USDA FOREST SERVICE RECREATIONAL FIRE PIT EMISSIONS TESTING

Final Report to the Minnesota Pollution Control Agency

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1. Introduction

This report presents the methods and results of recreational outdoor fire pit emissions testing conducted by the USDA Forest Service Fire Sciences Laboratory (FSL) in collaboration with the Minnesota Pollution Control Agency (MPCA). This project quantified fine particulate matter ($PM_{2.5}$) emissions from two commercially available outdoor fire pits designed to burn wood logs with minimal smoke production (low smoke) and from a traditional outdoor fire pit. This report provides $PM_{2.5}$ emission rates and emission factors for each fire pit based on emissions measured during burn-cycles designed to represent typical recreational use.

A total of four burns were conducted with each low smoke fire pit and two burns were conducted with the traditional fire pit. The experiment measured emissions of $PM_{2.5}$ (PM with an aerodynamic diameter < 2.5 µm), CO_2, CO, and CH_4. Measurements of CO_2, CO, and CH_4 are needed to quantify emission factors (EF) for $PM_{2.5}$. Radiant heat flux (RF) produced by the fires was also measured in order to normalize emissions across fire pits. The RF normalized emissions could be used to model emissions based on different fire pit activity scenarios which are linked to operator behavior. The premise being is that from the perspective of a fire pit user, the warmth provided by the fire is probably the best metric for to standardizing wood input and emission rates.

2. Methods

2.1 Combustion facility

The fire pit testing was conducted in the Fire Sciences Laboratory combustion chamber which is depicted in Figure 1. The combustion chamber measures 12.5 m × 12.5 m × 22 m high. An exhaust stack with an inverted funnel at its entrance extends from 2 m above the floor to the top of the chamber. A sampling platform surrounds the stack 17 m above the chamber floor. The funnel opening of the exhaust stack is 3.5 m diameter and the exhaust stack is 1.6 m diameter. Air is drawn through the stack and entrains emissions from fires burning directly beneath the funnel. Within the exhaust stack, a few meters from the funnel opening, is a diffuser ring (0.8 m inside

diameter) which mixes the air and entrained emissions. At the height of the sampling platform temperature and mixing ratio are uniform across the width of the stack (Christian et al., 2003, 2004). During our testing the gas and particle measurement equipment was positioned on the platform and the emissions were drawn through sample lines constructed of stainless steel, copper, Teflon, or conductive tubing as described in Section 2.4.

2.2 Fire Pits

Two commercially available outdoor fire pits designed to burn wood logs with minimal smoke production, the Solo Yukon Stove (Solo) and the Breeo (Breeo), and a traditional outdoor fire pit (Pilot) were tested. Photos of the fire pits and their dimensions and model numbers are provided in Figure 2. The Solo and Breeo fire pits included instructions for wood log loading which were followed as closely as possible during the testing. Both the Solo and Breeo fire pits instructed that wood logs be kept below the interior ventilation holes (Figure 2) which was done throughout the testing.

2.3 Fuels

A pallet of split firewood, a mix of red oak, maple, birch, and ash from Minnesota was used for the fire pit testing. The split firewood had typical dimensions of 15 inches in length and maximum cross section of 3 inches (Figure 3). The fire wood was cured in Missoula for nine months (April – December) at ambient conditions. During the fire pit testing the average moisture content was 7%, with a range of 5 – 8%. MPCA recommends only burning wood with a moisture content of less than 20%.

2.4 Laboratory setup

The experimental setup is shown in Figure 4. The fire pit being tested was placed directly under the center of the exhaust stack. Two radiant heat sensors were placed a distance of 27 inches for the fire pit center and vertically positioned approximately 4 inches above the fire pit rim. The inlet of a NDIR CO_2 gas analyzer (LI-COR LI-7000), which was used to monitor the background CO_2 concentration, was placed 52 inches from the fire pit center at a height of 3 feet above the chamber floor. A multi-species trace gas analyzer, a three wavelength nephelometer, and two particulate matter filter sampling units were positioned on the platform and the emissions were drawn from the exhaust stack through sample lines constructed of stainless steel and conductive tubing. A Cavity Ring-Down Spectroscopy (CRDS) gas analyzer was also positioned on the platform and sampled emissions from the exhaust stack through lines constructed of stainless steel and Teflon.

2.5 Burn procedure

The test burns involved three phases: burn up, steady burn, and burn down. The purpose of the burn up phase was to initiate a robust, steady fire. In the burn up phase, the ignition fuel bed was a small amount of excelsior shavings (< 100 g), several pieces of kindling spliced from split logs, and a single split log. A typical ignition fuel bed is shown in Figure 5a. Following ignition, logs were added to the fire, at irregular intervals, over a period of 20-25 minutes. The steady burn phase began after a regular, consistent fire was achieved. During the steady burn phase logs were added at a regular interval of 10 minutes over a period of 45-60 minutes. Each log addition during the steady burn phase was 1 to 3 logs, with number added varying in order to maintain a robust fire. The burn down phase was 20 minute period beginning 10 minutes after the final steady phase log addition. At the end of the burn down stage the fire was extinguished with water to preserve unburnt fuel to determine fuel consumption. The mass and log count for all fuel additions were recorded. Photos of typical fire behavior during the burn phases are provided Figure 5b-e.

2.6 Instrumentation

Particulate matter

Particulate matter ($PM_{2.5}$) emissions were measured using an ARA Instruments Low Flow Research Sampler (LFR-6) configured for stack sampling. The performance of the ARA sampler for measuring biomass burning smoke was evaluated against a Tisch Federal Reference Method (FRM) monitor in conjunction with the Environmental Protection Agency in a series of static chamber burn at the FSL in April, 2019 (see Appendix B). The sampler pulled emissions from the exhaust stack through a conductive tubing sample line connected to a copper tube inserted 60 cm into the exhaust stack. The sampler pulled emissions at 6 slpm from the exhaust stack through a Federal Reference Method style impactor with a cutoff of ≤ 2.5 µm aerodynamic diameter and onto a 47 mm Teflon filter. The 47 mm Teflon filters used in the PM determination were conditioned and weighed in a controlled- environment room at 68 F and 50 percent relative humidity. Prior to weighing, the filters are conditioned for at least 24 hours. Each filter is weighed three times on a Mettler M4 microbalance with a precision of one microgram. The balance is linked to a software program that collects and stores the weights and room condition. The balance is tared (zeroed) before each weighing. A calibration weight is used once every five filters to verify the accuracy and calibration of the microbalance. Filters whose weights are not reproducible to within 5 µg are withheld from analysis. Control filters are used to correct for environmental and handling variability in the filter weights. The control filters are handled in the same way at the treatment filters. Each filter is pre-weighed prior to sample collection using this procedure, and then again after field collection. They are again conditioned at least 24 hours to stabilize the particulate matter weights and to reduce the effects of static electricity on the weighing process. The PM concentrations are calculated based on the final particulate matter weights (post-weight minus pre-weight), control filter results, and the volume of air drawn through the filter during the emission sampling. During fire pit testing, at the end of each day the filters with samples were placed in a freezer to preserve semi-volatiles that may evaporate over time. The filters were analyzed using the methods described above, one week after completion of the fire pit testing.

CO_2, CO, and CH_4

Continuous measurements (data acquisition rate of 2 s) of CO_2, CO, CH_4, and H_2O were obtained using a CRDS trace gas analyzer (G2401-m, Picarro Inc., USA). Details of the CRDS method and this specific instrument may be found elsewhere (Urbanski, 2013). Air was sampled by the CRDS through Teflon tubing connected to a stainless steel tube inserted in the exhaust stack with its orifice near the stack's center. A three-point calibration was run daily to maintain accuracy of the CRDS measurements. Gas mixtures of CO_2, CO and CH_4 in Ultrapure air served as calibration standards. The CRDS response varied little from day to day and study average calibration factors were applied to the data offline. The NDIR CO_2 analyzer used to monitor the background CO_2 (Figure 4) was cross calibrated versus the CRDS analyzer. Details of the calibrations are provided in Appendix B.

Nephelometry

A TSI three wavelength nephelometer was used to measure total light scattering by PM at 700 nm (red), 550 nm (green), and 450 nm (blue) at a data acquisition rate of 0.5 Hz. Total light scattering at these wavelengths responds strongly to PM concentration, particle size distribution, and particle chemical properties. The nephelometer measurements at 700 nm may be used to estimate the temporal PM concentration profile based on the integrated PM measurements obtained with the filter sampling system.

Radiant Heat

Radiant energy flux was measured using Medtherm Dual Sensor Heat Flux sensors (Model 64-20T) contained in Fire Behavior Packages (FBP). These FBP have been widely used in field research projects conducted by the Fire Lab's fire behavior research group and details may be founds in Jimenez et al. (2007; https://www.fs.usda.gov/treesearch/pubs/28594). The heat flux sensors were calibrated in a black body over a range of 0 to 200kW m^{-2} and fit a power law curve to the calibration data resulting in a calibration error of less than 3% of reading over the range.

2.7 Emission Calculations

Emissions of a given species X were quantified using burn phase average excess mass mixing ratios ΔX ($\Delta X = X_{fire} - X_{background}$). Phase average emission factors for each species X, EF_X, were calculated using the carbon mass balance method (Yokelson et al., 1999) implemented with Eq. (1). In Eq. (1), ΔC_i are the excess mass mixing ratios of carbon in species X, and F_c is the mass fraction of carbon in the dry fuel which was taken as 0.50 for all wood used in this study.

Eq. 1 $$EF_x = F_c \times 1000\ (g\ kg^{-1}) \times \frac{\Delta X}{\Delta C_{CO_2} + \Delta C_{CO} + \Delta C_{CH_4} + \Delta C_{PM}}$$

The carbon mass balance method assumes that all the fuel carbon volatilized as gases or PM is measured. However, since the majority of carbon mass (> 95%) in fresh biomass smoke from efficient fires is contained in CO_2, CO, and CH_4 (Yokelson et al., 2007), neglecting other carbon containing gases in the carbon mass balance method introduces only a minor bias of < +5%. We assumed a PM carbon content of 75% (Reid et al., 2005) in our EF calculations. The difference in the denominator between assumed PM carbon content of 0% and 100% was < 1.0%. Combustion efficiency (CE) is the fraction of carbon evolved in gases and PM that is emitted as CO_2. Given most carbon is contained in CO_2, CO, and CH_4, we estimate CE as $\Delta CO_2/(\Delta CO_2 + \Delta CO + \Delta CH_4)$. In biomass burning, modified combustion efficiency (MCE; MCE = $\Delta CO_2/(\Delta CO_2 + \Delta CO)$) is used to characterize the relative amount of flaming and smoldering combustion (Akagi et al., 2011). MCE approaches 0.99 for "pure" flaming combustion (Yokelson et al., 1996).

Emissions of species X by fire phase were calculated using Eq. 2.

Eq. 2 $$E_iX = EF_iX \times FCON \times \frac{\Delta C_i \times \Delta t_i}{\sum \Delta C_i \times \Delta t_i}$$

In Eq. 2 the index i is the fire phase (burn-up, steady burn, burn-down), FCON is the total dry mass of fuel consumed in the fire (g), EF_iX is the EF for species X (Eq 1) for phase i, ΔC_i is average mass mixing ratio of carbon emitted during phase i (denominator of Eq. 1), and Δt_i is the sampling duration of phase I, and E_iX is in units of g of X. The emission rates for species X by fire phase were calculated using Eq. 3

Eq. 3 $$ER_iX = \frac{E_iX}{\Delta t_i}$$

Where E_iX is the amount of X emitted in phase i (Eq. 2) and Δt_i is the sampling duration of phase i, and ER_iX is in units of g of X per minute. Emissions of species X for phase I, normalized to radiant heat flux is given by Eq; 4:

Eq. 4 $$NE_iX = \frac{E_iX}{RF_i}$$

where E_iX is the amount of X emitted in phase i (Eq. 2) and RF_i is average radiant heat flux during of phase i, and NE_iX is in units of g m^2 kW^{-1}.

3. Results

A total of 10 test burns were conducted as summarized in Table 1. $PM_{2.5}$ emissions, RF, and fuel consumption (FC) are summarized by fire phase for each burn in Tables 2-4. Figure 6 shows temporal profiles of gaseous emissions, combustion efficiency (CE), radiant heat flux (RF), and fuel input for burn #2 (Breeo fire pit). Following ignition and during the first few rounds of fire wood addition, RF remains low (< 100 W m^{-2}) and gaseous carbon emissions (ΔC) are less than half the average value of the steady burn phase (Fig. 6, top). By the end of the burn-up phase ΔC has peaked and RF has neared the average value measured over the steady burn phase. During the later stages of the burn-up and throughout the steady burn, inputs of fire wood produced a large spike in ΔC, while RF spikes upon fire wood addition do not occur consistently. During the burn-down phase CE decreases rapidly (Fig. 6, bottom) due to shift in production from CO_2 to CO. The increase in CO production during the burn-down phase is due to glowing combustion of char (Yokelson et al., 1996). Glowing combustion of char is characterized by low MCE, relatively high EFCO, and low PM production. The burn-down phase $EFPM_{2.5}$ are less than or equal to those of the steady-burn phase (Tables 2 and 4). In contrast the burn-down EFCO is at least twice that of the steady burn phase (Tables A1 and A3).

We focus on the results of the steady burn phase since it represents the primary fire pit use mode. $PM_{2.5}$ emission factors, emission rates, and emissions normalized to radiant heat flux are summarized by burn in Table 2 and plotted in Figure 7. The Breeo fire pit had the lowest $EFPM_{2.5}$ at 1.2 g kg^{-1}, the Solo fire pit had the highest at 3.1 g kg^{-1}, and $EFPM_{2.5}$ for the Pilot Rock fire pit (standard fire pit) fell in between (1.3 g kg^{-1}). Actual emissions also depend on the fuel consumption and when this is taken into consideration the $PM_{2.5}$ production rates are follow a similar pattern Breeo < Pilot Rock < Solo. During the steady burn phase, wood was added to the fires at a standardized interval of 10 minutes. However, the amount of wood added was varied between one to three logs in order to maintain a fire that appeared visually to be steady and robust. From the perspective of a fire pit user, the warmth provided by the fire is probably the best metric for to standardizing wood input (i.e. users add wood to maintain the radiant heat received). Therefore, $PM_{2.5}$ emissions normalized to radiant heat flux (NE) may be the metric that best represents real world fire pit usage. Based on this metric, the Pilot Rock and Breeo fire pits were comparable at NE of 5.6 g m^2 kW^{-1} and 6.2 g m^2 kW^{-1}, respectively, significantly outperforming the Solo fire pit (NE = 13.3 g m^2 kW^{-1}) (Table 2, Figure 7).

