EVALUATION OF A HEATING STOVE CHANGEOUT PROGRAM IN THE NAVAJO NATION: PILOT STUDY

by

Naomi Y. Chang

B.S. Env. E., University of Delaware, 2014

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Master of Science

Department of Civil, Environmental, and Architectural Engineering

2019

This thesis entitled:

Evaluation of a Heating Stove Changeout Program in the Navajo Nation: Pilot Study
written by Naomi Y. Chang

has been approved for the Department of Civil, Environmental, and Architectural Engineering

____
Dr. Angela Bielefeldt, Committee Chair

____
Dr. Lupita D. Montoya

____
Dr. JoAnn Silverstein

Date: __________

The final copy of this thesis has been examined by the signatories, and we
find that both the content and the form meet acceptable presentation standards
of scholarly work in the above-mentioned discipline.

IRB protocol: #NNR19.335, #NNR-17.292, Diné College IRB 17.06, CU IRB 17-0508

Abstract

Chang, Naomi Y. (M.S., Department of Civil, Environmental, and Architectural Engineering)
Evaluation of a Heating Stove Changeout Program in the Navajo Nation: Pilot Study
Thesis directed by Dr. Lupita D. Montoya

Many homes on the Navajo Nation rely on wood and coal in old, inefficient heating stoves. An EPA-certified Navajo Hybrid Stove that can burn both wood and coal, was distributed to homes in the Navajo Nation. Collocation experiments were conducted to determine agreement among the DustTrak units and QTrak units. The correction factors and correlations for units of the same instrument were close to one; therefore, no adjustment to the data was necessary. A wood/coal smoke correction factor (W/CSCF) of 2.60 that is representative of wood/coal smoke exposure in Navajo homes was also determined for the DustTraks. This value was used to correct the DustTrak reported $PM_{2.5}$ concentrations from the pilot study, which yielded mixed results, but showed decreases in both median $PM_{2.5}$ and CO post-intervention. More sampling in Navajo homes should be conducted to determine a more accurate W/CSCF. Additionally, greater education efforts are necessary to achieve significant improvements in IAQ.

Acknowledgements

I would like to thank my advisor, Dr. Lupita Montoya, for her guidance and support throughout this journey. She provided valuable insight for my thesis and also in the nuances and challenges in conducting field research. Thank you also to Dr. Angela Bielefeldt and Dr. JoAnn Silverstein, my committee members, for their advice and support. I also owe a lot to Aaron, my lab-mate, for his support and guidance as well. To my mentor, Dr. Rita Klees, thank you for keeping me grounded and providing encouragement when I needed it most.

This thesis would not have been possible without the hard work and dedication of Michael King, Chris Yazzie, Tennille Denetdeel, and Sky Izzo from Navajo Nation EPA as well as Jeri Garfield from Diné College. It's been an absolute privilege to have collaborated with all of you.

I've also been fortunate enough to find amazing friends everywhere I go, who inspire me to be better and do more; specifically, Anisha, Pranav, Becca, Sarah, Kathy, and Lisa. You bring out the best in me and I'm so grateful for your encouragement and advice.

I owe the most to my family for their support and patience throughout the years. To my mother for her infinite wisdom and instilling in me the passion to work towards the betterment of people. Sorry for the years of worry I caused you and for the years of worry to come. My brother has been my closest friend and biggest rival, supporting me and inspiring me to achieve more than I thought I was capable of. Finally, to my father for setting me on this path from a young age and encouraging my curiosity, even when it resulted in a mess. You've been with me every step of this journey in spirit.

Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 Background on the Navajo Nation

The Navajo Nation (NN) is the largest sovereign Native Nation in the United States and is composed of 110 Chapters (similar to municipalities), with a population of 175,005 (U.S. Census Bureau, 2017c; Navajo Nation Department of Information Technology, 2011). The Navajo Nation is located in the Four Corners Region in Arizona, Utah, and New Mexico, and occupy an area of approximately 27,413 mi^2 (69,930 km^2).

Over 40% of the general NN population and 52.4% of Navajo children under 5 years old live below the poverty level, compared to 14.6% and 22.5% of the general US population (U.S. Census Bureau 2017h; U.S. Census Bureau, 2017j), respectively. Additionally, the unemployment rate in the NN is 15.0% (U.S. Census Bureau, 2017e) compared to 6.6% in for the United States (U.S. Census Bureau, 2017f). High rates of unemployment and poverty directly affect the ability of the Navajo to access clean energy.

A significant percentage of rural homes in the Navajo Nation (89%) rely on wood stoves as a heating source (NHA, 2011) and sixty-two percent (62%) of all Navajo homes use wood as a fuel source, making it the most common heating fuel in the NN (Arizona Rural Policy Institute, 2010; U.S. Census Bureau, 2015). In addition to solid fuel combustion, many homes in the NN rely solely on natural ventilation, resulting in low air exchange rates and enabling accumulation of emissions from combustion and other pollutants (Casey et al. 2018).

Although there are other factors, Bunnell et al. (2010) determined that indoor air quality had a larger impact on the respiratory health burden in the NN compared to ambient air quality. Additionally, the health disparities experienced by minority children and children in households below the poverty level, such as Navajo children, is a nationally recognized issue (USEPA

2012).

There are many factors that contribute or are suspected to contribute to respiratory diseases, such as emissions from heating and cooking sources, personal smoking, allergens (pet dander), endotoxins, and dampness and mold (Lowe et al., 2018). Of these factors, emissions from heating sources have been examined most frequently due to the large number of Navajos who rely on woodstoves for heat. Associations between solid fuel combustion and respiratory health in the Navajo Nation have been found in several studies (Bunnell et al., 2010; Robin et al., 1996; Morris et al., 1990; Champion et al., 2017a; Champion et al., 2017b; Li et al., 2018; Lowe et al., 2018). Lowe et al. (2018) also noted that addressing air pollution through wood/coal stove interventions should be prioritized.

Of the few studies conducted regarding the respiratory health burden of Navajos, all have looked at the impact of indoor air quality (IAQ) from wood stoves (Morris et al., 1990; Robin et al., 1996; Bunnell et al., 2010; Champion et al., 2017a; Champion et al., 2017b; Li et al., 2018). The pollutants of interest in those studies were fine particulate matter of aerodynamic diameter less than $2.5\mu m$, $PM_{2.5}$, (Bunnell et al., 2010; Robin et al., 1996; Morris et al., 1990; Champion et al., 2017b, Li et al., 2018), carbon monoxide (Champion et al., 2017b; Casey et al., 2018), and/or carbon dioxide (Champion et al., 2017b).

Several studies in Native Nations (Singleton et al., 2017) and in rural homes heated with wood stoves (Ward and Noonan, 2008; Noonan et al., 2012; Semmens et al., 2015) have used DustTraks, a real-time instrument, to measure $PM_{2.5}$ concentrations. While gravimetric methods are considered more accurate and robust (Kim et al., 2010; Chung et al., 2010;), it is significantly more complicated to set up, collect, and analyze the filter samples than to operate real-time monitors, like a DustTrak (Kingham et al., 2006; Chung et al., 2010; Kim et al., 2010).

Several studies (McNamara et al., 2011; Chung et al., 2010, Kingham et al., 2006, Trent, 2006) noted that DustTraks tended to over-report PM concentrations by a factor of 1.65 – 3 when compared to filter-based methods. The DustTraks use optical mass measurements to report PM concentrations, which are dependent on particle size and properties (TSI Incorporated, 2013a; McNamara et al., 2011). For this reason, source specific correction factors must be determined to accurately report certain PM concentrations. McNamara et al. (2011) determined a wood-smoke correction factor of 1.65 to accurately quantify indoor $PM_{2.5}$ concentrations due to wood combustion. Since the Navajo rely heavily on a mix of wood and coal as a fuel source for heating, the determination of a wood/coal-smoke specific correction factor is necessary to accurately quantify $PM_{2.5}$ concentrations in Navajo homes. Currently, there is no published correction factor for wood/coal-smoke; this is a significant gap in knowledge when quantifying indoor $PM_{2.5}$ concentrations in Navajo homes.

1.2 Residential Heating with Wood and Coal in the Navajo Nation

In addition to its affordability and accessibility within the reservation, wood such as naturally-harvested cedar and oak are culturally significant because "these woods produce red, yellow, or white fire flames, which are seen as the natural flames that represent Navajo sacred relative fires" (Champion et al., 2017a). Coal is also provided free of charge or at low cost to the Navajo people who live near coal mines within (Peabody/NTEC Coal Mine) and surrounding (Hesperus Coal Mine) the reservation. These factors contribute to the high utilization of coal by Navajo residents (Bunnell et al., 2010; T. Denetdeel, personal communication, April 2, 2019).

Previous studies (Champion et al., 2017a, Bunnell et al., 2010) concluded that the most economically and culturally appropriate intervention to reduce household emissions is to improve energy efficiency in homes (through weatherization) and replace old stoves with cleaner burning models. Champion et al. (2017a) holistically examined seven heating alternatives: natural gas, propane gas, electricity, wood pellet stoves, stove improvement, stove replacement with an improved wood burning stove, and passive solar heating. The analysis considered community perception, cultural importance, as well as environmental and health benefits. Importantly, Champion et al., 2017a also discussed the importance of including Navajo leaders and community members in the decision-making process, as well as providing options for heating and fuel use to meet the diverse economic and cultural needs of the Navajo. They concluded that a stove replacement designed to efficiently combust both wood and coal was the best option due to Navajo practices. This alternative was not initially included in the analyses but emerged as the best option for this community; therefore, a recommendation for a new dual (wood/coal) stove emerged from that study.

The conclusion by Champion et al. (2017a) acknowledged the economic and cultural factors that influence Navajo heating fuel demands. However, at the time, no EPA-certified wood/coal stoves existed, and the EPA-certified wood stoves were not designed for coal combustion. Although both the World Health Organization (WHO 2014) and Champion et al. (2017a) discouraged the use of coal in homes due to its adverse health effects, providing Navajo homes with EPA-certified wood stoves was not a practical option because of their preference in using both wood and coal for heating.

Following Champion et al., (2017a) recommendations, US EPA looked for stove designers willing to take on this challenge. In response, the Woodstock Soapstone Company (West Lebanon, NH) designed an EPA-certified, fuel efficient hybrid burning (wood/coal) stove specifically for the Navajo. To be EPA-certified, wood stoves must be evaluated by an independent party and emissions of $PM_{2.5}$ must be under 4.5 g/hr (USEPA 2015c). It is expected that the new Navajo Hybrid Stoves will result in reduced emissions due to more efficient combustion processes and a reduction in fuel use (both wood and coal). Reduced emissions indoors should lead to improved indoor air quality and, potentially, improved respiratory health in occupants.

1.3 Settlement Agreement

In 2009, US EPA began an investigation into the operations of the Four Corners Power Plant (FCPP), which resulted in a Settlement Agreement in 2015. From this Settlement Agreement, reductions on NO_x, SO_2, and PM emissions are to be pursued under the EPA's 2012 Clean Air Act Regional Haze Program's Best Available Retrofit Technology (BART). Additionally, the owners of the Four Corners Power Plant are providing $3.2 million to replace old stoves with newer, more efficient stoves and $1.5 million to weatherize homes participating in a stove changeout program (US EPA 2015b).

The stove changeout program started in 2018 and will occur over 5 years; it is expected to reach approximately 500-700 homes in the northern part of the Navajo Nation. Households with elders, children, veterans, and people with respiratory and cardiovascular health conditions are prioritized. Several criteria put forth by the Settlement Agreement must be met to be eligible to participate in the stove changeout and include: 1) the household receiving the stove must be at or below 150% of the federal poverty level; 2) the family must use an old, uncertified wood or coal stove as their primary source of heat; 3) the old, uncertified stove must be relinquished at time of installation of new stove; and 4) the home must be in such condition that allows the safe installation of a new stove.

A research study was designed to assess the expected improvements in air quality and respiratory health symptoms of participants in the stove changeout program. To participate in the research study, households requesting a Navajo Hybrid Stove were recruited through referrals from stove changeout program coordinators; recruitment flyers, and radio live-read announcements were used to promote the study. A First Pilot Study was conducted during the heating season (March-April) of 2018 in Shiprock, NM.

1.4 Thesis Overview

This thesis is composed of five chapters. The first chapter is the introduction, which includes background information for this project. Chapter 2 describes a series of collocation experiments needed to determine agreement among the instruments used. Chapter 3 describes the evaluation of a correction factor for wood/coal smoke needed to correct measurements from the DustTrak. Chapter 4 presents results from the First Pilot Study conducted from March to April, 2018. Chapter 5 presents overall conclusions from this study. The following hypotheses were addressed in these chapters.

Hypothesis 1: *1a. Intra-monitor correction factors will be close to one, indicating good agreement within the same instruments. 1b. The correction factor for DustTraks and E-BAMs will be large due to differences in instrument operation.* Collocation experiments were conducted for the different instruments to determine correction factors within the same group of instruments (intra-monitor) as well as between indoor and outdoor monitors. Intra-monitor correction factors were close to one for the five DustTraks and for Relative Humidity, temperature, barometric pressure, and CO_2 as measured by five QTraks. The carbon monoxide concentrations measured by the QTraks showed more variation, but were within the reported instrument accuracy for CO. These experiments are presented in Chapter 2.

Hypothesis 2: *Due to the methodology of calculating $PM_{2.5}$ concentrations, the DustTraks will* *over report $PM_{2.5}$ concentrations in homes where wood and coal are used as primary fuel sources.* Wood/Coal-Smoke Correction Factor (W/CSCF) experiments were conducted with three types of samplers and monitors to determine a wood/coal-smoke specific correction factor for the DustTraks, which are calibrated with ISO 12103-1, A1 Arizona test dust. Since the density of ISO 12103-1 is different from wood and coal smoke, the DustTrak reported $PM_{2.5}$ concentrations from wood/coal combustion will not be accurate. This W/CSCF is not currently available in the literature; only a wood-smoke specific correction factor (1.65) is available (McNamara et al., 2011). The chemistry of wood smoke and coal smoke is different, meaning that the monitors may over-estimate or under-estimate PM emissions from different fuel sources. A mean(sd) W/CSCF of 2.60(0.975) was determined from twelve samplings periods in a typical Navajo home. This value compared well with an estimated correction factor determined from published values for wood smoke and coal smoke. Determining a correction factor for coal smoke for the DustTrak will allow future investigations into wood/coal combustion PM concentrations to be more accurate. These experiments are presented in Chapter 3.

Hypothesis 3: *Following a culturally appropriate heating stove changeout in homes in Shiprock, NM, IAQ will improve.* Analysis of pre-intervention and post-intervention indoor air quality in six homes in Shiprock, NM was conducted to determine if the EPA-certified wood/coal Navajo Hybrid Stoves significantly reduced indoor air pollution. Sampling took place over two days during the pre-intervention and post-intervention periods. $PM_{2.5}$ concentrations were adjusted for wood/coal smoke using the W/CSCF determined in Chapter 3.

The results of the First Pilot Study were mixed, indicating that more intensive and culturally appropriate education may be required. One home was visited one year after the post-intervention sampling period and noticeable improvements in IAQ were measured in $PM_{2.5}$ and

CO concentrations. This indicates that in addition to improved education materials, more time may be required for stove users to become comfortable with the new stoves. This work is presented in Chapter 4.

A summary of findings, study limitations, and future recommendations are presented in Chapter 5.

2. Collocation Experiments

2.1 Introduction

A First Pilot Study was conducted in seven homes in Shiprock, NM, Navajo Nation from March to April 2018 to assess the impacts of a heating stove changeout on indoor air quality (IAQ). General household information as well as respiratory health surveys were also included in this study but are not part of this thesis. Fine particulate matter ($PM_{2.5}$) was measured using a DustTrak II Model 8530, and CO and CO_2 were measured with a QTrak Model 7575 at each participant home. DustTraks and QTraks were selected because they are real-time instruments and have been used in several studies involving Native Nations (Singleton et al., 2017) or in assessing IAQ in rural homes heated with wood stoves in the United States (Ward and Noonan, 2008; Noonan et al., 2012; Semmens et al., 2015). Collocation experiments are necessary for instruments of the same kind to determine if the reported values (i.e. $PM_{2.5}$ concentrations for DustTraks and CO and CO_2 concentrations for the QTraks) from different units can be compared without a correction factor.

Future assessments of the heating stove changeout are expected to include ambient (outdoor) monitoring for pollutants. An E-BAM Model 9800 will be used to measure $PM_{2.5}$ outside homes to help resolve contributions to IAQ from ambient sources. Therefore, a correction factor for the DustTraks and E-BAMs must also be determined.

Although the DustTraks and E-BAMs are not Federal Reference Methods (FRM), the "gold standard" of air pollution monitoring systems, there are several benefits to using real-time continuous monitoring devices like DustTraks and E-BAMs. As real-time instruments, both the DustTraks and QTraks are able to distinguish between temporal variations in concentrations and other measured parameters, which gravimetric methods are not capable of (McNamara et al., 2011). Temporal variations are important when relating PM and CO to potential health effects because brief, but intense exposure to elevated levels of have been linked to several adverse health effects such as inflammation and increased diastolic blood pressure for PM, and disorientation, coma, and death for CO (McNamara et al., 2011; Barrett et al., 2006; Urch et al., 2005; Raub et al., 2000; Goldstein, 2008).

Additionally, real-time continuous monitoring devices are relatively simple to operate and maintain. However, systematic differences among PM concentrations measured with DustTrak, E-BAM, and FRM have been reported in several publications (Heal et al., 2000; Chung et al., 2001; Yanosky et al., 2002; Kingham et al., 2006; McNamara et al., 2011). The DustTraks are calibrated with Arizona test dust, so PM generated from other sources, i.e. wood/coal may not be accurately reported (TSI 213a). Despite over-reporting concentrations, Heal et al. (2000) found that DustTraks "demonstrated excellent functionality in terms of ease of portability and real-time data acquisition". Kingham et al. (2006) also concluded that as long as reliable correction factors could be determined, the operational advantages of the DustTraks, such as low-cost, portability, and ease of use, could allow the DustTraks to be used in studies for less cost, time, and labor.

E-BAM PM measurements have been shown to correlate well with FRM methods (TSI 2013a; MetOne 2008; Trent 2006; CARB 2005). While time-integrated filter-based methods, such as those used in EPA's $PM_{2.5}$ monitoring networks (USEPA 2000), are robust and accurate for particulate matter (PM) measurements, high costs and long sampling periods make it challenging to implement them in some situations. Therefore, the use of real time continuous monitors like the E-BAM and DustTrak are a reliable and cost-effective alternative to FRM monitors.

A total of five DustTraks and five QTraks were used in the First Pilot Study. In order to compare $PM_{2.5}$, CO, and CO_2 measurements from multiple units of the same type of instrument, it is customary to determine the correction factors among those instruments. Correction factors for the DustTraks and E-BAMs were also determined for future studies that will include ambient PM measurements.

The collocation experiments had four objectives:

Objective 1: Determine correction factors for the 5 DustTraks.

Objective 2: Determine correction factors for the 5 QTraks.

Objective 3: Determine $PM_{2.5}$ and PM_{10} Ratios from two E-BAMs.

Objective 4: Determine correction factors for the DustTraks vs E-BAM

2.2 Materials and Methods

2.2.1 Locations

A first set of collocation experiments were performed at a single-family home in Fort Defiance, AZ from February 26, 2019 to March 1, 2019. This home was 432.4 ft^2 (40.2 m^2) and the floor plan and instrument placement are shown in Figure 2-1. instruments were placed in the same room as the heating stove, in the living room area. The distance from floor to ceiling in the open area of the home was 8.0 ft (0.74 m). The stove in the home was a Wonderluxe Model B2350, which was installed approximately 1 year prior to the collocation experiments. Home dimensions and monitor distances from each other and the stove were measured with a Distance Measurer Model DLR130 (Robert Bosch Tool Corp., Mt. Prospect, IL).

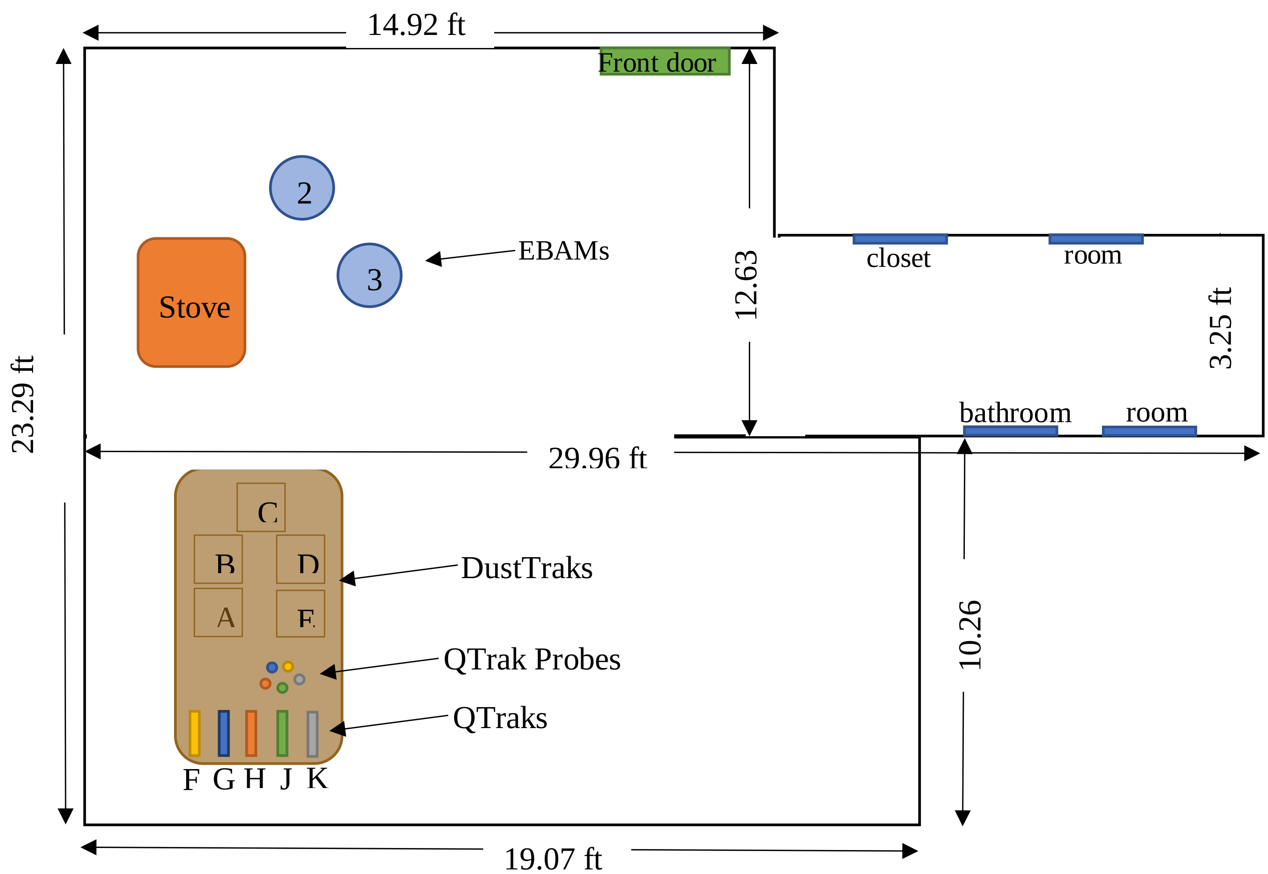

Figure 2-1. Floor Plan and Instrument Placement in Fort Defiance, AZ

The second set of collocation experiments were conducted in a Navajo home in Shiprock, NM from March 1, 2019 to March 4, 2019. The home was 393.4 ft^2 (36.5 m^2) and the floor plan and instrument placement are shown in Figure 2-2. The two bedrooms and the door in the living room were closed during these experiments and were not included in the calculation of the home volume. Instruments were placed in the same room as the heating stove, the living room area. The height from floor to ceiling was 8.1 ft (0.75 m) in all surveyed areas. The stove in the home was a Navajo Hybrid Stove, which was installed approximately 1 year prior to these experiments.

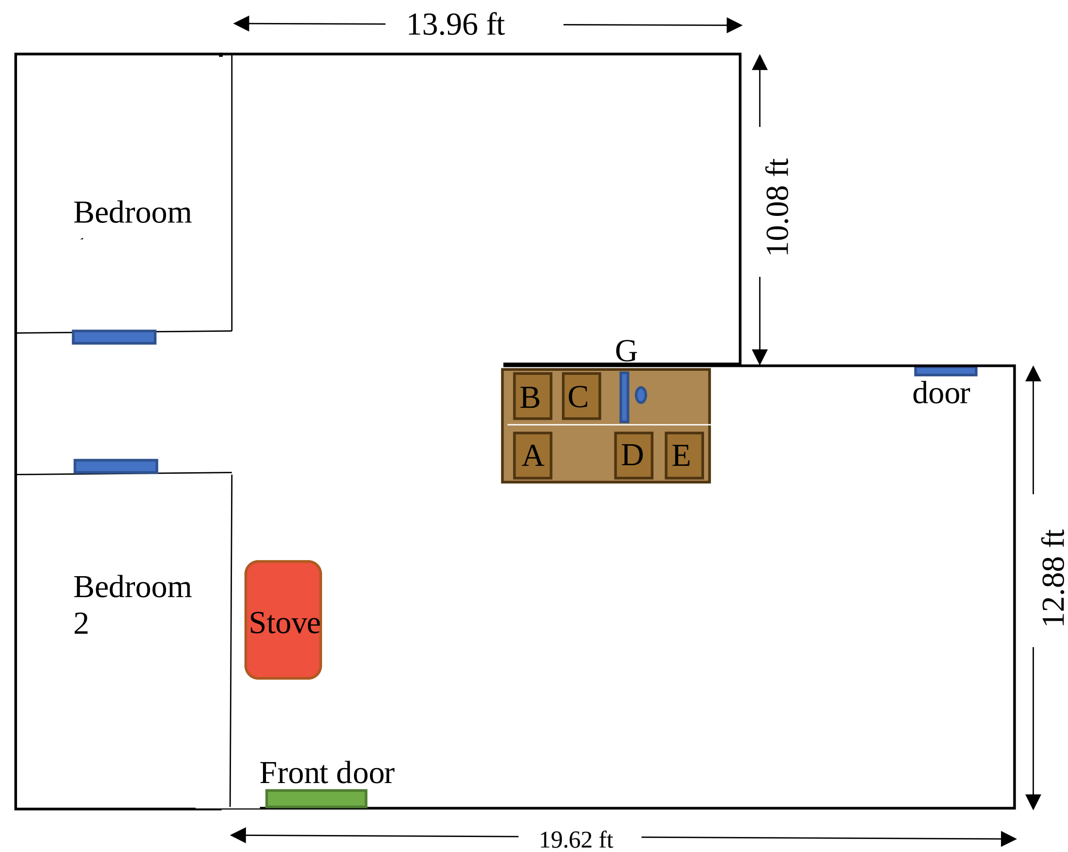

Figure 2-2. Floor Plan and Instrument Placement in Shiprock, NM

2.2.2 Fuels

Black Mesa coal was used in all experiments presented here. Although all the coal was purchased within the reservation, it is likely it came from multiple lots. Pine and cedar were used for kindling and to create the charcoal bed.

2.2.3 Stoves

At Fort Defiance, the home was heated with a Wonderluxe automatic coal burning circulator Model B2350 (United States Stove Co., South Pittsburg, TN) with a chimney (Figure 2-3). It is 32.25 in x 33.5 in x 19.25 in (81.9 cm x 85.1 cm x 48.9 cm), not including the blower, and weighs 240 pounds (109 kg). The brick-lined firebox has a volume of 4.05 ft^3 (0.115 m^3) and the stove is rated to heat an area of 1800 ft^2 (167.2 m^2). It was installed approximately one year before the experiments were conducted.

Figure 2-3. Wonderluxe stove at Ft. Defiance, Figure AZ

At Shiprock, a Navajo Hybrid Stove (Woodstock Soapstone CO., West Lebanon, NH) was used for the collocation experiments (Figure 2-4). This stove is 36.5 in x 19.5 in x 26 in (92.7 cm x 49.5 cm x 66.0 cm) and weighs 310 lbs (140.6 kg). It's rated to heat an area of up to 1,000 ft^2 (92.9 m^2) and has a firebox size of 1.2 ft^3 (0.034 m^2). The Navajo Hybrid Stove is EPA-certified, burns both wood and coal, and was designed specifically for the Navajo. The stove users received this stove about one year ago during the First Pilot Study.

Figure 2-4. Navajo Hybrid Stove

2.2.4 Pollutants

PM_{10}

PM_{10}, or particulate matter of aerodynamic diameter $\leq 10\ \mu m$ was measured because it is a byproduct of incomplete wood/coal combustion and can be formed through the condensation of combustion gases (Naeher et al., 2007). Elevated concentrations of PM_{10} have been associated with increased risks of mortality due to cardiovascular and respiratory disease in China (Lu et al., 2015).

$PM_{2.5}$

$PM_{2.5}$, particulate matter of aerodynamic diameter $\leq 2.5\ \mu m$, also known as the fine fraction, was measured because it is also a byproduct of incomplete wood and coal combustion and can also be formed through the condensation of combustion gases (Naeher et al., 2007; Belanger and Triche 2008). Due to the small size of the fine particulate matter, they are able to penetrate more deeply in to the lungs and be transported over longer distances (Pope and Dockery 2006).

Carbon Monoxide (CO) and Carbon Dioxide (CO_2)

CO and CO_2 were also measured because they are byproducts of incomplete combustion. Carbon monoxide is an asphyxiant as well as a principal gaseous pollutant from wood smoke (Naeher et al., 2007). Champion et al., 2017b also concluded that CO can be used to estimate $PM_{2.5}$ emissions using wood and coal that are commonly used in the Navajo Nation. Although carbon dioxide is not recognized by the USEPA as a criteria pollutant, it is recognized by many scientists as a major greenhouse gas (MacCarty et al., 2008; Lashof and Ahuja, 1990; Solomon et al., 2008; IPCC, 2014) and can lead to loss of consciousness and death at very high concentrations (Permentier et al., 2017).

2.2.5 Instruments

<u>DustTraks</u>

The DustTrak II Model 8530 (TSI, Shoreview, MN, Range: 0.001 – 400 mg/m^3, Resolution: $\pm$0.1% of reading or 0.001 mg/m^3) is a single-channel photometric instrument with an operational temperature range from 0 – 50°C and particle size range from 0.1 to 10 μm. The DustTraks are able to monitor PM_1, $PM_{2.5}$, PM_4, or PM_{10} depending on the size-selective impactor used at logging intervals between 1 second and 1 hour.

Prior to every sampling event, the DustTraks were zeroed, the flow was calibrated, and the $PM_{2.5}$ impactor was cleaned and the impactor plate was oiled as recommended in the manual (TSI 2013a). The flow was calibrated with a primary air flow DryCal calibrator, a MesaLabs Bios Defender 510-M (Brandt Instruments, Inc., Prarieville, LA) with a flow range of 50 – 5,000 mL/min, and accuracy of +/- 1.0%.

<u>QTraks</u>

CO and CO_2 were measured using five QTraks Model 7575 (TSI, Shoreview, MN, Range: 0 – 5000 ppm for CO_2 and 0 – 500 ppm for CO, Resolution: 1 ppm for CO_2 and 0.1 ppm for CO, Accuracy: $\pm$3% of reading or $\pm$50 ppm for CO_2 and $\pm$3% of reading or 3 ppm for CO). These units also measure relative humidity (RH), temperature, and barometric pressure (BP). The QTrak is operational between 5° and 50° C.

E-BAMs

The E-BAM Model 9800 (Met One, Grants Pass, OR, Range: -0.005 – 65.530 mg/m^3, Accuracy: $\pm$10% of the indicated value for hourly measurements, Resolution: 1 μg/m^3) measures and records $PM_{2.5}$ and PM_{10} concentration levels using beta-ray attenuation. One E-BAMs (E-BAM 2) sampled $PM_{2.5}$ and one E-BAM (E-BAM 3) sampled PM_{10} for this experiment. The operating temperature range for the E-BAM is from -25 to 40°C for continuous sampling.

Due to the different methods in determining PM concentration (beta-ray attenuation vs photometry), it was necessary to determine a correlation factor to allow comparison of the E-BAM and the DustTrak $PM_{2.5}$ concentrations.

Each instrument was identified by its serial number but relabeled with an identification information (ID) number for simplicity. Table 2-1 shows the corresponding ID for all instruments. The Schematic ID column contains the corresponding letter that identifies the specific instrument for Figures 2-1 and 2-2.

Table 2-1. Instrument ID and Serial Numbers

Instrument Type	ID Number	Serial Number	Schematic ID
DustTrak	4313	8530174313	B
DustTrak	4315	8530174315	C
DustTrak	4316	8530174316	E
DustTrak	4317	8530174317	A
DustTrak	4318	8530174318	D
QTrak	001	7575X1745001	J

QTrak	003	7575X1745003	G
QTrak	004	7575X1745004	F
QTrak	005	7575X1745005	H
QTrak	006	7575X1745006	K
E-BAM	2	J2568	2
E-BAM	3	M6068	3

2.3 Experimental Set Up:

2.3.1 Ft. Defiance, AZ

Figure 2-1 shows the placement of the instruments in these experiments. The mass of wood used for the charcoal bed and the mass of added coal were measured using a Digital Kitchen Scale Model 3899 (Taylor Precision Products, Inc, Las Cruces, NM, Maximum Weight: 30 lbs (13.6 kg)). The amount and times that coal and wood were added to the stove were also recorded. The time to establish the charcoal bed was recorded and then the first piece of coal was added to the stove. Enough coal was added to the stove for at least an 8-hour burn event. Fuel was added to the stove for about 8 hours each day, starting at about 9am and ending at around 5pm. Times, weights, and detailed notes regarding activities that may affect stove use and indoor air quality were recorded for this home.

