

**Effect of Appliance Type and Operating Variables  
on Particulate Matter Emissions from  
Residential Wood Combustion Appliances**

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March 2001

## Abstract

Very small airborne particles have been shown to cause adverse health affects, which resulted in Environment Canada declaring particulate matter (PM) less than 10 microns in diameter to be toxic[1]. The main sources of anthropogenic PM are dust from roads and construction activities, agricultural activities and residential wood combustion[2]. Emissions from residential wood combustion appliances are highly variable given the wide variety of stoves types, fuel and operating conditions. This study investigated the effect of appliance type, fuel and operating conditions on the amount and size of the PM produced. Presently three of four appliances have been tested. The complete results from seventeen tests are reported. Results showed that

- PM produced from residential wood combustion appliances is composed primarily of  $PM_{2.5}$
- Pellet stoves were found to produce less TPM than cordwood stoves. Also, the percent of the TPM which were  $PM_{2.5}$  was lower for pellet stoves.
- Emission control technologies on cordwood stoves can reduce PM emissions by approximately one order of magnitude.
- The use of hardwood as a fuel and high burn rates was shown to reduce cordwood stove emissions.

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## Introduction

Particulate matter (PM) includes all microscopic airborne solids and liquids, except for pure water. PM is defined by its size: total particulate matter (TPM) are particles 40  $\mu\text{m}$  or less in diameter,  $\text{PM}_{10}$  are particles 10  $\mu\text{m}$  or less in diameter and  $\text{PM}_{2.5}$  are particles 2.5 $\mu\text{m}$  or less in diameter.

Sources of PM can be natural (e.g., soil, mineral particles and forest fires) or anthropogenic (e.g., industrial processes, fuel combustion and transportation). PM is also classified as primary or secondary. Primary PM is mainly from natural sources and is emitted directly into the atmosphere (e.g. windblown soil and sea salt spray). Secondary PM is formed in the atmosphere via the chemical reaction of precursor gases and other particles. The primary precursor gases are sulphur dioxide ( $\text{SO}_2$ ), nitrogen oxides ( $\text{NO}_x$ ), volatile organic carbons (VOCs) and ammonia ( $\text{NH}_3$ ) which react to form sulphates, nitrates and organic carbon compounds. Secondary PM is mainly produced from anthropogenic sources.

The main concern about PM is its adverse effect on human health, specifically the respiratory system. Particles smaller than  $\text{PM}_{10}$  are inhalable and can penetrate deep into the lungs affecting pulmonary function. Exposure to high levels of PM has been known to increase the development of respiratory diseases such as asthma, bronchitis, emphysema and pneumonia; however, recent health studies indicate that current ambient PM levels cause adverse health effects[3]. As a result PM less than 10  $\mu\text{m}$  in diameter has been declared toxic[1].

An emissions inventory produced by Environment Canada shows that residential fuel combustion is the source of 3% of  $\text{PM}_{10}$  and 14% of  $\text{PM}_{2.5}$  in the air [4]. PM emissions from wood combustion includes elemental carbon, ash and toxic chemical species such as dioxins, furans, PAHs and heavy metals. Factors effecting the emissions from residential wood combustion appliances are the appliance, the fuel and the operating conditions; inefficient appliances and poor operating practices produce large amounts of PM. A recent review of residential wood combustion technologies has shown that the non-certified stoves produce the majority of PM emissions while new appliance technology and fuels can significantly reduce emissions[5]. Presently, there is insufficient data to quantify the effect of wood type and wood moisture on emissions[5].

## Objectives

The objective of this project is to characterize the PM emissions from residential wood combustion appliances. The effect of the stove type, fuel and operating conditions on the amount of PM produced is investigated. The portion of PM emissions which are TPM,  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  is determined.

## Experimental Methods

### Test Variables

The test program studied four factors which affect emissions: stove type, fuel species and fuel moisture content and burn rate. The test matrix is shown in Table 1. For the cordwood stoves a two level factorial design for three operating parameters is shown. A factorial design requires that each parameter be tested at two levels independent of the other parameters; thus, eight tests per stove should be conducted. The pellet stove has only two operating parameters, resulting in a total of four tests.

**Table 1** Factorial test matrix

Variable	Cordwood Stove		Pellet Stove	
	Low	High	Low	High
Fuel Type	Softwood	Hardwood	White wood	Industrial
Fuel Moisture	Low (<20%)	High (>20%)	-	-
Burn Rate	Low (1.5 kg/hr)	High (3 kg/hr)	Low (1.0 kg/hr)	High (1.5 kg/hr)

### Stoves

One objective of this study is to determine the emission rates from non-certified stoves and the reduction in these rates achieved with newer technology stoves. Four types of woodstoves representative of those which are currently present in Canadian homes are studied, three cordwood stoves and one pellet stove.

A Fisher Mama Bear stove is used to represent the air-tight cordwood stoves which were sold in the 1970's and 1980's prior to the establishment of emission standards. As woodstoves can have a lifetime of 40 years [6] many Canadian homes still have similar uncertified stoves. The Fisher stove has a firebox lined with firebricks and two "spin draft" controls located the door. The combustion gases vent directly from the firebox into the flue.

A new uncertified Century cordwoodstove was obtained for this investigation, as these are still available in Canada. The firebox floor and walls are lined with firebrick and a steel baffle blocks the firebox from the flue. Combustion air enters the firebox through six openings in the door. A slide controls the size of the openings.

An EPA phase 2 certified Regency stove is used as a typical non-catalytic stove. Combustion air is introduced at the bottom front of the firebox and is controlled via a sliding rod. Lower emissions are the result of a secondary draft system that continually adds combustion air through ports at the top of the firebox. A firebrick baffle also prevents combustion gases from

directly exiting the firebox to the flue.

The fourth stove investigated is a Dell Point pellet stove, which is also EPA certified. Pellet stoves control both the air and fuel feeding rates resulting in emission rates which are comparable to conventional fuels [6]. An auger is used to feed the fuel into the burner and the air supply to the burner is controlled by an induced draft fan. The Dell Point stove uses overfeed fuel feeding and the bed of pellets is supported by a shaking grate.

### Fuel Species and Moisture

Firewood used by homeowners can vary significantly due to the availability of many species of trees. Emission rates may be influenced by the differences in the chemical and physical composition of softwoods and hardwoods. To investigate this effect the cordwood stoves were run with one softwood species, red pine, and two hardwood species, elm and oak.

Properly seasoned firewood should have a moisture content of approximately 20%; however, woodpiles in the United States have moisture contents ranging from 17-41%[5]. Wood that has been stored inside can reach moisture contents well below 20% [7]. Fuel with low (dry) and high (wet) moisture content was used in each of the three cordwood stoves. The softwood fuel, pine, was available both “dry” (~14%) and “wet”(~20%), whereas, elm was used as a “dry”(~15%) hardwood and the oak as a “wet”(~26%) hardwood. See Table 4 for the average moisture contents of each fuel load.

All of the cordwood was split and the bark was intact. As fuel size can affect emission rates, it was kept as constant as possible. The cross-section of the fuel pieces ranged between 65 and 130 cm<sup>2</sup> and the length was 40 cm. A Delmhorst Moisture Metre was used to measure the wood moisture content. Two insulated pins were driven into the wood and the percent moisture was displayed on an analogue metre. The moisture of the content of each fuel load was the average of three readings on four of the logs used as the test charge.

The pellet stove was run with two types of pellets: white wood pellets and industrial pellets. Industrial pellets are a mixture of white wood and bark. The moisture content of the pellets was determined using ASTM D4442 [8], an oven drying method. A known weight of pellets were placed in an oven set at 103°C. The pellets are weighed at intervals until there is no change in their weight. The moisture content is the difference between the initial and final weights.

### Burn Rate

The target for the low burn rate was 1.5 dry kg/hr. This would represent a burning rate required to maintain a comfortable ambient temperature. The high burn rate target was 3.0 dry kg/hr and was representative of the heat required to warm up a cool house.

The Dell Point pellet stove produces lower burning rates than the cordwood stoves. The pellet stove target low and high burn rates were 1 dry kg/hr and 1.5 dry kg/hr, respectively.

### **Stove Setup and Operation**

The stove setup and operation was based on CAN/CSA B415.1-92 Performance Testing of Solid-Fuel-Burning Stoves, Inserts, and Low-Burn-Rate Factory Built Fireplaces [9]. The only deviation from the standard was that cordwood was used instead of wood cribs, as this is more representative of “real world” operation.

Each stove was placed on a platform scale to determine the weight of wood consumed during a burn. The flue stack for the cordwood stoves was a 150 mm diameter 24 MSG black stove pipe. This vented into a 2 m long factory-built chimney with 25 mm of solid-pack insulation. The chimney started 2.6 m above the platform. The pellet stove used a 76 mm diameter insulated pellet vent which was 4 m long. A hood collected all of the emissions exiting the chimney and mixed them with ambient air. The hood was part of a dilution tunnel used to condition and collect particulate samples.

