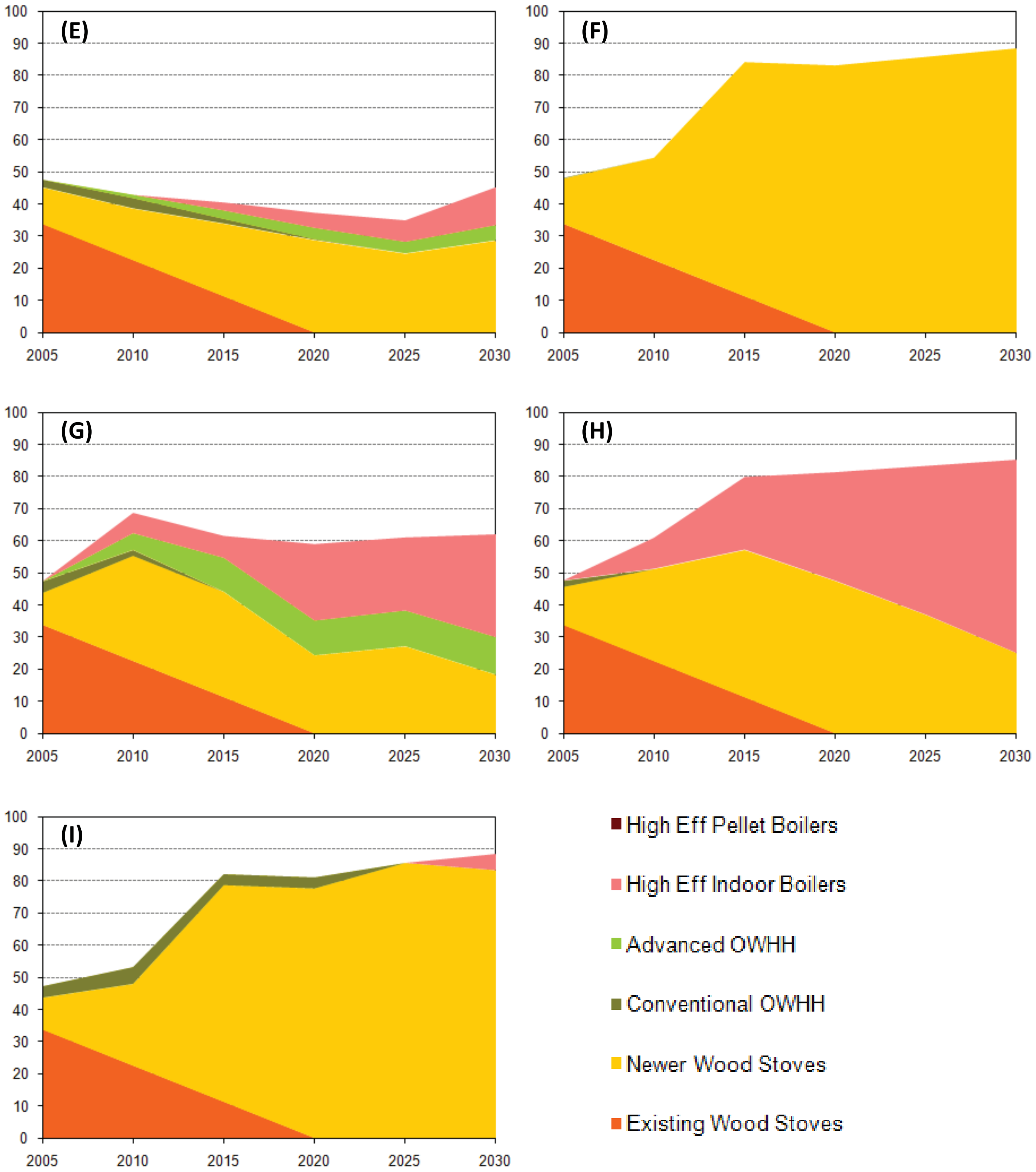

Figure 5-12. Additional Market Share Scenarios (E-I) for Wood Space Heating (PJ of Usable Energy). Note that the high efficiency pellet boilers do not enter the market.

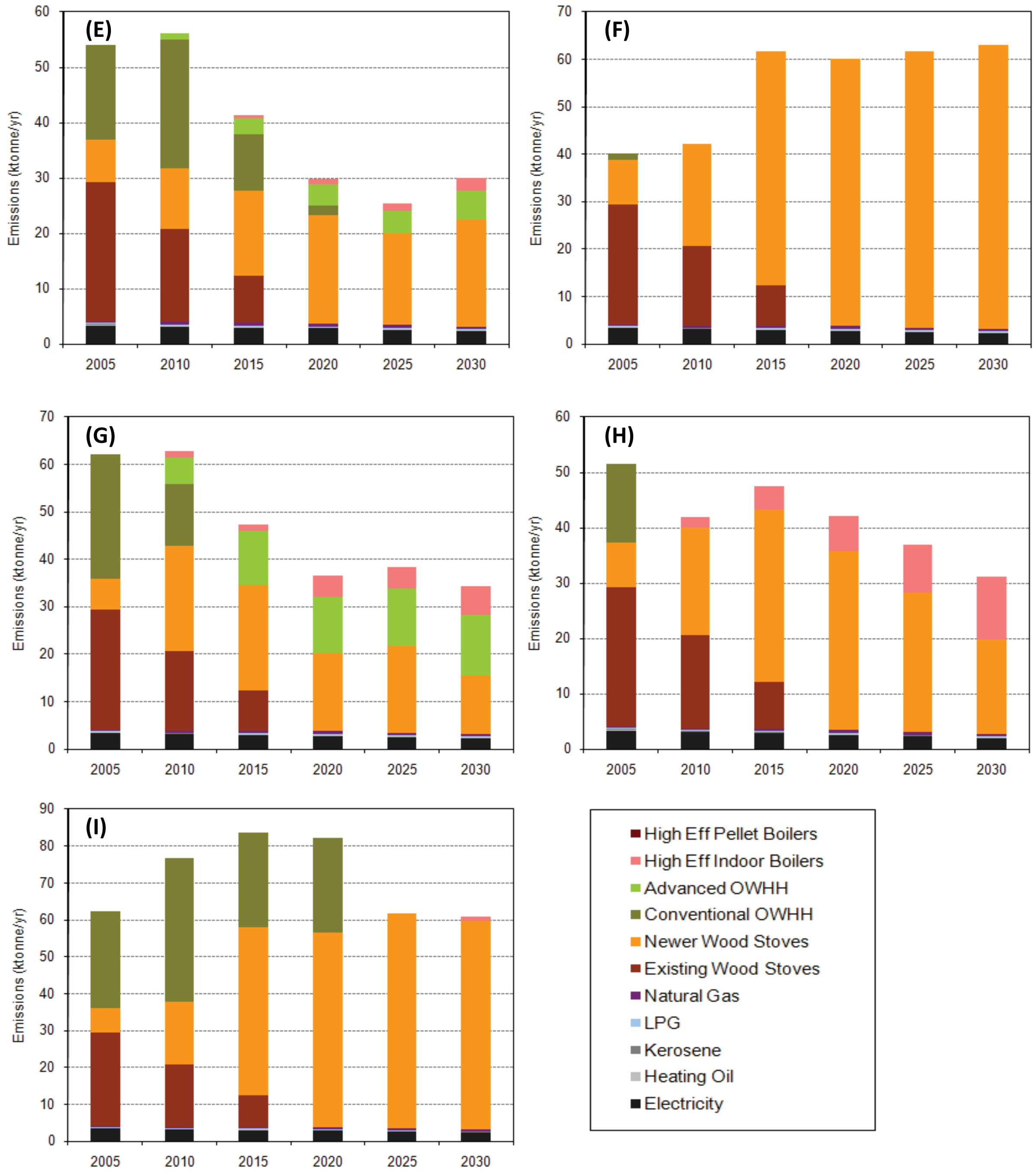

Figure 5-13. Emissions for Additional Market Scenarios (E-I) (ktonnes/yr). Note that the high efficiency boilers do not enter the market.

5.5.3 Scenario F: Full Optimization of Wood Heat Market

“Given only the cost and performance of different wood heating devices and the cost and supply of wood, what mix of wood heating devices would come out of an ‘optimized’ system?”

Inputs: This model run removes all constraints for the type of wood heating devices. The only share constraint is for the total share of HH in 2005.

Results: The model adds wood heat capacity only in the form of wood stoves. However, the total wood heat market share grows under this scenario, meaning that wood heat in general is more competitive relative to other fuels, particularly heating oil, when allowed to optimize the wood heat market itself. This result is seen again in Scenario I, but with the difference that the higher nameplate efficiencies are used in the model runs, leading to the same wood heat market share but with a slightly different technology mix.

5.5.4 Scenario G: More Free Wood, but Fewer Wood Stoves

“If there is more “free” wood available and a limit on wood stove growth, will there be additional growth in the HH market or more high efficiency units?”

Inputs: The quantity of "free" collected wood was doubled. In addition, the maximum share of wood stoves was ratcheted down to 25% in 2030. The model was still forced to increase the share of HHs (following Scenarios A-C) but can use any mix of conventional or advanced HHs.

Results: The model had a higher wood heat market share than Scenarios A-C but, interestingly, did not have as large as a market share as the fully optimized scenario (Scenario F), despite a higher supply of “free” wood in the form of collected firewood delivered at a zero cost to the system. The model added a large amount of additional capacity in the form of high efficiency boilers, and met the HH market share constraint with all advanced HH units, meaning that the model quit operating the conventional HHs before the end of their useful lifetime was reached. This result indicates that in an optimized framework, the overall efficiency of wood heat devices drives the market more than the supply of “free” wood. This somewhat counterintuitive logic highlights an important point: even in context of free or low cost fuel supplies, the model still attempts to optimize the use of those supplies, and forcing more inefficient units into the wood market could dampen the overall wood market growth.

5.5.5 Scenario H: No New HHs and Limited New Stoves

“What if the market moves away from wood stoves and HHs and has cheaper pellets?”

Inputs: This scenario limits the share of wood stoves, using the same constraint as used in Scenario G. This scenario also disallows all new purchases of HHs starting in 2010, although existing units can continue to operate. In addition, pellets are priced lower at $200/ton.

Results: The market still does not move toward use of pellet boilers, given their high capital cost and still relatively high annual fuel cost, given the combination of pellet prices and low efficiencies based on the tested efficiencies. Note that the pellet stoves were not moded as a separate technology option under this analysis, as pellet stoves may have entered the market, particularly under this scenario.

5.5.6 Scenario I: Full Market Optimization with Nameplate Efficiencies

“What would the market mix look like if the units operated at their nameplate efficiencies (Table 5-2)?”

Inputs: In this model run, the only constraint was for HH to take up the 2005 and 2010 share of market as specified in Scenarios A-C. After that, the model was allowed to fully optimize its choices for the residential space heating market.

Results: Similar to Scenario F, the model moved more aggressively toward new wood stoves. However, when the conventional and advanced HHs competed in the model at their nameplate efficiencies, the conventional HHs were a larger part of the wood heat market for a longer period of time. Even with the name-plate efficiencies which are much higher than the efficiencies measured in this study, the market still does not move toward high-efficiency pellet boilers.

6. AN ENGINEERING ECONOMIC ASSESSMENT OF HYDRONIC HEATERS IN THE STATE OF NEW YORK

6.1 INTRODUCTION AND OBJECTIVES

Outdoor wood HHs are space- and water-heating devices used to heat homes and commercial buildings. The main components of an HH are the firebox, the surrounding water jacket, the chimney (or stack), and the piping that delivers the hot water from the unit to the structure being heated, which may be several to tens of feet away. Some HHs and other wood heating devices also integrate a large hot water tank. The tank stores heat, distributing it when needed. Operation with a tank can improve the efficiency of units greatly.

In the past decade, the number of HHs in use has increased dramatically. Factors driving their adoption have included high and volatile prices for electricity and fossil fuels, concern about climate change, and a desire for energy independence. At the same time, however, many localities and states have instituted bans or other restrictions on HHs, driven by concerns about air pollution. In the context of these conflicting drivers, new, more efficient and lower emitting HH designs are appearing. The market is also being transformed by the emergence of automated pellet boilers and high efficiency indoor wood boilers, both of which compete with HHs.

The overall objective of the work presented in this section is to enhance the discussion of HHs by examining the drivers that have led to their penetration, including the extent to which these drivers are based on economics or other factors. Engineering economic techniques are used to compare the lifetime costs of alternative technologies, including HHs, automated pellet boilers, high efficiency indoor wood boilers with hot water storage, natural gas and fuel oil boilers/furnaces, and electric heat pumps. Sensitivity analysis is used to examine the impact of varying assumptions about fuel prices, home size, and other factors. The calculations are relatively simple, accounting for equipment, installation and fuel costs, but ignoring other costs. Care should be taken by the reader to understand the many caveats of this analysis and not to extend these insights to represent definitive judgments about the superiority of one technology or another.

This section of the report serves as a companion piece to Section 5, “MARKAL energy systems modeling of alternative HH market penetration scenarios.” In that section, the MARKAL energy system model is used to explore different scenarios of residential wood heating. Competition with other technologies is examined and the emissions implications of specific scenarios are estimated. Both sections make use of net present value calculations in evaluating HH competitiveness. While MARKAL examines technologies in a regional context, we focus here on a specific decision: the evaluation of heating costs for different devices for a hypothetical home in Syracuse, New York. Simple engineering economics calculations are not able to account for many of the complexities considered by MARKAL, such as temporal considerations (e.g., turnover of existing stock), resource supply curves, and competition with other sectors for fuels. This analysis is useful in providing insight into MARKAL's technology selections, however, as well as "ground-truthing" the MARKAL results to a hypothetical, but realistic, decision process.

First, we provide background information related to historic and recent trends in residential heating, as well as the emissions associated with HHs and how these compare with other sources.

6.2 BACKGROUND

6.2.1 Historic Trends In Residential Heating

Wood has long been used as a fuel for residential space heating in the U.S. The U.S. Census Bureau estimates that wood heating represented 23% of the national residential heating market in 1940. By 2000, however, this share had decreased to less than 2%. Figure 6-1 shows market shares for residential heating fuels in 1940 and in 2000, both at the national level and for the State of New York (U.S. Census Bureau, 2004).

At both of these geographic resolutions, market shares for natural gas and electricity experienced considerable growth at the expense of wood and coal. The expansion of natural gas and electricity distribution systems, as well as improvements in electric heat pump efficiencies, undoubtedly played a role in this trend. Natural gas and electricity also offer the advantage of convenience, with energy being available on demand to the home.

Figure 6-1 suggests there can be considerable regional variation in fuel use. The State of New York, for example, had a much higher market share for fuel oil in 2000 than the national average, but a lower share of electric heating. Within a state, there also can be considerable variation in heating technologies and fuels. For example, Figure 6-2 presents data collected by the U.S. Census Bureau regarding the fractions of households within each county of the State of New York that listed wood, natural gas, fuel oil and electricity as their primary heating fuel in 2000 (U.S. Census Bureau, 2007).

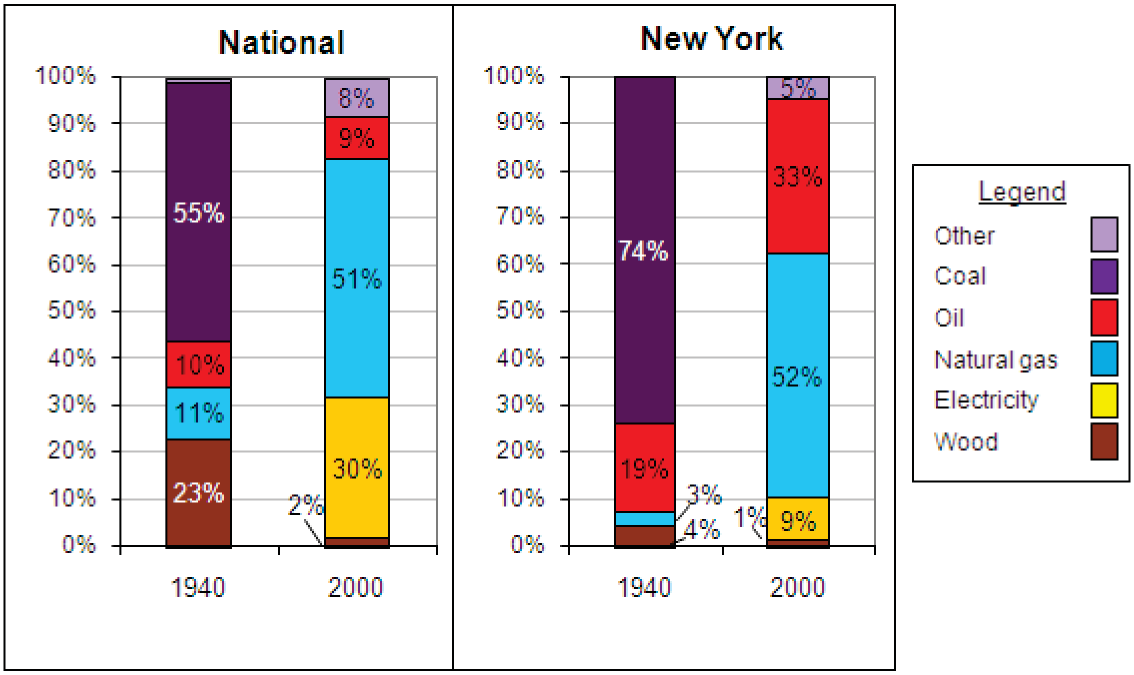

Figure 6-1. Residential Space Heating Market Share by Fuel: National and the State of New York. (U.S. Census Bureau, 2004).