4. Comparison to Previous Testing

This section compares steady burn phase results from final fire pit testing, conducted in December 2019 and described in this report, with those from preliminary testing performed in May 2019. Key results from the May testing are provided in Appendix C and the complete report is included as Appendix D. Differences between the test rounds are explained in the context of the combustion process: the less efficient a combustion process, the greater the abundance of incomplete combustion products such as CO, CH_4, non-methane organic compounds (NMOC), and organic aerosol (OA). Many previous laboratory studies of emissions from burning wildland fuels have found a strong correlation between MCE, a proxy for combustion efficiency, and EFs

for CH_4, NMOC, OA, and total PM (e.g. Burling et al. 2010; McMeeking et al. 2009; Yokelson et al. 2013; Jen et al. 2019). Next, MCE, EFCO, and $EFCH_4$ are used to explain EFPM measured for the Breeo and Solo fire pits during the two rounds of testing.

In preliminary fire pit testing conducted in May 2019, using moist (MC = 23-38%) and moderately cured (MC = 11-16%, Table C1) firewood, $EFPM_1$ for the Breeo and Solo fire pits were 2.2±1.8 g kg^{-1} (n=4) and 1.3±0.2 g kg^{-1} (n=4), respectively. In the final testing presented in this report, the burning of well-seasoned firewood (MC < 10%) resulted in $EFPM_{2.5}$ of 1.2±0.3 g kg^{-1} (n=4) for the Breeo fire pit and 3.1±0.3 g kg^{-1} (n=4) for the Solo fire pit. As expected, the well cured firewood used in the December 2019 testing burned with a greater combustion efficiency, having higher MCE (≥ 0.98) and lower EFCO and $EFCH_4$, than the May 2019 burns using moist and moderately cured firewood (Tables A1 & C3). Assuming the PM mass fraction in particles > 1µm is small (Reid et al. 2005), these results indicate the use of well cured firewood reduced EFPM (and EFCO and $EFCH_4$) for the Breeo fire pit (Figure 9a, A1, & C3). The two rounds of Breeo fire pit testing showed a well-defined difference in combustion efficiency with MCE=0.99 in December testing versus MCE=0.96 in the May tests (Tables A1 & C3). This finding is consistent with both the expectation that dry firewood burns more efficiently and with published studies of open biomass burning emissions showing EFPM, EFCO, and $EFCH_4$ decrease with increasing MCE (e.g. Burling et al. 2010; McMeeking et al. 2009; Yokelson et al. 2013; Jen et al. 2019).

In contrast to the Breeo fire pit, we observed a large increase in EFPM for the Solo fire pit when burning well cured firewood (Figure 9a), despite slightly lower average MCE and significantly lower EFCO and $EFCH_4$ (Tables A1 & C3). This observed increase in EFPM coinciding with increased combustion efficiency is contrary to expectations. One possible explanation for this result is that the relationship between combustion efficiency and OA and black carbon aerosol (BC, also referred to as soot or elemental carbon (EC)) production is different. Particulate matter produced by the open burning of forest surface fuels (litter and dead wood) is primarily carbonaceous, being either OA or BC, with ionic aerosols— sulfate, nitrate, ammonium, and chloride— generally comprise < 10% of aerosol mass generated by the combustion of forest fuels (McMeeking et al. 2009; Hosseini et al. 2013; May et al. 2014). Laboratory studies of emissions from burning wildland fuels have generally found a strong negative correlation of EFOA, EFOC (the carbon fraction of OA, typically ~70% by mass (Reid et al. 2008; McMeeking et al. 2009)), and EFPM (PM = total particulate mass) with MCE (e.g. McMeeking et al. 2009; Jen et al. 2019). The response of EFPM generally follows that of EFOA and EFOC because PM created by burning wildland fuels is mostly OA (McMeeking et al. 2009; Jen et al. 2019). Thus, one would expect the EFPM for the Solo fire pit from the December tests be similar or lower than that measured in the May tests, given the comparable MCEs, contrary to the actual results. However, if a sizeable fraction of the PM generated by the fire pits is BC, the observed increase of EFPM for the Solo fire pit would be consistent with current knowledge of biomass burning emissions. BC is associated with flaming combustion, and previous emissions studies show that EFBC increases with increasing MCE, as shown in Figure 9b, which reproduces a figure from Jen et al. (2019). This suggestion may explain the EFPM trend observed for the Solo fire pit, but not the Breeo fire pit, for which EFPM decreased with increasing MCE (Figure 9a).

Both fire pits performed at the high end of combustion efficiency as measured via MCE. However, in the December testing the average radiant heat flux produced by the Solo fire pit was nearly twice that of the Breeo fire pit (4544 W m^{-2} vs 2310 W m^{-2}, Table 2), indicating far

more intense flaming combustion. The comparatively high intensity fires produced by the Solo fire pit may have resulted in increased BC production and hence increased EFPM relative to the May testing. In contrast, the fires produced by the Breeo fire pit may not have been sufficiently intense to produce additional BC, or enough additional BC to offset a decrease in OA associated with the increased combustion efficiency.

5. Conclusions

The steady burn phase represents the primary use mode for the recreational outdoor fire pits. During steady phase burning the Breeo and Pilot Rock (standard) fire pits had the lowest $EFPM_{2.5}$ and heat flux normalized $PM_{2.5}$ emissions of the fire pits tested. Our measurements suggest that if all three fire pits were operated following the manufacturer's instructions and were fueled to provide the same radiant heat output, the Solo fire pit would produce about twice the $PM_{2.5}$ emissions of the Breeo or traditional fire pits. These results pertain only to the burning of well cured firewood, moisture content < 10% (of dry weight mass). However, given the limited number of test burns and the high variability of emission observed for the Breeo fire pit, this conclusion is somewhat uncertain. Over the burns the mean (± 1 standard deviation) of the radiant heat flux normalized $PM_{2.5}$ emissions were 13.3±2.3 g m^2 kW^{-1} for the Solo (n = 4) and 6.2±2.0 g m^2 kW^{-1} for the Breeo (n = 3). The $PM_{2.5}$ emission results in this study are opposite of those found in a preliminary study, conducted 7 months prior, which measured PM_1 emissions from the same fire pits burning moist fire wood (moisture content = 11 – 37%) In this previous study the PM_1 EF and radiant heat flux normalized emissions was lowest for the Solo fire pit and highest for the Breeo fire. Possible reasons for the differences between tests include…

5. References

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Table 1. Summary of test burns. Moisture content (MC) is percent of dry mass.

Burn No.	Date	Fire pit	Wood MC (%)	Dry wood mass (g)	Ash (g)	Dry wood consumed (g)	Percent consumption
1	20191209	Breeo	9	26496	3660	22836	78
2	20191210	Breeo	9	27798	4481	23317	76
3	20191210	Solo	7	29246	2272	26974	84
4	20191211	Solo	6	32503	2200	30303	85
5	20191212	Solo	8	33769	3470	30299	81
6	20191213	Breeo	8	24678	4559	20119	74
7	20191216	Pilot Rock	8	25006	3776	21230	77
8	20191217	Pilot Rock	8	27288	NA	23166[1]	77
9	20191218	Solo	9	26724	2215	24509	83
10	20191219	Breeo	8	25900	4983	20917	73

[1]The ash pit, which was left to cool overnight, was not fully extinguished and smoldered overnight preventing an accurate measurement of post burn ash. It was assumed the percent consumption for burn #8 was the same as that for the other Pilot Rock burn (77%).

Table 2. Steady burn phase results. $PM_{2.5}$ emission factors (EF), $PM_{2.5}$ emission rates (ER), $PM_{2.5}$ emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	EF g kg^{-1}	ER g min^{-1}	NE g m^2 kW^{-1}	FC g	RF W m^{-2}
			Breeo Fire Pit		
1	1.55	0.42		16334	
2	1.20	0.28	8.54	14058	1974
6	0.92	0.25	5.26	12371	2153
10	1.00	0.30	4.78	13399	2803
Average	1.17±0.28	0.31±0.08	6.19±2.04	14041±1679	2310±437
			Solo Fire Pit		
3	2.92	0.99	13.88	18608	3916
4	2.90	1.12	13.96	21214	4407
5	3.05	1.21	15.25	21705	4348
9	3.48	1.22	9.99	15794	5504
Average	3.09±0.27	1.13±0.11	13.27±2.28	19330±2721	4544±676
			Pilot Rock Fire Pit		
7	1.38	0.41	5.37	13248	3402
8	1.31	0.420	5.81	14569	3273
Average	1.34	0.41	5.59	13909	3337

Table 3. Burn up phase results. $PM_{2.5}$ emission factors (EF), $PM_{2.5}$ emission rates (ER), $PM_{2.5}$ emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	EF g kg^{-1}	ER g min^{-1}	NE g m^2 kW^{-1}	FC g	RF W m^{-2}
		Breeo Fire Pit			
1	1.92	0.34		3505	
2	1.27	0.31	4.51	4938	1393
6	1.75	0.42	8.61	4777	968
10	1.66	0.39	5.92	4627	1300
Average	1.65±0.28	0.36±0.05	6.35±2.09	4462±651	1220±223
		Solo Fire Pit			
3	2.62	0.61	9.45	4642	1284
4	1.93	0.46	7.83	4805	1187
5	1.80	0.54	6.23	5968	1721
9	2.57	0.70	4.93	5439	2833
Average	2.23±0.42	0.58±0.10	7.11±1.96	5213±610	1756±754
		Pilot Rock Fire Pit			
7	2.42	0.56	7.68	4601	1451
8	2.51	0.54	9.56	4329	1136
Average	2.46	0.55	8.62	4465	1293

Table 4. Burn down phase results. $PM_{2.5}$ emission factors (EF), $PM_{2.5}$ emission rates (ER), $PM_{2.5}$ emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	EF g kg^{-1}	ER g min^{-1}	NE g m^2 kW^{-1}	FC g	RF W m^{-2}
		Breeo Fire Pit			
1	1.93	0.31		2998	
2	1.27	0.22	4.35	4320	1262
6	1.37	0.20	3.79	2971	1071
10	1.43	0.21	2.38	2891	1739
Average	1.50±0.30	0.23±0.05	3.51±1.01	3295±685	1357±344
		Solo Fire Pit			
3	1.55	0.29	3.16	3724	1829
4	2.44	0.52	4.98	4285	2097
5	2.49	0.65	2.48	2626	2636
9	2.16	0.35	3.30	3276	2139
Average	2.16±0.43	0.45±0.17	3.48±1.06	3478±702	2175±337
		Pilot Rock Fire Pit			
7	1.53	0.26	1.77	3381	2928
8	1.78	0.38	2.54	4268	2999
Average	1.66	0.32	2.15	3824	2963

Figures

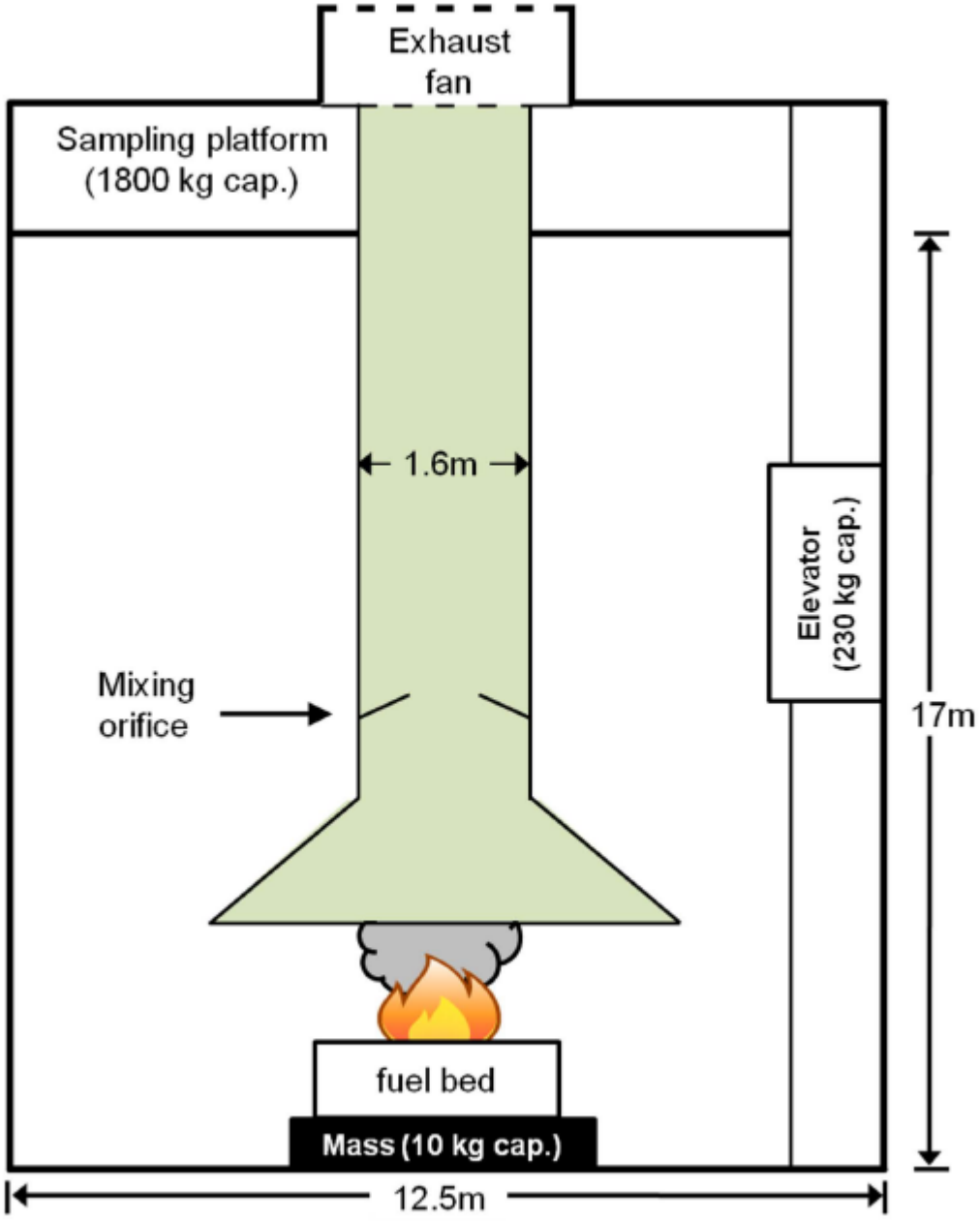

Figure 1. Schematic of combustion chamber at the Missoula Fire Sciences Laboratory (from Burling et al., 2010).

Figure 2. Fire pits post testing. Top row: Solo Yukon Stove, middle Row: Breeo, bottom row: Pilot Rock (traditional campground fire pit).

Figure 3. Left: Typical pieces of split firewood, right: firewood conditioning the environmental chamber at the Missoula Fire Sciences Laboratory.