The total weight of wood and coal added each day is reported in Table 2-2.

Table 2-2. Masses of Wood and Coal for Burn Events

	Wood (kg)	**Coal (kg)**	**Total (kg)**
Day 1	13.1	6.81	19.9
Day 2	8.46	3.83	12.3
Day 3	6.52	6.24	12.8

2.3.2 Shiprock, NM

Figure 2-2 shows the placement of the instruments in the Shiprock home. At this location, the home owner operated the stove without intervention from the researchers. Diné College and CU Boulder researchers visited the home once per sampling day to verify the instruments were working properly. Stove users received an activity log for each day of sampling to document non-stove activities such as cooking and cleaning as well as stove activities like the addition of wood and/or coal.

2.3.3 Combustion Process

In both locations, typical Navajo burning practices were followed. A wood charcoal bed was first established using cedar and pine wood prior to adding coal because this is common practice in the Navajo Nation (Bunnell et al., 2010; Champion 2017b).

2.3.4 Experiments

Experiment 1 – Determine correction factors for the 5 DustTraks

A total of 72 hours of continuous sampling was conducted at each location using the five DustTraks. All DustTraks were located between 3 – 5 ft (0.91 – 1.52 m) from the heating stove at both homes and between 8 - 12 in (20.3 – 30.5 cm) from each other and synced to the same time. They were also set to log every minute.

At Fort Defiance AZ, all five DustTraks were placed in the same room as the heating stove, with the inlet 2.92 ft (0.89 m) above the ground. The DustTraks were placed together as shown in Figure 2-1.

In Shiprock NM, all five DustTraks were between 3 – 4 ft (0.91 – 1.22 m) above the ground, on two shelves at a desk in the home. Three DustTraks were placed on the lower shelf and the other two were placed on the shelf above (Figure 2-2).

Experiment 2 – Determine correction factors for the 5 QTraks

A total of 72 hours of continuous sampling was conducted with five QTraks at Fort Defiance, AZ. Collocation of the QTraks was not conducted at the home in Shiprock, NM. All five QTraks were placed in the same room as the heating stove, such that the probe was 2.85 ft (0.87 m) off the ground and between 3 – 8 in (7.6 – 20.3 cm) from each other and synced to the same time. They were located between 3 – 5 ft (0.91 – 1.52 m) from the heating stove and set to log every minute. The QTraks monitors were arranged along the edge of the table and the probes were clustered together in a circle.

Experiment 3 – E-BAM $PM_{2.5}$ and PM_{10} Ratios

A total of 72 hours of continuous sampling was conducted with two E-BAMs in Fort Defiance, AZ. No experiments with the E-BAMs were conducted at the home in Shiprock, NM. The two E-BAMs were placed in the same room as the heating stove such that their inlet was 6.7 ft (2.04 m) above the ground and 3 ft (0.91 m) from each other (Met One Instruments, Inc. 2008). They were located between 3 – 5 ft (0.91 – 1.52 m) from the heating stove. The E-BAMs were set to log every hour because it is the most accurate concentration measurement according to the user manual (Met One Instruments, Inc 2008). Within the hourly concentration measurement, the E-BAM takes the first four minutes to establish a baseline reading and then the last four minutes to establish a span reading. Therefore, the E-BAM samples for 52 minutes every hour.

Experiment 4 – DustTrak and E-BAM Collocation

A total of 72 hours of continuous sampling was conducted with five DustTraks and one E-BAM (E-BAM 2) in Fort Defiance, AZ. This experiment was not repeated at the home in Shiprock, NM. The five DustTraks and E-BAM 2 were placed in the same room as the heating stove. The DustTraks were placed on a table with the inlet 2.92 ft (0.89 m) off the ground and clustered together with one in front and two on each side, behind the first DustTrak (Figure 2-1)

They were located between 3 – 5 ft (0.91 – 1.52 m) from the heating stove. E-BAM 2 was placed in the same room as the heating stove, such that its inlet was 6.7 ft (2.04 m) above the ground and synchronized with the DustTrak time. E-BAM 2 was located between 3 – 5 ft (0.91 – 1.52 m) from the heating stove. The DustTraks were set to log at minute intervals while E-BAM 2 was set to log hourly.

2.4 Data Analysis

Correction factors and correlations (R^2) for the DustTraks and QTraks were determined using linear regressions. To obtain a more robust set of correction factors, the hourly concentrations were compared between each unit and an average concentration calculated from the five units.

2.5 Results and Discussion

2.5.1 Experiment 1 – Determine correction factors for the 5 DustTraks

The 24-hour average $PM_{2.5}$ concentration for each of the three sampling days was averaged to obtain a single 24-hour average over the entire sampling period. The 3-day 24-hour $PM_{2.5}$ concentration in Fort Defiance, AZ was 50.4 $\mu g/m^3$. This value was higher than the average in Shiprock, NM (23.3 $\mu g/m^3$). This difference in concentrations was likely due to several reasons. First, the home in Fort Defiance used an uncertified Wonderluxe B2350 stove while the home in Shiprock used an EPA-certified Navajo Hybrid Stove. Second, Navajo EPA and CU Boulder researchers operated the stove in Fort Defiance and burned more fuel to generate more pollution, while the stove in Shiprock was operated only by the home owner.

Collocation data from Fort Defiance and Shiprock were combined because the reported concentrations or values are time dependent. Obtaining a single set of correlation factors for a larger concentration range will make the correlation factors more broadly applicable. Linear regressions for the DustTraks at each location are included in Appendix A.

Plots for each of the five DustTrak units versus the Average DustTrak for both locations are shown in Figures 2-3 to 2-7. The line of best fit, equation, and Pearson's correlation coefficient are also shown on each plot and tabulated in Table 2-3.

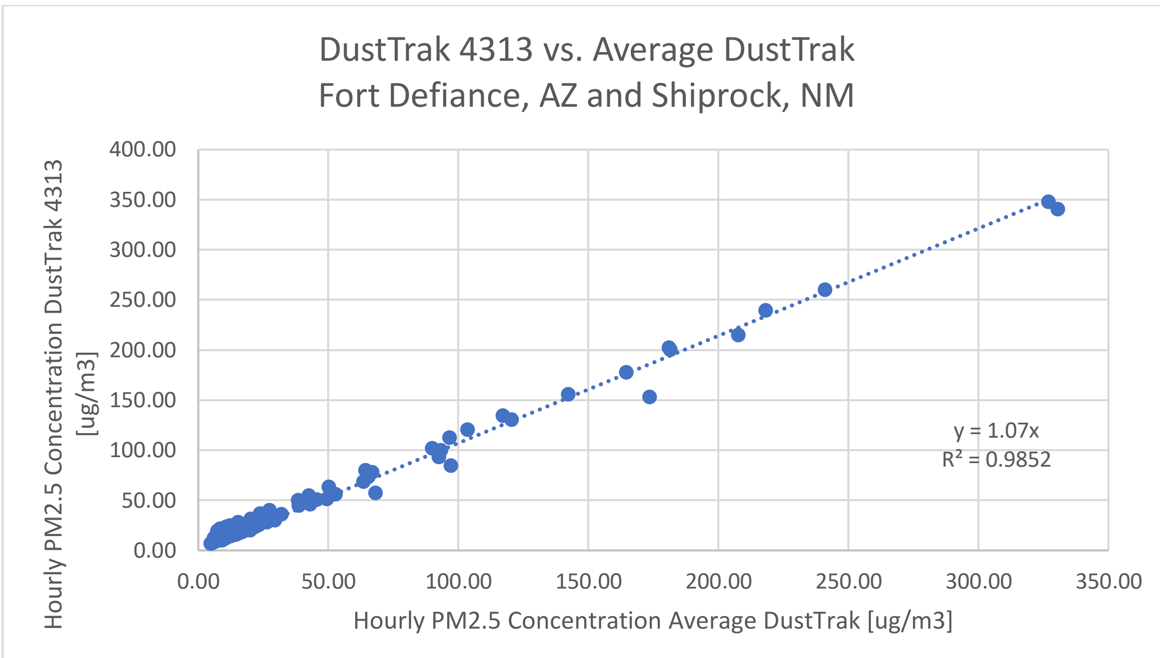

Figure 2-5. DustTrak 4313 vs. Average DustTrak

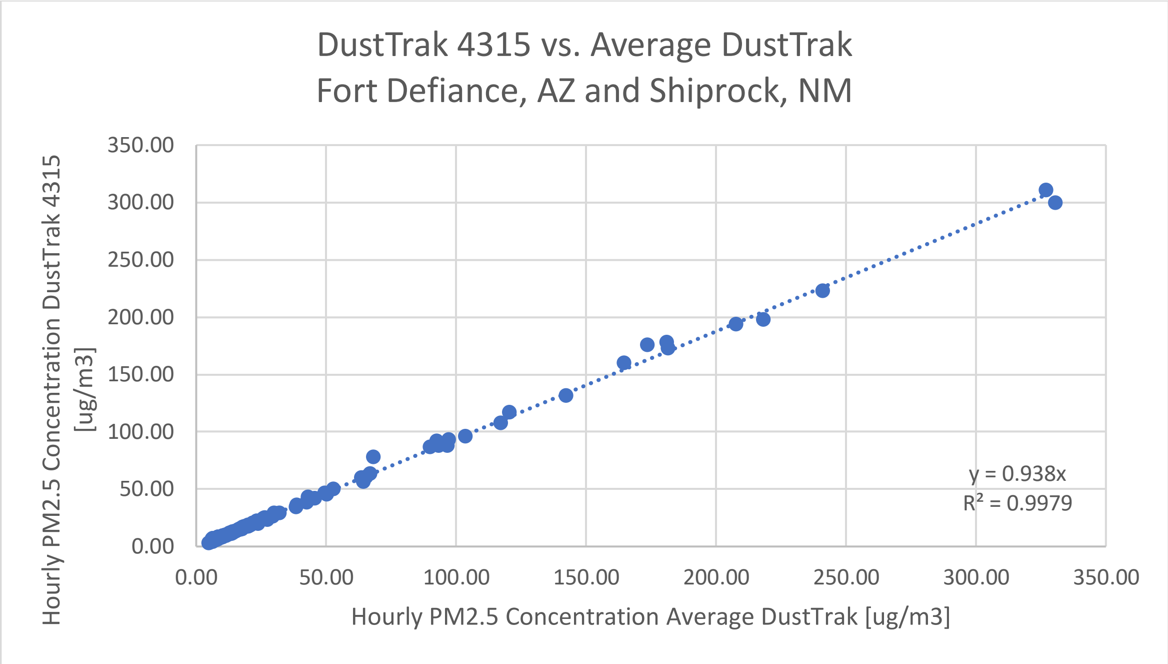

Figure 2-6. DustTrak 4315 vs. Average DustTrak

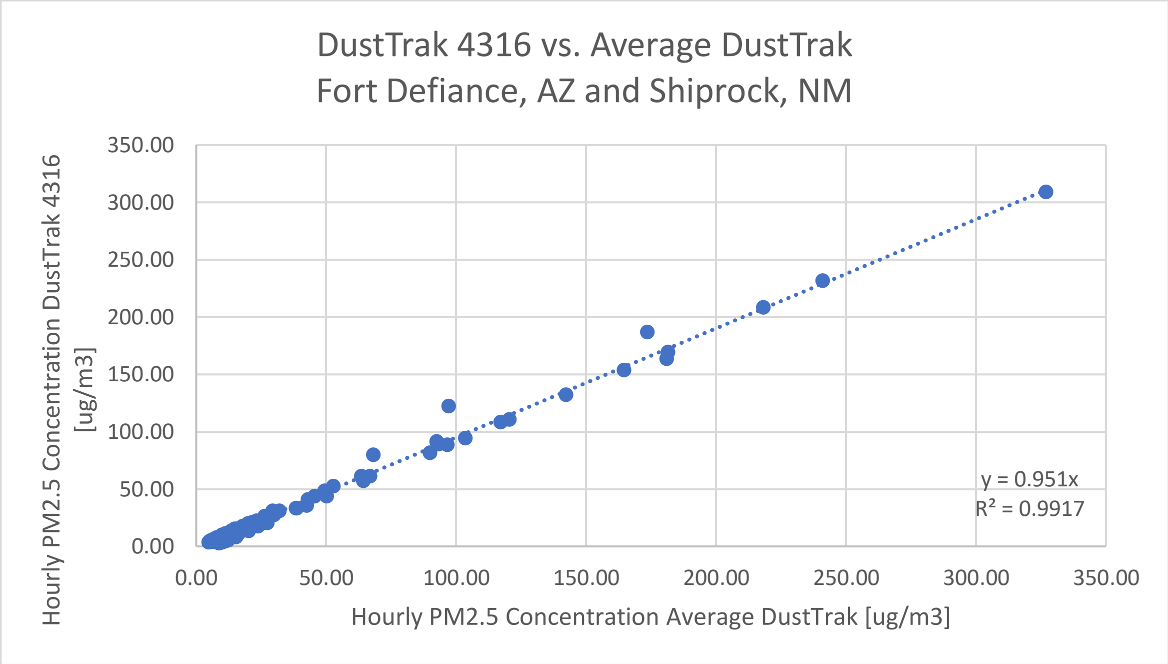

Figure 2-7. DustTrak 4316 vs. Average DustTrak

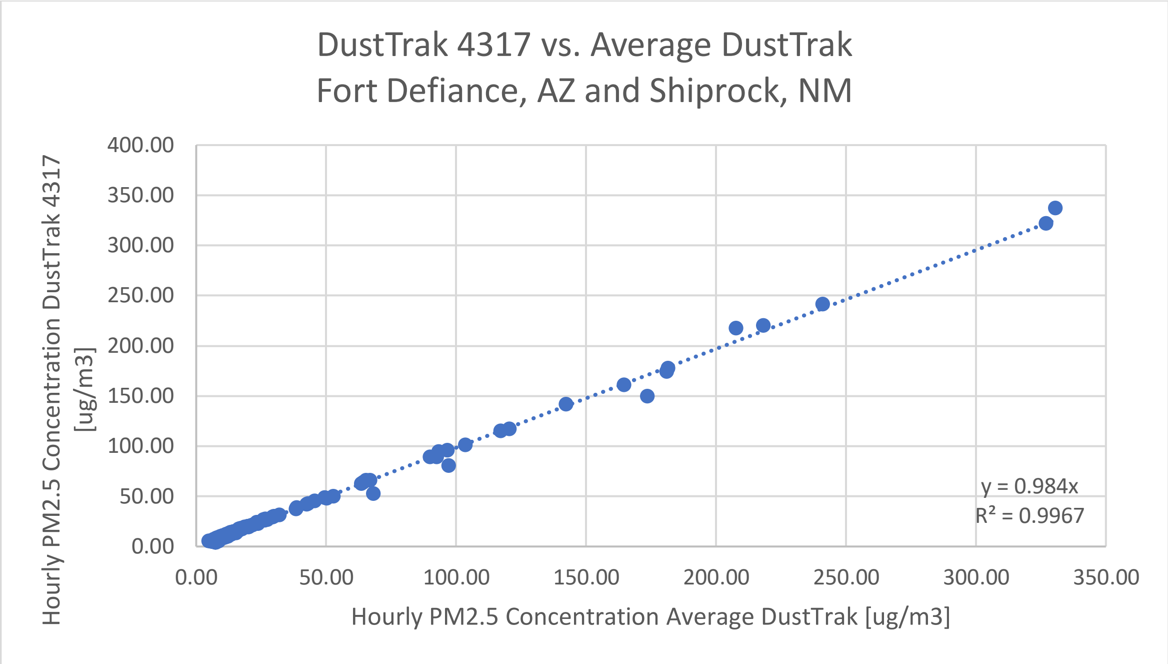

Figure 2-8. DustTrak 4317 vs. Average DustTrak

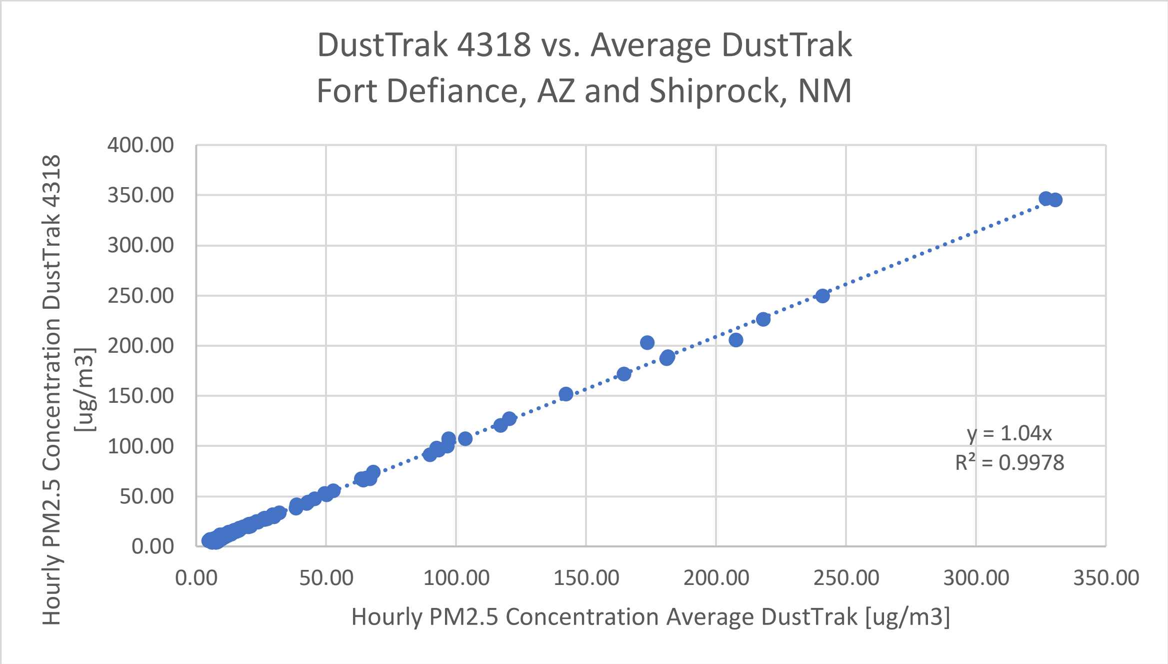

Figure 2-9. DustTrak 4318 vs. Average DustTrak

Table 2-3. Relative DustTrak m, b, and R^2 for Fort Defiance, AZ & Shiprock, NM

	Unfixed Intercept			**Fixed Intercept**	
DustTrak	***m***	***b***	**R^2**	**m**	**R^2**
4313	1.03	5.22	0.9909	1.07	0.9852
4315	0.943	-0.683	0.9981	0.938	0.9979

4316	0.968	-1.89	0.9928	0.951	0.9917
4317	0.993	-1.12	0.9970	0.984	0.9967
4318	1.06	-1.29	0.9981	1.04	0.9970
Average	1	0	1	1	1

The correlation slope factors and correlation for a fixed intercept (b = 0) are given in the two columns from the right. These values are not significantly different from the values where the intercept was not fixed. The correlation slope factors (m) for the fixed intercepts are the correction factors for the DustTrak units for the Average DustTrak. However, because they were all very close to one, a correction factor was not applied to the data.

2.5.2 Experiment 2 – Determine correction factors for the 5 QTraks

QTraks were collocated at Fort Defiance only. The minute data from the QTraks were used to compute hourly averages for each measured variable (temperature, relative humidity (RH), barometric pressure (BP), CO, and CO_2). For 15 minutes of one hour, QTrak 001 lost power because it was disconnected from the outlet. Therefore, one hourly averaged data point consists of 45 minutes worth of data for the five measured variables. The correlation slope factors, inherent biases, and correlations for each variable for each QTrak versus the average of all five were determined through linear regression. Rather than choosing a single QTrak to be the "reference", the average of all five was used. This method is more robust than selecting an actual monitor to be the "reference".

Overall, the five QTraks agreed well for measurements of temperature, carbon dioxide, Relative Humidity, and Barometric Pressure. Only the measurements for carbon monoxide showed large variations among QTraks. Following the collocation experiment, the CO probes for both QTrak 004 and QTrak 005 were rehydrated before being deployed in homes, as recommended by the manufacturer.

2.5.2.1 QTrak - Temperature

Table 2-7 shows the correlation slope factors, intercepts, and the correlations for indoor temperature. The linear regression analysis plots for each QTrak are shown in Figures 2-8 to 2-12).

Table 2-4. Relative Correlation Slope Factors, Intercepts, and Correlation for Temperature

	Unfixed Intercept			**Fixed Intercept**	
QTrak	***m***	***b***	**R^2**	**m**	**R^2**
001	1.01	-0.896	0.9998	1.00	0.9997
003	0.988	0.580	0.9998	0.996	0.9997
004	0.995	0.731	1	1.00	0.9999
005	0.993	0.163	0.9999	0.995	0.9999
006	1.01	-0.579	0.9998	1.01	0.9998
Average	1	0	1	-	-

For indoor temperature, all QTraks had correlation slope factors very close to 1, small inherent biases ($< 1°F$), and good correlation ($R^2 \geq 0.9998$) with the Average QTrak. When the intercept was fixed (b = 0), the values for the correlation slope factors and correlations did not change much, indicating that inherent biases are negligible.

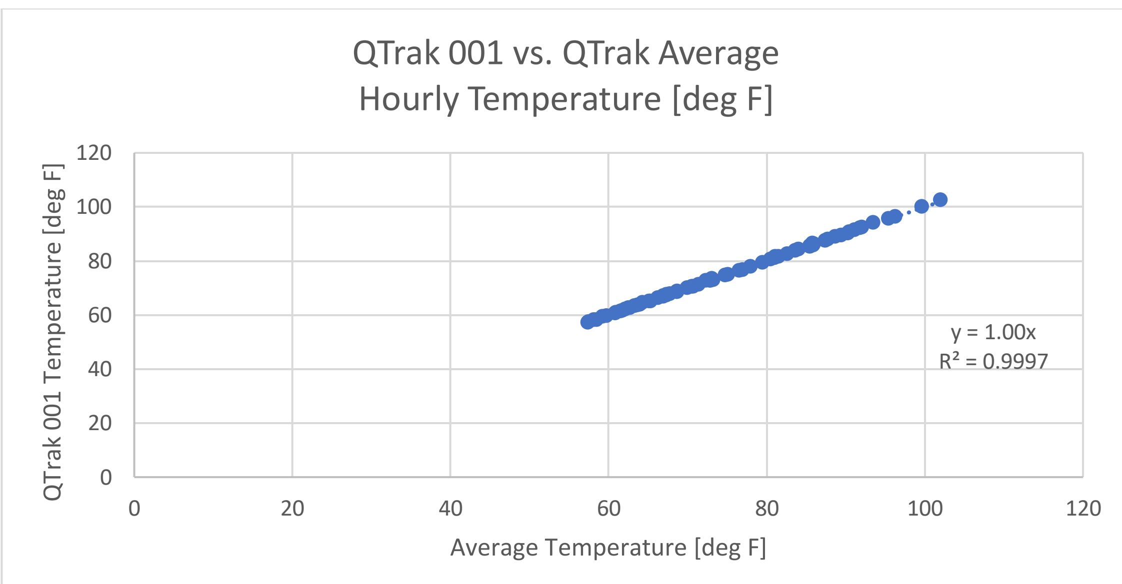

Figure 2-10. QTrak 001 vs. Average QTrak – Temperature

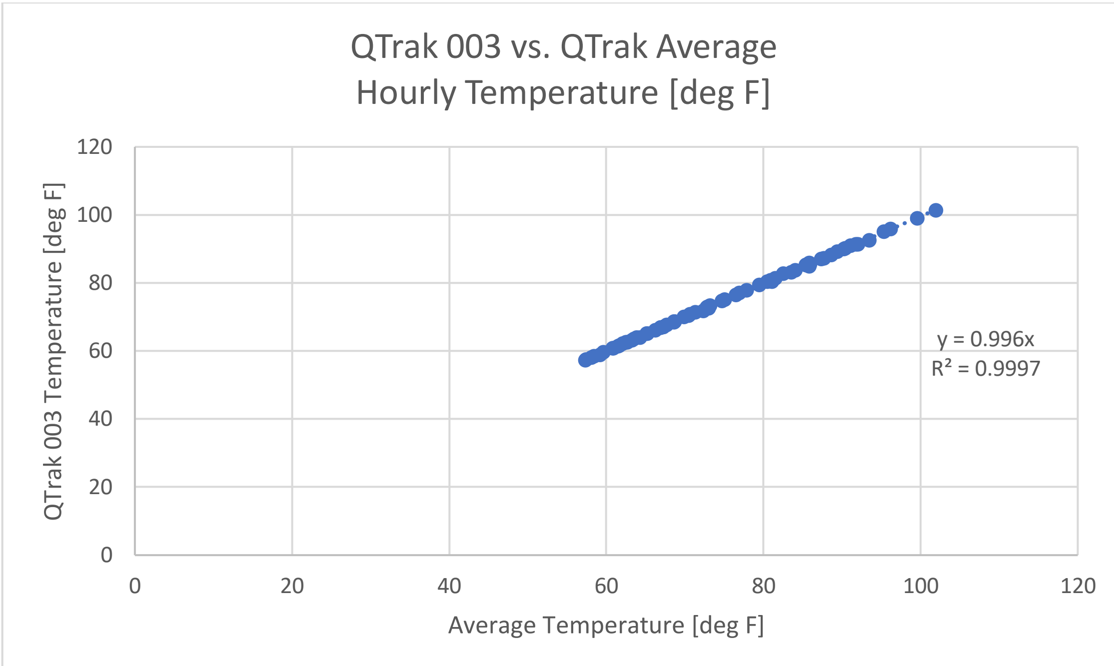

Figure 2-11. QTrak 003 vs. Average QTrak - Temperature

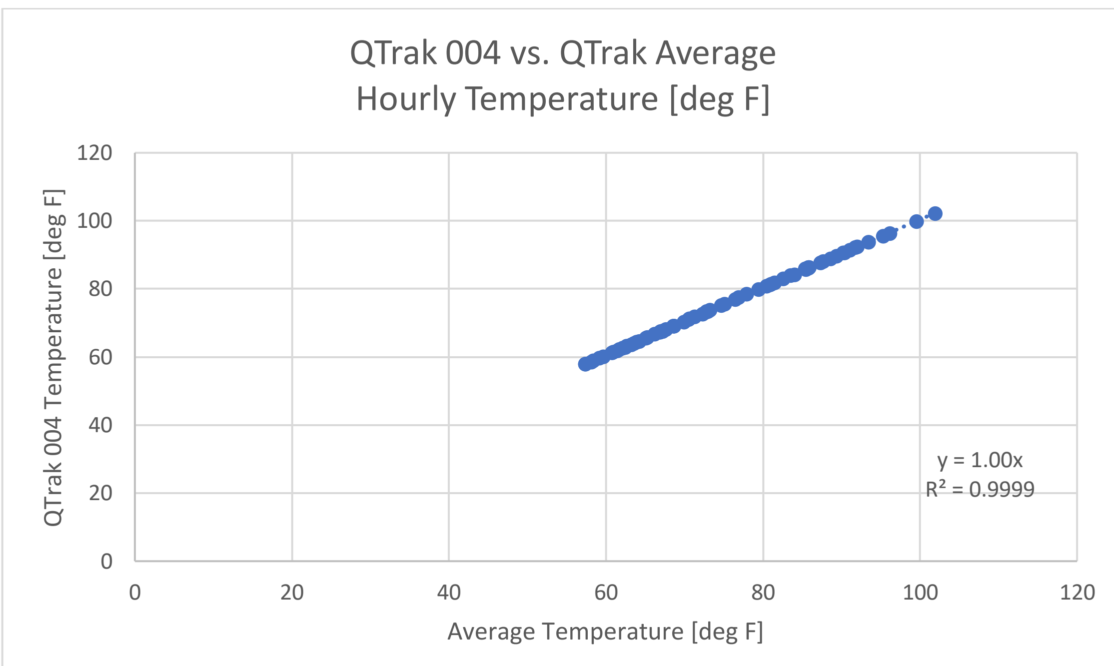

Figure 2-12. QTrak 004 vs. Average QTrak - Temperature

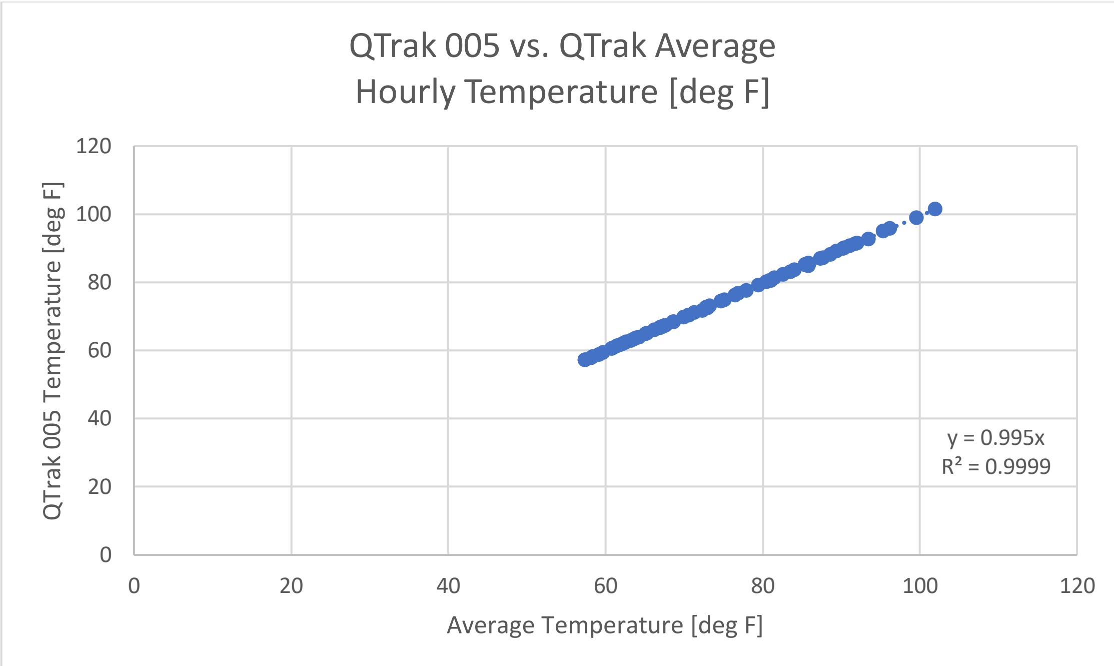

Figure 2-13. QTrak 005 vs. Average QTrak – Temperature

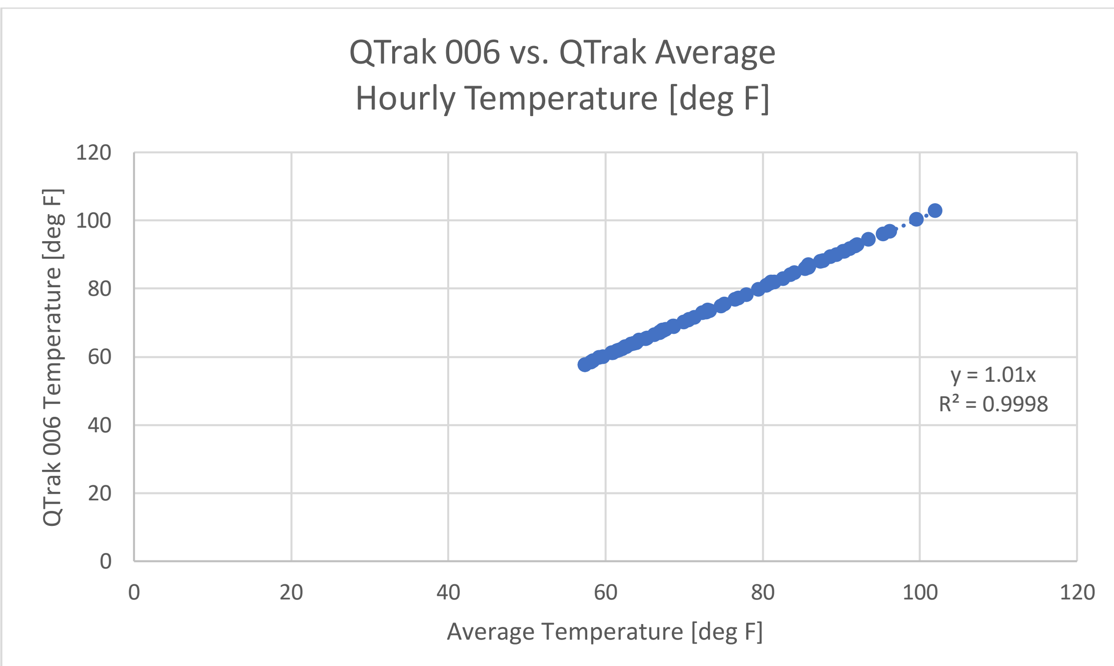

Figure 2-14. QTrak 006 vs. Average QTrak - Temperature

Overall, all five QTraks reported good correlation and low inherent biases for temperature with the Average QTrak. After fixing the intercept to zero, no significant differences were determined for the correlation slope factors or correlation. The correction factors didn't deviate from one significantly, so no correction factor was applied to the temperature data.

2.5.2.1 QTrak – Carbon Dioxide (CO_2)

Correlation slope factors, intercepts, and Pearson's correlation for carbon dioxide are tabulated below in Table 2-8. Plots with linear regression analysis for CO_2 concentrations reported by each QTrak are shown in Figures 2-13 to 2-17.