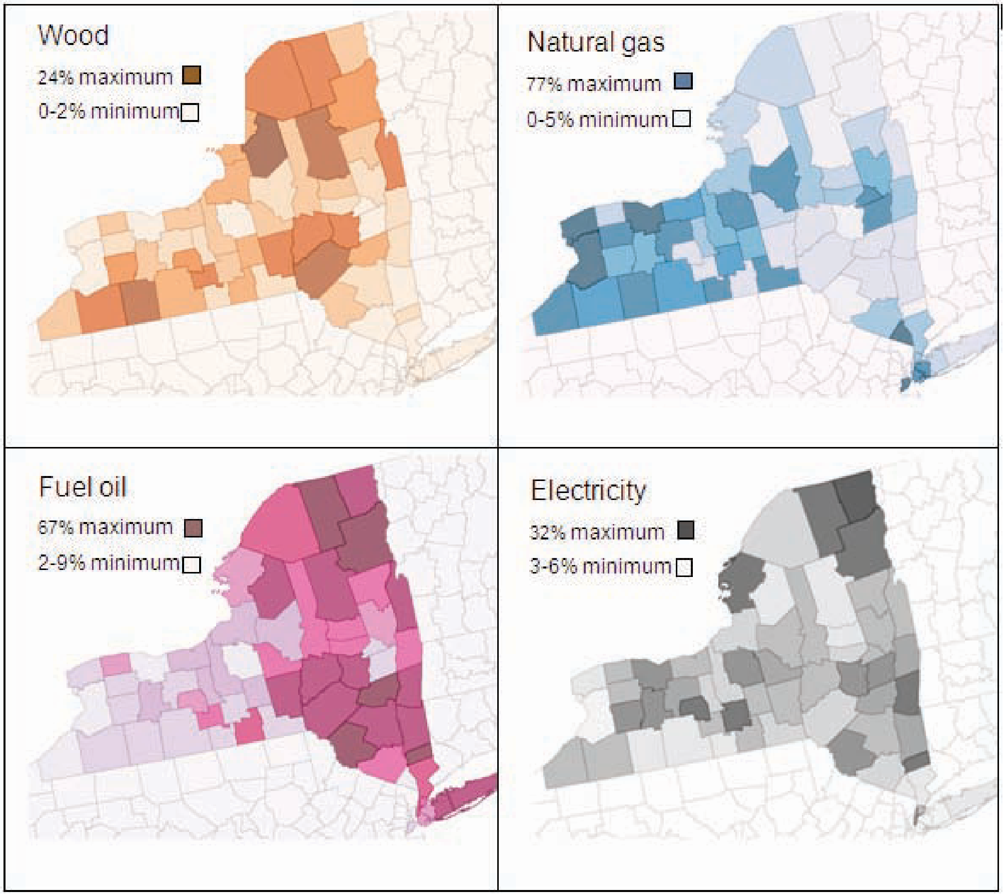

Figure 6-2. Fraction of Households in Each County of the State of New York Using Wood, Natural Gas, Oil and Electricity as Their Primary Heating Fuel in 2000. Darker shades represent higher levels of use. Figures Developed from U.S. Census Data. (U.S. Census Bureau, 2007).

A number of factors contribute to county-level variation. One such factor is the availability of natural gas. Figure 6-3 shows natural gas pipelines in the northeastern portion of the U.S., including the State of New York (U.S. Energy Information Administration, 2011b).

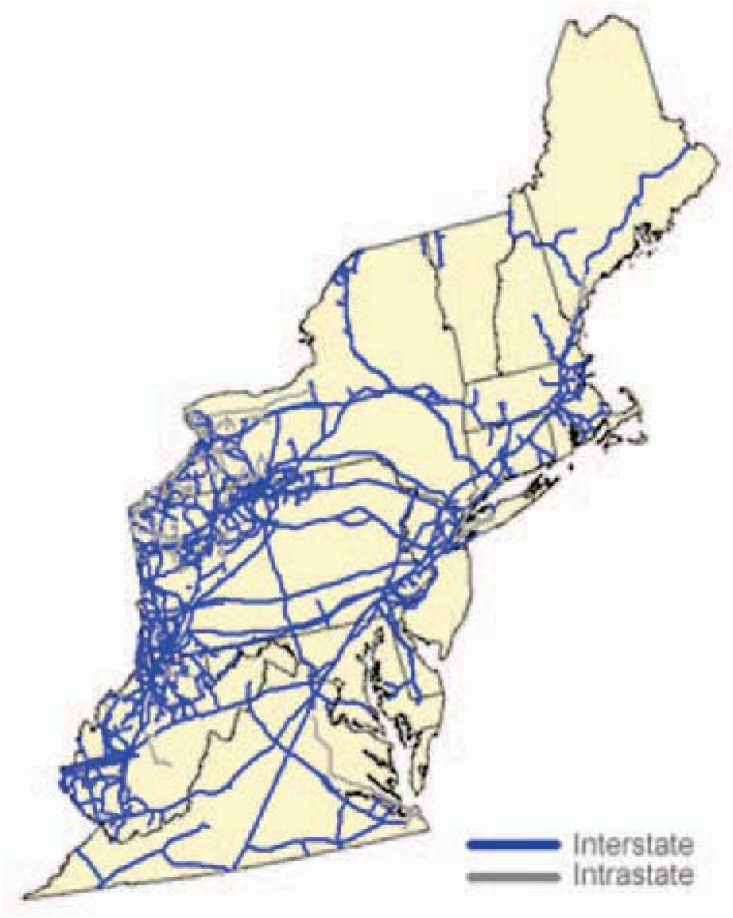

Figure 6-3. Natural Gas Pipelines in the State of New York and Surrounding States. Blue and Grey Lines Represent Pipelines. (U.S. Energy Information Administration 2011b.)

Comparing Figures 6-2 and 6-3 suggests that, by 2000, natural gas had become the primary fuel choice for residential heating in counties serviced by natural gas pipelines. In areas without pipelines, however, heating oil was the most common fuel. This relationship is corroborated by way of correlation analysis, which shows a strong inverse correlation, -0.93, between the county-level market shares of natural gas and oil.

Land use is another factor impacting fuel choices. The Census Bureau provides information about the fraction of each county's households that fall into the urban or rural categories (U.S. Census Bureau, 2007).

In 2000 there was a very strong correlation, 0.89, between the rural housing fraction and the market share of wood technologies for primary heating. Rural areas presumably have better access to wood resources and may have fewer restrictions related to wood combustion emissions.

6.2.2 Recent Trends in Residential Heating

Over the past decade, the declining market share for residential wood heating began to change in the State of New York. Contributing factors included increases in prices and in price volatility for natural gas and fuel oil. Figures 6-4 through 6-6 show monthly prices of natural gas, home heating oil, and electricity in the State of New York over the period of 1990 through 2010 (U.S. Energy Information Administration, 2010, 2010c, 2011).

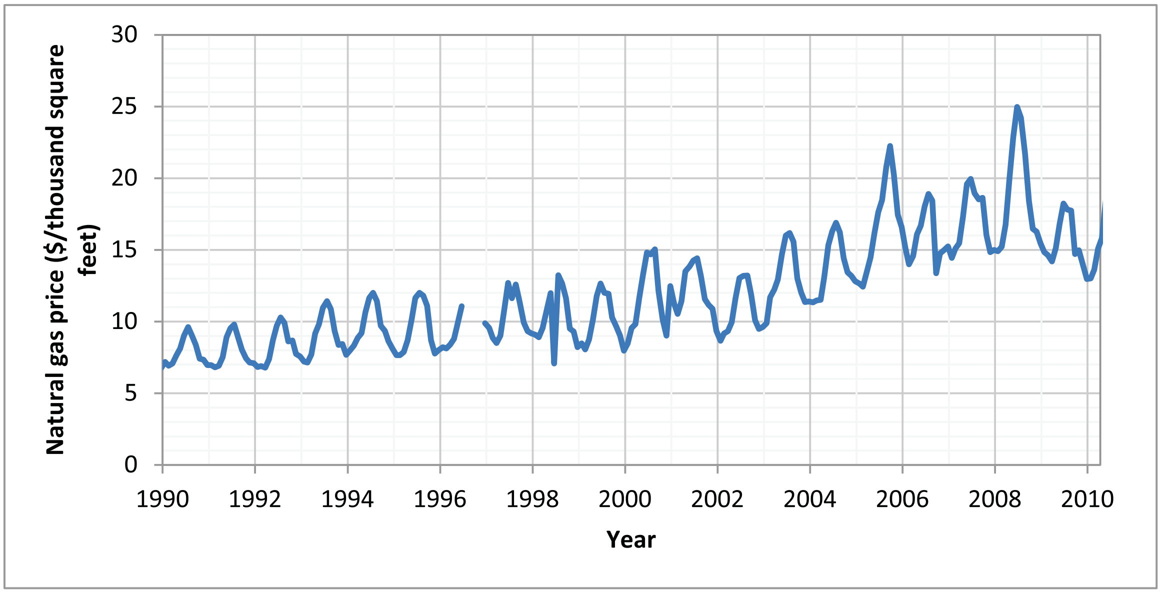

Figure 6-4. Residential Natural Gas Prices in the State of New York. (U.S. EIA, 2010).

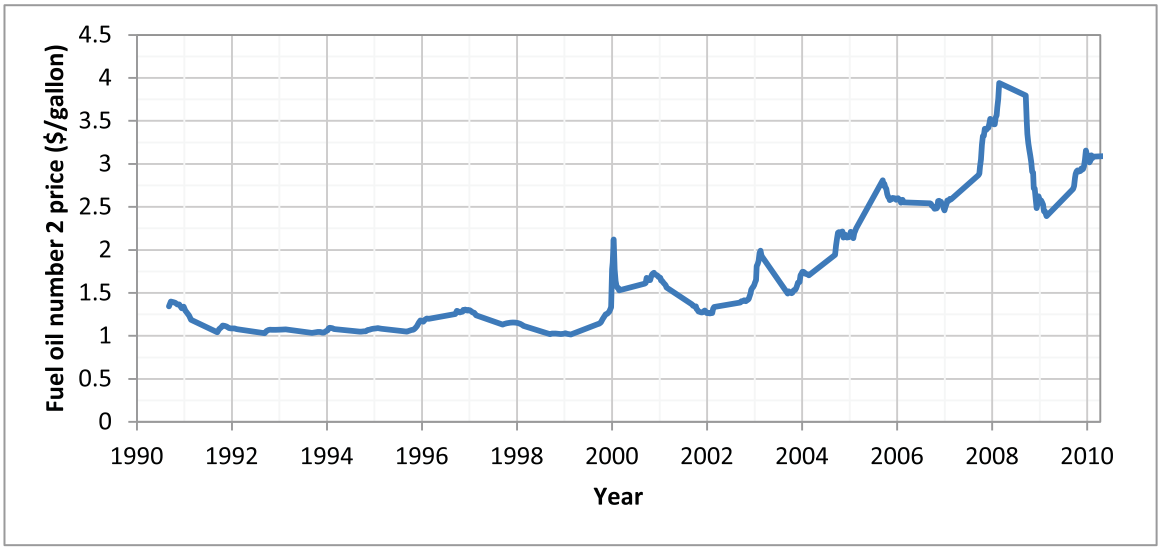

Figure 6-5. Residential Home Heating Oil Prices in the State of New York. (U.S. EIA, 2010c).

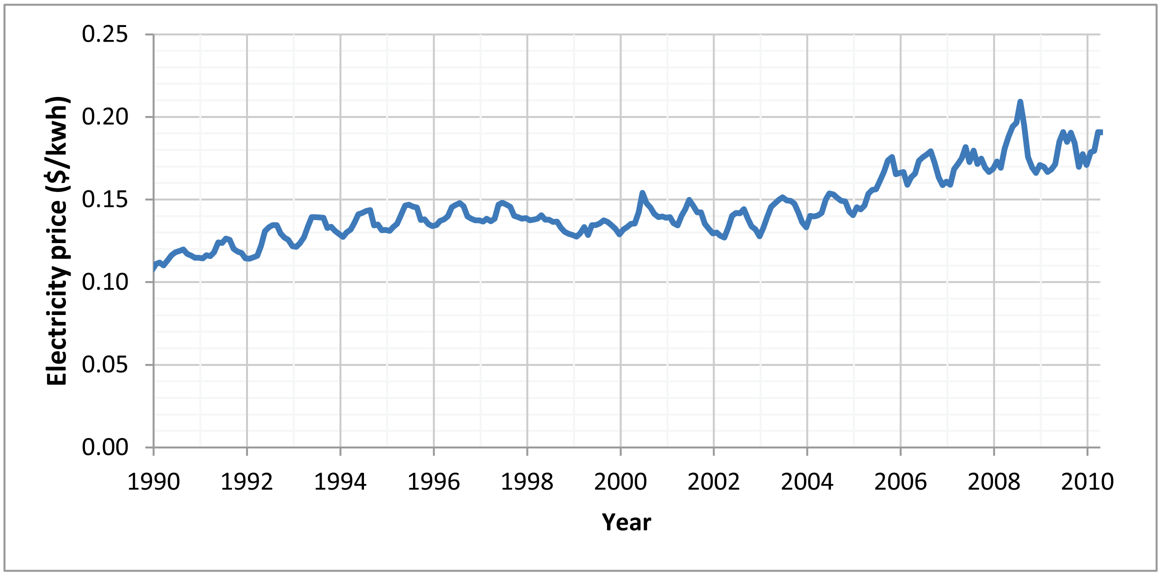

Figure 6-6. Residential Electricity Prices in the State of New York. (U.S. EIA, 2011).

For natural gas, the highest prices are experienced in the summer months when many electric utilities operate natural gas-fueled peaking plants to meet high air conditioning loads. Winter gas prices have steadily increased over the past decade, increasing by approximately 57% from 2000 through 2010. Over the same period, winter residential electricity prices increased by 34%. Home heating oil prices experienced the greatest jump, with winter prices increasing by nearly 200%. Prices for all fuels were highly volatile, experiencing peaks in 2000, 2005, and 2008. These trends led to residential heating bills that were considerably higher than their historic values and that varied unpredictably from year-to-year.

In response, many residential consumers have sought out lower cost alternatives, including wood heating. Wood has been particularly attractive in rural areas, where residents may have greater access to supplies of wood. Further, provided that space is available, cord wood can be purchased during periods of low demand and stored until needed. Non-economic factors have also driven recent wood use. High oil prices, for example, have fostered a desire for national fuel independence. As a domestic fuel, wood is viewed as a component of the solution. In the context of climate change, wood offers promise as a low-carbon renewable fuel. Many states have instituted policies that encourage wood use by subsidizing residential wood heating devices.

The category of residential wood-burning technologies has long been dominated by fireplaces, wood-burning fireplace inserts, and woodstoves. Indoor wood furnaces and boilers also provide options for those wishing to heat larger spaces with wood. In response to increasing demand, new technologies have begun to penetrate the market. Pellet stoves, for example, have created a new niche by using a biomass-derived fuel that typically burns cleaner and is easier to store and handle than cord wood. This development is important because many residential consumers have grown accustomed to the convenience of on-demand heat that natural gas and electricity provide.

Outdoor wood HHs have a unique niche. These units provide both space heating and water heating, are able to heat large spaces and, by moving combustion outdoors, do not require cord wood to be carried into or stored within the residence. Estimated HH annual and cumulative sales for the State of New York are shown in Figure 6-7 (Burkhard, 2011). The peak annual prices for oil, natural gas and electricity, normalized by their 1999 values, are superimposed on the figure. The large increase in sales in 2008 matches with particularly high energy prices.

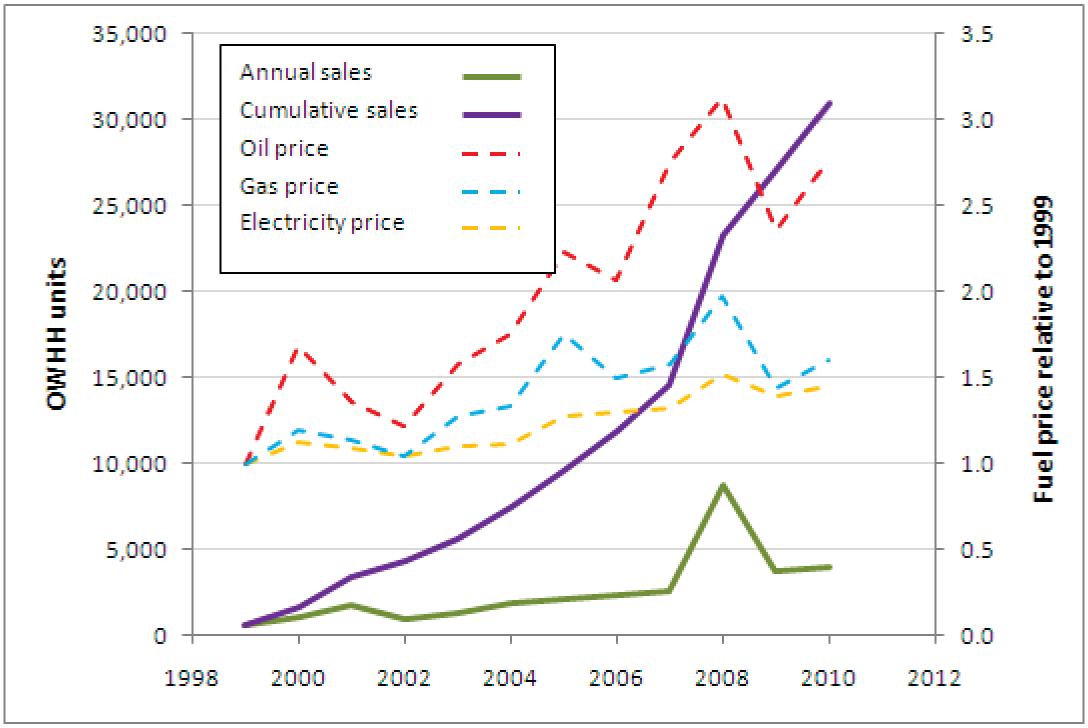

Figure 6-7. Outdoor Wood Boiler Annual and Cumulative Sales Estimates in the State of New York. (Burkhard, 2009).

6.2.3 Air Quality Concerns Associated with HHs

EPA's 2005 NEI characterizes the quantity of pollutant emissions from various sources (U.S. EPA, 2009). The NEI suggests that most of the residential emissions of carbon monoxide (CO), ammonia (NH_3), PM less than or equal to 10 micrometers (PM_{10}), PM less than or equal to 2.5 micrometers ($PM_{2.5}$) and volatile organic compounds (VOCs) originate from residential wood burning. For the State of New York, percentages of these pollutants attributed to wood burning were 91%, 58%, 88%, 90% and 92%, respectively. These percentages do not consider the upstream emissions associated with producing electricity or other fuels used within residences.

Emissions rates differ considerably from one wood technology to another. Figure 6-8 compares the PM emission rates (in grams per hour) from HHs, woodstoves, and other residential space heating devices (New York, 2005). These data suggest that HH units emit at a rate more than 17 times that of a Phase-II EPA-certified catalytic indoor wood stove and two orders of magnitude greater than an oil furnace. NESCAUM testing suggested that HH emission rates can be considerably higher, citing studies in which emissions range from 18 to 269 grams per hour (NESCAUM, 2006).