The flue gas temperature were measured 2.44 m from the platform using a type-K thermocouple. Flue gas samples were obtained 50 mm above the thermocouple. Continuous analysis of flue gas samples for O<sub>2</sub>, CO<sub>2</sub>, CO and NO<sub>x</sub> was performed. The CO and CO<sub>2</sub> were analysed using infrared analyser, O<sub>2</sub> using a paramagnetic analyser and NO<sub>x</sub> using a chemiluminescent analyser. Thermocouples were also used to measure the test room temperature and five stove surface temperatures. This data was recorded automatically using LabView.

The cordwood stoves used a “hot start”, in which a bed of hot coals was used to ignite the fuel charge. At the beginning of each test a small fire was built using newspaper and kindling, a pre-test charge was then loaded into the stove. The desired air rate was set and the pre-test charge was burnt until between 20 and 25% of the initial weight remained. A test charge was then loaded into the stove. Testing ended when all of the test charge had been consumed. The same fuel species was used for the kindling, pre-test charge and test charge.

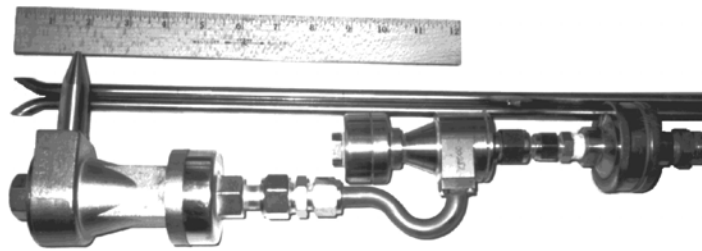
The standard states that the fuel loads should be 122 kg fuel/m<sup>3</sup> firebox. Therefore, the test charge for the Fisher stove was 7.7 kg, the Regency 6.3 kg and the Century 5.2 kg.

The pellet stove fires were started according to the manufacturers instructions. A handful of pellets mixed with ethanol gel were placed into the burner and ignited. The stove was turned on and operated at the desired burn rate for one hour prior to the start of the test run. The stove and particulate sampling system were run for at least two hours.

## Particulate Sampling

The B415.1 standard [9] uses a dilution tunnel to cool and dilute the particulate emissions prior to collection. Dilution tunnels collect pollutants in a form which is similar to the form they have when they exit a chimney. A blower was used to draw ambient air and the chimney emissions into the dilution tunnel. A series of elbows and baffles ensures that the flow was well mixed. The sampling section consists of ports for a velocity probe, a particulate sampling probe and a thermocouple. The dilution tunnel had a diameter of 150 mm and the blower provided velocities of 4 m/s. A S-type pitot tube connected to a micromanometer was used to determine the flow velocity in the dilution tunnel.

Particulate samples were collected from the dilution tunnel using the EPA's Draft Method for Determination of  $PM_{10}$  and  $PM_{2.5}$  Emissions [10]. The sampling train used for this method was a standard EPA Method 5 [11] except the probe was replaced with a combined cyclone sampling head, shown in Figure 1, and there was no heated filter box. The combined cyclone sampling head was supplied by Apex Instruments and consists of a  $PM_{10}$  cyclone, a  $PM_{2.5}$  cyclone and a 47 mm filter holder. A  $0.3\ \mu\text{m}$  glass filter is used. The  $PM_{10}$  and  $PM_{2.5}$  cyclones separate particulates with an aerodynamic diameter of 10 and  $2.5\ \mu\text{m}$  respectively. Particulate matter with a diameter less than  $2.5\ \mu\text{m}$  is captured on the filter.



**Figure 1.** Combined cyclone sampling head

Prior to a run a pre-weighed dessicated filter was placed in the filter holder and the sampling head was assembled. Runs performed with the pellet stove used the 47 mm filter holder that came with the sampling head. However, with the cordwood stoves the PM loading on this filter was too large to maintain isokinetic sampling. The 47 mm filter holder was replaced with a 102 mm filter holder for all of the cordwood stove runs. Once assembled the entire sampling train was leaked checked. If the flow was greater than 0.6 LPM, the leak was found and corrected. The sampling head nozzle was placed in the centre of the dilution tunnel and opening around the probe was blocked. The probe nozzle was then placed in the centre of the dilution tunnel for the entire run. The flow in the dilution tunnel was turbulent, so it was assumed that the velocity profile is flat and thus limited stratification of the particulates occurs.

The particulate sampling system was started when the test load was charged into the stove and stopped once the test load was consumed. Samples were drawn from the dilution tunnel into the combined cyclone sampling head, through a series of impingers, a dry test metre and an orifice. A Nutech 2010 control console was used to ensure isokinetic sampling.

After a run was completed, the sampling head was removed from the tunnel and disassembled. The filter was placed directly into a dessicator. PM collected in the sampling head cyclones was recovered using a brush and acetone rinse and transferred into three containers (the three size fractions) of a known weight. After the acetone evaporated, the samples were transferred to a dessicator. The filter and samples were weighed to a constant weight. The mass of each size fraction captured was the difference between the final and tare weights.

## Results

### Fuel Analysis

The fuels were analysed to characterize the differences between hardwood and softwoods and the two pellet types. Table 2 lists results from the proximate, ultimate and calorific analyses. The proximate analysis of the three cordwood fuels shows the composition variability between different tree species. The two hardwoods (elm and oak) have a higher ash content than the softwood (pine). The volatile and fixed carbon composition of the two hardwoods were very different, whereas the oak and pine composition were similar. The ultimate analysis shows that hardwoods have more carbon and less hydrogen and oxygen than softwoods. The calorific analysis indicates that hardwoods have a higher heat content than softwoods; however, other research has shown that the average heat content of softwoods is higher than hardwoods due to the higher resin and lignin concentrations in coniferous trees [5]. The industrial pellets have 3% more ash than the white wood pellets and 7% less volatiles. The industrial pellets heat content was also higher.

**Table 2** Fuel proximate, ultimate and calorific analyses

Analysis (dry basis)	Cordwood			Pellets	
	Pine	Elm	Oak	White Wood	Industrial
<b>Proximate (wt%)</b>					
Ash	0.56	1.13	1.93	0.42	3.45
Volatile	77.67	82.64	76.07	84.67	77.35
Fixed Carbon	21.77	16.23	22.00	14.91	19.20
<b>Ultimate (wt %)</b>					
Carbon	49.68	50.00	50.61	49.58	50.66
Hydrogen	6.01	5.92	5.88	5.91	5.75
Nitrogen	0.12	0.18	0.25	0.14	0.27
Sulphur	0.07	0.05	0.05	<0.03	<0.03
Oxygen	43.56	42.72	41.28	43.92	39.84
<b>Calorific (MJ/kg)</b>					
Heating Value	19.49	19.57	19.85	19.63	20.16

## Woodstove Experiments

Only the results from the Dell Point, Regency and Fisher stoves are reported, as the Century stove has yet to be tested. Each experiment was given a run codes, e.g., RSHL, which describes the variables used in that particular experiment. The run codes are explained in Table 3.

All testing was performed as described in the section Experimental Methods section. The

**Table 3** Description of run codes used for each test

Position	Variable	Description
First	Stove type	D = Dell Point, pellet stove R = Regency, EPA certified stove F = Fisher Mama Bear, conventional “old” stove C = Century, conventional “new” stove
Second	Fuel type	W = White wood pellets I = Industrial pellets S = Softwood, pine H = Hardwood, elm or oak
Third*	Fuel moisture	L = Low “dry”, pine or elm H = High “wet”, pine or oak
Fourth	Burn Rate	L = Low, target 1.5 drykg/hr H = High, target 3.0 drykg/hr

\* the pellets had a constant moisture content

test conditions for each run are listed in Table 4. One run, DWL, was performed twice to determine the repeatability of the sampling methods. Comparison of the results from the two DWL runs show good agreement. Runs RSHL and RSHH were not performed as the fuel was too moist (26% moisture) to ignite. The analyser sampling train malfunctioned during the FSHH run, resulting in flue gas analysis data for only the first hour of the test.

Efficiencies listed in Table 4 were calculated using the stack loss method described in CAN/CSA B415.1-92 [9]. The pellet stove efficiency is a steady-state efficiency, whereas the cordwood stove efficiency is an average over the entire cycle. The Regency stove has the highest average efficiency, 80%, followed by the Dell Point stove, 72%, and the Fisher stove, 69%. The results from the cordwood stoves indicate that the softwoods burn more efficiently than hardwoods.

**Table 4** Test conditions

Run	Stove	Fuel		Burn Rate (dry kg/hr)	Time (hr)	$\eta$ (%)
		Type	Moisture (%)			
DWL	Dell Point	White Wood	7	0.84	4.99	69.8
DWH1	Dell Point	White Wood	7	1.40	4.98	71.4
DWH2	Dell Point	White Wood	7	1.36	5.00	75.5
DIL	Dell Point	Industrial	7	1.04	4.29	73.3
DIH	Dell Point	Industrial	7	1.21	5.00	69.8
RSLL	Regency	Pine	12	1.85	2.80	85.4
RSLH	Regency	Pine	18	2.59	1.98	80.8
RHLL	Regency	Elm	12	1.74	3.09	77.3
RHLH	Regency	Elm	11	3.49	1.53	79.4
RHHL	Regency	Oak	22	1.54	3.28	82.8
RHHH	Regency	Oak	22	3.44	1.38	71.8
FSLL	Fisher	Pine	13	1.30	5.00	71.5
FSLH	Fisher	Pine	16	3.11	2.04	71.6
FSHL	Fisher	Pine	18	1.65	3.78	73.7
FSHH	Fisher	Pine	20	3.60	1.73	73.8*
FHLL	Fisher	Elm	20	1.95	3.09	63.8
FHLH	Fisher	Elm	16	3.44	1.92	76.4
FHHL	Fisher	Oak	30	1.78	3.00	61.8
FHHH	Fisher	Oak	26	3.16	1.74	64.6

\*data used in this calculation was only obtained during the first hour of the test

Average flue gas conditions are listed in Table 5. The NO<sub>x</sub> analyser was not functioning during the runs with the Dell Point stove. Both flue gas concentrations and temperature varied with the run conditions, though in general the O<sub>2</sub> concentrations were lower than the CO<sub>2</sub> concentrations.

