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Evaluation of small form factor, filter-based $PM_{2.5}$ samplers for temporary non-regulatory monitoring during wildland fire smoke events

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HIGHLIGHTS

- Problemo There is a need for rugged, lightweight, battery powered, $PM_{2.5}$ filter-based samplers in small and low-cost form factors that can be deployed during wildland fire events to improve spatial resolution and accuracy of $PM_{2.5}$ mass measurements.
- o EPA partnered with the United States Forest Service (USFS) in this research effort to improve confidence in small form factor filter-based $PM_{2.5}$ monitoring devices in smoke.
- Approacho The research was performed in an ambient environment at EPA's Ambient Air Innovative Research Site (AIRS, Research Triangle Parc, NC) in 2018.
- o In addition, evaluations were performed during controlled burn chamber experiments at the U.S. Forest Service Rocky Mountain Fire Sciences Laboratory in Missoula, MT in 2019.
- o $PM_{2.5}$ FRM methods were employed as reference to assess capabilities for accurate, interference-free determination of $PM_{2.5}$ in biomass smoke.
- Resultso All samplers in the study performed respectably in determining total $PM_{2.5}$ concentrations with accuracies ranging from 93.1 to 98.2%.
- o The ARA N-FRM was the only small form factor filter-based sampler to achieve EPA $PM_{2.5}$ FRM mass measurement accuracy performance targets along with study-best accuracies in both ambient and chamber-based smoke testing.

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ABSTRACT

Wildland fire activity and associated emission of particulate matter air pollution is increasing in the United States over the last two decades due primarily to a combination of increased temperature, drought, and historically high forest fuel loading. The regulatory monitoring networks in the Unites States are mostly concentrated in larger population centers where anthropogenic air pollution sources are concentrated. Smaller population centers in areas more likely to be impacted by wildland fire smoke in many instances lack adequate observational air quality data. Several commercially available small form factor filter-based $PM_{2.5}$ samplers (SFFFS) were evaluated under typical ambient and simulated near-to mid-field wildland fire smoke conditions to evaluate their accuracy for use in temporary deployments during prescribed and wildfire events. The performance of all the SFFFS tested versus the designated federal reference methods (FRM) was acceptable in determining $PM_{2.5}$ concentration in both ambient (2.7–14.0 μg m^{-3}) and chamber smoke environments (24.6–3044.6 μg m^{-3}) with accuracies ranging from ~92 to 98%. However, only the ARA Instruments model N-FRM Sampler was found to provide $PM_{2.5}$ mass measurement accuracies that meet FRM guideline performance specifications under both typical ambient (97.3 ± 1.9%) and simulated wildland fire conditions (98.2 ± 1.4%).

1. Introduction

Wildfires have been increasing in size and intensity in the Western United States (U.S.) in recent decades, a trend that is expected to continue (Gershunov et al., 2013; Reisen et al., 2015; Westerling et al., 2014; Yue et al., 2013). Numerous factors including land management

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practices, forest fuel loading, drought, and higher global temperatures have resulted in a longer wildfire season along with an increase in area burned and greater fire intensity (Kitzberger et al., 2007; Johnston et al., 2012; United States Department of Agriculture, 2014; United States Department of Agriculture, 2016; Westerling et al., 2014; Westerling, 2016; Landis et al., 2018). These fires produce significant air pollutant emissions which pose health risks to first responders and downwind populations (Adetona et al., 2016; Rappold et al., 2011; Johnston et al., 2012; Reid et al., 2016; Cascio, 2018; Weitekamp et al., 2020). Improved spatial quantification of smoke impacts from wildland fires remains an area of significant need to more successfully communicate associated risk to affected populations, to provide data for predictive smoke dispersion model development and validation, and to document exposures for subsequent public health analysis.

Particulate matter $\leq$2.5 μm in mass median aerodynamic diameter ($PM_{2.5}$) is one of the most important criteria pollutants impacting health (Chen et al., 2021; Ferguson et al., 2017; Liu et al., 2015; Reid et al., 2016; Youssouf et al., 2014; Kim et al., 2018, 2019; Orr et al., 2020; Zelikoff et al., 2002). Smoke emitted from wildland fires is known to have high levels of $PM_{2.5}$ that negatively impact air quality (Urbanski, 2014). Particulate matter is directly emitted from wildland fires along with oxides of nitrogen (NO_x) and volatile organic compounds (VOC) that can lead to the photochemical formation of secondary $PM_{2.5}$, which can significantly enhance downwind concentrations (Naeher et al., 2007). In recent years, wildfires have been estimated to account for as much as 25% of the total $PM_{2.5}$ across the continental U.S., and up to half of total $PM_{2.5}$ on an annual basis in the Western U.S. (Burke et al., 2021). During specific events, $PM_{2.5}$ monitors located near wildfires have reported hourly concentrations exceeding 3–5 mg m^{-3}, resulting in 107 reported exceedances of the daily $PM_{2.5}$ Alberta Ambient Air Quality Objective (AAAQO) of 30 μg m^{-3} in Fort McMurry (Landis et al., 2018). The transient and unpredictable nature of wildland fire events combined with varying meteorological conditions presents a significant challenge in capturing $PM_{2.5}$ to effectively assess a population's exposure.

