Air Emissions and Product Characterization of Wax/Fiber Firelogs Sold in the Great Lakes Region

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December 22, 2005

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1 Introduction

Tests to measure air pollutant emissions from five different wax/fiber firelog brands sold in the Great Lakes region of Canada and the United States were conducted. The tests were performed to measure air emissions of particles, carbon monoxide (CO), nitrogen oxides (NO_x), formaldehyde, polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), and benzene. In addition to the air emissions, the wax and fiber used in each firelog brand were characterized, the burning properties (duration and temperature) were evaluated, and the chloride and metal content of the combustion residue were measured. Fuel characterization tests (proximate-ultimate analyses) were also conducted on the combustion residue from the firelogs and on the firelogs themselves.

2 Test Program

The primary objective of the testing was the realistic measurement of emissions from the use of wax/fiber firelogs in a standard fireplace. The make-up and burning characteristic of the firelogs were documented to illustrate the range in properties that can reasonably be expected from commercially available firelog brands.

The five wax/fiber firelog brands tested were:

> **Java-Log**, 2.3 kg (5 lb.) firelog made of coffee grounds and wax by Robustion Technologies Inc., in Ottawa, Canada.
> **Northland**, 1.4 kg (3 lb.) firelog made of wood fiber and wax by the Conros Corporation, in Canada.
> **Pine Mountain Superlog**, 2.7 kg (6 lb.) firelog made of wood fiber and wax by the Conros Corporation, in Canada.
> **Easy Time Firelog**, 2.3 kg (5 lb.) firelog made of wood fiber and wax by Duraflame, Inc., in Canada.
> **Xtra Time Firelog**, 2.7 kg (6 lb.) firelog made of wood fiber and wax by Duraflame, Inc., in the U.S. (Kentucky).

All tests were performed in a standard 36-inch zero clearance radiant fireplace with open glass doors. During the tests an expanded metal grate (10 gauge, 3.2 cm [1.25 in] wide openings) was placed on top of the standard grate (about 15 cm [6 in] spacing between bars) that was supplied with the fireplace. A grate with closely spaced bars or an expanded metal grate overlay is recommended for firelog use and in fact labeling on some firelog wrappers instruct the home user to utilize a grate with bar spacing of less than 7.6 cm (3 in). The use of a grate with close bar spacing or a metal overly minimizes the physical break-up of the firelog allowing for more complete combustion.

Each test consisted of the burning two firelogs. The firelogs were burned one at a time per the package instructions. The second firelog was started after the first firlog's flame went out. Firelogs were lit with a standard butane lighter. Emissions were sampled until the interior chimney temperature, 30 cm (1 ft) above the fireplace, was (5.6ºC) 10ºF above the indoor laboratory temperature.

A 36 cm (14 in) diameter dilution tunnel was used to cool and dilute the fireplace emissions prior to sample collection. The fireplace chimney was located under the collection hood of the dilution tunnel and the entire exhaust stream was captured and mixed with room air. Dilution tunnels are used for source tests because they permit the sampling of air pollutants in a chemical and physical form similar to that which they will have once they exit the chimney and mix with ambient air. This is particularly important for characterizing emissions from the combustion of biomass fuels because a large fraction of their air emissions are comprised of semi-volatile organic compounds. The relative partitioning of these compounds between the vapor phase and sub-micron particles is primarily dependent on temperature.

Because different analytical laboratories that were contracted to analyze samples and various data summaries have referred to the same samples using different conventions a tabulation of these different conventions is provided as Appendix A to facilitate the review of the data. A summary of the data collected during the tests can be found in Appendix B. Appendix C contains graphs of the temperatures and gas concentrations throughout the tests. The calculated emission results are in Appendix D. Carbon monoxide test data, graphs, and calculated emissions have been compiled separately in Appendix E. Photographs of the test set-up are provided in Appendix F.

3 Sampling and Analytical Methods

3.1 Air Emissions

Pollutant samples were collected from a dilution tunnel and analyzed following standard sampling and analytical methods.