**Table 5** Flue gas conditions

Run	Average Flue Gas				
	Temperature (°C)	CO <sub>2</sub> (% vol)	O <sub>2</sub> (% vol)	CO (ppm)	NO <sub>x</sub> (ppm)
DWL	92.6	6.5	14.4	88	-
DWH-1	139.1	13.3	7.5	65	-
DWH-2	134.7	13.0	7.5	50	-
DIL	105.6	8.9	11.7	71	-
DIH	134.2	12.0	8.6	40	-
RSSL	178.6	10.2	9.7	6680	42
RSLH	207.1	11.4	8.6	6880	51
RHLL	185.6	9.0	11.2	6184	39
RHLH	276.9	10.9	9.1	4778	62
RHHL	159.7	13.0	7.3	4244	51
RHHH	294.6	11.3	9.1	3103	88
FSSL	106.4	10.9	8.5	21704	30
FSLH	214.8	15.1	4.2	23170	46
FSHL	111.3	11.4	7.5	28000	21
FSHH*	292.4	13.6	5.8	12923	53
FHLL	126.1	11.3	8.6	22720	46
FHLH	329.0	13.0	6.7	8955	57
FHHL	149.8	7.9	12.2	14165	37
FHHH	205.9	9.2	11.1	8922	62

\*concentration data only obtained during the first hour of the test

## Emissions

There is controversy over what units to use to express emissions from residential wood combustion appliances [12]. In this report emissions are reported with three units:

- mass of pollution discharged per unit time, i.e., g/hr
- mass of pollution discharged per mass of fuel burned, i.e., g/kg
- mass of pollution discharged per unit of useful room heat produced, i.e., g/MJ

The third set of units (g/MJ) is considered to be the most useful when comparing stoves with different efficiencies [12].

### Carbon Monoxide

CO emissions are reported in Table 6. Pellet stoves have CO emissions which are two orders of magnitude lower than cordwood stoves. Figure 2 compares the CO emissions from the Regency and Fisher cordwood stoves. The emission reduction technologies of the Regency reduce CO emissions by approximately 50%. It is evident that hardwoods produce less CO than softwoods.

### Particulate Matter

Table 7 lists PM emissions in three size fractions: particulate matter with a diameter greater than 10  $\mu\text{m}$  also known as total particulate matter (TPM), particulate matter with a diameter of 10  $\mu\text{m}$  or less ( $\text{PM}_{10}$ ) and particulate matter with a diameter of 2.5  $\mu\text{m}$  or less ( $\text{PM}_{2.5}$ ). The PM emissions for each run are also shown in Figure 3. Figure 4 plots the PM emissions from the pellet stove runs. TPM values range from 1.21 g/MJ (run DWH) to 264.4 g/MJ (run FSL). Again, the Dell Point stove has emission rates which are significantly lower than the cordwood stoves. The Regency stove has emissions which are one order of magnitude lower than the Fisher stove, once again indicating that the emission reduction technologies are effective.

Figure 5 shows the size composition of the PM captured during each test. All of the tests produced PM which was composed of at least 50%  $\text{PM}_{2.5}$ . Particulate matter captured during the pellet stove runs has a consistently higher percent of particles greater than 2.5  $\mu\text{m}$ . The operating conditions of the cordwood stoves had a significant effect on the size composition of the PM.

Figures 6, 7, 8 and 9 show total particulate matter collected from the cordwood stove runs compared by stove type, fuel type, fuel moisture and burn rate, respectively. The following can be observed in these figures:

- the Regency stove produces significantly less PM than the Fisher stove
- hardwoods have lower emissions than softwoods
- high burn rates decreased PM emissions in five of the six cases
-

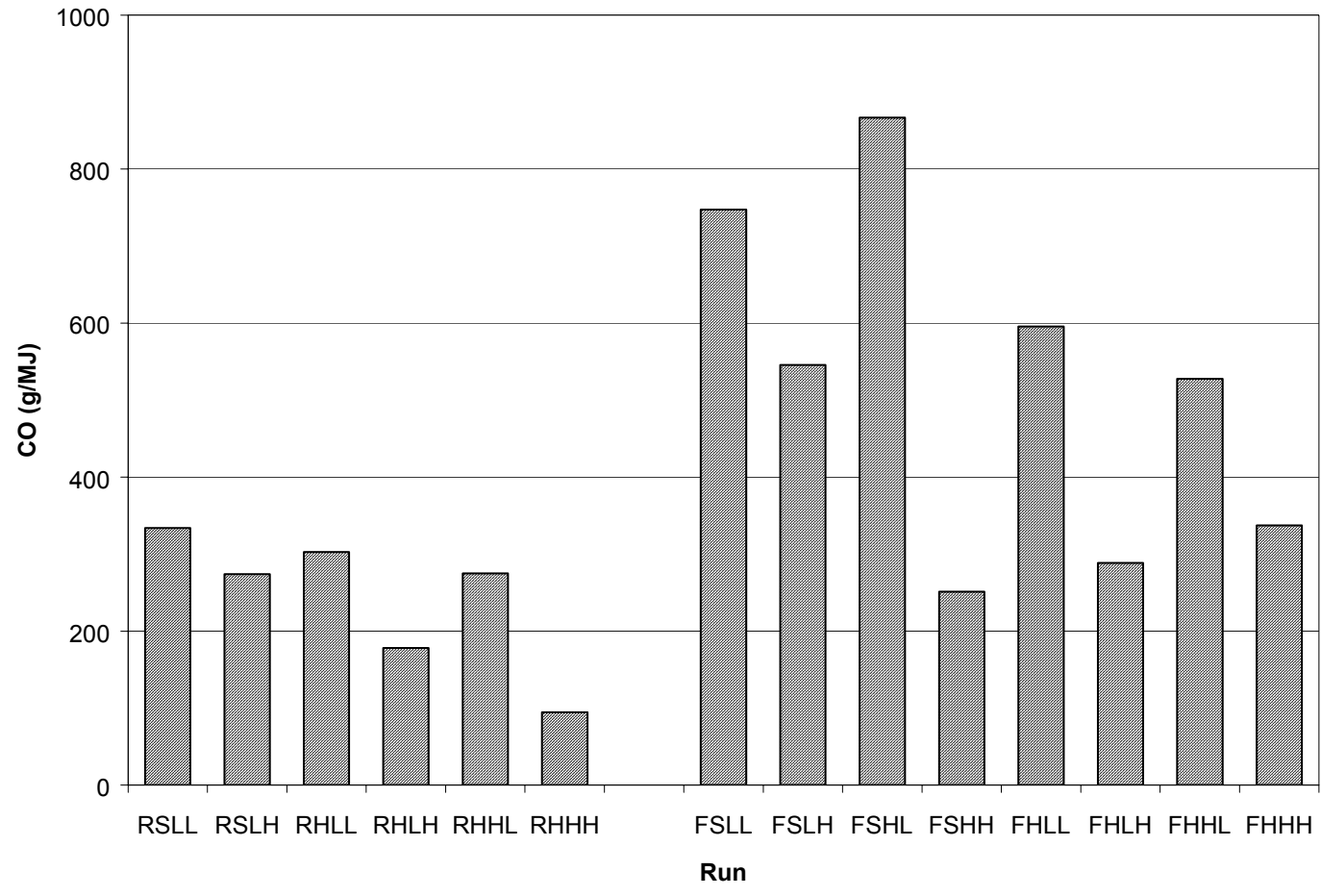
Figures 10, 11, 12 and 13 show the size composition of the PM collected from the cordwood stove runs compared by stove type, fuel type, fuel moisture and burn rate, respectively. These figures indicate that:

- the Fisher stove produces a higher percentage of fine ( $<2.5\mu\text{m}$ ) particulates
- softwoods produced approximately 20% more fine particulates, in three of the four cases
- due to limited range of values the effect of fuel moisture content is inconclusive
- the effect of the burn rate on the size composition is also inconclusive as in half the cases a high burn rate decreased emissions and the other half it increased emissions

**Table 6** Carbon dioxide emissions

Run	CO Emissions		
	g/hr	g/kg	g/MJ
DWL	0.18	0.22	0.77
DWH1	0.17	0.12	0.44
DWH2	0.12	0.09	0.35
DIL	0.36	0.34	1.24
DIH	0.10	0.08	1.66
RSSL	141.3	76.2	333.9
RSLH	171.2	66.1	274.0
RHLL	133.4	76.6	302.5
RHLH	153.3	43.9	178.2
RHHL	101.7	65.9	274.9
RHHH	90.0	26.2	94.6
FSSL	265.4	203.6	747.3
FSLH	461.6	148.4	545.6
FSHL	378.9	229.2	867.1
FSHH*	238.7	66.4	251.4
FHLL	355.97	182.7	595.5
FHLH	254.5	73.9	288.4
FHHL	302.3	169.4	527.6
FHHH	327.3	103.7	337.3