Routine regulatory NAAQS $PM_{2.5}$ compliance monitoring in the U.S. is conducted using a combination of 24-h integrated filter-based Federal Reference Method (FRM) or continuous Federal Equivalency Method (FEM) monitors (Hall et al., 2012). Long-term regulatory $PM_{2.5}$ monitoring network sites are concentrated in larger population centers where anthropogenic air pollution sources are located, are costly to establish and maintain, and require electrical/telecommunication/security infrastructure. As a result, more remote smaller population centers impacted by smoke typically lack adequate observational air quality data. A recent U.S. Government Accountability Office report found that 2,120 of the 3,142 counties (67.5%) in the U.S. had no regulatory monitor (U.S. GAO, 2020). During prescribed and wildfire events, regulatory long-term monitoring sites can be augmented with dedicated temporary non-regulatory monitors deployed by the U.S. Interagency Wildland Fire Air Quality Response Program (U.S. IWFAQRP, 2021) and by low-cost $PM_{2.5}$ sensors (2B Technologies, 2021; Clarity, 2021; PurpleAir, 2021). However, the accuracy and precision of low-cost sensor data during wildland fire smoke events is relatively uncertain (Delp and Singer, 2020; Holder et al., 2020; Mehadi et al., 2020; Landis et al., 2021). As mandated and due to strict performance and design specifications, gravimetric filter-based $PM_{2.5}$ FRM measurements remain the gold standard in accuracy. Technological advancements in microelectronics and battery performance have enabled the increased introduction of rugged, lightweight, battery powered, $PM_{2.5}$ filter-based samplers in smaller and lower cost form factors that can be deployed during wildland fire events to improve spatial resolution and accuracy of ambient $PM_{2.5}$ concentrations. Performance of battery powered filter-based sampling that is traceable to the U.S. Environmental Protection Agency (EPA) designated $PM_{2.5}$ FRM method provides for (i) more reliable temporary monitor deployment data, (ii) facilitates deployment flexibility, (iii) allows for the field performance evaluation of temporarily deployed continuous non-regulatory $PM_{2.5}$ mass monitors and low cost sensors under real world smoke conditions, and (iv) allows for subsequent chemical speciation of collected $PM_{2.5}$ constituents for health effects and emission factor characterization research applications.

The present study investigates the use of three models of commercially available small form factor filter based $PM_{2.5}$ samplers (SFFFS) in an ambient environment. The three models were tested in five total configurations in a chamber used to simulate near-to mid-field wildland fire smoke exposure conditions (Landis et al., 2021). Ambient testing took place at the EPA Ambient Air Innovation Research Site (AIRS) in Research Triangle Park, NC and simulated wildland fire smoke exposure testing was performed at the United States Forest Service (USFS) Rocky Mountain Fire Sciences Laboratory large combustion chamber research facility in Missoula, MT (Bertschi et al., 2003; Christian et al., 2004; Yokelson et al., 1996, 2008, 2008; Landis et al., 2021) where varying concentrations of smoke were generated from burning biomass typical of the Western U.S. under varying combustion conditions (e.g., smoldering, flaming). Each candidate sampler performance was evaluated as detailed in the EPA Candidate Equivalency Methods test specifications (40 CFR Part 53). The accuracy, collocated precision, slope, intercept, coefficient of determination (r^2), and $\Delta_{PM2.5}$ (FRM $PM_{2.5}$ - SFFF $PM_{2.5}$) of each $PM_{2.5}$ SFFFS was investigated through comparison to EPA designated FRM $PM_{2.5}$ samplers during ambient and simulated wildland fire exposure testing.

2. Methods

2.1. Small form factor filter samplers

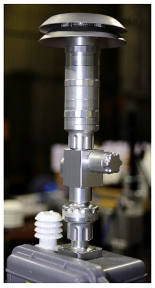
Three commercially available battery powered, $PM_{2.5}$ gravimetric SFFFS were evaluated during testing. Samplers were chosen based on availability; they were either already owned by EPA or were commercially available for immediate purchase. Devices were all able to be powered off an internal battery for rapid deployment to a field site where electricity may not be available. However, this study focuses on the accuracy and precision of each sampler, and therefore, the run-time and functionality on battery power was not investigated. All devices collect samples on standard EPA FRM 47 mm filter media and cassettes. Additional details of each instrument are shown in Table 1.

The BGI Omni FT Ambient Air Sampler (Mesa Laboratories, Inc., Butler, NJ) is well established and widely used. The Omni's inlet is dubbed the miniPM™ Multi-cut inlet and can be configured for total suspended particulate (TSP), PM_{10}, $PM_{2.5}$, PM_4, or PM_1 sampling and operates at a volumetric flow rate of 5 L per minute (Lpm). Our test devices were configured for $PM_{2.5}$ with a single stage inline impactor and cyclone. The Omni FT monitors temperature and barometric pressure to maintain constant volumetric flow.

Also tested was the Airmetrics (Springfield, OR) model MiniVol Tactical Air Sampler (TAS) which operates from a rechargeable, lead-acid battery that can power 24-h of continuous sampling. The MiniVol can be configured to sample TSP (no impactor), PM_{10} with a single impactor, or $PM_{2.5}$ with sequential impactors. Each impactor must be greased with high-vacuum grease and cleaned on approximately a weekly basis. The MiniVol operates at 5 Lpm and has no internal mass flow controller (MFC), flow is controlled by an internal needle valve and indicated by a rotameter. As such, sampled volumes are calculated by the run time and the flow rate recorded at calibration. Also featured is a 7-day programmable timer and an elapsed time totalizer.