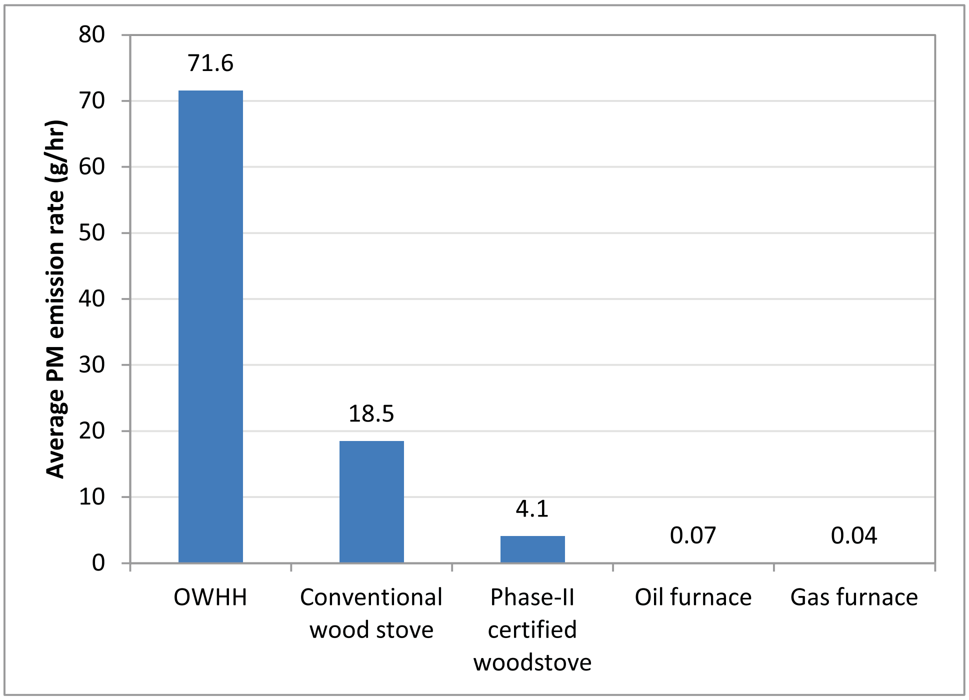

Figure 6-8. PM Emission Rates in Grams per Hour for a Variety of Sources. (NESCAUM, 2006).

The high emission rate for HHs, combined with their increasing sales, is cause for air quality concerns. A number of states have proposed or adopted rules to address smoke from HHs, including Maine, Maryland, Massachusetts, New Hampshire, New York, and Washington (State of Vermont, 2011a; State of Washington, 2011). Many of these rules provide phased emission limits and siting requirements for new HHs. Washington does not allow the use of HHs at all within the state. In 2007, NESCAUM released a model rule that can serve as a template for states and local agencies in addressing HH emissions (NESCAUM, 2007).

The State of New York's rule was adopted in late 2010 (State of New York, 2010). The rule sets operational requirements and lists approved and prohibited fuels. HHs are not allowed to activate indoor smoke alarms, impair highway visibility, or cause a visible plume that contacts buildings on adjacent properties. New HHs are required to meet a specific emission limit, as well as a minimum setback from property boundaries and a minimum stack height. The State of New York's proposed rule, however, also addressed existing HHs by including a phase-out schedule for existing HH units. This aspect of the proposed rule was dropped from the final rule.

Some states and towns have instituted local ordinances related to HHs. For example, as of January 2008, more than 60 towns, villages or counties in the State of New York had placed restrictions on these units (Schreiber and Chinery, 2008). By June, 2010, this number had increased to more than 100 (Schreiber, 2011). Wisconsin and Michigan have developed model rules that can be adopted by local governments (State of Vermont, 2011a).

While EPA regulates emissions from indoor woodstoves, there are no federal regulations currently in place that specifically address HHs. EPA does, however, administer a voluntary partnership with the HH industry (U.S. EPA, 2011). HH units meeting specific emission targets can be labeled and marketed as such. To address HH emissions more fully, EPA has developed a pre-proposal for a revision to the New Source Performance Standards (NSPS) for wood heaters. The revision would expand coverage of the NSPS to include new HHs and would require these units to meet specific emission limits (U.S. EPA, 2011b).

Given these conflicting drivers, an important step in understanding the current and prospective markets for HHs is to compare their lifetime costs with those of competing technologies. This step is carried out in the next section using engineering economic analysis.

6.3 APPROACH

6.3.1 Context

Engineering economic calculations were performed in the context of selecting a replacement heating technology for a hypothetical 2500 square foot house located in Syracuse, New York. The house has R-30 roof and attic insulation and is equipped with a radiant delivery system. Simulated hourly heating demands for a full year were obtained for a house with these general characteristics (Brookhaven National Laboratory, 2008). The simulation assumed the thermostat was set back to 65 degrees Fahrenheit each night in winter. The maximum hourly delivered heating demand from this profile was 55,000 British thermal units (BTU), equivalent to 22 BTU per square foot.

In determining the capital cost of the various heating technologies, an oversizing factor is applied to the heating demand. In practice, there is considerable variability in oversizing. Many heating units in older homes have been sized using factors of 2 or greater. Construction practices of the last several decades have decreased heat losses, however, and much lower oversizing factors are being used. For example, the State of New York's 2002 field guide for new residential construction includes the following requirement for a home to participate in the New York ENERGY STAR program: "…equipment must also be sized to no more than 115% of the heating or cooling load as calculated, or the next available size if no properly sized unit is available in the market." (Harley and Gifford, 2005). Since the simulated home is assumed to be an existing structure, we assume a moderate oversizing factor of 1.7. Thus, heating units are sized to meet a maximum hourly output of 93,500 BTU.

6.3.2 Technology and Fuel Characterization

The primary heating technologies considered in this analysis were natural gas and oil boilers, an electric heat pump, a conventional HH, an advanced HH, a high efficiency indoor wood boiler with hot water storage, and an automated pellet boiler. The conventional HH is intended to represent the units that have comprised the vast majority of HH sales to date. The advanced HH technology represents newer, higher efficiency and lower emitting designs. The high-efficiency indoor wood boilers and automated pellet boilers are two technologies that are in use in Europe and are beginning to be sold in the U.S. The high-efficiency indoor wood boiler is assumed to have a large hot-water storage tank.

Data for electric heat pumps were derived from the U.S. EIA's 2008 Annual Energy Outlook (U.S. EIA, 2008). Heat pump efficiency was adjusted to account for winter temperature conditions using an adjustment based on historical weather patterns in Buffalo, New York (U.S. EIA, 2010b). Information about natural gas and fuel oil boilers was obtained from a 2007 report developed for EIA (Navigant Consulting 2007). All of the devices had maximum outputs that exceeded the 93,500 BTU constraint except the heat pump, which was characterized as having a maximum output of 36,000. The cost of the heat pump was therefore scaled using the following equation:

$$\$4,345 * 93,500 / 36,000 = \$11,285 \qquad (6\text{-}1)$$

Prices for residential wood heating technologies proved very difficult to characterize. There is a lack of peer-reviewed information detailing and comparing the costs and efficiencies of these units. Most studies addressing residential wood technologies focus on indoor woodstoves, which are much more prevalent. These studies typically rely on the manufacturer's device characterizations and may not incorporate consideration of installation costs. Moreover, manufacturers will typically provide updated technical specifications for their units, but will not provide retail prices as those are often determined by local distributors. Because of these various reasons, the resulting characterizations are highly uncertain.

As with other studies, our characterizations of conventional and advanced HHs were derived from the websites of dealers and manufacturers. In addition, estimates of installation and hot water storage were considered. Existing Federal tax credits of $1,500 that were in effect at the time of this analysis are included in the prices of the advanced HH, automated pellet boiler, and high-efficiency indoor wood boiler with hot water storage. These rebates have since expired. The HH and wood boiler units are assumed to burn only wood, although dual-fuel units are also currently on the market. Information about the high-efficiency indoor wood boiler and automated pellet boiler units was obtained from Ellen Burkhard of

NYSERDA (Burkhard, 2009). The pellet boiler that is considered is a relatively high-end device that includes automated ash cleaning. Less expensive pellet boilers are available on the market.

Boiler efficiency refers to the fraction of the energy contained in the fuel that is transferred to the water in the surrounding water jacket. Boilers often state this value as their nameplate efficiency. For wood and pellet units, however, not all of this heat can be used to heat the house. Heat is lost from the boiler jacket and piping that delivers the hot water from an HH to the household, as well as from the indoor hot water storage tank, particularly if it is located in an unheated portion of the house such as the crawl space. As a result of these losses, the *thermal* or *operational* efficiency (which represents the energy delivered for space heating divided by the input energy) of the HH may be much less than the stated boiler efficiency.

Thermal efficiencies for wood- and pellet-burning devices were developed in the experimental portion of this project. For the HHs and automated pellet boiler, the observed thermal efficiencies were considerably less than the units' nameplate efficiencies. For example, the conventional HH that was tested had a stated efficiency of 55%, but the observed thermal efficiency was approximately 22% over three tests in which red oak was burned. Similarly, the advanced HH and automated pellet boiler had nameplate efficiencies of 75% and 87% but observed thermal efficiencies of only 30% and 44%, respectively.

The observed boiler efficiency was close to the nameplate efficiency for the high-efficiency indoor wood boiler with hot water storage (e.g., 80% to 87%). This unit burns at a relatively constant rate with excess heat stored in the water tank. The combustion component of the unit does not respond to changes in load and is thus able to avoid heat losses from the cycling and flue opening that the other units experienced. Thermal efficiency for this unit was not evaluated in the experimental portion of this project. For this unit, thermal (or operational) efficiency is assumed to be equivalent to boiler efficiency since the unit is indoors and additional heat losses would be within the heated structure.

Table 6-1 summarizes the efficiencies, maximum hourly outputs, and capital costs for each of these technologies. Prices are estimated in 2009 dollars. Efficiencies listed for the HH and pellet technologies are thermal efficiencies developed through the experimental stage of this work. The efficiency listed for the high efficiency indoor wood boiler with thermal storage is its boiler efficiency. Efficiency values in parentheses represent the units' nameplate efficiencies. The base cost is an estimate of the cost for a unit with the specified output. Scaled costs reflect increases in the sizing of units to meet or exceed a target output of 93,500 BTU per hour. Several of the wood technologies had outputs considerably greater than 93,500 BTU per hour. These units were assumed to be used at less than rated capacity, and their capital costs were not scaled down. In practice, utilization below capacity may lower efficiency. This effect was not considered.

Table 6-1. Assumed Residential Heating Device Characteristics. For the wood devices, nameplate efficiencies are shown in parentheses alongside the observed operational boiler efficiency.

Technology	Efficiency	Output (BTU/hour)	Base Cost	Scaled Cost
Natural gas boiler	85%	100k	$3,821	$3,821
Fuel oil boiler	85%	100k	$3,821	$3,821
Electric heat pump	173%	36k	$5,164	$11,285
Conventional HH	22% (55%)	250k	$9,800	$9,800
Advanced HH	30% (75%)	160k	$12,500	$12,500
High efficiency wood boiler with thermal storage	80% (87%)	150k	$12,000*	$12,000
Automated pellet boiler, no thermal storage	44% (87%)	100k	$9,750	$9,750

* The high-efficiency indoor wood boiler is assumed to have a supplemental hot water storage tank at a cost of $4,000.

Table 6-2 shows the prices that were assumed for various fuels. Oil, gas, and electricity prices were derived from historical values for the State of New York, reported by the EIA. Fuel oil and natural gas prices were for year-end, 2009 (U.S. EIA, 2010, 2010b). Electricity price was an average for 2008 since the 2009 price was not available at the time of the analysis (U.S. EIA, 2011). Values in parentheses are the equivalent average national prices.

Table 6-2. Assumed Fuel Prices for the State of New York. For reference, national values are provided in parentheses.

Fuel	Price
Fuel wood	\$225 / cord
Pellets	\$280 / ton
Fuel oil #2	\$2.83 / gal (\$2.80 / gal)
Natural gas	\$1.37 / therm (\$1.00 / therm)
Electricity	\$0.183 / kwh (\$0.109 / kwh)

These values show that natural gas and electricity prices in the State of New York were 37% and 68% greater than their respective national averages. The values in Table 6-2 were intended to be representative, and are in line with estimates provided by the Vermont Department of Public Service (State of Vermont, 2011b). An internet search for wood and pellet prices suggests that these prices can vary greatly over time and from one location to another (e.g., Woodpelletprice.com 2011). Prices may also differ considerably as a function of the degree to which wood is seasoned, the type of pellet, the proximity to supplies, and whether there is market competition that could drive down prices. The amount of variation makes exploration of sensitivities to wood and pellet prices particularly important.

A complicating factor is that the prices of different fuels may be correlated. For example, high oil prices yield increased demand for wood fuel. Increased demand, in turn, has the potential to drive up wood prices. Thus, wood and oil prices typically are correlated. Capturing the complexities of such correlations is beyond the scope of this work, although we do explore sensitivities in which wood and oil prices are altered together.

The energy content of wood can vary greatly, depending on the type of wood and whether it is green or has been seasoned. We use an energy content of 22,000 kBTU per cord, a typical value for seasoned wood in NY. For comparison, the energy content for air-dried (20% moisture content) red oak is estimated to be 25,300 kBTU, with other wood species ranging from 14,700 to 30,700 kBTU (Univ. of Maryland, 2010). Similarly, the energy content for pellets depends on composition and moisture content. We assume an energy content of 16,500 kBTU per ton for pellets.

6.3.3 Engineering Economic Calculations

At the heart of the engineering economic evaluation is the Net Present Value (NPV) calculation. NPV is typically calculated using Equation 2:

$$NPV = CAP + ANN * \left[\frac{(1+i)^n - 1}{i * (1+i)^n} \right] \tag{6-2}$$

Where:

NPV is net present value of cost
CAP is the capital cost of the technology
ANN is the annual cost of the technology, in this case the cost of fuel
i is the interest or discount rate
n is the number of years that the annual payment is made

This equation converts current and future expenditures into a single NPV. The NPVs of two or more technologies can be compared via this metric, allowing comparison of their lifetime costs. NPV is a particularly useful metric in comparing alternative technologies since it provides a means of comparing a technology with a high upfront cost and high efficiency with one that has a low upfront cost but low efficiency.

We use constant dollars in our NPV calculations, so inflation is neglected. Further, fuel prices are assumed to be constant over time. A discount rate of 1% is used to reflect the opportunity cost (over inflation) of investing capital in a money market or other low-yield investment. We assume that the lifetime of each device is 15 years and use this value for *n*. The NPV cost calculation was carried out for each primary heating technology using the technology and fuel price assumptions provided in Tables 6-1 and 6-2.

6.3.4 Additional Sensitivity Analyses

There was considerable uncertainty in many of the inputs that went into the NPV cost calculations. To address uncertainty, as well as to facilitate the development of broader insights, parametric sensitivity analysis was carried out. Parametric sensitivity analysis involves perturbing the value of one parameter at a time and tracking the response of the NPV cost of each candidate technology. Table 6-3 lists the parameters that were evaluated, including the high, baseline, and low value for each. High and low values reflect the endpoints of the values that were tested but were not intended to represent actual high and low estimates for each parameter. Most parameters were tested for at least five values within their respective ranges. Water heating costs were not changed for any of the sensitivities.

Table 6-3. Parameters Investigated in the Sensitivity Analysis.

Parameter	Low	Base	High
House size (square feet)	1000	2500	4000
Hurdle rate	0.01	0.045	0.44
Wood prices ($/cord)	0	225	360
Pellet prices ($/ton)	180	280	400
Heating oil price ($/gal)	$1.90	$2.83	$4.80
Natural gas ($/therm)	$1.03	$1.37	$2.74
Electricity ($/kilowatt-hour)	$0.09	$0.18	$0.37
Conventional HH efficiency (fraction)	0.2	0.55	0.8
Advanced HH efficiency (fraction)	0.2	0.75	0.8
Advanced HH cost ($)	7000	12,500	28,000

The hurdle rate sensitivity was included to capture an element of consumer behavior: the hesitation to make large, up-front expenditures. A detailed description of hurdle rates is discussed with the hurdle rate sensitivity results.

6.3.5 Caveats

A number of important caveats should be considered when evaluating the results of this engineering economic assessment. These caveats include:

- The analysis assumes that fuel prices will rise at the rate of inflation over the lifetime of the devices. All additional price dynamics, such as super-inflation and periodic, episodic, and other fluctuations, are ignored.
- All devices are assumed to have useful lives of 15 years. The actual life of a device could be less than or greater than this amount. Also, the average lifetime may differ from one type or brand of device to another or based on operational factors. For example, burning green wood or non-wood materials in an HH may decrease the lifetime of the device. These factors were not considered in the NPV equations.

- The type of wood and whether it has been seasoned have a considerable impact on its energy content. Similarly, pellet composition and moisture content impact energy content.
- Meteorological variability that would lead to changes in annual heating loads is not considered. Similarly, longer-term changes in regional meteorology due to climate change are also ignored.
- The ability of electric heat pumps to provide cooling in the summer is not considered. Consideration would effectively reduce the capital cost for these devices.
- Regulations and ordinances that limit or ban the use of HHs in the summer months are not considered. These requirements may necessitate that homes use supplemental water heating, which may yield an additional expense.
- Only primary heating technologies are included in the comparison. In practice, many homeowners may elect to supplement their primary heating device with a secondary heating device, such as an electric resistance heater or freestanding woodstove. These devices can be used under very cold conditions or during periods where the primary device's fuel cost is high. The impacts of secondary heating technologies are not included in the engineering economic calculations in this analysis.
- Electric heat pumps are limited in how much they can increase temperature over outdoor conditions. When conditions are very cold, the conditioned air may not feel sufficiently warm to the residents even if it is heating the house. Further, the temperature "lift" provided by the heat pump may not be sufficient to achieve the desired room temperature. Many residents may use supplementary heat under these conditions. These factors are beyond the scope of what can be considered within the engineering economic analysis carried out here.
- A number of additional space heating options are not considered in this analysis but may be competitive with those that were considered. These options include electric baseboard heat, ground source heat pumps, and propane-fueled boilers and furnaces. Also, many available units are capable of burning one or more fuels. Dual-fuel units are not considered.
- Heating devices are available in specific sizing options. Popular sizes may be offered at a discount, and economies of scale may impact prices on larger units. The approach used for scaling device costs does not account for these factors, and assumes that the prices for devices increase linearly with capacity.

- Higher efficiency heating devices may also be available at an increased cost. For example, electric heat pumps are available with widely varying efficiencies. We consider only one example of each technology.
- The NPV cost metric does not explicitly capture human behavior, personal preferences, or biases.
- There is considerable uncertainty in the degree to which the operating efficiency of each wood and pellet device is related to the efficiency stated by the manufacturer. The difference between rated and thermal efficiency is influenced by details of the installation and configuration of the units, considerations that are beyond the scope of this analysis.
- Under-utilization of a device's capacity can negatively impact efficiency. As a result, its efficiency may suffer during both periodic and seasonal conditions when loads are low. The experimental efficiencies for wood devices were estimated under simulated winter conditions. These values may overstate real-world efficiencies that would be experienced if the devices were operated at a lower fraction of capacity. Low capacity operation is expected during the spring and fall when cold temperatures are typically not as extreme as in the winter.
- The boiler efficiency, instead of the thermal efficiency, is used for the high efficiency indoor wood boiler with thermal storage since the thermal efficiency was not tested. Use the boiler efficiency implies that heat that is not captured by the hydronic system will be delivered to the structure.