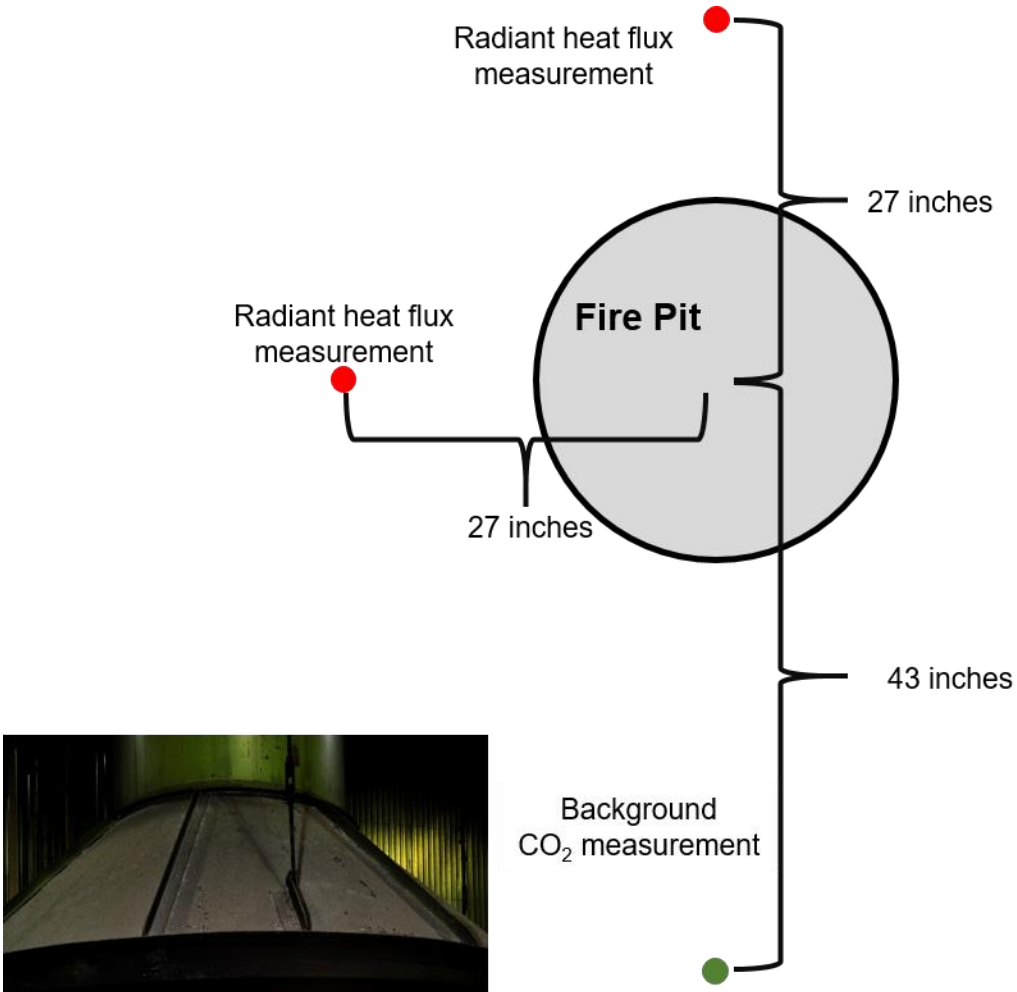

Figure 4. Schematic of experimental setup on the combustion chamber floor. The inset photo shows the position of the fire behavior packages containing the radiant heat flux sensors.

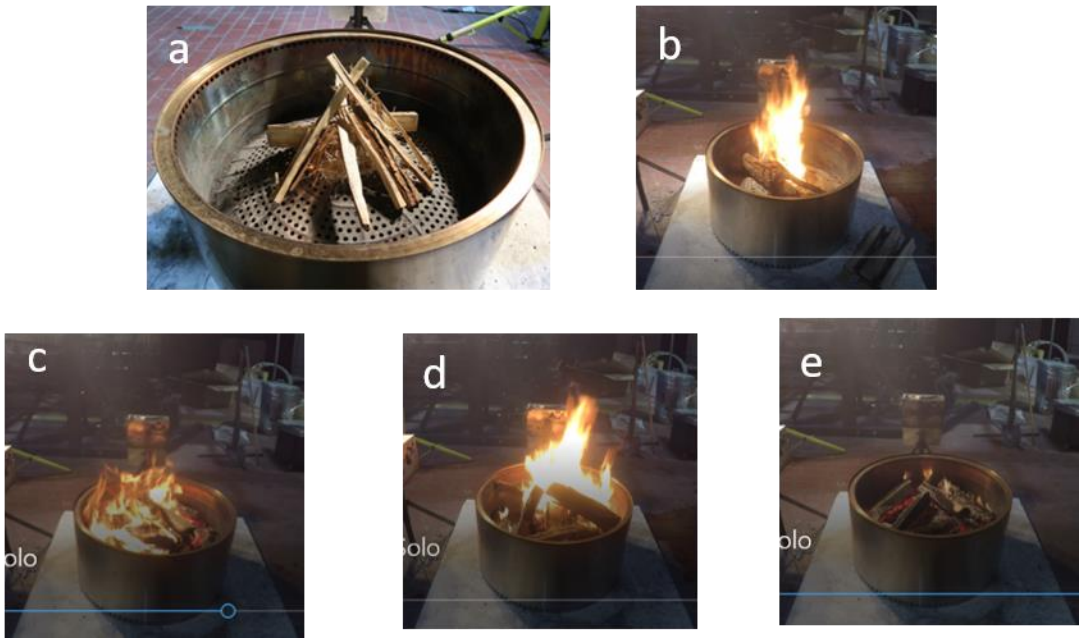

Figure 5. Burn phases of fire pit testing a) ignition fuel bed, b) ignition, c) burn-up phase, d) steady burn phase, and e) burn-down phase.

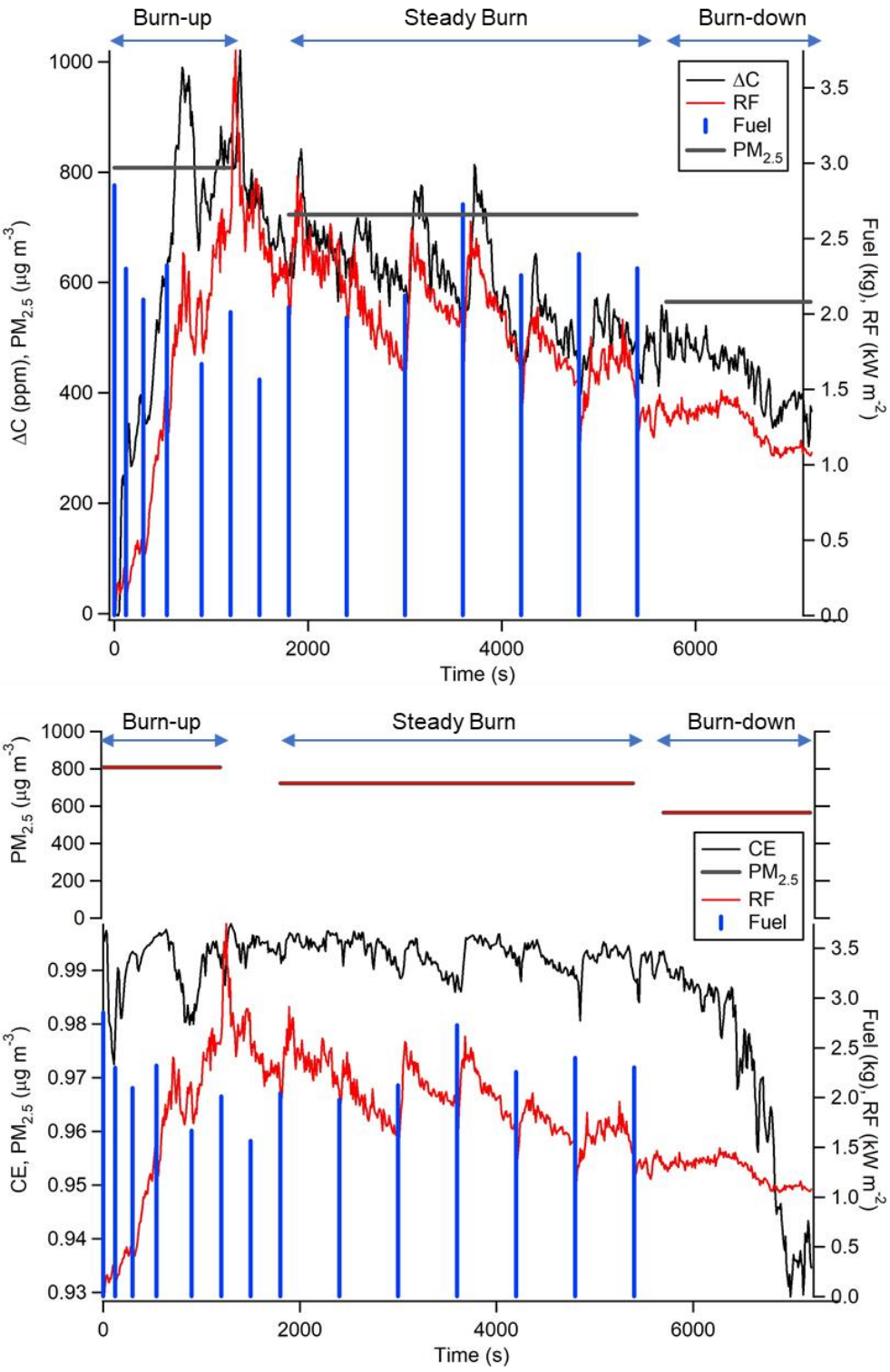

Figure 6. Top: Emissions of gaseous carbon (ΔC) in CO_2, CO, and CH_4 and radiant heat flux averaged to 10 s, fuel additions (dry mass), and average $PM_{2.5}$ concentration from filter measurements. Bottom: Same as top, except plot of combustion efficiency (CE) instead of ΔC.

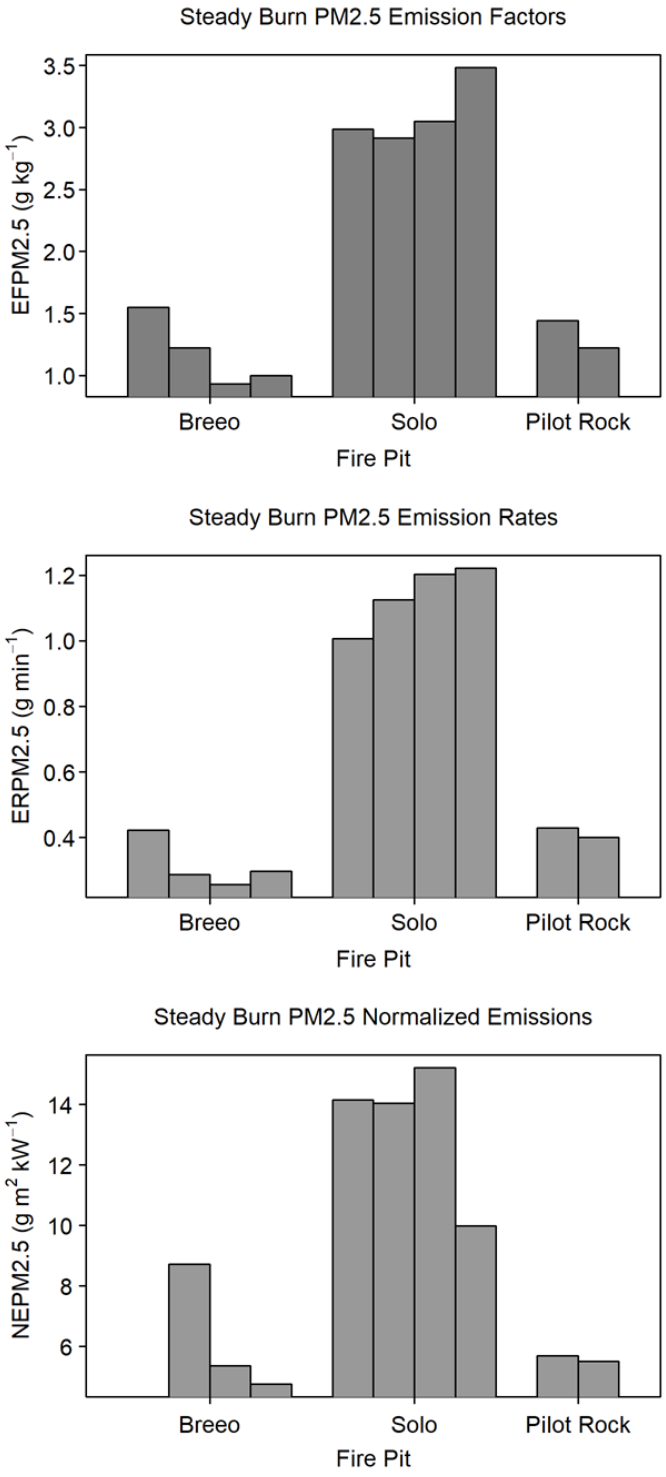

Figure 7. Steady burn phase results. Top: $PM_{2.5}$ emission factors, middle: $PM_{2.5}$ emission rates, bottom: $PM_{2.5}$ emissions normalized to radiant heat flux.

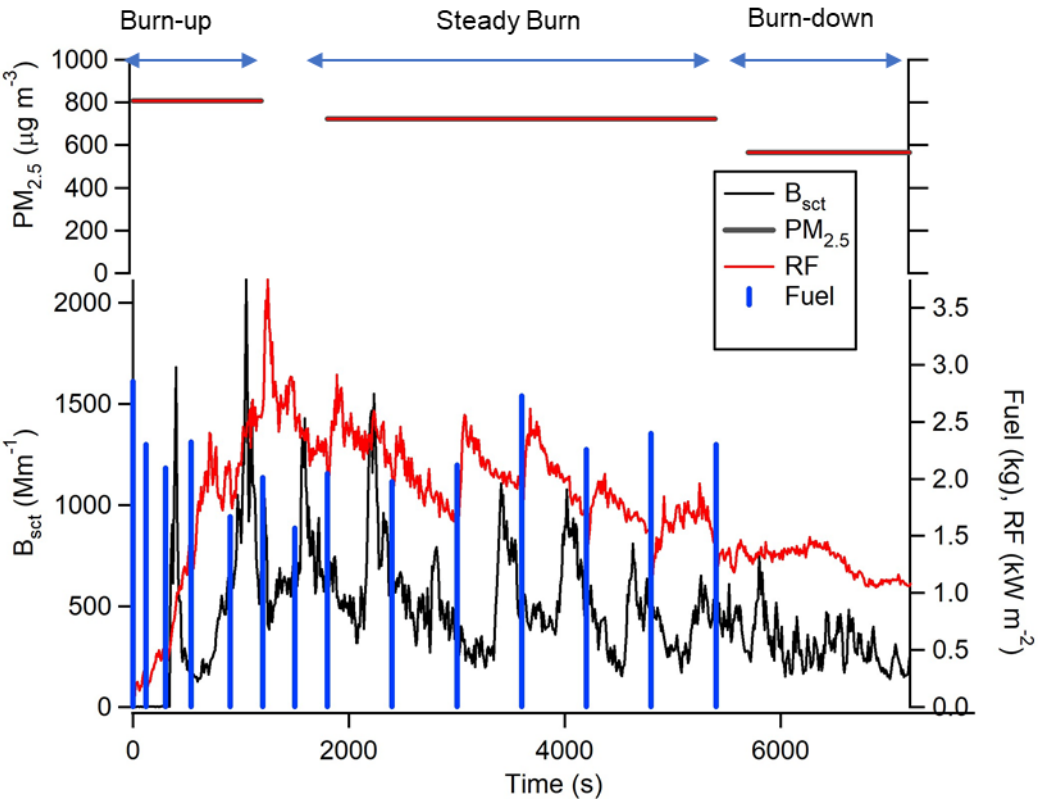

Figure 8 Light scattering at 700 nm (B_{sct}) and radiant heat flux averaged to 10 s, fuel additions (dry mass), and average $PM_{2.5}$ concentration from filter measurements.