The ARA Instruments (Eugene, OR) model N-FRM is the only battery-powered sampler that operates at 16.7 Lpm in its standard configuration. The sampler is equipped with two 18V/5Ah lithium-ion batteries. The N-FRM can be configured for TSP sampling with the louvered inlet, PM_{10} by adding an inertial impactor with moisture trap, and $PM_{2.5}$ by adding the ARA Vortex Inversion Separator (VIS-A) sharp-cut cyclone. The N-FRM incorporates a microprocessor-based active flow control system to maintain volumetric flow. The manufacturer indicates that the

Table 1
Specifications of selected samplers.

Sampler	BGI Omni FT	MiniVol TAS	ARA N-FRM	ARA LFR-6	LFR-6 URG Inlet
Image					
Manufacturer	Mesa Labs, Inc.	Airmetrics	ARA Instruments	ARA Instruments	ARA Instruments and URG
Inlet flow rate (Lpm)	5	5	16.7	6	5
Available fractionator	TSP, PM_{10}, $PM_{2.5}$, PM_1, or PM_4	TSP, PM_{10}, $PM_{2.5}$	TSP, PM_{10}, $PM_{2.5}$	TSP, PM_{10}, $PM_{2.5}$	$PM_{2.5}$
Fractionator type for $PM_{2.5}$	Single stage inertial impactor and cyclone	Two-stage inertial impactors	Inertial impactor and sharp-cut cyclone	Inertial impactor and sharp-cut cyclone	Cyclone
Stated battery runtime (hours)	Up to 48	24	30–40	30–40	30–40
Logged parameters	T, BP, and flow rate	none	T, P, flow rate (Std and actual), more with accessories	T, P, flow rate (Std and actual), more with accessories	T, P, flow rate (Std and actual), more with accessories
Available accessories	Solar panel	Tedlar bags for gas sampling	Real-time particulate sensor, wind sensor, hexavalent chromium sampling, solar panel	Real-time particulate sensor, wind sensor, hexavalent chromium sampling, solar panel	Real-time particulate sensor, wind sensor, hexavalent chromium sampling, solar panel

sampling rate is adjusted several times a second and logged at 5-min intervals maintaining the flow control within ±2%. The N-FRM has several unique features including the ability to be configured with an anemometer enabling directional sampling as well as a light scattering Real-Time Particle sensor (RTP) for aerosol trend and concentration triggered sampling.

The ARA model LFR-6 is similar to the model N-FRM but designed with a reduced flow of 6 Lpm. The reduced flow rate is designed to sample in near source environments where high concentrations exist that may otherwise result in excessive filter loading and an undesired automated shutdown (when actual flowrate is <90% of flow set point) resulting in shorter sampling duration. Other than a reduction in the design flow rate and the corresponding change in inlet and fractionator dimensions, the LFR-6 is functionally the same as the N-FRM.

A third iteration of the ARA sampler involved a novel inlet assembly for $PM_{2.5}$ designed and fabricated by URG Corporation (Chapel Hill, NC) consisting of a low volume inlet cap, stainless steel cyclone, and stainless steel filter housing (Model URG-2000-30CFA-5-2.5) with a flow of 5 Lpm was also evaluated. This inlet configuration was installed on two modified ARA LFR-6 units by URG in cooperation with ARA and evaluated during the chamber burns only.

2.2. Reference measurements, media, and size distribution

Reference measurements were performed according to 40 CFR Part 50 Appendix L (U.S. EPA) using Tisch Environmental (Cleves, OH) Model TE-WILBUR filter-based FRM samplers. Each Tisch FRM used a standard EPA PM_{10} louvered inlet and $PM_{2.5}$ fractionation was performed by a BGI by Mesa Labs (Butler, NJ) Model VSCCA very sharp cut cyclone (VSCC). Calibrations of sampler temperature, pressure, and flow rates were performed weekly using a BGI by Mesa Labs tetraCal® Air Flow Calibrator as outlined in each respective sampler user manual. Flow audits were performed with the same tetraCal Air Flow Calibrator.

Measurement Technology Laboratories (Minneapolis, MN) Model PT47P polytetrafluoroethylene (PTFE) 2 μm pore size pressure drop equivalent membrane filters, with a hydro-inert support ring from the same lot were used in every sampler. Filters were weighed in accordance with EPA Guidance Document 2.12 (U.S. EPA, 2016) for monitoring $PM_{2.5}$ in ambient air. Before and after sampling, filters were equilibrated for a minimum of 24-h in a temperature and humidity controlled clean room prior to being weighed by an MTL Model AH1 Automated Weighing instrument. The AH1 used a Mettler-Toledo (Columbus, OH) Model XP2U micro balance with an accuracy of up to a tenth of a microgram. The response of the micro balance was checked every ten filters by verification of Class 0 wt standards from Rice Lake Weighing Systems (Rice Lake, WI). Filter weights were performed in triplicate and were accepted as valid if the response to the weight standards were ±5 μg. Final weights were calculated from the average of the triplicate readings.