Given these various caveats, engineering economics alone cannot be expected to fully characterize the rich set of considerations that drive consumer choices. Nonetheless, the approach employed provides preliminary insights into the conditions under which these various heating technologies are competitive. These insights are important in evaluating the results of the MARKAL energy system analysis in a companion chapter. Care should be taken by the reader to understand the many caveats of this analysis and not to extend these insights to represent definitive judgments about the superiority of one technology or another.

6.4 RESULTS AND DISCUSSION

6.4.1 Competitiveness of HH Technologies

Annual space heating costs and the NPV cost were calculated for each technology using the State of New York fuel prices. These results are reported in Table 6-4.

Table 6-4. Annual Fuel Costs and the NPV of Total Lifetime Costs for Various Primary Residential Space Heating Technologies. Water Heating Costs are Ignored.

Technology	Annual Fuel Cost	NPV
Automated pellet boiler	$3,900	$64,000
High efficiency indoor wood boiler with hot water storage	$1,300	$30,000
Conventional HH	$4,700	$75,000
Advanced HH	$3,400	$62,000
Electric heat pump	$3,100	$55,000
Natural gas boiler	$1,600	$26,000
Fuel oil boiler	$2,400	$37,000

The results suggest that natural gas boilers represent the lowest lifetime cost option, even with the State of New York's high natural gas price. At a wood price of $225 per cord (for seasoned wood that is split, delivered and stacked) and a pellet price of $280 per ton, the HH and automated pellet boiler technologies had the highest NPV costs. In contrast, the high efficiency indoor wood boiler with hot water storage had annual fuel costs and a lifetime NPV cost that were competitive with the natural gas boiler.

Another observation that can be drawn from the information in Tables 6-1 and 6-4 is the high fraction of the lifetime costs that is attributable to fuel. For example, the cost of electricity contributed 79% of the lifetime cost of the heat pump. This fraction was 90% for the fuel oil boiler and 87% for the conventional HH unit. These ratios illustrate the importance of operational costs in comparing heating technology options.

6.4.2 Consideration of Water Heating

The values shown in Table 6-4 include the costs associated with space heating only. The NPV costs were recalculated to account for the water-heating services provided by the wood and pellet units. In this subsection, we make several assumptions to account for the costs associated with water heating. An informal survey of market literature suggests that a typical cost for a hot-water heater, including installation, is approximately $800. We added this amount to the capital costs of the electric heat pump, natural-gas boiler, and fuel oil boiler. Since the HHs typically are not operated year-round, we assumed that a hot-water tank would still be needed, but used a lower capital and installation cost of $600. The high-efficiency indoor wood boiler with thermal storage has its own hot water tank, so no additional cost for a tank was added. An operating cost of $500 per year was assumed for water heating. This amount was reduced by half for the wood and pellet units since they are assumed to provide hot water to the household during a portion of the year. Results are provided in Table 6-5 using estimated New York fuel costs.

Table 6-5. Annual Fuel Costs and the NPV of Total Lifetime Costs for Various Primary Residential Space Heating Technologies, Including Water Heating Costs.

Technology	Annual Fuel Cost	NPV
Automated pellet boiler	$4,200	$68,000
High efficiency indoor wood boiler with hot water storage	$1,600	$33,000
Conventional HH	$5,000	$79,000
Advanced HH	$3,700	$66,000
Electric heat pump	$3,600	$63,000
Natural gas boiler	$2,100	$34,000
Fuel oil boiler	$2,900	$45,000

Consideration of water heating costs makes the HH units slightly more competitive, but not enough to change their ranking with respect to NPV cost. When considering water heating, the high efficiency indoor wood boiler with thermal storage became the least cost option. In the following sections, we explore the sensitivity results to examine how these observations change with changes in assumptions. Water heating costs are not considered in the sensitivity runs that follow.

6.4.3 Sensitivity to Wood Price

Parametric sensitivity analysis allowed the impact of wood price on the competitiveness of HH and other technologies to be explored. Sensitivity results are shown in Figure 6-9. Costs for competing technologies were calculated using fuel price estimates for the State of New York. Several representative wood price values are highlighted on the graph.

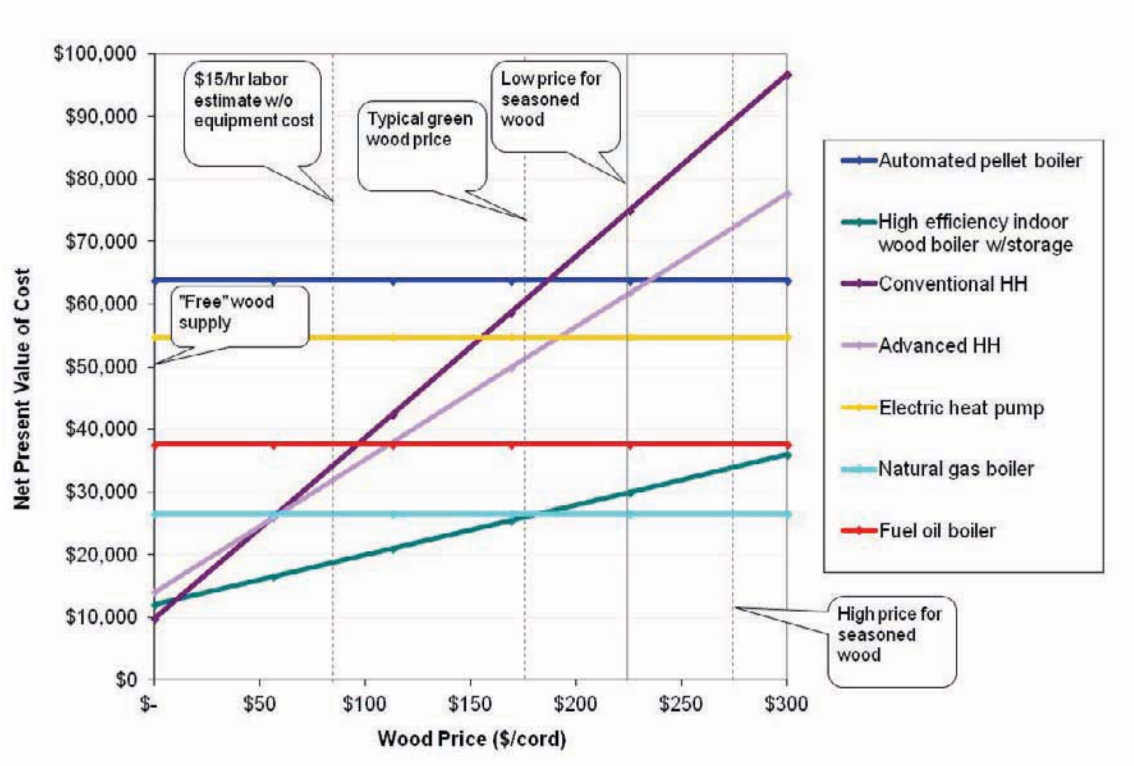

Figure 6-9. Sensitivity to Wood Price.

The results suggest that the conventional and advanced HHs become competitive with electric heat pumps for wood prices below approximately $190 and $150 per cord, respectively. Competitiveness with oil and natural gas is achieved at wood prices of approximately $100 and $55 per cord, respectively.

Figure 6-9 also provides some insight into the fuel and technology choices for the subset of rural residents who have their own wood resources. Many of these residents may perceive their wood supply as free. With a wood price of zero, both the conventional and advanced HH technologies dominate all non-wood alternatives. In reality, there likely is a non-zero cost associated with “free” wood for most residents. This cost is a function of the resident’s valuation of their own time used to collect and split the wood, as well as the opportunity cost of not selling the collected wood to others. One estimate was that it would require approximately six person-hours to haul, cut, split and stack a cord of wood (Burkhard, 2010). Excluding equipment costs and assuming a labor rate of $15 per hour, the wood would carry an added value cost of approximately $90 per cord.

6.4.4 Sensitivity to HH Thermal Efficiency

We examined thermal efficiencies that ranged from 20% to 80%. Results are shown in Figure 6-10.

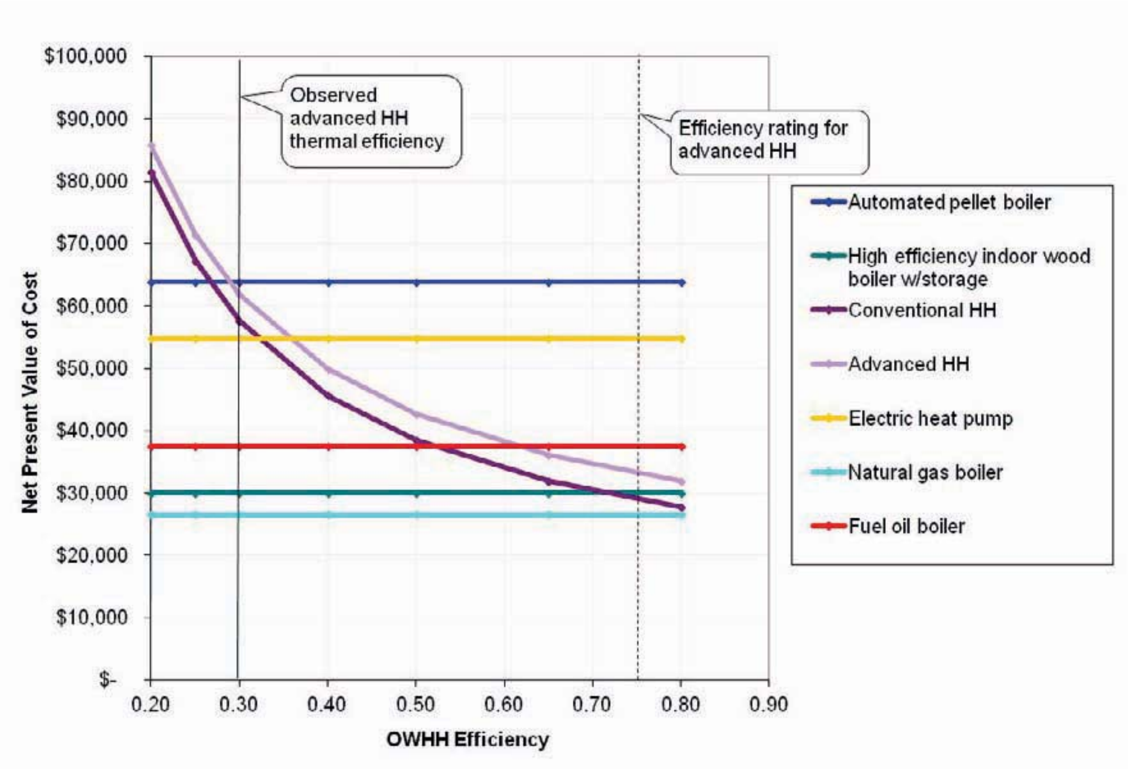

Figure 6-10. Sensitivity to HH Thermal Efficiency.

Figure 6-10 suggests that the competitiveness of HHs is influenced greatly by their efficiency. For example, the rated efficiency of the advanced HH results in the device having a lower NPV than both the fuel oil boiler and the electric heat pump. If, instead, the thermal efficiency that was experimentally determined is used, the technologies become far less competitive when all other assumptions are kept at their baseline values.

6.4.5 Sensitivity to Both Wood Price and HH Thermal Efficiency

Figure 6-11 synthesizes the information from both Figures 6-9 and 6-10. The x-axis represents wood price, while the y-axis represents the thermal efficiency of the advanced HH unit. The lines on the figure represent the combinations of wood price and HH efficiency at which the HH and the specified technology have the same NPV of lifetime costs.

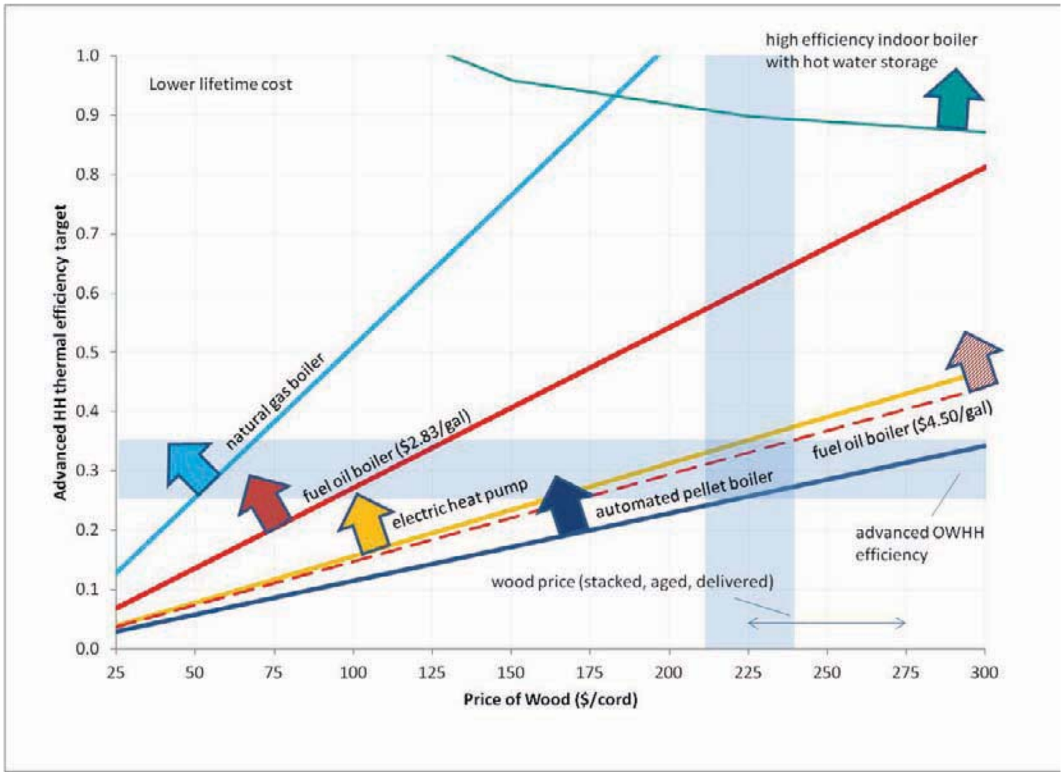

Figure 6-11. Competitiveness of Advanced HHs as a Function of Wood Price and HH Thermal Efficiency.

Figure 6-11 shows the combinations of wood price and thermal efficiency at which an advanced HH becomes cost competitive with other devices. A good starting point for interpreting the graph is the rectangular area created by the intersection of advanced HH efficiencies in the mid-20s to mid-30s and wood prices between $210 and $240, encompassing the baseline assumptions. The rectangle falls below all of the technology-specific lines on the graph except for the automated pellet boiler, indicating that the advanced HH is more costly than those technologies from a Net Present Value (NPV) perspective. Increasing efficiency or lowering the price of wood can result in the advanced HH becoming competitive, however. For example, increasing efficiency to above 35% results in the HH have a lower NPV cost than the electric heat pump (at a wood price of $225). Similarly, a wood price below $60 per cord results in a NPV cost less than natural gas (at an advanced HH efficiency of 30%). It is important to note that decreasing the wood price also has the effect of lowering the NPV cost of the high efficiency indoor wood boiler with storage, and the HH must achieve even higher efficiencies to be cost competitive. The solid and hashed red lines on the graphic indicate that competitiveness with oil is highly dependent on oil price. At a price of $4.50 per gallon, the advanced HH needs only achieve an efficiency of approximately 33% to rival the oil boiler. In contrast, at a fuel oil price of $2.83 per gallon, the HH unit must achieve a thermal efficiency greater than 60%.

6.4.6 Sensitivity to Changes in HH Equipment and Installation Cost

The upfront cost associated with purchasing and installing a heating device is one component of its lifetime cost. In the next set of sensitivity runs, the impact of changing these costs was examined. The baseline cost of the advanced HH was evaluated for values ranging from $7,000 to $28,000. The results are shown in Figure 6-12.

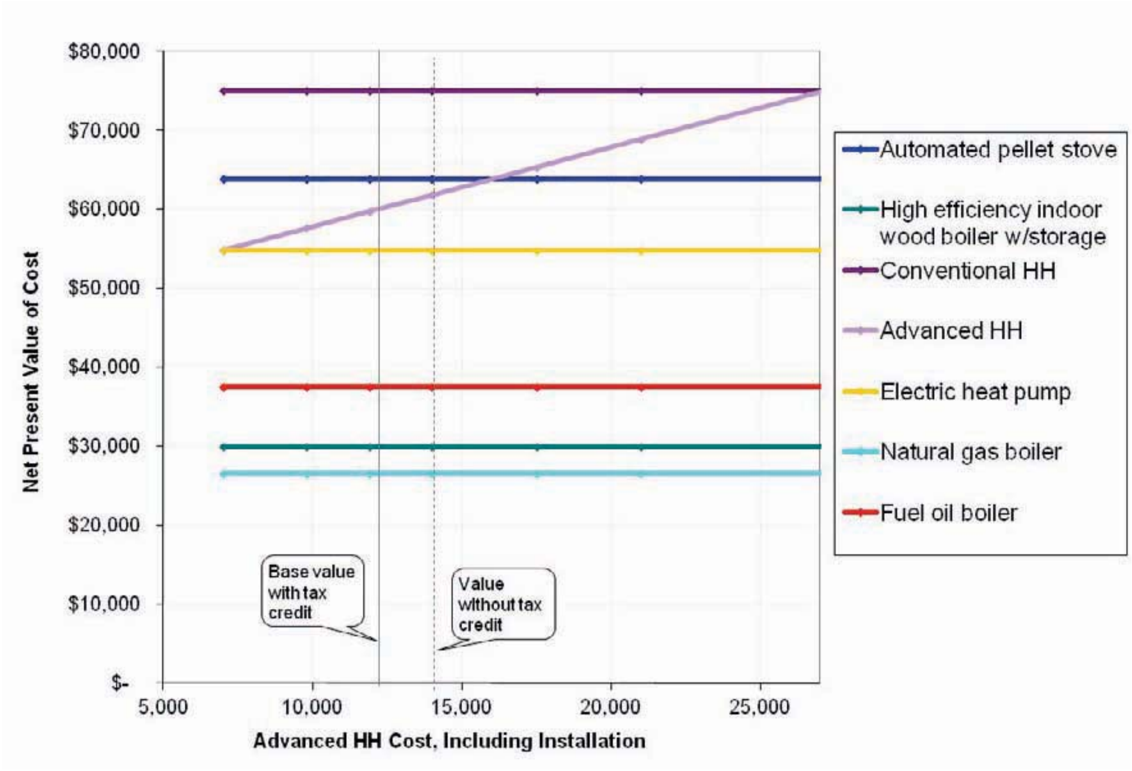

Figure 6-12. Sensitivity to Changes in Advanced HH Equipment and Installation Cost.