\*data only obtained during the first hour of the test

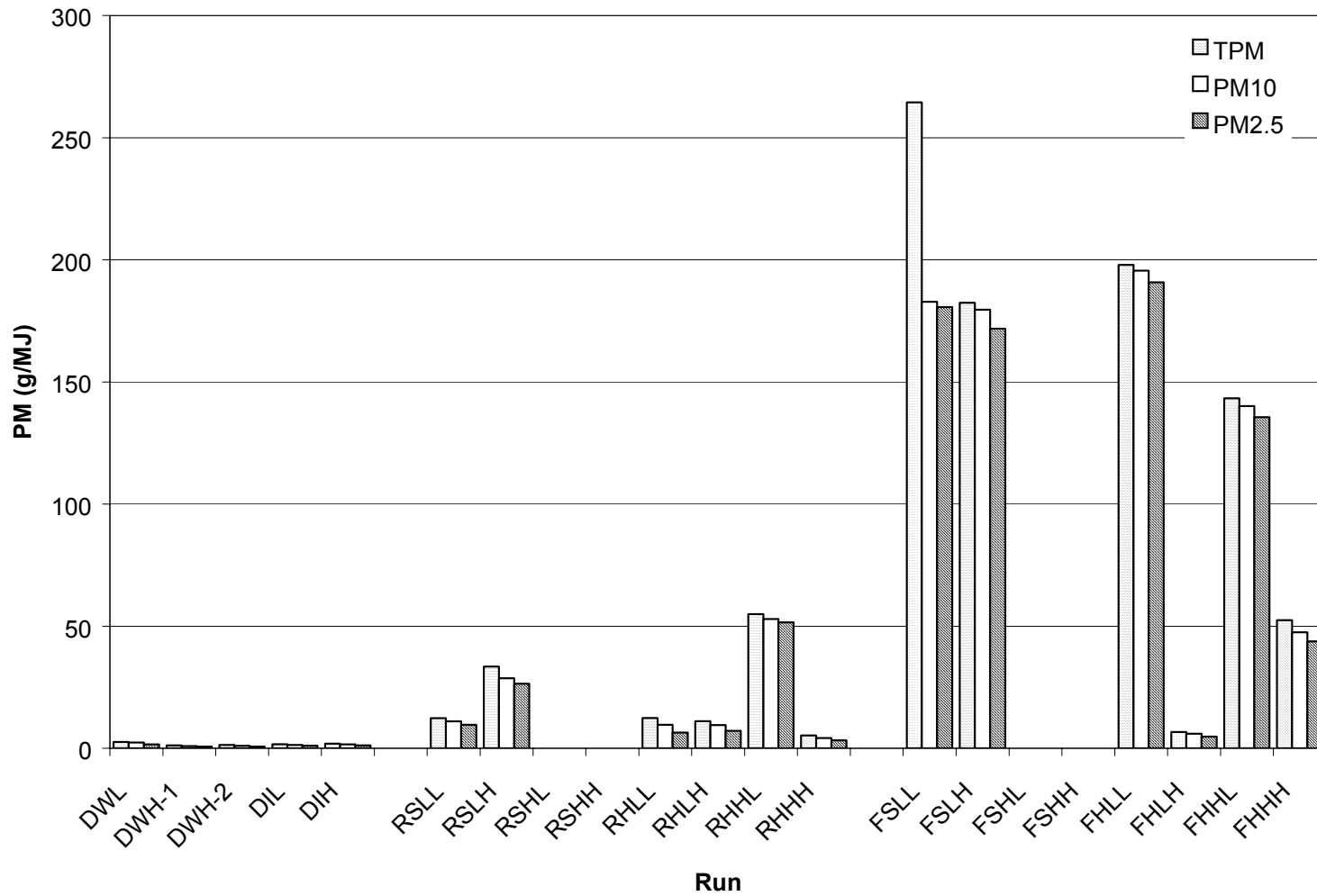


**Figure 2.** CO emissions from the Regency and Fisher cordwood stoves

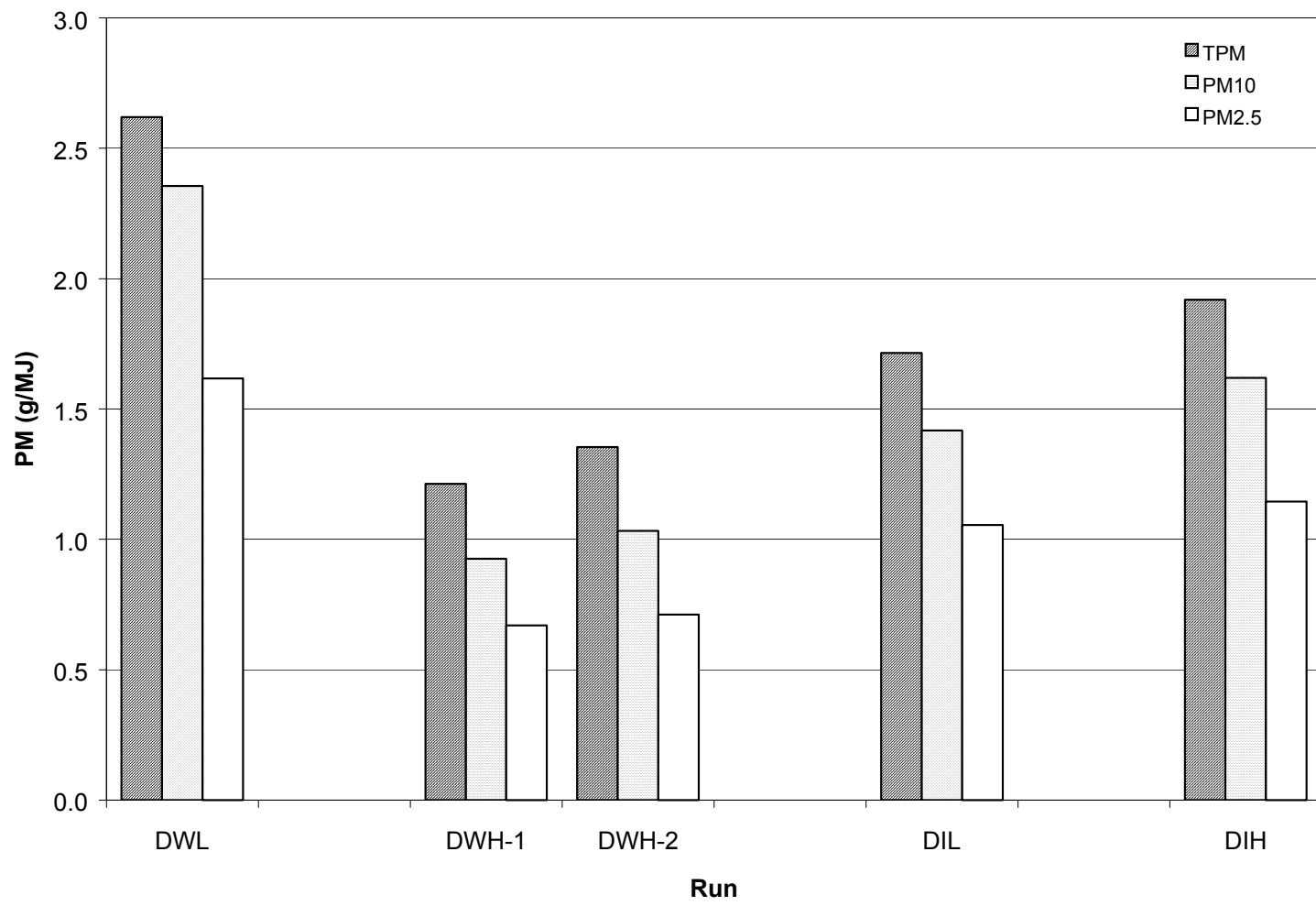
**Table 7**Particulate matter emissions

Run	TPM			PM <sub>10</sub>			PM <sub>2.5</sub>		
	g/hr	g/kg	g/MJ	g/hr	g/kg	g/MJ	g/hr	g/kg	g/MJ
DWL	0.62	0.74	2.62	0.56	0.66	2.36	0.38	0.46	1.62
DWH1	0.47	0.33	1.21	0.36	0.25	0.93	0.26	0.18	0.67
DWH2	0.48	0.35	1.35	0.36	0.27	1.03	0.25	0.18	0.71
DIL	0.49	0.47	1.71	0.41	0.39	1.42	0.30	0.29	1.06
DIH	0.67	0.55	1.92	0.57	0.47	1.62	0.40	0.33	1.14
RSL	5.2	2.8	12.3	4.6	2.5	11.0	4.1	2.2	9.6
RSLH	20.9	8.1	33.5	18.0	6.9	28.7	16.5	6.4	26.4
RHLL	5.5	3.2	12.5	4.3	2.4	9.6	2.8	1.6	6.5
RHLH	9.5	2.7	11.1	8.2	2.4	9.6	6.1	1.8	7.1
RHHL	20.3	13.2	54.9	19.6	12.7	52.9	19.1	12.4	51.5
RHHH	5.0	1.5	5.3	4.0	1.2	4.2	3.2	0.9	3.3
FSL	93.9	72.1	264.4	64.9	182.8	182.8	64.1	49.2	180.6
FSLH	154.4	49.6	182.5	151.9	179.5	179.5	145.4	46.7	171.8
FSHL*									
FSHH*									
FHLL	118.3	60.7	198.0	116.9	195.6	195.6	114.0	58.52	190.8
FHLH	5.8	1.69	6.6	5.2	5.9	5.9	4.2	1.2	4.8
FHHL	82.1	46.0	143.3	80.3	140.1	140.1	77.6	43.5	135.5
FHHH	50.8	16.1	52.4	46.0	47.4	47.4	42.5	13.5	43.8