Ambient aerosol size distributions were monitored on 5-min intervals using a TSI Incorporated (Shoreview, MN) Model 3321 Aerodynamic Particle Sizer (APS). During ambient sampling, the APS was located inside the sampling trailer and samples were drawn through a standard EPA PM_{10} louvered inlet affixed to a 31.75 mm diameter downtube penetrating the trailer roof. The downtube was attached to a custom isokinetic flow splitter mounted concentrically within a 31.75 mm tube and was used to allow the APS to sample 5 Lpm while allowing a bypass flow of 11.67 Lpm achieving the design flow rate of 16.67 Lpm through the PM_{10} inlet. During chamber sampling the APS was placed on a table within the designated smoke sampling area with no inlet.

2.3. Ambient field testing

Ambient field testing was performed at EPA's AIRS site in Research Triangle Park, NC (35.889159°N, −78:874927°W) from August 17 - October 25, 2018. All FRM and SFFF samplers were installed on the roof of an instrumented trailer with inlets nominally 1 m above the trailer roof and approximately 4 m above ground level (Appendix Figure B1). $PM_{2.5}$ samples were collected on each sample day for 23.75 h (12:00PM - 11:45AM the following day). This time period was chosen to facilitate

the manual filter change outs on all the samplers on concurrent sampling days. The 23.75-h sampling period is consistent with requirements for $PM_{2.5}$ gravimetric sampling outlined in 40 CFR Part 53 (Federal Register, 1997, 2006). Calibrations, maintenance, cleaning of inlet fractionators, and leak checks were performed at the beginning of the field sampling period and weekly thereafter to ensure proper operation of the samplers. Ambient temperature, barometric pressure, and volumetric flow calibration/checks and adjustments, if any, were referenced to a certified tetraCal primary standard Air Flow Calibrator.

2.4. Chamber smoke sampling

Testing was carried out at the USFS combustion testing facility at the Fire Sciences Laboratory in Missoula, Montana. The main combustion chamber is a square room with internal dimensions 12.4 × 12.4 × 19.6 m high and a total volume of 3000 m^3 and has been described previously (Bertschi et al., 2003; Christian et al., 2004; Yokelson et al., 1996, 2008). Prior to each "static" burn the chamber was flushed with outdoor ambient air and then sealed during each of the burns. Fuel beds were prepared, placed in the center of chamber, and ignited. The FRM and SFFF samplers were programed to start 10–15 min after fuel ignition to allow for the combustion of the fuel beds, flame out, and mixing of the smoke. Two large circulation fans mounted on the walls in the chamber facilitated mixing and maintained homogeneous smoke conditions during the tests. The fuels utilized were ponderosa pine (Pinus ponderosa) needles and fine dead wood, alone or mixed. Combustion efficiency of burns was varied by fuel bed bulk density and fuel moisture content as summarized in Appendix Table A1. A total of 31 discrete burns were performed from April 15–26, 2019 under different burn conditions resulting in 31 1-h filter sample periods. Three Tisch $PM_{2.5}$ FRMs were placed in a triangle around the center of the chamber floor while the SFFFS and APS were located within the triangle defined by the FRMs as depicted in Appendix Figure B2.

2.5. Test requirements and statistical analysis

The goal of this study was to evaluate the SFFFS performance for $PM_{2.5}$ in both an ambient environment and a near wildland fire type smoke event as compared to a designated FRM. The Federal Register has strict testing requirements which were not achieved in this study including specific $PM_{2.5}/PM_{10}$ ratios, acceptable concentration ranges of 3–200 μg m^{-3}, and a minimum requirement of three reference method and 3 candidate method samplers run concurrently. Three key regression parameters used for evaluation were bias (slope 1 ± 0.05), offset (intercept 0 ± 1 μg m^{-3}), and correlation coefficient ($r^2 \geq 0.97$) (U.S. EPA, 40 CFR Part 53).

Accuracy of samplers was calculated using Equation (1), and precision was calculated using the coefficient of variation or relative standard deviation using Equation (2).

$$Accuracy\ (\%) = 100 - \left[\frac{\left|\overline{X} - \overline{R}\right|}{\overline{R}}\right] \times 100 \quad (1)$$

Where X is the reported sampler concentration and R is the reference concentration.

$$Precision\ (\%) = \frac{\sqrt{\sum \frac{(x_i - \overline{x})^2}{(n-1)}}}{\overline{x}} \times 100 \quad (2)$$

Where $\overline{x}$ = mean of collocated sampler concentrations, $\sum (x_i - \overline{x})^2$ = the sum of square of differences between individual collocated sampler concentrations and the mean, and n = the number of collocated sampler observations.

Data processing and all statistical analyses were performed using SAS v.9.4 (SAS Institute, Cary, NC). Statistical procedures used in this analysis included simple least squared linear regression analysis, paired *t*-test, Pearson correlation, and multivariate analysis of variance (MANOVA). The assumptions of the parametric procedures were examined using residual plots, skewness and kurtosis coefficients, Shapiro-Wilk test, and the Brown-Forsythe test. If parametric assumptions of the paired *t*-test procedures were violated after log transformation, then the Wilcoxon Sign Rank non-parametric procedure was used. One-sided tests and a level of significance of $\alpha = 0.05$ were used for all statistical procedures. The SAS UNIVARIATE, TTEST, REG, CORR, and GLM procedures were used for calculation of sample population central tendency and variance, Wilcoxon Sign Rank test, paired *t*-test, least square general linear model regressions, Pearson correlation analysis, and MANOVA analysis, respectively.