Particulate samples were collected isokinetically onto Gelman type A/E filters and processed following the protocols specified for wood heaters (40 CFR Pt. 60, App. A, Method 5G) in OMNI's EPA accredited wood heater testing laboratory (certified under 40 CFR Subpart AAA, Pt. 60). The total particulate values were the sum of the mass of material collected on the filter and the material removed from the filter holder and buttonhook nozzle with an acetone rinse. The $PM_{2.5}$ samples were collected using an impactor pre-separator developed for the California Air Resources Board. All filters were desiccated to constant weights before and after sampling.

Polycyclic aromatic hydrocarbons were sampled with an EPA Method 23 sampling train (often referred to as modified Method 5 or MM5), and analyzed for the 16 individual polycyclic aromatic hydrocarbons making-up the 16-PAH list. (The compounds making up the 7-PAH list were also simultaneously quantified as the 7-PAH list is a subset of the

16-PAH list.) Analyses were conducted following EPA Method TO-13A procedures. The PAH laboratory data are provided in Appendix G.

Formaldehyde was collected and analyzed by EPA Method SW-846 0011/8315A. Appendix H contains the laboratory data.

Benzene samples were collected in evacuated stainless steel canisters and analyzed by EPA Method TO-14A (GC/MS Scan). The entire EPA Method TO-14A list was analyzed. Benzene is reported in the text. The TO-14 data are provided in Appendix I and the reader is referred to that appendix for the data for those compounds which are beyond the scope of this work to quantify.

Carbon monoxide was measured with a gas filter correlation analyzer following EPA Method 10. The carbon monoxide testing was done separately from the other testing on a second set of tests due to difficulties with the carbon monoxide analyzer encountered during the first set of tests. Background levels of carbon monoxide in the laboratory were routinely measured during testing and found to be less than 1 ppm at all times.

Volatile organic compounds(VOC) were measured with a flame ionization detector analyzer following EPA Method 25A.

Nitrogen oxides (NO_x) concentrations were measured with a chemiluminescent gas analyzer by EPA Method 6C. All gas analyzers were calibrated with EPA Protocol 1 certified gas standards.

Gas flow within the dilution tunnel was measured with a P-type pitot tube and manometer. Chimney, dilution tunnel, and laboratory temperatures were measured with type-K thermocouples and data logged every minute.

3.2 Log Composition

The chloride content of each of the firelog combustion residues was determined by EPA Method 300.0. Metals were analyzed in the residue by EPA Method 6010 except for mercury which was analyzed by EPA Method 7471. Appendix J contains the chloride and metal laboratory data.

The heat content (higher heating value, HHV), as well as, moisture, ash, carbon, hydrogen, oxygen, nitrogen, and sulfur contents of both the firelogs and their combustion residues were determined by proximate/ultimate analyses. Laboratory results are in Appendix K.

Wax content was determined gravimetrically by weighing the fiber and wax separately after multiple hexane extractions to separate the fiber and the wax. After separation, the wood fiber was sent to the USDA Forest Services' Forest Products Laboratory for tree species identification and the wax was characterized by measuring the percent oil (ASTM Standard D721), carbon count (ASTM Standard D5442), and by needle penetration (ASTM Standard D1321). Appendix L contains the wax analysis laboratory data and

Appendix M contains the notes from the Forest Service regarding the tree species identification.

The mass of combustion residue produced per unit mass of each firelog burnt was determined gravimetrically by the weight of the logs before the tests and by the weight of the residue left in the fireplace after the tests. Combustion residue is the material remaining after combustion, generally and imprecisely referred to as “ash”. Combustion residue is made up of both char, which is unburned organic material and elemental carbon, and ash, which is composed of inorganic compounds.

4 Results

Table 1 contains the pollutant emission factors (mass of pollutant/mass fuel on a dry basis) for each of the five firelog brands individually and the mean emission factors for the firelogs as a group averaged across all five firelog brands for each pollutant. The associated standard deviations are also provided. Table 2 contains the emission factors for each of the individual PAH compounds that make up the 16-PAH list. Values for individual firelog brands and the overall mean PAH compound emission factors for the firelogs as a group averaged across all five firelog brands are shown. The associated standard deviations are provided. The emission factors for some PAH compounds for some firelog brands were below detection limits. When the emission factors were below the detection limit, one-half the detection limit is shown in Table 2 and the one-half detection limit value was used in the calculation of 7-PAH and 16-PAH emission factors shown in Table 1.