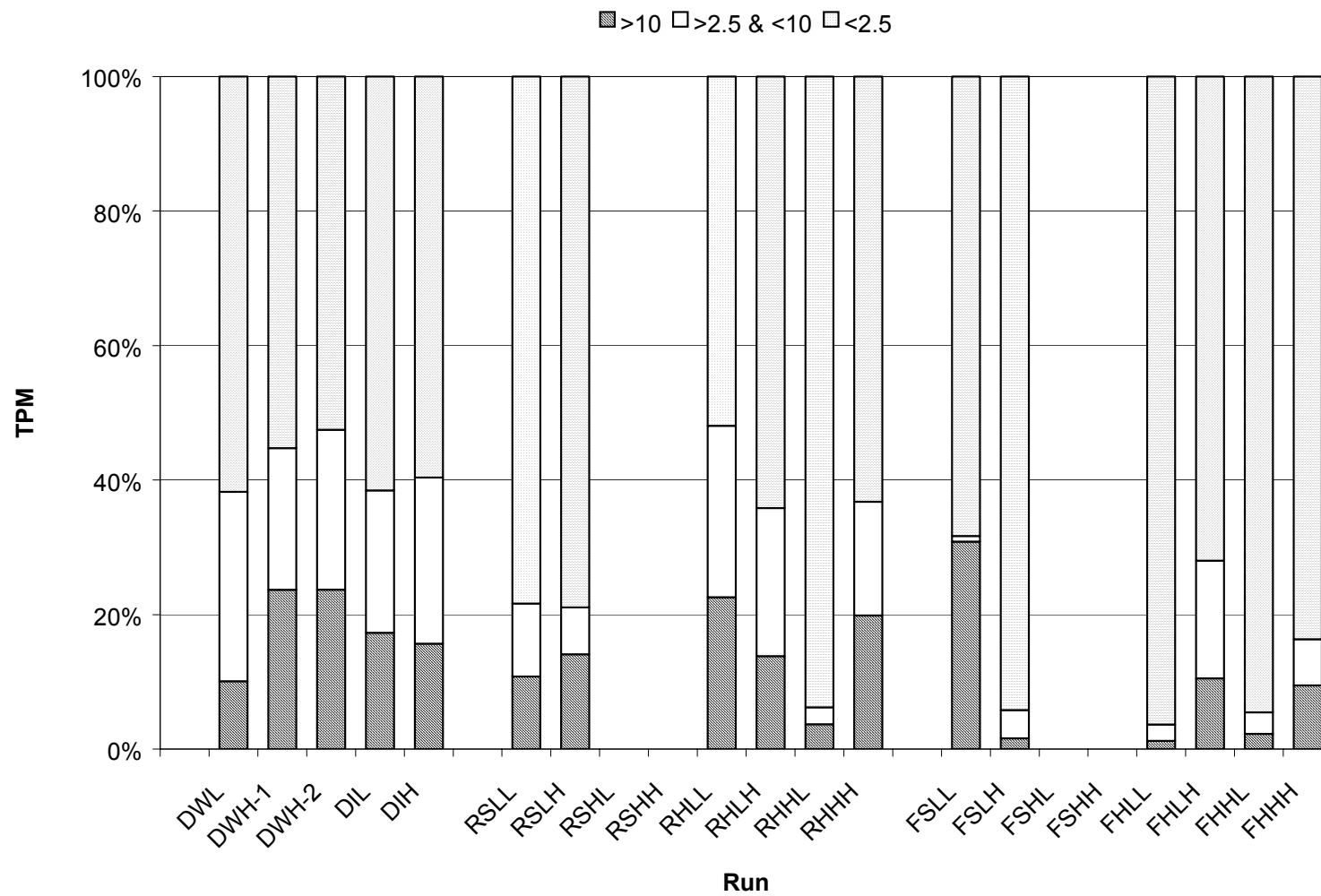
\* data not available yet



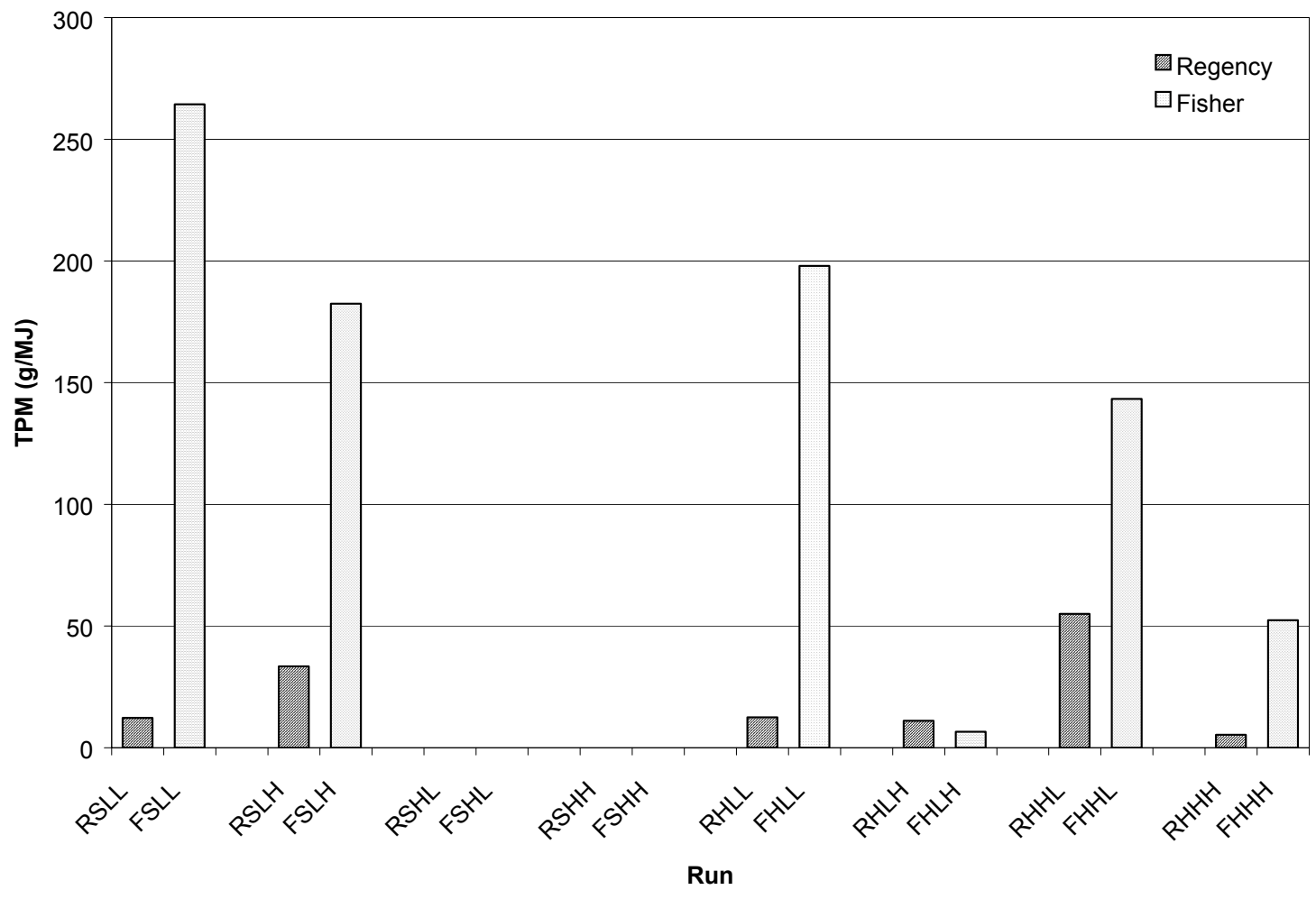
**Figure 3.** TPM, PM<sub>10</sub> and PM<sub>2.5</sub> captured during each run.