3. Results and discussion

3.1. Ambient testing

Ambient testing involved 32 sample days conducted at EPA's AIRS research site where Tisch $PM_{2.5}$ FRMs were collocated with three pairs of SFFFSs for evaluation of performance. Samplers were time synced and programmed to start at 12:00PM or were manually started and stopped (Omni FT). A total of four Tisch FRMs were operated during the study with two sampling on any given sample day with the exception of sample Day 1 (Appendix Table A2). During the first half of the study Tisch FRM #16 was operated every sample day due to a malfunctioning temperature sensor on Tisch FRM #22. Upon repair, Tisch FRMs #16 and 20 and Tisch FRMs #21 and 22 were operated in pairs (Appendix Table A2). Scatter plots of each Tisch FRM pairing during ambient sampling indicating slope, intercept, and r^2 values of 1.04, −0.21 and 0.98 for Tisch FRM #20 and #16, 1.05, −0.39, 0.99 for #21 and #16, and 1.00, −0.22, and 0.99 for #22 and #21, respectively (Appendix Figure B.3). Across all 32 sample days the Tisch FRMs indicated a mean daily $PM_{2.5}$ concentration of 7.62 ± 2.60 μg m^{-3} (Table 2), only four days exceeded a 24-h concentration of 10 μg m^{-3} (Appendix Table A2).

The ARA N-FRM pair had all 32 sample days returned as valid while the MiniVol had two samples that were invalidated (one sample that did not run for the full sample duration and one sample that the calculated $PM_{2.5}$ concentration was a factor of 32 high indicating a potential filter contamination issue), and the Omni FT had one sample that was invalidated (a calculated sample concentration that was a factor of 2 high indicating a potential filter contamination issue). The daily reported concentrations for each sampler and pair are reported in Appendix Table A2. The N-FRMs reported a study mean concentration of 7.49 ± 2.70 μg m^{-3}, and a pairwise study mean accuracy of 97.3 ± 1.9% as calculated by Equation (1), both the best values in the study (Table 2). A scatter plot of each SFFFS pair mean *versus* the Tisch FRM pair mean (Fig. 1a, e, 1c) indicates slope, intercept, and r^2 values of 1.04, 0.41 μg m^{-3}, and 0.99 for the N-FRM pair; 1.05, −0.03 μg m^{-3}, 0.95 for the Omni FT pair; and 1.01, 0.03 μg m^{-3}, 0.96 for the MiniVol pair, respectively (Fig. 1 and Table 3). Only the N-FRM met performance requirements for bias, offset, and correlation coefficient (Table 3). While not passing the bias requirements, the Omni FT also had the worst precision (5.7 ± 5.7%) and $\Delta_{PM2.5}$ (−0.4 ± 0.6 μg m^{-3}) in the ambient portion of this study. Failing the correlation coefficient requirements with an r^2 of 0.96, the MiniVol had marginally better yet with a larger standard deviation (5.6 ± 6.3%) and $\Delta_{PM2.5}$ (−0.1 ± 0.5 μg m^{-3}) when compared to the Omni FT. The Wilcoxon sign rank test indicated the MiniVol sampling pair to be significantly different ($p = 0.441$), the only pair in the ambient environment. This can likely be attributed to the absence of active flow control resulting in flow drift between units and subtle changes due to variations in the pressure drop between filters loaded in a particular instrument on a daily basis. The N-FRM exceeded performance requirements, with precision of 1.3 ± 1.2% and a mean $\Delta_{PM2.5}$ of only 0.1 ± 0.2 μg m^{-3}, the N-FRM was the best performing SFFFS in an ambient environment. Working in the N-FRM's favor, the

Table 2
$PM_{2.5}$ study means and small form factor filter sampler accuracy (outliers removed).

		AIRS Chamber					
Sampler	Unit	n	Mean ± Std Dev $PM_{2.5}$ ($\mu g\ m^{-3}$)	Accuracy (%)	n	Mean ± Std Dev $PM_{2.5}$ ($\mu g\ m^{-3}$)	Accuracy (%)
Tisch FRM	Ave	32	7.62 ± 2.60	–	31	598.7 ± 637.0	–
ARA N-FRM	25	32	7.48 ± 2.67	97.2 ± 2.1	31	605.9 ± 651.8	97.4 ± 2.7
	97	32	7.49 ± 2.74	97.0 ± 2.0	31	605.5 ± 645.1	98.2 ± 1.9
	Both	32	7.49 ± 2.70	97.3 ± 1.9	31	605.7 ± 648.5	98.2 ± 1.4
Omni FT	232	31	8.15 ± 2.78	90.6 ± 13.1	31	593.0 ± 623.2	94.3 ± 5.0
	235	32	7.93 ± 2.84	93.2 ± 6.5	31	595.6 ± 621.2	96.1 ± 4.5
	Both	32	7.98 ± 2.80	93.1 ± 9.1	31	594.3 ± 622.1	96.3 ± 3.8
MiniVol	56	30	7.73 ± 2.69	92.8 ± 7.4	29	609.6 ± 641.0	95.8 ± 3.6
	57	32	7.72 ± 2.81	93.2 ± 6.4	30	568.5 ± 620.3	91.8 ± 6.9
	Both	32	7.76 ± 2.69	94.2 ± 5.5	31	575.7 ± 618.9	94.1 ± 5.0
ARA LFR-6	01	–	–	–	31	594.3 ± 635.6	97.2 ± 2.3
	02	–	–	–	31	596.4 ± 638.9	96.0 ± 4.1
	Both	–	–	–	31	595.3 ± 637.2	97.5 ± 2.6
LFR-6 URG Inlet	01	–	–	–	30	622.5 ± 664.6	95.6 ± 4.8
	02	–	–	–	30	612.9 ± 664.2	94.9 ± 9.9
	Both	–	–	–	31	611.7 ± 654.1	96.4 ± 4.5