Table 3 contains the pollutant emission rates (mass of pollutant/hour of fireplace operation) for each of the five firelog brands individually and the mean emission rates for the firelogs as a group averaged across all five firelog brands for each pollutant. The associated standard deviations are also provided. Table 4 contains the emission rates for each of the individual PAH compounds that make up the 16-PAH list. Values for individual firelog brands and the overall mean PAH compound emission rates as a group averaged across all five firelog brands are shown. The associated standard deviations are provided. The emission rates for some PAH compounds for some firelog brands were below detection limits. When the emission rates were below the detection limit, one-half the detection limit is shown in Table 4 and the one-half detection limit value was used in the calculation of 7-PAH and 16-PAH emission rates shown in Table 3.

The calculation of emission rates requires fire duration to be defined by a reproducible metric. There is no standardized definition of end time for fireplace emissions tests. The convention used in this study was to divide the total mass of pollutant emitted during the entire sampling period (the total time from the first firelog being lit until the interior chimney temperature had cooled to 5.6ºC [10ºF] above the laboratory room temperature) by the time that there was a visible flame (the time from the first firelog being lit until the second firelog's flame went out). By using this approach it can be assumed that virtually all pollutants associated with using the firelog are captured/measured and a "standardized," realistic, and easily determined end point is used to characterize the burning duration. The emission rates being calculated in this manner also makes it easier to apply them to the time a home operator burns their fireplace based on visible flame and for comparing the actual burn duration to packaging claims. It should be noted that only a small fraction of the total mass of pollutants are emitted between the time when the last visible flame goes out and when the interior chimney temperature cools to 5.6ºC (10ºF) above room temperature. Combustion is nearly completed when the last flame goes out.

Details of the emission testing, intermediate calculations, and supporting laboratory data are provided in Appendices B, C, D, E, G, H, and I. Emissions of other VOC's besides benzene can be calculated from data provided in Appendix I as the complete TO-14 scan was conducted which included 62 VOC compounds.

The mass of residue per mass of fuel (dry basis) remaining after burning the firelog in a normal fashion on an expanded metal overlay on a standard grate in a fireplace is provided in Table 5 for each individual firelog brand. The mean averaged across all firelog brands with its associated standard deviation is also provided.

The results of analysis of the residue are provided in Table 6. Analyses for 26 metals were conducted. These included traditional "toxic" transition and heavy metals and common crustal metals. Chloride analysis was conducted due to the corrosive nature of chloride salts, which can damage fireplaces and their chimneys, and due to the toxic and recalcitrant nature of many chlorinated organic compounds. Standard fuel analysis was also conducted on the residue. The fuel analysis included the heat, moisture, carbon, hydrogen, nitrogen, sulfur, oxygen, and ash contents. Data are provided for each individual firelog brand. The means averaged across all five firelog brands along with their associated standard deviations are provided for each parameter. Supporting laboratory data are contained in Appendices J and K.

Unburned firelogs were characterized by (1) conducting standard fuel analysis (heat, moisture, carbon, hydrogen, nitrogen, sulfur, oxygen, and ash contents), (2) determining the fraction of wax and fiber by hexane extraction, (3) conducting fiber analysis, and (4) conducting standardized wax analyses (needle penetration, oil content, and carbon number distribution). The results of fuel analysis, wax/fiber proportioning and fiber identification are presented in Table 7. Appendices K and M contain the supporting laboratory data. The results of the wax analysis are provided in Table 8. Supporting laboratory data are provided in Appendix L. It should be noted that while "wax" analyses were used, other materials could be added to wax/fiber logs. These have included molasses, various plant and petroleum oils, and stearic acid. Data for each individual firelog brand are provided in Tables 7 and 8. Where appropriate the means averaged across all five firelog brands with their associated standard deviations are also provided in the tables.

The characteristic burning properties of each firelog brand were documented and the data are shown in Tables 9 and 10. The duration of the fire as determined by when the last flame goes out, by when the interior chimney temperature cools to 38ºC (100ºF) and by when it cools to 5.6ºC (10ºF) above room temperature are shown for each firelog brand in Table 9. Two values are shown in the first "flame-out criteria" row in Table 9. One number is for the first log burned during the first set of tests and the second number is for an identical log used in the subsequent carbon monoxide testing that was done separately. The difference between the two numbers illustrates the variability in burn duration among firelogs of the same brand. The mean and maximum interior chimney temperatures during the burning measured 30 cm (1 ft) above the fireplace are shown in Table 10.

