Investigate Woodsmoke and Interventions in an Exposure Chamber: A Tent Project

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2022

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Program Authorized to Offer Degree:

Department of Environmental and Occupational Health Sciences
School of Public Health

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Abstract

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Background: Particulate matter (PM)-related health effects have been studied extensively, yet wildfire smoke-specific PM health effects and its dose-response relationship have not reached a consensus due to variations in exposure scenarios and health outcome measurements. Additionally, researchers have not tested the wildfire smoke PM intervention strategies, especially HEPA (high-efficiency particulate air)-filter portable air cleaners (PACs) and HEPA-installed powered air-purifying respirators (PAPRs), for their particle removal efficiency and effectiveness in a laboratory setting.

Objectives: This research was dedicated to designing and engineering an exposure system that can be generalized, repeated, adjustable, and easily accessed by future controlled wildfire smoke human exposure studies. Woodsmoke particle size distribution and composition from different sources were investigated and we also tested woodsmoke particle removal efficiency and effectiveness of HEPA-filter PACs and the HEPA-installed PAPR system.

Methods: A total of 15 experimental trials were conducted to test and trial-run the exposure system with different sources of woodsmoke generation. Woodsmoke particles were introduced from the generation sources to the mixing chamber, and eventually to the exposure chamber where we monitored the particle concentrations and size distribution with low-cost and research-grade instruments. We assessed the woodsmoke particle composition using an aethalometer and monitored the CO and CO2 levels using a gas monitor. In addition, HEPA-filter PAC woodsmoke particle removal efficiency and HEPA-installed PAPR particle removal effectiveness were tested in two of the experimental trials, separately, with woodsmoke particles introduced into the exposure chamber.

Results: With time series on the particle mass and count concentration plots, we demonstrated the ability to relatively tightly control the woodsmoke particle concentrations (50 $\mu g/m^3$ and 90 $\mu g/m^3$) inside the exposure chamber with both wood pellet stove and cooking smoke guns as smoke generation sources. We also observed an overall higher particle count concentration from the wood pellet stove (around 700 particles greater than 0.3 μm per cc) than the cooking smoke gun (around 500 particles greater than 0.3 μm per cc) despite the target woodsmoke particle mass concentration from the cooking smoke gun trial being higher than the wood pellet stove trial. The wood pellet stove (around 5000 particles smaller than 0.3 μm per cc) also was believed to generate more smaller particles by count than the cooking smoke gun (around 2000 particles

smaller than 0.3 μm per cc) and the black carbon content was also higher in the wood pellet stove trial.

In terms of the particle removal efficiency and effectiveness from PM mitigation strategies, we discovered that regardless of the HEPA filter age, when PACs were turned on at the highest speed, both new and used HEPA filters removed woodsmoke particles effectively at similar efficiency. HEPA-installed PAPR system also reduced the woodsmoke particle concentration from around 50 $\mu g/m^3$ to close to 0 in less than 1 second.

Conclusions: The results further proved that with further refining and engineering of the exposure system, researchers would have the opportunity to standardize their wildfire smoke controlled human exposure study protocol and migrate to an exposure system that is similar to ours. Both HEPA-filter PAC and HEPA-installed PAPR systems are efficient and effective in woodsmoke particle removal to potentially improve indoor air quality and reduce occupational wildfire smoke exposure.

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ACKNOWLEDGEMENTS

With the unconditional guidance and support from Drs. Edmund Seto and Elena Austin, I have made my "zero to one" step in conducting air pollution research that would, one day, help the greater population. I sincerely appreciate every individual (Trina Sterry, Shirley Huang, Nancy Carmona, Chris Zuidema, Jeff Shirai, Tim Larson, Time Gould, Scott Meschke, Chris Simpson, Eddie Kasner, Karen Levy, Yona Sipos, Adam Drewnowski, Jennifer Doherty, Terry Kavanagh, Mike Yost, Marissa Baker, Helen Chu, and many more) for shaping and supporting me along the way to better myself, to grow to be someone who can offer help and support, and to stay humble and grounded. Two years of study was a glimpse of time, yet I was rewarded with more love, care, and support than I could ever ask for. I also am forever grateful to my family and friends for their understanding of my "workaholic" lifestyle and their encouragement for the pursuit of my dreams. My biggest aspiration is to help others and we always get better by lifting others. I said it three years ago during my undergraduate commencement and I am going to say the same thing years from now. With a strong support system that I cherish much, I am more confident than ever to continue my journey with endurance, foresight, strength, and skill, in exploration, study, research, and building hopes. And now I see with eye serene, the very pulse of the machine.

Chapter 1. INTRODUCTION

1.1 WILDFIRE SMOKE AND PARTICULATE MATTER

With the increased occurrence of wildland fires due to challenges of climate change and vegetation management, exposures to particulate matter (PM) air pollution from wood combustion has become a top public health concern in recent years (Gill et al., 2013). Populations experiencing traumatic episodes of wildfire suffer not only physical and mental health impacts from the smoke and heat, but also undergo economic and financial difficulties from the aftermath. During major wildfire events, large quantities of PM are released into the atmosphere due to biomass combustion and the PM jeopardizes both outdoor air quality, and through infiltration, indoor air quality.

Wildfire smoke events are increasingly recognized as a concern for the Pacific Northwest. In 2020 a major wildfire smoke event impacted Washington State, which was due to the migration of aged PM particles from fires in nearby states of Oregon and California (Liu et al., 2021). The smoke raised the Air Quality Index (AQI) for PM2.5 (particles with a diameter smaller than 2.5 μm) to the “very unhealthy” category. Despite public health guidance to seek shelter indoors, researchers also found considerable infiltration of outdoor particles into the residential indoor environment during the wildfire smoke episode, with the PM infiltration factors ranging from 0.3 to 0.8 (Xiang et al., 2021). The same research found that the use of portable air cleaners (PAC) has the potential to further reduce indoor particle concentrations.

1.2 Exposure Studies on Wildfire Smoke PM Health Outcomes

Along with many wildfire smoke hazards such as carbon oxides (CO and CO2), hydrocarbons (Vincente et al., 2013), volatile organic compounds (VOCs), and more depending on the combustion modes and mass burned, PM is the most significant substance for human health that is released during combustion. Coarse particles (those with diameters between 2.5 to 10 μm) pose human health impacts to a lesser extent and are less related to wildfire smoke than smaller particles. In contrast, fine particles, typically referred to as PM2.5 (particle diameter smaller than 2.5 μm, including ultrafine particles which have a diameter less than 0.1 μm), make up around 90% of the total particle by mass and are much more harmful to human health (Vincente et al., 2013).

Existing studies have investigated woodsmoke PM2.5 and its health impacts from controlled exposure experiments and epidemiological observations (Schwartz et al., 2020). Both acute and chronic negative health impacts were found to be correlated to different lengths of various concentrations of woodsmoke exposure. Respiratory and cardiovascular outcomes are prominent and have been found to be linked to exposure to wildfire smoke PM both in the short and long term. Asthma, acute bronchitis, exacerbated chronic obstructive pulmonary disease (COPD), cardiopulmonary symptoms, and congestive heart failure were shown to have increased relative risks due to acute exposures to wildfire events (Rappold et al., 2011; Rappold et al., 2012; Muala et al., 2015; Yao et al., 2020, Schwartz et al., 2020). Wildfire exposure's long-term health effects include respiratory and cardiovascular morbidities and mortalities (Rappold et al., 2012; Reid et al, 2016; Matz et al., 2020; Chen et al., 2021; Liu et al., 2015). In addition to the commonly observed cardiovascular and respiratory health effects, researchers also found exposure to wildfire smoke PM is associated with diabetes development (Yao et al., 2020) as well as neurodegenerative diseases like Alzheimer's disease (Schuller et al., 2020) and mental health conditions (Brown et al., 2019). Additionally, epidemiological studies on vulnerable population groups' health effects from wildfire PM exposures complemented the studies looking only at healthy adult populations. The pediatric group also bears the same respiratory health risks as their healthy adult counterparts and studies even found that younger children might be more affected than older pediatrics by wildfire PM (Leibel et al., 2019; Lipner et al., 2019; Aguilera et al., 2021). Wildfire exposure during pregnancy may also be linked with poor birth outcomes (Amjad et al., 2021; Heft-Neal et al., 2022; Park et al., 2021; Abdo et al., 2019).

Wildfire smoke particle spatial and temporal distributions also contribute unevenly to population health impacts. The spatiotemporal distribution of woodsmoke particles can vary greatly (Bartlein et al., 2007) depending on the time of the day or year (Bartlein et al., 2008), the geology and topology of the area (Robinson et al., 2007), diverse social factors that impact the degree of social vulnerability to wildfire (Paveglio et al., 2018), and meteorological conditions (Lu et al., 2013). Environmental and atmospheric scientists have used satellite imaging, GIS tools, data modeling, and prediction (Paveglio et al., 2018; Acevedo-cabra et al., 2014; Junghenn Noyes et al., 2020) to examine the heterogeneity in health effects in relation to the spatiotemporal distribution of wildfire smoke particles.

Ultimately, researchers have also been looking into the mechanism and toxicology of wildfire smoke PM exposure on negative health outcomes. The most noticeable outcome is respiratory-tract conditions like asthma and chronic obstructive pulmonary disease (COPD). Diagnostic approaches and markers like the fraction of exhaled nitric oxide (FeNO), cytokines, and enzymes from bronchoalveolar lavage, bronchial wash, and nasal lavage are the commonly used to assess and evaluate the respiratory outcomes from wildfire PM exposures (Barregard et al., 2006; Muala et al., 2015; Sehlstedt et al., 2010; Stockfelt et al., 2012; Ghio et al., 2012; Muala et al., 2015; Rebuli et al., 2019; Riddervold et al., 2012; Sehlstedt et al., 2010). Controlled human exposure study results suggested increases in FeNO markers, neutrophil counts, and lymphocytes following exposures to woodsmoke PM2.5. Systemic inflammations could be measured by biomarkers, for instance, serum hemoglobin, serum hematocrit, serum cell counts (platelets, neutrophils, lymphocytes, leukocytes, red blood cells), serum proteins, and serum cytokines, and various levels of changes in the markers were observed from human exposure studies (Ghio et al., 2012; Barregard et al., 2006; Stockfelt et al., 2012; Forchhmammer et al., 2012; Bønlønkke et al., 2014; Muala et al., 2015; Hunter et al., 2014). Oxidative stress biomarkers, such as serum uric acid and Trolox equivalent antioxidant capacity, 8-isoprostane, lipid hydroperoxides, 3-nitrotyrosine, myeloperoxidase, serum modified purines, malondialdehyde, glutathione, and related markers, along with cardiophysiology markers like heart rate variability, heart rate, blood pressure, arterial stiffness, forearm blood flow bradykinin infusion, ECG, and microvascular responsiveness index/microvascular function had different levels of changes from diverse woodsmoke PM exposure scenarios and doses (Ghio et al., 2012; Sehlstedt et al., 2010; Ferguson et al., 2016; Peters et al., 2018; Barregard et al., 2006; Murgia et al., 2016; Stockfelt et al., 2012; Forchhammer et al., 2012; Muala et al., 2015; Fedak et al., 2019; Pope et al., 2011; Forchhmammer et al., 2012; Bønlønkke et al., 2014; Unosson et al., 2013; Hunter et al., 2014).

1.3 Exposure Chamber and Intervention Strategy

To better investigate wildfire smoke PM on acute human health impacts, carefully designed and repeatable exposure settings are needed. Previous studies on controlled human exposure studies showed promising but varied findings on human health effects (Schwartz et al., 2020) due to inconsistency in woodsmoke exposure composition, concentrations, durations, and exposure doses during the exposure experiments. 10 studies (Ghio et al., 2012; Fedak et al., 2019; Sehlstedt et al., 2010; Pope et al., 2011; Ferguson et al., 2016; Barregard et al., 2006; Stockfelt et al., 2012; Riddervold et al., 2012; Unosson et al., 2013; Hunter et al., 2014) from Schwartz et al. were identified as crossover studies where researchers assigned participants to exposure scenarios in either random or sequential orders without repetition. As all 10 studies were conducted independently, the exposure scenarios varied greatly from each other. Study durations ranged from 1 to 3 hours with exercise components added in 6 studies. PM2.5 exposure types and concentrations also differed due to various types of fuel and combustion environments. Reported exposure concentrations varied from 46 to 500 $\mu g/m^3$ with particle characterization reporting different mixtures consisting of organic carbon, soot, and ash. Due to the variability of the exposure scenario, it is difficult to make generalizable conclusions about woodsmoke-specific toxicity in human cardiopulmonary and systemic effects. Yet the crossover studies provided advantages, as they assess within-person effects of exposure on measured health outcomes, identifying those that are associated with woodsmoke PM exposure rather than other potential confounding factors that are difficult to control for in non-crossover study designs. Therefore, a well-built, accessible, and replicable exposure system is in great need for researchers to conduct exposure studies with easy access anywhere, a reliable controlling system of woodsmoke generation, precise tuning of the system to ensure the health and safety of the study subjects, and most importantly, attested measurements of both exposure and health outcomes.

Despite the existing examinations of wildfire particle human exposures, controlled exposure studies using a chamber system and air treatment methods have not been thoroughly investigated. Previous studies investigated intervention studies to mitigate natural infiltration of wildfire smoke (Xiang et al., 2021) and indoor woodsmoke air pollution from cooking and heating (Noonan et al., 2007; Allen et al., 2009; Robinson, 2016; Bergauff et al., 2009), and all present mitigation strategies involve either PAC deployment or pollutant source elimination. Studies that analyzed PAC woodsmoke particle removal took place in residential settings without a uniform and/or controlled study design. The diverse factors in the indoor environment, for instance, temperature, relative humidity, woodsmoke generation sources, sampling chamber air exchange rate, and more dynamic factors from both ambient and human components, contribute to varying assessment results. Hence, testing PAC removal effectiveness for woodsmoke particles and other constituents in smoke such as VOCs and polycyclic aromatic hydrocarbons (PAHs) using a controllable and repeatable experimental system will produce complementary results to the prior observational research.

Unlike PACs and their effectiveness in cleaning particles, aerosols, and chemicals in indoor environments (Lee et al., 2021; Barn et al., 2016; Mobasser et al., 2022), personal protective equipment (PPE), such as powered air-purifying respirators (PAPR) has the potential to provide more protection from hazardous air pollutants in occupational settings (Licina et al., 2020; Chazelet et al., 2018; Sekoguchi et al., 2022). Different types of filters can be installed in PAPR to facilitate the removal of various air pollutants and high-efficiency particulate air (HEPA) filters are studied extensively and proved to be effective in removing at least 99.97% of airborne particles with a size of 0.3 µm (US EPA. n.d). However, wildfire smoke-specific PM removal using HEPA filter-installed PAPR has not yet been analyzed and controlled human intervention studies could fill the gap and provide more evidence for occupational as well as personal use of PAPR in future wildfire smoke events. A controlled exposure test environment may also facilitate comparisons of health effects with alternative PPE such as comparisons of PAPR with HEPA filter vs PAPR with particle and organic filtration (i.e., to identify the health effects specifically of the VOC components of woodsmoke), or comparisons of PAPR vs N95, KN95, or other non-powered, less effective strategies.

1.4 Wildfire Smoke Outdoor Worker Protection Rule Assessment

In addition to population-wide exposures to wildfire smoke, occupational exposures to wildfire and biomass smoke have also been found to pose health concerns for workers including wildland firefighters in the United States (Adetona et al., 2017). With the increase in wildfire events on the west coast states (California, Oregon, and Washington), state-level Occupational Safety and Health Administrations (OSHA) have released new rules to protect outdoor workers (excluding wildland firefighters) from excessive work-related woodsmoke exposure. Washington State Labor and Industries (WA L&I) released an emergency worker protection rule in July 2021 in response to the state-wide wildfire smoke and subsequently leased a more recent draft emergency rule in April 2022 to renew these policies.

Harry Bridges Center for Labor Studies at the University of Washington funded a qualitative research study at the Department of Environmental and Occupational Health Sciences. Although not the focus of this thesis research, the qualitative study used survey response and interview script analysis to assess stakeholder engagement in the 2021 emergency rule and provided useful context for the need to better study wildfire smoke health effects exposures and exposure reduction in occupational settings. Preliminary survey results (n=30) from age groups ranging from 18-65+ years and various racial and ethnic groups showed over three-quarters of participants were familiar with the rule and many participants indicated that they are worried about occupational exposure to wildfire smoke and general exposure for their friends and family. Interviewee stakeholders also stated that the 2021 emergency rule was protective of workers but needed more clear language and consistency on the action levels (> 20.5 $\mu g/m^3$ or Air Quality Index (AQI) of 69) among nearby states. Overall, both groups of participants had negative perceptions of wildfire smoke and work-related exposures and found the WA L&I emergency rules to be beneficial in protecting outdoor workers to a certain degree with room for improvement in future permanent rulemaking.