**Figure 4.** TPM, PM<sub>10</sub> and PM<sub>2.5</sub> captured from the pellet stove runs.



**Figure 5.** Size composition of the PM collected from each run.



**Figure 6.** Effect of cordwood appliance type on PM emissions.

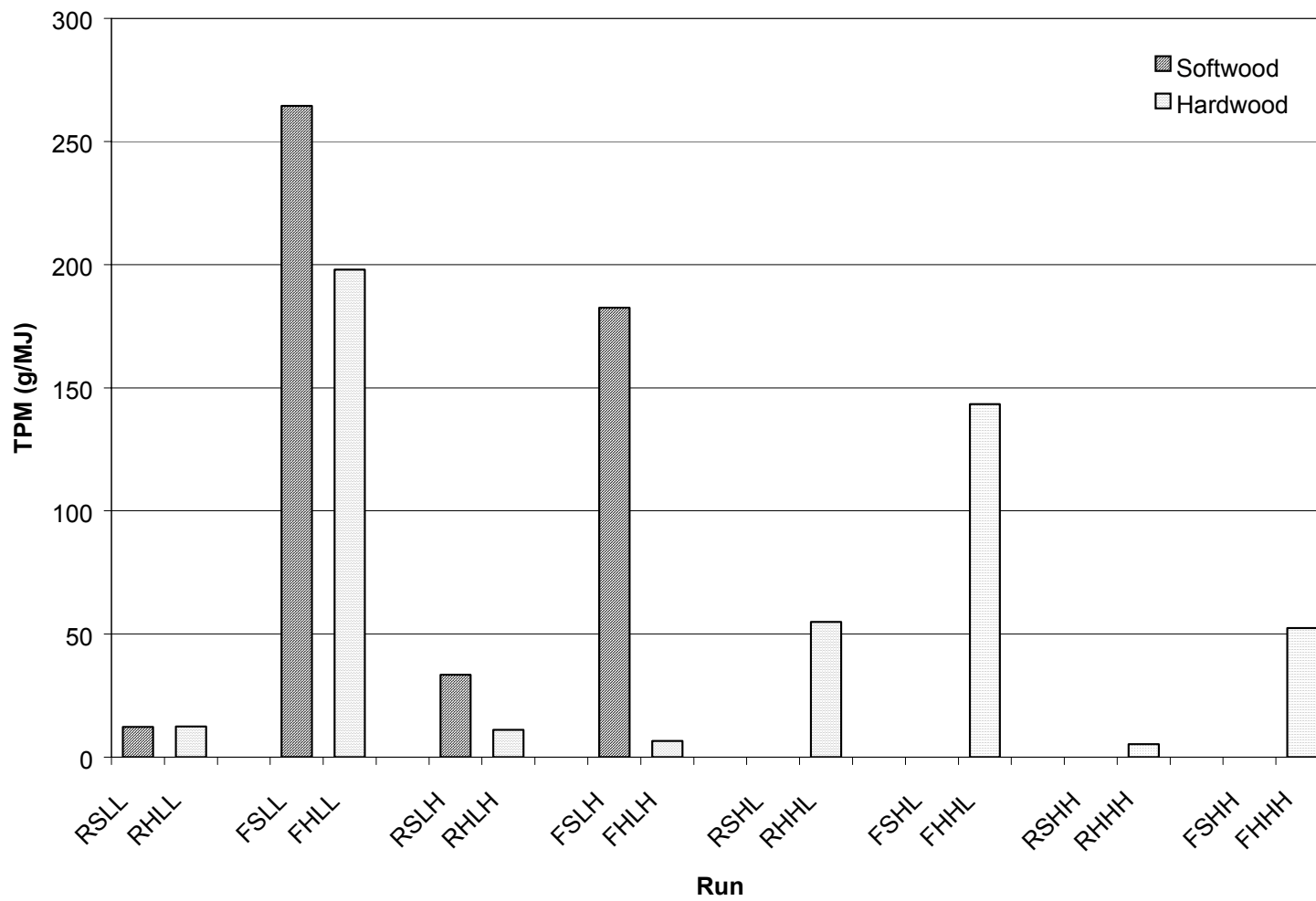
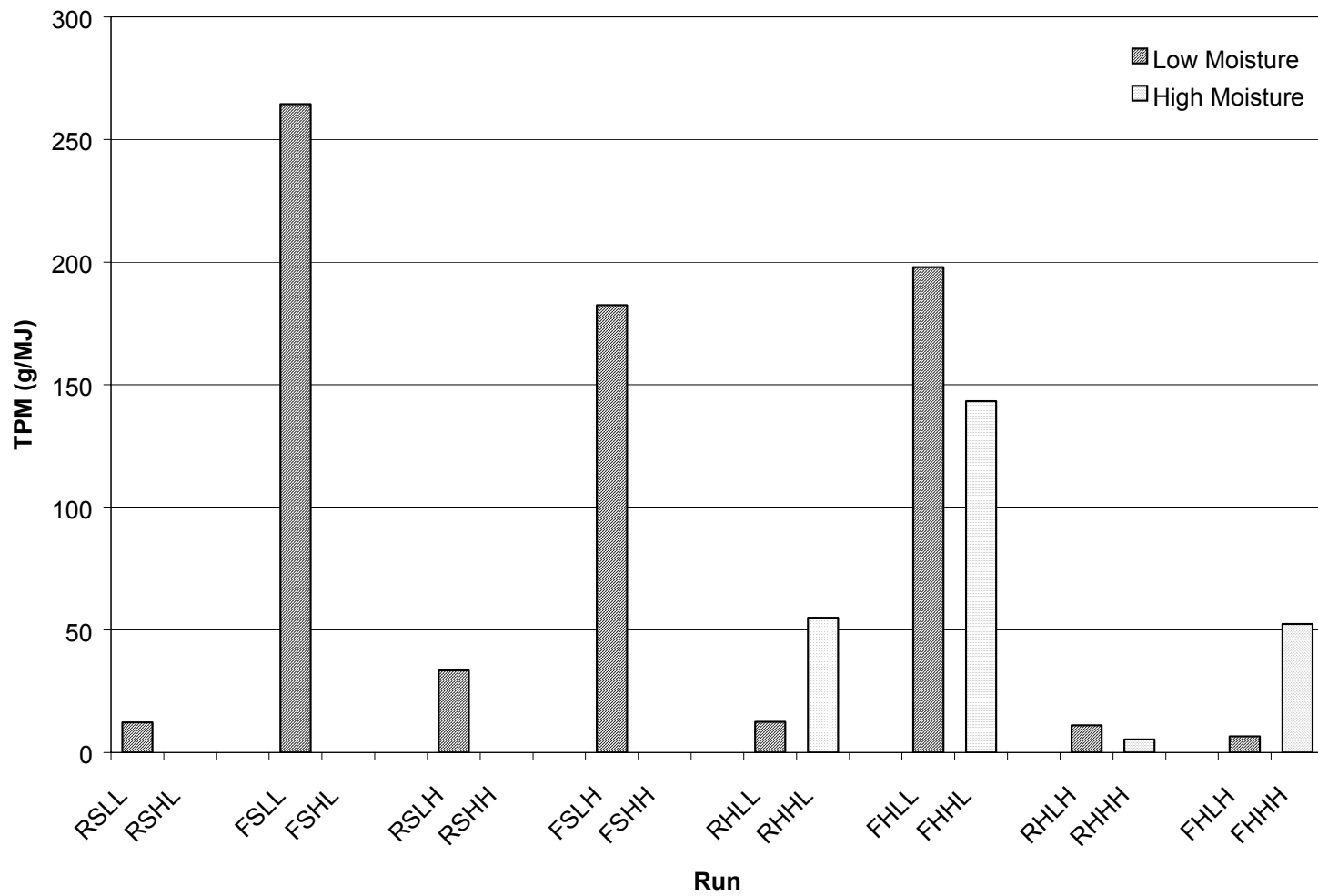
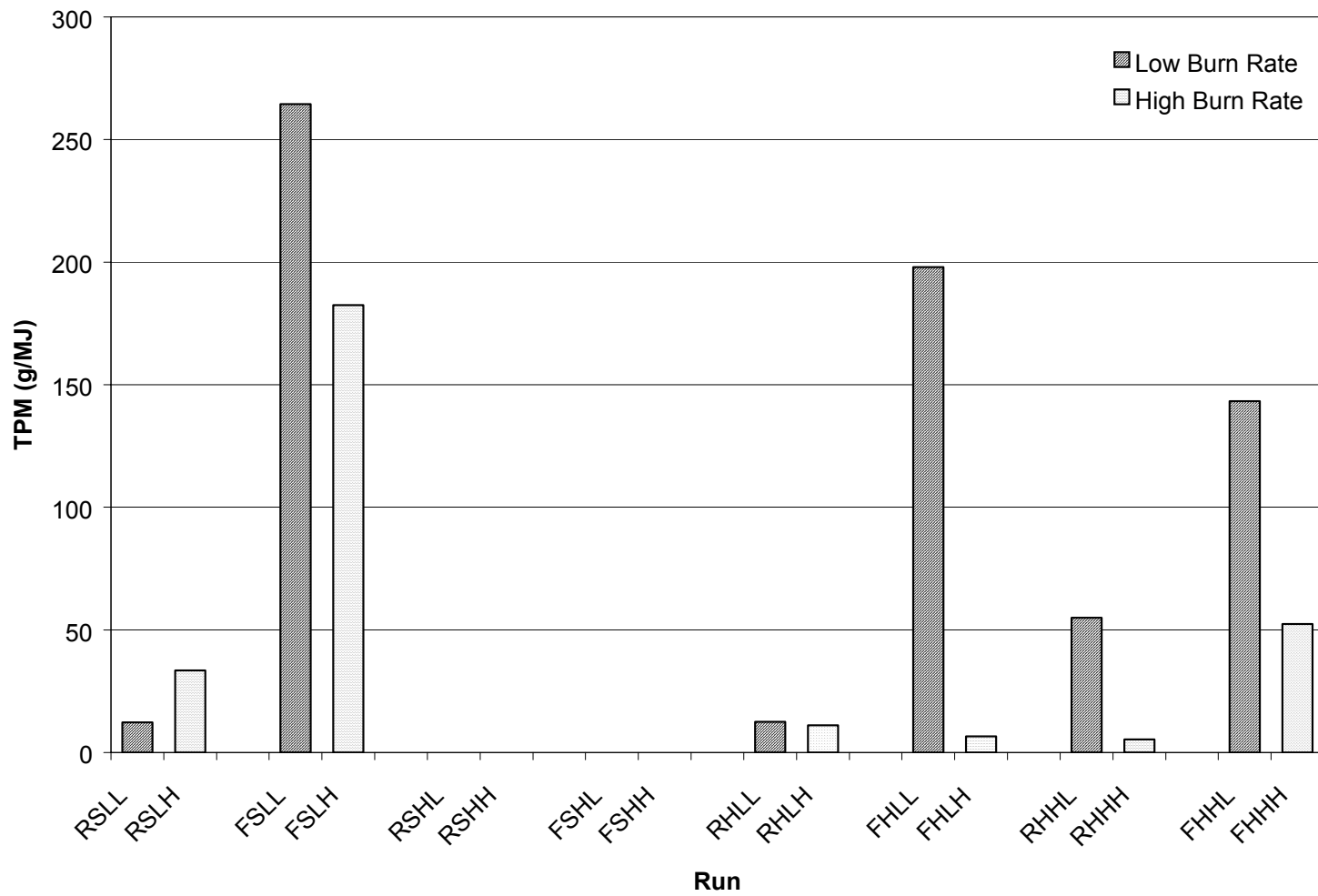