5 Conclusions

With a few exceptions all five firelog brands have similar bulk chemical makeup, generally burned in a similar fashion, and have similar emission and residue characteristics. All five of the firelogs lit easily and had visible flames for approximately the burning time indicated on the packaging. There is, however, variability in burning duration among firelogs of the same brand.

The Java-Log and Pine Mountain Superlog had higher nitrogen oxides emissions than the Northland firelog, Easy Time Firelog and Xtra Time Firelog (Tables 1 and 3). This is consistent with the higher nitrogen content in the Java-Log and Pine Mountain Superlog (Table 7).

The Easy Time Firelog and the Xtra Time Firelog had higher carbon monoxide emissions than the other three firelogs (Tables 1 and 3).

The residue remaining after burning the Java-Log had markedly more copper and zinc than the residue from the other four firelogs (Table 6). The copper content in the Java-Log residue was 2190 mg/dry kg as compared to a mean of 267 mg/dry kg for the other four firelog residues and a zinc content of 1410 mg/dry kg as compared to a mean of 259 mg/dry kg for the other four firelog residues.

The residue of the Java-Log also had more inorganic ash and less organic compounds (as evidenced by the percent, ash, carbon and hydrogen values) than the other firelogs. Commensurately, the levels of crustal elements associated with inorganic ash (e.g., aluminum. calcium, iron, magnesium) were higher in the residue of the Java-Log and the heat content of the residue was lower. The higher inorganic fraction and lower organic fraction in the residue suggests slightly more complete combustion than for the other firelogs.

The residue of Xtra Time Firelog had markedly more nickel and vanadium than the residue from the other four firelogs (Table 6). The nickel content in the residue from the Xtra Time Firelog was 2730 mg/dry kg as compared to a mean of 52 mg/dry kg for the other four firelog residues and a vanadium content of 79 mg/dry kg to a mean of 8 mg/dry kg for the other four firelog residues. Nickel and vanadium are common metals used in the petroleum refining process as catalysts.

The analysis of the Java-Log showed that it contained a much higher percentage of high molecular weight waxes (C51-C70) (Table 8). It is possible that this is simply an artifact of the fact that the fiber source in the Java-Log is coffee grounds rather than hardwood fiber and bark which comprises the fiber portion of the other four firelogs (Table 7), i.e., the difference may be due to oils and related compounds from the coffee grounds not from the wax portion.

The wax in the Northland firelog is significantly different than the waxes in the other four firelogs (Table 8). It is harder, with a needle penetration of 15 mm as compared to a mean of 210 mm for the waxes from the other four firelogs. It also has the lowest oil content (9.9%) as compared to waxes from the other four firelogs (mean of 25%). As previously noted, other types of additives are sometime used along with or in lieu of true waxes.

While few studies have been conducted quantifying emissions from the use of wax/fiber firelogs in fireplaces, limited published particulate and carbon monoxide results are available (references 1-5). The particulate and carbon monoxide emission rates reported from the previous studies are reasonably consistent with the results of this study (Table 11) particularly when the fact that a variety of waxes, fibers, firelog shapes and sizes, and manufacturing processes have been used for the various firelogs tested in this and the previous studies.

Data demonstrate that when wax/firelogs are used in fireplaces, as recommended by manufacturers, lower particulate, carbon monoxide, formaldehyde, benzene, and polycyclic aromatic hydrocarbon emissions will be produced than from the typical use of cordwood in fireplaces (Tables 11 and 12). This is reasonable in light of the facts that: (1) The higher heat content of wax/fiber firelogs (32.3 Mj/dry kg – mean this study) as compared to cordwood (approximately 20 Mj/dry kg) corresponds to less fuel being used. (2) The consequences of the one-at-a-time recommended usage of firelogs typically printed on packaging are a lower burn rate and less fuel being burnt. (3) Approximately one-half of a wax/ fiber firelog is made up of waxes (47.8 % – mean this study). Aliphatic waxes are less likely to create complex products of incomplete combustion such as the aromatic molecules of benzene and polycyclic aromatic hydrocarbons than wood, which is composed of cellulose, lignin and resins. Cellulose contains cyclic structures, lignin is composed of complex aromatic structures and most resins are aromatic. Further waxes are hydrocarbons (made up of only hydrogen and carbon, i.e., no oxygen) whereas wood contains about 43% oxygen, which suggests fewer oxygenated products of incomplete combustion such as formaldehyde and carbon monoxide will be produced.