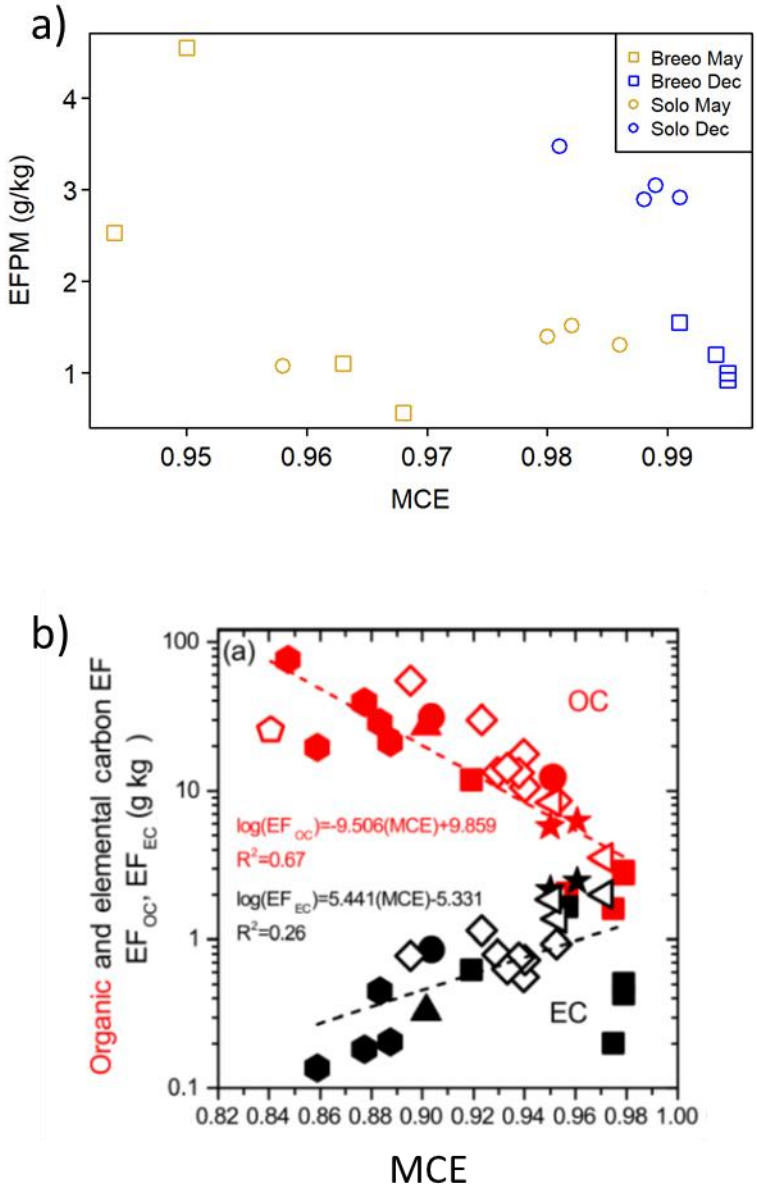

Figure 9. a) EFPM plotted versus MCE for steady burn phases of May 2019 and Decmeber 2019 fire pit testing b) EFOC and EFEC plotted versus MCE for burning of western US wildland fuels at Missoula Fire Sciences Laboratory during FIREX laboratory intensive. Figure is reproduced from Jen et al. (2019), Figure 1.

Appendix A

Table A1. Steady burn phase results. CO_2, CO, CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values include ± standard deviation.

Burn	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
		CO_2	CO	CH_4	CO_2	CO	CH_4	CO_2	CO	CH_4
					Breeo Fire Pit					
1	0.99	1817	10	0.4	495	2.7	0.10			
2	0.99	1822	7	0.2	427	1.6	0.05	12977	50	1.6
6	0.99	1824	5	0.3	502	1.4	0.07	10481	30	1.5
10	0.99	1823	6	0.3	543	1.8	0.08	8714	29	1.3
Average	0.99±0.00	1821±3	7±2	0.3±0.1	491±48	1.9±0.6	0.08±0.02	10724±2142	36±12	1.5±0.1
					Solo Fire pit					
3	0.99	1817	10	0.1	615	3.5	0.04	8633	50	0.6
4	0.99	1811	14	0.2	699	5.3	0.08	8717	66	1.0
5	0.99	1812	13	0.2	715	5.3	0.08	9044	66	1.1
9	0.98	1797	22	0.5	631	7.8	0.18	5157	64	1.5
Average	0.99±0.00	1809±8	15±5	0.3±0.2	665±49	5.5±1.8	0.10±0.06	7888±1829	62±8	1.0±0.4
					Pilot Rock Fire Pit					
7	0.990	1813	12	0.6	534	3.4	0.18	7063	45	2.4
8	0.990	1812	12	0.7	587	4.0	0.23	8067	54	3.2
Average	0.990	1813	12	0.7	560	3.7	0.21	7565	50	2.8

Table A2. Burn up burn phase results. CO_2, CO, CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values include ± standard deviation.

Burn	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
		CO2	CO	CH4	CO2	CO	CH4	CO2	CO	CH4
					Breeo Fire Pit					
1	0.99	1813	12	0.5	318	2.1	0.08			
2	0.99	1817	10	0.4	449	2.4	0.11	6442	35	1.5
6	0.99	1808	15	0.7	432	3.6	0.16	8917	74	3.4
10	0.99	1813	12	0.5	419	2.8	0.13	6451	44	1.9
Average	0.99±0.00	1813±4	12±2	0.5±0.1	404±59	2.7±0.6	0.12±0.03	7270±1426	51±21	2.3±1.0
					Solo Fire Pit					
3	0.99	1821	7	0.2	423	1.7	0.04	6584	26	0.7
4	0.99	1821	7	0.2	438	1.7	0.05	7371	29	0.8
5	0.99	1824	6	0.1	544	1.7	0.04	6327	19	0.5
9	0.99	1824	6	0.2	496	1.6	0.05	3502	11	0.3
Average	0.99±0.00	1823±2	6±1	0.2±0.0	475±56	1.7±0.1	0.05±0.00	5946±1689	21±8	0.6±0.2
					Pilot Rock Fire Pit					
7	0.98	1799	20	0.9	414	4.6	0.20	5706	64	2.8
8	0.98	1804	18	0.8	390	3.8	0.17	6873	67	3.0
Average	0.98	1801	19	0.8	402	4.2	0.19	6290	65	2.9

Table A3. Burn down burn phase results. CO_2, CO, CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values include ± standard deviation.

Burn	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
		CO2	CO	CH4	CO2	CO	CH4	CO2	CO	CH4
					Breeo Fire Pit					
1	0.93	1698	83	1.8	268	13.1	0.29	NA	NA	NA
2	0.97	1779	33	0.9	307	5.7	0.15	6087	113	2.9
6	0.94	1727	65	1.7	257	9.6	0.25	4791	180	4.7
10	0.94	1728	64	1.9	250	9.2	0.28	2873	106	3.2
Average	0.95±0.02	1733±34	61±21	1.6±0.5	270±26	9.4±3.0	0.24±0.06	4584±1617	133±41	3.6±0.9
					Solo Fire Pit					
3	0.90	1642	120	0.9	306	22.4	0.17	3343	245	1.9
4	0.87	1587	156	0.7	340	33.3	0.15	3243	318	1.4
5	0.94	1720	70	1.2	452	18.4	0.31	1713	70	1.2
9	0.87	1590	152	1.6	261	24.9	0.27	2436	232	2.5
Average	0.89±0.03	1635±62	124±40	1.1±0.4	339±82	24.8±6.3	0.22±0.08	2684±764	216±105	1.7±0.6
					Pilot Rock Fire Pit					
7	0.926	1693	86	2.0	286	14.6	0.33	1955	99	2.3
8	0.966	1766	40	1.6	377	8.6	0.34	2513	57	2.3
Average	0.946	1729	63	1.8	331	11.6	0.34	2234	78	2.3

Table A4. Steady burn phase results. $PM_{2.5}$ emission factors (EF), $PM_{2.5}$ emission rates (ER), $PM_{2.5}$ emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	EF pound ton^{-1}	ER oz hr^{-1}	NE oz min in^2 Btu^{-1}	FC pound	RF Btu min^{-1} in^{-2}
			Breeo Fire Pit		
1	3.11	0.90		36.0	
2	2.40	0.59	8.21	31.0	72.4
6	1.83	0.53	5.06	27.3	79.0
10	2.00	0.63	4.60	29.5	102.9
Average	2.32±0.57	0.66±0.16	5.96±1.97	31.0±3.7	84.8±16.0
			Solo Fire Pit		
3	5.84	2.09	13.35	41.0	143.7
4	5.80	2.37	13.42	46.8	161.7
5	6.11	2.55	14.66	47.9	159.5
9	6.96	2.59	9.60	34.8	201.9
Average	6.18±0.54	2.40±0.23	12.76±2.19	42.6±6.0	166.7±24.8
			Pilot Rock Fire Pit		
7	2.76	0.86	5.16	29.2	124.8
8	2.61	0.89	5.59	32.1	120.1
Average	2.68	0.88	5.37	30.7	122.4

$$EF\ unit\ converison\text{:}\ \left(X\frac{g}{kg}\right)\left(\frac{907.185\ kg}{1\ ton}\right)\left(\frac{1\ lb}{453.592\ g}\right)$$

$$ER\ unit\ conversion\text{:}\ \left(X\frac{g}{min}\right)\left(\frac{1\ oz}{28.3495\ 5}\right)\left(\frac{60\ min}{1\ hr}\right)$$

$$NE\ unit\ conversion\text{:}\ \left(X\frac{g\ m^2}{kW}\right)\left(\frac{1\ kW}{3412.142\ Btu\ hr^{-1}}\right)\left(\frac{60\ min}{1\ hr}\right)\left(\frac{1\ oz}{28.3495\ g}\right)\left(\frac{1550\ in^2}{m^2}\right)$$

$$RF\ unit\ conversion\text{:}\ \left(X\frac{kW}{m^2}\right)\left(\frac{3412.142\ Btu\ hr^{-1}}{1\ kW}\right)\left(\frac{1\ hr}{60\ min}\right)\left(\frac{1\ m^2}{1550\ in^2}\right)$$

Appendix B

Evaluation of the ARA Instruments Low Flow Research Sampler (LFR-6) sampler for measuring biomass burning $PM_{2.5}$ versus a Tisch Federal Reference Method (FRM) monitor. The evaluation was conducted in conjunction with the Environmental Protection Agency at the FSL combustion chamber in April, 2019. A total of 31 burns were conducted. The ARA Low Flow sampler was in excellent agreement with the FRM monitor as shown in Figure B1.

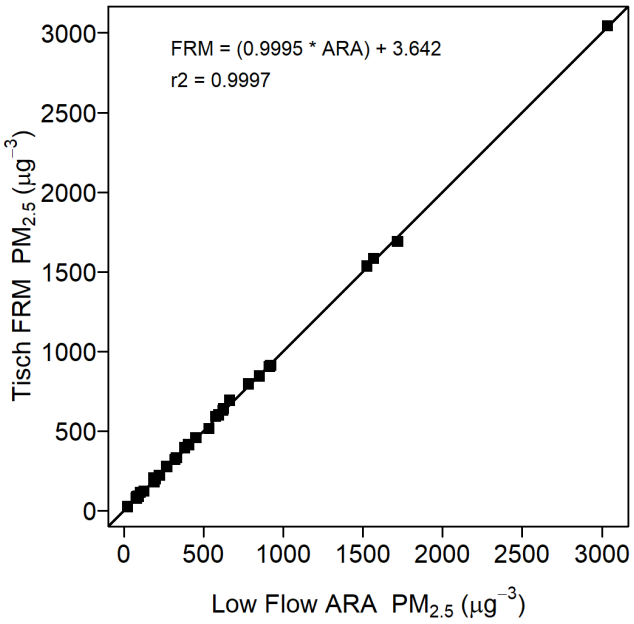

Figure B1 Comparison of $PM_{2.5}$ concentrations measured in biomass burning smoke with the ARA Low Flow research Sampler (used in recreational fire pit testing) and a Tisch FRM monitor.

Summary of Picarro CRDS and LICOR gas analyzer calibrations

Table B1. Calibration standards for Picarro trace has analyzer and LICOR-7000 CO2 analyzer. CO2, CO, and CH4 in Ultrapure air. Concentrations in ppm.

	Low	Mid	High
CO	3.03	9.75	50
CO2	510	745	3000
CH4		3.04	4.96

Table B2. Statistics for three-point calibration of Picarro trace gas analyzer For CO_2 and CO and two-point challenge for CH_4.

	CO			CO2			CH4 (ppm)	
Date	Intercept	Slope	R2	Intercept	Slope	R2	Mid	High
20191212	-0.79	1.142	1	-12.3	1.029	1	3.04	4.95
20191217	-0.77	1.139	1	-11.7	1.028	1	3.04	4.95
20191219	-0.80	1.142	1	-13.00	1.029	1	3.04	4.95

Table B3. Picarro Calibration applied to all data (y_true = y_measured*slope + intercept			
Species	Intercept	Slope	R2
CO2	-12.3	1.029	1.00
CO	-0.79	1.141	1.00

LICOR calibration versus Picarro

A two-point calibration was used to cross calibrate the LICOR and Picarro gas analyzers. The resultant calibration was applied to the LICOR measurements of background CO2 measured throughout the study.

Table B3. LICOR cross calibration versus Picarro CRDS

	Low Span CO2 (ppm)	High Span CO2 (ppm)
Standard	510	745
Picarro	507	742
Licor	508	747
Picarro = 5.5 + 0.986*Licor		

Appendix C

Key results from prelimary fire pit testing in May 2019. See Apepdnix D for complete report.

Table C1. Summary of test burns. Moisture content (MC) is percent of dry mass.