Nowhere along this range of values did the advanced HH technology have a lifetime NPV less than the electricity, oil, or gas technologies. This result reinforces the earlier observation that the purchase and installation costs amount to only a fraction of the lifetime costs. The results also allow us to test how the competiveness of the advanced HH changes with and without the $1,500 tax credit. The credit has very little impact on NPV and no impact on the ranking of the technologies.

6.4.7 Impact of High Fuel Prices in the State of New York

New York is known for having high energy prices, as indicated in Table 6-2. The next step of our analysis is to examine how these high prices may impact the competitiveness of HH technologies. Figure 6-13 is similar to Figure 6-9, but indicates the NPV of heat pumps and gas and oil boilers using national average prices. Electric heat pump efficiency is not changed in the calculations, however.

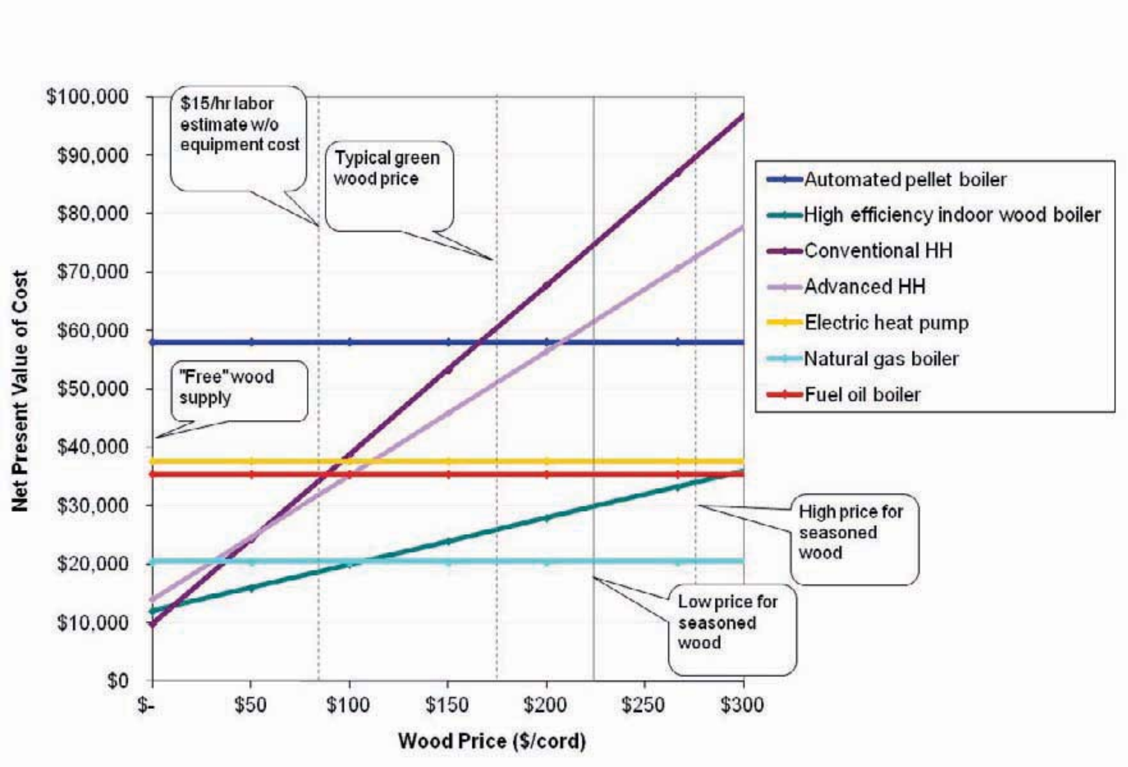

Figure 6-13. Sensitivity to Wood Price, using National Average Prices for Electricity, Natural Gas, and Fuel Oil. NPV of fuel oil boilers and electric heat pumps are roughly equivalent.

These figures suggest that New York's high natural gas and fuel oil prices have an impact HH competitiveness. For example, the advanced HH is competitive with the electric heat pump at a wood price of approximately $190 per cord in New York. Using the much lower national average electricity price, wood must be priced less than approximately $100 per cord to be competitive.

6.4.8 Impacts of Natural Gas, Oil and Electricity Price Changes

Figures 6-14, 6-15, and 6-16 show sensitivities to the prices of competing fuels, including fuel oil, natural gas and electricity.

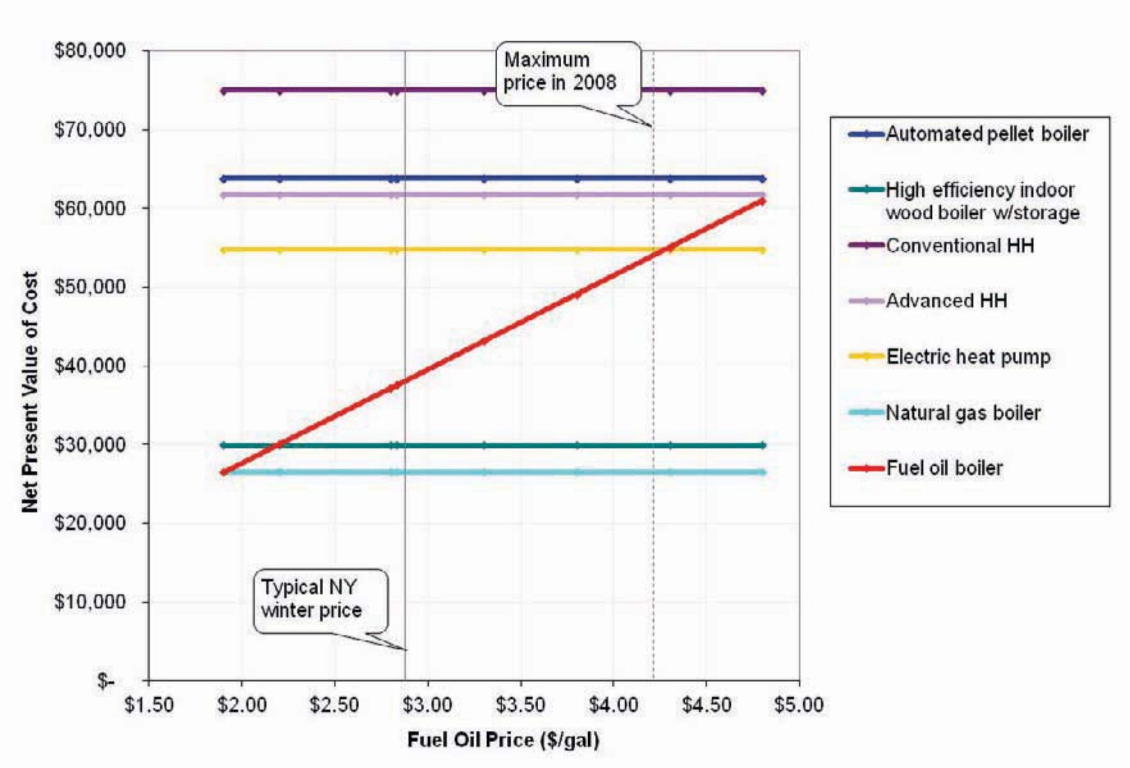

Figure 6-14. Sensitivity to Fuel Oil Price.

Over most of the range of oil prices evaluated, the oil boiler had a lower cost than the heat pump, but a higher cost than the natural gas boiler. At baseline HH efficiencies and wood prices, neither HH technology was competitive with the oil boiler at any oil price that was examined.

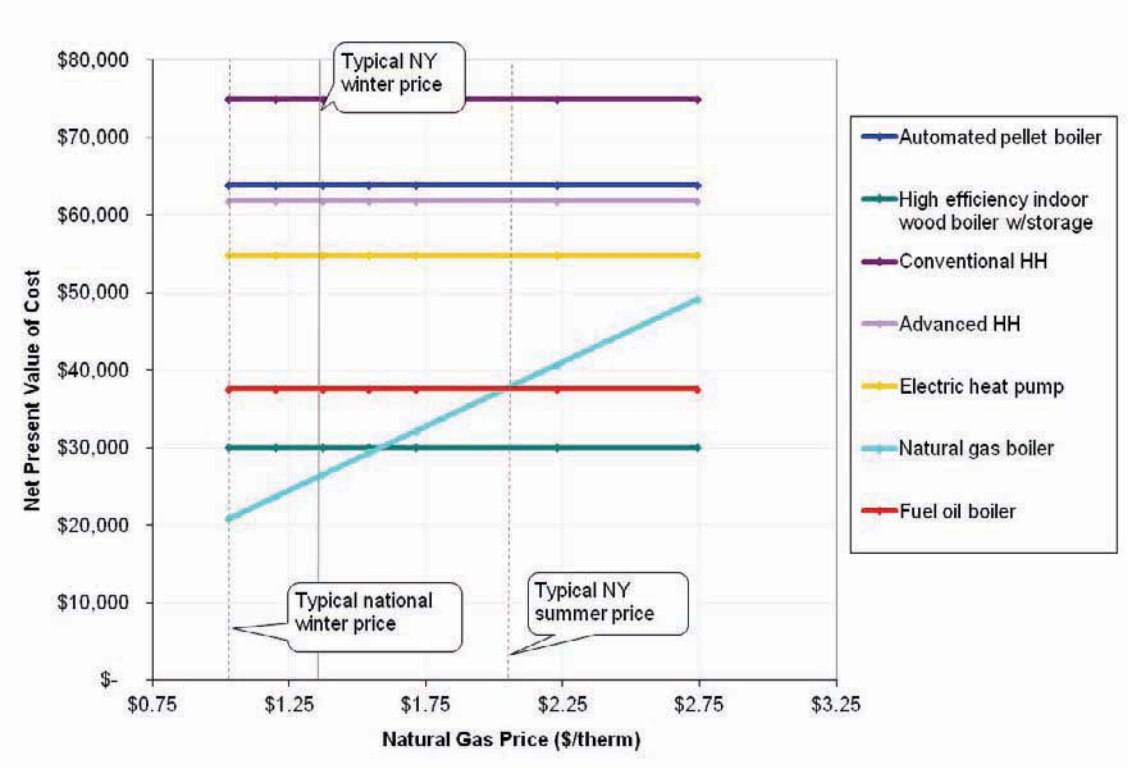

Figure 6-15. Sensitivity to Natural Gas Price.

Natural gas boilers were the least cost option until natural gas prices were increased to approximately $1.50 per therm, after which the natural gas boiler became more expensive than the indoor wood boiler with storage. The gas boiler was less expensive than the electric heat pump, pellet boiler, and HH units across all natural gas prices that were evaluated. Recent advances in techniques for extracting natural gas from shale formations may result in relatively stable and potentially lower natural gas prices in the future. Long-term predictions of natural gas prices are difficult, however, because of competition with other sectors and environmental and climate considerations.

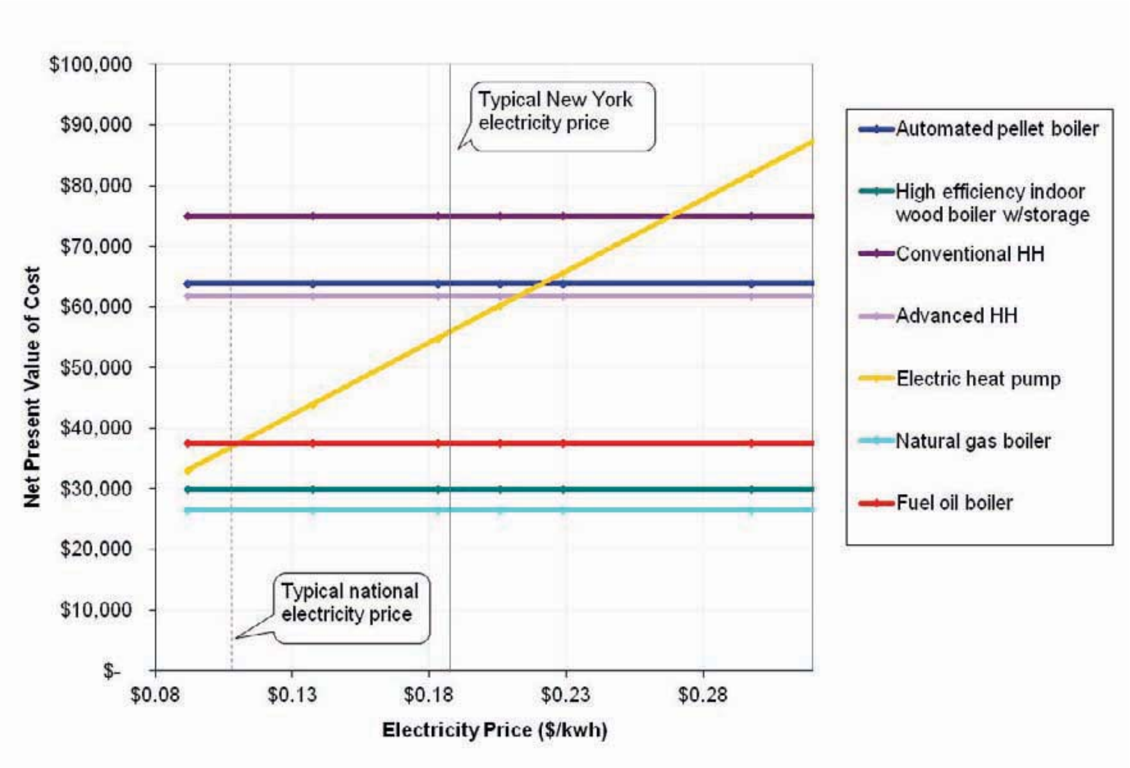

Figure 6-16. Sensitivity to Electricity Price.

This figure shows a result similar to the previous two: at baseline efficiencies and wood prices, HHs have a higher NPV than electric heat pumps. An electricity price of over $0.2 per kwh is required before HH units have a lower NPV than electric heat pumps.

6.4.9 Sensitivity to Simultaneous Changes in Wood Price and Oil Price

In practice, the market prices for many fuels are correlated. For example, high oil prices yield higher demand for wood. Wood prices rise as a result. Figure 6-17 shows the NPV costs for the various technologies, with wood and fuel oil prices shifted by similar percents.

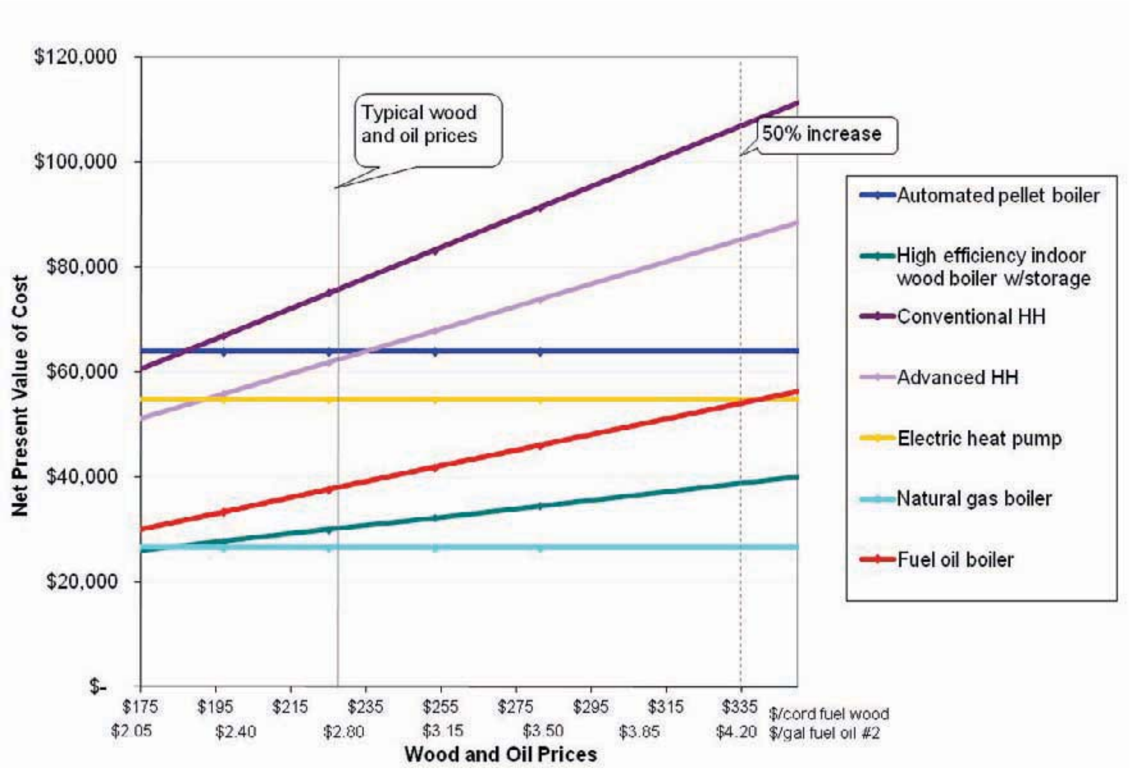

Figure 6-17. Sensitivity to Wood and Oil Prices.

An important observation is that the correlated price changes result in the lines for wood and oil technologies shifting in parallel. There are no thresholds at which the wood and oil technology lines cross. These results suggest that HH competitiveness will be affected negatively where wood supply is limited or where cord wood vendors adjust their prices relative to the price of fuel oil.

6.4.10 <u>Sensitivity to House Size</u>

In previous sensitivities, all heating units were required to be oversized relative to the maximum hourly heating load by a factor of at least 1.7. With an hourly maximum load of 55,000 BTU, the design capacity was 93,500 BTU per hour. The HH units had rated capacities of 250,000 and 160,000 BTU per hour, and thus were oversized at ratios of 4.5 and 2.9, respectively. Would these devices be more competitive on a different size house? The answer to this question is explored by comparing device costs over a range of houses ranging in size from 1000 through 4000 square feet. The results are shown in Figure 6-18.