Table 2-5. Relative Correlation Slope Factors, Intercepts, and Correlation for CO_2

	Unfixed Intercept			**Fixed Intercept**	
QTrak	***m***	***b***	**R^2**	**m**	**R^2**
001	0.992	-4.21	0.9992	0.986	0.9992
003	0.940	26.1	0.9921	0.982	0.9900
004	1.01	-2.06	0.9999	1.00	0.9999
005	1.03	-1.38	0.9979	1.02	0.9979
006	1.04	-18.4	0.9962	1.01	0.9953

For CO_2, the correlation slope factors for the QTraks are relatively close to one. When the intercept was fixed to zero, the correlation slope factors didn't change significantly. Since they were also close to one, no correction factor was applied to the CO_2 data.

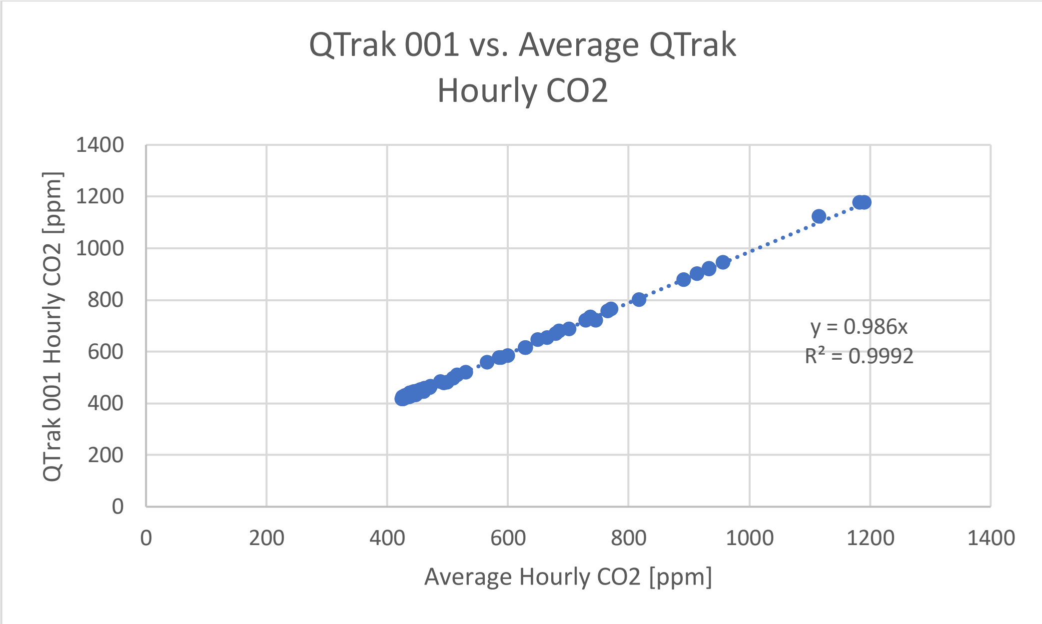

Figure 2-15. QTrak 001 vs. Average QTrak – CO_2

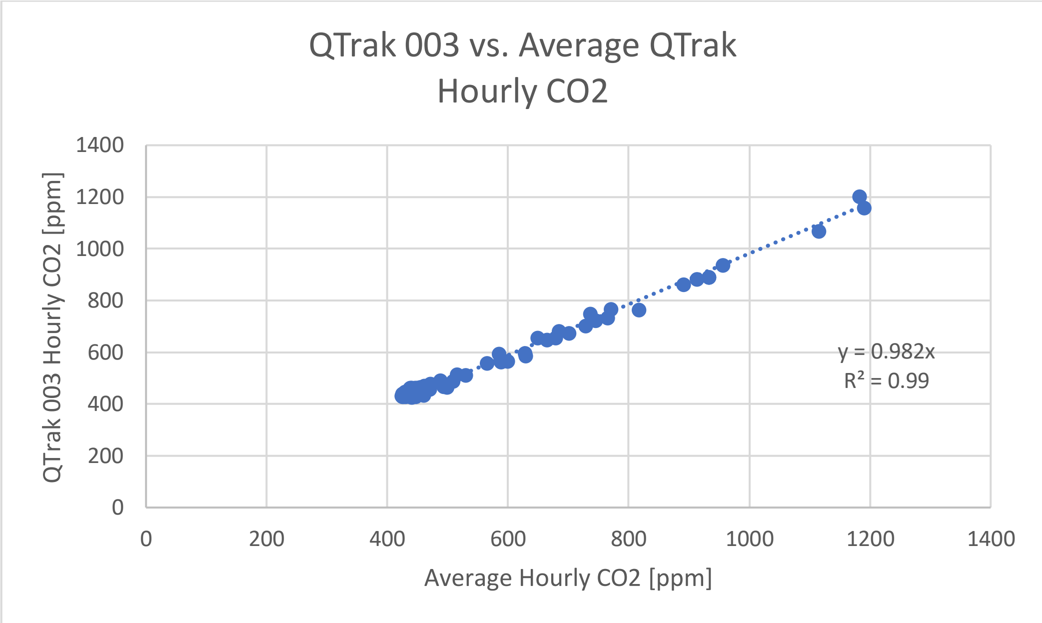

Figure 2-16. QTrak 003 vs. Average QTrak – CO_2

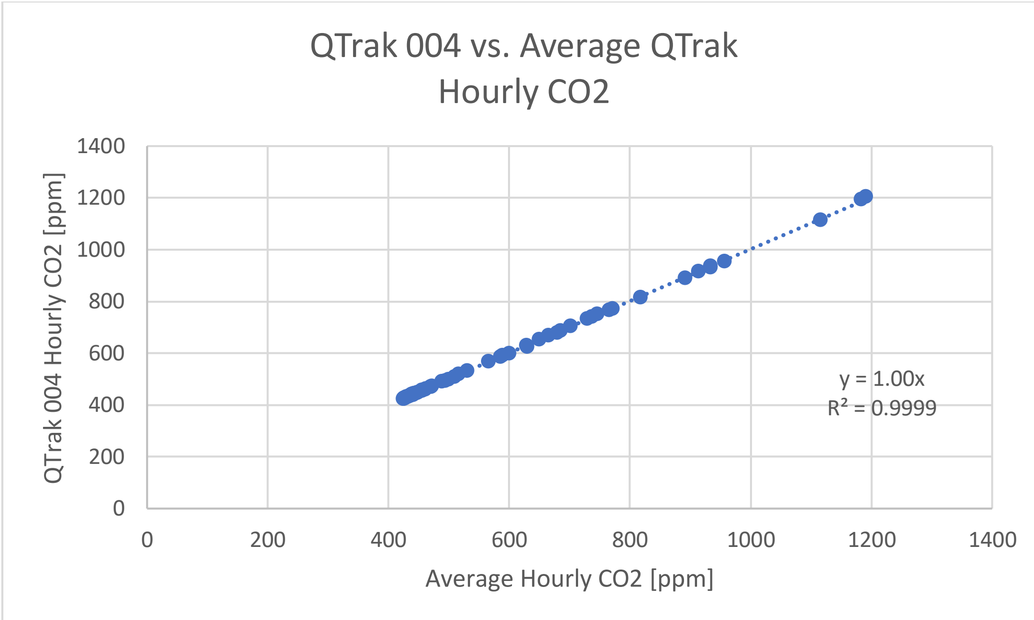

Figure 2-17. QTrak 004 vs. Average QTrak – CO_2

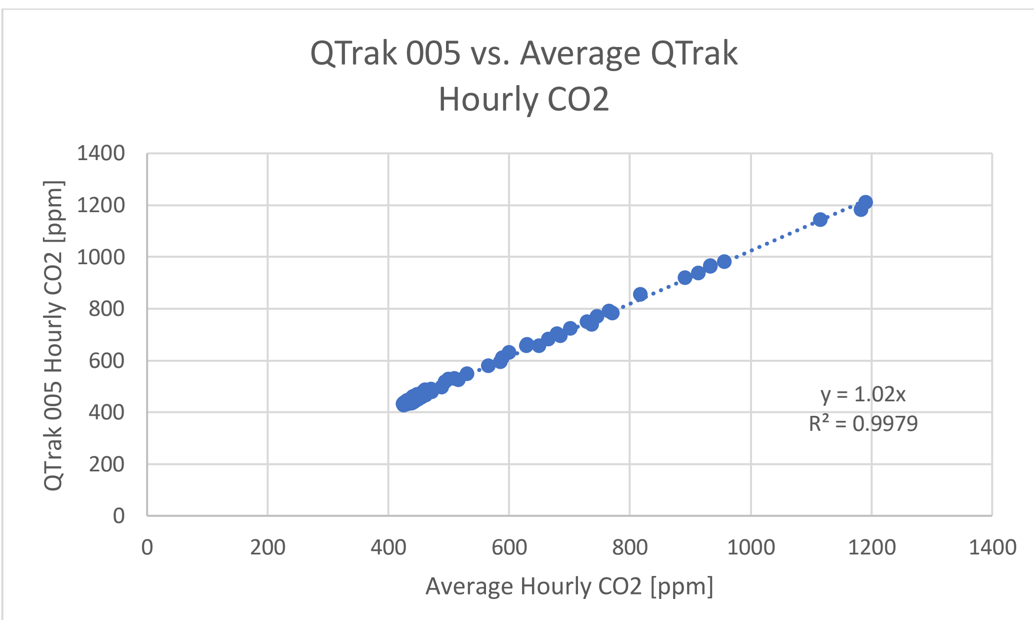

Figure 2-18. QTrak 005 vs. Average QTrak – CO_2

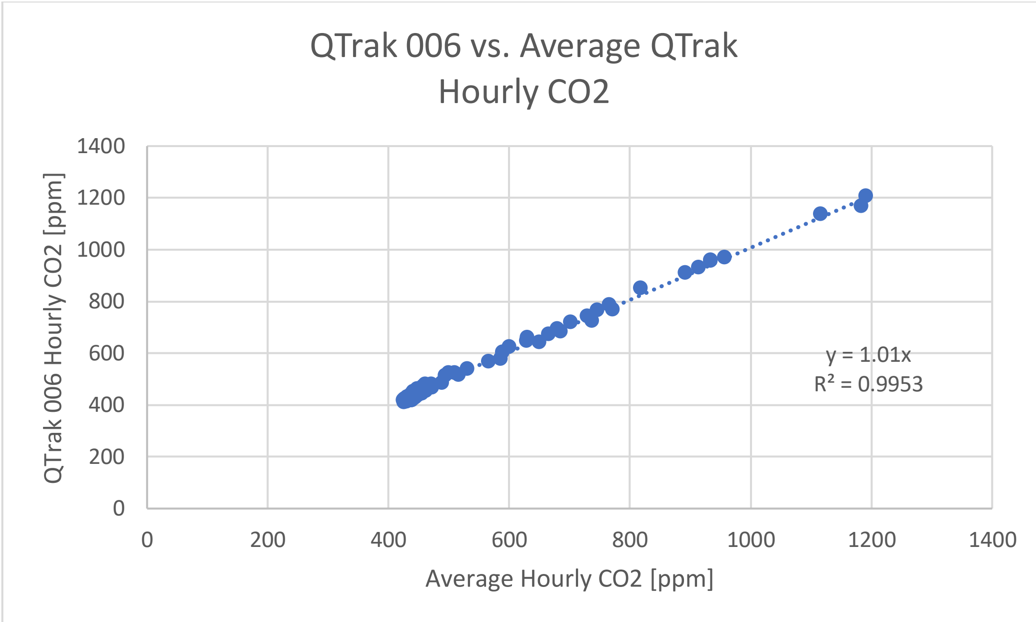

Figure 2-19. QTrak 006 vs. Average QTrak – CO_2

2.5.2.1 QTrak – Relative Humidity (RH)

Table 2-9 shows the correlation slope factors, intercepts, and correlation for relative humidity. Plots with linear regression analysis for RH (%) reported by each QTrak are shown in Figures 2-18 to 2-22.

Table 2-6. Relative Correlation Slope Factors, Intercepts, and Correlation for RH

	Unfixed Intercept			Fixed Intercept	
QTrak	***m***	***b***	$\mathbf{R^2}$	**m**	$\mathbf{R^2}$
001	1.02	-0.259	0.9989	1.01	0.9252
003	0.957	1.35	0.9979	1.02	0.9937
004	0.998	-0.249	0.9994	0.986	0.9993
005	0.967	0.692	0.9993	0.990	0.9982
006	1.06	-1.53	0.9979	0.986	0.9934

The correction slope factors and correlations for Relative Humidity for all five QTraks are close to one and their intercepts are relatively small. The largest deviation (QTrak 006) is about 7.2% of the 24-hour average RH (21.2%). Aside from QTrak 003 and 006, the intercepts of the remaining QTraks are less than or equal to about 3%. No correction factor was applied to the data for RH.

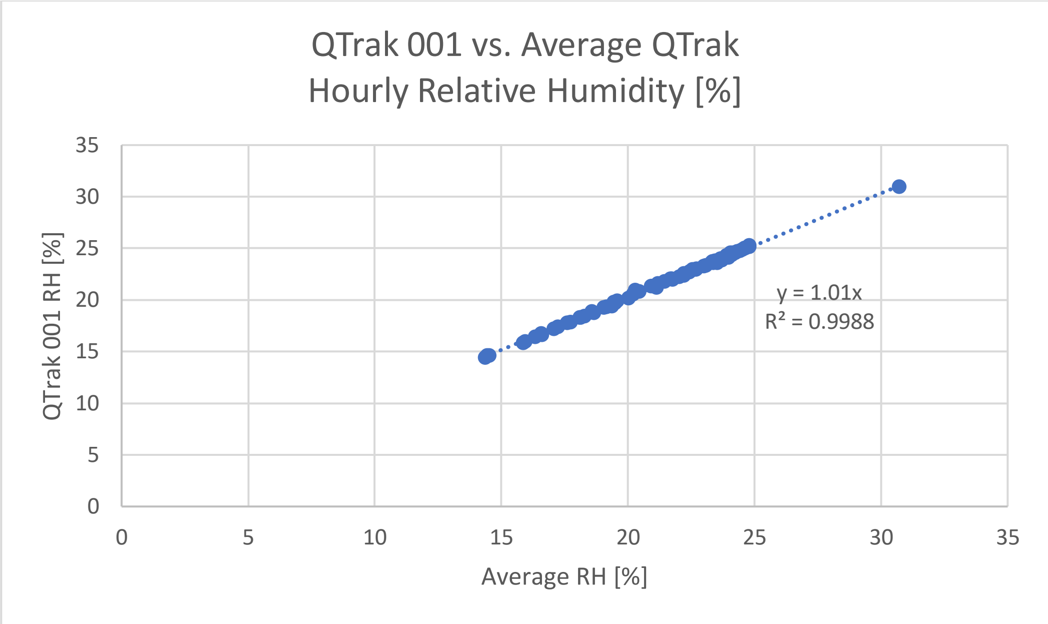

Figure 2-20. QTrak 001 vs. Average QTrak – RH

QTrak 001 reports a very good correlation (R^2) and correlation slope factor (m) with the Average QTrak RH values. The intercept is close to zero. There is one high RH value, ~31% for both the Average QTrak and QTrak 001. This was the RH of the first hour of sampling. Once the stove had been running for around hour, the relative humidity in the home dropped around 5% (from 30.74% to 16.6%). Researchers from CU and Navajo EPA noticed the significant decrease in RH in the home after an hour. Typically, Navajo homes place a pot of water on top of the stove to counteract the dryness. This practice was followed for this experiment as well, and around 1:00 PM on the first day, a pot of water was placed on top of the Wonderluxe stove. The RH values increased slightly after placing the water on top of the stove.

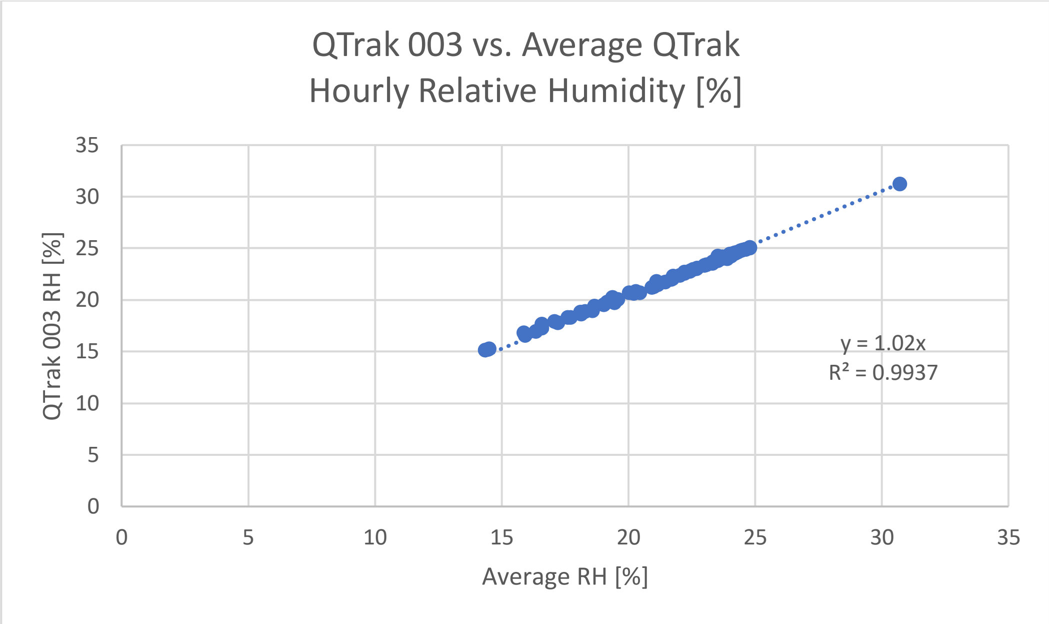

Figure 2-21. QTrak 003 vs. Average QTrak – RH

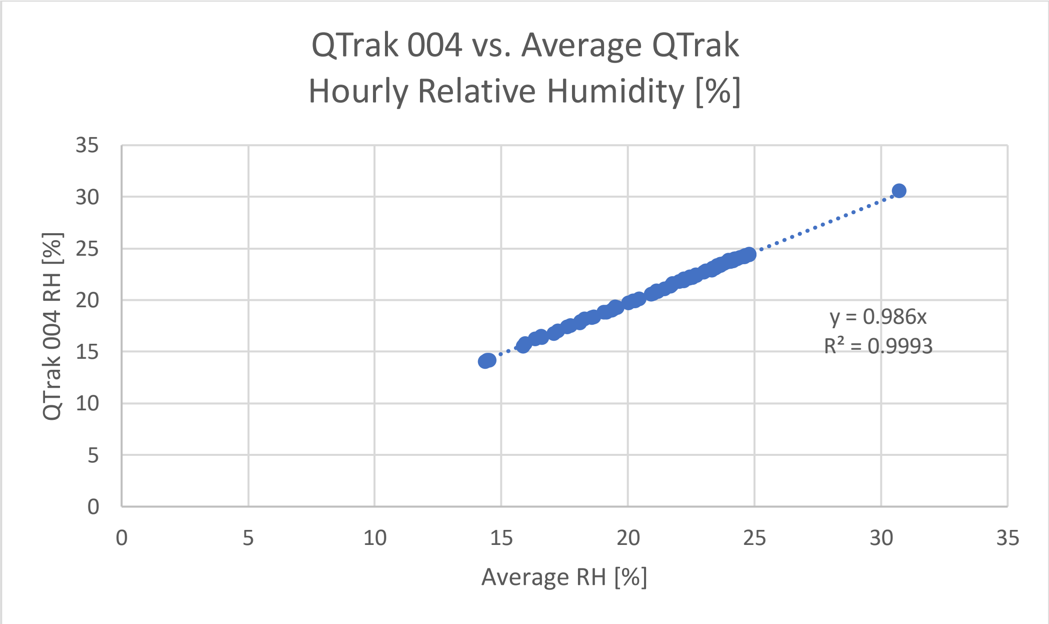

Figure 2-22. QTrak 004 vs. Average QTrak – RH

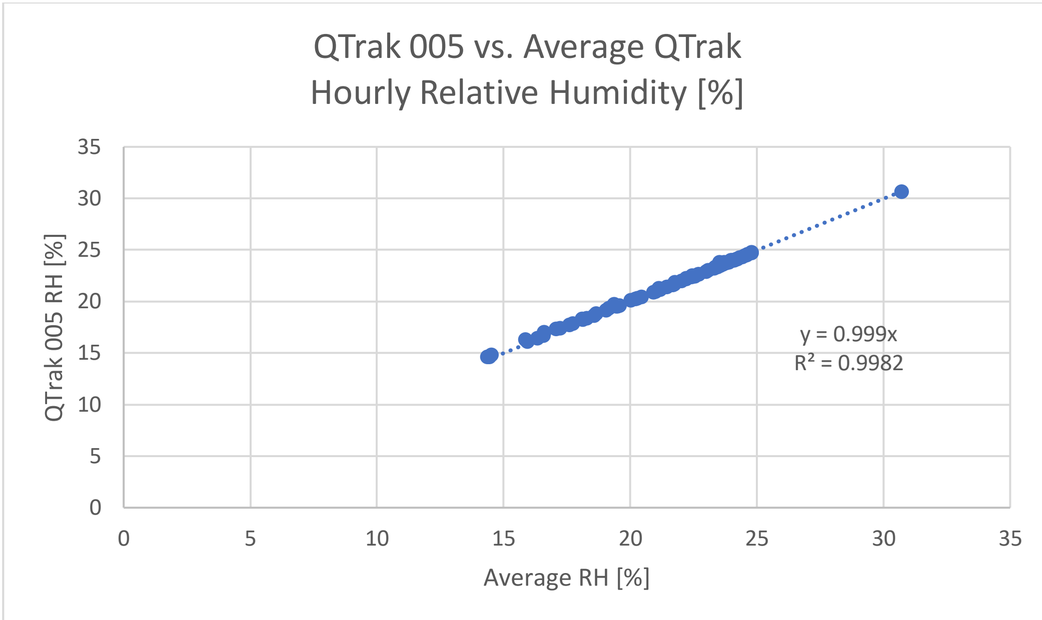

Figure 2-23. QTrak 005 vs. Average QTrak – RH

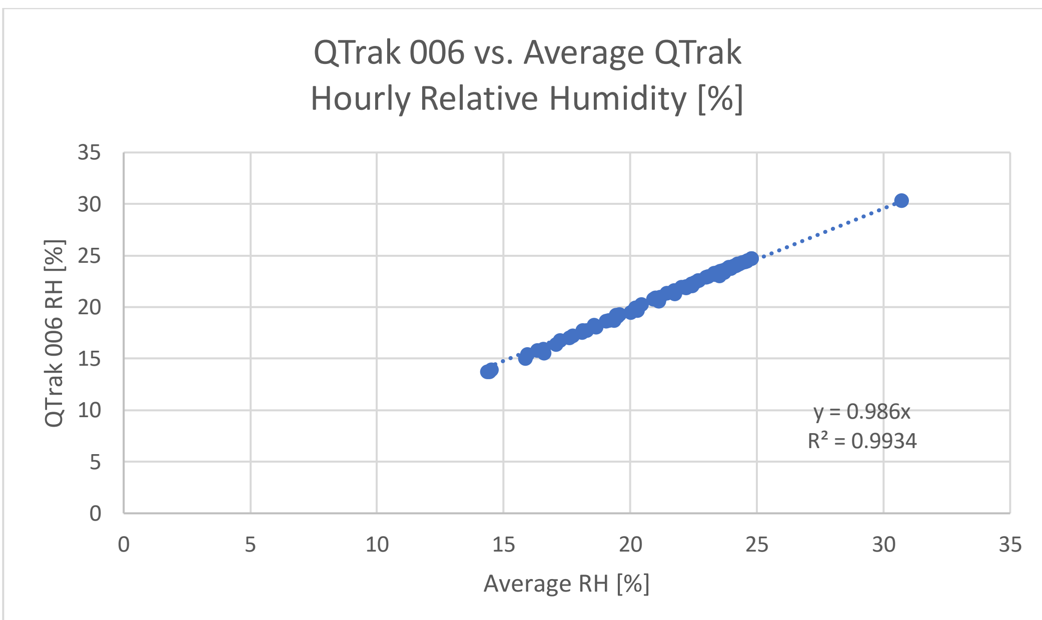

Figure 2-24. QTrak 006 vs. Average QTrak – RH

2.5.2.1 QTrak – Carbon Monoxide (CO)

Table 2-10 lists the correlation slope factors, intercepts, and correlations for CO. Plots with linear regression analysis for CO concentrations are shown in Figures 2-23 to 2-27, as reported by each QTrak.

Less than two months before the start of this experiment, the QTrak CO probes were calibrated according to standard protocol (TSI 2013b). However, both QTrak 004 and QTrak 005 reported an error (flashing 8888) with the maximum and minimum CO values. This error indicated that the value was over range, but since all QTraks reported CO concentrations lower than 5 ppm, this error likely has another cause. Following the collocation experiment and prior to being deployed for sampling, the CO probes for all QTraks were rehydrated.

Table 2-7. Relative Correlation Slope Factors, Intercepts, and Correlation for CO

	Unfixed Intercept			**Fixed Intercept**	
QTrak	***m***	***b***	**R^2**	**m**	**R^2**
001	1.56	0.0133	0.9606	1.57	0.9598
003	1.60	0.0148	0.957	1.61	0.9561
004	1.13	-0.0199	0.9007	1.11	0.8975
005	0.228	0.0023	0.7935	0.229	0.7926
006	0.486	-0.0104	0.8802	0.477	0.8756

The correlation slope factors for carbon monoxide for the five QTraks ranged from 0.2275 to 1.5631. The highest maximum CO concentration recorded was 4.6 ppm while the lowest maximum was 1 ppm. These values are within the published accuracy of the CO readings (3% of the reading or ±3 ppm, whichever is greater). Since the range of CO concentrations was small (~4 ppm), the variation in correlation slope factors between the QTraks is attributable to the QTrak CO probe limits of detection (T. Dieringer, personal communication, April 1, 2019).

Although two QTraks (005 and 006) had correction factors that were not close to one, no correction factor was applied to the data because of the reported errors. The data was collected a year prior to the collocation experiment and the QTraks were calibrated and deployed several times within that time period. The QTraks were recalibrated and a collocation experiment should be conducted again under conditions where higher concentrations of CO are generated to determine if there is a systematic error with the QTrak units.

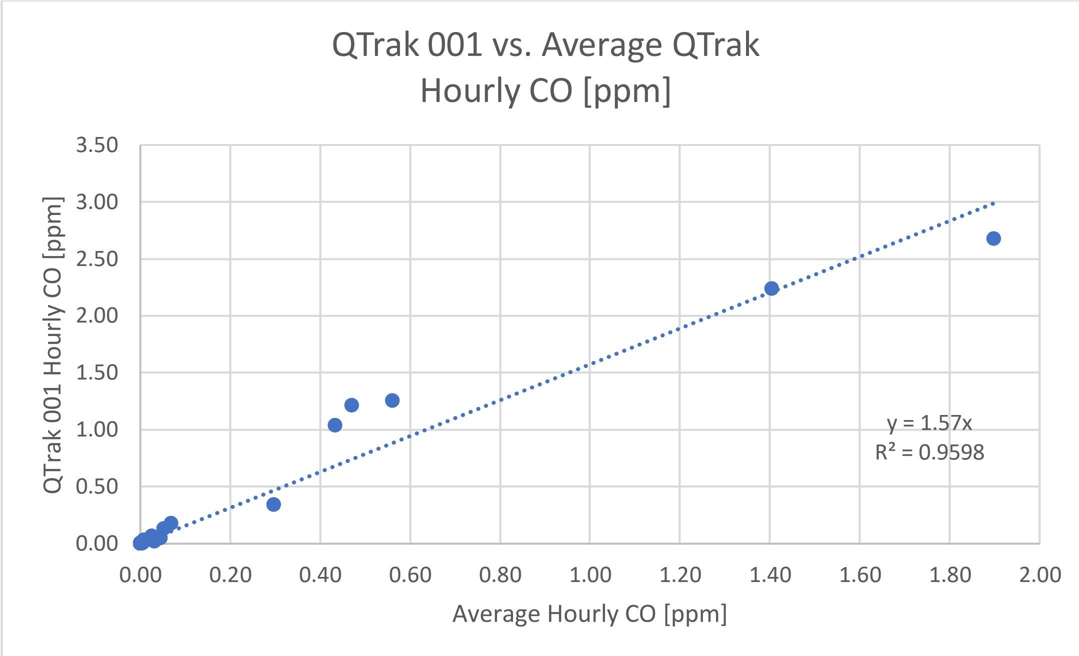

Figure 2-25. QTrak 001 vs. Average QTrak – CO

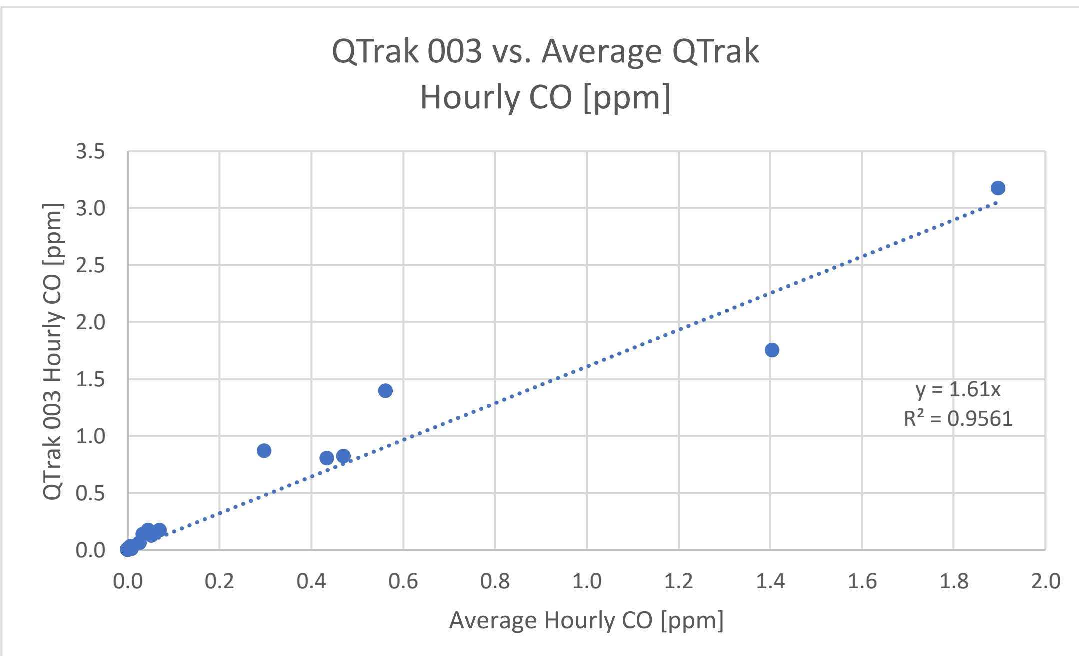

Figure 2-26. QTrak 003 vs. Average QTrak – CO

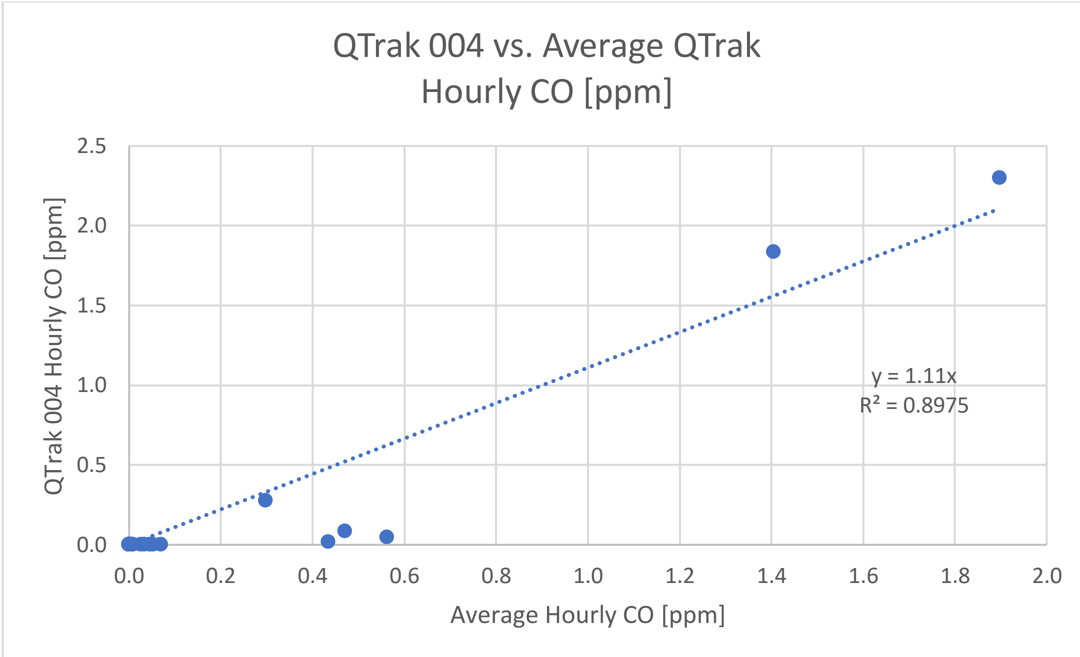

Figure 2-27. QTrak 004 vs. Average QTrak – CO

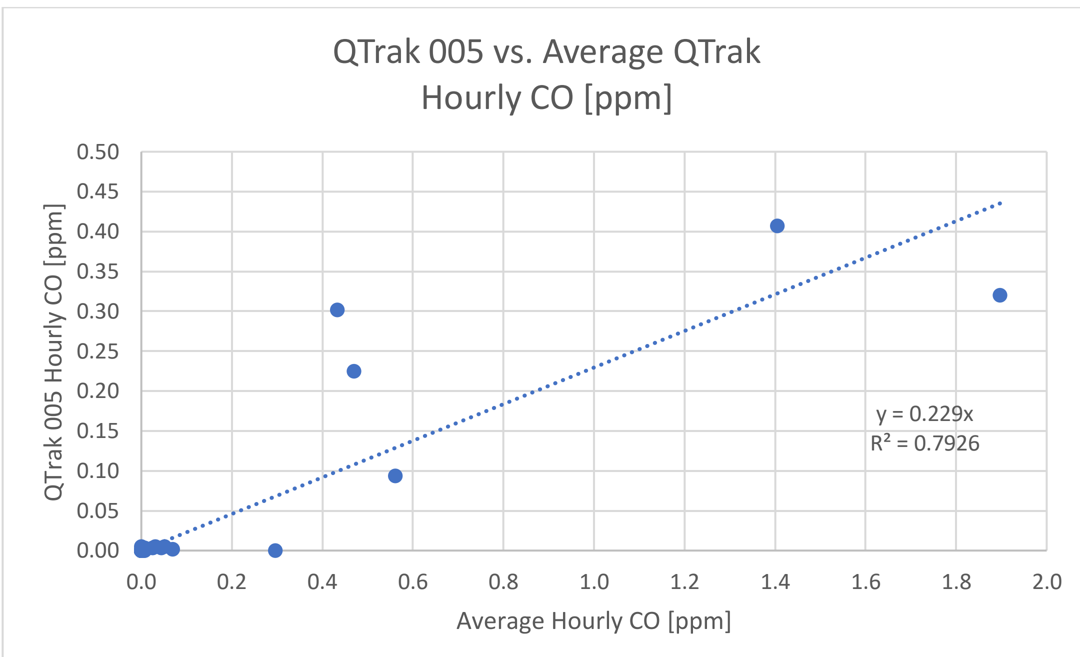

Figure 2-28. QTrak 005 vs. Average QTrak – CO

The correlation slope factor for QTrak 005 was 0.229, and showed that QTrak 005 may require a correction factor (4.36) for concentrations of CO to allow comparisons with different instruments. Reported QTrak 005 CO concentrations are consistently lower than the Average

QTrak reported CO concentrations. However, QTrak 005 also indicated an error when reporting the maximum and minimum CO concentrations. It is likely that the CO probe dried out and therefore was unable to record accurate measurements of CO.