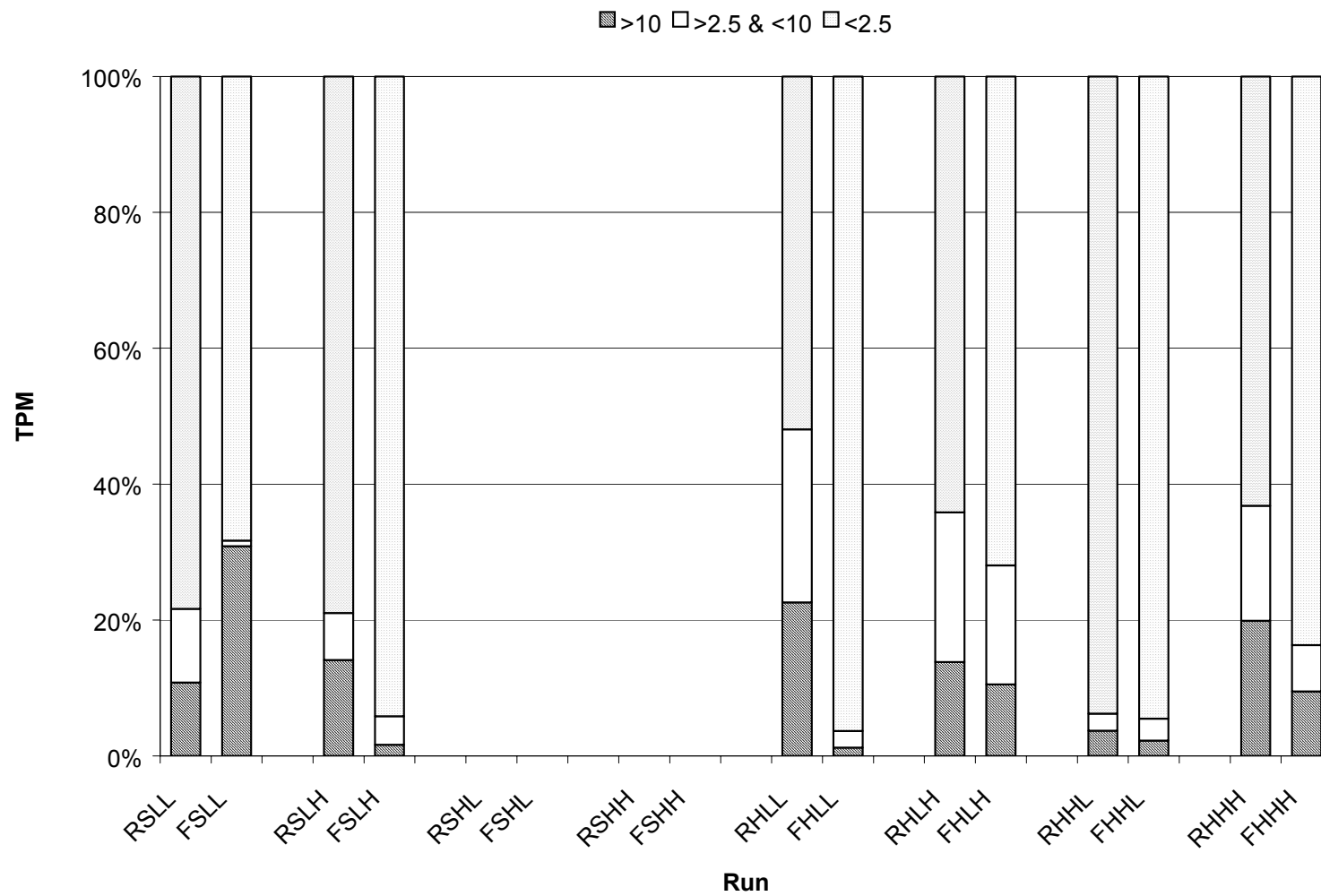
Figure 7. Effect of fuel type on PM emissions.



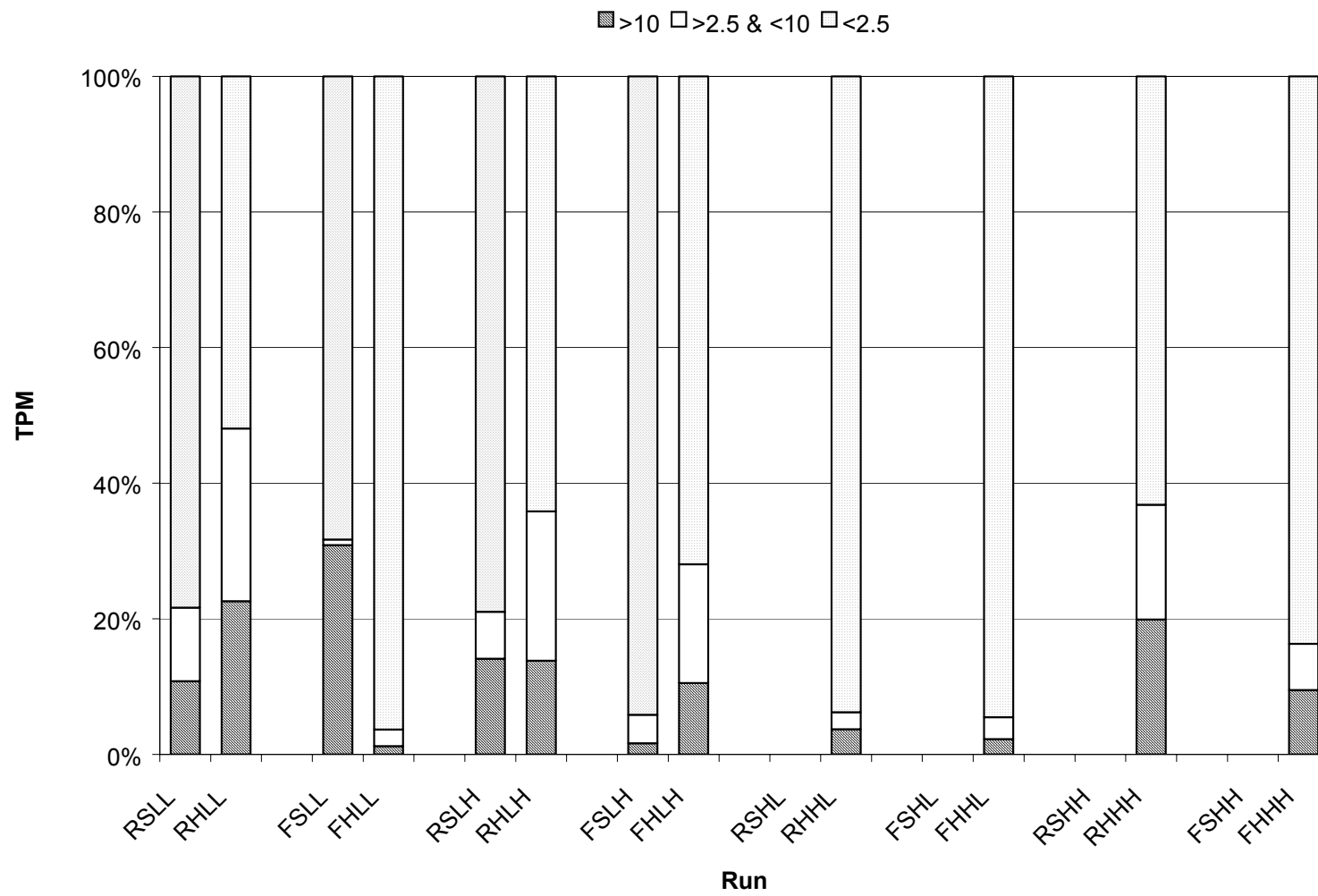
**Figure 8.** Effect of fuel moisture content on PM emissions.