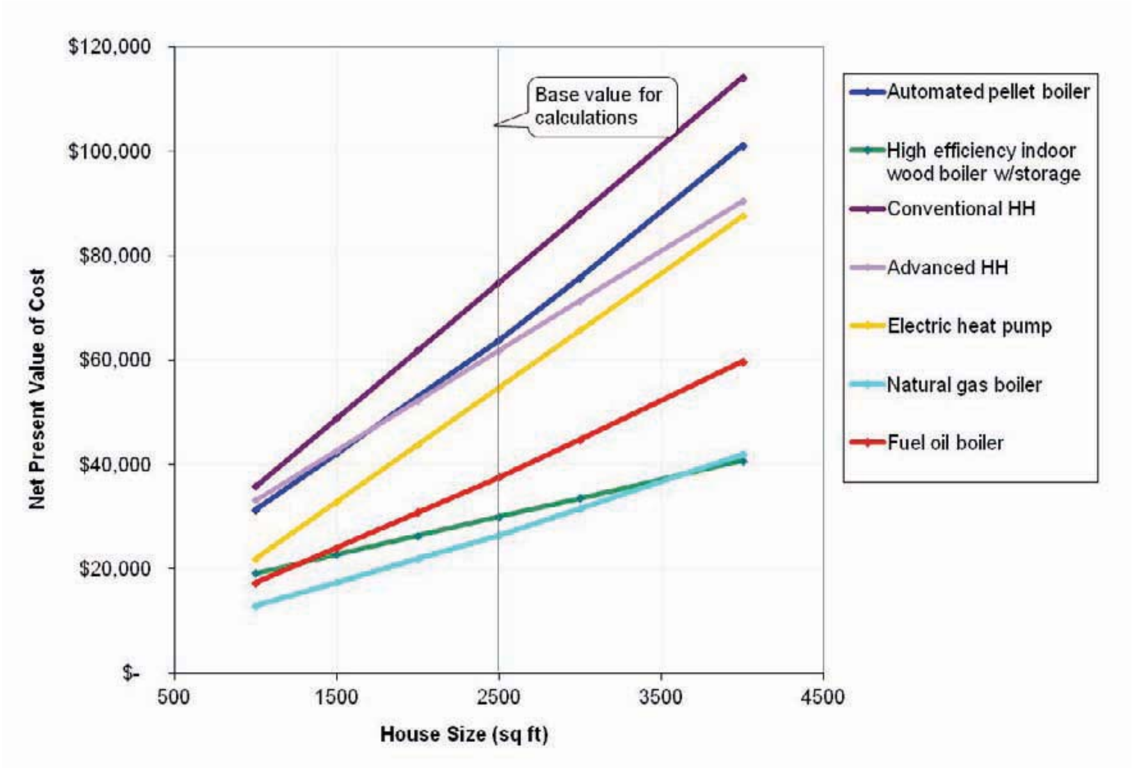

Figure 6-18. Sensitivity to House Size.

Over these sensitivities, the efficiencies of devices are not altered, so only capacity utilization increases with house size. Similar to levelized cost of energy (LCOE) calculations for utilities, increased capacity utilization allows the capital cost to be spread over more units of output. This spread results in some degree of curvature for the lines traced by the wood-fueled devices in Figure 6-18. Since the fuel cost represents a large portion of the NPV for each device, this curvature is small. Instead, the relationship between house size and cost is dominated by device efficiency.

The efficiency of real-world heating devices would also be a function of their capacity utilization. For example, cycling on and off could lower efficiency considerably. This effect is not modeled here.

6.4.11 Sensitivity to Hurdle Rate

A hurdle rate can be added to the NPV equation to approximate a consumer’s hesitancy to make a large up-front capital investment, to simulate a required pay-back period to recoup these costs, or to incorporate consideration of the cost of borrowing money.

Incorporating a hurdle rate, Equation 3 becomes:

$$NPV = \left[CAP * \left[\frac{h*(1+h)^n}{(1+h)^n - 1} \right] + ANN \right] * \left[\frac{(1+i)^n - 1}{i*(1+i)^n} \right] \tag{6-3}$$

where:

h is the hurdle rate.

In Equation 3, the capital cost is transformed into an equivalent annualized cost using the hurdle rate. The resulting value is added to the annual fuel cost, and the combination is brought back to present value using the discount rate. Effectively, the hurdle rate increases the magnitude of the capital cost relative to the annual thermal cost. Use of hurdle rates to incorporate the cost associated with borrowing money is generally straightforward. For example, a hurdle rate of 0.16 would be equivalent to an 18.5% interest rate on a loan (16% + 2.5% inflation) to purchase a heating device.

To explore the impact of the hurdle rate, we explore values ranging from 1% through 44%. The results are shown in Figure 6-19.

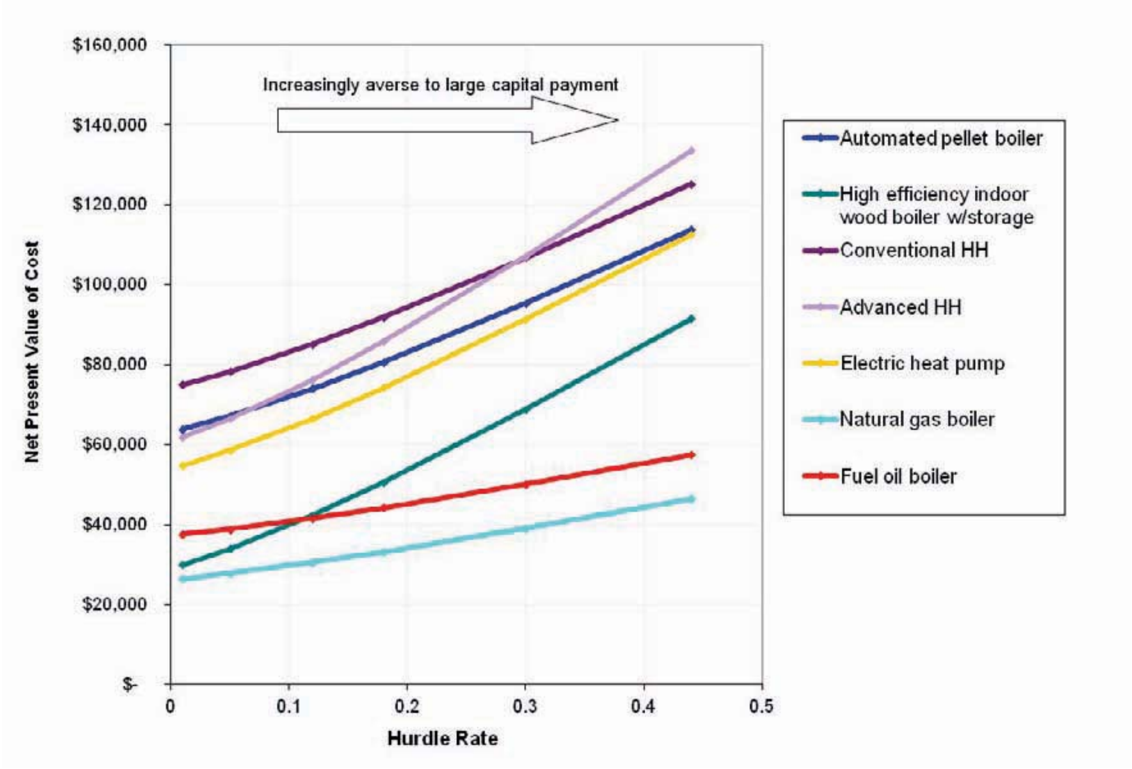

Figure 6-19. Sensitivity to Hurdle Rate.

As expected, these results show that increasing the hurdle rate favors technologies with lower capital costs. The natural gas boiler has the lowest capital cost and thus benefits the most. Relative to natural gas and oil boilers, the wood technologies have high capital costs and thus are penalized.

6.4.12 HH Competition with Indoor Wood and Pellet Boilers

The sensitivity results in Figure 6-9 show that HHs can be very competitive with electric and fuel oil at low-to-moderate wood prices. High efficiency indoor wood boilers also benefit from low wood prices. These units are sufficiently cost-effective that they may even be competitive with natural gas boilers given small increases in natural gas prices or small decreases in wood prices. Competitiveness of these units with natural gas boilers may open new markets for residential wood in the future.

Automated pellet boilers are another emerging technology. Pellets may be made of a variety of materials, including sawdust, wood wastes, energy crops, and cellulosic materials. At current pellet prices, automated pellet boilers have a higher NPV cost roughly equivalent to advanced HHs and greater than all of the other technologies considered. Since the automated pellet boilers are an emerging technology, there is still a limited supply of pellets available. If additional suppliers emerge, pricing may become more competitive.

Figure 6-20 suggests that a 25% drop in pellet prices would allow the pellet boiler to achieve an NPV cost equivalent to electric heat pumps. Some markets have seen significant drops in pellet prices recently, so this outcome could be reasonable (woodpelletprice.com 2011).

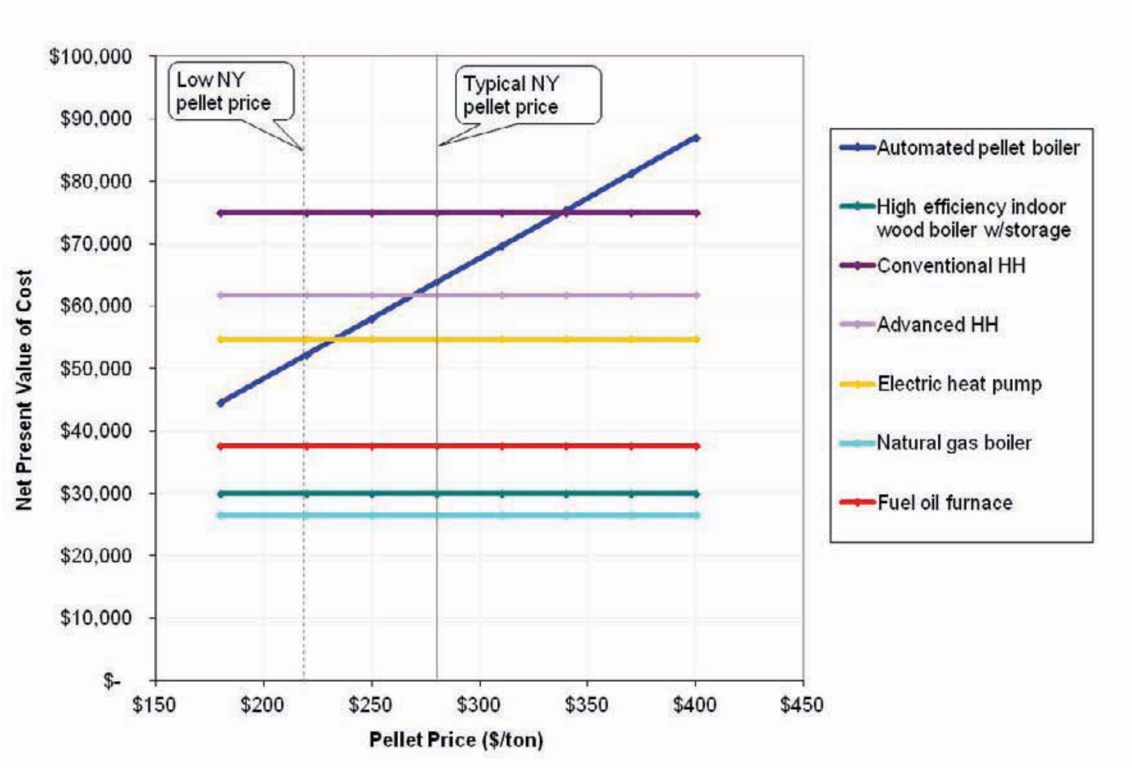

Figure 6-20. Sensitivity to Pellet Price.

6.5 SUMMARY AND CONCLUSIONS

The work presented here is a relatively simple engineering economic analysis in which the lifetime costs of conventional and advanced HHs are compared with the lifetime costs of other technologies. Parametric sensitivities are carried out to examine the impacts of alternative assumptions about HH efficiencies and costs, fuel prices, house size, and other factors. As outlined in Section 6.3.5, there are many caveats that must be considered when evaluating the results of this analysis. Nonetheless, some very important, and likely robust, observations can be made.

Over a broad range of sensitivities, natural gas boilers tend to have the lowest lifetime NPV cost compared to electric heat pumps, fuel oil boilers, HH and pellet technologies. Census data visualized in Figure 6-2 corroborate: where natural gas is available, natural gas has tended to be the fuel of choice. Natural gas is not available in all parts of the State of New York, however. Real-world economics dictates that many low-density rural areas do not have access to natural gas distribution systems. In these rural areas, HHs are likely to compete with electricity and fuel oil for market share.

For baseline assumptions, HHs are not cost competitive with fuel oil and electric heat pump technologies. Working against HH units are their relatively high capital costs, as well as their low thermal efficiencies.

Further, the thermal efficiencies used in this analysis are likely to be higher than would be experienced in practice since the units would likely be used during the fall and spring months when loads and efficiencies would be lower.

The real world produces additional constraints that work against HHs. For example, their high emission rates have resulted in passing of ordinances that ban or limit HH use in some counties and communities. Further, households must have room to store delivered wood fuel, and many residents may find it inconvenient to have to go outside to load wood into the boiler. The high efficiency indoor wood boiler also requires firewood storage. The high efficiency indoor wood boiler that was examined, however, addresses efficiency concerns by storing heat in a large water tank, allowing the unit to operate without cycling. The increased efficiency associated with this configuration is dramatic, and the increased efficiency allows the unit to compete well in NPV cost with even the natural gas boiler. Staged combustion (gasification) units with thermal storage are being selected increasingly in the marketplace.

A major wildcard in the engineering economic assessment is the price for wood fuel. A typical range for aged, split, delivered and stacked cord wood in the State of New York is \$225 to \$275 per cord. A subset of residents may have access to lower-cost supplies of wood. Our sensitivity analysis suggests that wood prices of less than \$190, \$110, and \$55 per cord may allow HHs to be competitive with heat pumps, fuel oil boilers, and natural gas boilers, respectively (Figure 6-9). It is important to note that decreasing price of wood also lowers the NPV cost of the high efficiency indoor wood boiler with storage. Thus, the HH must achieve even higher efficiencies to be cost competitive with these higher efficiency wood-burning devices.

Many rural households have their own supply of wood, which they may perceive to be free. Even if the labor costs associated with carrying and splitting the wood are factored in, these homeowners may still perceive HHs as the most cost-effective option even if it is not. This last point begins to hint at the importance of perception and other difficult-to-quantify factors. Most homeowners may not undertake the analysis carried out here. Homeowners may also not go through an explicit process to evaluate the value of their time. The homeowners may not be aware of the correlation between wood and oil prices in many markets. Instead, it is likely that those who have chosen to install HHs have been motivated by qualitative perceptions of the technology’s cost, the perception of environmental benefits, and an ability to hedge against increases in fuel prices. They may also have been influenced by their interest in the exercise associated with splitting wood or the amount of time that they have available for splitting wood and for loading the fuel into the HH. The availability of land to store wood fuel plays a role. Tax credits may also be a highly motivating factor, even if they are far less important than device efficiency and fuel cost in determining lifetime heating costs. These factors cannot easily be quantified within an engineering economic assessment and yet may be the dominant factors in decision-making.

Given our simple engineering economic analysis and investigation of parametric sensitivities, there would seem to be very little market for HHs. In reality, there are many combinations of assumptions that lead to niches where HH units would make economic sense to a homeowner, reinforcing the point that a heterogeneous set of market conditions is leading to HH penetration. This heterogeneous set of market conditions includes varying ownership and access to wood and pellet resources, varying energy prices, varying access to a natural gas infrastructure, varying local and state ordinances, varying incentives, and varying personal experiences and preferences. Developing a deeper understanding of this variability and the niches that it creates will be an important step in more fully characterizing and understanding the markets for residential heating systems.

6.6 POSSIBLE NEXT STEPS

The analysis presented here provides a starting point for evaluating the competitiveness of HHs when compared to a range of alternatives. This analysis also highlights the fact that many of the most important drivers for the adoption of HHs are not quantitative, but are instead related to perception and preference. Examination of these qualitative drivers was beyond the scope of the work presented here, but would be an interesting and useful endeavor.

Incorporation of a few additional parameters into the cost calculations may be useful. For example, explicit consideration of capacity utilization and its impact on thermal efficiency would have the potential to improve the cost estimates. Omission of this consideration likely results in lower NPV costs than would otherwise be calculated. Consideration of price projections for various fuels may also provide insights regarding how these projected trends will impact heating costs and competitiveness. The choice of discount rate could be explored further to investigate how opportunity costs impact the competitiveness of wood. Determination and use of a thermal efficiency value for the high efficiency indoor wood boiler with thermal storage will improve the fuel cost estimations for those units.

Another potential follow-up activity would be to explore how other technologies perform relative to those examined here. For example, ground source heat pumps, propane systems, and electric baseboard heating could be evaluated. HHs with integrated hot water storage could also be examined and compared.

7. PROJECT CONCLUSIONS

Four wood-fired HH units representing various technologies and fuels were tested under conditions representative of homeowner operation with a Syracuse winter heat load demand for energy performance and emissions. Emissions were tested for inhalation effects, laboratory-based experiments were compared to full-scale unit performance, an energy systems model examined the broader energy and emissions impact of HHs, and economic techniques compared lifetime costs of alternative technologies. A schematic of the test system is shown in Figure 7-1.

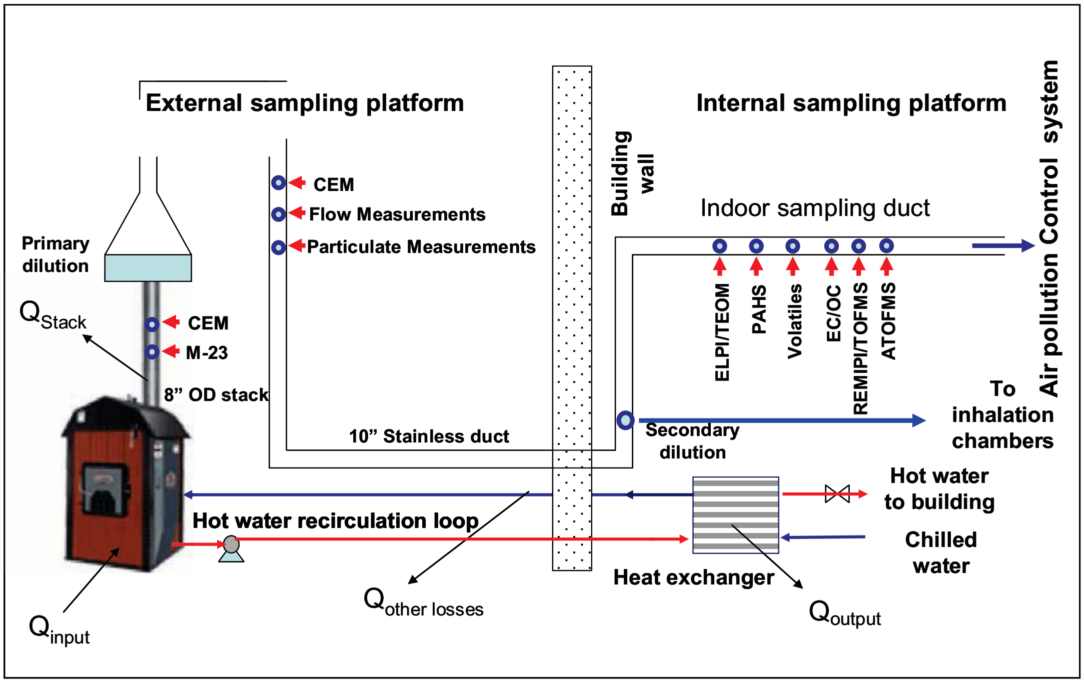

Figure 7-1. Test System for Wood-Fired HHs.