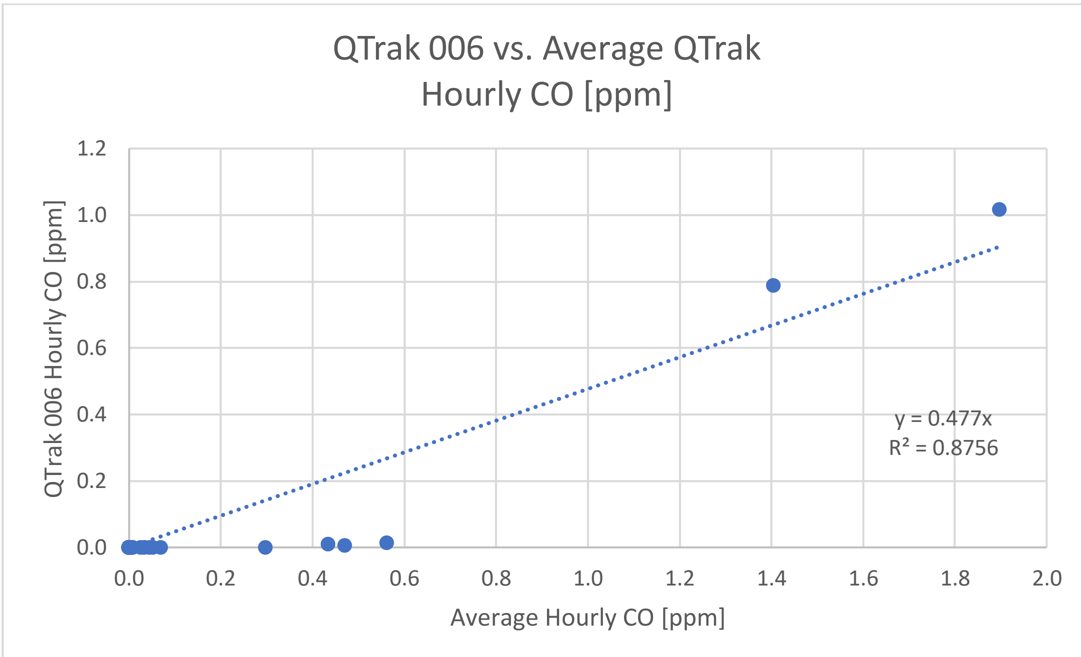

Figure 2-29. QTrak 006 vs. Average QTrak – CO

The correlation slope factor for QTrak 006 is 0.447, but there was no reported error by this QTrak. The correlation is the second lowest of the five QTraks, likely influenced by the fact that QTrak 006 reported CO concentrations of 0 ppm when the Average QTrak reported values between 0.3 and 0.6 ppm.

Although there was greater reported variability in the CO measurements compared to those of CO_2, BP, and T, it is important to note that this is likely because most of the data collected during the collocation experiments at Fort Defiance were below the detection limit (3 ppm). Consequently, these readings should not be considered accurate measurements of CO.

Overall, the individual QTrak units correlated relatively well with the Average QTrak value. It is recommended, however, that prior to deployment in homes, the CO probes in all

QTraks be rehydrated and calibrated according to standard operating procedure (TSI 2013b). Collocation experiments under a wider range of CO concentrations (i.e. 0 – 10 ppm) should also be conducted.

2.5.2.1 QTrak – Barometric Pressure (BP)

Table 2-11 shows the correlation slope factors, intercepts, and correlation for Barometric Pressure. The corresponding plots with linear regression analysis are shown in Figures 2-28 to 2-32.

Table 2-8. Relative QTrak Correlation Slope Factors, Inherent Bias, and Correlation for BP

	Unfixed Intercept			**Fixed Intercept**	
QTrak	***m***	***b***	**R^2**	**m**	**R^2**
001	0.955	26.5	0.9272	1.00	0.9252
003	0.984	9.03	0.9937	0.999	0.9934
004	0.977	13.9	0.973	1.00	0.9724
005	1.05	-29.6	0.9231	1.00	0.921
006	1.03	-19.9	0.962	1.00	0.961

The correlation slope factors for BP are close to one for a fixed and unfixed intercept. The BP data were not adjusted with the correction factors because the values are close to one.

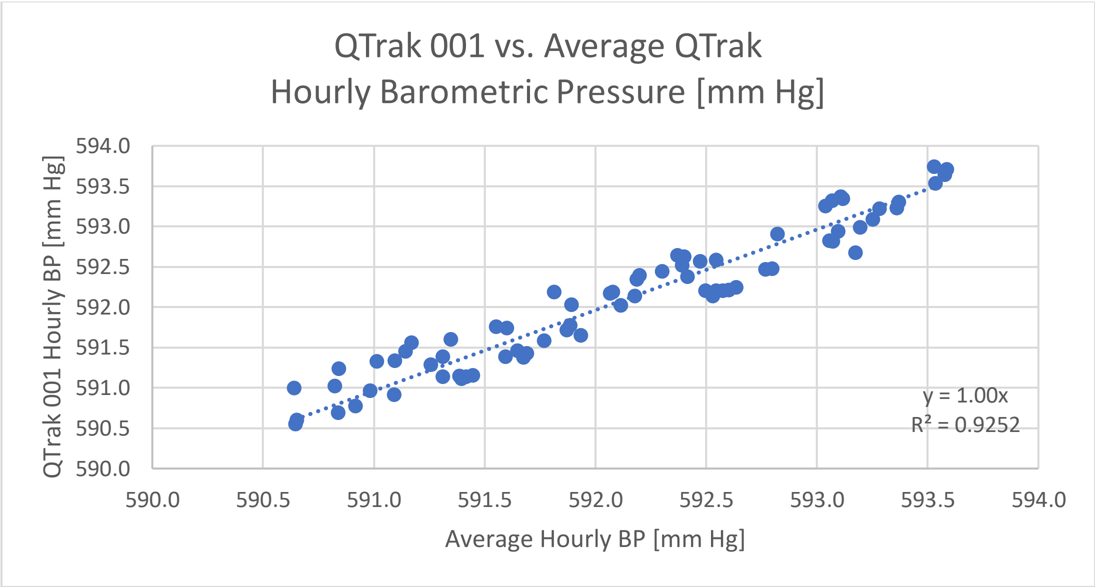

Figure 2-30. QTrak 001 vs. Average QTrak – BP

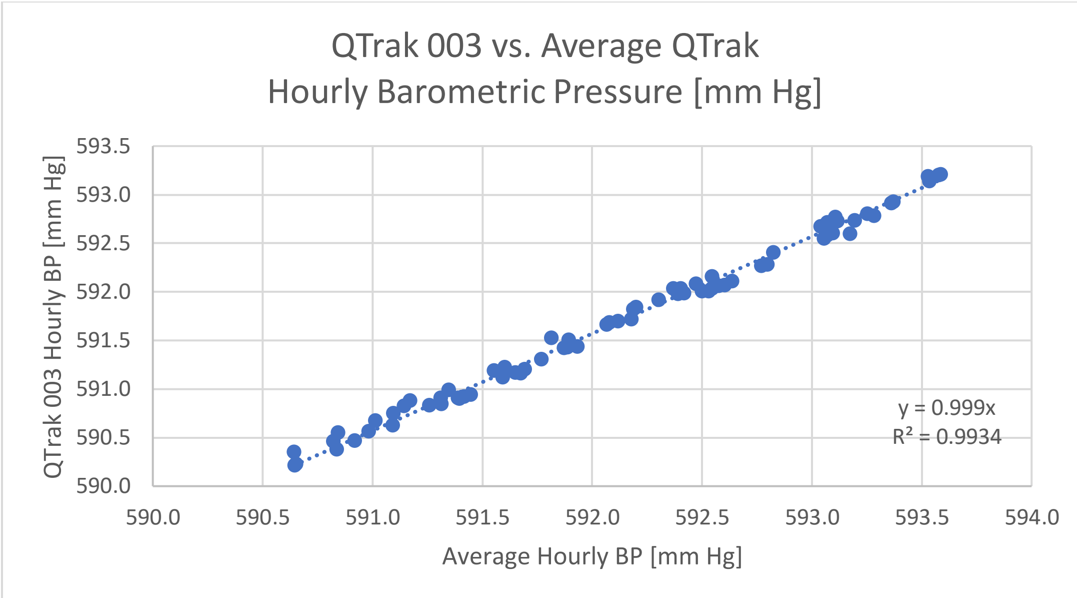

Figure 2-31. QTrak 003 vs. Average QTrak – BP

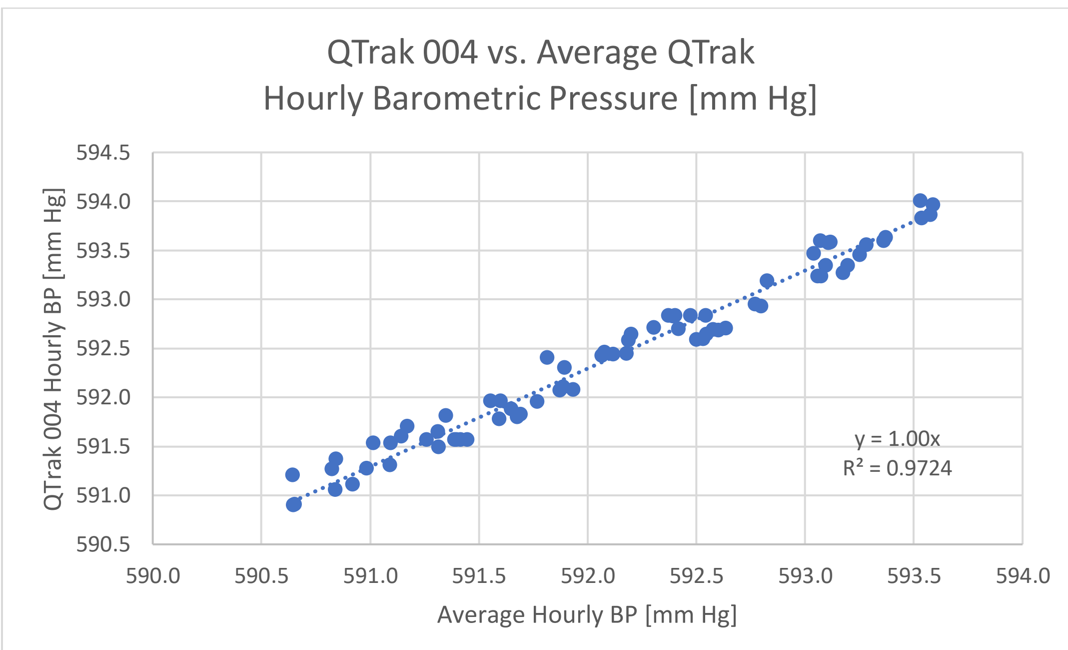

Figure 2-32. QTrak 004 vs. Average QTrak – BP

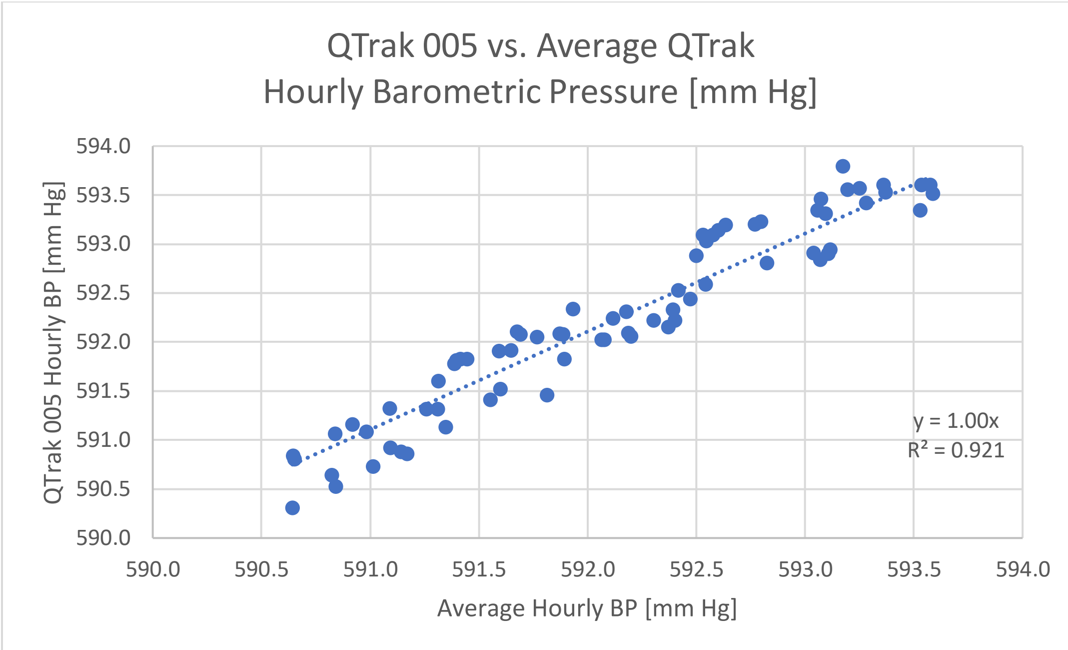

Figure 2-33. QTrak 005 vs. Average QTrak – BP

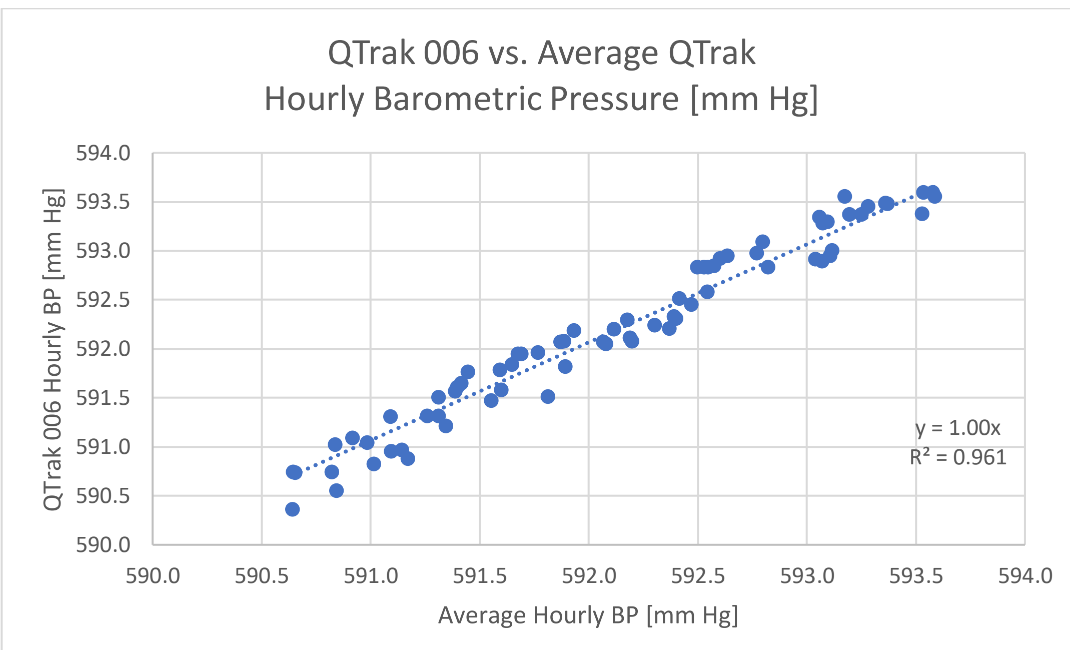

Figure 2-34. QTrak 006 vs. Average QTrak – BP

2.5.3 Experiment 3 – DustTrak and E-BAM Collocation

When comparing the hourly $PM_{2.5}$ concentrations for the DustTraks and E-BAMs, the first and last four minutes of data from the DustTraks were discarded. This is because the E-

BAM takes a zero reading for four minutes (minutes 2 – 5) at the beginning of the hour and establishes a span reading and advances the filter tape during the last four minutes (minutes 57 – 60) of the hour. As a result, the hourly $PM_{2.5}$ concentration reported by the E-BAM is actually a 52-minute reading. Therefore, the "hourly" $PM_{2.5}$ concentration in this experiment actually refers to a 52-minute central period for all instruments.

Additionally, the first hour of data for E-BAM 2 was removed from analysis because of a reported error (256: power outage). Correspondingly, the first hour of data for the DustTraks was also removed. Since E-BAM 2 and the DustTraks began sampling around 11:20AM, the first "hour" of data is actually around 40 minutes, ending at 12:00PM.

The hourly $PM_{2.5}$ concentrations for each DustTrak were plotted against the hourly $PM_{2.5}$ concentrations reported by E-BAM 2. Although the E-BAM is not a recognized Federal Equivalency Method (FEM), it has been shown to correlate strongly with Federal Reference Methods (FRM), overestimating smoke particulate concentration by about 1 percent (Trent 2006).

All DustTraks overestimated the $PM_{2.5}$ concentration from wood/coal smoke by between 184% - 253% (2.83 – 3.53 times). These values match those of a previous study (Trent 2006), which found that DustTraks overestimated $PM_{2.5}$ and PM_{10} concentrations from pine needle smoke by 217% (3.17 times).

Table 2-12 lists the correlation slope factors, intercepts and correlations between individual DustTrak units and E-BAM 2. All DustTraks showed a strong correlation ($R^2 > 0.7$) with the $PM_{2.5}$ concentrations reported by E-BAM 2.

Table 2-9. DustTrak and E-BAM Correlation Slope Factors, Intercepts, and Correlations

	Unfixed Intercept			**Fixed Intercept**	
Instrument	***m***	***b***	**R^2**	**m**	**R^2**
DustTrak 4313	3.13	19.1	0.8046	3.48	0.7595

DustTrak 4315	2.84	8.38	0.8112	2.99	0.8005
DustTrak 4316	2.85	5.40	0.7733	2.96	0.7684
DustTrak 4317	3.05	7.38	0.8076	3.18	0.8004
DustTrak 4318	3.21	7.33	0.8083	3.35	0.8019
Average DustTrak	3.02	9.51	0.8100	3.20	0.7964

The correlation slope factors among the instruments show little variation, which is expected because each DustTrak unit was shown to correlate well to the Average DustTrak value in Experiment 1 (Section *2.5.1*). Linear regression plots for each DustTrak and the Average DustTrak versus the E-BAM 2 $PM_{2.5}$ concentrations follow.

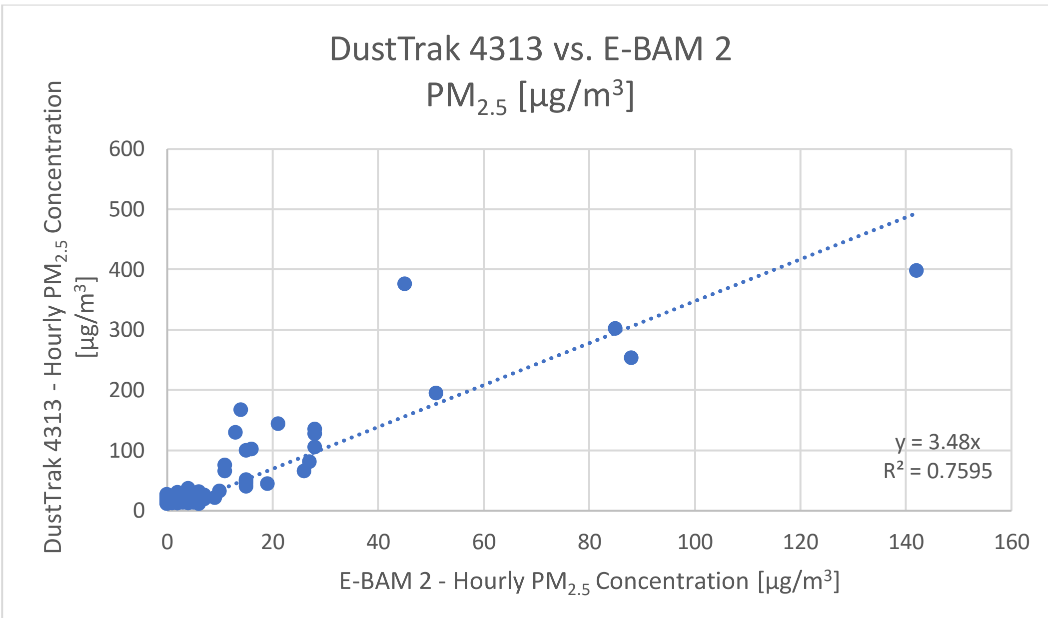

Figure 2-35. DustTrak 4313 vs. E-BAM 2 – $PM_{2.5}$

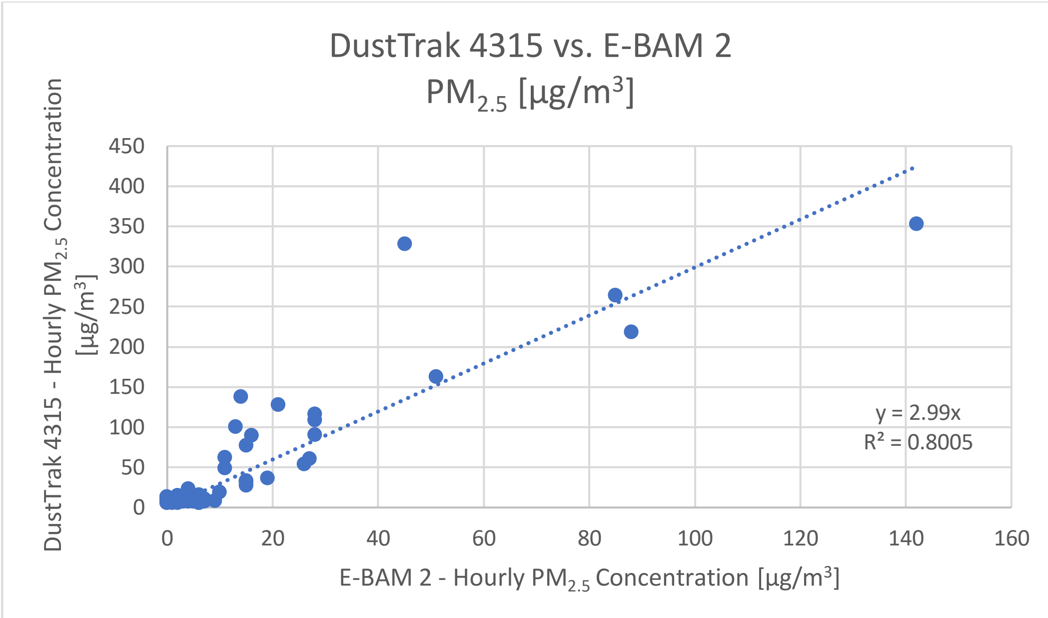

Figure 2-36. DustTrak 4315 vs. E-BAM 2 – PM2.5

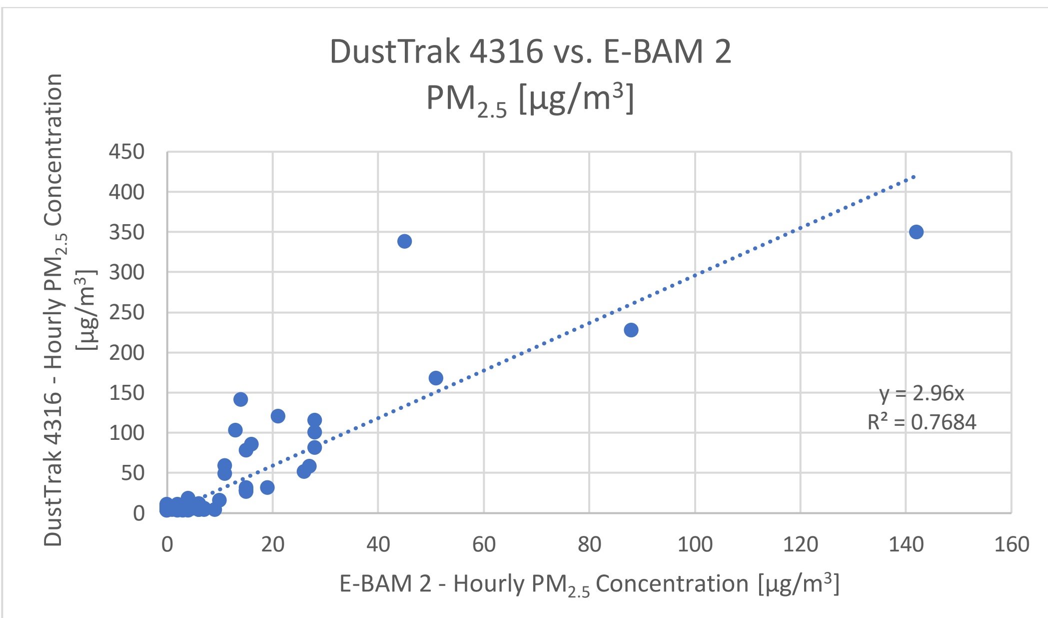

Figure 2-37. DustTrak 4316 vs. E-BAM 2 – PM2.5

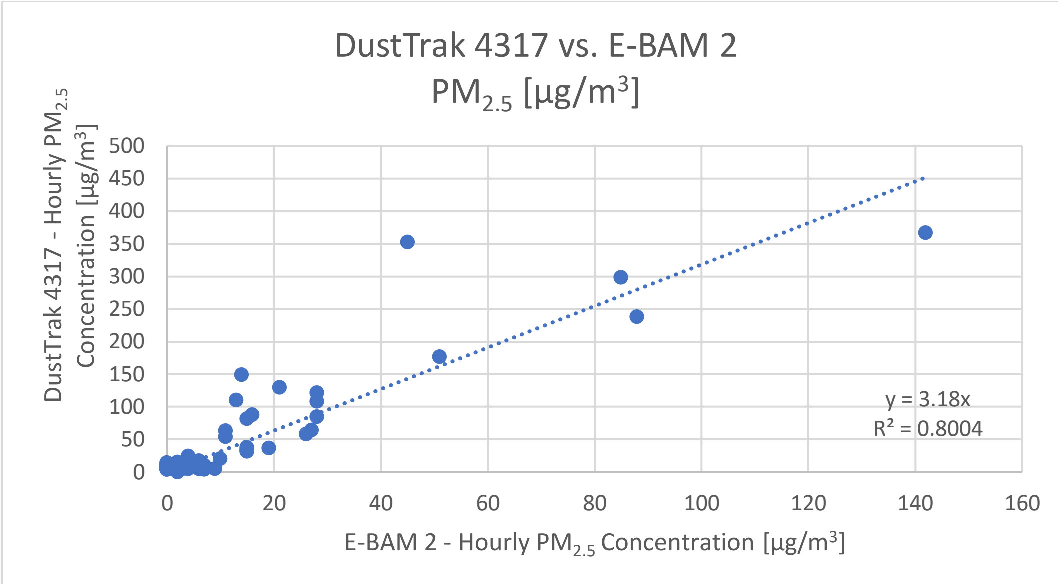

Figure 2-38. DustTrak 4317 vs. E-BAM 2 – $PM_{2.5}$

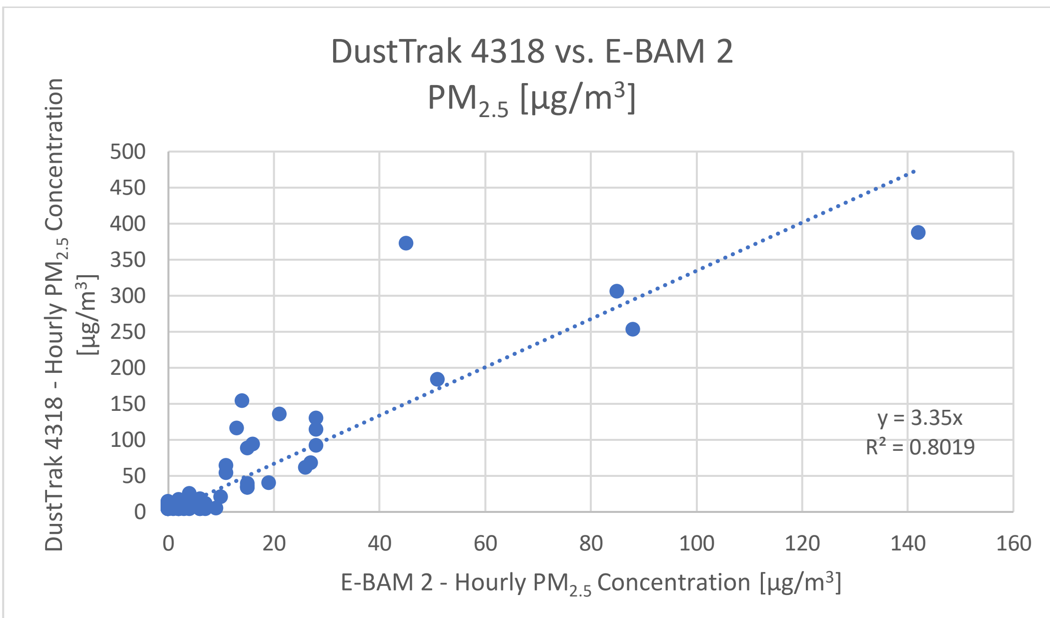

Figure 2-39. DustTrak 4318 vs. E-BAM 2 – $PM_{2.5}$

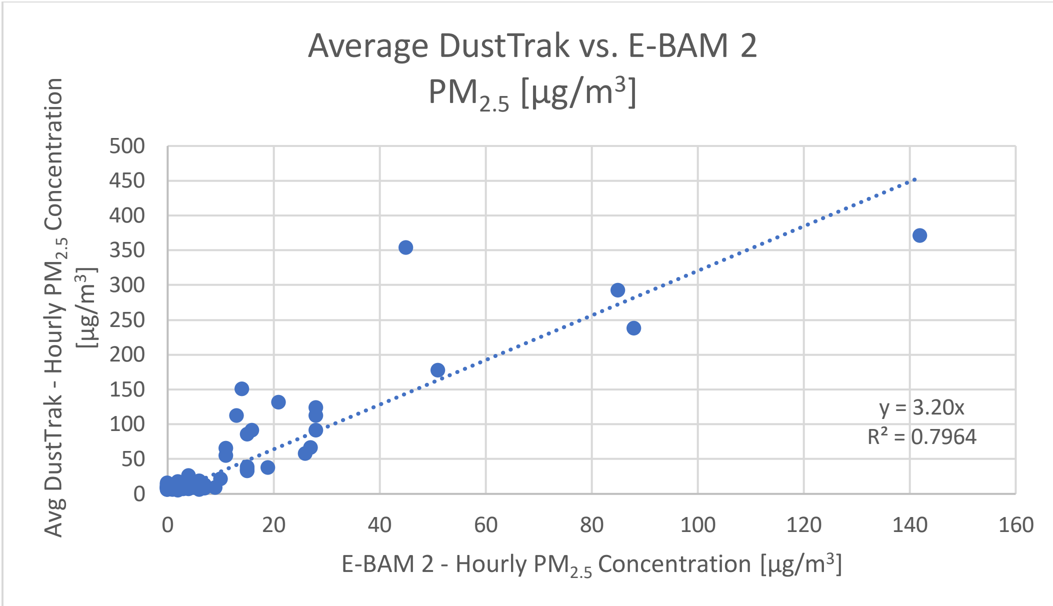

Figure 2-40. Average DustTrak vs. E-BAM 2 – $PM_{2.5}$

The mean(sd) correlation slope factor for the DustTraks and E-BAM was 3.19(0.225). The small standard deviation indicates that while there is some variation in the correlation slope factor for the individual DustTrak units, a single correlation slope factor can be used to relate the five DustTrak reported $PM_{2.5}$ concentrations to the E-BAM reported $PM_{2.5}$ concentrations.