In summary, commercially available wax/fiber firelogs are reasonably similar in their burning characteristics, air emissions and the character of the residue left after burning. Some differences can be seen among them, which are primarily related to the raw materials used in their manufacture. They produce significantly lower emissions from their use in fireplaces than does cordwood. Additional work should be conducted to measure and compare other pollutants.

6 References

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Table 1
Emission Factors

Pollutant	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog	Mean ± Standard Deviation
Nitrogen Oxides (NO_x)	g/kg fuel, db	4.8	1.2	9.4	3.1	0.71	3.8±3.5
Volatile Organic Compounds (VOC)	g/kg fuel, db	14.6	22.9	22.4	19.6	19.4	19.8±3.3
Respirable Particles ($PM_{2.5}$)	g/kg fuel, db	11.5	17.5	13.7	13.1	17.5	14.7±2.7
Total Particles (PM)	g/kg fuel, db	11.3	15.6	13.5	14.3	16.3	14.2±2.0
7-PAH*	mg/kg fuel, db	3.2	5.1	3.0	2.6	4.5	3.6±1.2
16-PAH*	mg/kg fuel, db	62.1	62.3	71.4	81.6	93.4	74.2±13.4
Carbon Monoxide (CO)	g/kg fuel, db	57.1	47.3	40.0	88.1	80.2	62.5±20.8
Benzene	g/kg fuel, db	0.42	0.41	0.43	0.64	0.77	0.53±0.16
Formaldehyde	g/kg fuel, db	0.67	1.3	1.1	0.93	0.58	0.92±0.30

*½ of the detection limit value was used for the calculation of 7-PAH and 16-PAH values for compounds that were below detection limits.

Table 2
Polycyclic Aromatic Hydrocarbon (PAH) Emission Factors

PAH Compound	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time	Xtra Time Firelog	Mean ± Standard Deviation
Naphthalene	mg/kg fuel, db	40.2	38.6	45.9	58.7	60.5	48.8±10.3
Acenaphthene	mg/kg fuel, db	0.5*	0.7*	1.0	0.8	1.2	0.8±0.3
Acenaphthalene	mg/kg fuel, db	3.6	2.2	4.5	2.8	5.6	3.7±1.4
Fluorine	mg/kg fuel, db	2.4	2.2	2.4	2.8	3.9	2.7±0.7
Phenanthrene	mg/kg fuel, db	6.9	8.2	8.5	8.8	10.7	8.6±1.4
Anthracene	mg/kg fuel, db	1.0	0.7*	1.4	1.3	1.4	1.2±0.3
Fluoranthene	mg/kg fuel, db	1.8	2.0	2.3	1.9	2.7	2.1±0.4
Pyrene	mg/kg fuel, db	2.0	1.9	2.3	1.8	2.6	2.1±0.3
Benzo(ghi)perylene	mg/kg fuel, db	0.5*	0.7*	0.1*	0.1*	0.3	0.3±0.3
Benzo(a)anthracene	mg/kg fuel, db	0.5*	0.7*	0.6	0.4	0.8	0.6±0.2
Chrysene	mg/kg fuel, db	0.5*	0.7*	1.2	0.8	1.5	0.9±0.4
Benzo(b)fluoranthene	mg/kg fuel, db	0.5*	0.7*	0.4	0.3	0.9	0.6±0.2
Benzo(k)fluoranthene	mg/kg fuel, db	0.5*	0.7*	0.1*	0.1*	0.1*	0.3±0.3
Benzo(a)pyrene	mg/kg fuel, db	0.5*	0.7*	0.4	0.6	0.8	0.6±0.2
Dibenzo(a,h)anthracene	mg/kg fuel, db	0.5*	0.7*	0.1*	0.1*	0.1*	0.3±0.3
Indeno(1,2,3-c,d)pyrene	mg/kg fuel, db	0.5*	0.7*	0.1*	0.1*	0.3	0.3±0.3