1.5 Significance and Aims

In 2020, Schwartz et al. performed a meta-analysis on 23 studies related to woodsmoke exposure health effects. Among all pieces of literature reviewed, 12 of them were controlled human exposure studies with variations in exposure durations (ranging from 1 to 4 hours) and exposure scenarios (woodsmoke generation modes) where 7 of the studies included exercise as a part of the research. Additionally, the PM mass concentrations during the exposure also varied greatly from 100 to 1000 $\mu g/m^3$. Differences in exposure dose, duration, type of particles that were generated, and inhalation dose based on variations in physical activity intensity all contribute to the variations in findings in woodsmoke health effects. Moreover, none of the controlled exposure studies from the meta-assessment or from any existing literature to our knowledge demonstrated the role of interventions such as PAC or PAPR use on woodsmoke particle removal effectiveness and efficiency.

Therefore, to address the inconsistencies in controlled human woodsmoke PM exposure studies and the knowledge gaps on PAC and PAPR mitigation on wildfire smoke PM, it was crucial to conduct a project to engineer a reliable and replicable system for future woodsmoke human exposure studies and to show the feasibility of using various interventions in woodsmoke particle removal. We conducted 15 experiments between November 2021 and May 2022 for exposure chamber characterization by using a wood pellet stove and cooking smoke guns as smoke generations sources and later tested HEPA filter PAC and HEPA-installed PAPR particle removal efficiency in four of all experiments:

- Trial 1: Smoke gun- HEPA filter air cleaner study (02/21/2022)
- Trial 2: Smoke gun- mixing bucket- tent study (04/09/2022)
- Trial 3: Wood pellet stove- mixing chamber- tent study (04/23/2022)
- Trial 4: Wood pellet stove- mixing chamber- tent (with PAPR) study (04/23/2022)
- Trial 5: Smoke gun- mixing chamber- tent sensor comparison study (04/29/2022)

Our study tested the working hypotheses that a well-engineered exposure chamber system would allow for dynamically control and maintenance of a woodsmoke particle concentration at the desired level, and that both the PAC and PAPR can be efficient and effective in woodsmoke particle removal inside the exposure chamber (or under the facepiece in the case of the PAPR). The study aimed to:

Aim 1: Design and build a particle concentration-controllable exposure chamber with alternative woodsmoke generation sources using a wood pellet stove and cooking smoke guns.

Aim 2: Assess the particle concentration and size distributions from both smoke generation methods using direct reading particle instruments.

Aim 3: Demonstrate the feasibility of testing intervention strategies with HEPA filter air cleaners and HEPA-installed PAPR in the exposure chamber.

Chapter 2. METHODS

2.1 EXPOSURE SYSTEM DESIGN

2.1.1 *System Overview*

Woodsmoke generation sources were a crucial component of the exposure system set-up. To best simulate wildfire smoke, the woodsmoke sources needed to be easy to collect/introduce to other study chambers, easy to control, and accessible. A more detailed discussion on exposure system design and intervention experimental trials is shown in sections 2.1.2 to 2.1.6 and 2.2.

The exposure chamber system contains three main parts: the smoke generation, the smoke reservoir/mixing chamber, and the exposure chamber. A wood pellet stove and cooking smoke guns were used to generate continuous and episodic woodsmoke particles, respectively. We employed gallon containers to temporarily store woodsmoke particles and to bridge the smoke sources and the exposure chamber. We also prioritized developing a woodsmoke exposure chamber that was rugged enough to withstand repeated use, had minimal leakage, and had inside dimensions large enough to allow for a later HEPA PAC and HEPA-installed PAPR intervention study. The system was also designed to be relatively cost-effective and portable to allow it to be moved to different sites and adapted to alternative particle smoke generation sources.

From woodsmoke generation to the mixing chamber to the exposure chamber, all three parts of the system were connected and linked together using galvanized metal ducting and venting and vinyl tubing (Fig 1). Additionally, when we used smoke guns as woodsmoke generation sources, we used a 500 ml syringe to transfer smoke particles from the mixing chamber to the exposure chamber (Fig 2).

All intervention studies involved only air treatment technologies like HEPA filter portable air cleaners and the HEPA-installed PAPR system. No human subjects were recruited to be inside the exposure chamber.

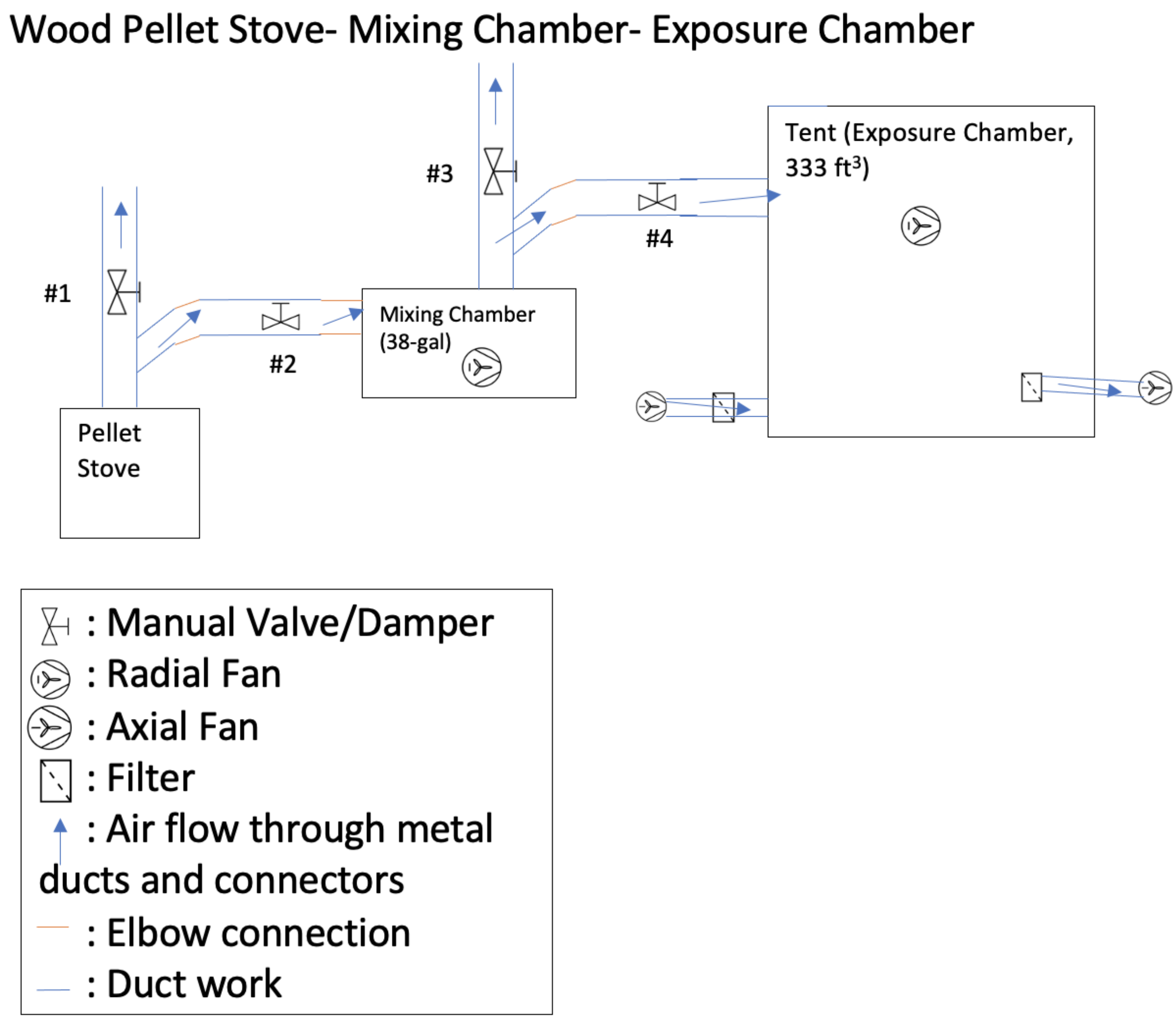

Figure 1. Wood pellet stove-mixing chamber-exposure chamber system engineering diagram. (Wood pellet stove chimney: 4”; wood pellet stove exhaust: 4”x 5’; wood pellet stove wye connector: 4”; wood pellet stove damper 1: 4”; wood pellet stove elbow: 4”; wood pellet stove connecting duct: 4”x 5’; damper 2: 4”; mixing chamber elbow: 4”; mixing chamber duct: 6”; mixing chamber wye connector: 6”; mixing chamber exhaust: 6”x 6’; mixing chamber damper 3: 6”; mixing chamber connecting tubing 6”; damper 4: 6”; inline fans for input/output air: 4”; filter window register: 12”*20”)

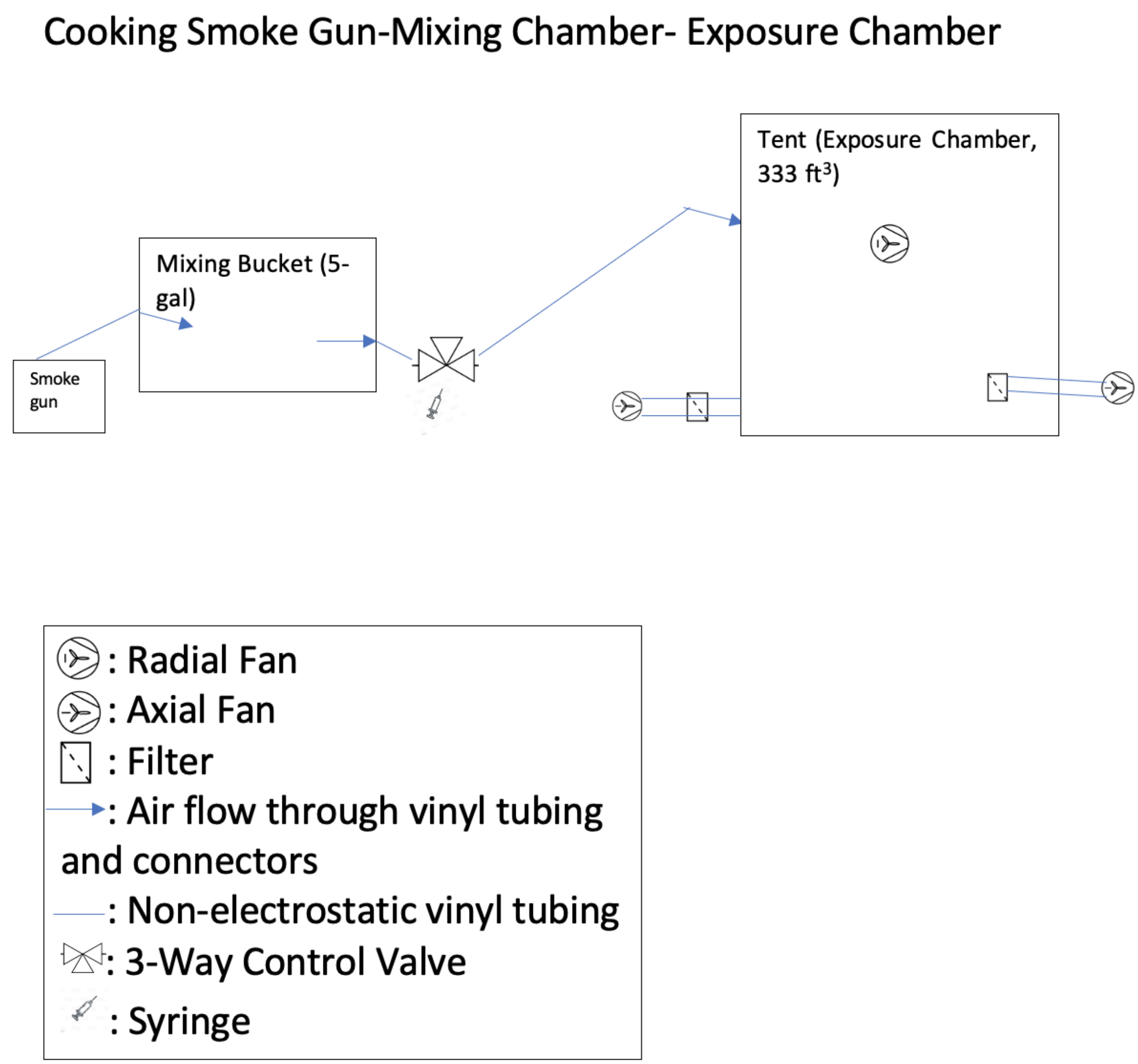

Figure 2. Cooking smoke gun-mixing chamber-exposure chamber system engineering diagram. (Non-electrostatic vinyl tubing: ⅜” OD, ¼” ID; inline fans for input/output air: 4”; filter window register: 12” *20”)

2.1.2 *Woodsmoke Generation Sources*

Both the wood pellet stove and cooking smoke guns were used to generate different types of woodsmoke scenarios. The wood pellet stove gave us the opportunity to generate and introduce continuous woodsmoke to the mixing and exposure chambers whereas cooking smoke guns were used to create episodic woodsmoke as needed. One difference between the two woodsmoke generation methods was the different generated woodsmoke types. The wood pellet stove used the temperature-controlled direct combustion system and burned larger pieces of wood pellets to produce warm smoke at as low as 160°F, and the cooking smoke guns used the direct flame from a handheld butane lighter to ignite finer woodchips and produce cold smoke. Both woodsmoke generation equipment could use a variety of types of biomass and we used hickory wood pellets for the wood pellet stove and hickory and applewood woodchips for the cooking smoke guns.

2.1.2.1 Wood Pellet Stove

A commercially available wood pellet stove (Camp Chef PG24MZG) was employed to produce continual woodsmoke. Pit Boss Hickory 20-lb Wood Pellets were used to generate smoke particles and refilled each time before the start of the experiments. To initiate the combustion, we set the temperature to be 165° F and the smoke level at 1, which was the lowest smoke level. Through its built-in proportional-integral-derivative (PID) automated temperature control, the stove attempts to maintain steady heat and smoke concentrations using an electric auger that adds pellets to the stove's burn box, and an electric fan that introduces air to the combustion. When a lower temperature is detected, the stove brings it back to its set point. This can result in periodic productions of large amounts of smoke due to low-temperature incomplete combustion. Nonetheless, during its non-adjusting period, the stove produced continuous smoke for continuous woodsmoke particle introduction to the mixing and exposure chambers. The stove took around 6 minutes to warm up and around 5 minutes to cool down each time at the beginning and the end of an experiment.

One piece of Y-shaped metal ductwork was connected to the stove chimney with one branch of the Y directing smoke particles to the mixing chamber (section 2.1.3) and the other branch serving as exhaust with a mechanical damper (Fig 1. Damper 1) built downstream for controllable exhaust. Additionally, when the mechanical damper 1 was fully closed, woodsmoke particles would be all directed to the mixing chamber due to less resistance from the generation-mixing chamber route. When mechanical damper 1 was fully open, the majority of warm smoke particles would rise, and exhaust and minimal smoke would flow to the mixing chamber.

2.1.2.2 Cooking Smoke Gun

Two battery-powered cooking smoke guns were selected and employed for episodic woodsmoke generation. Breville PolyScience Breville Gun Pro Smoke Infuser and NezActive Cocktail Smoker were both used for experimental trials as woodsmoke sources. Both smoke guns had a built-in fan system to propel smoke particles to the outlet, which was connected with a flexible silicone tube and nozzle for easy flow direction. At a higher price, the Breville smoke gun gave more options on fan speed adjustment. Applewood and hickory wood fine woodchips were used in combustion scenarios and each combustion cycle took approximately 0.1 g of woodchips to produce sufficient smoke particles targeting at desired exposure chamber woodsmoke concentration at 50 $\mu g/m^3$. A handheld butane lighter was used to ignite the combustion and Weigh Gram digital pocket scale was used to weigh woodchips for smoke generation. From particle mass concentration direct-reading result, we saw an increase in the concentration with an increase in the mass of woodchips during combustion. However, we did not conduct any trial to determine the relationship between the amount of woodchip used and the particle mass concentration achieved.

Unlike the wood pellet stove, the cooking smoke gun had a flexible tube that easily pointed the smoke particle to the desired mixing chamber and the gun's built-in fan would push the particles to the outlet rubber tube instead of relying on the ambient environment to help with the flow. No damper or control parts were used for the cooking smoke gun, and we depended solely on the fan switch to power on and off the equipment.

2.1.3 *Mixing Chamber*

Two mixing chambers were designed and built to pair up with different smoke generation methods. For continuous woodsmoke generation and flow from the wood pellet stove, a 38-gallon heavy-duty storage container with a removable lid was used to reserve and mix woodsmoke particles. The mixing in the large container helped in dampening the variations in smoke produced by the stove. Two pieces of metal ducts were connected to the mixing chamber where one piece bridged between the wood pellet stove and the mixing chamber with a mechanical damper (Fig 1. Damper 2) constructed upstream of the mixing chamber to manage the woodsmoke flow. When damper 2 was fully open, woodsmoke would flow into the mixing chamber and when it was fully closed, smoke particles would be blocked. The other piece of the metal duct was also Y-shaped with one branch directing woodsmoke to the exposure chamber and the other branch, with a built-in mechanical damper (Fig 1. Damper 3). to adjust the exhaust. Since the heavy-duty container was large, we placed a computer fan inside to provide better mixing and dilution before introducing the woodsmoke to the exposure chamber. When damper 3 was fully open, more woodsmoke would exhaust due to its warmer temperature and fewer particles would flow to the exposure chamber. When damper 3 was fully closed, smoke particles would be redirected to a lower resistance area which was the exposure chamber.