When compared to the DustTraks, the E-BAMs over-reported $PM_{2.5}$ concentrations from wood/coal smoke by a factor of 3.19. This value agrees with the correction factor (3.17) determined by Trent (2006).

2.5.4 Experiment 4 – E-BAM $PM_{2.5}$ and PM_{10} Ratios

The reported $PM_{2.5}$ (E-BAM 2) and PM_{10} (E-BAM 3) concentrations for the first and last hour of sampling on the first and last day, respectively, were discarded. This adjustment was necessary since both E-BAM 2 and E-BAM 3 displayed an error (256: power outage) message in the logs.

Due to the nature of the measurement cycle for the E-BAM, some hourly $PM_{2.5}$ concentrations were reported as negative values. This is because at concentrations close to zero, the E-BAMs are operating in the noise range. These values were included in the calculation of the 24-hour averages because discarding these data points or setting them to zero would bias the averages high (T. Frederickson, personal communication, March 15, 2019).

Table 2-13 reports the 24-hour $PM_{2.5}$ and PM_{10} concentrations from E-BAM 2 and E-BAM 3, respectively. The mean(sd) ratio of fine to coarse particulate matter for coal smoke was 0.897(0.070), indicating that the majority of particulate matter generated from wood and coal combustion have an aerodynamic diameter of less than 2.5 μm. This is not unexpected since Houck and Tiegs (1998) reported that the particle size distribution of PM from residential wood combustion is 92% $<$ 1 μm, 93% $<$ 2.5 μm, and 96% $<$10 μm. Other studies also confirm that the particle size distribution of PM from wood and coal combustion is mostly below 2.5μm (Hays et al., 2003; Shen et al., 2010; Kleeman et al., 1999).

Table 2-10. 24-hour $PM_{2.5}$ and PM_{10} Concentrations – Fort Defiance, AZ

	E-BAM 2	**E-BAM 3**	**E-BAM 2/E-BAM 3**
	24-hour $PM_{2.5}$ Concentration	24-hour PM_{10} Concentration	$PM_{2.5}/PM_{10}$
	$\mu g/m^3$	$\mu g/m^3$	-
Day 1	13.88	16.67	0.83
Day 2	7.64	7.88	0.97
Day 3	14.09	15.75	0.89

As expected, the 24-hour PM_{10} concentration is greater than the 24-hour $PM_{2.5}$ concentration on all days. However, on Day 2, the reported $PM_{2.5}$ and PM_{10} concentrations were almost half of those reported on Day 1 and Day 3. The total amount of fuel used (Table 2-2) was similar on Day 2 (27.1 lb [12.3 kg]) and Day 3 (28.2 lb [12.8 kg]); therefore, it was expected that the 24-hour PM concentrations would be around the same magnitude.

On Days 1, 2, and 3, a total of 6.81, 3.83, and 6.24 kg of coal were used, respectively. Because combustion of wood and coal produce more $PM_{2.5}$ than PM_{10}, it is unlikely that the different ratios of wood to coal contributed to the decrease in both $PM_{2.5}$ and PM_{10}

concentrations measured by the E-BAMs. Another difference on Day 2 was that the researchers were not in the home as much compared to Days 1 and 3. On Day 2, after starting the fire, the researchers left the home and returned a few hours later to find that the fire had gone out almost immediately. After restarting the fire, the researchers left the home again. Therefore, there was less mixing in the home due to lack of movement. It is also possible that some of the PM began to settle or deposited on the walls/ceilings, but it is unlikely that the settling and deposition occurred within hours because the particulate matter is so small. Future studies with the E-BAMs should include forced mixing using fans to better circulate the generated pollutants.

2.5.5 Correction Factors

Because the correlation slope factors and intercepts among the same instruments were all close to one and zero, respectively, no correction factors were applied among instruments. The results from the collocation experiments of the DustTraks and QTraks provide justification that the values reported by the instruments can be compared without applying a correction factor.

In order to compare the $PM_{2.5}$ concentrations measured by the DustTrak to those of the E-BAM, the intercept was set to zero and the concentrations was multiplied by the inverse of the correlation slope factor (m), as done by Trent (2006). The correlation slope factors (m), correction factors (m^{-1}), and correlation (R^2) values are reported in Table 2-14. The linear regression plots are included in Appendix C.

Table 2-11. DustTrak and E-BAM 2 Correction Factors for Fixed Intercept

Instrument	***m***	**Correction Factor**	**R^2**
DustTrak 4313	3.48	0.287	0.7595
DustTrak 4315	2.99	0.334	0.8005
DustTrak 4316	3.57	0.280	0.723
DustTrak 4317	3.18	0.314	0.8004
DustTrak 4318	3.35	0.299	0.8019
Average DustTrak	3.20	0.313	0.8008

The mean(sd) DustTrak correction factors were 0.303(0.0217) and 0.313 for the Average DustTrak. These values were similar to the value (0.32) recommended byTrent (2006) when comparing the DustTrak to an FRM sampler.

2.6 Conclusion

The correlation slope factors for each DustTrak unit compared to the Average DustTrak were close to 1 and the intercept values were also close to 0 for all the units. This indicates that the DustTraks agreed with each other; therefore, the $PM_{2.5}$ concentrations measured by the different DustTraks can be compared without a correction.

The five parameters measured by the QTraks: temperature, relative humidity, barometric pressure, CO, and CO_2 can also be compared among QTraks without the use of a correction factor. Concentrations of CO were shown to be more variable with lower correlation values; however, this is likely because the CO levels were below the instrument's limits of detection. QTrak 004 and 005 also reported an error during the CO readings that could not be associated with an instrument bias or with the probe itself. This experiment for CO was not conclusive in determining if a specific QTrak unit will report biased concentrations even after calibration. Therefore, future collocation experiments for the QTraks should be performed to determine if the reported CO concentrations can be compared without a correction factor.

The correction factor determined for $PM_{2.5}$ concentration for the DustTraks and E-BAMs (0.313) agreed to the value reported by Trent (2006). The instruments used in the collocation experiment all showed good agreement amongst each other and the correction factor determined for the DustTraks and E-BAMs also agreed well with published values.

3. Wood/Coal Smoke-Specific Correction Factor Experiment

3.1 Introduction

Coal smoke is a complex mix of particulate matter (PM) and gaseous species such as CO, nitrogen oxides (NO_x), and polycyclic aromatic hydrocarbons (PAHs). Many coal types also contain sulfur, arsenic, silica, fluorine, lead, and/or mercury, which are released into the air in their original or oxidized form following combustion (Zhang and Smith 2007). The chemical composition of coal smoke also depends on the maturity of the coal, which is ranked, from least to most mature as: peat, lignite, sub-bituminous, bituminous, and anthracite (Miller and Tillman, 2008).

Wood, coal, and other solid fuels are used by nearly 3 billion people worldwide for cooking and heating (WHO 2015), with China responsible for 66% of world's total residential coal combustion (Kerimray et al., 2017). More than 60% of the population in China is rural, with 80% and 10% of the energy consumed by these homes a result of biomass and coal burning, respectively (Zhang and Smith 2007).

Although residential heating with coal has decreased significantly within the US, from 55% in 1940 to 0.1% in 2000, coal is still commonly used in the Navajo Nation for home heating as it is often accessible for free or at low cost (U.S. Census Bureau 2011; Bunnell et al., 2010). Mixed use of wood and coal is common because woods such as cedar and oak "produce red, yellow, or white flames, which are seen as natural flames that represent Navajo sacred relative fires" and, in addition to its low cost, coal can heat the home overnight (Champion et al., 2017a).

Bunnell et al. (2010) reported that 77% of homes surveyed (n = 137) in and around Shiprock, NM, the largest chapter in the NN, used wood stoves and that 25% of those homes burned coal in stoves that were not designed for coal. Many of these stoves had cracks and fissures, partly because 26% were 10 years old or older, and also because these stoves weren't designed for the higher temperatures that coal combusts at, affecting the stove's structural integrity (Bunnell et al., 2010).

Champion et al. (2017a) established a new framework based on a combination of perception, cultural, and technical assessments to identify the best heating options for the Navajo Nation. The study concluded that a stove replacement and weatherization was the recommended option and should lead to improved IAQ. At the time of that study, US EPA was pilot testing a dual burning wood/coal stove to meet the cultural and economic needs of the Navajo. In this case, recognizing that although exposure to emissions from heating with coal have been linked to serious health effects such as elevated risks of respiratory diseases (Torres-Duque et al., 2008; Desai et al., 2004; Mishra, 2002) and cardiovascular diseases (McCracken et al., 2012), coal will remain an important fuel source for the Navajo people.

3.1.1 Theory of Operation for Instruments

DustTraks have been used to measure $PM_{2.5}$ concentrations in homes in Native Nations (Singleton et al., 2017) and rural homes heated with wood stoves in the United States (Ward and Noonan, 2008; Noonan et al., 2012; Semmens et al., 2015). They are relatively easy to operate and are not as expensive as FRM or FEM instruments (Kingham et al., 2006; McNamara et al., 2011).

Although FEM and FRM instruments can provide accurate measurements of PM concentration irrespective of the particulate source, they have several drawbacks. There is often a delay between data collection and analysis, and integrated sampling precludes quantification of real-time PM concentrations (e.g., peaks). They also tend to be more expensive and difficult to operate (Chung et al., 2001). As such, more portable and affordable instruments such as the

DustTrak (TSI, Shoreview, MN) are commonly used in research studies (McNamara et al., 2011). However, the DustTrak is an optical sensor and is affected by the source of the particulate matter (TSI Incorporated, 2012).

McNamara et al. (2011) determined a wood smoke correction factor of 1.65 during an indoor sampling campaign in Libby, Montana. Another study determined a DustTrak correction factor of 3.49 for Pittsburgh Seam Coal under smoldering conditions (Perera and Litton, 2015). Since the Navajo utilize both wood and coal in their stoves, a wood/coal smoke correction factor that falls between the two values is expected.

To date, few studies have measured $PM_{2.5}$ in homes using coal for heating (Bunnell et al., 2010; Hu et al., 2014; Jedrychowski et al., 2006). Moreover, in 2014, nine countries accounted for 86% of the global consumption of coal for residential heating (Kerimray et al., 2017). A correction factor specific to wood or coal smoke were of great value to those previous studies. Similarly, a wood/coal correction factor for the DustTrak was necessary to properly quantify PM concentrations from wood/coal combustion in the Navajo context.

The objectives of the Wood/Coal Smoke Correction Factor experiment are:

Objective 1: Determine a wood/coal smoke correction factor (W/CSCF) for the DustTrak by performing concurrent $PM_{2.5}$ measurements using two MiniVol Tactical Air Samplers (Airmetrics, Springfield, OR) for gravimetric analysis and five DustTraks.

Objective 2: Determine a wood/coal smoke correction factor (W/CSCF) for the DustTrak by comparing $PM_{2.5}$ concentrations from an E-BAM with the reported $PM_{2.5}$ concentrations from five DustTraks.

3.2 Materials and Methods

3.2.1 Locations

W/CSCF experiments were performed at a single-family home in Fort Defiance, AZ from February 26, 2019 to March 1, 2019. This home was 432.4 ft^2 (40.2 m^2) and the floor plan and instrument placement are shown in Figure 3-1. The doors to the two rooms, the closet, and the bathroom remained closed for the majority of the experiment. For this reason, they were not included in the calculation of the area of the home. The distance from floor to ceiling in the open area of the home was 8.0 ft (0.74 m).

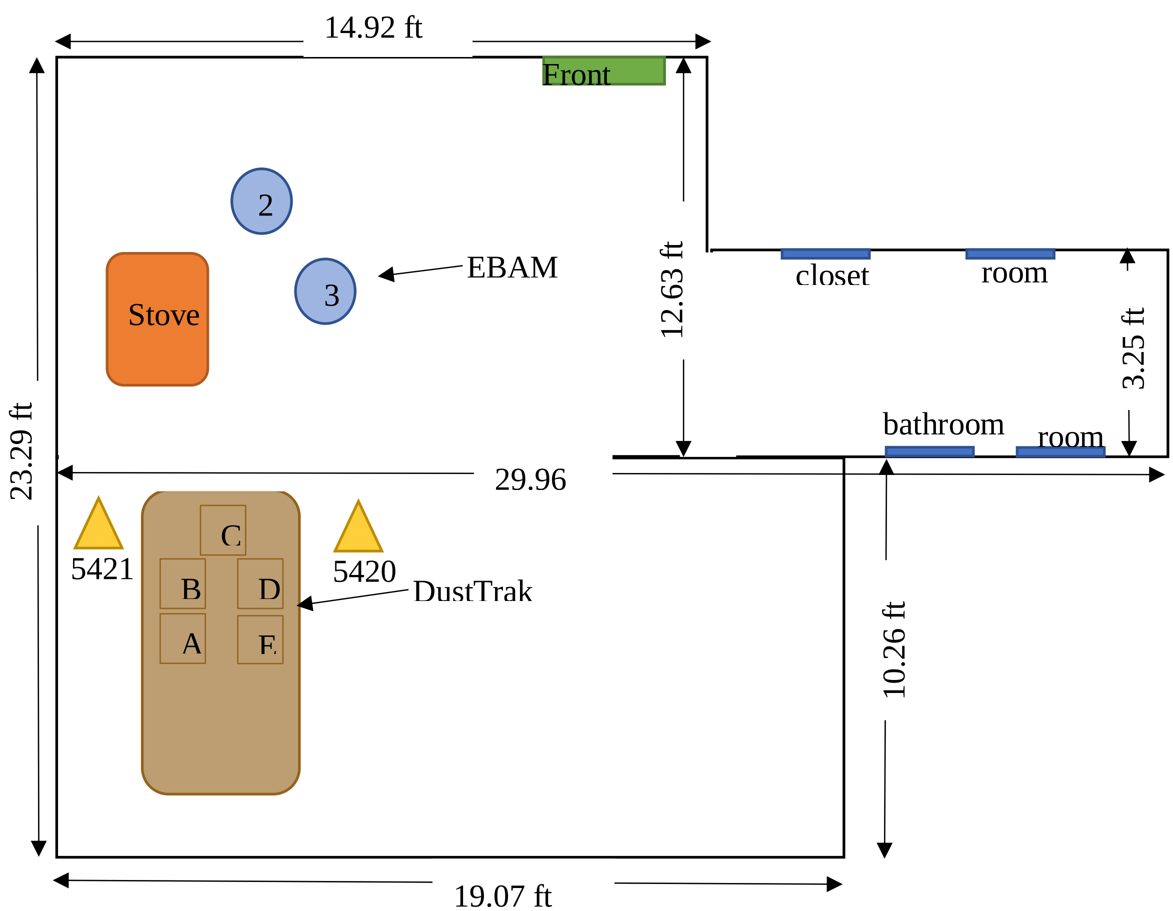

Figure 3-1. Instrument Placement at Fort Defiance, AZ

A second set of CSCF experiments were conducted in another Navajo home in Shiprock, NM from March 1, 2019 to March 4, 2019. The home was approximately 393.4 ft^2 (36.5 m^2) and the floor plan and instrument placement are shown below in Figure 3-2. The two bedrooms and the door in the living room were closed during visits by CU researchers and were not included in the calculation of the home volume. The height from floor to ceiling was 8.1 ft (0.75 m) in all surveyed areas.

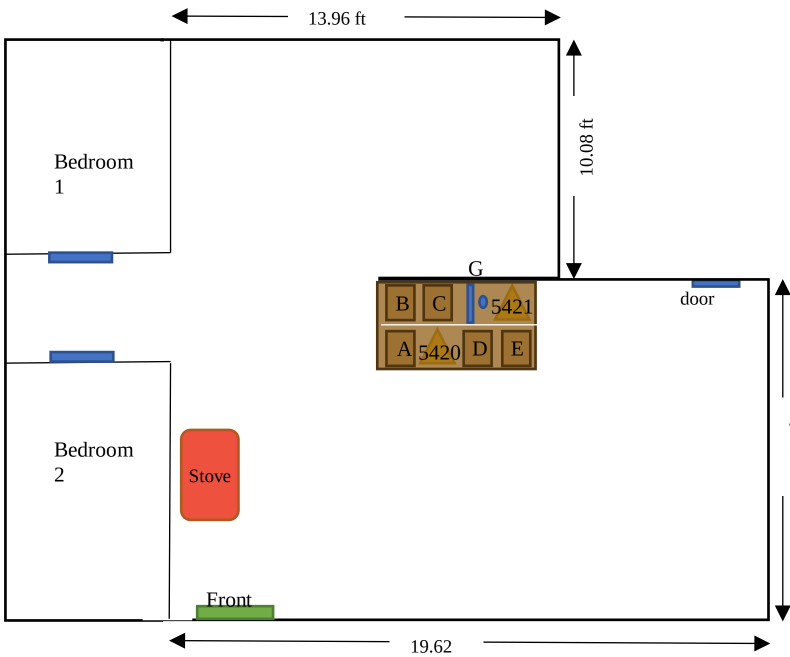

Figure 3-2. Instrument Placement at Shiprock, NM

3.2.2 Fuels

Black Mesa coal, pine, and cedar were used as fuel in both homes. Pine and cedar were used for kindling and to create the charcoal bed.

3.2.3 Stoves

At Fort Defiance, the stove used was a Wonderluxe automatic coal burning circulator Model B2350 (United States Stove Co., South Pittsburg, TN) with a chimney. It was installed approximately one year before the experiments were conducted.

At Shiprock, a Navajo Hybrid Stove (Woodstock Soapstone CO., West Lebanon, NH) was used for the collocation experiments. The stove was installed about one year prior to these experiments; this household was part of the First Pilot Study.

3.2.4 Filters

Gravimetric analysis was conducted on Teflon filters (Pall, Port Washington, NY, diameter: 47 mm, pore size: 2.0 µm, PTFE with PMP support ring) based on published protocols (Dutton et al., 2009). PTFE filters were allowed to condition at 35 - 45% relative humidity (RH) and 75 - 81°F for 24-36 hours. After equilibration, the mass of each filter was measured using a LabServe microbalance Model BP210D (Sartorius Corporation, Göttingen, Germany, weighing capacity: 210 g, Readability: 10 µg, Operating Temperature: 5 - 40°C) and then placed back into Petri dishes sealed with Teflon tape and stored in a freezer.

3.2.5 Instruments

3.2.5.1 TSI DustTrak II Model 8530

The DustTrak II Model 8530 (TSI, Shoreview, MN, Range: 0.001 – 400 mg/m^3, Resolution: $\pm$0.1% of reading or 0.001 mg/m^3, Operating Temperature: 0 – 50°C) is a real-time optical scanning device that relies on a calibration factor to determine the PM concentration. The calibration factor is ISO 12103-1, A1 Arizona test dust, which has a different composition from both wood smoke and coal smoke. Prior to every sampling event, the impactors in the DustTraks were cleaned and frits greased, the DustTraks zeroed, and the flow calibrated.

3.2.5.2 EBAM, Model 9800

The EBAM Model 9800 (Met One, Grants Pass, OR, Range: -0.005 – 65.530 mg/m^3, Accuracy: $\pm$10% for indicated value for hourly measurement, Resolution: 1 µg/m^3, Temperature: -25 to 40°C) measures and records $PM_{2.5}$ and PM_{10} concentration levels using beta ray attenuation. Only $PM_{2.5}$ was measured for this experiment. Beta particles (high-energy electrons) are emitted from a small ^{14}C element, which are then detected and counted by a scintillation detector. A known volume of air is pumped into the EBAM and particulate matter is impacted onto the filter tape. This filter tape is then cycled between the detector and the beta radiation source. The particulate matter located on the tape will prevent some of the radiation from being detected (attenuation). The degree of attenuation of the beta particles is proportional to the amount of material that is present. Mass density is based on measurements and do not require adjusting for the source of the $PM_{2.5}$ (Met One Instruments, Inc 2008).

3.5.2.3 MiniVol Tactical Air Sampler

The MiniVol TAS utilizes a pump controlled by a programmable timer to collect particulate matter (PM) onto a filter. When sampling PM, air is drawn through a particle size separator (impactor) and then through a filter medium. Since the particulate of interest was $PM_{2.5}$, both the PM_{10} and $PM_{2.5}$ impactors were used in series.

The PM_{10} and $PM_{2.5}$ impactor assemblies for the MiniVols were cleaned according to established protocol. The impactor/filter holder assemblies were soaked for 15-20 minutes in Alconox and warm tap water, then scrubbed with a glassware brush, rinsed in tap water and set on top of a Kimwipe. The sets were then rinsed with DI (Milli-Q) water three times and set on top of a Kimwipe after each rinsing. The impactor/filter holder assemblies were then rinsed with isopropanol under a fume hood for 3 seconds before stored in baked aluminum foil until use. The aluminum foil was baked at 550°C for ~14 hours.

Flow Calibration

The flow rates of the two MiniVols were calibrated within one month prior to and following the wood/coal smoke correction factor experiments. The calibrations were conducted while the units were loaded with PTFE filters (Pall, Port Washington, NY) to reproduce field conditions. The flow rates were measured with a primary flow calibrator, a mini-Buck Calibrator, Model M-30 (A.P. Buck, Inc, Orlando, FL, Range: 0.100 – 30.00 Lpm, Accuracy: $\pm$ 0.5%).

The MiniVol TAS has an integrated rotameter that reports the air flow but must be calibrated. The rotameter calibration was performed by adjusting the flow from 3.5 to 6.5 Lpm in increments of 0.5 Lpm, following established protocol in the MiniVol TAS Operation Manual (Airmetrics, Rev. 1.2), while connected to the mini-Buck. For each MiniVol, the average of three flow measurements was determined from the mini-Buck at each of the seven rotameter readings (3.5 – 6.5 Lpm). A total of five calibration trials were conducted for each MiniVol; the results are included in Appendix B.

Determination of MiniVol Field Study Flow Rate

Using the flow data collected from the mini-Buck and rotameter, linear regression results were determined from a line of best fit comparing the rotameter flow rate to the mini-Buck flow rate for each MiniVol. This calibration curve was then used during the field study.

At the time of calibration, the pressure in Boulder was 745.6 mmHg for MiniVol 5420 and 747.1 mmHg for MiniVol 5421 and the temperature was 295 K. According to the flow calibrations, a rotameter reading of 4.5 Lpm for MiniVol 5420 and 4.6 Lpm for MiniVol 5421 correlated to an actual flow rate of 5 Lpm.

In Fort Defiance, the average barometric pressure was approximately 759.5 mmHg (NOAA, 2019b). A value of 20°C (293 K) was used for T_{act} because the MiniVols were placed inside a home heated with a Wonderluxe stove. The average barometric pressure at Shiprock, NM wa around 764.1 mmHg (NOAA, 2019c). Rotameter readings of 4.5 Lpm and 4.6 Lpm for MiniVol 5420 and 5421 respectively were used in Fort Defiance and Shiprock.

MiniVol Procedure

The filters were loaded into the impactor/filter holder assembly immediately before each sampling event. At the end of each sampling event, the filters were removed from the impactor/filter holder assembly, placed into their respective Petri dish, sealed with Teflon tape, and stored at -4°C. On the last day, the third set of filters were removed and the field blanks were loaded into the filter holder and then placed back into their respective Petri dishes, sealed and stored.

The PM_{10} and $PM_{2.5}$ impactor plates for the MiniVol were cleaned and greased prior to each sampling event. A mixture of 30 mL DMT and 1 inch of Dow Corning High-Vacuum Grease was used on the impactors. Six drops of the mixture were placed on the PM_{10} impactors and four drops were placed on the $PM_{2.5}$ impactors.

Instrument Identification

Each instrument was identified by its Serial Number but relabeled with a number or unique code for simplicity, aside from the MiniVols. Table 3-1 shows the corresponding identification information for all instruments.

Table 3-1. Instrument Type and Identification

Instrument Type	**ID Number**	**Serial Number**
DustTrak	4313	8530174313
DustTrak	4315	8530174315
DustTrak	4316	8530174316
DustTrak	4317	8530174317
DustTrak	4318	8530174318
EBAM	2	J2568
MiniVol TAS	5420	5420
MiniVol TAS	5421	5421

3.3 Experimental Set Up

The first set of W/CSCF experiments were conducted by CU Boulder and Navajo EPA researchers in a Navajo home in Fort Defiance, AZ from February 26, 2019 to March 1, 2019. For each burn event, approximately 1 kg of cedar was used to kindle the stove, followed by 1 – 2 kg of pine to create the coal bed, and then the coal was added. This is common practice in the Navajo Nation (Bunnell et al., 2010). The researchers kindled and maintained the fire. The mass of wood used for the charcoal bed and the mass of added coal were measured using a Digital Kitchen Scale Model 3899 (Taylor Precision Products, Inc, Las Cruces, NM, Maximum Weight: 30 lbs). The amount and times that coal and wood were added to the stove were recorded as well. Enough coal was added to the stove for at least an 8-hour burn event. Even if the fuel was used up, sampling continued for the full 24-hours. The instruments were placed in the living room about 3 ft – 5 ft from the heating stove.

The second set of W/CSCF experiments were conducted in a Navajo home in Shiprock, NM from March 1, 2019 to March 4, 2019. The mass of wood and coal used was not recorded since each burn event was started by the resident of the home. However, the residents completed activity logs for each day of burning to provide information on activities that may impact indoor air quality like cooking, cleaning, and opening windows and doors.

3.3.3 Experiments

Experiment 1 – DustTrak and MiniVol W/CSCF

A total of 72 hours of continuous indoor sampling was conducted with five DustTraks, one E-BAM, and two MiniVols at the home in Fort Defiance, AZ. The nine instruments were placed in the same room as the Wonderluxe B2350 heating stove, such that the inlets of the DustTraks and MiniVols were 3 ft above the ground. The DustTraks were clustered together with one in front and two on each side, behind the first DustTrak. The MiniVols were placed on either side of the table, approximately 2 – 3ft from the DustTraks. The DustTraks were between 8 - 12 in from each other and all instruments were synced to the same time. The DustTraks were set to log every minute and the EBAMs were set to log every hour. The MiniVols were programmed to sample for 24 hours. All instruments were located between 3 – 5 ft from the heating stove.

A total of 72 hours of continuous indoor sampling was conducted with five DustTraks and two Minivols at a single-family home in Shiprock, NM. The seven instruments and a QTrak were deployed in the same room as the Navajo Hybrid Stove. The DustTraks, spaced between 8 – 12 in from each other, were placed on two shelves on a desk so their inlet heights were between 2.9 ft and 3.78 ft from the ground. The DustTraks and MiniVols were synced to the same time. The DustTraks were set to log every minute and the MiniVols were programmed to sample for 24 hours. All instruments were located between 3 – 5 ft from the heating stove.

Experiment 2 – DustTrak and E-BAM W/CSCF

Sampling for a continuous 72 hours was conducted at the home in Fort Defiance using the five DustTraks and one E-BAM. No experiments with the DustTraks and E-BAMs were conducted at the home in Shiprock, NM. The five DustTraks and E-BAM 2 were placed in the same room as the heating stove. The DustTraks were arrayed exactly as in Experiment 1. E-BAM 2 was placed in the same room as the heating stove, such that its inlet was 6.7 ft (2.04 m) above the ground and synchronized with the DustTrak time. E-BAM 2 was located between 3 – 5 ft (0.91 – 1.52 m) from the heating stove. The DustTraks were set to log at minute intervals while E-BAM 2 was set to log hourly.

3.4 Data Analysis

Normality could not be assumed for the reported $PM_{2.5}$ concentrations from the DustTraks, MiniVols, and E-BAM. This was confirmed with the Shapiro-Wilk test for normality, Q-Q plots, and histograms. Therefore, non-parametric tests like the Wilcoxon Rank-Sum Test was used to determine significance between correction factors determined at the two locations.

The DustTrak W/CSCF from the MiniVol was determined with the following equation:

$24 - hour\ DustTrak\ PM_{2.5}\ concentration/24 - hour\ PM_{2.5}\ filter\ concentration.$

The DustTrak W/CSCF from E-BAM 2 was determined by the formula:

$DustTrak\ PM_{2.5}\ concentration\ at\ hour\ t/E - BAM\ PM_{2.5}\ \ concentration\ at\ hour\ t.$

3.5 Results and Discussion

3.5.1 Experiment 1 – DustTrak and MiniVol W/CSCF

In total, twelve 24-hour continuous sampling events were conducted to determine a W/CSCF for the DustTrak. The 24-hour average $PM_{2.5}$ concentrations from the Average DustTrak (average of the five DustTraks) were determined for each event and compared to the 24-hour average $PM_{2.5}$ concentrations for each MiniVol.

One W/CSCF data point (MiniVol 5420 on Day 3) was removed from the analysis because there was dried MiniVol grease on the filter when it was removed from the filter holder. The grease was dried and cracked on both the PM_{10} and $PM_{2.5}$ impactors. It is likely that the high temperatures and dried grease impacted the collection of $PM_{2.5}$ on the filter, which resulted in an outlier (6.54) W/CSCF. Therefore, 11 W/CSCFs were determined from the five DustTraks and two MiniVols at Fort Defiance (n = 5) and Shiprock (n = 6).

The Shapiro-Wilk Test for normality generated p-values of 0.3485 and 0.271 for the W/CSCFs for Fort Defiance and Shiprock respectively, meaning that the distributions could be normal. However, visual inspection with Q-Q plots and histograms indicated that the distribution of W/CSCFs at Shiprock may not be normal. Bridge and Sawilowsky (1999) recommended the use of the Wilcoxon Rank Sum Test over the t-test when the population characteristics are unknown.

The boxplot of the wood/coal smoke correction factors from the two locations with the MiniVols is shown in Figure 3-3.

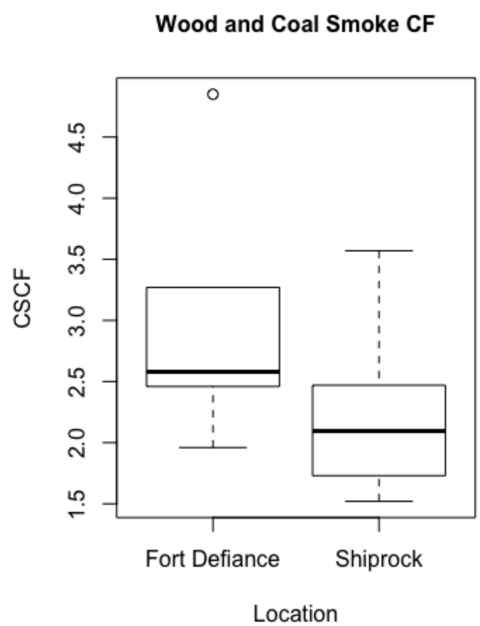

Figure 3-3. Boxplot of W/CSCF for Shiprock, NM and Fort Defiance, AZ

The mean(sd) CSCF for Fort Defiance and Shiprock were 3.02(1.12) and 2.25(0.754), respectively. A non-parametric Wilcoxon Rank Sum Test determined that the two sets of CSCFs were not statistically different (p-value = 0.1775, $\alpha = 0.05$) from each other.

The difference in mean(sd) W/CSCFs at the two locations may be due to the difference in 24-hour $PM_{2.5}$ concentrations at Shiprock (23.3 μg/m^3) and Fort Defiance (50.4 μg/m^3). The W/CSCF from the two locations were broken into four groups: 1 – 10 μg/m^3, 11- 19 μg/m^3, 20 – 50 μg/m^3, and 50+ μg/m^3. No statistically significant differences between the four groups were found. Therefore, while the range of W/CSCF values determined at each location was different, it is currently not possible to conclude that the concentration of $PM_{2.5}$ generated will affect the wood/coal smoke correction factor.

Since the W/CSCFs determined at the two locations cannot be said to be statistically different from each other, the two data sets were combined (n = 11) to determine an overall mean(sd) W/CSCF for the two locations of 2.60(0.976). The range in concentrations of $PM_{2.5}$ generated at Fort Defiance and Shiprock are representative of typical values expected in Navajo homes; therefore, combining the W/CSCFs should result in a more representative W/CSCF for residential combustion from wood and coal in Navajo homes.

There were several issues with the MiniVols that should be considered. Figure 3-4 shows that the correlation between the two MiniVols is good, but not as high as expected for instruments of the same type.