db, dry basis
*1/2 the detection limit

Table 3
Emission Rates

Pollutant	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time	Xtra Time Firelog	Mean± Standard Deviation
Nitrogen Oxides (NO_x)	g/hr	3.3	0.52	6.1	2.0	0.49	2.5±2.3
Volatile Organic Compounds (VOC)	g/hr	9.9	10.3	14.5	13.0	13.5	12.2±2.0
Respirable Particles ($PM_{2.5}$)	g/hr	7.9	7.0	8.9	8.7	12.2	8.9±2.0
Total Particles (PM)	g/hr	7.7	7.9	8.8	9.5	11.4	9.1±1.5
7-PAH*	mg/hr	2.2	2.3	1.9	1.7	3.1	2.2±0.5
16-PAH*	mg/hr	42.2	28.0	46.2	54.1	65.1	47.1±13.8
Carbon Monoxide (CO)	g/hr	35.7	25.3	27.8	61.0	59.7	41.9±17.2
Benzene	g/hr	0.29	0.18	0.28	0.42	0.53	0.34±0.14
Formaldehyde	g/hr	0.45	0.60	0.70	0.62	0.40	0.55±0.12

Note: The g/hr values were calculated by measuring the total grams of pollutant emitted during the entire test and by dividing it by the time that the logs had visible flames.
*1/2 of the detection limit value was used for the calculation of 7-PAH and 16-PAH values for compounds that were below detection limits.

Table 4
Polycyclic Aromatic Hydrocarbon (PAH) Emission Rates

PAH Compound	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time	Xtra Time Firelog	Mean ± Standard Deviation
Naphthalene	mg/hr	27.3	17.3	29.6	38.9	42.1	31.0±9.9
Acenaphthene	mg/hr	0.3*	0.3*	0.6	0.5	0.8	0.5±0.2
Acenaphthalene	mg/hr	2.4	1.0	2.9	1.9	3.9	2.4±1.1
Fluorine	mg/hr	1.7	1.0	1.6	1.9	2.7	2.0±0.8
Phenanthrene	mg/hr	4.7	3.7	5.5	5.8	7.5	5.4±1.4
Anthracene	mg/hr	0.7	0.3*	0.9	0.8	1.0	0.7±0.3
Fluoranthene	mg/hr	1.2	0.9	1.5	1.3	1.9	1.4±0.4
Pyrene	mg/hr	1.3	0.8	1.5	1.2	1.8	1.3±0.4
Benzo(ghi)perylene	mg/hr	0.3*	0.3*	0.1*	0.1*	0.2	0.2±0.1
Benzo(a)anthracene	mg/hr	0.3*	0.3*	0.4	0.3	0.6	0.4±0.1
Chrysene	mg/hr	0.3*	0.3*	0.8	0.5	1.1	0.6±0.3
Benzo(b)fluoranthene	mg/hr	0.3*	0.3*	0.3	0.2	0.6	0.3±0.2
Benzo(k)fluoranthene	mg/hr	0.3*	0.3*	0.1*	0.1*	0.1*	0.2±0.1
Benzo(a)pyrene	mg/hr	0.3*	0.3*	0.3	0.4	0.6	0.4±0.1
Dibenzo(a,h)anthracene	mg/hr	0.3*	0.3*	0.1*	0.1*	0.1*	0.2±0.1
Indeno(1,2,3-c,d)pyrene	mg/hr	0.3*	0.3*	0.1*	0.1*	0.2	0.2±0.1

*1/2 the detection limit

Table 5
Residue Produced in a Fireplace

	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog	Mean± Standard Deviation
Residue	g/kg fuel, dry	10	16	11	11	16	12.8±2.9

*Residue is the material remaining after combustion, generally referred to as "ash." Residue is made up of both char, which is unburned organic material and elemental carbon, and ash, which is composed of inorganic compounds.