Another smaller mixing chamber was used exclusively for woodsmoke generation from the cooking smoke gun. We used a 5-gallon empty paint bucket with a removable lid to withhold the smoke once the cooking smoke gun pushed the smoke into the bucket. We did not build damper systems in the smoke gun woodsmoke generation experiments as the 500 ml syringe worked to extract smoke from the mixing bucket and inject the woodsmoke into the exposure chamber. However, vinyl tubing was used to connect the mixing bucket and syringe for better control of smoke transfer.

We also used a 3-way valve (Fig 2) for one experiment with the cooking smoke gun for woodsmoke generation. With the help of the syringe, which provided a controlled method to introduce woodsmoke to the exposure, this smoke generation scenario would produce episodic woodsmoke flow to target a desired concentration in the exposure chamber. When using a syringe to extract and inject smoke into the exposure chamber, we needed to connect and disconnect the syringe with the mixing chamber outlet vinyl port. This caused woodsmoke particles to escape from the mixing chamber and would require us to refill the chamber more frequently. A 3-way valve acted as a connector to bridge the vinyl tubing coming from the mixing chamber and the exposure chamber and would provide a more uninterrupted system for woodsmoke introduction using the syringe. The valve was easily removable from the exposure system when not needed. The 3-way valve was built downstream of the mixing bucket and upstream of the exposure chamber with vinyl tubes connecting all parts. When the valve was shut on the valve-exposure chamber end, we could extract the woodsmoke from the mixing chamber to the syringe and would pump the smoke to the exposure chamber when the valve was shut on the mixing bucket-valve end. When the 3-way valve was removed from the system, the syringe-alone system also worked for introducing woodsmoke periodically as needed.

2.1.4 *Exposure Chamber*

A 333.33 ft^3 mylar-lined grow tent (120 inches* 80 inches* 60 inches) from VIVOSUN with zipper seals was set up and used as the exposure chamber. (Fig 3) A standing radial fan was placed in the center of the tent to help with homogenizing the existing air with the incoming woodsmoke. A standing foldable table was placed next to the front zipper and was used to hold the monitoring instruments and intervention systems when needed.

For the wood pellet stove-mixing chamber-exposure chamber system, the metal ductwork connected the mixing chamber and the tent, with a mechanical damper (Fig 1. Damper 4) built between for incoming woodsmoke flow adjustment. Since damper 4 was engineered in a one-way duct, the woodsmoke traveling direction could be dictated by the opening and closing of the damper itself.

For the cooking smoke gun-mixing chamber-exposure chamber system, the syringe was the only mechanical force that drove the woodsmoke from the mixing chamber to the tent. The tent was zipped open and closed temporarily to allow woodsmoke injection. Due to the lower woodsmoke concentration inside the exposure chamber, woodsmoke particles injected into the exposure chamber would diffuse naturally down the concentration gradient and the loss through the opening of the exposure chamber was negligible.

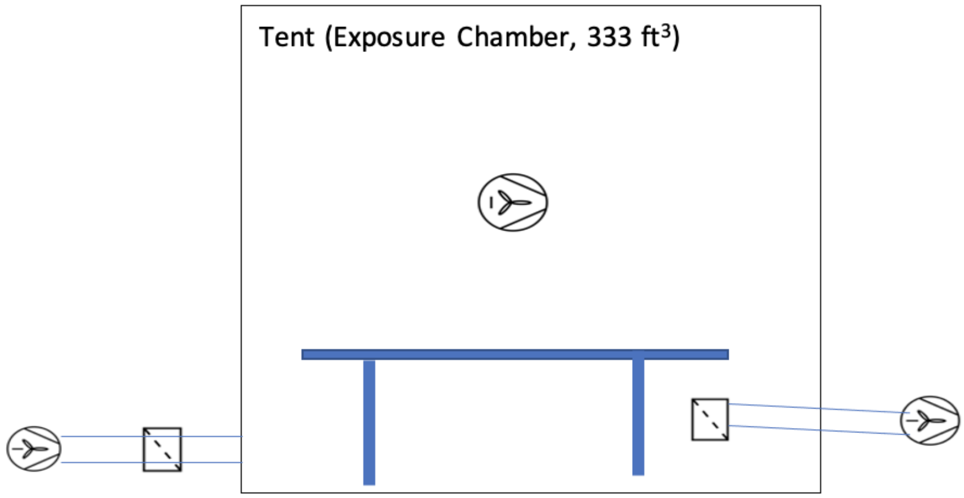

Figure 3. Exposure chamber interior design diagram. A standing fan (radial fan depicted here) was placed behind the foldable table and the table was placed right next to the exposure tent zip opening. Inlet and outlet fan systems as well as MERV 13 filters were shown in the diagram.

2.1.4.1 Inlet and Outlet Fan Systems

The exposure chamber was also engineered with two fan systems from AC Infinity CLOUDLINE T4 with each one rated by the manufacturer with a maximum airflow of 205 CFM: the inlet for fresh air and the outlet for the exhaust. Each fan system was equipped with a 12"x20"x1" MERV 13 filter from Filterbuy to make sure the incoming fresh air through the inlet and the exhaust air via the outlet fans were filtered. Additionally, each fan system had adjustable fan speeds from 1 to 10 where 10 was the highest flow. By tuning the fan speed on the inlet and outlet fans, we were able to control the woodsmoke concentration inside the exposure chamber in addition to adjustments of the upstream dampers. When both fans were turned on, more freshly filtered air would be introduced into the tent and dilute the woodsmoke and the outlet fan would exhaust the high woodsmoke concentration when needed. Additionally, the inlet fan also worked as a method to maintain safe levels of CO_2 and CO as the gas particles would also be diluted when fresh air mixed with the existing air inside the exposure chamber.

2.1.5 *Particle Monitoring Instruments*

Four instruments were used to monitor and record the woodsmoke particles during various experimental trials. Two relatively low-cost particle monitors, modified Dylos DC1700 and Met One AEROCET 531, and a lab-grade instrument TSI 3330 Optical Particle Sensor were used to assess the count and mass concentrations from woodsmoke particles that were greater than 0.1 μm in diameter. Another lab-grade monitor TSI 3910 Nanoparticle Sizer was also used to supplement the experiment results with woodsmoke particle size distributions for particles that were smaller than 0.1 μm in diameter.

Dylos DC1700 was modified by the manufacturer to our specifications with the additional capability to export the direct reading results to laptops with a serial cable, and 4 size bins. Dylos DC1700 Air Quality monitor used a laser to sample four types of PM particles PM0.5, PM1, PM2.5, and PM10 to provide count concentrations per cubic foot (ft^3), every ten seconds. Dylos device has a non-conventional particle categorization tactic where the bin size that is named PM0.5 includes anything with a diameter of 0.5 μm or greater and the same convention for the rest of the particle categories. Therefore, for visualizing one type of particle count concentration, we subtract the desired particle type from the particle type that was one size greater. Due to its limited sensitivity, we could not capture particles with diameters that were smaller than 0.5 μm.

Another low-cost PM sensor was used to measure particle mass concentration. AEROCET 531 from Met One Instruments is a battery-operated, handheld, optical sensor that samples PM1, PM2.5, PM7, PM10, and Total Suspended Particles (TSP) at a two-minute interval. The underlying operating principle of the AEROCET 531 is optical particle count with particle sizing, but it has the option to estimate mass concentration from those particle counts. We recorded through serial cable on laptops for particle concentrations in mg/m^3, with a 0.001 mg/m^3 precision, and later converted the mass concentrations to μg/m^3 for better comparison between the lab-grade TSI 3330.

TSI 3330 Optical Particle Sizer was used to record woodsmoke particles with diameters ranging from 0.3 to 10 μm. This instrument produced recorded particle count concentrations and estimates of real-time mass concentration readings. With the help of the instruction manual, we were able to convert recorded particle count concentrations to mass concentrations as needed. In TSI 3330 Aerosol Instrument Manager Software Manual Appendix C. Calculations Used for OPS Spectrometers, particle number and particle volume were the factors that impacted the particle mass concentration statistic calculation (Eq 1.) TSI 3330, as a particle counter, provided us with particle number concentrations for each size bin. According to the equations provided in the manual, size bin-specific particle number concentrations were converted to particle volume concentrations. This calculation was carried out for all individual size channels defined by the upper and lower bounds and not the entire size range of the instruments. We used the instrument's default particle density of 1 g/cm^3 for all sized particles to calculate the estimated mass concentration. For PM2.5, we summed up all individual mass concentrations from channels for particles between 0.3-2.5 μm diameters.

$$m = \rho v$$

Equation 1. Particle mass concentration using TSI 3330 Aerosol Instrument Manager Software manual. ρ is particle density in g/cm^3 and particle volume (v, cm^3) is calculated using $v = \pi D^3_{pv} n/6$, and D^3_{pv} is the volume-weighted diameter of a particle; D_{pv} is further calculated by $D_{pv} = LB[¼\,(1+(UB/LB)^2 *(1+(UB/LB))]^{⅓}$; LB and UB stand for channel lower boundary and upper boundary; Particle number (n) is defined as $n = (c/tQ)\Phi$ where c is the particle counts per channel, t stands for sample time, Q is the flow rate, and Φ is the dilution factor.

Moreover, TSI 3330 provided us with a more frequent sampling rate every 1 second and better accuracy as well as precision. With a faster sampling rate, we would be able to observe changes in particle concentrations in real-time and we were able to adjust the mechanical dampers and inlet and outlet fan systems to regulate the number of particles that stayed inside the exposure chamber.

TSI 3910 Nanoparticle Sizer was used to measure the concentration of woodsmoke particles with diameters ranging from 11.5 to 365.2 nm and both direct-reading results and recorded data from the instruments were particle count concentrations. In the total range of measured particles, when using the data from the TSI 3910 and smaller-sized channels in TSI 3330, we were able to capture particles with diameter sizes from 11.5 nm to 10 µm. TSI 3910 size profiling scanned particles for distribution at a slower rate of one scan every 1 minute.

2.1.6 *Black Carbon Instruments*

AETHLABS microAeth/AE51 was used to monitor black carbon concentrations from woodsmoke generated from trials 2 and 3. AE51 sampled particles every 1 second and recorded data in ng/m^3. The amount of black carbon generated using different woodsmoke combustion methods could potentially provide more information on the relative amount of black carbon (measured by the AE51) to overall PM (measured by the other particle instruments) in the woodsmoke particles produced from different combustion scenarios.

2.1.7 *CO and CO2 Instruments*

TSI Q-Trak Indoor Air Quality Monitor 7575 was used to monitor CO and CO2 concentrations inside the exposure chamber. One of the intentions for future use of the exposure system is to perform wildfire smoke-specific health outcome measurements in human subjects, thus, it is crucial to ensure the safety requirements were met. The device is a battery-powered, handheld, indoor air quality sensor that provides users with CO2 (ppm), CO (ppm), temperature (°F), and relative humidity (%) every 1 second. Both direct reading and recorded data were easily accessible. The Q-Trak was calibrated by the UW DEOHS Field Group before use in tent experiments.

2.2 EXPERIMENT DESIGN

We performed 15 experiments in total to design, engineer, and test the exposure chamber system, as well as to evaluate intervention studies. Among all trials, 5 representative experiments were selected for demonstration. Trial 1 was the smoke gun- HEPA filter air cleaner study

(02/21/2022) where we tested the HEPA filter air cleaner efficiency in woodsmoke particle removal. Trial 2 tested the smoke gun- mixing bucket- tent system (04/09/2022) for exposure chamber evaluation. Trial 3 was similar to trial 2 but we used the wood pellet stove to generate woodsmoke (04/23/2022). Trial 4 was mainly testing the HEPA-installed PAPR system using the wood pellet stove- mixing chamber- tent (04/23/2022). Lastly, trial 5 used the smoke gun- mixing chamber- tent with all particle sensors for low-cost vs. lab-grade sensor performance comparison (04/29/2022).

Both intervention studies (trials 1 and 4) took place inside the exposure chamber with varied smoke generation sources. The goal of the intervention experiments was to evaluate the air treatment woodsmoke particle removal effectiveness and efficiency.

2.2.1 *Exposure System Particle Concentration Control*

Once all three parts of the exposure system were connected and set up, we experimented with woodsmoke introduction into the exposure chamber with different woodsmoke generation methods and dynamically controlled the concentrations inside the exposure chamber. Concentration controls for both smoke generations differed as the setups varied.

For the approach with the wood pellet stove during trial 3, we used TSI 3330 and relied on its real-time particle mass concentration to read and adjust the woodsmoke introduction into the exposure chamber. The wood pellet stove was turned on at 160°F with smoke level 1. At the beginning of the experiment, we set dampers 1 to be fully closed, damper 2 ⅓ open, and damper 3 fully open, while the inlet fan was off and outlet fan was at speed of 5. When we observed an increase in particle concentration from TSI 3330, we dialed down the damper settings to have more woodsmoke go to the exhaust and less travel to the exposure chamber. Damper 1 was fully open, dampers 2 and 3 and outlet fan remained the same, and the inlet fan was turned on to a speed of 5. When woodsmoke concentration started to decrease, we turned down the inlet fan to introduce less fresh air for less dilution inside the exposure chamber, and when the concentration approached the desired level at around 50 $\mu g/m^3$, damper 1 was ⅔ open, damper 2 was changed to ½ open, and inlet fan was turned off. We then opened damper 1 to ½ when the concentration declined to around 25 $\mu g/m^3$, but to prevent overshoot, the inlet fan was also turned on to a speed of 1. From then, we were able to control the concentration fluctuation between 40 and 55 $\mu g/m^3$ by turning on the inlet fan to a speed of 1 when concentration was high and turning the fan off when concentration was low while maintaining the other damper and fan settings constant. To conclude the experiment, we kept the damper settings constant and turned both inlet and outlet fans to the maximum speed of 10 and the wood pellet was turned off. A caveat to note was when we introduced smoke into the tent and kept damper 4 closed, we still observed an increase in woodsmoke concentration inside the exposure chamber. This indicated that damper 4 was leaky. However, we did not change the degree of opening on damper 4 and relied on its leakiness throughout the experiment for woodsmoke particle introduction. A more detailed illustration of this control system can be found in Figure 4.

During experiment trial 2, we used the cooking smoke gun as the woodsmoke generation method. Cooking smoke gun combustion produced periodic woodsmoke where we injected the smoke particles directly into the mixing chamber as frequently as needed. Once the mixing chamber was filled with woodsmoke, we used the syringe to extract the smoke once at a time and injected the smoke directly into the exposure chamber as described previously. We were able to determine the timing and numbers of syringes to target the desired concentration at about 90 μg/m^3. A detailed description of the controlling of woodsmoke particle concentration inside the exposure chamber using this setup is illustrated in Figure 5.

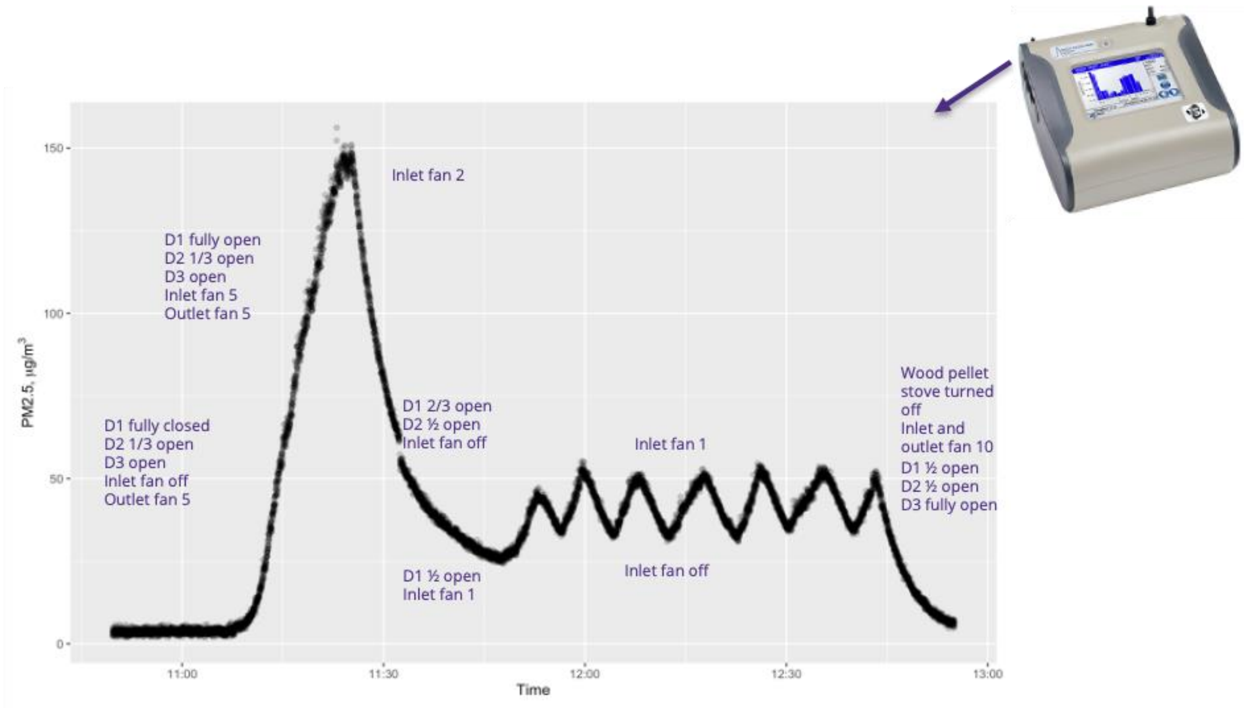

Figure 4. Wood pellet stove-mixing chamber-exposure chamber woodsmoke concentration control using TSI 3330 particle mass concentration reading. D1, D2, D3 stand for damper 1, damper 2, damper 3. Damper 4 was not depicted here as we did not change its setting during the experiment.