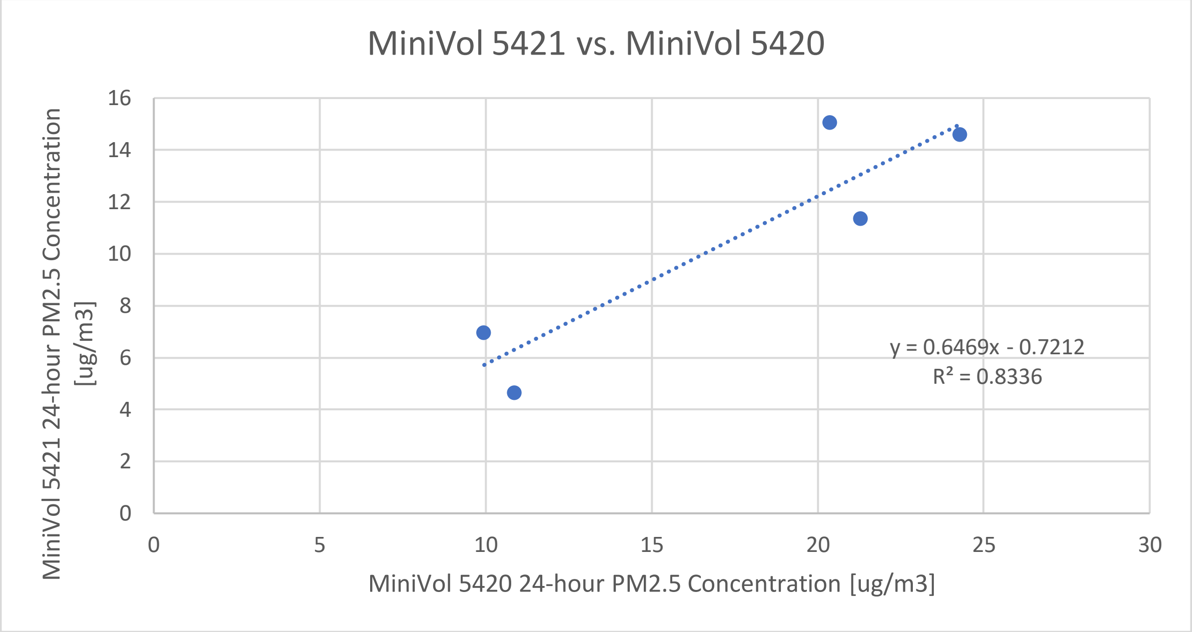

Figure 3-4. MiniVol 5421 vs. MiniVol 5420

A study by Baldauf et al. (2001) found that two MiniVols had a good correlation (R^2 = 0.95) for $PM_{2.5}$ measurements. One significant difference between that study and this one is the number of samples collected. Baldauf et al. (2001) collected over 1500 samples compared to 11 in this experiment. Therefore, the Pearson's correlation for MiniVol 5421 and MiniVol 5420, while not as strong as would be expected, is still a good indicator of the correlation between the two MiniVols.

The lower correlation of the MiniVols in this experiment is likely due to the difference in the collected mass on the filters. The filter masses collected with MiniVol 5421 were higher than those collected with MiniVol 5420 for all days, at both locations. Additionally, because both MiniVols were operated under similar conditions, it is unlikely that environmental factors were the cause of this discrepancy. Since the difference in readings also occurred at both locations, this suggests that there was an issue with the MiniVols themselves or from user error. Since the same methodology was followed for filter handling and setting up of the MiniVols, it is unlikely that a systematic difference in handling MiniVol 5420 and 5421 would occur from user error. It is also possible that the location and lack of forced mixing in the homes affected the mass collected on the filters.

Flow calibration for both MiniVols was conducted following the conclusion of the CSCF experiment (see Appendix B) and no significant deviation from the flow calibration results pre-experiment were found. Neither MiniVol indicated the presence of a leak following the experiments. It is most likely that the difference in concentrations reported by the two MiniVols is a result of a lack of mixing in the homes. In Fort Defiance, the only mixing occurred from natural ventilation and from movement of researchers in the home.

Additionally, variance between the measured $PM_{2.5}$ concentration for all instruments at the Fort Defiance location was noted. Table 3-2 shows the 24-hour average $PM_{2.5}$ concentrations for the three days for the Average DustTrak, MiniVol 5420, and 5421.

Table 3-2. 24-Hour Averaged PM2.5 for Average DustTrak, MiniVols 5420 & 5421, and E-BAM 2 – Fort Defiance

Fort Defiance 24-hour $PM_{2.5}$ Concentration	**Average DustTrak** µg/m³	**5420** µg/m³	**5421** µg/m³	**E-BAM 2** µg/m³
Day 1	55.03	21.30	11.34	14.24
Day 2	47.75	24.31	14.58	9.84
Day 3	48.42	-	19.68	13.43

The trends for the Average DustTrak, two MiniVols, and E-BAM 2 do not agree with each other. The 24-hour $PM_{2.5}$ concentration on Day 3 for MiniVol 5420 is not included because that was the filter that was affected by the MiniVol grease drying out.

The trend for E-BAM 2, however, agrees with the trend of the Average DustTrak, but the difference in reported $PM_{2.5}$ concentration is unexpected. The fact that the E-BAM 2 reported $PM_{2.5}$ concentration on Day 2 much lower than Day 1 and especially compared to Day 3, indicates that something occurred during the sampling period to affect $PM_{2.5}$ concentrations and distributions. This disagreement in $PM_{2.5}$ concentrations and trends across the four instruments only occurred at the Fort Defiance home, which indicates that the difference was likely due to user error in the field, rather than instrument error. It is also unlikely that filter measurements were the cause of the error because the filters were weighed three times each, sequentially.

The 24-hour averaged $PM_{2.5}$ concentrations for the Average DustTrak and MiniVols 5420 and 5421 at the home in Shiprock are given in Table 3-3.

Table 3-3. 24-Hour Averaged PM2.5 for Average DustTrak and MiniVols 5420 & 5421 – Shiprock, NM

Shiprock 24-hour $PM_{2.5}$ Concentration	**Average DustTrak** µg/m³	**5420** µg/m³	**5421** µg/m³
Day 1	16.53	10.88	4.63
Day 2	36.28	20.37	15.05
Day 3	17.17	9.95	6.94

The trends and magnitudes of the $PM_{2.5}$ concentrations at the home in Shiprock, NM agree well with each other. This fact supports the hypothesis that user error in the field was the cause of the variation in $PM_{2.5}$ trends and concentrations at Fort Defiance. Because no specific actions or events can fully explain the different trends and concentrations, the $PM_{2.5}$ concentration data from Fort Defiance was included in the analysis of the W/CSCF.

Figures 3-5 and 3-6 show the linear regression plots for the Average DustTrak and MiniVol 5420 and 5421, respectively. These plots contain the combined W/CSCFs from Fort Defiance and Shiprock. Overall, the MiniVols and DustTraks correlated well with each other. The 24-hour DustTrak concentrations, however, correlated better with MiniVol 5420 (R^2 = 0.862) than with MiniVol 5421(R^2=0.5787).

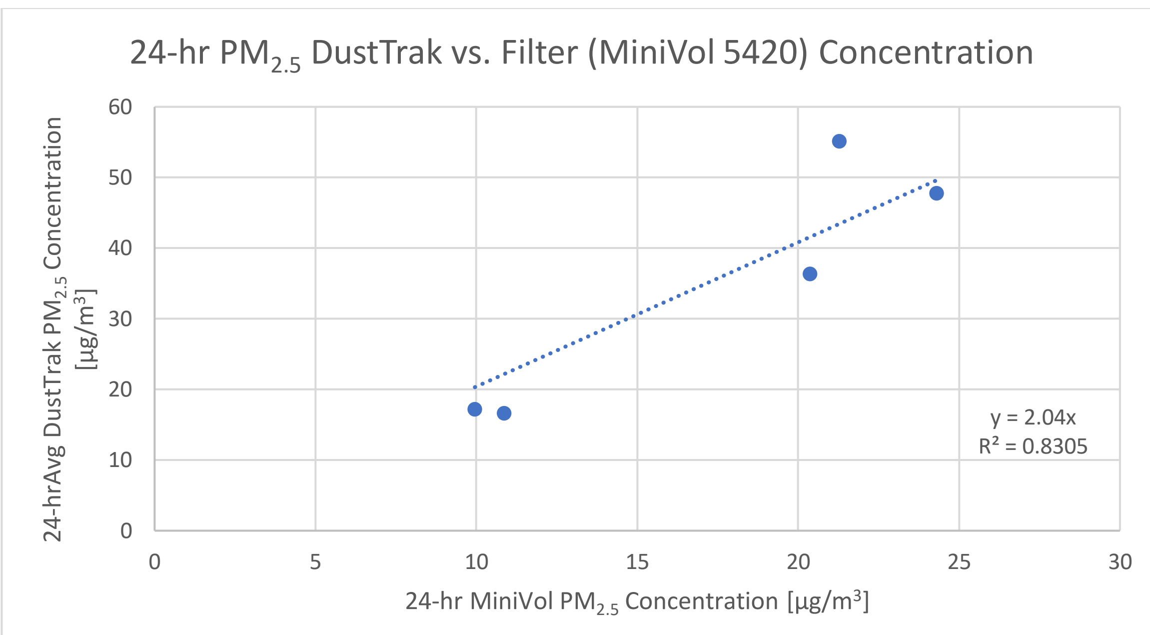

Figure 3-5. Average DustTrak vs. MiniVol 5420 – 24-hour $PM_{2.5}$ Concentration

The 24-hour mass concentration of $PM_{2.5}$ collected by MiniVol 5420 correlated well with the 24-hour $PM_{2.5}$ concentrations from the Average DustTrak. The correlation slope factor (m = 2.04) shows that the DustTrak overestimates the $PM_{2.5}$ concentration generated from wood/coal smoke.

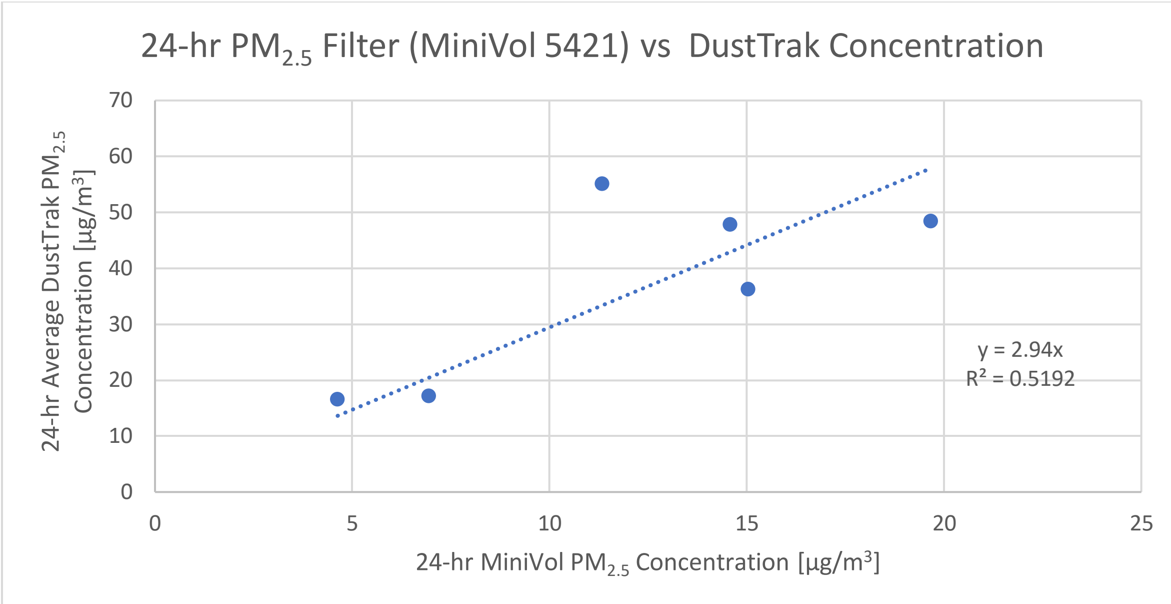

Figure 3-6. Average DustTrak vs. MiniVol 5421– 24-hour $PM_{2.5}$ Concentration

The Average DustTrak and MiniVol 5421 had a lower correlation ($R^2 = 0.5192$) compared to MiniVol 5420. This correlation value was similar to the one reported by Kingham et al. (2006) for ambient monitoring in a wood smoke environment using a MiniVol and DustTrak ($r^2 = 0.53$); therefore, it was deemed an acceptable value.

Despite the variation in correlations between the two MiniVols and the discrepancies between the $PM_{2.5}$ concentrations and trends at Fort Defiance, it is expected that the mean W/CSCF of 2.60 determined in Experiment 1 is a good preliminary value. It can be further improved with more sampling in future studies.

Additionally, the published values for the DustTrak correction factors for wood smoke, 1.65 (McNamara et al., 2011) and Pittsburgh seam coal under smoldering conditions 3.49 (Perera and Litton, 2015) can be used to estimate a correction factor for a mixture of wood/coal fuels to compare to the value determined in this study. This analysis was only done for the Fort Defiance home for which fuel usage was controlled by researchers.

Table 3-4. Estimated W/CSCF from Published Values

Fort Defiance	Wood (kg)	Coal (kg)	%wood*1.65	%coal*3.49	Estimated Correction Factor
Day 1	13.1	6.81	1.09	1.19	2.28
Day 2	8.46	3.83	1.14	1.09	2.23
Day 3	6.52	6.24	0.843	1.71	2.55

To estimate a correction factor from the published data for each day, the percent wood mass used ($\frac{m_{wood}}{m_{Total}} * 100\%$) was multiplied by the published wood smoke correction factor of 1.65 and the percent coal mass used ($\frac{m_{coal}}{m_{Total}} * 100\%$) was multiplied by the Pittsburgh seam coal correction factor of 3.49. The estimated correction factors ranged from 2.23 to 2.55, which compare well with the W/CSCF of 2.60 determined in this study. This value was, therefore, considered a good value to correct the $PM_{2.5}$ data from the Pilot Study.

3.5.2 Experiment 2 – DustTrak and E-BAM 2 W/CSCF

The E-BAMs utilize beta-ray attenuation to determine the concentration of $PM_{2.5}$ and are, in theory, insensitive to particle properties (Met One 2008). Therefore, the 24-hour mass concentrations reported by E-BAM 2 (n = 3) and the Average DustTrak can also be used to determine a coal smoke correction factor that should agree with the W/CSCF determined in Experiment 1 through gravimetric analysis. E-BAM 2 was only deployed at Fort Defiance.

Although the E-BAMs report real-time hourly averages, Schweizer et al. (2016) cautioned against using these values because they found that the E-BAMs tended to overestimate hourly $PM_{2.5}$ concentrations. Negative hourly average $PM_{2.5}$ concentrations were discarded in determining the E-BAM W/CSCFs because comparison of hourly averages requires that the negative $PM_{2.5}$ values be set to zero (Schweizer et al., 2016; T. Fredrickson, personal communication, March 15, 2019), which would result in an error due to a division by zero when calculating W/CSCFs.

The mean(sd) hourly W/CSCF for the Average DustTrak and E-BAM 2 is 3.87(2.31) compared to the mean(sd) 24-hour averaged W/CSCF of 3.91(0.836). The 24-hour averaged W/CSCF value should be taken as a more accurate representation of the E-BAM determined W/CSCF for two reasons. First, by removing the negative concentrations of $PM_{2.5}$, the E-BAM data are biased high and second, the 24-hour averaged data are the most accurate measurements (MetOne 2008; Schweizer et al., 2016).

Although the $PM_{2.5}$ concentrations reported by the E-BAMs should not be dependent on particle properties, the difference in calculated W/CSCFs from the two experiments (MiniVol derived W/CSCF and 24-hour averaged E-BAM derived W/CSCF) warrant a further analysis.

No statistically significant differences for the W/CSCF based on concentrations were found, matching the findings of McNamara et al. (2011) for a wood smoke correction factor.

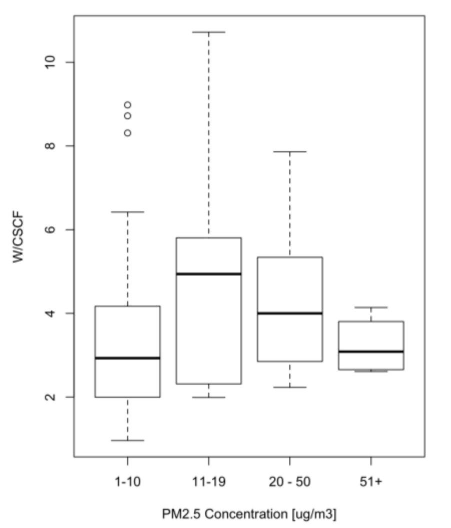

Figure 3-7. W/CSCF by Concentration

The mean(sd) 24-hour average W/CSCF from E-BAM 2 is 3.91(0.836), which is higher than the W/CSCF determined from the MiniVols. This is shown in Figure 3-7. The boxplot of the two instruments are very different; however, the two distributions are not significantly different from each other (p-value = 0.06044, α = 0.05).

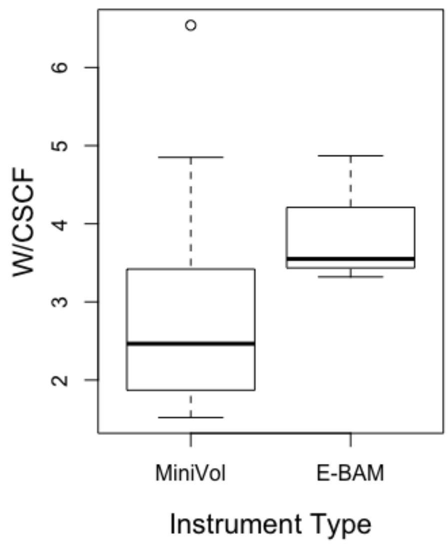

Figure 3-8. Boxplots of W/CSCF for DustTrak from E-BAM and MiniVol

There is disagreement in published literature over how well the E-BAMs correlate and predict PM with respect to FRMs. Schweizer et al. (2016) collocated E-BAMs and BAMs and determined that E-BAMs tended to over-predict BAM reported concentrations by 24% but Trent (2006) found that two E-BAMs collocated with a BGI Inc. PQ-200, an FRM gravimetric sampler, overestimated PM by 1%. Schweizer et al. (2016) conducted their study outdoors and Trent (2006) conducted their study under controlled conditions indoors. Different environmental conditions (variable RH, windspeed, temperature) likely contributed to the difference in these two studies. The wood/coal smoke correction factor experiments were conducted indoors, but under uncontrolled conditions and the difference in W/CSCFs from the MiniVols and E-BAMs are not entirely explained by different environmental factors.

Internal relative humidity affects E-BAM reported $PM_{2.5}$ concentrations, but below RH of 40% the agreement between E-BAM and gravimetric methods is good (Schweizer et al., 2016). The RH reported by E-BAM 2 at Fort Defiance was below 20% during sampling periods and the maximum indoor RH reported by the Average QTrak was 30.7%. Therefore, the disagreement between the MiniVols and E-BAM 2 is likely not due to RH.

3.6 Conclusions

A wood/coal smoke correction factor of 2.60 was determined from 11 sampling events in Navajo homes. The range in concentrations of $PM_{2.5}$ generated at Fort Defiance and Shiprock are representative of typical values expected in Navajo homes; therefore, the calculated W/CSCF is a good initial value for correcting the DustTrak data. The MiniVol W/CSCF is likely a more accurate value than the E-BAM W/CSCF because it is possible that the E-BAM does not accurately measure $PM_{2.5}$ concentrations from wood/coal smoke. More experiments with MiniVol and E-BAM are needed to explain why they don't match well currently. The E-BAM may require a correction factor for different particles, even if, in theory, they are not supposed to.

Comparison of a correction factor estimated from published values of wood and coal smoke showed good agreement with the W/CSCF determined here. Although a preliminary W/CSCF was determined, more sampling should be conducted under typical conditions in Navajo homes. Sampling should be conducted in homes that use uncertified and old stoves as well as in homes using EPA-certified wood/coal burning stoves. Additionally, more experiments should be conducted to determine if the W/CSCF is dependent on concentration.

4. First Pilot Study

4.1 Introduction

The Shiprock Chapter of the Navajo Nation (NN) is located in NM, southeast of the Four Corners Monument and is the largest chapter in the NN (U.S. Census Bureau, 2014). In 2017, 95.2% of the population (8,956) identified as Navajo only (U.S. Census Bureau, 2017a). Children under 5 years of age and the elderly (65+ years old) make up 7.2% and 9.0% of the population in Shiprock, respectively (U.S. Census Bureau, 2017a). The majority of Shiprock's residents live in single unit, detached housing (61.7%) or in mobile homes (25.7%), and an estimated 2.2%, 2.4%, and 2.5% of homes lack complete plumbing facilities, kitchen facilities, and telephone services respectively (NHA 2011; U.S. Census Bureau, 2017b).

According the U.S. Census Bureau (2017d), in 2017, 31.6% of the population in Shiprock was living below the poverty level, with 47.4% of children under 5 years old living below the poverty level. High rates of poverty directly impact access and use of cleaner energy sources, as evidenced by the high percentage (77%) of surveyed Navajos in Shiprock that utilized an indoor stove for heating (Bunnell et al., 2010).

Several factors affect ambient and indoor air quality in Shiprock. The Four Corners Power Plant (FCPP), a 1540-Megawatt coal fired power plant (CFPP) located near Shiprock, was constructed prior to USEPA's preconstruction permit regulations (NNEPA, 2008). In 2007, a Federal Implementation Plan was promulgated by USEPA to regulate emissions from the FCPP (USEPA 2007) because of the Tribal Authority Rule that gives tribes the right to implement their own Clean Air Act program (USEPA 2010). Navajo Nation EPA issued the Title V permit for the FCPP in 2008 and amendments in 2009 and 2012 (T. Denetdeel, personal communication, April 9, 2019). The Title V Permit is a legally enforceable document that promotes compliance with air pollution emissions by the FCPP (T. Denetdeel, personal communication, April 5, 2019).

During winters in Shiprock, meteorological inversion layers trap air pollution close to the ground (Bunnell et al., 2010). Although the CFPPs emitted more pollutants in the summer, hospitalization rates for respiratory illnesses and symptoms such as asthma, bronchitis, COPD, cough, pneumonia, upper respiratory tract infection, and wheezing in Shiprock were higher in the winter compared to the summer (Bunnell et al., 2010). This indicates that indoor heating from wood stoves likely contributes significantly to poor indoor air quality and increased rates of respiratory illnesses.

The First Pilot Study investigating the impacts of a heating stove changeout in Shiprock was conducted from February to March 2018. Navajo Nation EPA led the fieldwork and collected pre-intervention and post-intervention data in seven homes. Eight homes signed up to participate in the research study, but one home, Home 007, was unwilling to give up their old stove. Per Settlement Agreement requirements, they did not receive a Navajo Hybrid Stove and were not eligible to participate in the post-intervention sampling period. Therefore, only seven homes were sampled to completion.

The University of Colorado Boulder was the lead institution in this study, with support from NNEPA, US EPA, and Diné College, a tribal college in the Navajo Nation. NNEPA led the fieldwork with the support of Diné College interns and CU researchers. This process involved setting up samplers and monitors as well as distributing and conducting surveys with the residents.

The objective of this study was to evaluate the effects of EPA-certified hybrid (wood/coal) stoves on indoor air quality in Shiprock, NM.

4.1.1 Navajo Hybrid Stove

The Navajo Hybrid Stove Model 212 was designed by the Woodstock Soapstone Company (West Lebanon, NH) specifically for the Navajo. This EPA-certified stove burns both wood and coal because the Navajo typically use wood and coal as a fuel source for economic and cultural reasons (Bunnell et al., 2010; Champion et al., 2017a).

For wood, the Navajo Hybrid Stove has an average efficiency of 79.4% and an average $PM_{2.5}$ emission rate of 1.05 g/hr, which meets the 2020 New Source Performance Standards (NSPS) PM emissions limit of 2.0 g/hr (Woodstock Soapstone Company, 2015; USEPA, 2015). The average coal $PM_{2.5}$ emission rate is 4.95 g/hr with an average efficiency of 59.7% (Services Polytests, Inc, 2017). This wood/coal hybrid stove is the first to be certified by the US EPA and is also one of the cleanest and most efficient wood burning stoves to be certified by the US EPA (Woodstock Soapstone Company, 2015).

4.1.2 Pollutants

Fine Particulate Matter ($PM_{2.5}$)

Fine and ultrafine particles are generated from combustion processes like residential heating from wood/coal stoves, and from aggregated ultrafine particulate matter (Pope and Dockery, 2006). Several studies have demonstrated that fine and ultrafine particulate matter may have a larger impact on respiratory health, cardiovascular disease, asthma, COPD, lung function, and mortality than coarse (PM_{10}) particulate matter (Wu et al., 2018; Brook et al., 2010; Guo et al., 2018; Apte et al., 2015; WHO, 2016; Haikerwal et al., 2016; von Klot et al., 2002). A study by Pope et al. (2002) found an increase of 10 $\mu g/m^3$ in $PM_{2.5}$ concentration was associated with approximately a 4%, 6%, and 8% increased risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively.

Carbon Monoxide (CO)

Carbon monoxide (CO), is an odorless, tasteless, colorless, and non-irritating gas that is generated as a byproduct of incomplete combustion such as from motor vehicle exhaust, heaters, furnaces, ovens, and cigarette smoke (Prockop 2009). When inhaled, CO forms a tight bond with hemoglobin (Hb), creating carboxyhemoglobin (COHb), which reduces the availability of oxygen to the body resulting in tissue hypoxia (Raub et al., 2000).

Carbon Dioxide (CO_2)

Carbon dioxide is also a colorless, odorless, and nonflammable gas that is about 1.5 times heavier than air, sinking to the ground and displacing oxygen from the area (Permentier et al., 2017). At ambient concentrations, CO_2 has little to no effect on human health.

While not classified as a criteria pollutant, carbon dioxide (CO_2) is a gaseous byproduct of incomplete combustion. Current average ambient levels of CO_2 are around 400 ppm (approximately 0.04% in air) and these levels are rising every year (NOAA 2019a; Permentier et al., 2017). Carbon dioxide is also recognized by many scientists as a major greenhouse gas (MacCarty et al., 2008; Lashof and Ahuja, 1990; Solomon et al., 2008; IPCC, 2014).

4.1.3 Institutional Review Board (IRB) Approvals

Prior to beginning the study, Institutional Review Board approvals were obtained from the University of Colorado – Boulder IRB (17-0508), Diné College IRB (#DCIRB-17.06), and the Navajo Nation Human Research Review Board (#NNHRRB-17.292). Appropriate approvals for modifications and amendments were also obtained before experiments were conducted in 2019. NNHRRB approval (#NNHRRB – 19.335) was also obtained before using the data from the research study in support of this master's thesis. A timeline of this process is included in Appendix E.

4.2 Materials and Methods

4.2.1 Locations and Homes

All sampling in the First Pilot Study occurred in the Shiprock Chapter of the Navajo Nation. The homes were single family houses or mobile homes, and none were weatherized during the pre nor post-intervention sampling periods. All homes used gas for cooking and only two homes (Home 002 and 003) had a ventilation device for their cooking appliance.

4.2.2 Instruments

<u>DustTrak II Model 8530</u>

A DustTrak II Model 8530 (TSI, Shoreview, MN, Range: 0.001 – 400 mg/m^3, Resolution: $\pm$0.1% of reading or 0.001 mg/m^3) was used to monitor $PM_{2.5}$ concentrations in the homes. The DustTrak is a single-channel basic photometric instrument with an operational temperature range from 0 – 50°C and particle size range is from 0.1 to 10 µm. Prior to every sampling event, the DustTraks were zeroed, the flow was calibrated, and the $PM_{2.5}$ calibration impactor was cleaned and oiled. The flow was calibrated with a MesaLabs Bios Defender 510-M (Brandt Instruments, Inc., Prairieville, LA, Flow Range: 50 – 5,000 mL/min, Accuracy: +/- 1.0%), which is a primary air flow calibrator using DryCal technology.

<u>QTrak Model 7575</u>

CO and CO_2 were measured with a QTrak Model 7575 (TSI, Shoreview, MN, Range: 0 – 5000 ppm for CO_2 and 0 – 500 ppm for CO, Accuracy:$\pm$3% of reading or $\pm$50 ppm for CO_2 and $\pm$3% of reading or 3 ppm for CO). These units also measure relative humidity (RH), temperature, and barometric pressure (BP). The QTrak is operational between 5° C and 50° C. The CO probe for each QTrak was rehydrated prior to the sampling campaign.

USB-501-TC with K-type thermocouple

The USB-501-TC (Measurement Computing Company, Norton, MA) and k-type thermocouple with a logger that measures temperature from -328°F to 2462°F with an internal resolution of 1°F and an accuracy of ±2°F. These were used to provide quantitative data regarding stove use in the seven homes following the stove changeout.

4.2.3 Survey Tools and Procedure

Table 4-1 below describes the data collection tools and timeline for the home visits to collect pre-intervention and post-intervention data. During the first visit, the responsible adult in the household filled out the consent form and aided the field researcher in completing the General Household Survey 1 (GHS1). Other field researchers installed the samplers and monitors; a DustTrak II Model 8530, QTrak Model 7575, and an MCC USB-500 Temperature Logger (post-changeout only) in the home.

Table 4-1. Home Visit and Procedure

Visit Number	Procedures/Tools
Visit 1: Pre-intervention	·Obtain Consent ·Complete General Household Survey 1 ·Place instruments
Visit 2	·Retrieve instruments ·Verify Activity Logs are completed
Visit 3: Post-intervention	·Install instruments ·Provide new Activity Log ·Complete General Household Survey 2
Visit 4	·Retrieve instruments ·Verify Activity Logs are completed

General Household Survey 1 and 2

The GHS1 was completed by the responsible adult on the first visit to gather qualitative data regarding the home, heating stove, fuel use, cooking appliances, and other potential sources of pollution. The GHS2 was completed on the third visit, or the first day of post-intervention sampling. This survey was used to document changes to the home from GHS1 and the stove user's perception regarding the Navajo Hybrid Stove.

<u>Activity Logs</u>

In addition to samplers and monitors, homes were provided with daily activity logs to provide more information on activities that may impact IAQ. Stove and non-stove activities (like cooking and cleaning) were recorded on an hourly basis by the stove users.

4.3 Experimental Set Up

Instruments were located between 3.5 ft and 16 ft from the stove. When possible, the instruments were placed in the same room as the heating stove. DustTraks and QTraks were placed in the same location, 3 – 5 ft off the ground. The location of the instruments for each home was the same for the pre and post-intervention sampling periods.

4.4 Data Analysis

The Shapiro-Wilk test for normality, histograms, and QQ plots returned non-significant results for normality, therefore, non-parametric tests were used. The Friedman Rank Order of Repeated Measures Test was used to compare the two 24-hour sampling periods pre-intervention and post-intervention to determine if there were any significant differences in the four sets of data. The Wilcoxon Sign Rank Test was used to compare the pre-intervention and post-intervention data.

4.5 Results and Discussion

Home 008 was removed from the data analysis because there was a wildfire across the street when the post-intervention sampling occurred. No outdoor measurements were recorded during the First Pilot Study; therefore, the contribution of ambient $PM_{2.5}$, CO, and CO_2 could not be determined. $PM_{2.5}$, CO, and CO_2 concentrations for Home 008 were included in the appropriate tables and figures, but the data was not used in the statistical analysis.

Comparisons of pre and post-intervention $PM_{2.5}$ and CO concentration are reported below in addition to the adjusted concentrations. For the adjusted concentrations, stove temperature, home temperature, and activity logs were used to remove increases in $PM_{2.5}$ and CO that were not due to stove use. Because this process relied on indirect measures of stove use as well as stove user reported activities, the unadjusted data were also analyzed and included in this study.

Comparison using the Friedman Test of the Barometric Pressure and temperature for the pre and post-intervention periods did not yield any statistically significant results ($p = 0.2482$ and $p = 1$, respectively). There was a statistically significant difference between Relative Humidity for pre-intervention Day 2 and post-intervention Day1 ($p = 0.002165$) as well as for post-intervention Day 1 and Day 2 ($p = 0.04113$). However, the range of RH over the four days of sampling was 7.01% – 27.79%. Jayaratne et al. (2018) reported that DustTrak readings were not affected until RH exceeded 75%; therefore, it is likely that the reported $PM_{2.5}$ concentrations were unaffected by the difference in RH. The boxplot for RH over the four days of sampling is in Figure 4-1 below.

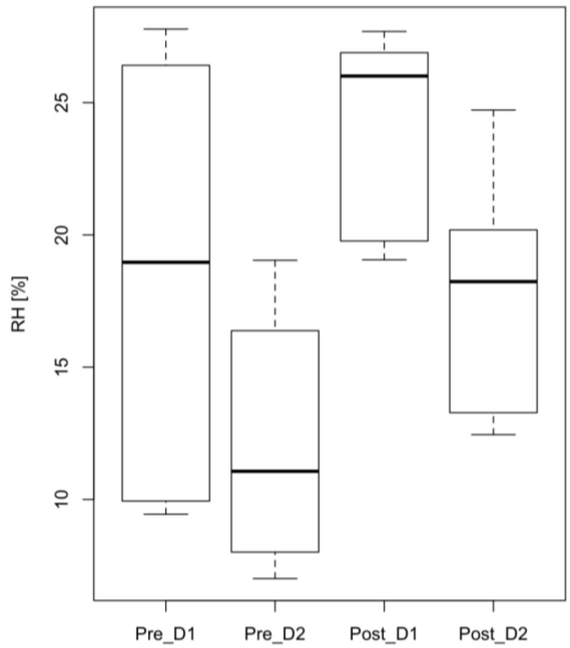

Figure 4-1. Relative Humidity

4.5.1 Pre and Post-Intervention Sampling

Two continuous 24-hour sampling periods (48 hours total) were conducted pre and post-intervention during the Pilot Study.

4.5.1.1 $PM_{2.5}$

The absolute value of percent change in 24-hour averaged $PM_{2.5}$ concentrations over the two days ranged from 11% to 129% pre and post intervention. This variability within the two-day sampling period required verification that there was a statistically significant difference in concentrations within homes on Day 1 and Day 2 for the pre and post-intervention periods. Figure 4-2 below contains the boxplots of Day 1 (D1) and Day 2 (D2) for the pre-intervention as well as Day 1 and Day 2 for the post-intervention $PM_{2.5}$ concentration for the six homes.