Table 6
Residue Analysis

Analysis	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog	Mean± Standard Deviation**
Aluminum	mg/kg residue, dry	6210	3220	6170	3860	2550	4402±1697
Antimony	mg/kg residue, dry	<10	13	<10	<10	<10	6.6±3.6
Barium	mg/kg residue, dry	338	412	521	1530	469	654±494
Beryllium	mg/kg residue, dry	<1.0	<1.0	<1.0	<1.0	<1.0	0.5
Boron	mg/kg residue, dry	48	90	100	122	97	91.4±27.0
Cadmium	mg/kg residue, dry	1.0	3.2	3.8	3.7	2.7	2.9±1.1
Calcium	mg/kg residue, dry	120,000	46,500	70,600	35,300	26,300	59,740± 37,550
Chromium	mg/kg residue, dry	31	147	21	60	14	54.6±54.5
Cobalt	mg/kg residue, dry	21.3	3.6	2.9	4.6	6.1	7.7±7.7
Copper	mg/kg residue, dry	2190	524	70	274	201	652±876
Iron	mg/kg residue, dry	17,300	2240	3090	3700	2280	5722±6500
Lead	mg/kg residue, dry	<20	23	23	25	28	21.8±6.9
Magnesium	mg/kg residue, dry	12,900	7700	7090	5830	3750	7454±3399
Manganese	mg/kg residue, dry	2470	1170	2790	1410	727	1713±879
Mercury	mg/kg residue, dry	<0.02	<0.02	<0.02	<0.02	<0.02	<0.01
Molybdenum	mg/kg residue, dry	7.6	4.3	2.3	2.3	5.3	4.4±2.2
Nickel	mg/kg residue, dry	124	34	29	20	2730	587±1199
Phosphorus	mg/kg residue, dry	8630	1820	2160	3190	2520	3664±2822
Potassium	mg/kg residue, dry	49,000	60,900	43,600	23,600	33,300	12,830± 14344

Table 6 (continued)
Residue Analysis

Analysis	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog	Mean± Standard Deviation**
Silver	mg/kg residue, dry	<2.0	<2.0	<2.0	<1.9	<2.0	0.99±0.02
Sodium	mg/kg residue, dry	6710	5350	16,000	9220	5330	8552±4470
Strontium	mg/kg residue, dry	188	196	212	204	154	191±22
Tin	mg/kg residue, dry	<10	<10	20	15	<10	8±4
Titanium	mg/kg residue, dry	280	172	413	255	65.3	237±129
Vanadium	mg/kg residue, dry	12	8.3	5.7	5.6	74	21±30
Zinc	mg/kg residue, dry	1410	201	400	283	151	489±523
Chloride	mg/kg residue, dry	95	708	153	43	136	227±272
Heat content	Btu/lb, dry basis	4290	6600	7990	6490	8220	6718±1568
	Mj/kg, dry basis	10.0	15.3	18.5	12.7	19.1	15.1±3.9
Moisture	% dry basis	3.4	10	11	3.2	5.1	6.5±3.7
Carbon	% dry basis	32	44	51	43	53	44.6±8.3
Hydrogen	% dry basis	1.2	2.3	2.9	2.2	2.8	2.3±0.7
Nitrogen	% dry basis	3.1	1.0	4.5	0.77	1.7	2.2±1.6
Sulfur	% dry basis	4.8	1.9	1.8	1.4	2.9	2.6±1.4
Oxygen	% dry basis	29	24	23	21	27	24.8±3.2
Ash*	% dry basis	50	37	25	39	24	35.0±10.8

*Ash here refers to inorganic compounds left after complete, high-temperature combustion in the laboratory.

**When the measured value was less than the detection limit, ½ the detection limit was used in the calculation of the mean and standard deviation