instrument's ability to maintain volumetric flow through an internal mass flow meter and ambient temperature and pressure correction. As the only SFFFS operating at the same 16.7 Lpm flow rate as the FRM, the N-FRM likely benefits by collecting the same nominal on filter mass, also resulting in the same filter face velocity and pressure drop minimizing uncertainty in potential loss in volatile and semi-volatile aerosol fractions.

3.2. Chamber smoke testing

Chamber testing consisted of a set of thirty-one static chamber burns in the USFS combustion research center. The chamber conditions, fuels combusted, and modified combustion efficiencies (MCE; Landis et al., 2021) are presented in Appendix Table A1. Chamber temperatures ranged from 18.6 to 23.6 °C, relative humidity ranged from 21 to 53%, and MCEs ranged from 0.854 to 0.964. Three Tisch FRMs were used to establish reference $PM_{2.5}$ levels over the 31, 60-min sampling periods (Appendix Table A3). A low reference concentration of 24.63 ± 1.06 μg m^{-3} was achieved for Burn 21, corresponding to a fuel loading 59 g, moisture content 12.3%, and an MCE of 95.9%. Appendix Figure B.4.20 and B.5.20 indicate a bimodal distribution with the majority of the $PM_{2.5}$ mass in the 0.5 μm aerodynamic diameter range, along with the high MCE this indicates efficient flaming combustion of the fuel. The highest reference concentration achieved was 3044.59 ± 37.76 μg m^{-3} during Burn 31 with corresponding fuel loading 349 g, moisture content 15.2%, and MCE of 87.8% indicating a less efficient overall average burn consisting of some smoldering conditions during the burn. APS data from Burn 31 indicate a tri-modal mass distribution with $PM_{2.5}$ mass peaks at approximately 0.75 and 1.5 μm aerodynamic diameter (Appendix

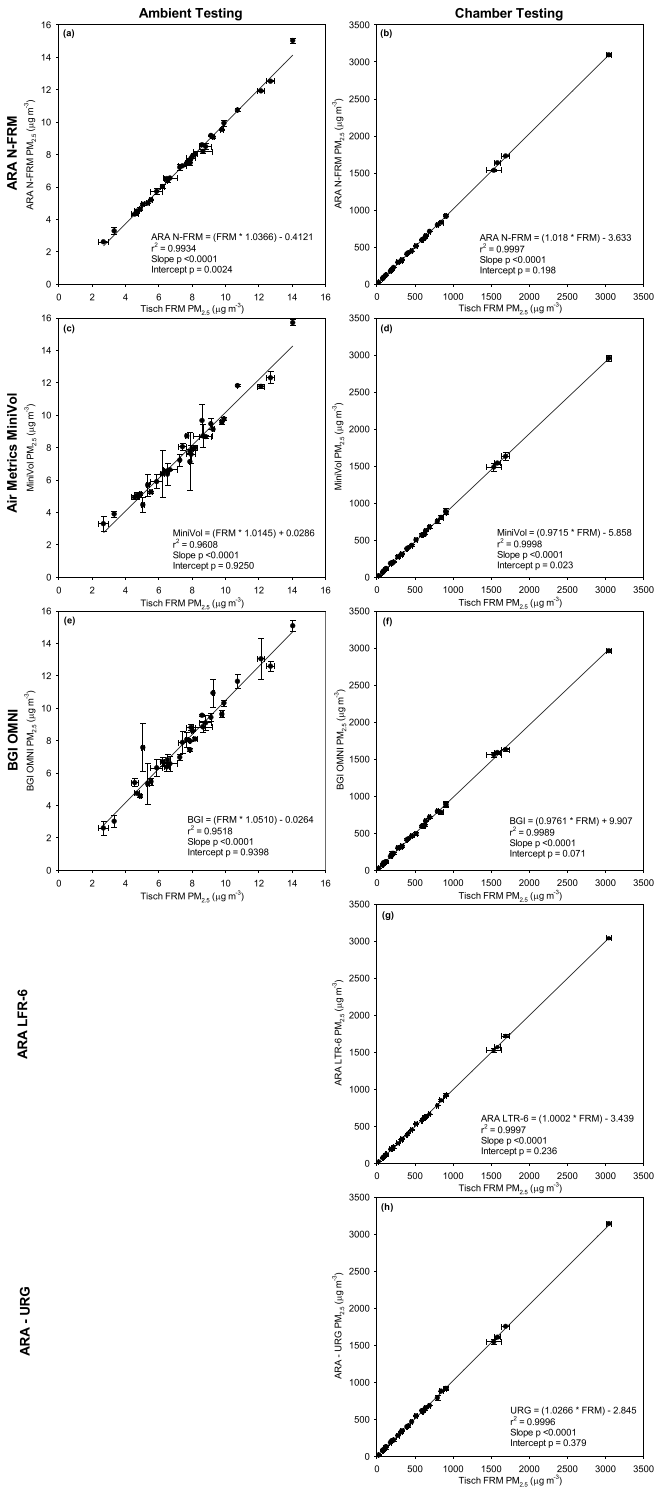


Fig. 1. Scatter Plots of FRM *versus* Small Form Factor Sampler $PM_{2.5}$ ($\mu g\ m^{-3}$).