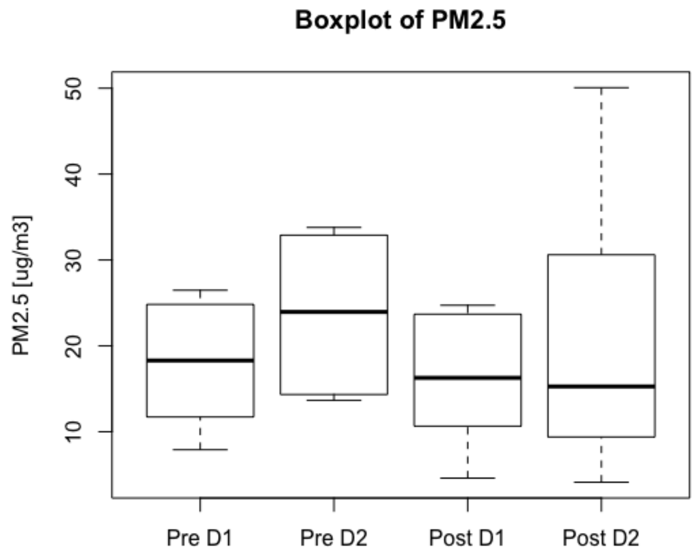

Figure 4-2. Boxplots of $PM_{2.5}$

The Friedman Test returned a p-value of 0.4575 (α = 0.05), meaning there were no statistically significant differences in the four sets of data. Pre-intervention Day 2 and post-intervention Day 2 are not significantly different from each other (p-value = 0.6875).

Because there were no statistically significant differences between Day 1 and Day 2 $PM_{2.5}$ concentrations for the pre and post-intervention periods, the average of the two days (the average of the 24-hour average on Day 1 and 24-hour average on Day 2) was calculated for each home. The boxplots for the homes pre-intervention and post-intervention are shown in Figure 4-3. The 24-hour average of $PM_{2.5}$ pre-intervention and post-intervention did not differ significantly from each other (p-value = 0.3125).

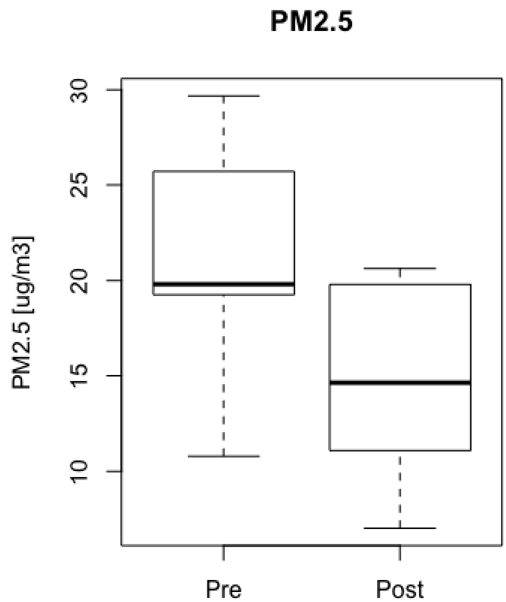

Figure 4-3. Boxplots of 24-Hour Averaged Pre and Post $PM_{2.5}$

Although overall there were no overall significant differences in $PM_{2.5}$ concentration pre and post-intervention, decreases in $PM_{2.5}$ concentrations post-changeout were observed in Homes 001, 003, 005, and 006. Increases were observed in Homes 002 and 004.

Figure 4-4 below shows the 24-hour averaged $PM_{2.5}$ for the six homes pre and post-intervention. Although the results are mixed, a 72.8% and 43.4% reduction in $PM_{2.5}$ concentrations were observed in Homes 005 and 001, respectively.

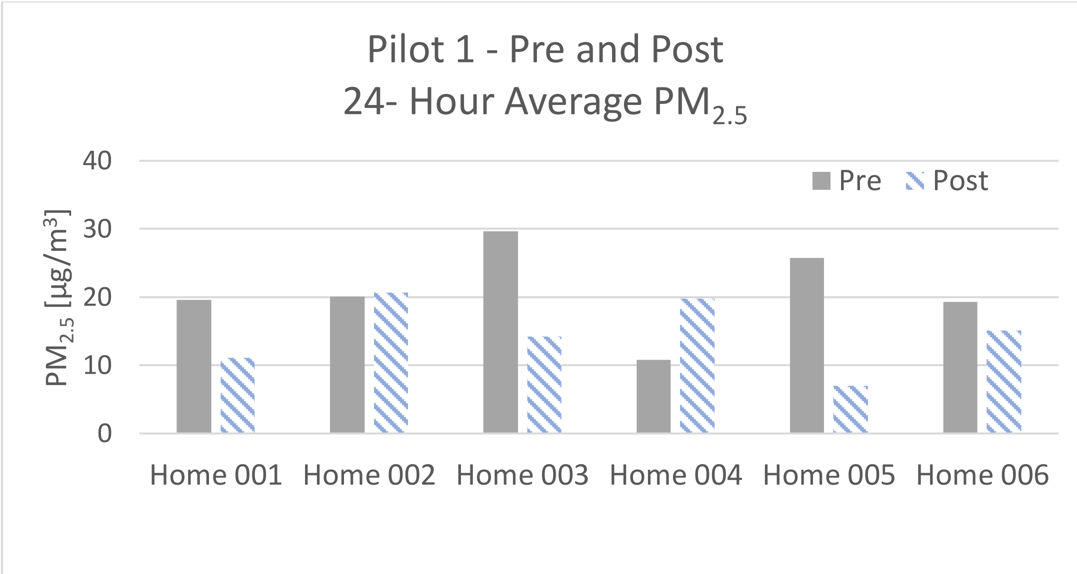

Figure 4-4. Pre and Post-Intervention 24-hour $PM_{2.5}$ Concentrations

The 83.6% increase in $PM_{2.5}$ concentrations post-intervention in Home 004 is examined further in Figure 4-5 below.

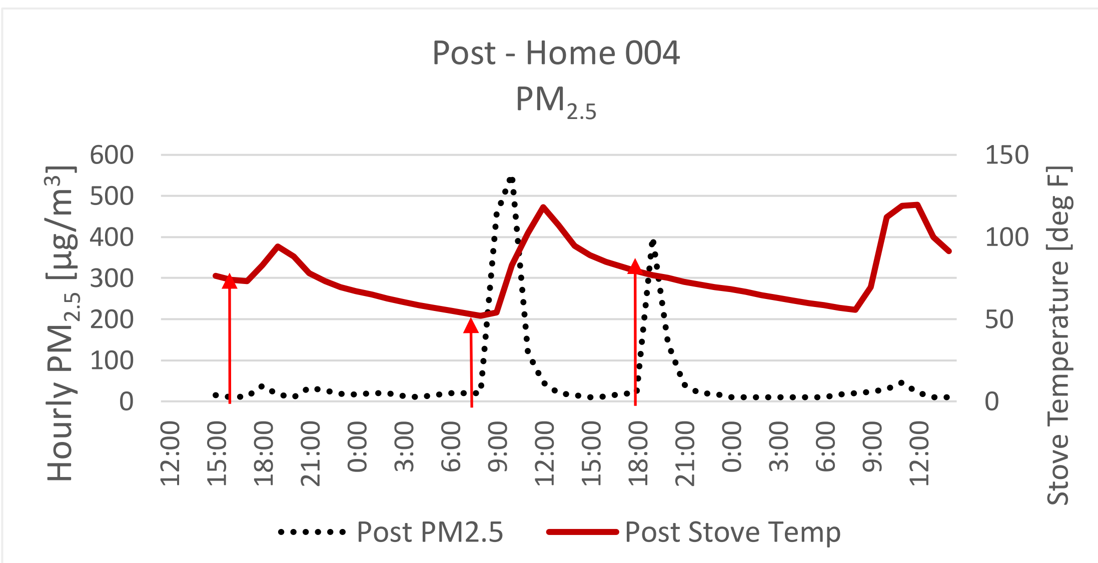

Figure 4-5. Post-Intervention Home 004 – $PM_{2.5}$ and Stove Temperature

The first increase in $PM_{2.5}$, denoted with the first red arrow, is correlated with an increase in stove temperature. The second increase in $PM_{2.5}$ is also correlated with stove use, but the magnitude of the increase in $PM_{2.5}$ concentration is much larger than the magnitude of the first increase, implying that there was probably another activity contributing to PM generation at this time. The third increase in $PM_{2.5}$ occurs when stove temperature decreased. Therefore, the second increase in $PM_{2.5}$ concentration was also likely not due to stove use. To further reconcile these activities, the time series for $PM_{2.5}$ pre and post intervention are examined in Figure 4-6.

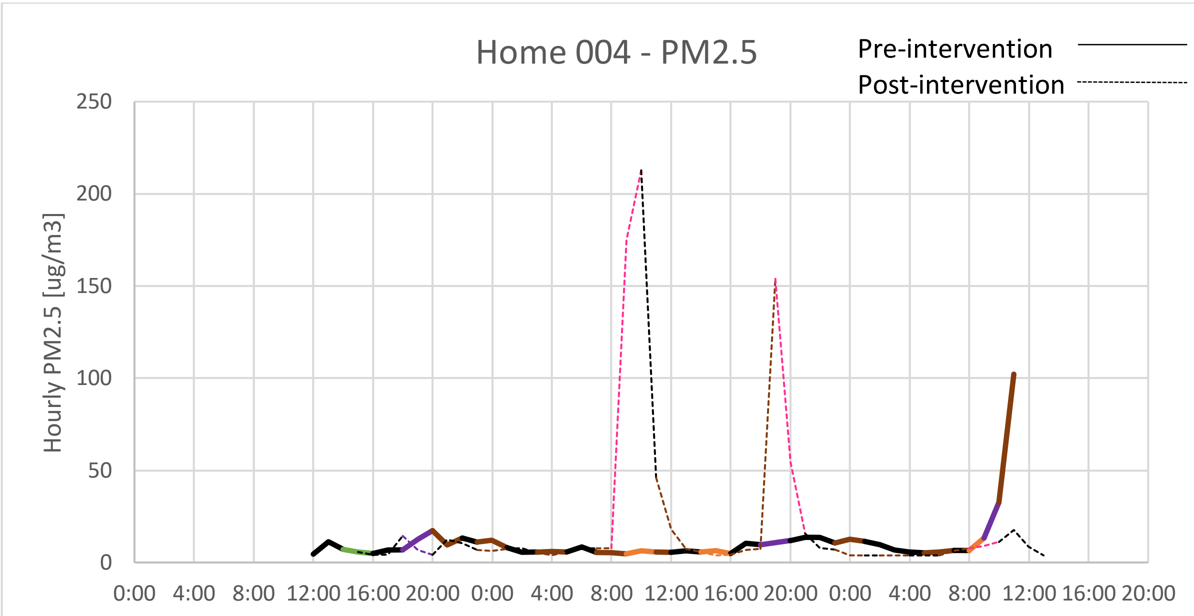

Figure 4-6. Home 004 Time Series for $PM_{2.5}$

The pre-intervention (solid line) and post-intervention (dashed line) $PM_{2.5}$ concentrations are broken down by activity and color coded according to the legend in Figure 4-6. It is apparent that the two large increases in $PM_{2.5}$ concentration during the post-intervention sampling period are not due solely to stove use. The stove users noted that they burned other items during this period. Although they didn’t note what was being burned, burning cedar is very common among the Navajo for its cultural significance (Williams, 2009). Since this activity was not seen during the pre-intervention sampling period and it’s known to be common practice among Navajo, this indicates that the sampling period of two days was likely not sufficient to capture all typical home activities.

Overall, the mixed results in $PM_{2.5}$ concentrations indicate that the stoves were not operated correctly or that there were other activities, like cooking or burning other items, that contributed to $PM_{2.5}$ in the homes. With a longer sampling time (at least 3 days) and the use of a stove temperature sensor both pre-intervention and post-intervention, occupant activities can be better characterized for a more accurate assessment of $PM_{2.5}$ contribution from stove use.

4.5.1.2 Carbon Monoxide

The same process used for $PM_{2.5}$ to determine significance within sampling periods and between the pre and post-intervention periods was followed for CO. Boxplots of CO for the two 24-hour periods pre-intervention and post-intervention are in Figure 4-7.

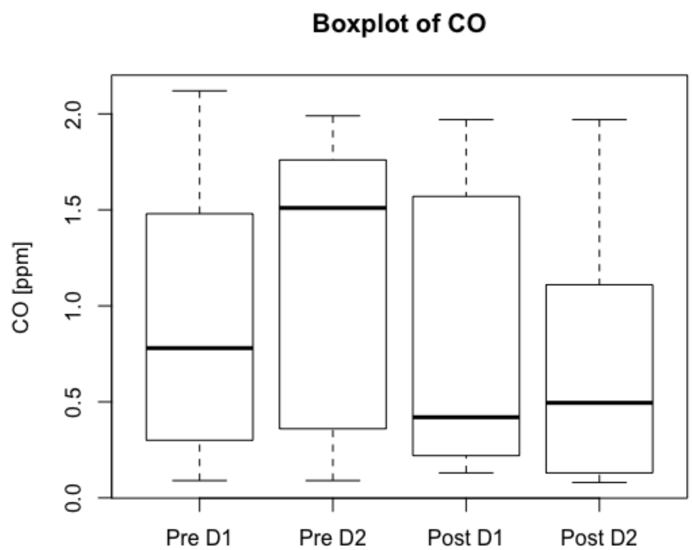

Figure 4-7. Boxplots of CO

The Friedman Test did not determine any statistically significant differences between the CO concentrations for the four data sets (p-value = 0.7505). Further analysis of the relationship between pre-intervention Day 2 and post-intervention Day 1 (p-value = 0.4375) and pre-intervention Day 2 and post-intervention Day 2 (p-value = 0.2188) also did not yield statistically significant results.

No statistically significant differences between the two 24-hour pre-intervention (p-value = 0.2897) and two 24-hour post-intervention (p-value = 0.8551) data were found; therefore, the average of the two days pre-intervention and the average of the two days post-intervention were calculated, and the boxplots of the six homes pre-intervention and post-intervention are shown in Figure 4-8 below.

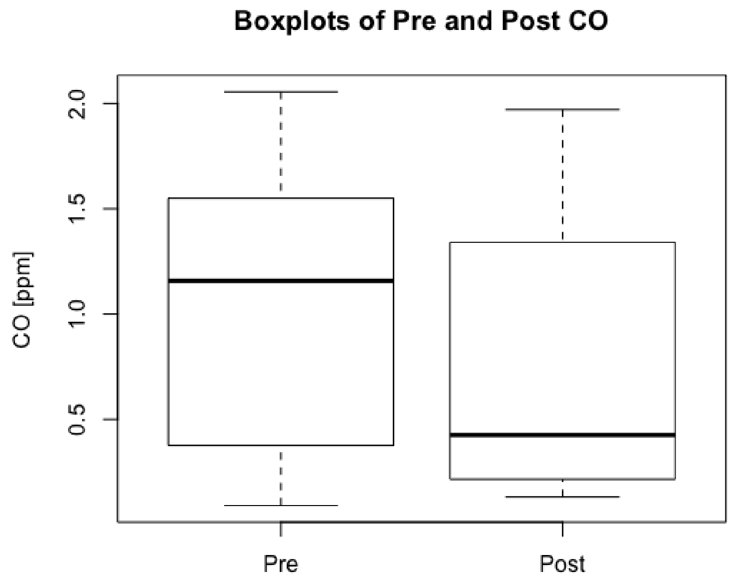

Figure 4-8. Boxplots of 24-Hour Averaged Pre and Post CO

Although there was a noticeable decrease in CO concentration post-intervention, it was not statistically significant (p-value = 0.4375). Overall, CO concentrations in homes were low, below the WHO 24-hour standard of 6.11 ppm (WHO 2010). There were decreases in CO concentration post-intervention in Homes 001, 002, 004, and 006. Increases in CO concentration post-intervention were observed in Homes 003 and 005.

The 24-hour averages for the two days of pre and post-intervention sampling for CO are shown below in Figure 4-9. An 86% and 65.6% decrease in CO concentration were observed at Home 006 and Home 004 respectively. Increases of 53.6% and 338.8% in CO were observed at Home 003 and Home 005 respectively.

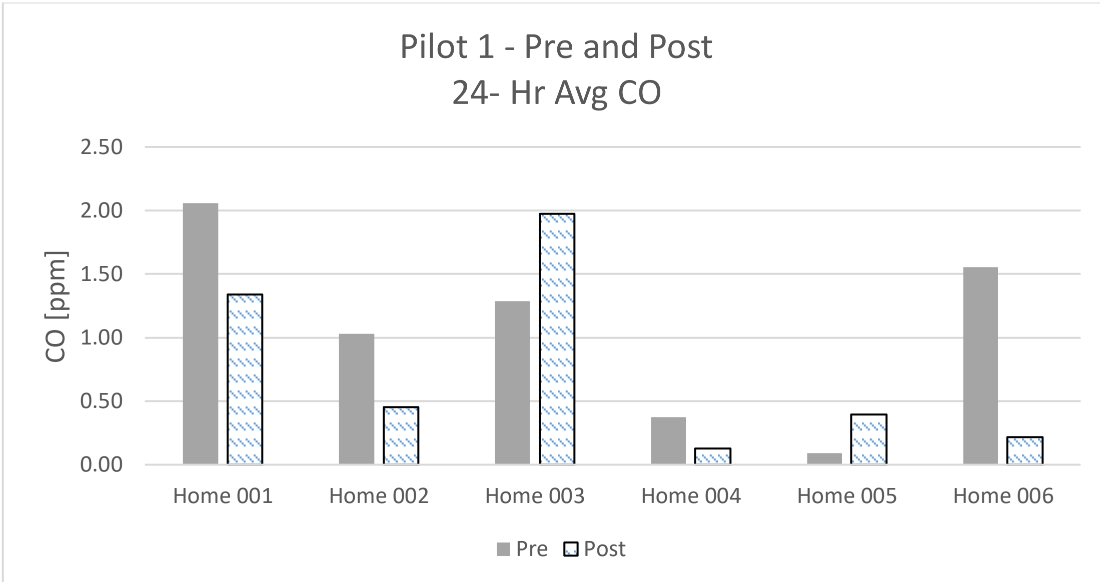

Figure 4-9. Pre and Post-Intervention CO Concentrations

In Home 003, the occupant noted that they cooked four times over the two-day sampling period. The four blue arrows associated with increases in CO in Figure 4-10 denote those four cooking events and only one correlates to an increase in stove temperature. Therefore, the biggest source of CO in Home 003, post-intervention, is likely due to cooking activity and not stove activity. The second blue arrow from the left is also associated with an increase in stove temperature because the occupant added wood/coal to the stove at around 5AM. The increase in CO at that time is likely a result of combustion and cooking activity. The occupants noted that they cooked twice during the pre-intervention period. The difference in cooking frequency is likely a significant factor in the increase in CO concentration post-intervention.

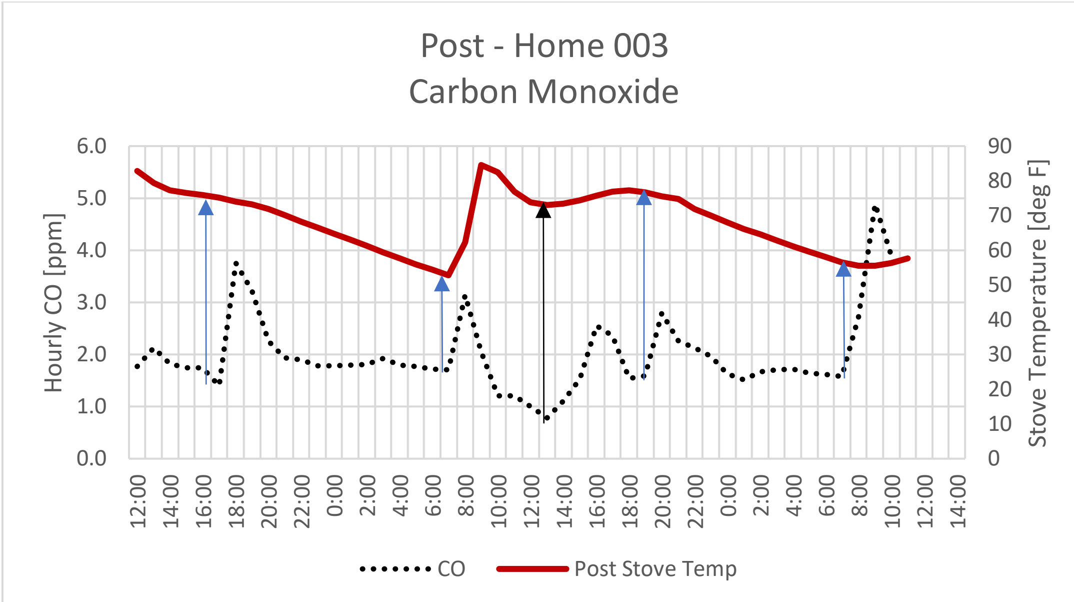

Figure 4-10. Post-Intervention Home 003 – CO and Stove Temperature

Figure 4-11 shows the time series of the stove temperature dta and CO concentration for Home 005. The large increase in CO concentrations post-intervention for Home 005 are likely due to cooking and cleaning activity, which occurred at the same time as three of the four increases in CO concentration. Since stove temperature also increased during three of these times, it is not possible to discern the contribution from combustion in the stove versus cooking activities.

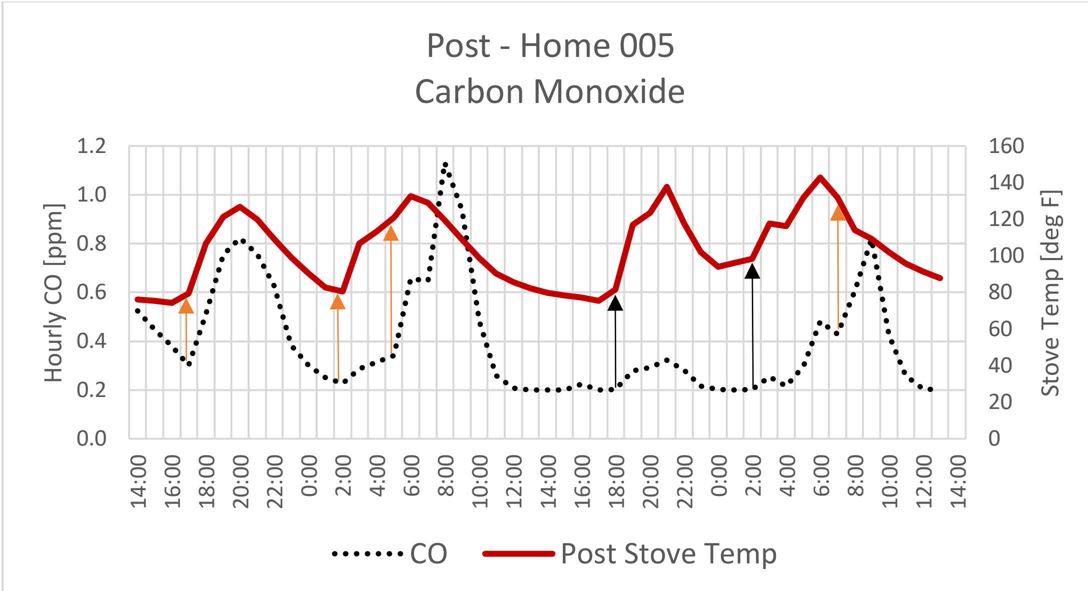

Figure 4-11. Time Series for Carbon Monoxide – Home 005

4.5.1.3 Carbon Dioxide (CO_2)

Pre and post-intervention data for CO_2 are included here because it is a byproduct of incomplete combustion. Minor changes in CO_2 concentration were observed between the pre and post-changeout and are shown in Table 4-4.

Figure 4-12 shows boxplots of the two 24-hour pre and two 24-hour post intervention CO_2 concentrations from the six homes.

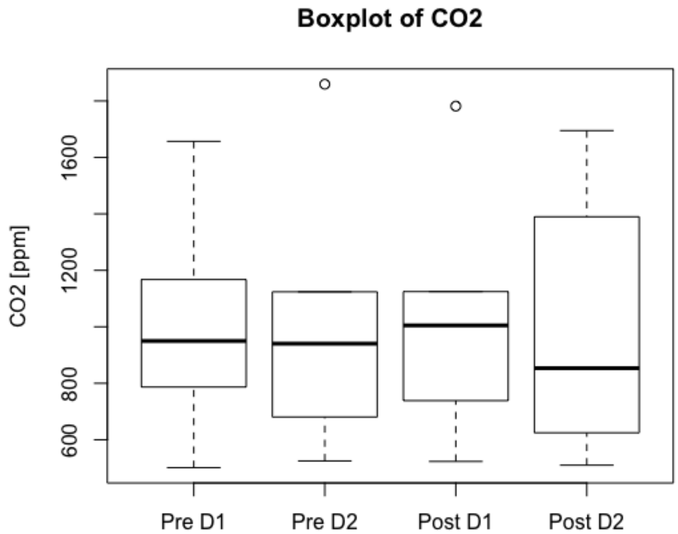

Figure 4-12. Boxplots of CO_2

There were no statistically significant differences in the four data sets (p-value = 0.9402) and no statistically significant differences for the two pre-intervention data sets (p-value = 1) nor for the two post-intervention data sets (p-value = 1). The largest difference in medians Pre Day-1 and Post Day-2 (p-value = 0.4375) as well as Pre Day-2 and Post Day 2 (p-value = 0.8438) were also not significant

Figure 4-13 shows the 24-hour average CO_2 concentrations pre-intervention and post-intervention. The two boxplots are nearly identical, with similar medians and IQRs.

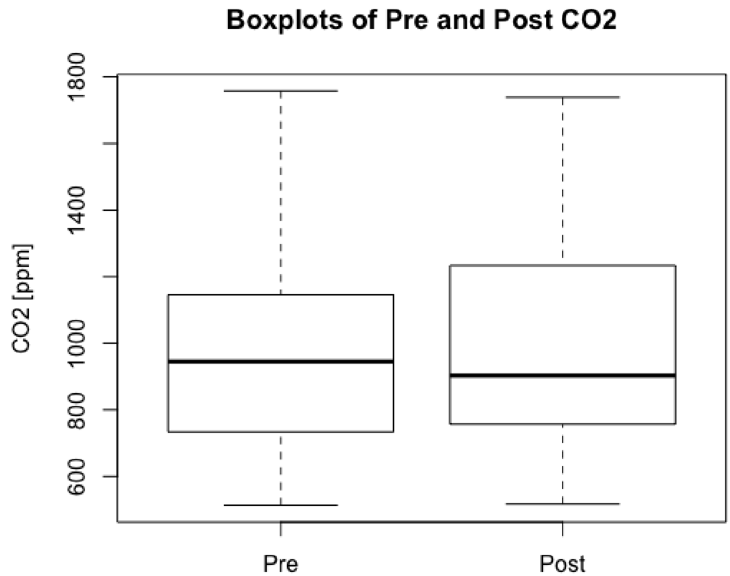

Figure 4-13. Boxplots of 24-Hour Averaged CO2 Concentration Pre and Post

Although significant decreases in CO_2 were not expected, it is somewhat surprising that the pre and post-intervention median concentrations of CO_2 were very similar. CO_2 is not considered a pollutant by the EPA, so there are no NAAQS. None of the concentrations of CO_2 were significantly high (~10%) to warrant concern for the occupants' health.

4.5.2 Home Temperature as Proxy for Stove Use

Stove temperature sensors were not deployed during the pre-intervention sampling period due to operational issues. The stove temperature sensors supplemented the activity logs to provide a better idea of when the stove was used, and which increases in pollutant concentrations were due to stove activity versus other activities like cooking and cleaning.

For each of the homes, the post-intervention home temperature was plotted against the stove temperature data and linear regression was used to determine the correlation (see Appendix D). Home and stove temperatures in Homes 001, 003, 004, and 005 had a strong correlation (R^2 between 0.7346 and 0.8184), while moderate correlations were found for Home 002 (R^2 =

0.5118) and Home 006 (R^2 = 0.5878). Of these six homes, the two homes with a moderate correlation between stove and home temperature were the only ones that did not have a secondary heating source. All other homes had a small electric heater or an electric blanket (Home 005).

Due to the good correlation between home and stove temperature, the activity logs for the pre-intervention time series for $PM_{2.5}$ and CO concentrations were supplemented with the home temperature data. Although the stoves were replaced and, therefore the correlation is likely not the same pre and post-intervention, it is not unreasonable to assume that the home temperature can be used as a proxy for stove use.

The time series of $PM_{2.5}$ and home temperature for Home 001(R^2 = 0.7713) is in Figure 4-14 below. It is apparent that there are increases in $PM_{2.5}$ that are likely not due to stove activity (i.e. decreasing home temperature with increasing concentrations of $PM_{2.5}$). The activity log for this day did not document any activity, so the home temperature data could be used to supplement missing activities and provide an approximation for stove vs. non-stove generated $PM_{2.5}$.

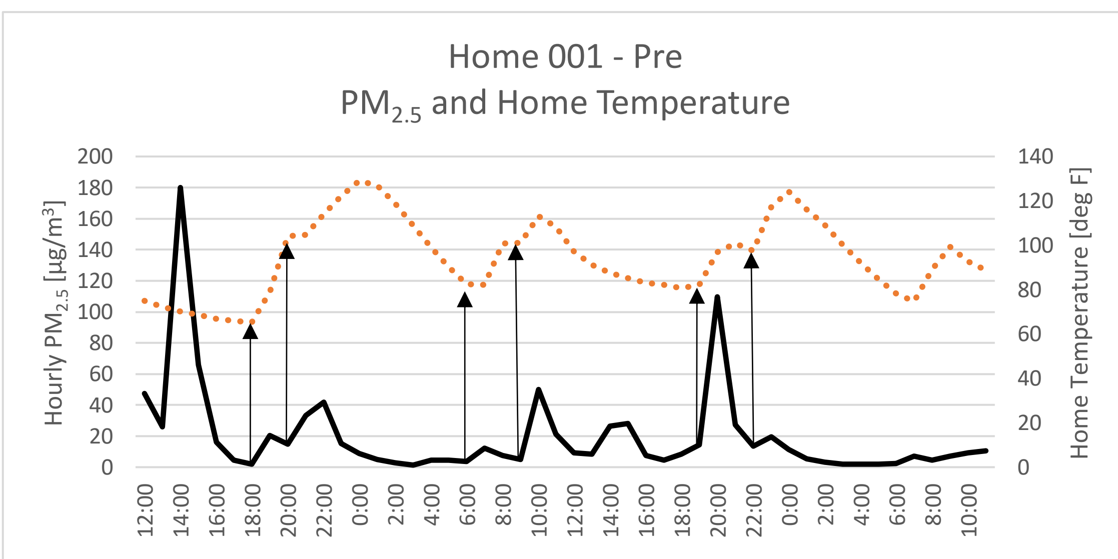

Figure 4-14. Pre-Intervention Home 001 $PM_{2.5}$ and Home Temperature

The pre-intervention indoor temperature and $PM_{2.5}$ concentration time series for Home 002 (R^2 = 0.5118) is shown below in Figure 4-15. The second increase in $PM_{2.5}$ (i.e. first black arrow) is not associated with an increase in home temperature, however, the stove user wrote down that they added wood/coal to the stove at this time. Additionally, the increase in $PM_{2.5}$ at 7:00PM (i.e. second black arrow) appears to be associated with stove use (i.e. increasing home temperature), but wood/coal addition to the stove was not noted in the activity log. This discrepancy shows that while the home temperature data can be used to supplement the available information, they should not be used alone.

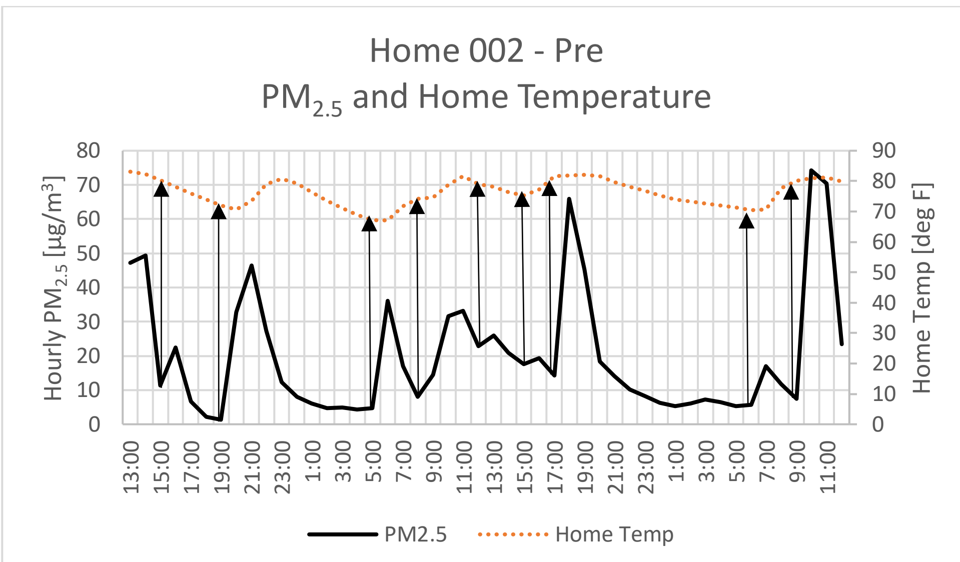

Figure 4-15. Pre-Intervention Home 002 $PM_{2.5}$ and Home Temperature

4.5.3 Hourly Time Series for $PM_{2.5}$ and CO for Selected Homes

The hourly time series for $PM_{2.5}$ and CO pre and post-intervention for selected homes are included in here. The time series for the remaining homes are in Appendix E. The activity logs, home temperature, and stove temperature sensor data (for post-intervention) were used.