The units with cyclical damper operation to modulate their heat release showed considerable variation of heat transfer and concomitant emissions. When the dampers were closed, combustion became oxygen-starved, resulting in incomplete combustion of the fuel and formation of pollutants. Upon damper opening and gas flow through the system, these pollutants are released, resulting in a cyclic increase in pollutant release. The modulating combustion also led to considerable nuisance odor (despite the emissions passing through a downstream APCS consisting of an afterburner and scrubber) and threatened to shut down the project.

The heat release rate as shown in Figure 7-2 also reflects the cyclic damper frequency, increasing during open damper enhanced combustion periods. The frequency and duration of the damper openings is a function of the degree to which the unit is oversized for the heat load. The damper openings and closings also impact the thermal efficiency of the unit, which ranges between 22% and 31% for the Conventional, Single Stage HH and Three Stage HH units. The European Two Stage Pellet Burner unit had a thermal efficiency of 44%. Its cyclic heat release more closely matches the heat load demand. Comparative measurements for the non-cycling U.S. Two Stage Downdraft Burner unit were not made and no thermal efficiency can be determined.

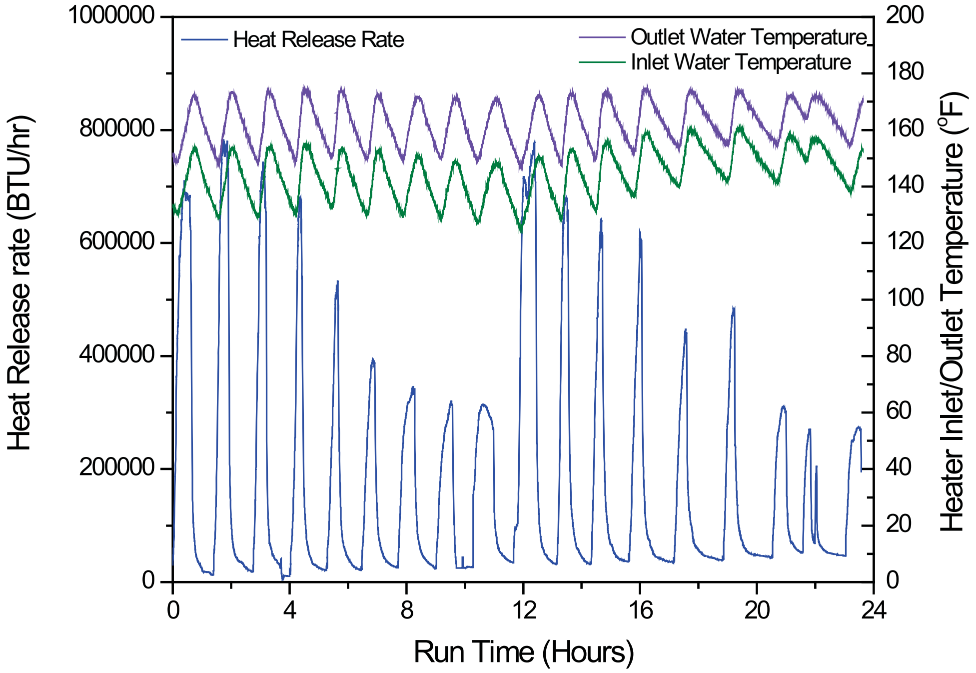

Figure 7-2. Heat Release Rate and System Water Temperatures for the Conventional, Single Stage HH Unit Firing Red Oak.

Testing showed a wide range of PM emissions depending on both unit and fuel types. For the Conventional, Single Stage HH, the PM emissions on a thermal input basis for the three fuels vary between approximately 2.9 and 5.1 lb/MM BTU with the emissions from the red oak and the red oak plus refuse being generally similar (2.9-3.0 lb/MMBTU). The PM emissions almost double, however, when white pine is burned in the same unit. Average emissions on a thermal energy input basis for the Three Stage HH, U.S. Two Stage Downdraft Burner gasifier unit, and European Two Stage Pellet Burner hardwood pellet units ranged from 0.54 lb/MMBTU for the Three Stage HH, 0.39 lb/MMBTU for the U.S. Two Stage Downdraft Burner gasifier, and 0.037 lb/MMBTU for the European Two Stage Pellet Burner heater. Lower PM emissions from these three units reflect the more advanced technologies and generally higher combustion efficiencies compared to the older Conventional, Single Stage HH unit. The Three Stage HH employs a secondary combustion chamber and larger thermal mass. The European Two Stage Pellet Burner unit uses a consistent uniform fuel and a more steady-state, but still cyclic, fuel feeding approach. The lower emissions from the U.S. Two Stage Downdraft Burner unit are likely related to both its two-stage gasifier/combustor and its thermal storage design, where batches of fuel are burned during short, highly intensive, presumably more efficient, periods and the extracted heat is stored for future demand (see Figure 7-3). Due to our inability to measure the thermal flows through the heat storage properly, the thermal output for the U.S. Two Stage Downdraft Burner unit was estimated using the heat loss method (boiler efficiency).

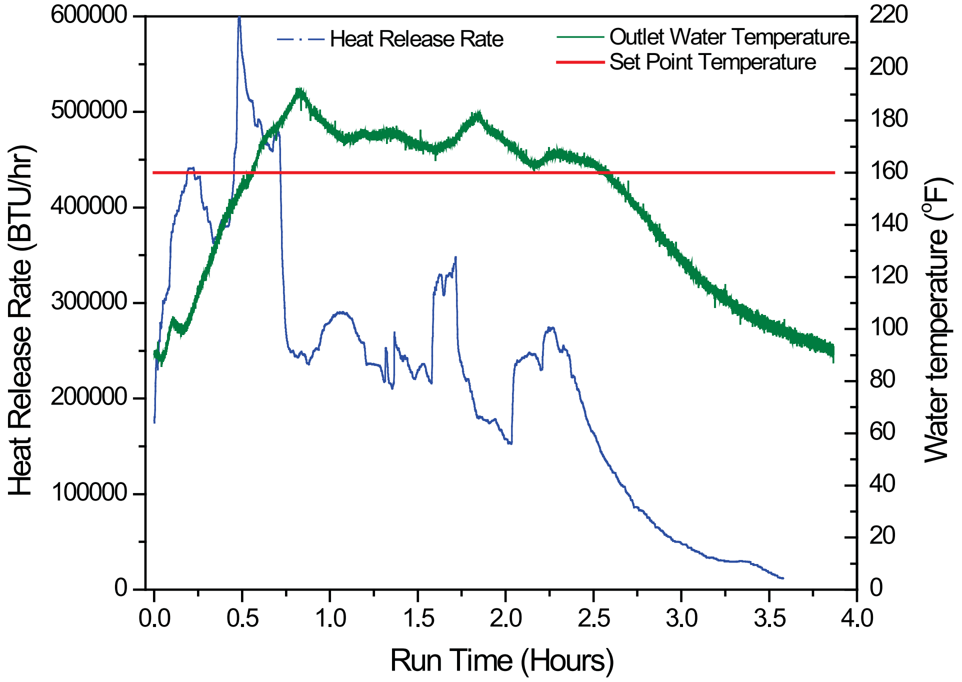

Figure 7-3. Heat Release Rate from the U.S. Two Stage Downdraft Burner Unit with Thermal Storage.

Figure 7-4 compares average daily PM emissions from the four units and different fuels for a typical Syracuse, New York, home on a January heating day. These data are analogous to the emissions based on thermal output as the different units attempt to match their thermal output to the Syracuse load demand. The Conventional, Single Stage HH burning white pine produced the highest total daily PM emissions (6.3 kg (14 lbs)) and the European Two Stage Pellet Burner heater the lowest (0.036 kg (0.08 lb)). Emissions for the Three Stage HH and U.S. Two Stage Downdraft Burner units were comparable at 0.69 and 0.62 kg/day (1.51 and 1.37 lbs/day), respectively. Again, white pine combustion in the Conventional, Single Stage HH unit produced daily PM emissions that were 40% greater than red oak and 70% greater than red oak plus refuse.

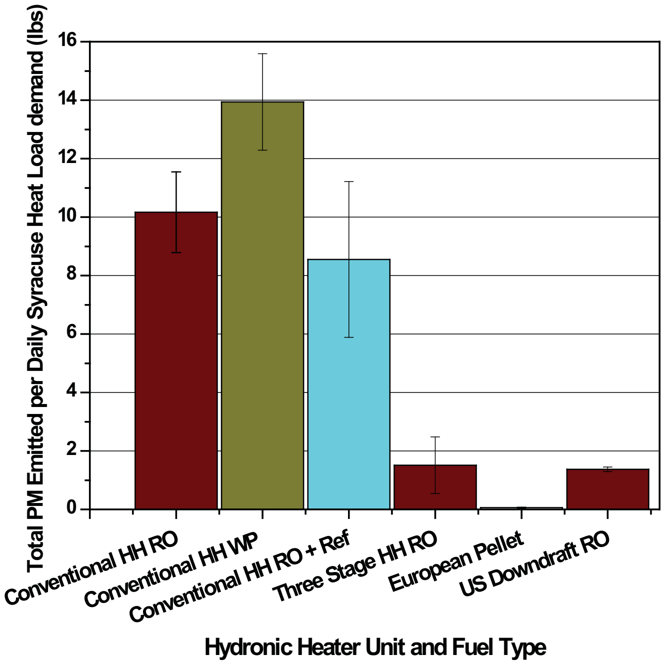

Figure 7-4. PM Generated per Syracuse Day for All Six Unit/Fuel Combinations.

Particle number concentrations as well as particle size distributions (PSDs) were measured continuously and range from a high of ~ 2.6×10^{13} particles/MMBTU for the Conventional, Single Stage HH burning white pine to a low of ~ 4.0×10^{12} particles/MMBTU for the European Two Stage Pellet Burner. For the three fuels burned in the Conventional, Single Stage HH unit, the trend in the particle number emissions is similar to the PM mass emissions discussed above with pine combustion having the highest value and the oak plus refuse having the lowest. Due to the cyclic damper operation of several of the units, the PM number emissions were also both cyclic and highly variable. The exception was the U.S. Two Stage Downdraft Burner gasifier where a single high burn condition (consistent with its thermal storage design) was tested.

Number-based PSDs, based on one-minute “snapshots” taken 5 minutes into the damper open cycle, were also determined from the ELPI data for all units tested. For the Conventional, Single Stage HH, the PSDs all tend to be bimodal, with well-established accumulation modes between 100 and 300 nm and evidence of predominant nuclei modes indicated by increasing concentrations for particles less than 30 nm. The accumulation modes are likely comprised of an evolving aerosol, formed within the combustors, and comprised of soot, ash, and condensing organics. In contrast, the nuclei modes are likely the result of nucleating organics which form much closer to the sampling location. For the Three Stage HH, the PSDs appear to be somewhat similar to those generated by the Conventional, Single Stage HH except with respect to the lower number concentrations and the related shift in the accumulation mode toward smaller sizes (70-150 nm). In the case of the European Two Stage Pellet Burner, the PSDs exhibit a well-established accumulation mode between 100 and 200 nm with no evidence of a nuclei mode. Finally, PSDs measured from the U.S. Two Stage Downdraft Burner gasification unit suggest a single evolving mode. For the replicate tests, this mode varied from less than 30 to 80 nm.

The ratio of OC to EC (OC/EC) was within the range of 20-30 for the first two units regardless of fuel type. The OC/EC ratio for the European Two Stage Pellet Burner unit, on the other hand, was much lower indicative of higher combustion efficiency and lower emissions. The OC/EC ratio of the U.S. Two Stage Downdraft Burner unit, however, was only slightly lower than the first two units indicating somewhat better combustion efficiency. Emission factors for BC were determined; these BC emission factors are believed to be the first such data for these unit types.

Temporal emission profiles were more a function of the elapsed time from the last fuel charging than of the heat load on the unit. The emissions of CH_4, THC, and CO are consistent with the cyclic nature of the damper openings. These emissions are associated with the damper cycle, creating alternately poor and good combustion conditions. Units that cycle the damper opening to regulate the heat production have much higher emissions than the pellet burner and the non-cycling U.S. Two Stage Downdraft Burner unit. Predictably, higher CO_2 emission factors result from those units that minimize pollutant formation, such as the European Two Stage Pellet Burner.

GC/MS techniques identified and quantified the PM-bound SVOCs, which accounted for 9% w/w of the PM emitted from the HH boilers on average. The HH PM comprised 1-5% w/w levoglucosan, an anhydro-sugar and important molecular maker of cellulose pyrolysis. The levoglucosan compound accounted for approximately 40% of the quantified species. Organic acids and methoxyphenol (lignin pyrolysis products) SVOCs were the compound/functional group classes with the highest average concentrations in the HH PM. These compounds are naturally abundant, also used as atmospheric tracers, and are important to understanding the global SVOC budget.

The PAHs explained between 0.1-4% w/w of the PM mass. All 16 of the original EPA priority PAHs were detected in the HH PM emissions. The older Conventional, Single Stage HH unit technology emitted PM with higher PAH fractions. In general, the unit/technology type significantly influenced the SVOC emissions produced. Combustion of the white pine fuel using the older unit produced notably high SVOC emissions per unit energy and per unit mass of wood consumed; particle enrichment of SVOCs was also confirmed for this case. Addition of refuse to the red oak biomass generally resulted in a negligible increase in SVOC emissions per unit energy produced with the saturated HCs noted as an exception. Use of the pellet boiler generated the lowest SVOC emissions of the HH tested on a mass of fuel burned basis. However, the gasifier unit showed the lowest SVOC emissions per unit energy produced. Results show that the phase of the burn cycle can influence the emissions on a compound class basis. These and similar differences are highlighted in the main body of the report.

PCDD/PCDF emissions were sampled and ranged from 0.07 to 2.1 ng TEQ/kg dry fuel input, with the lowest value from the U.S. Two Stage Downdraft Burner unit and the highest from the Conventional, Single Stage HH with red oak + refuse (see Figure 7-5). The lowest value, from the U.S. Two Stage Downdraft Burner unit, may be due to the non-cyclic combustion resulting in consistent combustion and more complete burnout, but the limited data make this observation speculative. These values are consistent with biomass burn emission factors of 0.91 to 2.26 ng TEQ/kg (Meyer et al., 2007), woodstove/fireplace values of 0.25 to 2.4 ng TEQ/kg (Gullett et al., 2003), pellet and wood boiler values of 1.8 to 3.5 ng TEQ/kg, and wood stoves and boilers of 0.3 to 45 ng TEQ/kg (Hübner et al., 2005).

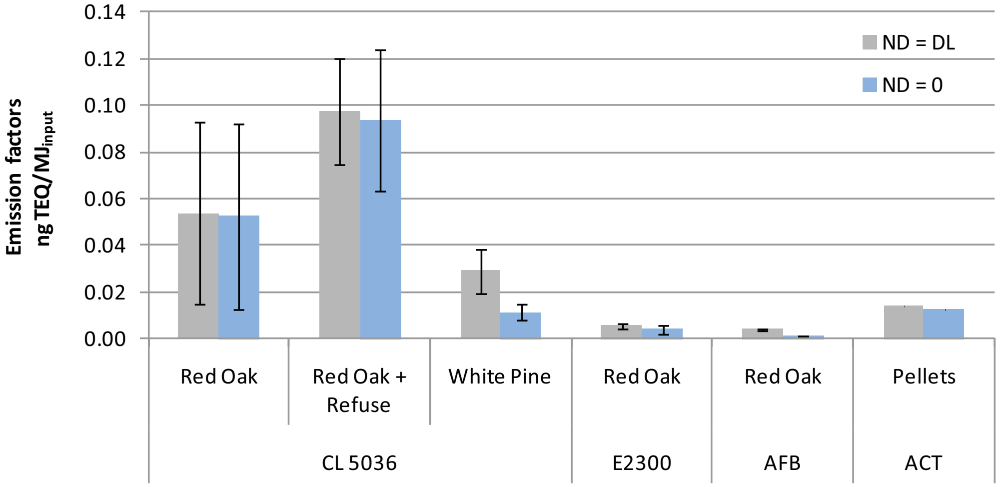

Figure 7-5. PCDD/PCDF Emissions with Non-Detects = Detection Limit and Zero.

Total PAH emission factors are shown in Figure 7-6 for all six unit/fuel combinations. The white pine fuel on the Conventional, Single Stage HH consistently had the highest PAH emissions, while the European Two Stage Pellet Burner unit with hardwood pellets had the lowest. PAH levels seem to be a clear function of fuel type (compare white pine with red oak on the Conventional, Single Stage HH) and unit type (compare red oak on the Conventional, Single Stage HH, Three Stage HH, and U.S. Two Stage Downdraft Burner units).