Burn[1] No.	Date	Fire pit	Wood MC (%)	Dry wood mass (g)	Ash (g)	Dry wood consumed (g)	Percent consumption
2	19 May 07	Solo	16	12500	2847	27261	91%
3	19 May 08	Solo	38	30108	1262	17466	93%
4	19 May 08	Breeo	26	18728	3460	16746	83%
5	19 May 09	Breeo	32	20206	4097	15374	79%
6	19 May 09	Solo	13	19471	2084	24017	92%
7	19 May 10	Breeo	15	26101	3337	17764	84%
8	19 May 10	Solo	16	21101	3270	24974	88%
9	19 May 13	Breeo	11	28244	2922	18525	86%
10	19 May 13	Pilot Rock	23	21447	3314	14677	82%
11	19 May 14	Pilot Rock	17	17991	4363	16747	79%

[1]Burn number 1 was a trial burn and the results are not included in this report.

Table C2. Steady burn phase results. PM1 emission factors (EF), PM1 emission rates (ER), PM1 emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	MC (%)	MC	EF g kg^{-1}	ER g min^{-1}	NE g m^2 kW^{-1}	FC g	RF W m^{-2}
			Breeo Fire Pit				
4	26	moist	2.53	0.37	34.2	10254	758
5	32	moist	1.10	0.18	13.8	10407	830
7	15	dry	4.55	0.80	68.5	11575	769
9	11	dry	0.56	0.11	6.1	10906	1005
	Average		2.18±1.78	0.36±0.31	30.6±27.9	10785±596	841±114
			Solo Fire Pit				
2	16	dry	1.31	0.40	17.4	22168	1672
3	38	moist	1.52	0.24	13.0	11272	1317
6	13	dry	1.40	0.32	12.0	15055	1748
8	16	dry	1.08	0.35	9.5	16102	1834
	Average		1.33±0.19	0.33±0.06	13.0±3.3	16149±4517	1643±227
			Pilot Rock Fire Pit				
10	23	moist	2.35	0.36	26.1	8123	730
11	17	dry	2.23	0.32	24.7	8870	800
	Average		2.29	0.34	25.4	8496	764

Table C3. Steady burn phase results. CO_2, CO, and CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values given with ± 1 standard deviation for Breeo and Solo fire pits.

Burn	MC (%)	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
			CO_2	CO	CH_4	CO_2	CO	CH_4	CO_2	CO	CH_4
					Breeo						
4	26	0.94	1713	64.8	4.05	249	9.4	0.59	23175	157	9.8
5	32	0.96	1754	43.4	2.75	285	7.1	0.45	22001	118	7.4
7	15	0.95	1718	57.5	4.49	303	10.1	0.79	25870	169	13.2
9	11	0.97	1765	37.4	2.72	132	2.8	0.20	15619	47	3.4
Average		0.96±0.01	1738±26	50.8±12.6	3.50±0.90	242±77	7.4±3.3	0.51±0.25	21666±4344	123±55	8.5±4.1
					Solo						
2	16	0.99	1802	16.4	0.55	547	5.0	0.17	23903	83	2.8
3	38	0.98	1794	20.8	0.75	289	3.4	0.12	15354	56	2.0
6	13	0.98	1791	23.5	0.69	406	5.3	0.16	15420	89	2.6
8	16	0.96	1750	48.8	1.23	564	15.7	0.40	15368	262	6.6
Average		0.98±0.01	1784±23	27.4±14.6	0.81±0.3	452±129	7.3±5.6	0.21±0.13	17511±4261	122±94	3.5±2.1
					Pilot Rock						
10	23	0.96	1738	51.6	2.91	129	3.8	0.22	14381	64	3.6
11	17	0.95	1730	55.2	3.74	129	4.1	0.28	15065	69	4.7
Average		0.95	1734	53.4	3.33	129	4.0	0.25	14723	66	4.1

Appendix D

USDA FOREST SERVICE RECREATIONAL FIRE PIT EMISSIONS TESTING

Preliminary Report to the Minnesota Pollution Control Agency

Update: March 23, 2020

Initial Report: June 14, 2019

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1. Introduction

This report presents the methods and results of recreational outdoor fire pit emissions testing conducted by the USDA Forest Service Fire Sciences Laboratory (FSL) in collaboration with the Minnesota Pollution Control Agency (MPCA). This project quantified fine particulate matter (PM1) emissions from two commercially available outdoor fire pits designed to burn wood logs with minimal smoke production (low smoke) and from a traditional outdoor fire pit. This report provides PM1 emission rates and emission factors for each fire pit based on emissions measured during burn-cycles designed to represent typical recreational use.

The original testing plan was to measure emissions produced from the burning of dry and moist firewood. A total of four burns were conducted with each low smoke fire pit and two burns were conducted with the traditional fire pit. The experiment was designed to measure emissions of PM2.5 (PM with an aerodynamic diameter < 2.5 µm), PM1 (PM with an aerodynamic diameter < 1 µm), CO2, CO, and CH4. Measurements of CO2, CO, and CH4 are needed to quantify emission factors (EF) of PM2.5 and PM1. Radiant heat flux (RF) produced by the fires was also measured in order to normalize emissions across fire pits. The RF normalized emissions could be used to model emissions based on different fire pit activity scenarios which are linked to operator behavior. The premise being is that from the perspective of a fire pit user, the warmth provided by the fire is probably the best metric for to standardizing wood input and emission rates.

The original study design called for the measurement of PM2.5 emissions. However, due to a failure of the PM2.5 sampling system, which is discussed in Appendix A, the testing did not

measure PM2.5 emissions. Instead we must report PM1 emissions. While the literature on biomass burning PM indicates the majority of fine particulate matter mass (PM2.5) in fresh smoke is contained in submicron particles (PM1) (Hosseini et al., 2010; Reid et al., 2005), the PM1 emission measurements reported will nonetheless be an underestimate of PM2.5. The FSL will repair the PM2.5 sampling system and repeat the fire pit testing in order to report PM2.5 emissions are originally intended. In the interim the PM1 emissions results may serve as a lower limit for PM2.5.

2. Methods

2.1 Combustion facility

The fire pit testing was conducted in the Fire Sciences Laboratory combustion chamber which is shown in Figure 1. The combustion chamber measures 12.5 m × 12.5 m × 22 m high. An exhaust stack with an inverted funnel at its entrance extends from 2 m above the floor to the top of the chamber. A sampling platform surrounds the stack 17 m above the chamber floor. The funnel opening of the exhaust stack is 3.5 m diameter and the exhaust stack is 1.6 m diameter. Air is drawn through the stack and entrains emissions from fires burning directly beneath the funnel. Within the exhaust stack, a few meters from the funnel opening, is a diffuser ring (0.8 m inside diameter) which mixes the air and entrained emissions. At the height of the sampling platform temperature and mixing ratio are constant across the width of the stack (Christian et al., 2003, 2004). During our testing the gas and particle measurement equipment was positioned on the platform and the emissions were drawn through sample lines constructed of stainless steel, copper, Teflon, or conductive tubing as described in Section 2.4.

2.2 Fire Pits

Two commercially available outdoor fire pits designed to burn wood logs with minimal smoke production, the Solo Yukon Stove (Solo) and the Breeo (Breeo), and a traditional outdoor fire pit (Pilot) were tested. Photos of the fire pits and their dimensions and model numbers are provided in Figure 2. The Solo and Breeo fire pits included instructions for wood log loading which were followed as closely as possible during the testing. Both the Solo and Breeo fire pits instructed that wood logs be kept below the interior ventilation holes (Figure 2) which was done throughout the testing.

2.3 Fuels

A pallet of split firewood, a mix of red oak, maple, birch, and ash from Minnesota was used for the fire pit testing. The split firewood had typical dimensions of 15 inches in length and maximum cross section of 3 inches (Figure 3). Upon arrival in Missoula, an initial check found the firewood moisture content varied between 22% and 33%. MPCA recommends only burning wood with a moisture content of less than 20%; therefore this threshold we used to define “dry” wood in our tests. Firewood was conditioned in a large environmental chamber (Figure 3) at T = 30 C and RH = 10%, to reduce its moisture content to below 20%. Firewood taken directly from the pallet and burned without conditioning was the “moist” wood in our tests.

2.4 Laboratory setup

The experimental setup is shown in Figure 4. The fire pit being tested was placed directly under the center of the exhaust stack. Two radiant heat sensors were placed a distance of 27 inches for the fire pit center and vertically positioned approximately 4 inches above the fire pit rim. The

inlet of a NDIR CO2 gas analyzer (LI-COR LI-850), which was used to measure the background CO2 concentration, was placed 44 inches from the fire pit center at a height of 3 feet above the chamber floor. A multi-species trace gas analyzer, a three wavelength nephelometer, and two particulate matter filter sampling units were positioned on the platform and the emissions were drawn from the exhaust stack through sample lines constructed of stainless steel and conductive tubing. A Cavity Ring-Down Spectroscopy (CRDS) gas analyzer was also positioned on the platform and sampled emissions from the exhaust stack through lines constructed of stainless steel and Teflon.

2.5 Burn procedure

The test burns involved three phases: burn up, steady burn, and burn down. The purpose of the burn up phase was to initiate a robust, steady fire. In the burn up phase, the ignition fuel bed was a small amount of excelsior shavings (< 100 g), several pieces of kindling spliced from split logs, and a single split log. A typical ignition fuel bed is shown in Figure 5a. Following ignition, logs were added to the fire, at irregular intervals, over a period of 20-25 minutes. The steady burn phase began after a regular, consistent fire was achieved. During the steady burn phase logs were added at a regular interval of 10 minutes over a period of 60 minutes. Each log addition during the steady burn phase was 1 to 3 logs, with number added varying in order to maintain a robust fire. The burn down phase was a 20 minute period beginning 10 minutes after the final steady phase log addition. At the end of the burn down stage the fire was extinguished with water to preserve unburnt fuel to determine fuel consumption. The mass and log count for all fuel additions were recorded. Photos of typical fire behavior during the burn phases are provided Figure 5b-e.

2.6 Instrumentation

Particulate matter

Particulate matter (PM) emissions were measured using two filter sampling systems. Both systems pulled emissions from the exhaust stack through a conductive tubing sample line connected to a copper tube inserted 60 cm into the exhaust stack. One PM sampler pulled emissions at 19 slpm from the exhaust stack through a cyclone with a cutoff of ≤ 2.5 µm aerodynamic diameter (URG-2000-30EC, URG Corp., USA) and onto a 37 mm Teflon filter. The other PM sampler pulled emissions at 14 slpm through a cyclone with a cutoff of ≤ 1 µm aerodynamic diameter (URG-2000-30EC, URG Corp., USA). The 37 mm Teflon filters used in the PM determination are conditioned and weighed in a controlled- environment room at 68 F and 50 percent relative humidity. Prior to weighing, the filters are conditioned for at least 24 hours. Each filter is weighed three times on a Mettler M4 microbalance with a precision of one microgram. The balance is linked to a software program that collects and stores the weights and room condition. The balance is tared (zeroed) before each weighing. A calibration weight is used once every five filters to verify the accuracy and calibration of the microbalance. Filters whose weights are not reproducible to within 5 µg are withheld from analysis. Control filters are used to correct for environmental and handling variability in the filter weights. The control filters are handled in the same way at the treatment filters. Each filter is pre-weighed prior to sample collection using this procedure, and then again after collection. They are again conditioned at least 24 hours to stabilize the particulate matter weights and to reduce the effects of static electricity on the weighing process. The PM concentrations are calculated using a Visual Basic software program, based on the final particulate matter weights (post-weight minus pre-weight), control filter results, and the volume of air drawn through the filter during the emission sampling. During fire pit testing, at the end of each day the filters with samples were placed in a freezer to preserve semi-volatiles that may evaporate over time. The filters were analyzed using the methods described above, one week after completion of the fire pit testing.

CO2, CO, and CH4
Continuous measurements (data acquisition rate of 2 s) of CO2, CO, CH4, and H2O were obtained using a CRDS trace gas analyzer (G2401-m, Picarro Inc., USA). Details of the CRDS method and this specific instrument may be found elsewhere (Urbanski, 2013). Air was sampled by the CRDS through Teflon tubing connected to a stainless steel tube inserted in the exhaust stack with its orifice near the stack's center. A three-point calibration was run daily to maintain accuracy of the CRDS measurements. Gas mixtures of CO2, CO and CH4 in Ultrapure air served as calibration standards. The CRDS response varied little from day to day and study average calibration factors were applied to the data offline. The NDIR CO2 analyzer used to measure the background CO2 (Figure 4) was cross calibrated versus the CRDS analyzer. Details of the calibrations are provided in Appendix B.

Nephelometry
A TSI three wavelength nephelometer was used to measure total light scattering by PM at 700 nm (red), 550 nm (green), and 450 nm (blue) at a data acquisition rate of 0.5 Hz. Total light scattering at these wavelengths responds strongly to PM concentration, particle size distribution, and particle chemical properties. The nephelometer measurements at 700 nm were used to estimate the temporal PM concentration profile based on the integrated PM measurements obtained with the filter sampling system.

Radiant Heat
Radiant energy flux was measured using Medtherm Dual Sensor Heat Flux sensors (Model 64-20T) contained in Fire Behavior Packages (FBP). These FBP have been widely used in field research projects conducted by the Fire Lab's fire behavior research group and details may be founds in Jimenez et al. (2007; https://www.fs.usda.gov/treesearch/pubs/28594). The heat flux sensors were calibrated in a black body over a range of 0 to 200kW m^{-2} and fit a power law curve to the calibration data resulting in a calibration error of less than 3% of reading over the range.

2.7 Emission Calculations

Emissions of a given species X were quantified using burn phase average excess mass mixing ratios ΔX ($\Delta X = X_{fire} - X_{background}$). Phase average emission factors for each species X, EF_X, were calculated using the carbon mass balance method (Yokelson et al., 1999) implemented with Eq. (1). In Eq. (1), ΔC_i are the excess mass mixing ratios of carbon in species X, and F_c is the mass fraction of carbon in the dry fuel which was taken as 0.50 for all wood used in this study.

Eq. 1 $$EF_x = F_c \times 1000\ (g\ kg^{-1}) \times \frac{\Delta X}{\Delta C_{CO_2} + \Delta C_{CO} + \Delta C_{CH_4} + \Delta C_{PM}}$$

The carbon mass balance method assumes that all the fuel carbon volatilized as gases or PM is measured. However, since the majority of carbon mass (> 95%) in fresh biomass smoke from efficient fires is contained in CO2, CO, and CH4 (Yokelson et al., 2007), neglecting other carbon containing gases in the carbon mass balance method introduces only a minor bias of < +5%. We assumed a PM carbon content of 75% (Reid et al., 2005) in our EF calculations. The difference in the denominator between assumed PM carbon content of 0% and 100% was +0.6% on average, with maximum effect being +4%. Combustion efficiency (CE) is the fraction of carbon evolved in gases and PM that is emitted as CO2. Given most carbon is contained in CO2, CO, and CH4, we estimate CE as ΔCO2/(ΔCO2 + ΔCO + ΔCH4). In biomass burning, modified combustion efficiency (MCE; MCE = ΔCO2/(ΔCO2 + ΔCO)) is used to characterize the relative

amount of flaming and smoldering combustion (Akagi et al., 2011). MCE approaches 0.99 for "pure" flaming combustion (Yokelson et al., 1996).