Figure B.4.30 and B.5.30) supporting a high concentration smoldering burn. Study mean aerosol size distributions are shown in Fig. 2. Scatter plots of the relative concentrations indicated by the three Tisch FRMs are shown in Appendix Figure B.6. Over the 31 burns the Tisch FRMs indicated a burn mean concentration of 598.7 ± 637.0 μg m^{-3} (Table 2).

Five configurations of SFFFS were evaluated in chamber smoke testing. The overall SFFFS testing accuracy relative to the EPA FRM reference in descending order was N-FRM (98.2 ± 1.4%), LFR-6 (97.5 ± 2.6%), LFR-6 URG inlet variant (96.4 ± 4.5%), Omni FT (96.3 ± 3.8%),

Table 3
Summary performance of small form factor filter samplers.

	Performance Requirement[a]	ARA N-FRM		Omni FT		MiniVol TAS		ARA LFR-6	LFR-6 URG Inlet
		AIRS	*Chamber*	*AIRS*	*Chamber*	*AIRS*	*Chamber*	Chamber	Chamber
n		32	31	31	31	30	28	31	31
Bias	1 ± 0.05	1.0366	1.0180	1.0510	0.9761	1.0145	0.9715	1.0002	1.0266
Offset (μg m^{-3})	0 ± 1	−0.4121	−3.633	−0.0264	9.907	0.0286	−5.8580	−3.439	−2.845
r^2	>0.97	0.9934	0.9997	0.9518	0.9989	0.9608	0.9998	0.9997	0.9996
Precision (%)		1.3 ± 1.2	1.4 ± 3.0	5.7 ± 5.7	4.1 ± 4.5	5.6 ± 6.3	4.5 ± 5.4	3.2 ± 3.3	5.0 ± 11.2
$\Delta_{PM2.5}$ (μg m^{-3})		0.1 ± 0.2	−7.1 ± 15.8	−0.4 ± 0.6	4.4 ± 25.8	−0.1 ± 0.5	22.9 ± 20.6	3.3 ± 11.3	−13.1 ± 21.1
Wilcoxon Sign Rank Test[b]		p < 0.0001	p = 0.034	p = 0.004	p = 0.970	p = 0.441	p < 0.0001	p = 0.067	p < 0.0001

[a] Performance Requirements from 40 CFR Part 53 Subpart C, Table C-4.
[b] Non-parametric test of the null hypothesis that the population of the $\Delta_{PM2.5}$ Mu0 = 0 (Paired Instruments are not significantly different).

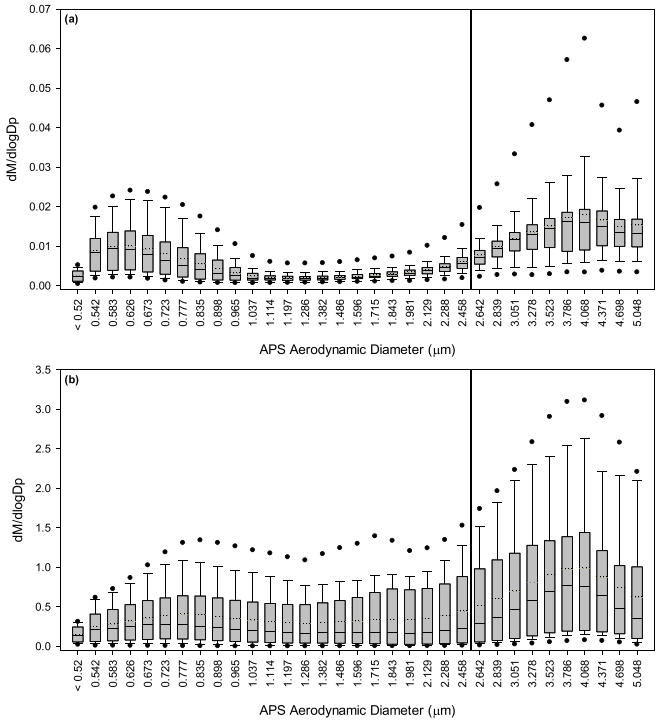


Fig. 2. Box and whisker plots of AIRS (a) and chamber burn (b) APS mean aerosol mass by aerodynamic diameter size bin.