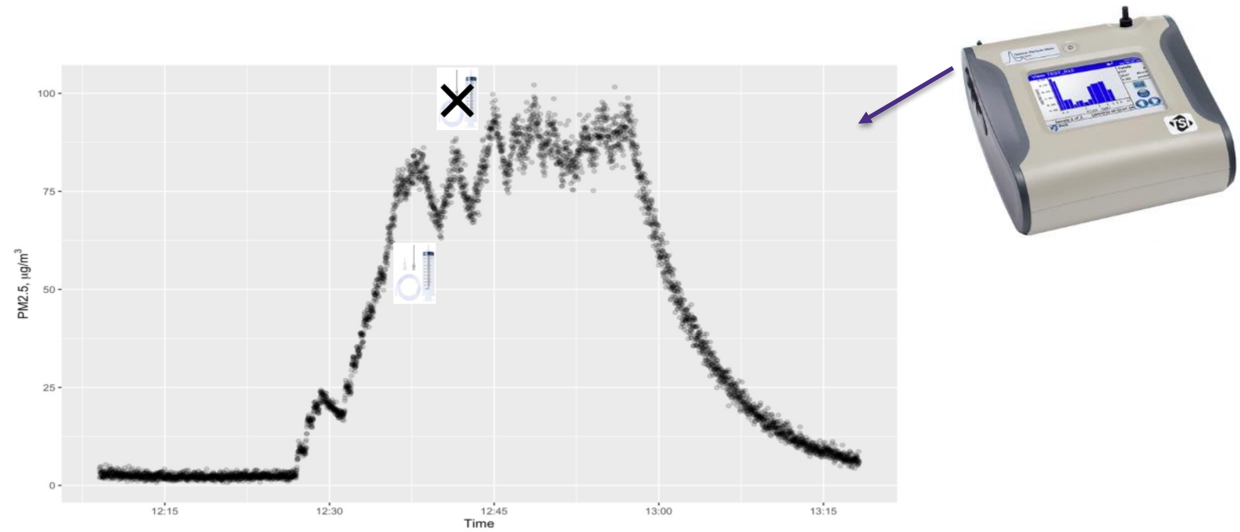

Figure 5. Cooking smoke gun-mixing chamber-exposure chamber woodsmoke concentration control using TSI 3330 particle mass concentration reading. When particle concentration was below 75 µg/m^3, smoke was injected into the exposure chamber using the syringe. When concentration reached the desired level at around 90 µg/m^3, syringe injection was stopped.

2.2.2 *HEPA-Filter Air Cleaner Intervention*

The University of Washington (UW) deployed over 2,000 portable HEPA-filter air cleaners to be used in classrooms and public shared spaces on campus in response to the in-person instruction amid the COVID-19 pandemic. Due to the feature of particle removal, we decided to borrow two HEPA air filter PACs from UW Facilities (UWF) and evaluate their effectiveness in removing woodsmoke particles that mimicked wildfire smoke in addition to viral particle removal. UWF generously loaned two Field Controls Trio Plus portable air purifiers with H13 HEPA filters. H13 HEPA filters installed in two air purifiers had service lengths of 0 and 5-month, respectively.

To compare the fan speeds on woodsmoke particle removal efficiency, we placed the used and new PACs inside the exposure chamber and introduced woodsmoke using the cooking smoke gun. The inlet and outlet inline fans and filters on the exposure chamber were removed for this intervention study so that the main decay in particle concentrations would be from the operation of the PAC in the chamber. In our experiment, purifiers were set to auto mode and manual mode at the highest fan speed in sequential order with the first two trials using the used PAC and the last two trials with the new PAC. When the particle mass concentration was around 200 $\mu g/m^3$, PAC was turned on and then turned off when the concentration reduced to below 10 $\mu g/m^3$. When the air purifiers were set to auto mode, the PM sensor integrated into the PAC measured PM concentration and adjusted the fan speed automatically on a scale of 1-5 where, according to the manufacturer specification sheet, 1 is the lowest fan speed with a CFM of 52 ft^3/min, and 5 is the highest with a CFM of 370 ft^3/min. We performed 5 trials where the second trial was deemed invalid due to an unknown filter fan speed setting and the data was excluded for later analysis.

To monitor and record the data, we used both modified Dylos DC1700 and Met One AEROCET 531 with serial cables. Particle count concentration in #/ft^3 and mass concentration in mg/m^3 were captured by sensors for later time series and decay analysis. Decay parameters could be calculated from the data from Dylos. However, the true decay of the HEPA filter air cleaner is shown in a rearranged calculation (Eq 2.) derived from Xiang et al.

$$dC_{in}(t)/dt= (AER+k_d+k_{PAC})*C_{in}(t)$$

Equation 2. True HEPA filter air cleaner particle removal decay calculation. $C_{in}(t)$ is the indoor PM2.5 level at time t, which in trial 1, $C_{in}(t)$ was the concentration from cooking smoke gun woodsmoke introduction. AER is the air exchange rate (h^{-1}); k_d is the rate constant for PM2.5 deposition to indoor surfaces (h^{-1}); k_{PAC} is the indoor PM2.5 decay rate from air cleaner filtration (h^{-1}).

2.2.3 *HEPA-Installed PAPR Intervention*

For this intervention trial, we used the TR-600-ECK Versaflo Easy Clean PAPR kit from 3M. This HEPA-installed PAPR system is a battery-powered, portable, and personal protective equipment intended to use for personal air pollutant removal. Its effectiveness of woodsmoke particle removal was assessed during one of the exposure tent experiments. No one was in the chamber wearing the PAPR in this experiment. Instead, we sampled outside vs. under the facepiece of the PAPR in the stream of filtered air to determine the effect of the PAPR on particle concentration.

First, we introduced woodsmoke particles from the wood pellet stove to the heavy-duty mixing chamber and eventually to the exposure tent. With the adjustment and tuning from mechanical dampers 1, 2, and 3, and inlet and outlet fan systems, we maintained a woodsmoke concentration of approximately 50 $\mu g/m^3$. Before the introduction of PAPR in the exposure system, the inlet fan was at speed of 3, and the outlet fan was set to a speed of 5 and remained at 5 throughout the experiment. Dampers 1 and 2 were half open and damper 3 was fully open. Damper 4 was closed but based on our observation, it had some inherent leakiness and allowed woodsmoke particles to diffuse into the exposure chamber. However, we did not change the opening on damper 4 for all our experiments.

When the woodsmoke concentration reached around 50 μg/m^3 inside the exposure chamber, we turned off the inlet fan so the air inside would not be diluted. HEPA-installed PAPR was then turned on at the lowest speed and we sampled the air under the PAPR facepiece with the TSI 3330 and TSI 3910. Once the filtered particle concentration went below 10 μg/m^3, which matched the ambient concentration, we turned off the PAPR and concluded the trial.

2.3 Data Analysis

All data analysis and plotting were performed in R version 4.0.2 and the scripts are uploaded to GitHub Repository.

2.3.1 *Time Series*

Time series analyses were plotted for TSI 3330, TSI 3910, modified Dylos DC1700, and Met One AEROCET 531. Thanks to Dr. Edmund Seto, time series analysis R scripts for all four instruments were available and we were able to use the script for our experimental datasets after each experiment. Datasets from TSI 3330 and TSI 3910 for trials 2, 3, 4, and 5 and from the modified Dylos and Met One dataset for trials 1 and 5 were analyzed. Uncalibrated and calibrated Dylos and MetOne time series were also plotted based on the linear relationships between the low-cost instruments and TSI 3330. Dylos data was calibrated based on the TSI 3330 particle count concentration and MetOne's was calibrated by TSI 3330 particle mass concentration. CO and CO2 concentrations were also plotted using an additional experimental trial from a similar experimental setup. Black carbon data was read in using the R script provided by Dr. Edmund Seto. Since AE51 used an aethalometer to measure black carbon, the result itself was impacted by the amount of particle that was loaded on the filter and the amount of light that could be transmitted through. Raw black carbon data was noisy, and we used an optimized noise-reduction algorithm (ONA) developed by the US Environmental Protection Agency (US EPA) to maximize the time solution of the black carbon results.

2.3.2 *Particle Size Distribution*

Particle count distributions were assessed from datasets generated by TSI 3330 and TSI 3910 for before, during, and after experiment trials. We analyzed the size distributions for trials 2 and 3 to compare the differences between particles generated by the cooking smoke gun and the wood pellet stove. Additionally, for each trial, we also plotted the before, during, and end of the experiment particle size distributions to compare the differences in the particle sizes at various stages of the experiment. For trial 2 (04/09/2022), we selected 12:15:00 PM, 12:50:00 PM, and 13:15:00 PM for 3 stages from TSI 3330 data, 12:15:56 PM, 12:40:56 PM, and 13:07:57 PM from TSI 3910. For trial 3 (04/23/2022), we chose 11:00:00 AM, 12:05:00 PM, and 12:55:00 AM from TSI 3330 dataset, 11:00:58 AM, 12:17:58 PM, and 12:52:58 PM for different stages of the TSI 3910 measurements. One thing to note here is that for trial 3, TSI 3910 sampling ended prematurely and the last data point at 12:53:58 PM was invalid.

2.3.3 *Correlation Analysis*

Linear regression was performed for Dylos vs. TSI 3330 particle count concentration and MetOne vs. TSI 3330 particle mass concentration, respectively. Particle count concentration readings were converted to particle counts per cc and particle mass concentrations were converted to μg/m^3. Pearson's correlation was computed for Dylos vs. TSI 3330 data. Linear correlation coefficients from both regression analyses were used in low-cost instrument data calibration. Four more time series plots for both log-transformed calibrated and uncalibrated Dylos vs. TSI 3330 and MetOne vs. TSI 3330 were also drafted for easier visualization of the low-cost vs. lab-grade instrument performance correlations.

Additionally, to assess the particle counters performances from Dylos DC17000 and TSI 3330, we analyzed the decay curve using data from both instruments and generated a decay model for the actual vs. theoretical decay curve. The decay was assessed using the uncalibrated Dylos DC1700 data. Decay parameters helped us to quantify the performance differences between the low-cost and research-grade particle counters.

2.3.4 *Real-Time Time Series Reading Using R*

Dr. Edmund Seto connected Dylos DC1700 and MetOne AEROCET 531 through serial cables and TSI 3330 through an ethernet cable to laptops. Dr. Seto then formulated R scripts for 3 instruments to generate real-time particle mass concentration time series plots from the instruments for easier visualization and woodsmoke concentration control. R scripts for 3 instruments' real-time plots are uploaded to the shared DEOHS Microsoft Team channel for DEOHS-affiliated use.

2.3.5 *Decay Analysis*

Particle decays were assessed for both the HEPA filter PAC and the exposure tent itself. We did not evaluate the decay of the HEPA-installed PAPR system for woodsmoke particle removal since the PAPR system removed woodsmoke particles instantaneously and we intended to evaluate the effectiveness of HEPA-installed PAPR in providing clean air instead of removing the woodsmoke particles inside the exposure chamber.

2.3.5.1 Exposure Chamber Intrinsic Decay

Thanks to the current Ph.D. student at UW Department of Environmental and Occupational Health Sciences Shirley Huang and her unconditional help and support, we were able to retrieve the data from her previous projects involving the exposure tent and artificial woodsmoke introduction with the cooking smoke gun. TSI 3330 Optical Particle Sizer mass concentration data from Shirley's HEPA air cleaner smoke decay experiment from January 25, 2022, was used and the second plateau at 11:20-11:28 AM PDT, where she introduced the smoke particle with the cooking smoke gun and waited before turning on the HEPA air cleaner at sleep mode, was fitted for a decay curve. A particle mass concentration time series plot was also made to illustrate the varying particle concentrations during the entire experiment.

2.3.5.2 HEPA-Filter Air Cleaner Particle Removal

Data from the modified Dylos DC1700 dataset from trial 1 was used to evaluate particle decay for all four experiment settings, sequentially: used filter at auto fan speed, used filter at highest fan speed, new filter at auto fan speed, and new filter at highest fan speed. One thing to note was the initial woodsmoke particle concentrations inside the exposure chambers were not tightly regulated for two reasons: first, we were not able to weigh a precise amount of woodchips for the cooking smoke gun combustion, and the environmental condition affected each burn differently; secondly, controlling the woodsmoke concentration was not of our concern as HEPA-filter air cleaners would theoretically have a constant decay parameter regardless of variations in their initial air pollutant concentrations.

2.3.6 *Black Carbon to PM2.5 Ratio Analysis*

ONA method was used to smooth the black carbon data file to reduce noise and negative values. Time series plots on black carbon were generated for trials 2 and 3. Two trials used different smoke generation methods and had different target concentrations. Trial 2 used the cooking smoke gun to generate woodsmoke particles and was targeting a mass concentration of approximately 90 μg/m^3, whereas trial 3 generated woodsmoke from the wood pellet stove and controlled particle concentration at approximately 50 μg/m^3. Therefore, we calculated the black carbon to PM2.5 ratio using the smoothed black carbon and TSI 3330 PM2.5 mass concentration during the experiment.

For trial 2, we picked the black carbon (734.5 ng/m^3) and PM2.5 (69.7 μg/m^3) data from 04/09/2022 at 12:40:00 PM, and for trial 3, we picked the black carbon (1150.2 ng/m^3) and PM2.5 (41.7 μg/m^3) data from 04/23/2022 at 12:15:00 PM. Both ratios were calculated using Equation 3. By calculating ratios from black carbon to PM2.5, we would be able to account for the difference in target woodsmoke particle concentrations and make assumptions about particle composition differences from various woodsmoke generation methods.

$$\text{Black carbon to PM2.5 ratio} = \text{Black carbon } (ng/m^3) / \text{ PM2.5 } (\mu g/m^3)$$

Equation 3. Black carbon (ng/m^3) to PM2.5 (μg/m^3) ratio calculation. Black carbon was derived from ONA smoothed data from AE51 and PM2.5 was from TSI 3330.

Chapter 3. RESULTS

3.1 Time Series

Time series plots from Trials 2, 3, 4, and 5 demonstrated several findings. First of all, once the smoke generation sources started combusting wood products and introducing the woodsmoke particles, the exposure chamber, where we sampled the woodsmoke particle level, would be able to hold the concentration (Figs 6, 10, and 11.). Second, from trials 2, 3, 4, and 5 at around 12:35 PM, 11:45 AM, 15:10 PM, and 13:47 PM, respectively, we observed the regulated fluctuation of particle mass concentrations captured by TSI 3330. By comparing our experimental notes with the results here, we found that the peaks in each oscillation period represented the times we purposefully held the concentration to the higher end of our desired concentration ranges, and the bottoms of each fluctuation period were the times when we adjusted the exposure system to intentionally decrease the woodsmoke concentration to the lower end of our desired concentration ranges. Moreover, we noticed that the TSI 3910 nanoparticle time series plots (Fig 7.) were noisier than the TSI 3330 particle counter and the plots from TSI 3910 did not show clear oscillation patterns like TSI 3330s'. This could be due to the reason that woodsmoke combustions from both the wood pellet stove and cooking smoke guns were partially insufficient burns which produced more larger particles than nanoparticles. Also, the coarser temporal resolution of the 1-minute TSI 3910 scans potentially masked some of the temporal variations more clearly observed in the 1-second TSI 3330 data. Lastly, from panels A, B, and D (Fig 7.), the nanoparticle count concentrations did not decrease to be similar to the ambient environment level.