Emissions of species X by fire phase were calculated using Eq. 2.

Eq. 2 $$E_iX = EF_iX \times FCON \times \frac{\Delta C_i \times \Delta t_i}{\sum \Delta C_i \times \Delta t_i}$$

In Eq. 2 the index i is the fire phase (burn-up, steady burn, burn-down), FCON is the total dry mass of fuel consumed in the fire (g), EF_iX is the EF for species X (Eq 1) for phase i, ΔC_i is average mass mixing ratio of carbon emitted during phase i (denominator of Eq. 1), and Δt_i is the sampling duration of phase I, and E_iX is in units of g of X. The emission rates for species X by fire phase were calculated using Eq. 3

Eq. 3 $$ER_iX = \frac{E_iX}{\Delta t_i}$$

Where E_iX is the amount of X emitted in phase i (Eq. 2) and Δt_i is the sampling duration of phase i, and ER_iX is in units of g of X per minute. Emissions of species X for phase I, normalized to radiant heat flux is given by Eq; 4:

Eq. 4 $$NE_iX = \frac{E_iX}{RF_i}$$

where E_iX is the amount of X emitted in phase i (Eq. 2) and RF_i is average radiant heat flux during of phase i, and NE_iX is in units of g m^2 kW^{-1}.

3. Results

A total of 10 test burns were conducted as summarized in Table 1. PM1 emissions, RF, and fuel consumption (FC) are summarized by fire phase for each burn in Tables 2-4. Figure 6 shows temporal profiles of gaseous emissions, combustion efficiency (CE), radiant heat flux (RF), and fuel input for burn #6 (Solo fire pit). Following ignition and during the first few rounds of fire wood addition, RF remains low (< 200 W m^{-2}) and gaseous carbon emissions (ΔC) are less than half the average value of the steady burn phase (Fig. 6, top). By the end of the burn-up phase ΔC has peaked and RF has neared the average value measured over the steady burn phase. During the later stages of the burn-up and throughout the steady burn, inputs of fire wood produced a large spike in ΔC, while RF spikes upon fire wood addition do not occur consistently. During the burn-down phase CE decreases rapidly (Fig. 6, bottom) due to shift in production from CO2 to CO. The increase in CO production during the burn-down phase is due to glowing combustion of char (Yokelson et al., 1996). Glowing combustion of char is characterized by low MCE, relatively high EFCO, and low PM production. The burn-down phase EFPM1 are less than or equal to those of the steady-burn phase (Tables 2 and 4). In contrast the burn-down EFCO is at least twice that of the steady burn phase (Tables A1 and A3).

We focus on the results of the steady burn phase since it represents the primary fire pit use mode. PM1 emission factors, emission rates, and emissions normalized to radiant heat flux are summarized by burn in Table 2 and plotted in Figure 7. The Solo fire pit had the lowest EFPM1 at 1.3 g kg^{-1}, the standard campground fire pit had the highest at 2.3 g kg^{-1}, and EFPM1 for the Breeo fell in between (2.2 g kg^{-1}). Actual emissions also depend on the fuel consumption and when this is taken into consideration the PM1 production rates are similar 0.33 – 0.36 g min^{-1} due

to the different fueling rates. During the steady burn phase, wood was added to the fires at a standardized interval of 10 minutes. However, the amount of wood added was varied between one to three logs in order to maintain a fire that appeared visually to be steady and robust. From the perspective of a fire pit user, the warmth provided by the fire is probably the best metric for to standardizing wood input (i.e. users add wood to maintain the radiant heat received). Therefore, PM1 emissions normalized to radiant heat flux (NE) may be the metric that best represents real world fire pit usage. Based on this metric, the Solo fire pit (NE = 13.0 g m^2 kW^{-1}) out performs both the Breeo (NE = 30.6 g m^2 kW^{-1}) and traditional (25.4 g m^2 kW^{-1}) fire pits (Table 2, Figure 7).

The Breeo EFPM1 ranged between 0.56 (burn 9) and 4.55 (burn 9) with a factor of 10 difference in NE (2.5 vs. 25.1). Wood moisture content was not the cause of the difference (Table 2). We suspect the high EFPM1 in burn 7 resulted from difficulties maintain a robust fire during the early stages of the steady phase. Figure 8 plots 10 s average RF, CE, and Bsct, fuel input, and average PM1. During the initial 20 minutes of the steady phase, CE (avg. = 0.92) and RF (avg. = 518 W/m2) were low indicating an inefficient fire. Following the 9th fuel addition (3rd of steady phase), the fire pit was stirred with a shovel. This act invigorated the fire, resulting in a rapid increase in CE and RF, a dramatic decrease in bscat, and greatly reduced PM1. EFPM1 was 8.0 g kg over the first ~20 minutes of the steady phase compared with 1.0 g/k over the last 50 minutes.

We did not observe an MC effect on emissions. However, the sample size used in the MC measurements may have been inadequate to properly represent the true MC of logs used in a given burn. For each burn we measured MC of two or three logs from the batch that was burned. The range in MC among the two or three logs measured varied between 1 and 12 percentage points.

4. Conclusions

The steady burn phase represents the primary use mode for the recreational outdoor fire pits. During steady phase burning the Solo fire pit had the lowest EFPM1 and heat flux normalized PM1 emissions of the fire pits tested. Our measurements suggest that if all three fire pits were operated following the manufacturer's instructions and were fueled to provide the same radiant heat output, the Solo fire pit would produce about half the PM1 emissions of the Breeo or traditional fire pits. Likewise, the Solo fire pit would emit less than half the amount of CO and CH4 that would be generated by Breeo or traditional fire pit. The However, given the limited number of test burns and the high variability of emission observed for the Breeo fire pit, this conclusion is somewhat uncertain. Over the four burns the mean (± 1 standard deviation) of the radiant heat flux normalized PM1 emissions were 13.0±3.3 g m^2 kW^{-1} for the Solo and 30.6±27.9 for the Breeo. The original study design called for the measurement of PM2.5 emissions. However, due to a failure of the PM2.5 sampling system PM2.5 emissions are not reported and instead we must report PM1 emissions. The FSL will repair the PM2.5 sampling system and repeat the fire pit testing in order to report PM2.5 emissions are originally intended. In the interim the PM1 emissions results may serve as a lower limit for PM2.5.

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Table 1. Summary of test burns. Moisture content (MC) is percent of dry mass.

Burn[1] No.	Date	Fire pit	Wood MC (%)	Dry wood mass (g)	Ash (g)	Dry wood consumed (g)	Percent consumption
2	19 May 07	Solo	16	12500	2847	27261	91%
3	19 May 08	Solo	38	30108	1262	17466	93%
4	19 May 08	Breeo	26	18728	3460	16746	83%
5	19 May 09	Breeo	32	20206	4097	15374	79%
6	19 May 09	Solo	13	19471	2084	24017	92%
7	19 May 10	Breeo	15	26101	3337	17764	84%
8	19 May 10	Solo	16	21101	3270	24974	88%
9	19 May 13	Breeo	11	28244	2922	18525	86%
10	19 May 13	Pilot Rock	23	21447	3314	14677	82%
11	19 May 14	Pilot Rock	17	17991	4363	16747	79%

[1]Burn number 1 was a trial burn and the results are not included in this report.

Table 2. Steady burn phase results. PM1 emission factors (EF), PM1 emission rates (ER), PM1 emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	MC (%)	MC	EF g kg^{-1}	ER g min^{-1}	NE g m^2 kW^{-1}	FC g	RF W m^{-2}
			Breeo Fire Pit				
4	26	moist	2.53	0.37	34.2	10254	758
5	32	moist	1.10	0.18	13.8	10407	830
7	15	dry	4.55	0.80	68.5	11575	769
9	11	dry	0.56	0.11	6.1	10906	1005
	Average		2.18±1.78	0.36±0.31	30.6±27.9	10785±596	841±114
			Solo Fire Pit				
2	16	dry	1.31	0.40	17.4	22168	1672
3	38	moist	1.52	0.24	13.0	11272	1317
6	13	dry	1.40	0.32	12.0	15055	1748
8	16	dry	1.08	0.35	9.5	16102	1834
	Average		1.33±0.19	0.33±0.06	13.0±3.3	16149±4517	1643±227
			Pilot Rock Fire Pit				
10	23	moist	2.35	0.36	26.1	8123	730
11	17	dry	2.23	0.32	24.7	8870	800
	Average		2.29	0.34	25.4	8496	764

Table 3. Burn up phase results. PM1 emission factors (EF), PM1 emission rates (ER), PM1 emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	MC (%)	MC	EF g kg^{-1}	ER g min^{-1}	NE g m^2 mW^{-1}	FC g	RF W m^{-2}
			Breeo Fire Pit				
4	26	moist	7.52	0.72	104.27	2858	206
5	32	moist	5.48	0.44	37.09	2382	352
7	15	dry	9.39	0.93	214.34	2646	116
9	11	dry	3.33	0.49	29.47	4344	491
	Average		6.43±2.61	0.64±0.22	96.3±85.6	3057±879	291±143
			Solo Fire Pit				
2	16	dry	12.00	3.34	225.90	2743	145
3	38	moist	3.73	0.42	35.30	2677	283
6	13	dry	1.69	0.27	11.52	4656	682
8	16	dry	1.86	0.42	6.32	6124	1799
	Average		4.82±4.88	1.11±1.49	69.8±104.9	4050±1660	727±649
			Pilot Rock Fire Pit				
10	23	moist	3.43	0.46	28.36	3964	479
11	17	dry	2.28	0.35	19.81	4641	533
	Average		2.85	0.41	24.09	4302	506

Table 4. Burn down phase results. PM1 emission factors (EF), PM1 emission rates (ER), PM1 emissions normalized to radiant heat flux (NE), total fuel consumption (FC), and radiant heat flux (RF).

Burn	MC (%)	MC	EF g kg^{-1}	ER g min^{-1}	NE g m^2 mW^{-1}	FC g	RF W m^{-2}
			Breeo Fire Pit				
4	26	moist	1.68	0.30	10.58	3635	576
5	32	moist	2.03	0.26	9.43	2586	556
7	15	dry	1.30	0.24	9.86	3543	467
9	11	dry	2.23	0.37	11.87	3275	614
	Average		1.81±0.35	0.29±0.06	10.4±1.1	3260±475	553±54
			Solo Fire Pit				
2	16	dry					
3	38	moist	0.82	0.15	4.40	3517	652
6	13	dry	1.80	0.38	8.58	4306	902
8	16	dry	1.08	0.15	5.50	2748	538
	Average		1.23±0.42	0.22±0.13	6.2±2.2	3524±779	697±152
			Pilot Rock Fire Pit				
10	23	moist	1.63	0.21	8.35	2590	505
11	17	dry	1.44	0.23	5.64	3236	825
	Average		1.53	0.22	7.00	2913	665

Figures

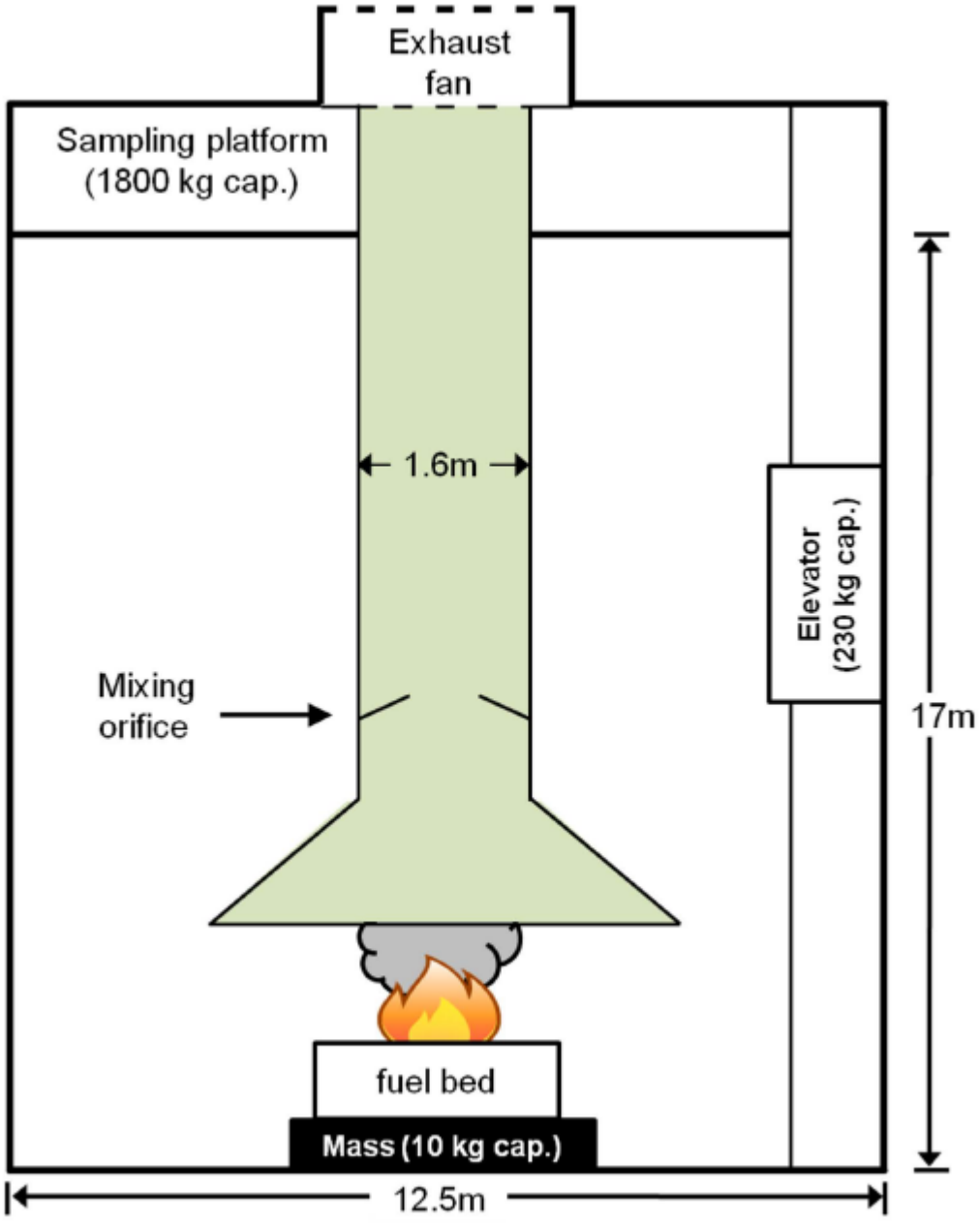

Figure 1. Schematic of combustion chamber at the Missoula Fire Sciences Laboratory (from Burling et al., 2010).