and MiniVol (94.1 ± 5.0%) (Table 2). All five samplers achieved the slope target of 1 ± 0.05 and the r^2 target of >0.97, however none of the tested SFFFS could meet the EPA FRM criteria intercept target of 0 ± 1 μg m^{-3} likely due to the relatively extreme concentrations measured during chamber smoke testing. The overall SFFFS testing collocated precision in descending order was the N-FRM (1.4 ± 3.0%), LFR-6 (3.2 ± 3.3%), Omni FT (4.1 ± 4.5%), MiniVol (4.5 ± 5.4%), and LFR-6 URG variant (5.0 ± 11.2%) (Table 3). The LFR-6 led the way in terms of mean $\Delta_{PM2.5}$ and standard deviation of the mean $\Delta_{PM2.5}$ at 3.3 ± 11.3 μg m^{-3}. A non-parametric Wilcoxon Sign Rank test of the $\Delta_{PM2.5}$ indicated the LFR-6 URG variant ($p < 0.0001$), the N-FRM ($p = 0.034$), and the MiniVol ($p < 0.0001$) were significantly different (Table 3). The same analysis on the LFR-6 ($p = 0.067$), and the Omni ($p = 0.970$) indicated their $\Delta_{PM2.5}$ was not significantly different from the FRM. For the Omni, this is not an indicator of overall accuracy but rather this is driven by the precision being so noisy the test could not determine a difference. Given the abbreviated sampling time and the inability to guarantee uniformity of chamber particle distribution, the overall performance of each of these SFFFS compared to the Tisch FRM reference is relatively good with well-fit linear responses from r^2 = 0.9989–0.9998 (Table 3) and only the MiniVol failed to achieve an accuracy of greater than 95% in chamber testing. Consistent with the ambient results, chamber testing found the N-FRM to have the best accuracy and precision in the field, with the LFR-6 achieving the lowest mean $\Delta_{PM2.5}$. The performance of the ARA N-FRM and ARA LFR-6 samplers suggest they are both capable of providing acceptable and accurate $PM_{2.5}$ mass concentration measurements when deployed for use in high concentration wildfire smoke events.

3.3. Considerations and conclusions

Aerosol size distributions as measured by APS during ambient sampling were typically bimodal (Appendix Figures B.7.1 through B.7.27). Aerosol size distributions during chamber sampling were also typically bimodal with several burns showing a tri-modal aerosol mass distribution (Appendix Figures B.4.1 through B.4.30 and Figures B.5.1 through B.5.30). A significant portion of aerosol mass was regularly observed to have a mass median diameter of approximately 3.5 μm. It was hypothesized that a $PM_{2.5}$ fractionator with an effective Dp^{50} >2.5 μm or an aerosol penetration curve sharpness is significantly greater than the VSCC's value of 1.157 (Kenny and Thorpe, 2001) would result in systematic oversampling. A MANOVA analysis was performed on chamber data to determine the impact of aerosol concentration on the SFFFS in bins of D_a > 2.5–4.4 μm as measured by the APS. The Type III Sum of Squares results of this analysis are summarized in Appendix Table A.4 and indicate only the MiniVol has a statistically significant correlation for bins D_a = 2.642, 2.839, and 4.068 μm. For ambient sampling a Pearson correlation coefficient was determined between the ratio of $PM_{2.6\text{-}4.5}/PM_{2.5}$ and each instruments $\Delta_{PM2.5}$. No significance was found (Appendix Table A.4). It is possible that the various $PM_{2.5}$ fractionators used by the SFFFS in this study have an effective $Dp^{50} \neq 2.5$ μm and/or the penetration curve sharpness is significantly >1.157, a complete static fractionator test in accordance with 40 CFR Part 53 Subpart F SS53.64 (U.S. EPA, 2015) would need to be performed.

To be considered an FRM, a $PM_{2.5}$ sampler must meet both a design and performance specifications (Federal Register, 1997). Ultimately, none of the SFFF samplers in this study meet the minimum design requirements for designation as a FRM due to the filter cassettes being located external to the housing, thereby unable to guarantee the filter within ±5 °C of the ambient environment. With that said, during ambient testing at AIRS the N-FRM did achieve the performance requirements for slope, intercept, and r^2 (Table 3). However, during chamber testing where much higher concentrations than would typically be used for FRM certification were observed, the N-FRM intercept of −3.633 did not meet the intercept requirement of 0 ± 1. All the samplers in this study performed respectably in determining total $PM_{2.5}$ concentration in both ambient and smoke environments, but only the ARA N-FRM at 16.7 Lpm could achieve the EPA $PM_{2.5}$ FRM mass measurement accuracy performance target. Given additional testing in strict

accordance of FEM designation, there is potential that one or more of the samplers evaluated in this paper would meet the criteria for designation as an FEM.

Finally, with the growing impact of wildfire smoke on population centers in the United States, these samplers have shown their utility in providing scientifically and regulatory relevant $PM_{2.5}$ concentration data at lower cost and easier deployment than traditional FRM samplers. All samplers in this study have the capability of functioning off internal batteries, and several offer the addition of solar panel to extend the operational window while on battery. A future study investigating the operation of the samplers on battery power, with solar panel supplementation would be informative. All the samplers in this study are small and light enough that they could be carried in a backpack to more inaccessible locations, allowing for gravimetric sampling in locations that may be relevant to Wildland Firefighters.

CRediT authorship contribution statement

Jonathan Krug: Conceptualization, Investigation, lead author. **Russell Long:** Data collection, study planning. **Maribel Colón:** Gravimetric analysis lead, sample tracking. **Andrew Habel:** Instrument preparation and operation. **Shawn Urbanski:** Conceptualization, facilitation of experiments. **Matthew S. Landis:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2021.118718.

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