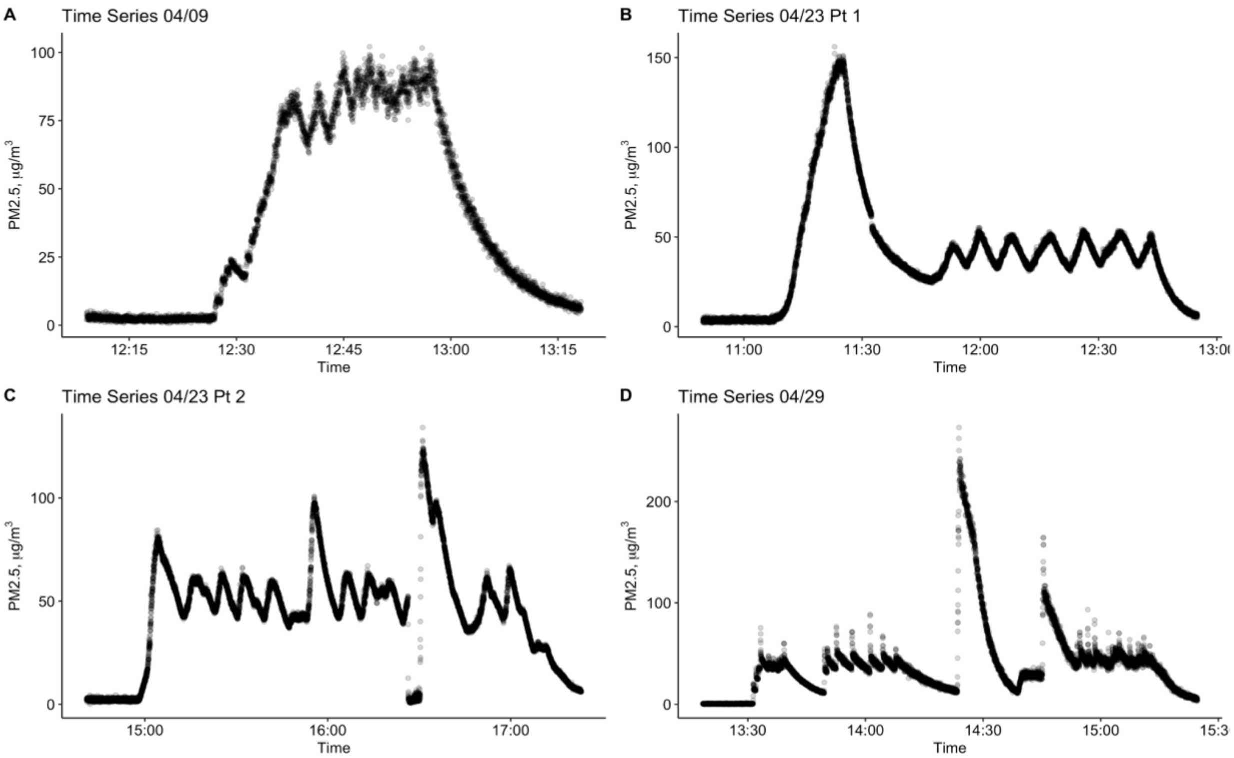

Figure 6. Fine woodsmoke particle mass concentrations (µg/m^3) time series plots from TSI 3330 measurements. Trial 2 had a target concentration of 100 µg/m^3; Trial 3 had a target concentration of 50 µg/m^3; Trial 4 had a target concentration of 50 µg/m^3; Trial 2 had a target concentration of 50 µg/m^3. (Plot A: trial 2; Plot B: trial 3; Plot C: trial 4; Plot D: trial 5)

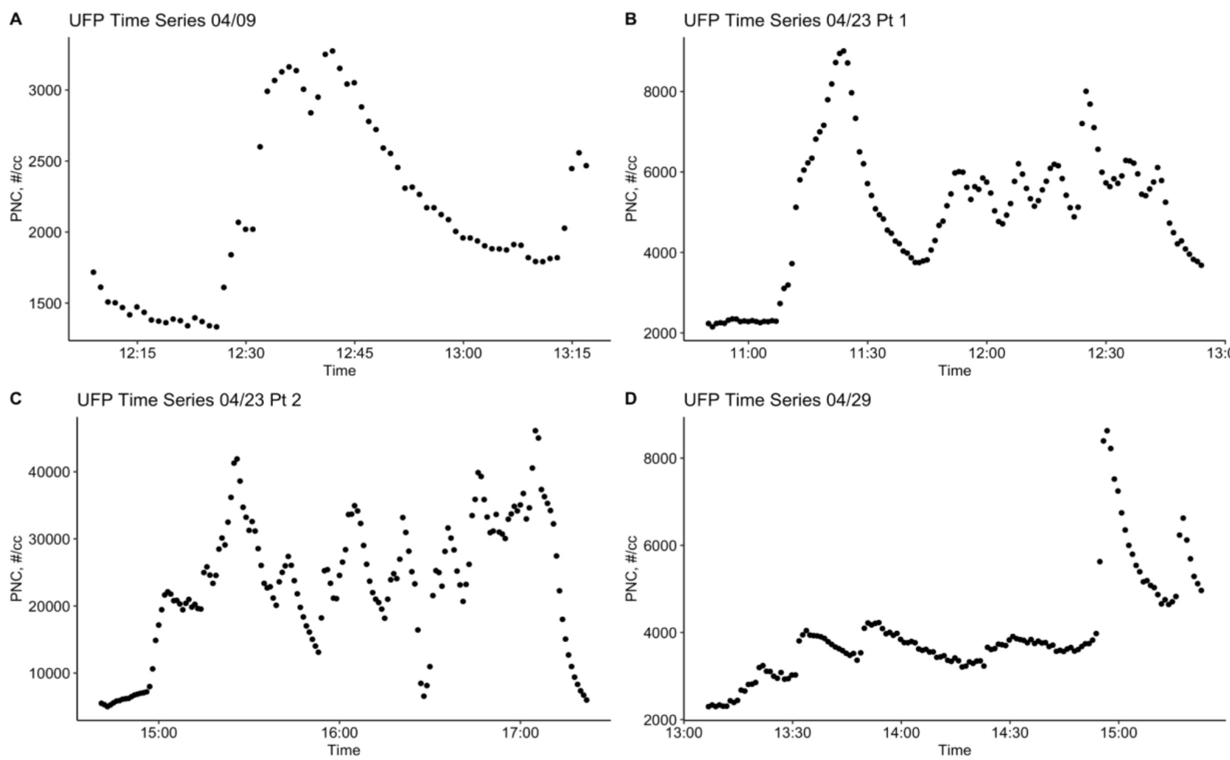

Figure 7. Ultrafine woodsmoke particle count concentrations (total particle #/cc) time series plots from TSI 3910 measurements. Trial 2 had a target concentration of 100 μg/m^3; Trial 3 had a target concentration of 50 μg/m^3; Trial 4 had a target concentration of 50 μg/m^3; Trial 2 had a target concentration of 50 μg/m^3; Ultrafine particle (UFP). (Plot A: trial 2; Plot B: trial 3; Plot C: trial 4; Plot D: trial 5)

From HEPA filter PAC air treatment and HEPA-installed PAPR intervention experiments (trials 1 and 4), we would be able to see declines in particle count and mass concentrations (Fig 8; Fig 6. Plot C). For the HEPA filter PAC intervention experiment, all four channels of Dylos DC1700 (Fig 8) captured the declines of particle mass concentrations in number per ft^3 at approximately 15:35 PM, 16:15 PM (invalid trial), 16:45 PM, 17:15 PM, and 17:55 PM. The same timestamps of woodsmoke particle mass concentrations also showed up on the MetOne AEROCET 531 time series (Fig 9). These times matched up with our experiment note where we recorded the time of turning on the HEPA filter air cleaners. From the time series plots, we observed that the HEPA filter air cleaners were able to remove PM0.5 to PM10 woodsmoke particles from concentrations as high as $1*10^7$ per ft^3 to as low as less than 10 particles per ft^3. MetOne AEROCET 531 also recorded particle mass concentrations with particle sizes ranging from PM1 to PM10 were reduced from 1250 $\mu g/m^3$ to less than 10 $\mu g/m^3$. The reductions in particle concentrations registered from both instruments showed that HEPA filter air cleaners successfully removed woodsmoke particles with diameters from 0.5 μm to 10 μm regardless of the fan speeds of air cleaners or the service lengths of installed HEPA filters.

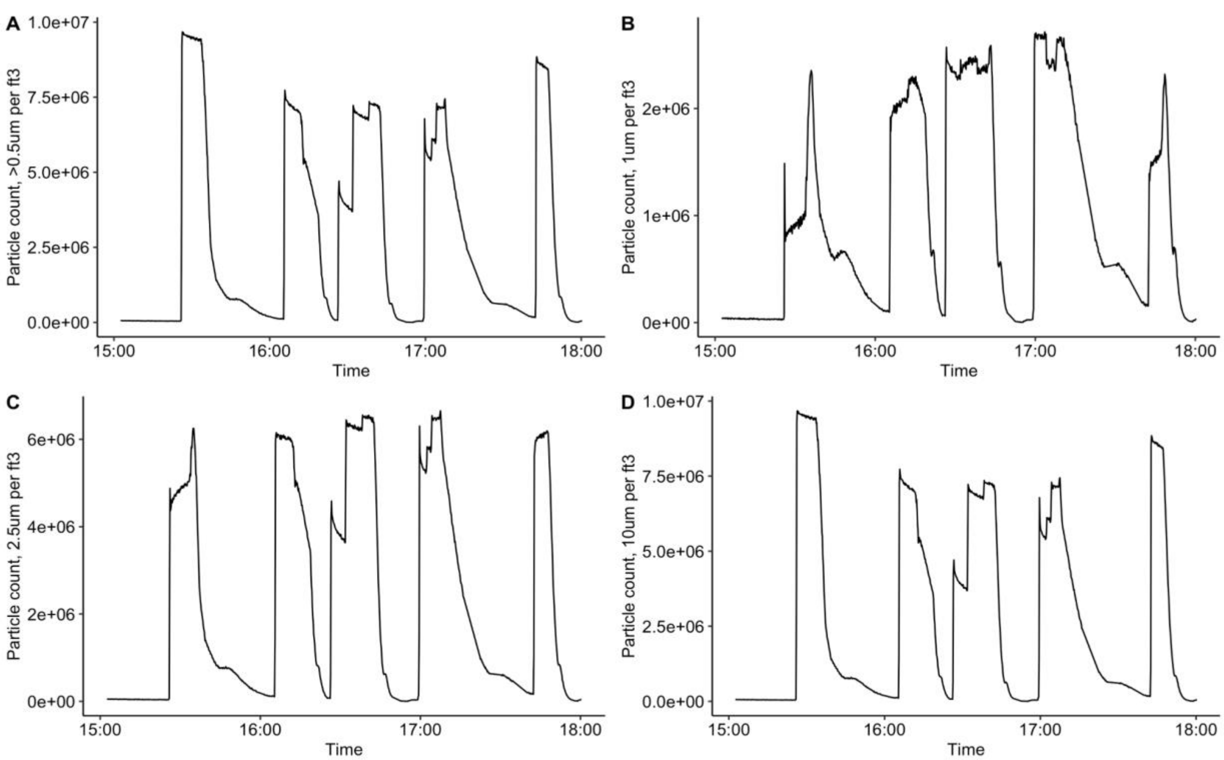

Figure 8. Woodsmoke particle count concentration (particle count #/ft^3) time series plots from Dylos DC1700 measurements from trial 1. (Plot A: particle size> 0.5μm; Plot B: PM1; Plot C: PM2.5; Plot D: PM10)

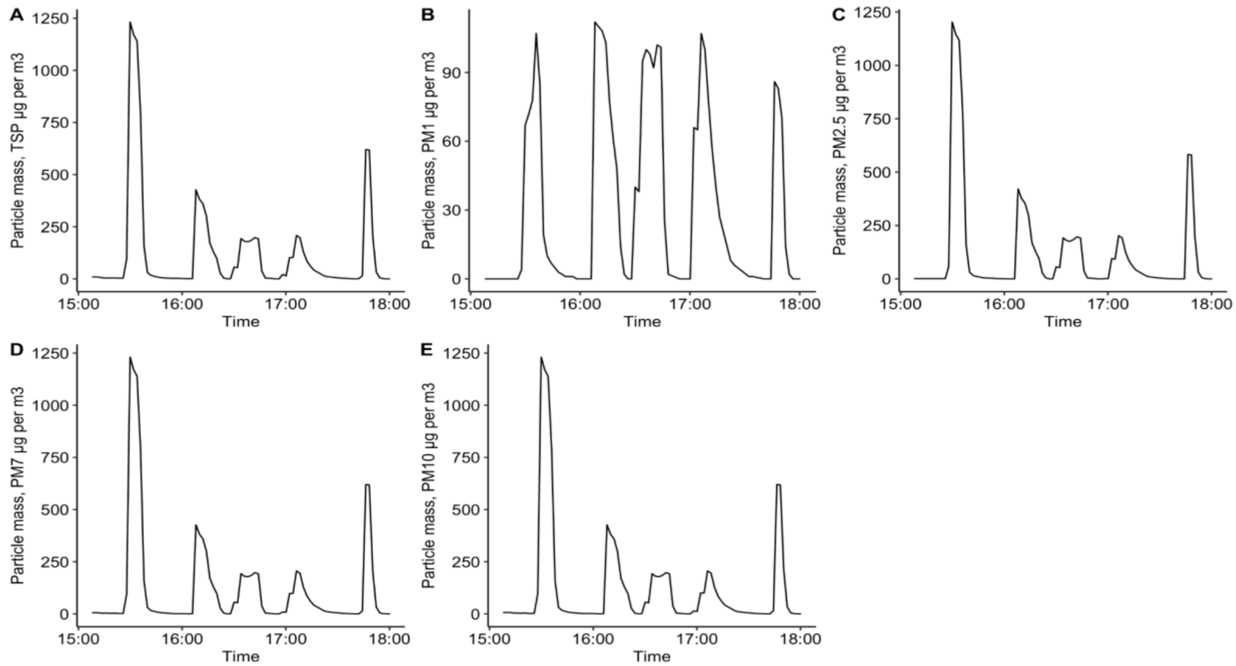

Figure 9. Woodsmoke particle mass concentration (µg/m^3) time series plots from MetOne AEROCET 531 from trial 1. (Plot A: total suspended particle (TSP); Plot B: PM1; Plot C: PM2.5; Plot D: PM7; Plot E: PM10)

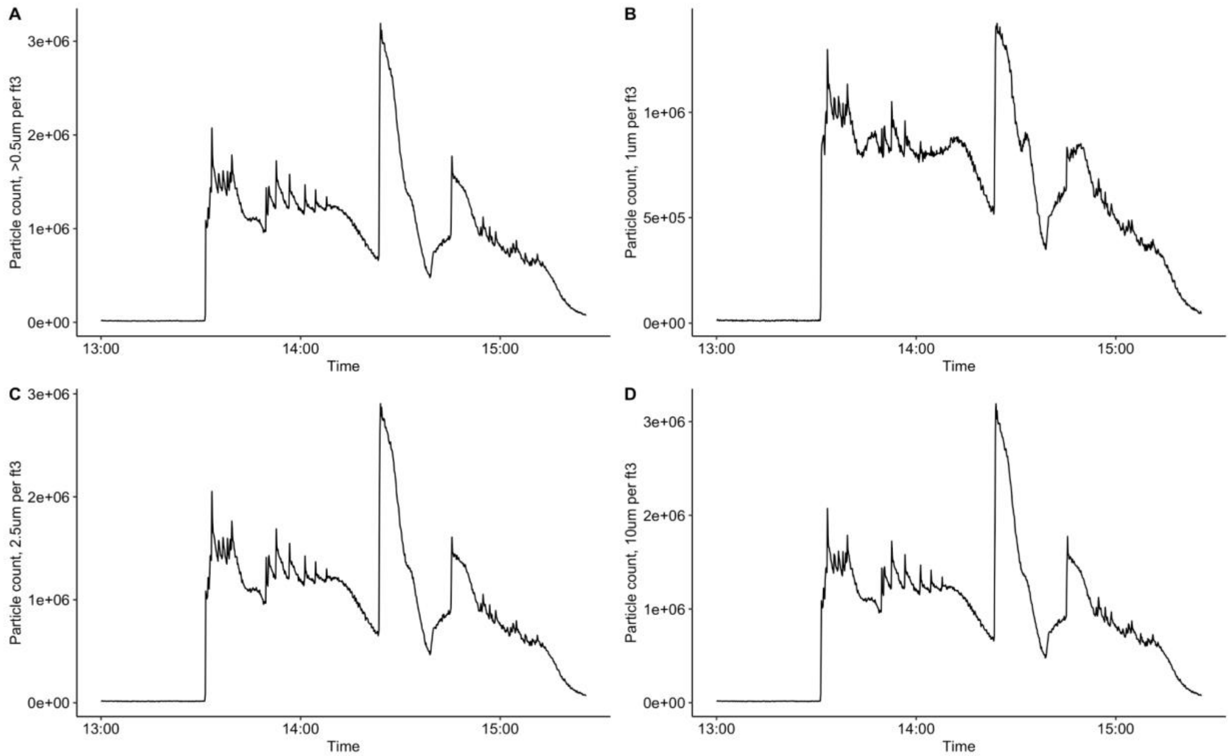

Figure 10. Woodsmoke particle count concentration (particle count #/ft^3) time series plots from Dylos DC1700 measurements from trial 5. (Plot A: particle size> 0.5μm; Plot B: PM1; Plot C: PM2.5; Plot D: PM10)