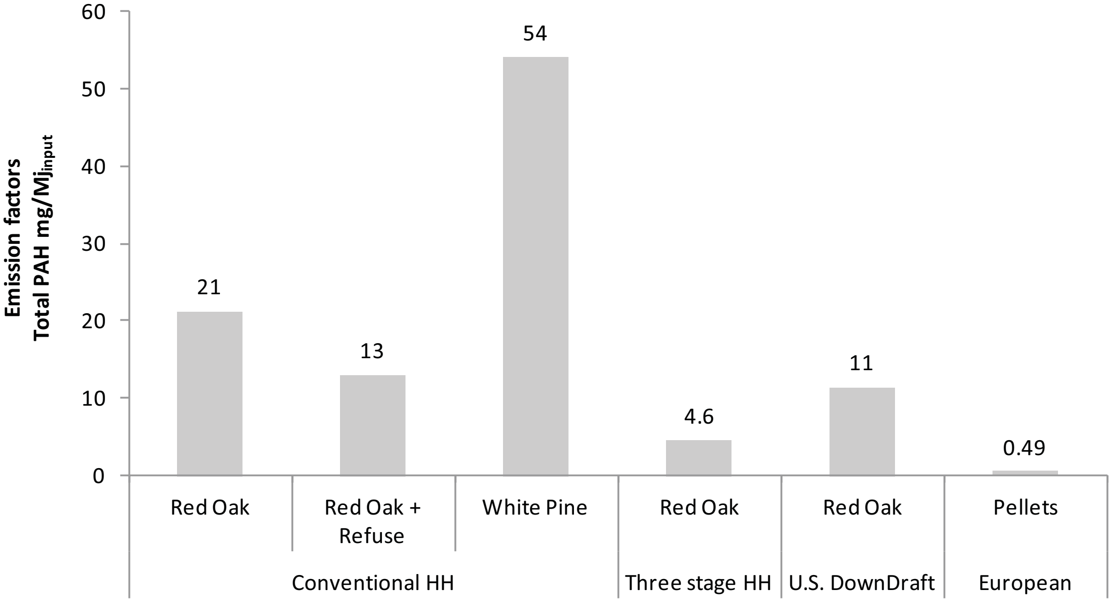

Figure 7-6. Total PAH Emission Factors.

A laboratory-scale study using a cone calorimeter test facility allowed testing of multiple fuels and comparison with full scale emission testing on the HHs. The emissions data/emission factors for four types of wood (red oak, ash wood, sugar maple and pine) and wood pellets were compared and showed that the cone calorimeter system can be used to obtain emission factors to compare different samples and to predict some emission factors from HHs. The emission factors from the cone tests, when compared to the Conventional Single Stage HH, predict the PM trend but fail to predict the trends for CO/CO_2, PCDDs/Fs and PAHs. These discrepancies are attributed to the two different combustion conditions, i.e., the well-ventilated condition in the cone calorimetry tests versus the oxygen-starved conditions in HHs. If the cone calorimeter is to be used to obtain emission factors more representative of emissions from HHs, then a range of combustion conditions (i.e., from well-ventilated to oxygen-starved) should be investigated.

An energy systems model termed **MARKAL** was used to examine the broader energy and emissions impact of HHs. The goals of this analysis were: (a) to identify possible future scenarios for the penetration of HHs and other advanced wood heating systems, (b) to place those scenarios in the context of total residential demand for space heating and total residential energy demand, and (c) to determine the emissions implications of those scenarios between 2010 and 2030. Because of the unique nature of the market for wood heating devices and wood and pellet fuels and the non-economic variables that often come into play, modeling this market in a pure cost optimization framework presents a challenge. We therefore used the model in a "what if" scenario framework, asking a number of targeted questions and running the model to assess the impact of certain assumptions regarding total wood heat market size, technology mix, rates of turnover, availability (or lack of availability) of advanced and high efficiency units, fuel price and availability, and emissions rates.

A baseline scenario and four alternative scenarios were examined. The baseline scenario models a modestly decreasing market share for wood heat in general, but greater penetration of conventional HHs over the 2005 through 2015 time period, along with a changeover from existing wood stoves to cleaner wood stoves. The contribution of wood stoves and HHs to the full market for residential space heating is shown in Figure 7-7.

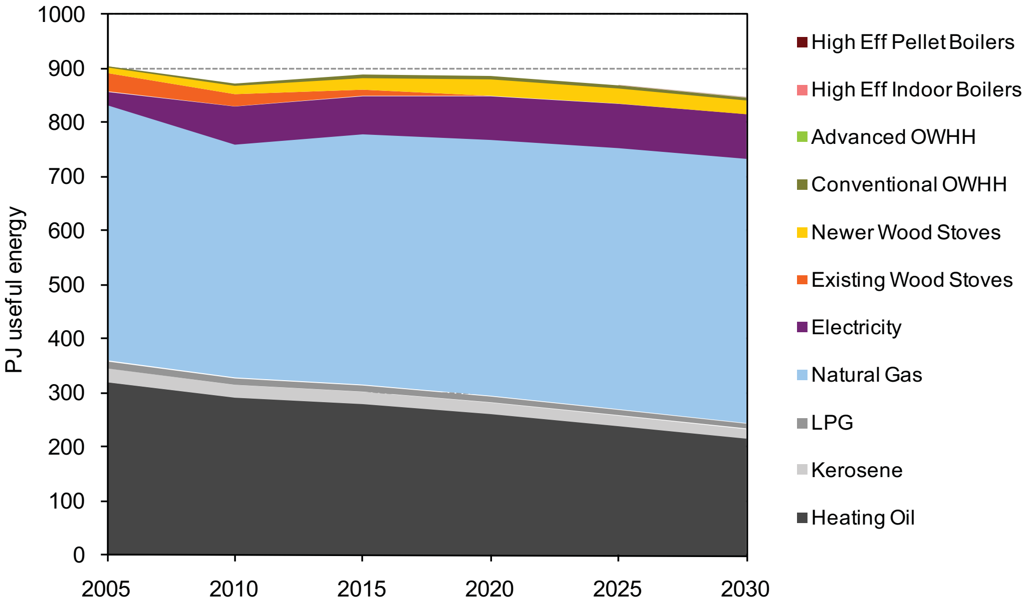

Figure 7-7. Market for Residential Space Heating for "Baseline" Scenario (PJ of Usable Energy).

In terms of emissions, this scenario was pessimistic in the assumption that cleaner, more efficient HHs would not be available for the entire modeling horizon. Figure 7-8 shows the PM emissions trends over time for this scenario for all residential energy use (not just space heating). From this comparison, it becomes clear that even though wood heat is a relatively small contributor to meeting total residential energy demand, it can dominate the emissions profile for the residential sector.

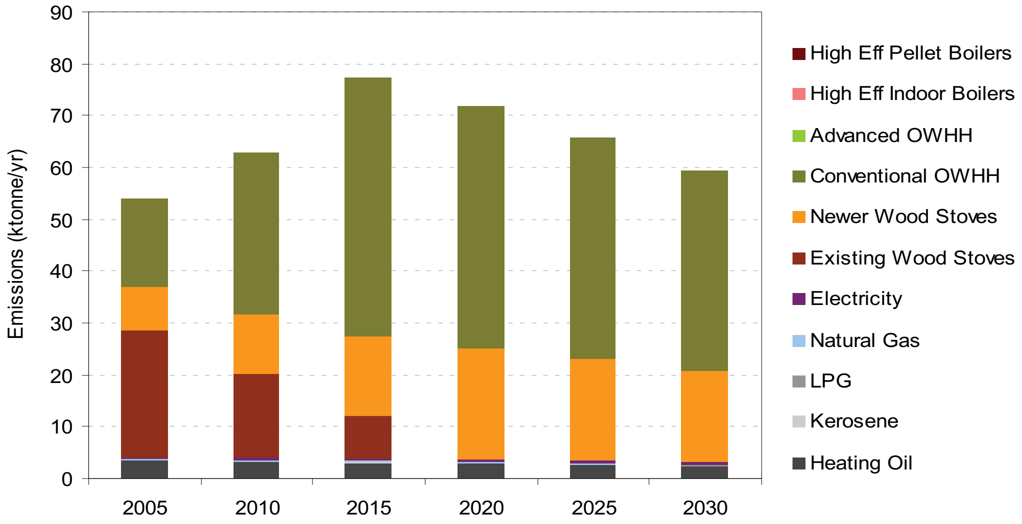

Figure 7-8. PM Emissions for Total Residential Energy Use for "Baseline" Scenario.

The "baseline" represents only one possible scenario, and not necessarily the most likely. How the market for wood heat, and HH units in particular, will evolve over the next 5-15 years is highly uncertain, and is driven by consumer preferences and behavior that are difficult to capture in a quantitative framework. The role that policy measures will play in terms of the rate of technology turnover, efficiency of new units, and emissions, adds another layer of uncertainty. Figure 7-9 shows the range of potential emission outcomes for a number of scenarios.

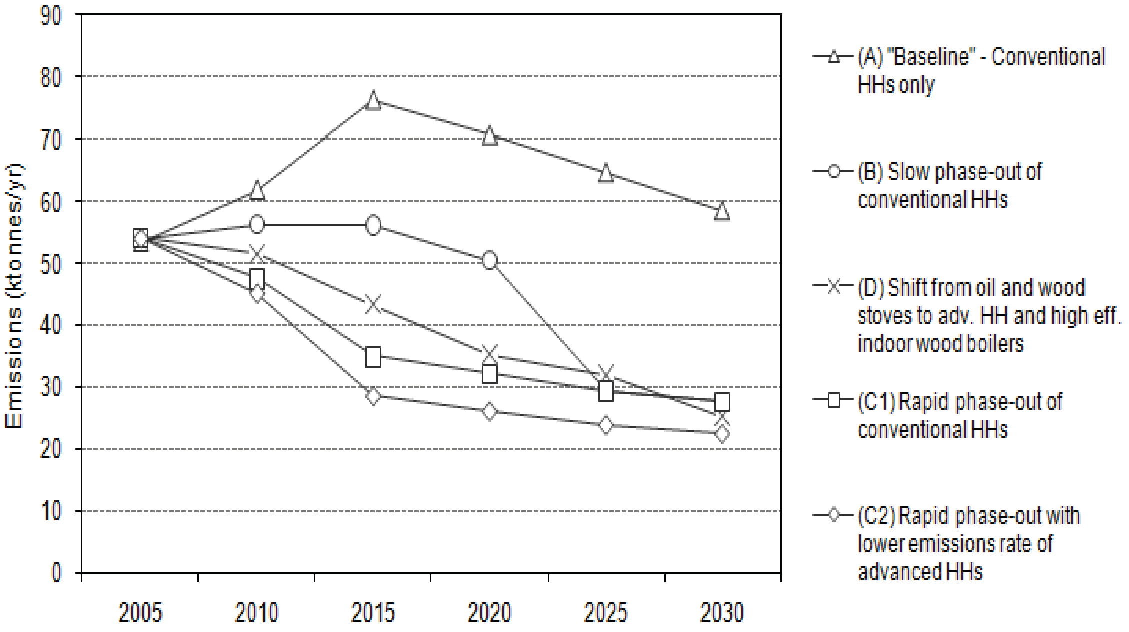

Figure 7-9. PM Emissions Baseline and Four Alternative Scenarios (ktonnes/yr).

In contrast to the "baseline" scenario, the "slow introduction of advanced HH" scenario assumes the same wood heat market share, but now allows for the introduction of advanced HHs. However, this scenario forces the conventional HH units to maintain part of the total HH market at least out to 2020. For 2015, the market for conventional HH and advanced HH is split 50/50, but by 2025 there are no conventional HHs in the market. Two additional scenarios examine what happens under the same wood heat market share, when advanced HHs come into the market more rapidly. Under the scenario, "rapid introduction of advanced units," new HHs start to enter the market in 2010. Another scenario "rapid introduction of advanced units with lower EFs" looks at the same market split over time, but with lower emissions for the advanced units coming. This scenario is the most optimistic from the PM standpoint. Finally, "high wood heat share and advanced units" illustrates a different scenario both for wood heat in general and for the mix of technologies within the wood heat market. In contrast to the earlier scenarios, this scenario shows a growth in the wood heat market, with a large decline in heating oil, and a major shift in the mix of wood heat technologies away from stoves. The key insights from this comparison are: (1) the extent to which wood space heating emissions dominate the total emissions from total residential energy usage, even out to 2030; and (2) the potential for wide variation in future emissions, depending upon the evolution of the technology mix within the market for wood heat.

Engineering economic techniques were used to compare the lifetime costs of alternative technologies, including HHs, automated pellet boilers, high efficiency wood boilers, natural gas and fuel oil boilers, and electric heat pumps. A sensitivity analysis was used to examine the impact of varying assumptions about fuel prices, home size, and other factors. The calculations are relatively simple, accounting for capital and fuel costs, but ignoring other costs. Under baseline assumptions, natural gas boilers are less costly from a lifetime net present value perspective than electric heat pumps, oil boilers, and any of the wood and pellet technologies. Natural gas is not available in all parts of the State of New York, however. Real-world economics dictate that many low-density, rural areas do not have access to natural gas distribution systems. In these rural areas, HHs are likely to compete with electricity and fuel oil for market share. Under baseline assumptions, HHs are more costly than these technologies as is illustrated in the figure below. Figure 7-10 shows the combinations of wood price and HH thermal efficiency at which HHs become cost competitive with other devices. For example, at an efficiency of 35% and a wood price of $225 per cord, the advanced HH is equivalent to the electric heat pump with respect to lifetime cost. At higher efficiencies or lower prices of wood, the HH has a lower cost than the heat pump. At the baseline advanced HH efficiency of 30%, however, a wood price of approximately $55 or less is required for the HH to be competitive with the natural gas boiler.

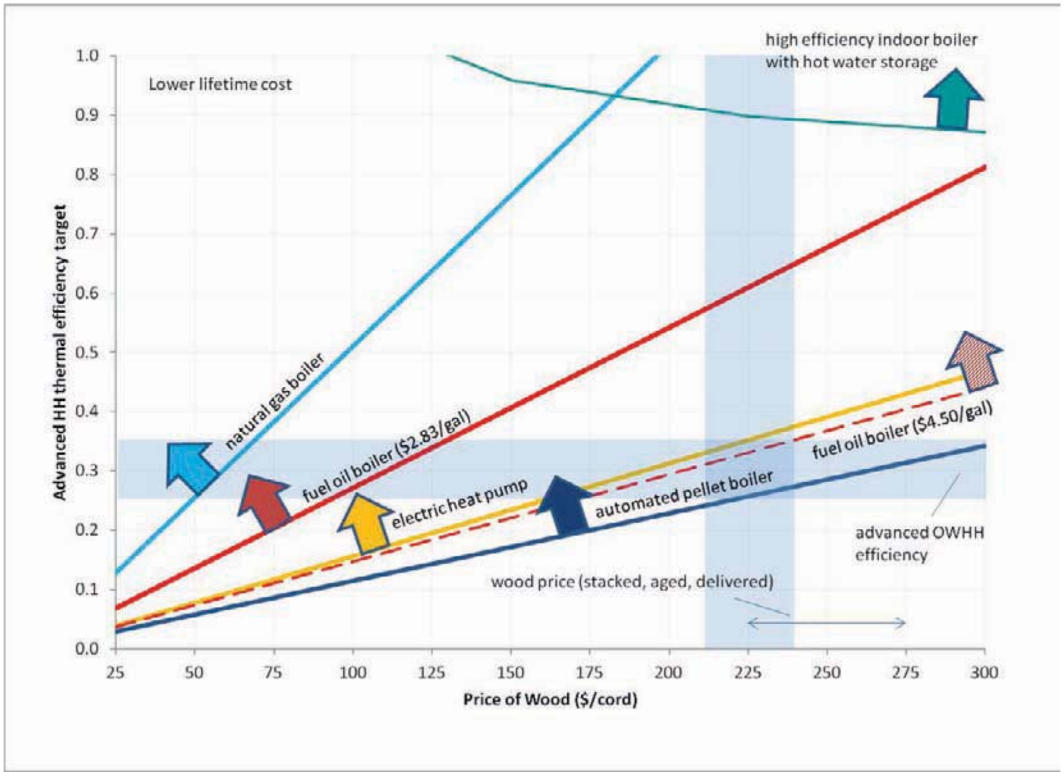

Figure 7-10. Comparative Technology Costs.

Many rural households have their own supply of wood, and thus may perceive HHs as the most cost-effective option. This outcome may not be the case, however, if the homeowner factors in the labor costs associated with carrying and splitting the wood or the opportunity cost associated with using firewood instead of selling it.

This point begins to hint at the importance of perception and other difficult-to-quantify factors. Most homeowners would not be expected to undertake as detailed an analysis as was carried out here. They may not go through a process to calculate the value of their time, nor be aware of the correlation between wood and oil prices in many markets. Instead, qualitative perceptions of the technology's cost, environmental benefits, and ability to hedge against increases and volatility in fuel prices may be the largest factors in decision making. The homeowners may also have been motivated by their interest in the exercise associated with splitting wood loading the fuel into the HH. These factors cannot easily be quantified within an engineering economic assessment.

There are additional unmodeled factors that affect competitiveness of HHs. For example, the high emission rates associated with HHs have resulted in the passing of ordinances that ban or limit HH use in some counties and communities. Space considerations also come into play: households must have room to store delivered wood fuel. The high efficiency indoor wood boiler with thermal storage also requires space for storing firewood, but its higher efficiency reduces these space requirements considerably. The analysis also highlights the fact that many of the most important drivers for the adoption of HHs are not quantitative, but are instead related to perception and preference. Examination of these qualitative drivers was beyond the scope of the work presented here, but such an examination would be an interesting and useful endeavor.

While this analysis provides a starting point for evaluating the competitiveness of HHs, it could be expanded upon through additional consideration of factors that impact overall system efficiency. System efficiency is a function of combustion efficiency, boiler efficiency, and how the units are sized and operated. HH units typically operate most efficiently at steady-state under full load. For an HH without thermal storage, however, the device must cycle on and off to deliver heat in the desired quantities over time. Cycling negatively impacts efficiency as heat is lost through the flue. Cycling is increased if the device's heat output exceeds heating demands; thus, oversizing of devices can lead to more cycling and decreased efficiency. There are also seasonal considerations. In coldest periods of the year, for example, the HH device would cycle less because space heating demands would be high. In the more temperate Spring and Fall months, however, the HH device likely will cycle more often and thus operate well below its optimal efficiently. The use of thermal storage allows the operational profile to be maintained closer to steady-state. However, if the maximum combustion efficiency is 60%, the theoretical best efficiency of the system is 60%, and no amount of thermal storage can improve upon this.

In summary, while wood heat is a relatively small contributor to meeting total residential space heating demands, it is the largest contributor to particulate matter emissions from not only residential space heating, but all residential energy use. The emissions profiles of wood heating devices differ greatly from one type of device to another, however, HH devices have been shown to have particularly high emission rates. Regulatory and technology scenarios that target HH emissions as well as efficiency improvements are shown to greatly reduce wood heating emissions into the future. Nonetheless, air pollution from residential wood space heating is likely to dominate the total particulate matter emissions from residential energy usage through 2030 Economic calculations for residential heating options, accounting for capital and fuel costs over the lifetime of the device, suggest that natural gas systems have the lowest net present value cost of all examined home heating options, including HHs. However, residential natural gas is not available in all parts of the State of New York. In the predominantly rural areas where it is unavailable, HHs are likely to compete with electricity and fuel oil for market share. The rate of turnover and retirement of older, highly emitting wood heating units to more efficient, lower emitting units is critical to avoid what could be substantial increases in emissions related to residential wood heat over the next 5-10 years.

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