Figure 2. Fire pits post testing. Top row: Solo Yukon Stove, middle Row: Breeo, bottom row: Pilot Rock (traditional campground fire pit).

Figure 3. Left: Typical pieces of split firewood, right: firewood conditioning the environmental chamber at the Missoula Fire Sciences Laboratory.

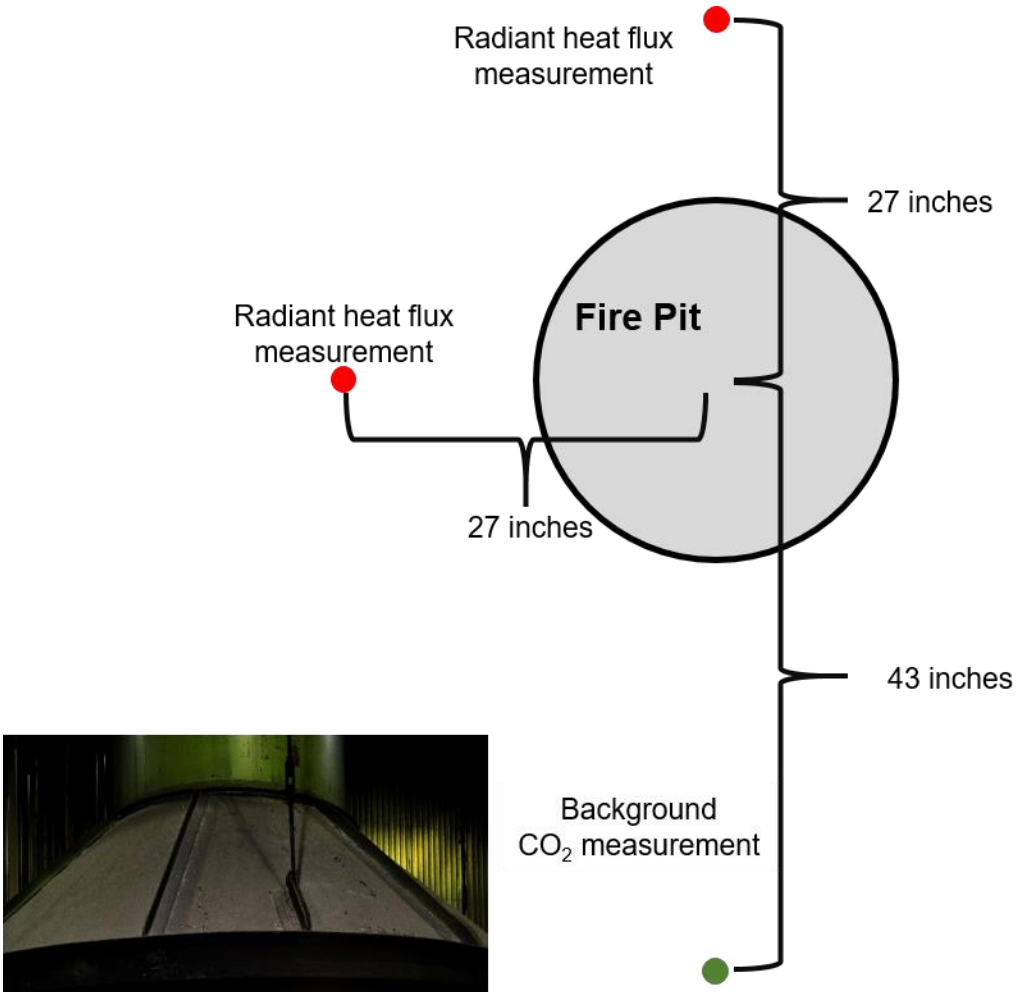

Figure 4. Schematic of experimental setup on the combustion chamber floor. The inset photo shows the position of the fire behavior packages containing the radiant heat flux sensors.

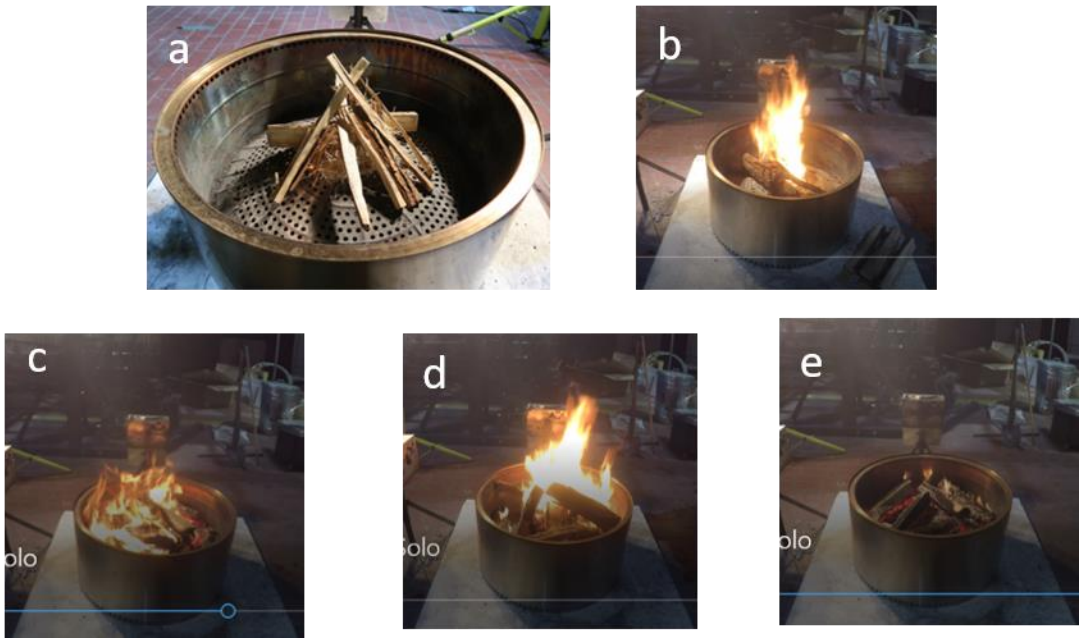

Figure 5. Burn phases of fire pit testing a) ignition fuel bed, b) ignition, c) burn-up phase, d) steady burn phase, and e) burn-down phase.

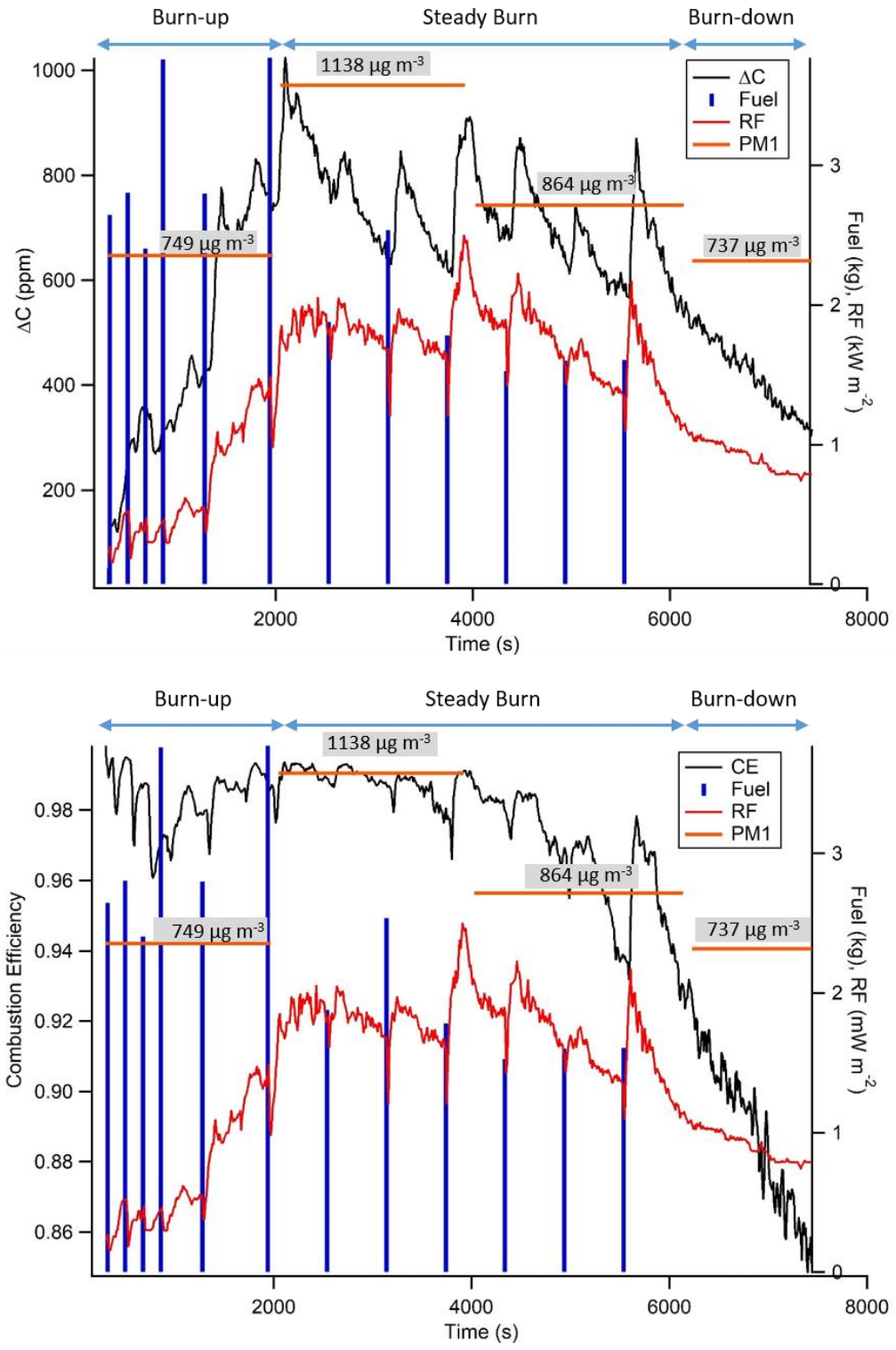

Figure 6. Top: Emissions of gaseous carbon (ΔC) in CO2, CO, and CH4 and radiant heat flux averaged to 10 s, fuel additions (dry mass), and average PM1 concentration from filter measurements (obtained over period of orange line). Bottom: Same as top, except plot of combustion efficiency (CE) instead of ΔC.

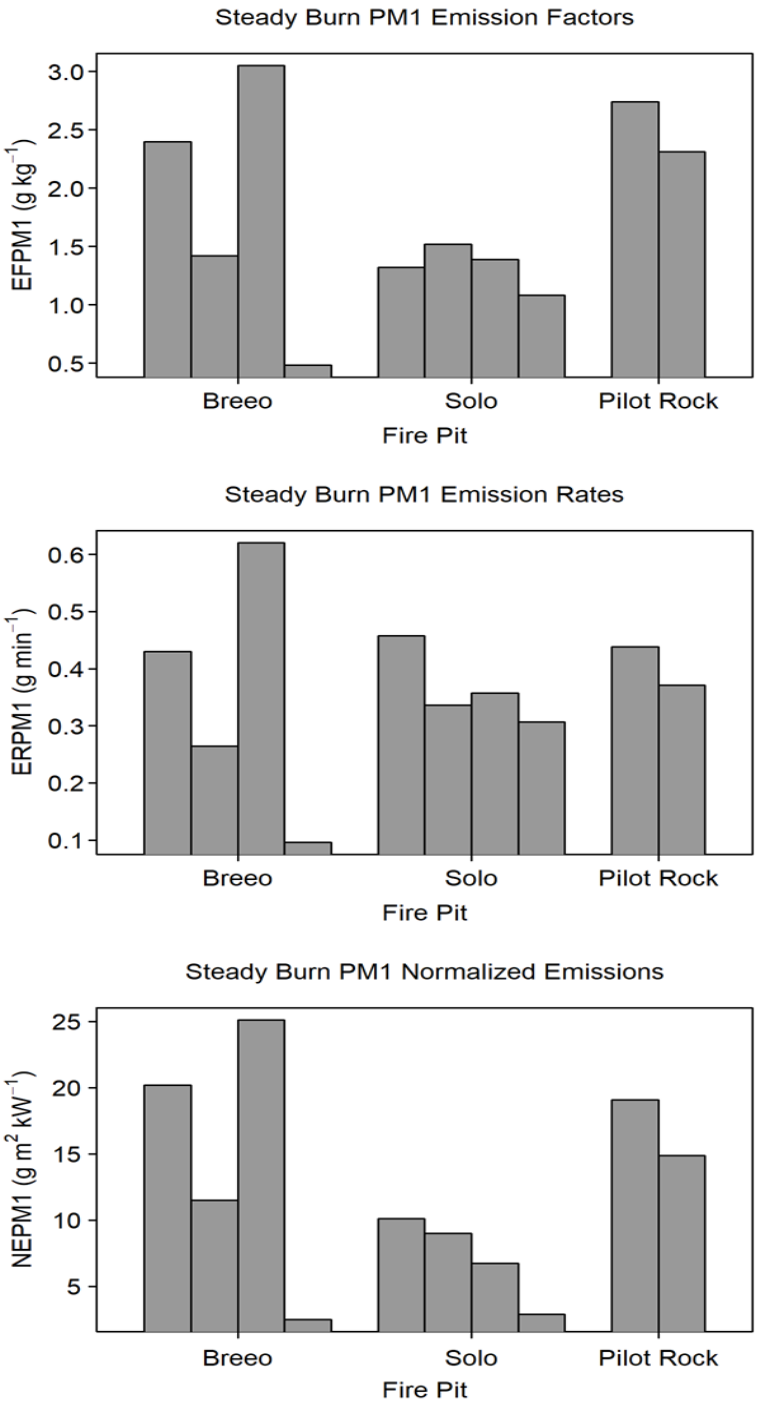

Figure 7. Steady burn phase results. Top: PM1 emission factors, middle: PM1 emission rates, bottom: PM1 emissions normalized to radiant heat flux.