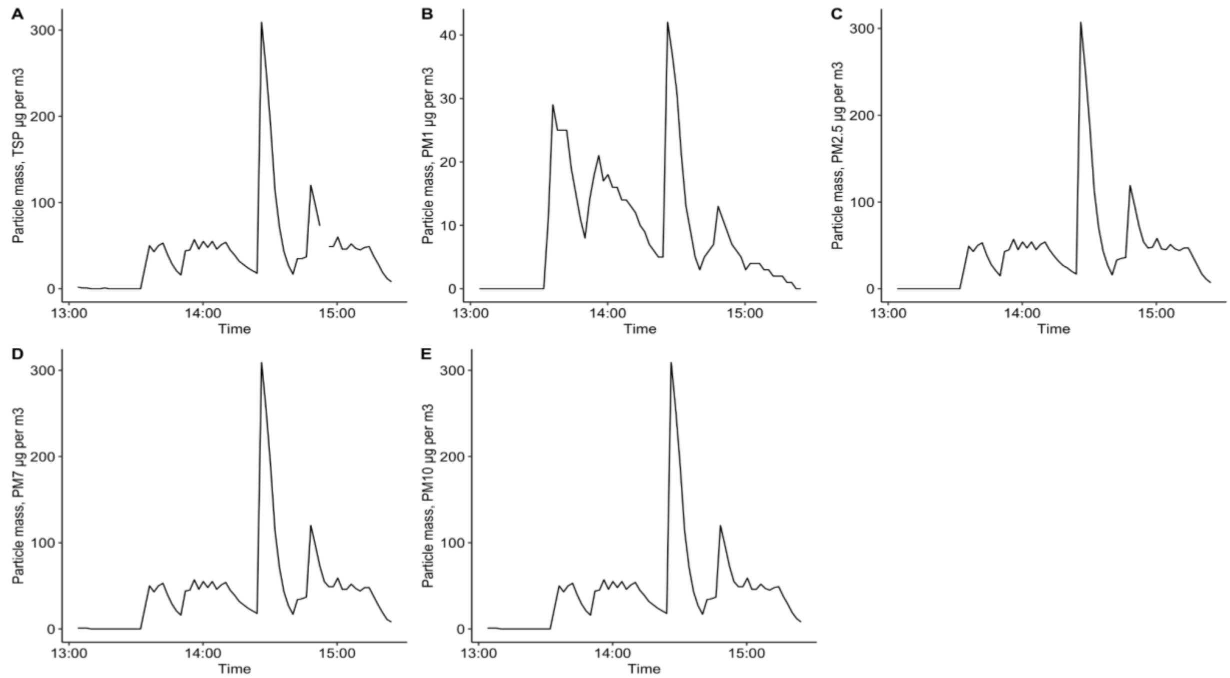

Figure 11. Woodsmoke particle mass concentration (µg/m^3) time series plots from MetOne AEROCET 531 from trial 5. (Plot A: total suspended particle (TSP); Plot B: PM1; Plot C: PM2.5; Plot D: PM7; Plot E: PM10)

3.2 Particle Size Distribution

Trials 2 and 3 were both conducted using the entire exposure system with alterations in the mixing chamber selection based on the woodsmoke generation methods. From TSI 3330 particle size distribution plots, we observed an overall increase in particle concentrations in all sizes during the experiment where we started the woodsmoke introduction (Fig 12. B and E) and lower particle concentrations before (Fig 12. A and D) and after (Fig 12. C and F) the woodsmoke introduction. From TSI 3910 plots, we saw a shift or a dual-peak phenomenon during the experiment (Fig 13. B and E) where the smaller particle concentration decreased, and large particles showed up after smoke introduction into the exposure chamber.

Moreover, we noticed that the woodsmoke particle size distributions were different when the smoke generation methods differed. During trials 2, our target woodsmoke concentration was 90 $\mu g/m^3$ and 50 $\mu g/m^3$ for trial 3. Theoretically, the particle size distributions for all size ranges should be similar. However, we detected around two folds higher concentrations of particles with diameters greater than 0.3 μm when the woodsmoke particles were generated from wood pellet stove combustion (Fig 12. B and E). On UFP plots (Fig 13. B and E), particle size distribution also showed a higher overall concentration from trial 3 with the wood pellet stove despite the target overall mass concentration of trial 2 with the cooking smoke gun being higher. The bi-modal phenomena were seen from both plots (Fig 13. B and E) where particle sizes shifted from smaller to larger when woodsmoke particles got introduced into the exposure chamber.

Lastly, we saw similar peaks of 27.4 and 36.5 nm size bins at high particle concentrations for even the environment before the experiment (Fig 13. A and E). The peaks for same size bins showed similar patterns but higher concentrations at the end of the experiment (Fig 13. C and F). Two possible reasons could lead to these peaks of before and end of the experiment in particle count concentrations. One explanation was that both datasets from TSI 3910 finished sampling prematurely, and we might not wait long enough for the overall particle concentrations to decrease to the background level. Another possibility was that the attached leaky damper 4 unintentionally introduced particles from ambient environment into the exposure chamber and the sampling instruments measured the unfiltered ambient particle concentrations instead of the filtered air inside the exposure chamber. In the latter case, the “before” concentrations could serve as a baseline and later analysis for “during” and “end” of the experiment would subtract the “before” to reflect the true introduced particle concentrations.

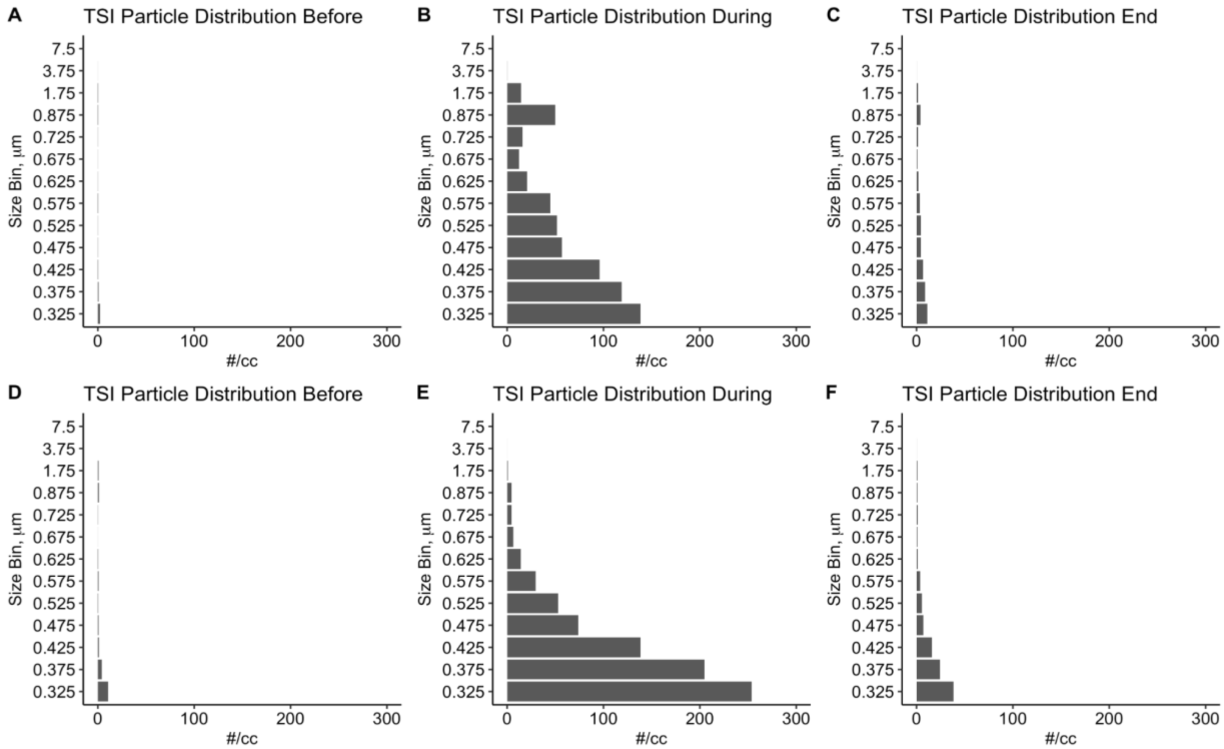

Figure 12. Woodsmoke particle size distributions from trial 2 (plots A, B, C) and trial 3 (plots D, E, F) ranged from 0.3-2.5μm from TSI 3330 Optical Particle Sizer.

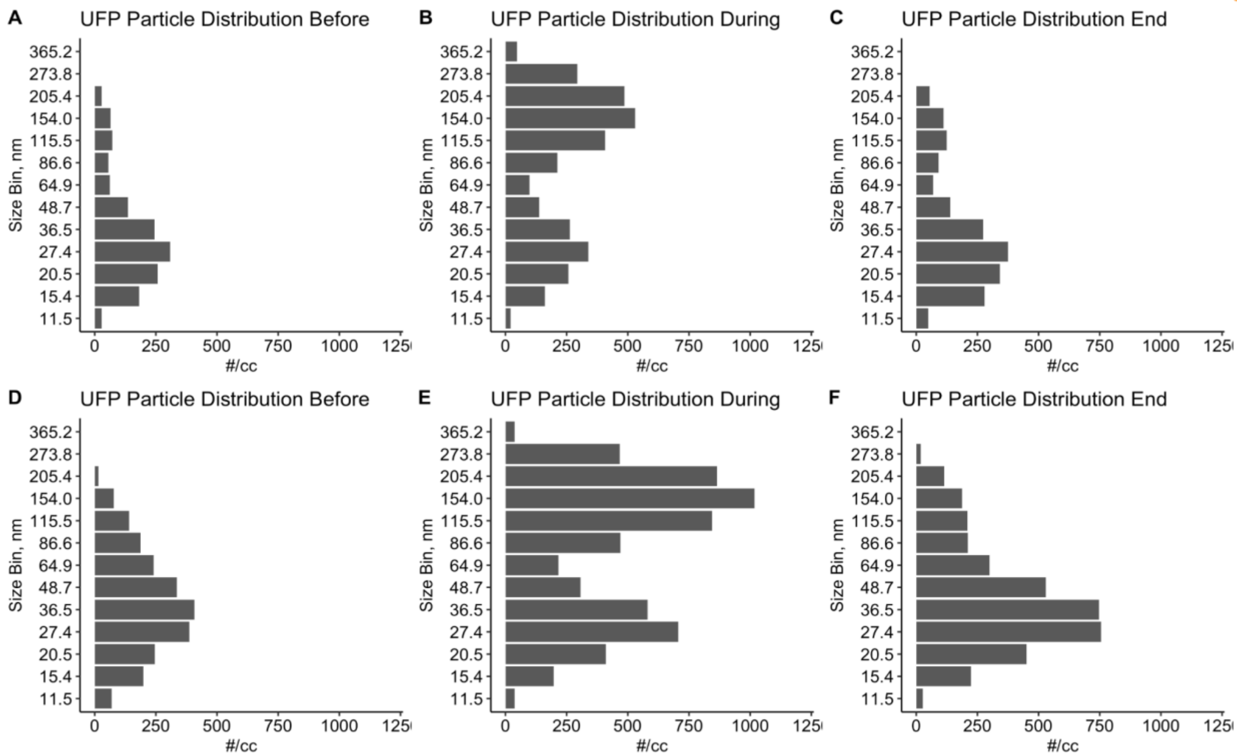

Figure 13. Woodsmoke particle size distributions from trial 2 (plots A, B, C) and trial 3 (plots D, E, F) ranged from 11.5-365.2 nm from TSI 3910 Nanoparticle Scanner.

3.3 Woodsmoke Particle Composition

ONA smoothed black carbon data time series from trials 2 and 3 showed a clear concentration difference between two woodsmoke generation methods. Trial 2 with the cooking smoke gun (Fig 14. Plot A) produced less black carbon in mass concentration (less than 1000 ng/m^3) than trial 3 (around 3500 nm/m^3) with the wood pellet stove (Fig 14. Plot B) despite trial 2 had a higher target woodsmoke particle concentration at 90 µg/m^3 compared to trial 3 at 50 µg/m^3. Additionally, the black carbon to PM2.5 ratios for trial 2 and 3 were 10.5 and 27.6, respectively. The ratios also confirmed the assumption that the wood pellet stove produced more black/elemental carbon than the cooking smoke gun.

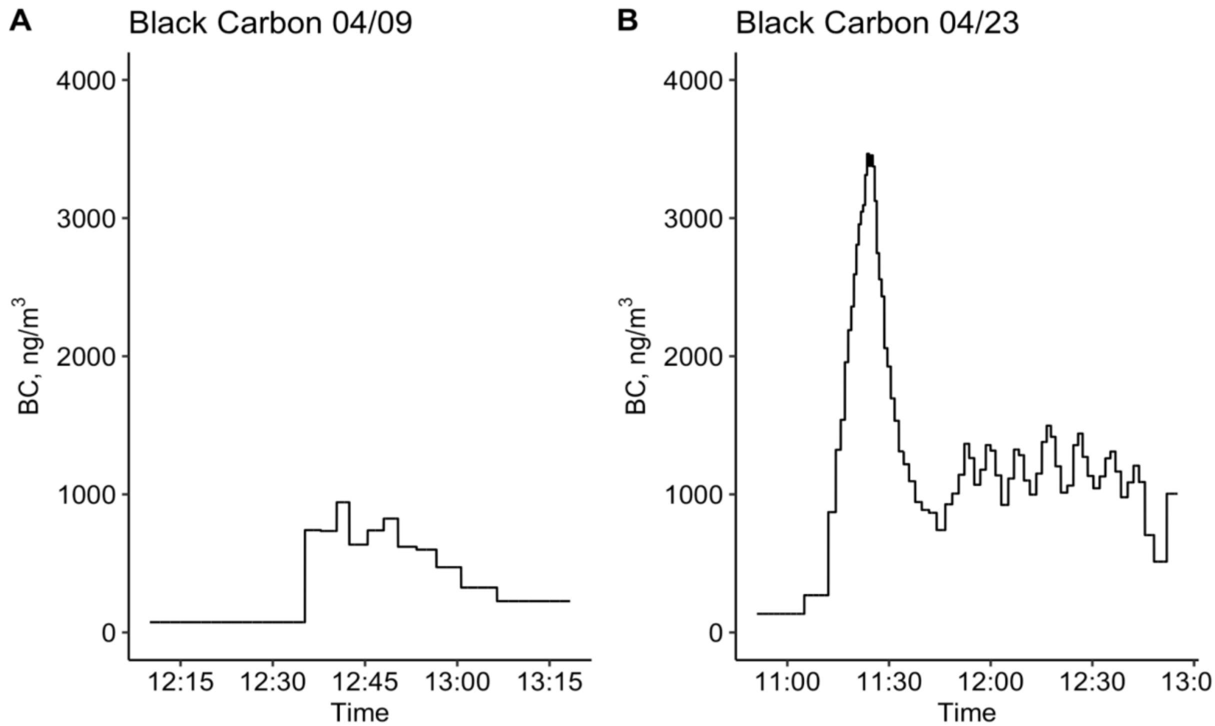

Figure 14. Black carbon mass concentration (ng/m^3) time series plots from trial 2 (Plot A) and trial 3 (Plot B).

3.4 Low-Cost vs. Research-Grade Particle Sensors

We modeled linear regression assessments for comparisons between low-cost and research-grade particle sensors. Particle count concentration TSI 3330 was plotted against the Dylos DC1700 data. Pearson's correlation coefficient from this relationship was 0.81 and a linear model coefficient was calculated to be 7.3 ($p < 0.001$). Despite the high correlation between the particle counts assessments, we still observed diverged measurement patterns (Fig 15.) in which we observed a better correlation when the particle count concentrations were approximately 100 total particle/cc for TSI 3330 and 30 total particle/cc for Dylos, and the measurements diverged as the concentrations increased. The correlation between TSI 3330 and MetOne showed a more converged trend with fewer data points when particle mass concentrations were higher than 100 $\mu g/m^3$ for both instruments. The diverging pattern also showed in the calibrated and uncalibrated log-transformed total particle counts concentration plots (Fig 17. A and B).

Variations in decay parameters (Fig 15. A and B), where TSI 3330 showed a decay of 9.7/h and Dylos with a decay of 6.5/h, also proved the particle counting performances from the two instruments were different despite both instruments being employed during the same experiment simultaneously. The differences in performance could be due to differences in instrument sensitivity or precision. TSI 3330 is a more sensitive particle sensor where it has 16 size channels ranging from 0.3 to 10 μm whereas Dylos DC1700 can only capture particles that fall under size ranges of 0.5-10 μm. Particles that had a diameter between 0.3 to 0.5 μm would be missed by Dylos and this caused an inherent shortage of particle counts from Dylos.

Looking at the combined time series plots from MetOne AEROCET 531 and TSI 3330 (Fig 17 C and D), we noticed a highly overlapped pattern from both calibrated and uncalibrated results. Nonetheless, we still could conclude that MetOne did not have the identical performance as TSI 3330 in counting particles by mass. One of the reasons that could explain this finding is that MetOne has 5 channels that measure particles with diameters from 1-10 μm but TSI 3330 can detect particles ranging from 0.5 μm to 10 μm. Therefore, similar to Dylos, MetOne was not sensitive enough to match the particle counting capability to TSI 3330 and would miss particles smaller than 0.5 μm in diameter. Additionally, MetOne samples particles every 1 minute while TSI 3330 samples at a rate of 1 sample per second. A longer sampling rate would cause misses in particle sensing and recording from MetOne. Lastly, TSI 3330, in spite of being a particle sizer, does not measure the particles by particle mass and we had to use equations provided by the manufacturer to convert particle count concentrations to particle mass concentrations based on assumed particle densities of 1 g/cm^3 for particles with all sizes of diameters. The same issue also applied to MetOne where the direct readings in particle mass concentration were also calculated in lieu of truly weighted and measured. Thus, the particle mass concentration from both instruments were assumptive and might be subject to systematic errors. Similarly, the MetOne AEROCET 531 is inherently a particle counter that estimates particle mass concentration. Future research should collect true mass concentration using a gravimetric filter or other reference mass concentration approaches, in addition to using similar particle sensing instruments that could capture the particle decay.