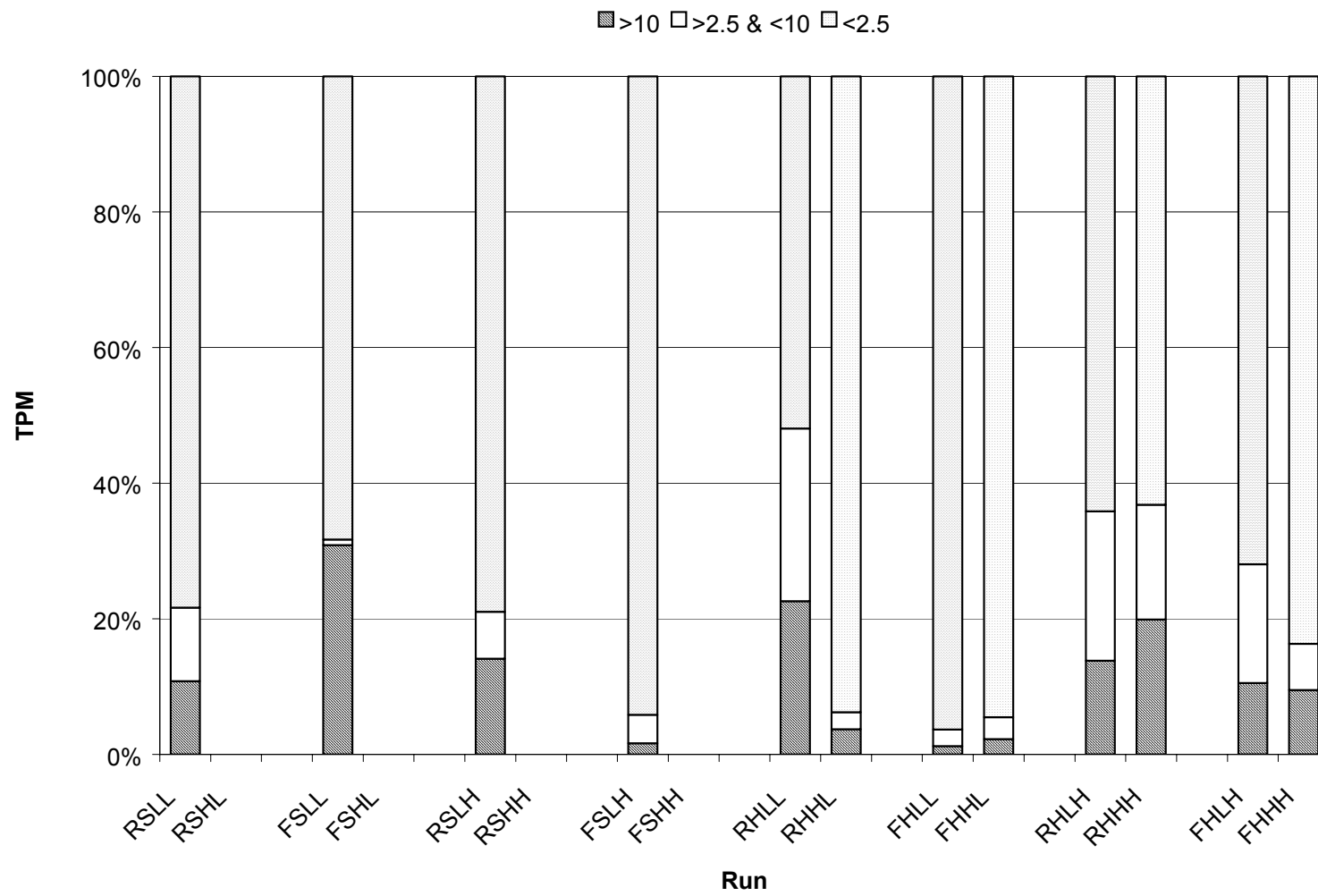
**Figure 9.** Effect of burn rate on PM emissions.



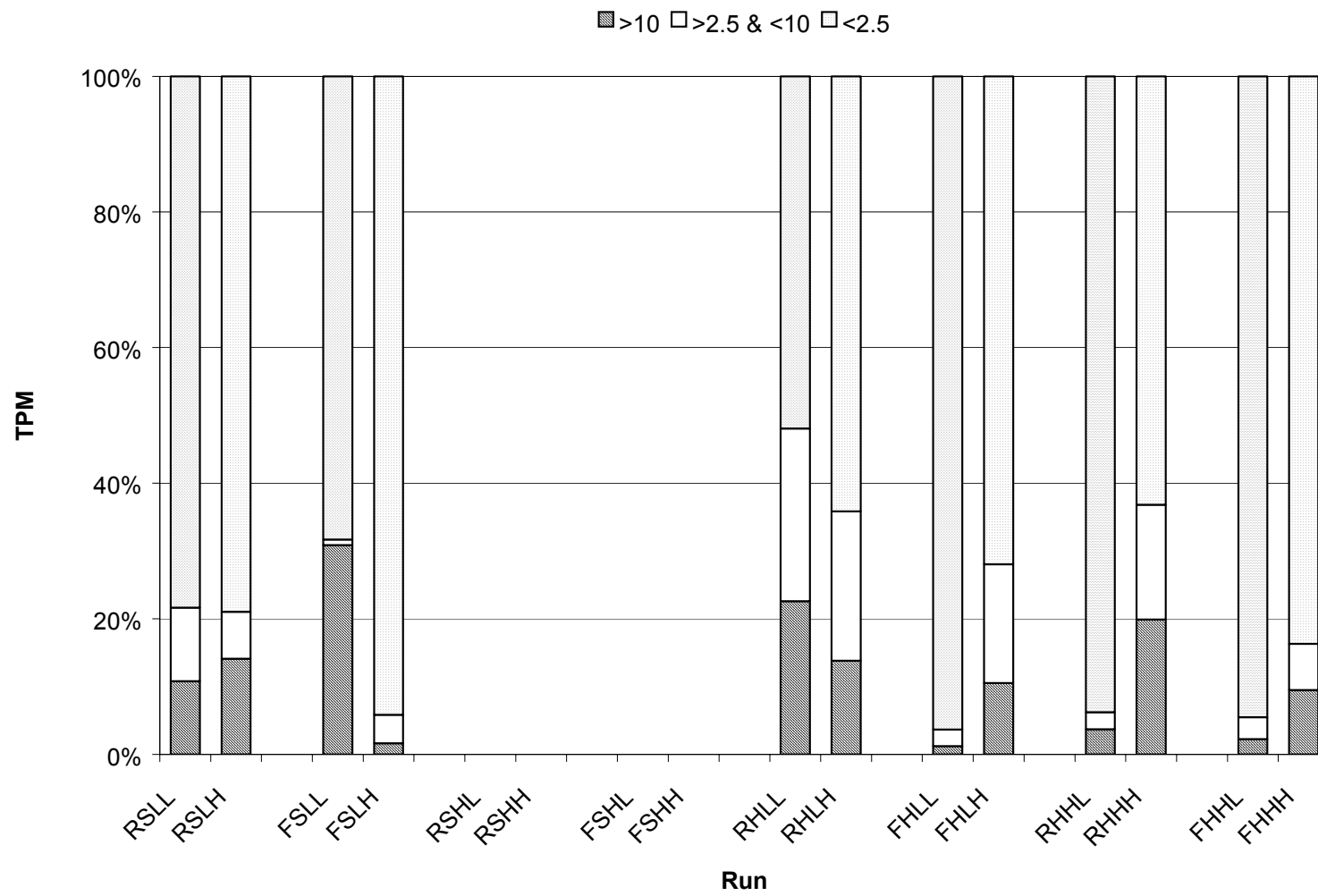
**Figure 10.** Effect of appliance type on the size composition of PM emissions.



**Figure 11.** Effect of fuel type on the size composition of PM emissions.



**Figure 12.** Effect of fuel moisture content on the size composition of PM emissions.



**Figure 13.** Effect of burn rate on the size composition of PM emissions.

## Conclusions

Experiments were conducted on residential wood combustion appliances to determine the effect of appliance type and operating conditions on pollutant emissions. The results from seventeen tests have led to the following conclusions:

1. PM produced from residential wood combustion appliances is composed primarily of PM<sub>2.5</sub>.
2. Pellet stoves have significantly lower total PM emissions than cordwood stoves.
3. Pellet stove PM is composed of less fine particulates (<2.5 μm diameter) than cordwood PM.
4. Emission control technologies on cordwood stoves can reduce PM by approximately one order of magnitude.
5. To reduce emissions, cordwood stoves should be run at a high burn rate and use hardwoods as a fuel.

## **Acknowledgments**

Thanks to Vivien Ko for assistance with the woodstove experiments.

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