Table 7
Fuel Characterization

Analysis	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog	Mean± Standard Deviation
Moisture	% dry basis	9.5	15	9.8	4.8	4.8	8.8±4.2
Carbon	% dry basis	62	67	72	69	65	67±4
Hydrogen	% dry basis	9.0	9.8	11	10	9.4	9.8±0.8
Nitrogen	% dry basis	1.3	0.29	1.4	0.11	0.33	0.7±0.6
Sulfur	% dry basis	0.23	0.08	0.08	0.08	0.20	0.13±0.07
Oxygen	% dry basis	28	22	18	20	22	22±4
Ash*	% dry basis	0.57	0.58	0.46	0.61	0.47	0.54±0.07
Heat content	Btu/lb, dry basis	12,620	13,540	15,190	14,420	13,770	13,908±964
	Mj/kg, dry basis	29.3	31.4	35.2	33.5	32.0	32.3±2.2
Wax content	%	44	49	55	45	46	47.8±4.4
Fiber content	%	56	51	45	55	54	52.2±4.4
Fiber Identification		coffee grounds	maple, "other" hardwoods,& some bark	unidentified hardwoods & bark (highest % bark of all samples)	maple, birch, "other" hardwoods, & some bark	hardwoods, & some bark, possibly includes willow & poplar	-

*Ash here refers to inorganic compounds left after complete, high-temperature combustion in the laboratory.

Table 8
Wax Analysis

Analysis	Units	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog	Mean± Standard Deviation
Needle Penetration	mm	246	15	289	160	145	171±106
Oil Content	%	34	9.9	16	17	32	22±11
Carbon Number Distribution (see Appendix L for detailed results)	% <C13	6.2	5.9	44	10	36	20±18
	% C13-C30	26	68	37	57	53	48±17
	% C31-C50	21	17	14	32	9.8	19±8
	% C51-C70	47	9.8	4.6	0.8	1.4	13±19

Table 9
Firelog Burning and Sampling Durations in Minutes*

Criteria	Java-Log	Northland	Pine Mountain Superlog	Easy Time Firelog	Xtra Time Firelog
Flame Out, 1st Log**	165,220	142,161	225,232	188,205	231,221
Flame Out, 2nd Log	378	335	464	398	458
Chimney Temp. < 100°F (38°C)	472	422	511	508	484
Chimney Temp. < 10°F (5.6°C) above Indoor Temp.	510	438	639	533	627

*Means and standard deviations were not calculated because the firelogs had different masses and their burn durations were inherently not comparable.
**The first number is the flame-out time for the first firelog used in the first set of tests. The second number is for an identical firelog use for the subsequent carbon monoxide testing.

Table 10
Mean and Maximum Temperatures

Temperature	Java-Log °F(°C)	Northland °F(°C)	Pine Mountain Superlog °F(°C)	Easy Time Firelog °F(°C)	Xtra Time Firelog °F(°C)
Mean Chimney*	160(71)	145(63)	160(71)	159(71)	133(56)
Maximum Chimney*	330(166)	225(107)	372(189)	342(172)	245(118)
Mean Room	82(28)	82(28)	77(25)	85(29)	69(21)
Mean Chimney Temp. above Mean Room Temp.	78(26)	63(17)	83(28)	74(23)	64(18)

*Measured 30 cm (1 ft) above fireplace.

Table 11
Comparison of Wax/Fiber Firelog Total Particulate and Carbon Monoxide Emission Rates Measured in This Study with Wax/Fiber Firelog Emission Rates Reported in Previous Studies and with Emission Rates for Cordwood

Pollutant, Units	Wax/Fiber Firelogs		Cordwood
	Mean ± Std. Dev. this study[1]	Mean ± Std. Dev. previous studies[2]	Mean ± Std. Dev. previous studies[3]
PM, g/hr	9±2	11±5	36±20
CO, g/hr	42±17	25±12	214±65

[1] Five firelog brands this study
[2] Fifteen firelog brands, 17 test runs (some runs consisted of multiple brands). References 1-5.
[3] Cordwood from 9 tree species, 17 runs. References 1-5.

Table 12
Comparison of Wax/Fiber Firelog Emission Rates of Pollutants Measured in This Study with Emission Rates for Cordwood

Pollutant, Units	Mean ± Std. Dev. for Wax/Fiber Firelogs, This Study	Mean ± Std. Dev. for cordwood from a previous study[1]
PM, g/hr	9±2	60±19
$PM_{2.5}$, g/hr	9±2	57±22
CO, g/hr	42±17	241±30
Formaldehyde, g/hr	0.6±0.1	5±1
Benzene, g/hr	0.3±0.1	1.4±0.4
16-PAH, mg/hr	47±14	730±300

[1] Cordwood from three tree species, four runs. Reference 1