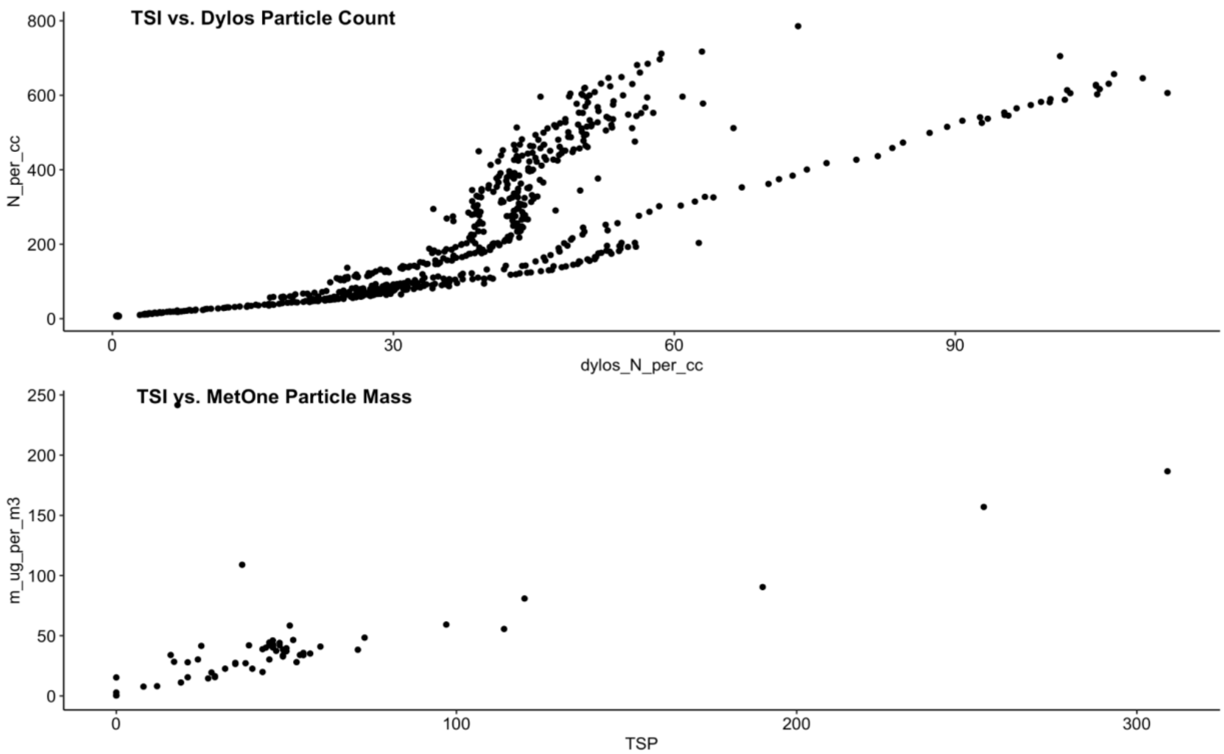

Figure 15. Particle concentration correlation plots between low-cost and research-grade instruments. The plot on top shows the correlation between TSI 3330 and Dylos total particle count concentration (#/cc). The plot on the bottom shows the correlation between TSI 3330 and MetOne total particle mass concentration (μg/m^3).

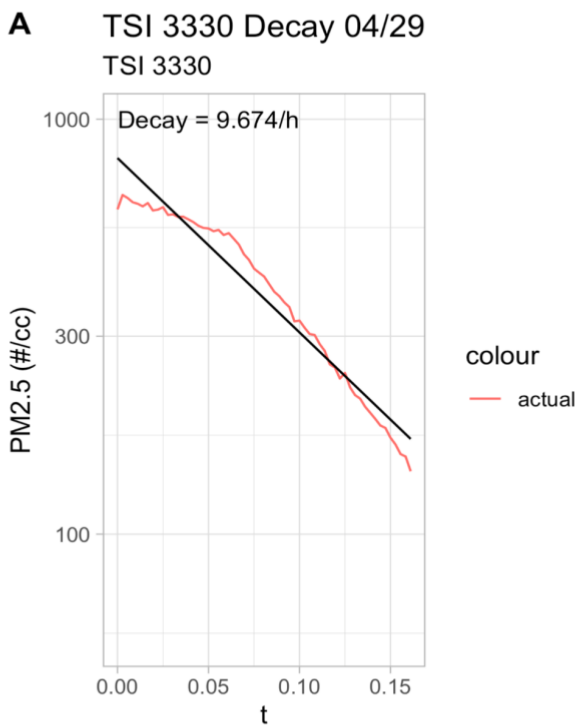

Figure 16. Decay calculation comparisons between research-grade and low-cost instruments. Plot A shows the decay calculated from using PM2.5 particle count concentration (#/cc) data from TSI 3330; Plot B shows the decay calculated from using PM2.5 particle count concentration (#/cc) data from Dylos DC1700.

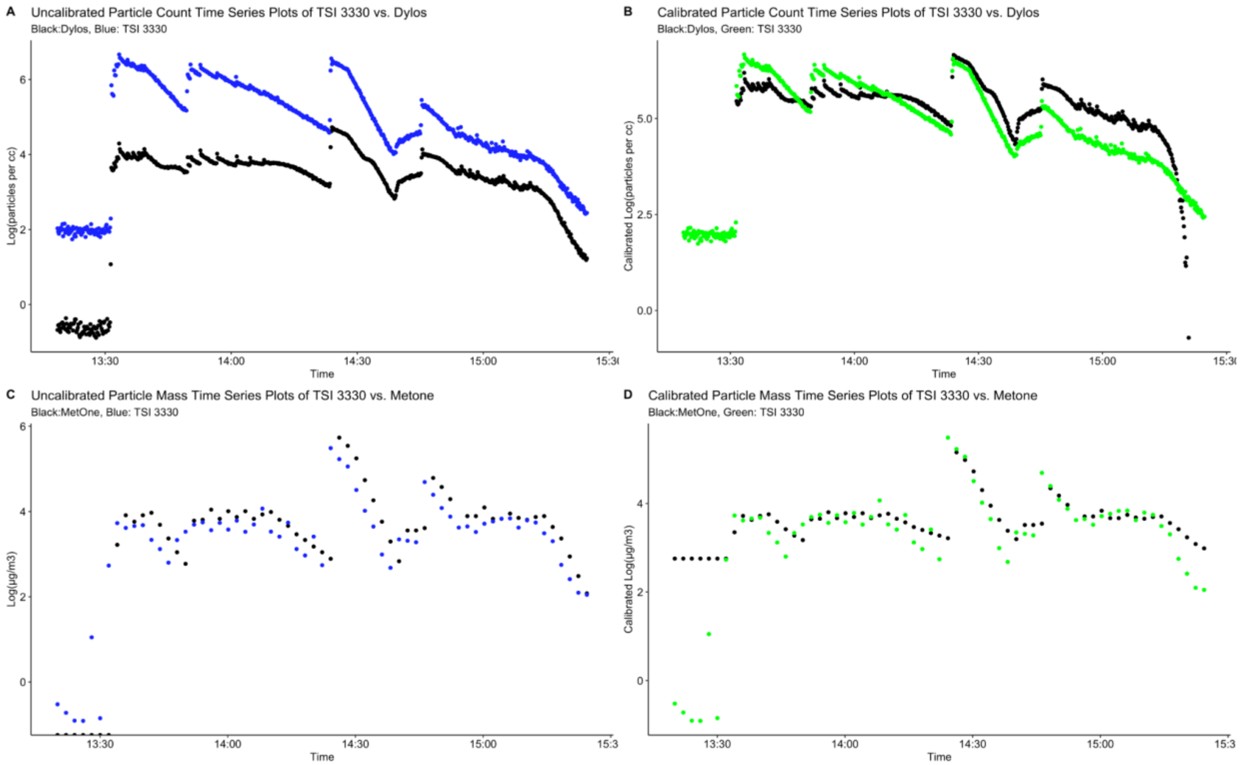

Figure 17. Merged time series plots for uncalibrated and calibrated low-cost and research-grade instruments. Plot A shows the uncalibrated log-transformed total particle count concentration (#/cc) time series for data from Dylos DC1700 (black) and TSI 3330 (blue); Plot B shows the calibrated log-transformed total particle count concentration (#/cc) time series for data from Dylos DC1700 (black) and TSI 3330 (green); Plot C shows the uncalibrated log-transformed total particle mass concentration ($\mu g/m^3$) time series for data from MetOne AEROCET 531 (black) and TSI 3330 (blue); Plot D shows the calibrated log-transformed total particle mass concentration ($\mu g/m^3$) time series for data from MetOne AEROCET 531 (black) and TSI 3330 (green).

3.5 Intervention Performance

Before assessing the actual decay parameter for HEPA filter PAC, we needed to assess the intrinsic decay of the exposure tent itself. R decay analysis showed a decay of 0.2/h when the exposure tent was completely zipped after the woodsmoke introduction from the cooking smoke gun and before turning on the air treatments. Additionally, we could also observe a steady concentration of particle mass during the same period (11:20-11:28 AM) from the TSI 3330 time series, and the duration corresponding to the period where Shirley intentionally held the concentration before assessing HEPA filter PAC performance for her pioneering research.

Using a simplified equation (Eq 4.) under assumptions that outdoor PM2.5 concentration was insignificant comparing to the smoke gun generation source and PM2.5 infiltration was negligible, we were able to calculate the actual HEPA filter PAC decay parameters when the air cleaners were turned on at different fan modes. Table 1 shows decay parameters for unadjusted and adjusted results. After adjustments, we observed similar parameters when air cleaners were set to the highest fan speed regardless of their HEPA filter lives. However, the used filter at the auto fan setting did have a greater decay parameter than the new filter at the same setting. This indicated that the used filter on auto mode filtered roughly 6.0 particles per ft^3 in one hour whereas the new filter on auto mode only filtered 3.2 particles per ft^3 in one hour. Despite the unexpected observation, we assumed the better performance seen in the used filter scenario with auto fan speed could possibly be due to added filtering capacity on the HEPA filter from previously adhered particles through filtration.

$$\kappa_{PAC} = \kappa_{measured\ PAC} - \kappa_{intrinsic\ decay}$$

Equation 4. Decay parameter adjustment calculation. κ_{PAC} is the actual HEPA filter portable air cleaner decay parameter (h^{-1}); $\kappa_{measured\ PAC}$ is the measured HEPA filter portable air cleaner decay parameter (h^{-1}); $\kappa_{intrinsic\ decay}$ is the intrinsic decay parameter (h^{-1}) of the exposure chamber.

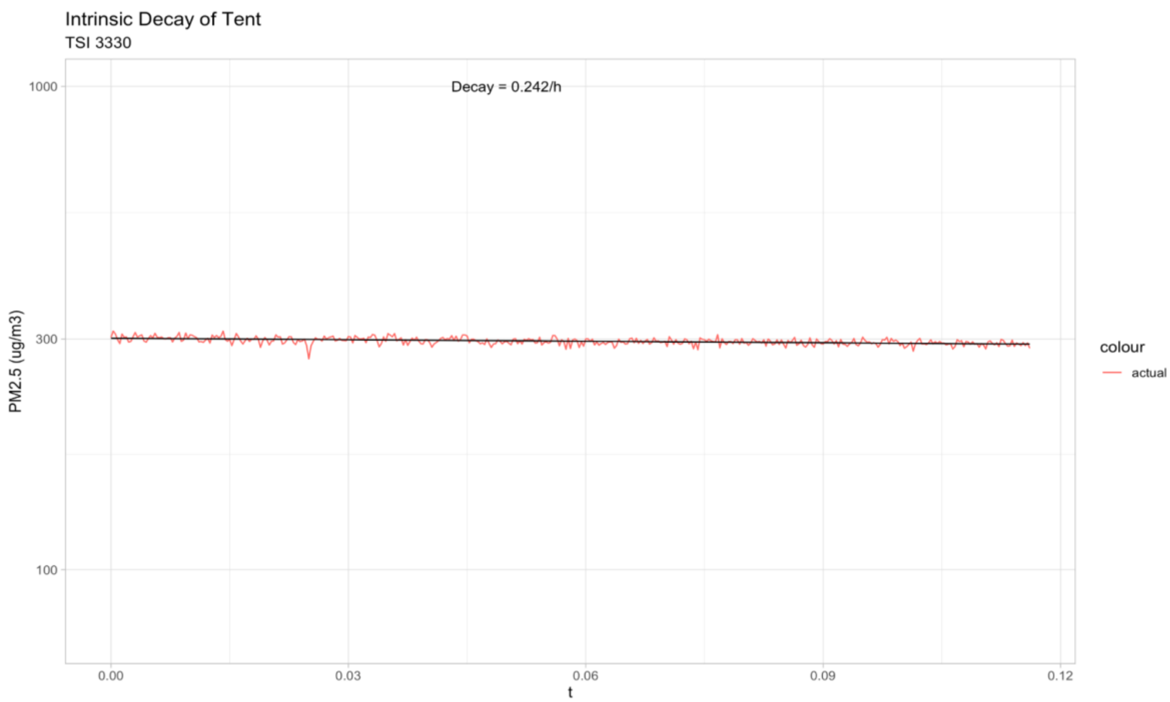

Figure 18. Intrinsic decay, actual (red) vs. predicted (black) of exposure chamber from TSI 3330 data on 01/25/2022.

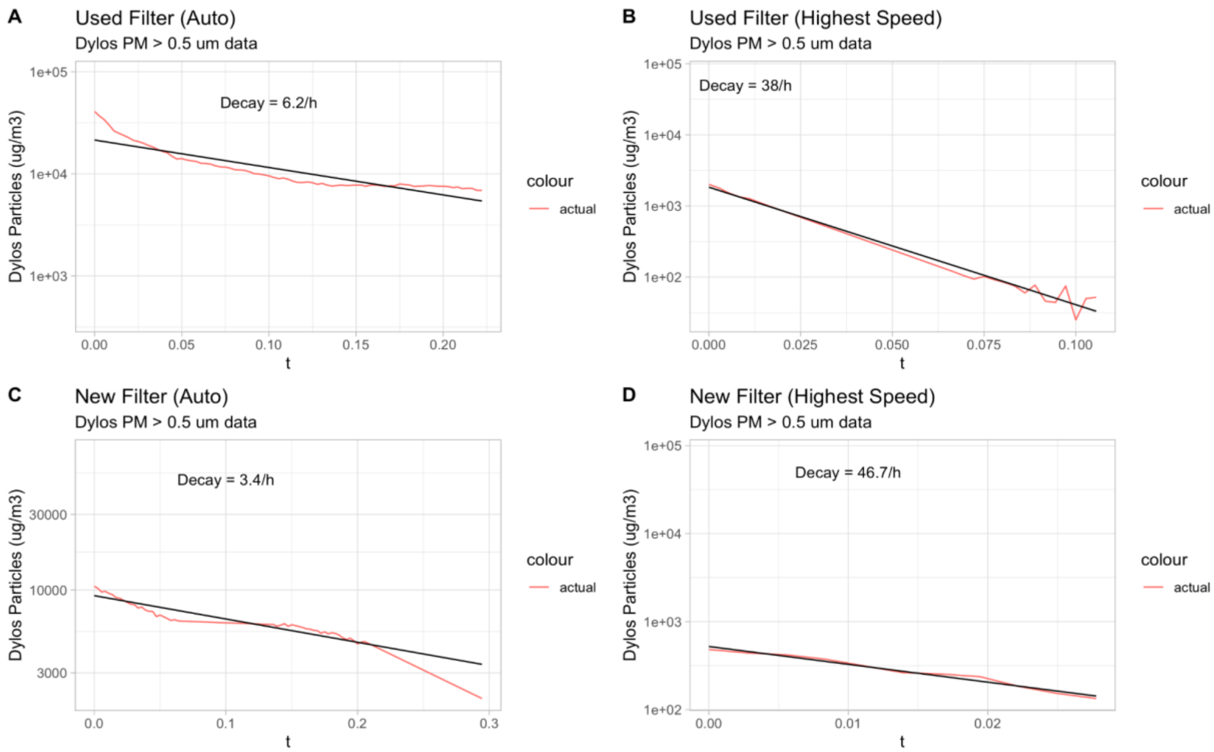

Figure 19. Measured HEPA filter air cleaner decays, actual (red) vs. predicted (black), from Dylos DC1700 particle count concentration (#/ft^3) data. Plot A displays decay from a portable air cleaner with a used filter at auto fan speed. Plot B displays decay from a portable air cleaner with a used filter at the highest fan speed. Plot C displays decay from a portable air cleaner with a new filter at auto fan speed. Plot A displays decay from a portable air cleaner with a new filter at the highest fan speed.

Table 1. Unadjusted and adjusted decay parameters (h^{-1}) using Equation 3. at different fan speeds.