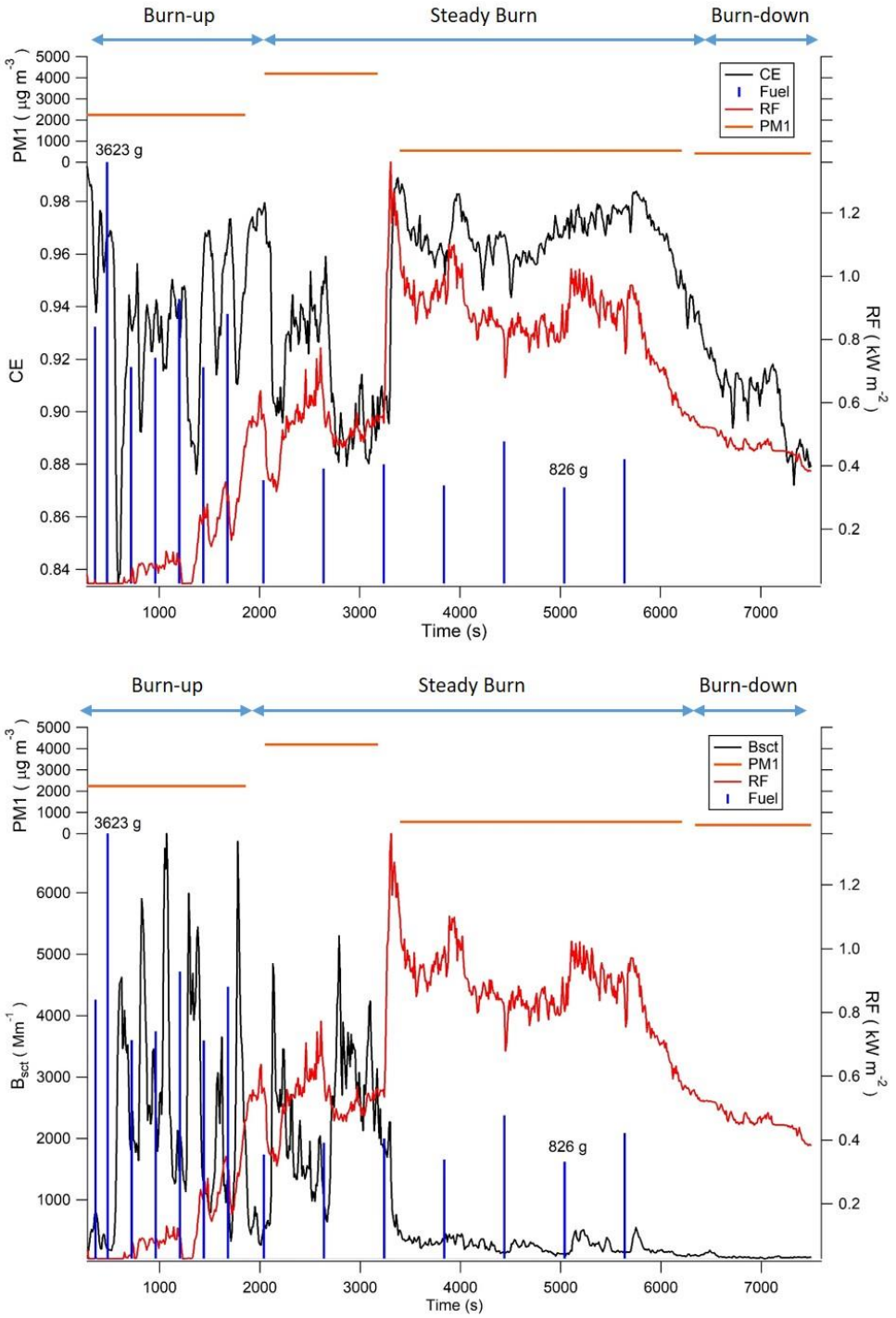

Figure 8 Top: Combustion efficiency and radiant heat flux averaged to 10 s, fuel additions (dry mass), and average PM1 concentration from filter measurements (obtained over period of orange line). Bottom: Same as top, except light scattering at 700 nm (Bsct) instead of CE.

Appendix A

Table A1. Steady burn phase results. CO_2, CO, and CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values given with ± 1 standard deviation for Breeo and Solo fire pits.

Burn	MC (%)	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
			CO_2	CO	CH_4	CO_2	CO	CH_4	CO_2	CO	CH_4
					Breeo						
4	26	0.94	1713	64.8	4.05	249	9.4	0.59	23175	157	9.8
5	32	0.96	1754	43.4	2.75	285	7.1	0.45	22001	118	7.4
7	15	0.95	1718	57.5	4.49	303	10.1	0.79	25870	169	13.2
9	11	0.97	1765	37.4	2.72	132	2.8	0.20	15619	47	3.4
Average		0.96±0.01	1738±26	50.8±12.6	3.50±0.90	242±77	7.4±3.3	0.51±0.25	21666±4344	123±55	8.5±4.1
					Solo						
2	16	0.99	1802	16.4	0.55	547	5.0	0.17	23903	83	2.8
3	38	0.98	1794	20.8	0.75	289	3.4	0.12	15354	56	2.0
6	13	0.98	1791	23.5	0.69	406	5.3	0.16	15420	89	2.6
8	16	0.96	1750	48.8	1.23	564	15.7	0.40	15368	262	6.6
Average		0.98±0.01	1784±23	27.4±14.6	0.81±0.3	452±129	7.3±5.6	0.21±0.13	17511±4261	122±94	3.5±2.1
					Pilot Rock						
10	23	0.96	1738	51.6	2.91	129	3.8	0.22	14381	64	3.6
11	17	0.95	1730	55.2	3.74	129	4.1	0.28	15065	69	4.7
Average		0.95	1734	53.4	3.33	129	4.0	0.25	14723	66	4.1

Table A2. Burn up burn phase results. CO_2, CO, and CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values given with ± 1 standard deviation for Breeo and Solo fire pits.

Burn	MC (%)	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
			CO_2	CO	CH_4	CO_2	CO	CH_4	CO_2	CO	CH_4
						Breeo					
4	26	0.96	1728	50.0	2.30	165	4.8	0.22	23941	80	3.7
5	32	0.96	1741	45.2	2.43	141	3.7	0.20	11781	61	3.3
7	15	0.94	1696	64.2	3.69	167	6.3	0.36	38731	106	6.1
9	11	0.96	1738	49.1	3.19	635	17.9	1.17	18864	299	19.4
Average		0.95±0.01	1726±20	52.1±8.3	2.90±0.65	277±239	8.2±6.6	0.49±0.46	23329±11415	136±110	8.1±7.7
						Solo					
2	16	0.89	1576	126.7	9.18	440	35.3	2.56	29814	589	42.7
3	38	0.98	1776	27.8	1.13	198	3.1	0.13	16826	52	2.1
6	13	0.99	1800	16.9	0.65	292	2.7	0.11	12287	46	1.8
8	16	0.99	1812	9.6	0.32	406	2.2	0.07	6170	36	1.2
Average		0.96±0.05	1741±111	45.2±54.8	2.82±4.25	334±110	10.8±16.3	0.72±1.23	16274±10027	181±272	11.9±20.5
						Pilot Rock					
10	23	0.97	1773	29.3	1.60	486	8.0	0.44	19734	134	7.3
11	17	0.98	1780	27.2	1.46	529	8.1	0.43	19738	135	7.2
Average		0.98	1777	28.3	1.53	507	8.1	0.44	19736	134	7.3

Table A3. Burn down burn phase results. CO_2, CO, and CH_4 emission factors (EF), emission rates (ER), and emissions normalized to radiant heat flux (NE). Average values given with ± 1 standard deviation for Breeo and Solo fire pits.

Burn	MC (%)	MCE	EF g kg^{-1}			ER g min^{-1}			NE g m^2 kW^{-1}		
			CO_2	CO	CH_4	CO_2	CO	CH_4	CO_2	CO	CH_4
						Breeo					
4	26	0.92	1676	91.1	3.58	302	16.4	0.65	10573	274	10.8
5	32	0.92	1674	93.0	2.96	211	11.7	0.37	7782	195	6.2
7	15	0.91	1661	99.8	4.40	304	18.3	0.81	12592	305	13.4
9	11	0.91	1652	105.8	3.08	273	17.5	0.51	11588	291	8.5
Average		0.92±0.01	1666±11	97.4±6.7	3.50±0.66	273±43	16.0±2.9	0.58±0.19	10634±2072	266±49	9.7±3.1
						Solo					
2	16										
3	38	0.91	1662	103.8	2.05	302	18.9	0.37	8971	315	6.2
6	13	0.89	1629	121.8	2.77	342	25.6	0.58	7777	426	9.7
8	16	0.90	1640	112.8	4.93	227	15.6	0.68	8376	261	11.4
Average		0.90±0.01	1644±17	112.8±9.0	3.25±1.50	291±58	20.0±5.1	0.55±0.16	8375±597	334±85	9.1±2.6
						Pilot Rock					
10	23	0.89	1612	128.4	5.50	211	16.8	0.72	8267	279	12.0
11	17	0.90	1633	115.1	5.61	266	18.8	0.92	6406	313	15.3
Average		0.89	1623	121.7	5.55	238	17.8	0.82	7337	296	13.6

Appendix B

Summary of Picarro CRDS and LICOR gas analyzer calibrations

Table B1. Calibration standards for Picarro trace has analyzer and LICOR-850 CO2 analyzer. CO2, CO, and CH4 in Ultrapure air. Concentrations in ppm.

	Low	Mid	High
CO	3.03	9.75	40
CO2	510	745	1400
CH4	1.493	3.04	4.96

Table B2. Statistics for three-point calibration of Picarro trace gas analyzer.

	CO			CO2			CH4		
Date	Intercept	Slope	R2	Intercept	Slope	R2	Intercept	Slope	R2
20190507	-0.338	1.066	1	36.027	0.95	1	-0.012	1.004	1
20190508	-0.352	1.066	1	34.797	0.951	1	Not calibrated		
20190509	-0.345	1.066	1	34.797	0.951	1	Not calibrated		
20190510	-0.343	1.065	1	35.201	0.95	1	Not calibrated		
20190513	-0.352	1.066	1	34.959	0.951	1	Not calibrated		
20190514	-0.359	1.066	1	34.797	0.951	1	-0.012	1.004	1

Table B3. Picarro Calibration applied to all data (y_true = y_measured*slope + intercept

Species	Intercept	Slope	R2
CO2	34.8	0.95	1.00
CO	-0.35	1.07	1.00
CH4	-0.0120	1.004	1.00

LICOR calibration versus Picarro

On May 14 the LICOR and Picarro gas analyzers sampled three standards to cross calibrate the LICOR CO2 measurements against the Picarro for background CO2 concentrations. The resultant calibration was applied to the LICOR measurements of background CO2 measured throughout the study.

Table B3. LICOR cross calibration versus Picarro CRDS			
	Low CO2 (ppm)	Mid CO2 (ppm)	High CO2 (ppm)
Standard	351	510	745
Picarro	349.6	504	741
Licor	361	530	771.5
Picarro_CO2 = 0.955*Licor_CO2 + 2.07, R2 = 0.9996			

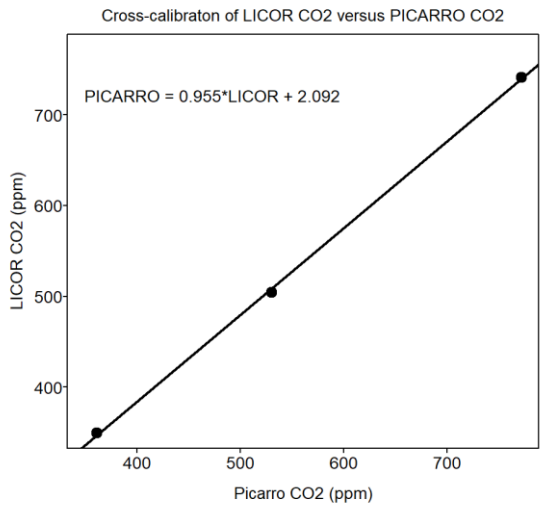

Figure B1. Cross-calibration of LICOR CO2 versus Picarro CRDS CO2.

Appendix C

Failure of PM2.5 sampler

The original study design called for the measurement of PM2.5 emissions. The PM2.5 sampling unit employed an in-house designed pump to draw 16.7 slpm of air/emissions through a cyclone with a cutoff of ≤ 2.5 µm aerodynamic diameter (URG-2000-30EC, URG Corp., USA) and onto a 37 mm Teflon filter. Unlike the PM1 sampling unit, the PM2.5 sampling unit did not have a flow controller that logged or displayed the flow rate. However, flow rates of the sampling units were periodically verified using a Gilibrator-2 Primary Standard Air Flow Calibrator. Two weeks prior to the fire pit study, both the PM2.5 and PM1 sampling units were evaluated against an EPA Federal Reference Method (FRM) PM2.5 instrument in static tests in the Fire Science Laboratory (FLS) combustion chamber. During the static testing, ponderosa pine and spruce needles and fine dead woody debris were burned in the combustion chamber allowing the chamber to fill with smoke. Once nephelometry (continuous, 1 minute measurements of light scattering) indicated the PM concentrations had stabilized, the filter samplers (including the FRM) were triggered to sample for 60 minutes. Between test burns the chamber was completely flushed and a new fuel sample was burned to provide a sample of fresh smoke. In addition to recent evaluation versus EPA FRM instruments, the PM2.5 sampling unit has been in many previous studies to sample PM emissions from the FSL combustion lab exhaust stack. In these previous studies it has compared well with PM measurements obtained with other FSL PM sampling units as well as those from outside research groups e.g. (Hosseini et al., 2013).

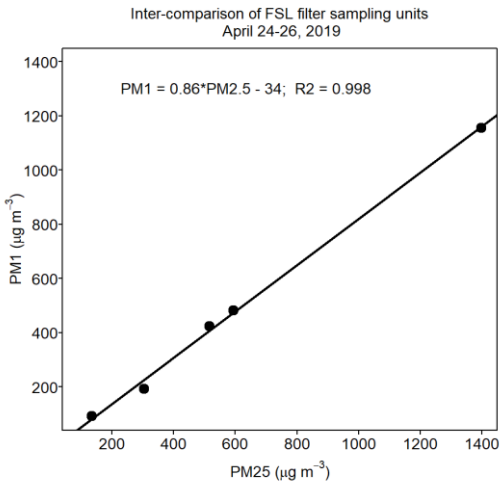

Figure C1. Mass concentrations measured by the two FSL PM filter sampling units during the static testing.

During fire pit sampling the PM2.5 sampling had difficulty properly regulating the sample flow; the pump frequently sounded labored during operation and the flow consistently measured 19 slpm during periodic checks. Analysis of the filters showed the PM concentration measured by the PM2.5 sampler to be systemically lower than that measured by the PM1 sampler. Each sampler collected emissions through a separate, dedicated sampling line, however, their inlets were collocated within the exhaust stack. The sampling lines were stainless steel tubing into the exhaust stack which was connected to the sampling units through conductive tubing. The results indicate that there was a significant PM loss in the PM2.5 sampling line compared with the PM1 sampler. At the time of this report, the combustion chamber is being used for a fire behavior research study. When the combustion chamber becomes available for emission experiments, we

plan to investigate the sampling lines used in the fire pit testing, test new inlet sample lines, and repeat the fire pit testing.

WAITING ON QC/QA FILTER ANALYSIS FROM EPA.

THEY CANNOT RELEASE THE DATA UNITL QA/QC IS COMPELTE

SHOULD BE COMPLETED BY MID-JUNE, THEN FIGURES AND STATS WILL BE INSERTED

Figure A2. Mass concentrations measured by the FSL filter sampling units versus that measured by the EPA FRM.