Experiment	Filter	Fan speed	Decay parameter (/h)	Decay parameter (/h) adjusted
1	old	auto	6.20	5.96
2	old	highest	38.00	37.76
3	new	auto	3.40	3.16
4	new	highest	46.70	46.46

Lastly, from plots for trial 4 (Fig 20.) where we tested the HEPA-installed PAPR system's effectiveness in removing woodsmoke particles, we found that, after 2 rounds of controlled oscillation of woodsmoke concentrations, when the woodsmoke concentration went up to 150 μg/m^3 at 16:26 PM, the concentration dropped back down to less than 10 μg/m^3 instantaneously after turning on PAPR at lowest fan speed. This trial demonstrated the possibility of using a HEPA-installed PAPR system for personal woodsmoke removal and indicated that even at the lowest PAPR fan speed, this personal protective respirator could decrease the woodsmoke concentrations from "unhealthy" to the "good" on the scale of EPA's Air Quality Index.

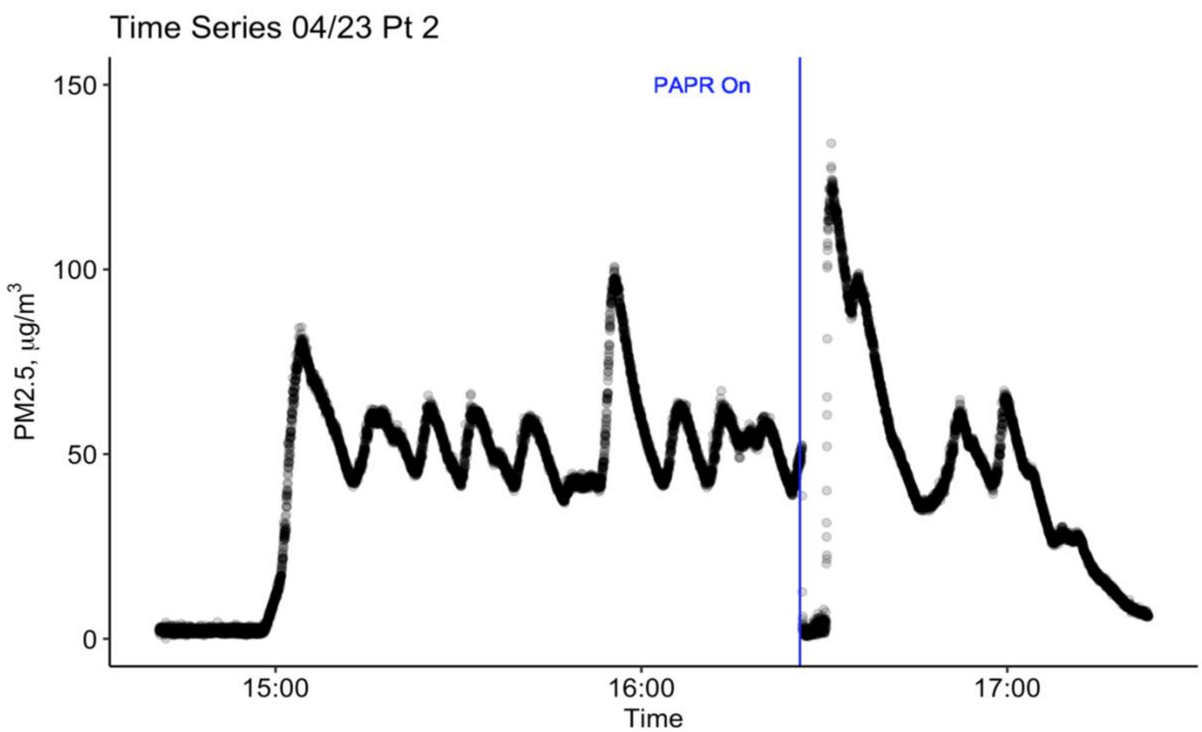

Figure 20. TSI 3330 particle mass concentration (μg/m^3) time series plot from trial 4. Blue line shows the time when the PAPR with HEPA filter was turned on at the lowest fan setting. The particle concentration decreased from around 50 μg/m^3 to close to 0 μg/m^3 right after the PAPR system started working.

3.6 Safety Parameters

Time series plots for CO and CO2 from previous experiments with similar settings showed 0 and non-concerning levels of CO and CO2 in ppm. Due to the lack of agreement on indoor CO level, in general, a household without gas stoves is expected to have a CO level from 0.5 to 5 ppm and, 5-15 ppm on average, with an occasional 30 ppm or higher, for a house with gas stoves (Indoor Air Quality, EPA, n.d.). Our analysis showed a CO concentration range of 0-1 ppm throughout the entire experiment which showed no signs of concern for possible carbon monoxide poisoning. A typically occupied building is regulated for an upper limit on indoor CO2 levels of 1000 ppm (EPA, n.d.). Our study result showed a less than 500 ppm CO2 level across the experimental period. Therefore, both CO and CO2 levels indicated the exposure system was safe for upcoming human subject exposure studies.

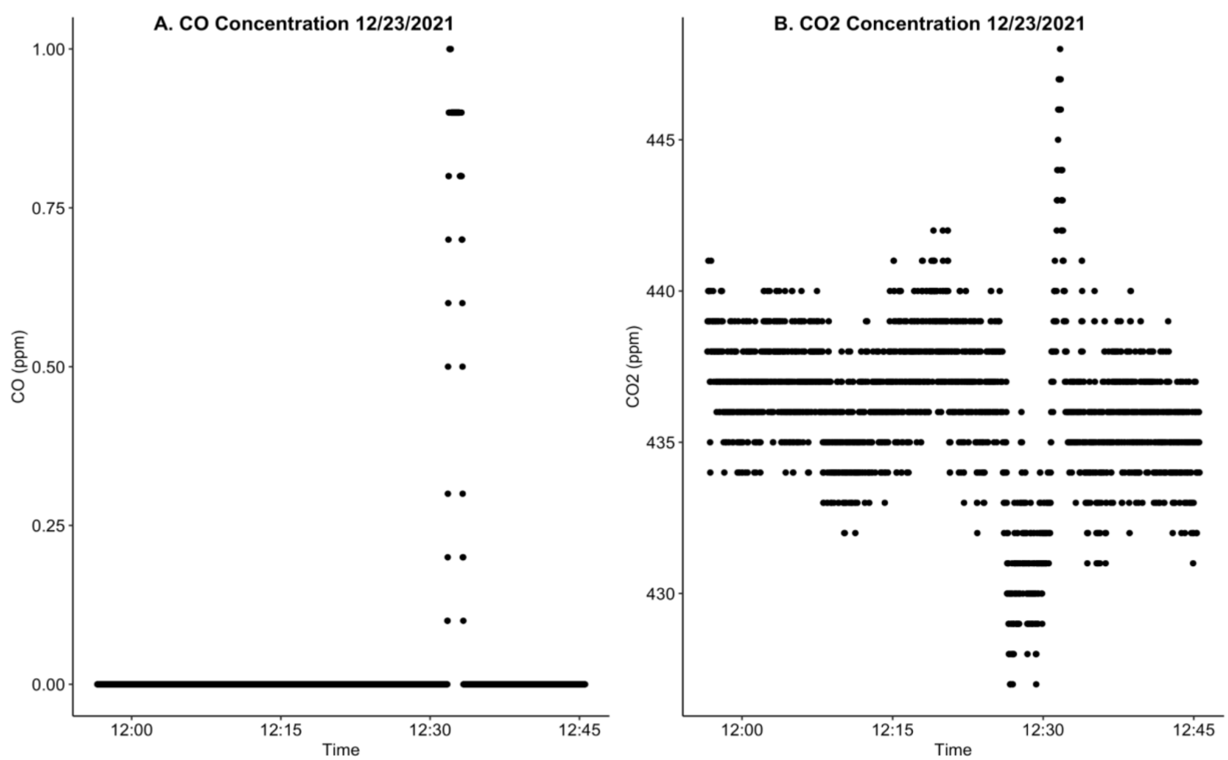

Figure 21. CO (Plot A) and CO2 (Plot B) concentrations (ppm) from a previous experiment trial using the cooking smoke gun to generate woodsmoke.

Chapter 4. DISCUSSION

4.1 EXPOSURE SYSTEM FEASIBILITY FOR FUTURE STUDIES

Researchers have been closely following the increased frequency of major wildfire smoke events and studying its ecological and human health effects. In addition to observational studies, pioneering efforts are being made towards performing controlled experiments to assess the health effects of wildfire smoke exposure (Schwartz et al. 2020). Controlled exposure studies depend upon repeatable experiment protocols, which includes repeatable establishment of “standardized” experimental exposure conditions. The variations observed in health effects findings from previous controlled exposure studies have been inconclusive and inconsistent due to heterogeneity in experimental factors. Therefore, an important advancement for the field is the creation of a more controlled experimental environment. The exposure system we designed, engineered, and tested makes progress towards this goal, which with further refinement may be an ideal setup for future woodsmoke exposure studies. Our study results indicated that with the exposure system, we were able to reliably generate woodsmoke from two methods (wood pellet stove vs. cooking smoke gun) with different types of biomass (hickory pellets vs. apple wood chips). Additionally, we could dynamically control the woodsmoke concentrations inside the exposure to the desired level (i.e., approximately 50 $\mu g/m^3$ which was closed to one of the Fedak et al’s exposure study trials using a gasifier) by adjusting the mechanical dampers and the inlet and outlet fan system based on the real-time particle concentration feedback from instruments like TSI 3330. By testing the different smoke generation methods, plotting the particle concentrations data from low-cost and research-grade instruments, and assessing the air treatment interventions in the exposure chamber, this exposure system was demonstrated to provide an experimental space for future woodsmoke exposure studies.

Furthermore, by comparing different smoke generation methods and their particle size distribution, we concluded that particles from wood pellet stove combustion tended to be smaller than the cooking smoke gun which mirrors previous observational study findings (Makkonen et al. 2010). However, because there is no standard wildfire smoke particle distribution, our result may not reflect all possible wildfire smoke events. Therefore, an important goal of this study was to develop and demonstrate the flexibility of using the same exposure chamber (i.e., the tent) with alternative woodsmoke generation sources.

There are potential implications for future exposure studies that measure health effects from woodsmoke exposure. Previously, researchers have described the need for a consistent experimental system setup, yet we also feel that there is utility in having a flexible exposure system that can be used to examine different exposure scenarios (particle composition, concentration, and exposure duration), exercise component (exercise vs. no exercise, and types of exercise), and health endpoint measurements (cardiovascular, respiratory, systemic, and oxidative stress). Future exposure studies, besides using the similar experimental system setup, should also report their exposure parameters discussed earlier to make a generalizable conclusion on the health effects. This is particularly important as new policies are being developed to protect different population groups from the potential harmful effects of wildfire smoke exposures, such as children in schools, outdoor workers, etc. – groups that may have very different exposure scenarios and specific health endpoints of concern. While a more standardized experimental design and outcome measurement regime would result in more consistent findings, there may also be value in having a simple exposure system that is reconfigurable with notes on the system design such as the baseline air exchange rate the exposure chamber, woodsmoke combustion procedures including type of combustion sources, biomass used, combustion temperature, mixing and dilution systems, woodsmoke particle size distribution and composition (if possible), dynamic of the flow, and the stability of the woodsmoke concentration in the exposure chamber over the experimental trial. As such, findings from studies will be able to provide more powerful insight for educational, occupational, and other specific policy rule-making purposes.

4.2 HEPA-Filter Air Cleaner for Wildfire Smoke Infiltration Remediation

The study demonstrated the use of the woodsmoke exposure system for the evaluation of HEPA-filter air cleaners. Previous observational studies have shown PACs with HEPA filtration to be effective at wildfire smoke removal. Our study results from the exposure chamber experiment approach suggested that HEPA-filter air cleaners would be both effective and efficient in filtering woodsmoke particles indoors even for a 5-month used filter. However, for better removal effectiveness, our experimental results suggested that the manual highest fan setting removed woodsmoke particles better than the auto fan setting.

4.3 HEPA-Installed PAPR System for Personal Wildfire Smoke Removal

With limited access to indoor environments, outdoor workers may not benefit from having clean air shelters with proper air treatments such as HEPA or higher MERV-rated filtration systems during wildfire seasons. Woodsmoke-specific PM exposure adds another layer of health burden on top of heat exposures which co-occur in summer-fall wildfire seasons, especially for outdoor working groups like agricultural (Austin et al., 2021) and construction workers (Zuidema et al., 2022). The case study presented here, demonstrated the use of the exposure system to experimentally evaluate a PAPR system performance in removing both particle and gas components of woodsmoke, suggesting that it would be effective at removing wildfire smoke particles and would be able to provide filtered air for people who wear this personal protective respirator. Of course, the PAPR is designed to be effective at particle removal and has the advantages over other forms of PPE in that it depends less upon fit and tight seal to the face of a worker. Moreover, its price at around $2000 per unit, and additional ongoing costs for replacement HEPA filters makes it impractical for all workers. Nevertheless, the experimental evaluation in the exposure chamber suggests that future work with more cost-effective PPE, such as N95 and KN95 respirators may be possible either with standard NIOSH 3D face models or recruited workers for a study of particle exposure reduction and potential changes in health effects with/without PPE. There is an increasing need for such studies as recent wildfire smoke protection rules have included the provision and use of respirators for outdoor workers when smoke levels reach high levels.

4.4 Strengths and Limitations

This research project demonstrates the use of a commercially available grow tent combined with real-time data from continuous direct-reading particle instruments and controllable particle generation sources and dampers/fans as a relatively cost-effective woodsmoke exposure system for future controlled exposure studies and studies of air treatment strategies. The instruments and equipment are commercially available and accessible for personal and scientific use. Those interested in running similar experiments can easily duplicate the study procedures with alternative instruments and equipment of similar specifications around the world. Additionally, the study does not require extensive labor or room to perform. With further tuning and automation of the woodsmoke introduction into the exposure chamber of the system and the control of the woodsmoke concentration inside of the exposure chamber, this and similar types of studies can be more easily conducted.

Several limitations are important to highlight when interpreting these findings. First, we performed 15 experimental trials with a variety of instruments and equipment, some trials had variations in environmental conditions that were not controlled (i.e., environmental temperature, humidity, and weather conditions). The variations in weather conditions, especially in the Pacific Northwest where rain is often expected, of experimental trials could produce biased results from the true observations. This contributes to some variations in results. Secondly, for the intervention studies, we did not collect repeated measures when comparing HEPA filter PAC and HEPA-installed PAPR systems limiting our ability to perform statistical testing comparing scenarios. Thus, the results for both intervention methods ideally might be repeated to obtain more robust results related to intervention effectiveness. Moreover, for our experimental trials 3 and 4, we relied solely on the leakiness of damper 4 to allow woodsmoke particles to travel to the exposure chamber despite the fact that the degree of leakiness was kept constant for both trials. Future experimental trials could benefit from slightly improved components, such as better dampers. Thirdly, real-time instruments used in this study, such as the TSI 3330 Optical Particle Sizer are primarily particle counters and not reference particle mass measurement instruments. Due to the optical operating principle of the instrument, the TSI 3330 does not directly measure the mass of the woodsmoke particles that travel through the sampling port. Therefore, all the particle mass concentrations from TSI 3330 were calculated based on the theoretical values and conversion equations and a default particle density provided by the TSI manufacturer. In the fourth place, optical particle sensor performance specificity is dependent on relative humidity as water particles would adhere to the particulate matter and cause them to increase in overall size, attach to the exposure chamber wall, or fall onto the exposure chamber floor due to growing in weight. The HEPA filter air cleaner decay parameters we measured consisted of the particle decay rates after adjustment for the intrinsic exposure tent decay. To better understand the efficacy of the air cleaners and their clean air delivery rate in future studies, we could measure the airflow rate both upstream and downstream of the air cleaner. Finally, for all our experiments, we measured only particles, CO, and CO2 from woodsmoke and neglected other hazards that were a part of the wildfire smoke. Future studies could also include measurement of other gaseous components (NO and NO2) and hazardous chemicals (VOCs and polycyclic aromatic hydrocarbons), especially since exposures to these aspects of woodsmoke may contribute to health outcomes.

4.5 Conclusion and Future Recommendation

In conclusion, our study successfully designed, engineered, and constructed an exposure system that consisted of components for woodsmoke generation, woodsmoke mixing, and woodsmoke exposure. We used low-cost air sensors Dylos DC1700 and MetOne AEROCET 531, as well as research-grade sensors TSI 3330 Optical Particle Sizer and TSI 3910 Nanoparticle Scanner to profile the particle distribution and plot the time series for woodsmoke particle changes overtime. We demonstrated the running of the HEPA-filter air cleaners and HEPA-installed

PAPR system as woodsmoke intervention strategies. The results from both case studies indicated the possibility of using this exposure system for other future intervention and exposure studies.

This system is a feasible option for woodsmoke exposure studies. However, there is still room for improvement and advancement. We recommend researchers who share similar interests continue engineering this system to be more automated and less labor-intensive with better precision in controlling the exposure. With an improved exposure system, we will be able to conduct more exposure studies on woodsmoke exposures to further our understanding of the environmental and occupational health of wildfire events.

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