Solid lines are pre-intervention $PM_{2.5}$ concentrations and the dashed lines are $PM_{2.5}$ concentrations post-intervention. Additionally, the different colors indicate a different activity or activities: cooking (blue), cleaning (green), addition of wood/coal to the stove (brown), cooking and cleaning (orange), cleaning ash (grey), burned other items (red), cooking and cleaning and wood/coal (purple), cooking and wood/coal (light blue), cleaning and wood/coal (light green), cooking and cleaning and burned other items (yellow), burned other items and cleaning (light orange), burned other items and wood/coal (pink).

Figure 4-16 shows the pre (solid line) and post-intervention (dashed line) time series of $PM_{2.5}$ for Home 002.

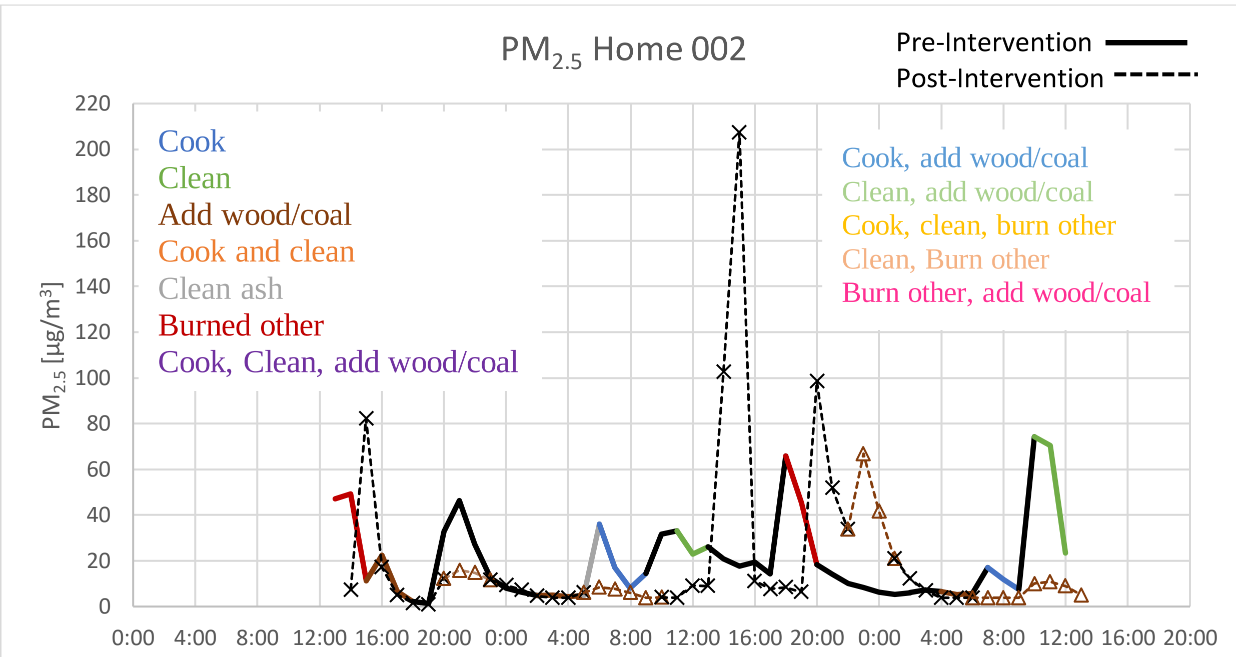

Figure 4-16. Hourly $PM_{2.5}$ Averages Pre and Post-Intervention for Home 002

The post-intervention activity logs for Home 002 were not filled out; consequently, activities like cooking and cleaning were not indicated. Using the stove temperature sensor data, the times and duration when the stoves were in use were noted and coded in this figure (i.e. triangles and brown dashed lines). The largest increase in $PM_{2.5}$ concentration was due to unknown activity/activities (i.e. crosses and black dashed lines), but likely cannot be attributed to stove use because the stove temperature decreased at this time.

4.5.4 Adjusted Data

The concentration data for pre and post-intervention $PM_{2.5}$ and CO were adjusted to remove increases in concentration not related to stove use. It is important to keep in mind that the removal of concentration data pre-intervention was done with activity logs and home temperature, whereas post-intervention data was examined with activity logs and stove temperature data. Therefore, there is some uncertainty regarding the pre-intervention adjusted concentrations. The boxplots for CO and $PM_{2.5}$ pre and post-intervention are shown in Figures 4-17 and 4-18, respectively.

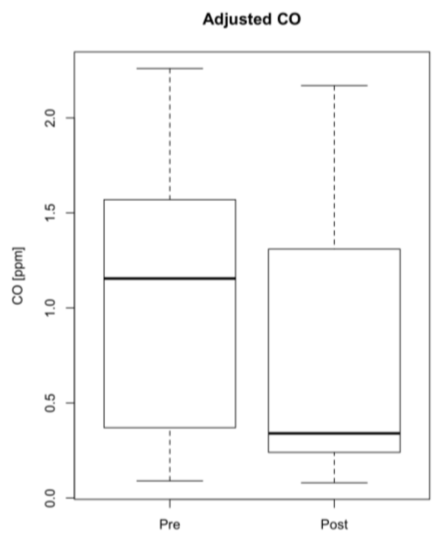

Figure 4-17. Adjusted CO

Even after adjusting the CO data in the six homes, no statistically significant difference between the two was found ($p = 0.3125$).

The adjusted time series for $PM_{2.5}$ are shown in Figure 4-18. The solid purple line is the adjusted post-intervention data and the dashed orange line is the adjusted pre-intervention data. Gaps between the two lines are the data that were removed, and largely correspond to either unrecorded activity or cooking and cleaning activity. Prior to removing data, the home temperature (pre-intervention) or stove temperature (post-intervention) data was consulted to ensure that stove activity did not occur during the same time.

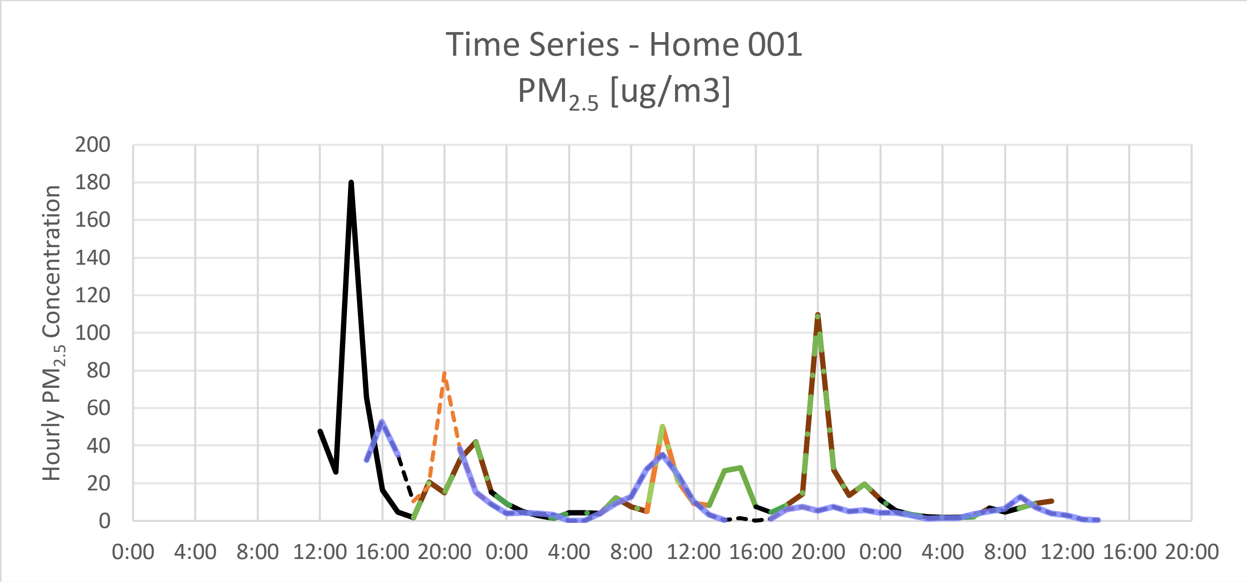

Figure 4-18. Home 001 Adjusted $PM_{2.5}$

Figure 4-19 shows is the boxplot of the adjusted $PM_{2.5}$ concentrations. After adjusting for $PM_{2.5}$, a statistically significant difference ($p = 0.03125$) between the pre and post-intervention concentrations was found.

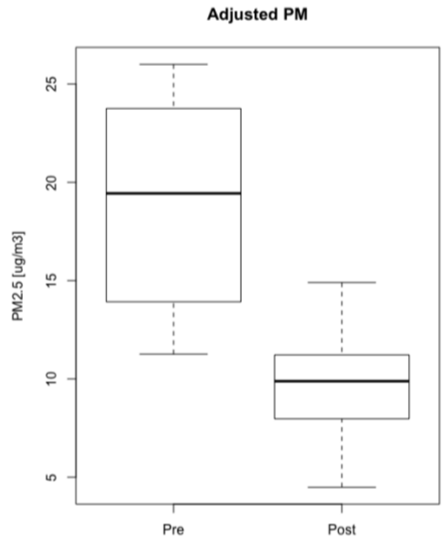

Figure 4-19. Adjusted $PM_{2.5}$

4.5.5 Home 006

Home 006 was sampled three times: pre-intervention, post-intervention, and approximately 1 year following the post-intervention (henceforth referred to as post-post intervention) sampling period. Pre-intervention sampling in this home occurred March 8 – 10, 2018, post-intervention sampling occurred March 27 – 29, 2018, and the post-post intervention sampling occurred March 2 – 4, 2019. Stove temperature sensors were not used in the post-post intervention nor pre-intervention sampling period.

The three 24-hour $PM_{2.5}$ concentrations for the Post-Post sampling period were 16.53 μg/m^3, 36.28 μg/m^3, and 17.17 μg/m^3. On the first day of sampling, coal was added to the stove four times, the ash was cleaned five times, and there was no significant increase in $PM_{2.5}$ concentration.

The second day had a higher concentration of $PM_{2.5}$, largely due to two increases in $PM_{2.5}$ concentration between 6PM – 12AM and 5AM – 11AM. During the first time period, 6PM – 12AM, coal was added to the stove at 7PM and ash was cleaned at 9:26PM. For the second period (5AM – 12PM), coal was added at 10AM and ash was cleaned at 7AM. However, these two activities do not fully explain the significant increases in concentration (157.02 μg/m^{3}and 80.81 μg/m^3 from baseline concentrations ~15 μg/m^3), especially considering that these increases were not seen during the other times where wood/coal was added or when the ash was cleaned.

This is supported by the time series of home temperature and hourly $PM_{2.5}$ concentration show in Figure 4-20 below.

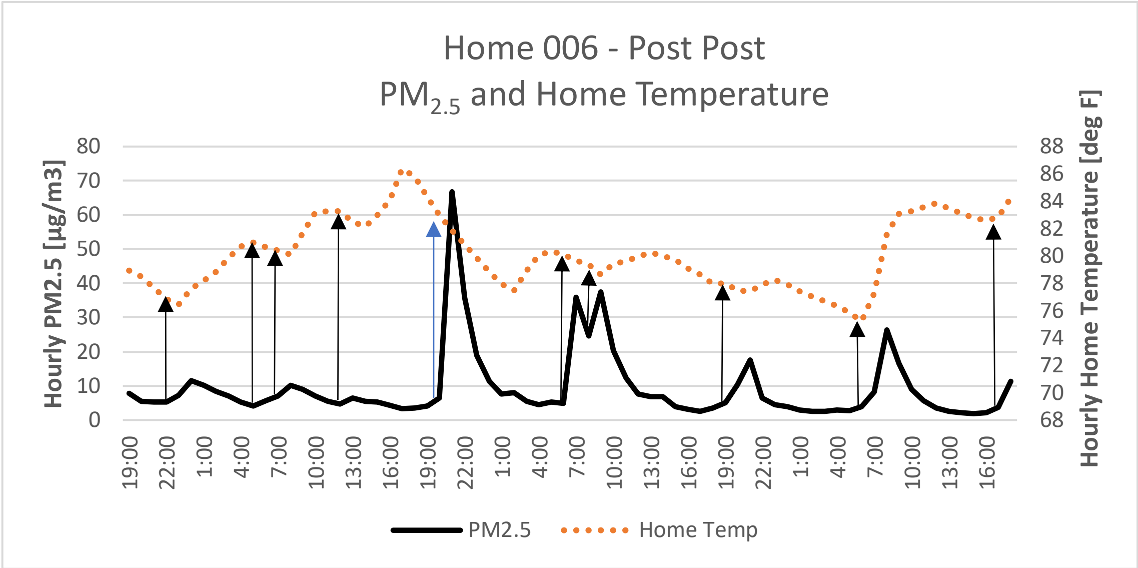

Figure 4-20. Post Post-Intervention Home 006 $PM_{2.5}$ and Home Temperature

The first significant increase in $PM_{2.5}$ (i.e. blue arrow) does not appear to be associated with any increase in home temperature. It is likely that the large increase in $PM_{2.5}$ concentration during this time was a result of unrecorded home activity, like cleaning. Upon entering Home 006, a strong chemical smell, likely attributable to cleaning products, was prominent and the occupant also spoke at length about the importance of maintaining a clean home.

The homeowner also noted that they regularly clean the walls and couches and take the rugs to the cleaners monthly. Unrecorded cleaning activity like sweeping or vacuuming could contribute to $PM_{2.5}$ concentrations (Meng et al., 2009; Zhou et al., 2016

The two-day 24-hour $PM_{2.5}$ concentration for the pre-intervention and post-intervention period was 50.07 µg/m^3 and 39.41 µg/m^3. The post-post intervention 24-hour concentration for all three days was 23.33 µg/m^3. CO concentrations over the three days was 0.04 ppm. The concentrations of CO and $PM_{2.5}$ in Home 006 for the different sampling periods are shown below in Figure 4-21.

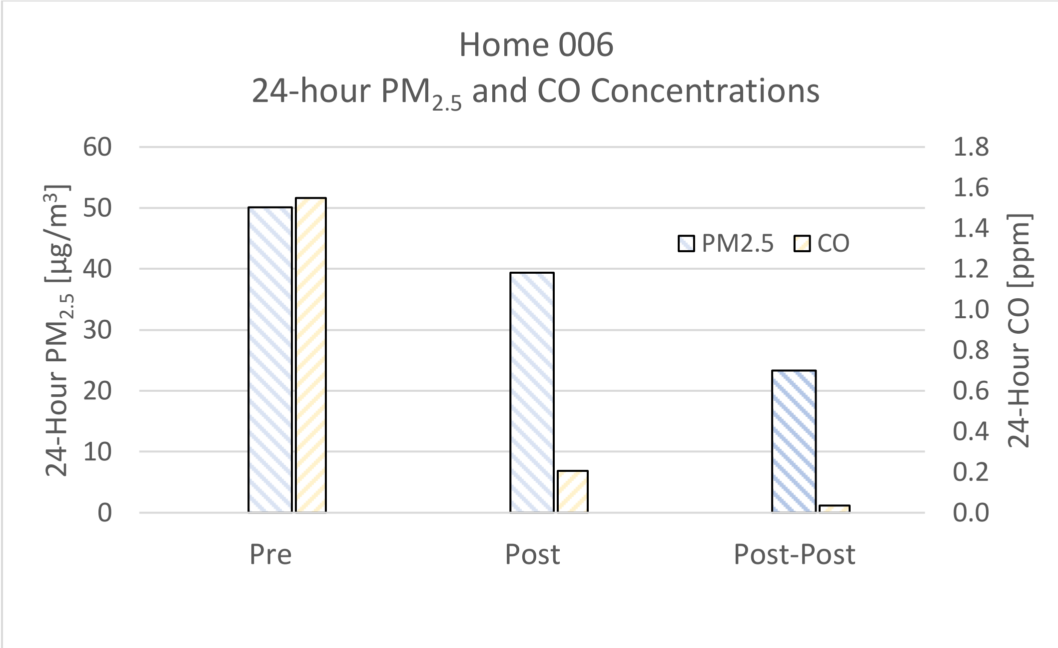

Figure 4-21. Pre, Post, and Post-Post-Intervention Concentrations – Home 006

From Pre-intervention to Post-Post intervention measurements, there was a noticeable decrease in PM2.5 and carbon monoxide in Home 006. A 50% decrease in $PM_{2.5}$ and 97.4% decrease in CO were observed in Home 006 from post-post intervention to pre-intervention concentrations. This indicates that as stove users have more time to become familiar with the operation of their new stoves, indoor air quality should also improve. It would be very beneficial to follow up in homes that received a Navajo Hybrid Stove the following year to determine if the stoves are being operated correctly and if significant improvements in IAQ are observed.

4.5.6 Reported Satisfaction with Stoves

The General House Household Survey 2 was completed during the post-intervention period. In addition to documenting any changes to the home, stove users were asked about their perception and satisfaction with the Navajo Hybrid Stove. The questions included in the survey are listed below:

1. Is your new appliance keeping you more warm, less warm or about the same?

2. Inside the house, did you notice more smoke, less smoke, or about the same amount of smoke after your stove was replaced?

3. Overall, are you happy with the change?

4. On average, considering the weather, are you using more wood, less wood, or about the same amount of wood since before the change?

5. On average, considering the weather, are you using more coal, less coal, or about the same amount of coal since before the change?

Table 4-2 lists the responses selected by the stove user in each home along with any comments by the stove user and observations from the field researcher.

Table 4-2. Stove User Perception and Satisfaction

	Warmth	Smoke	Happy	Wood	Coal	Comments
Home 001	More	Less	Yes	Less	Less	Only use 2 pieces of coal; less work to start fire
Home 002	More	Less	Yes	Less	Less	Stove puts out a lot of heat with less fuel; needs more education on stove operation; less ash
Home 003	More	Less	Yes	Less	Same	-
Home 004	More	Less	Yes	Less	Less	Weather is warmer during post changeout
Home 005	More	Less	Yes	Same	Less	Uses mostly wood; coal is used during Oct-Jan
Home 006	Same	Less	Yes	Less	Less	Received stove one week prior to post-changeout sampling
Home 008	More	Less	Yes	Less	Less	-

Of the seven homes that received the Navajo Hybrid stove and participated in the First Pilot Study, 85.7% (6/7 homes) responded that it kept them warmer, 100% responded that there was less smoke in the home, 85.7% responded they used less wood, and 85.7% responded they used less coal with the Navajo Hybrid Stove.

Of the six homes that responded the Navajo Hybrid Stove kept them warmer, only two homes (Home 002 and Home 003) showed an increase in indoor temperature. Home temperature in Homes 001 and 004 were reduced by 19.2% and 10% post-intervention to pre-intervention. Minimal (< 1%) increases or decreases in temperature were observed in Homes 005, 006, and 008. Of the responses, fewer than half of the homes (Home 002, 003, and 006) provided a response that matched the measured change in indoor temperature.

Regarding fuel use, Home 005 and Home 003 were the only ones to say that fuel use was the same for wood and coal respectively and all other homes responded that they used less wood and coal. Although the activity logs asked for both the time and amount (number of pieces) of wood/coal added to the stove, few users recorded the amounts of fuel added and a few didn't completely fill out the activity logs (no activities were recorded for some days), making it difficult to accurately assess these questions.

4.6 Conclusion

For the un-adjusted data, no statistically significant differences were observed in the pre and post-intervention concentrations for $PM_{2.5}$, CO, or CO_2. Lack of significant improvement in $PM_{2.5}$ and CO concentration indicates that the stoves were not operated correctly or that there were other sources that contributed to CO and $PM_{2.5}$ in the homes. Since the Navajo Hybrid Stoves require different operation for burning wood or coal, it's likely that the stove users weren't used to the different operation. In addition to greater education and outreach on stove operation, improvements in IAQ may require time for the users to become more comfortable with the stove.

Although the results were mixed, decreases in $PM_{2.5}$ and CO were observed in several homes. In the homes where increases in CO or $PM_{2.5}$ were observed, many of them were attributable to activities other than from the stove. In addition to more culturally appropriate education, a more holistic look into the pollution generated by activities that are specific to the Navajo, i.e. burning cedar or trash, typical meals that are cooked, should be examined.

Adjusted data that removed $PM_{2.5}$ and CO concentrations from non-stove related activities found a statistically significant difference in $PM_{2.5}$ but not for CO. However, this analysis was not robust as it relied on qualitative data collected from the stove users as well as home temperature data, which is not a direct measurement of stove use. In spite of these limitations, it is encouraging that $PM_{2.5}$ attributable to stove use decreased significantly post-intervention. These results also illustrate the complexity of resolving confounding factors and the significant contribution that cooking, cleaning, and burning of other items has on IAQ.

Future studies should increase sampling time (at least 3 days to help counteract the effect of confounding factors), include outdoor measurements to identify ambient contribution to IAQ, and include the use of stove temperature sensors pre and post-intervention to supplement the activity logs. Additionally, homes that received stoves and participated in the First Pilot Study (and any subsequent study) should be sampled in subsequent years during the heating season. This will help determine if indoor air quality improves over time and if the stoves are being operated correctly.

5. Conclusion

5.1 Summary of Findings

From the collocation experiments (Chapter 2), a good correlation and agreement in $PM_{2.5}$ concentrations within the DustTrak units was determined. Therefore, the $PM_{2.5}$ concentrations reported from the DustTraks were not need corrected prior to analyses. The same outcome was determined for the temperature, relative humidity, barometric pressure, and CO_2 for the different QTrak units. The CO data, however, showed more variability. This was likely due to limits in accuracy for the CO probe (3% of reading or $\pm$3ppm, whichever is greater) since reported CO concentrations didn't exceed 4 ppm. A second collocation experiment should be conducted with the QTraks after the probes are rehydrated and the instruments recalibrated. The correction factor determined for the DustTraks and E-BAM (0.313) was also in close agreement with a published value of 0.32 (Chapter 2).

This study determined a wood/coal smoke specific correction factor of 2.60 (Chapter 3) that was representative of typical indoor wood/coal smoke exposure in the Navajo Nation. This W/CSCF compared well with an estimated correction factor that accounted for the amounts of wood and coal used from published correction factors for wood smoke and coal smoke. Studies examining IAQ in homes using similar grade coal and wood as fuel sources can obtain more accurate measurements of PM by using this W/CSCF to adjust the DustTrak reported PM concentrations.

The results were mixed from the First Pilot Study (Chapter 4), with some homes experiencing increases in CO and/or $PM_{2.5}$ and decreases observed in others. Activity logs, stove temperature data, and home temperature data were used to associate increases in pollutant levels with stove and non-stove activity. Some increases in post-intervention pollutant levels were attributable to cooking and cleaning activity as well as activity that involved burning things other than wood/coal in the stove. The stove sensor data helped clarify when the stove was used but was only available for the post-intervention data. A good correlation between home temperature and stove temperature was determined for the homes, allowing for the use of the home temperature data as an approximate proxy for stove use in addition to the activity logs.

Adjusting the data to remove increases in $PM_{2.5}$ and CO concentrations unrelated to stove use resulted in a significant decrease in $PM_{2.5}$ concentration post-intervention. This result, while encouraging, is not robust as it relied on qualitative data as well as indirect measures of stove use (home temperature). No significant differences in CO concentrations were found.

Results from Home 006 one year after the First Pilot Study showed promising trends, with a 50% decrease in $PM_{2.5}$ and a 97.4% decrease in CO observed from pre-intervention to post-post-intervention. Allowing the stove users to become better acquainted with their Navajo Hybrid Stove may result in significant improvements in IAQ.

5.2 Study Limitations

The small sample sizes for the Collocation experiment (Chapter 2), Wood/Coal Smoke Correction Factor experiment (Chapter 3), and the First Pilot Study (Chapter 4) were one of the main limitations for this study. The number of participants depended heavily on the availability of NN EPA researchers to deploy the instruments as well as limited initial interest in the study among the Navajo stove recipients.

The First Pilot Study was also unable to resolve the ambient (outdoor) contribution to indoor air quality because the E-BAMs were not available during that period (they were being factory calibrated at Met One at the time). The lack of stove temperature sensor data was also a limitation, but the use of the activity logs in addition to home temperature data helped to provide greater clarity on stove and non-stove related activities that affected pollutant concentrations in the home.

5.3 Future Work

A Second Pilot Study began in February 2019 and it included pre-intervention sampling in three homes for four days each. The post-intervention sampling did not occur because the stove changeout coordinators were unable to install the Navajo Hybrid Stoves during the heating season. Installation of the hybrid stoves are now scheduled for summer 2019.

Improved educational materials, a stove user quick guide and operational video in Navajo, were also distributed during the second campaign (February – March, 2019). It is expected that the E-BAMs will be placed in a central location to measure outdoor concentrations of $PM_{2.5}$ in future campaigns.

More experiments should be conducted to improve the W/CSCF of 2.60 determined in this study, especially accounting for the mass of wood and coal used in each case. Additionally, further investigation into the correlation between the MiniVols and E-BAMs is warranted to determine if the E-BAMs report accurate concentrations of $PM_{2.5}$ generated from wood/coal smoke.

Bibliography

Airmetrics. MiniVol TAS Manual, Ver 1.2. Eugene, OR. http://www.airmetrics.com/downloads/MiniVol_TAS_Manual_Web.pdf (accessed Feb 4, 2019).

A.P. Buck, Inc. The mini-Buck Calibrator: Model M-1, Model M-5, Model M-30 -Instruction Manual Version 2. Orlando, FL. http://www.buckservice.com/Manuals/mini%20manual%208-96.pdf (accessed Feb 4, 2019).

Apte, J.S., Marshall, J.D., Cohen, A.J., Brauer, M. 2015. Addressing Global Mortality from Ambient $PM_{2.5}$. Environmental Science and Technology. 49: 8057 – 8066. doi: 10.1021/acs.est.5b01236

Arizona Rural Policy Institute. 2010. Demographic Analysis of the Navajo Nation Using 2010 Census and 2010 American Community Survey Estimates. http://www.nec.navajo-nsn.gov/Portals/0/Reports/NN2010PopulationProfile.pdf (accessed March 16, 2019).

Baldauf, R.W., Lane, D.D., Marotz, G.A., Wiener, R.W. 2001. Performance evaluation of the portable MiniVol particulate matter sampler. Atmospheric Environment. 35:6087-6091. https://doi.org/10.1016/S1352-2310(01)00403-4

Barnes, P.M., Adams, P.F., Powell-Griner, E. 2010. Health Characteristics of the American Indian or Alaska Native Adult Population: United States, 2004 – 2008. National Health Statistics Reports. 20:1-23. Pubmed ID: 20583451

Barrett, E.G., Henson, R.D., Seilkop, S.K., McDonald, J.D., Reed, M.D. 2006. Effects of Hardwood Smoke Exposure on Allergic Airway Inflammation in Mice. Inhalation Toxicology. 18(1): 33-43. doi: 10.1080/08958370500282340.

Belanger, K., Triche, E.W. 2008. Indoor Combustion and Asthma. Immunol Allergy Clin North Am. 28(3): 507 – 517. doi: 10.1016/j.iac.2008.03.011. s

Bridge, P.D. and Sawilowsky, S.S. 1999. Increasing Physicians' Awareness of the Impact of Statistics on Research Outcomes: Comparative Power of the t-test and Wilcoxon Rank-Sum Test in Small Samples Applied Research. Clinical Epidemiology. 52(3):229 – 235. https://doi.org/10.1016/S0895-4356(98)00168-1

Brim, S.N., Rudd, R.R., Funk, R.H., Callahan, D.B. 2008. Asthma Prevalence Among US Children In Underrepresented Minority Populations: American Indian/Alaska Native, Chinese, Filipino, and Asian Indian. Pediatrics. 122(1): e217-e222. doi: 10.1542/peds.2007-3825.

Brook, R.D., Rajagopalan, S., Pope III, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith Jr, S.C., Whitsel, L., Kaufman, J.D. 2010. Particulate Matter Air Pollution and Cardiovascular Disease: An Update to the Scientific Statement From the American Heart Association. Circulation. 121:2331-2378. doi: 10.1161/CIR.0b013e3181dbece1

Bunnell, J.E., Garcia, L.V., Furst, J.M., Lerch, H., Olea, R.A., Suitt, S.E., Kolker, A., 2010. Navajo coal combustion and respiratory health near Shiprock, New Mexico. J. Environ. Public Health:260525 http://dx.doi.org/10.1155/2010/260525.

CARB (California Air Resources Board). 2005. Memo. Operation Support Section E-BAM Evaluation. Sacramento, CA. https://www.arb.ca.gov/carpa/toolkit/data/ebam-eval.pdf?bay (accessed April 6, 2019).

Casey, J.G., Ortega, J., Coffey, E., Hannigan, M. 2018. Low-cost measurement techniques to characterize the influence of home heating fuel on carbon monoxide in Navajo homes. Science of the Total Environment. 625:608-618. https://doi.org/10.1016/j.scitotenv.2017.12.312

Champion, W.M., P.H. Charley, B. Klein, K. Stewart, P.A. Solomon, and L.D. Montoya. 2017a. Perception, cultural, and technical assessment of heating alternatives to improve indoor air quality in the Navajo Nation. Sci. Total Environ. 580:297– 306. doi:10.1016/j.scitotenv.2016.11.053.

Champion, W.M., Connors, L., Montoya, L.D. 2017b. Emission factors of fine particulate matter, organic and elemental carbon, carbon monoxide, and carbon dioxide for four solid fuels commonly used in residential heating by the Navajo Nation, Journal of the Air & Waste Management Association, DOI: 10.1080/10962247.2017.1334717

Chung, A. Chang, D.P.Y., Kleeman, M.J., Perry, K.D., Cahill, T.A., Dutcher, D. McDougall, E.M., Stroud, K. 2001. Comparison of Real-Time Instruments Used To Monitor Airborne Particulate Matter. *Air and Waste Management Association*. doi: 10.1080/10473289.2001.10464254

Desai, M.A., Mehta, S., Smith, K.R. 2004. Indoor smoke from solid fuels: Assessing the environmental burden of disease at national and local levels. Geneva, World Health Organization, WHO Environmental Burden of Disease Series, No. 4).

Dockery, D.W., Pope III, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E. 1993. An Association Between Air Pollution and Mortality in Six U.S. Cities. The New England Journal of Medicine. 329(24): 1753 – 1759.

Dutton S.J., Schauer J.J., Vedal, S., Hannigan, M.P. 2009. $PM_{2.5}$ charaterization for time series studies: Pointwise uncertainty estimation and bulk speciation methods applied in Denver. *Atmos. Environ.* 43:1135-1146. doi: 10.1016/j.atmostenv.2008.10.003

Ford, E.S., Croft, J.B., Mannino, D.M., Wheaton, A.G., Zhang, X, Giles, W.H. 2013. COPD Surveillance – United States, 1999-2011. Chest. 144(1): 284 – 305. https://doi.org/10.1378/chest.13-0809

Goldstein, M. 2008. Carbon Monoxide Poisoning. Emergency Nursing. 34(6): 538 – 542. doi: 10.1016/j.jen.2007.11.014

Guo, C., Zhang, Z., Lau, A.K.H., Lin, C.Q., Chuang, Y.C., Chan, J., Jiang, W.K., Tam, T., Yeoh, E.K., Chan, T.C., Chang, L.Y., Lao, X.Q. 2018. Effect of long-term exposure to fine particulate matter on lung function decline and risk of chronic obstructive pulmonary disease in Taiwan: a longitudinal, cohort study. Lancet Planet Health. 2:114 – 125. https://doi.org/10.1016/S2542-5196(18)30028-7

Haikerwal, A., Akram, M., Sim, M.R., Meyer, M., Abramson, M.J., Dennekamp, M. 2015. Fine particulate matter ($PM_{2.5}$) exposure during a prolonged wildfire period and emergency department visits for asthma. Respirology. 21: 88-94. doi: 10.1111/resp.12613

Hays, M.D., Smith, N.D., Kinsey, J., Dong, Y., Kariher, P. 2003. Polycyclic aromatic hydrocarbon size distributions in aerosols from appliances of residential wood combustion as determined by direct thermal desorption – GC/MS. Aerosol Science. 34:1061-1084. doi: 10.1016/S0021-8502(03)00080-6

Heal, M.R., Beverland, I.J., McCabe, M., Hepburn, W., Agius, R.M. 2000. Intercomparison of five PM_{10} monitoring devices and the implications for exposure measurement in epidemiological research. Journal of Environmental Monitoring. 2:455-461. doi: 10.1039/B002741N

Hickmott, D.D., Brown, L.F., Currier, R.P., Semken, S.C., Lameman, T., Martin, S., Yazzie, S. 1997. Environmentally Conscious Coal Combustion. *DOE*. doi: 10.2172/516052

Houck, J.E. and Tiegs, P.E. 1998. Residential Wood Combustion – $PM_{2.5}$ Emissions. OMNI Environmental Services, Inc. Beaverton, OR. https://www3.epa.gov/ttn/chief/efdocs/rwc_pm25.pdf (accessed April 5, 2019).

Hu, W., Downward, G.S., Reiss, B., Xu, J., Bassig, B.A., Hosgood, III, H.D., Zhang, L, Seow, W.J., Wu, G., Chapman, R.S., Tian, L., Wei, F., Vermeulen, R., Lan, Q. Personal and Indoor $PM_{2.5}$ Exposure from Burning Solid Fuels in Vented and Unvented Stoves in a Rural Region of China with a High Incidence of Lung Cancer. *Environmental Science and Technology*. 48: 8456 – 8464. doi: 10.1021/es502201s.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, Pachauri, R.K. and Meyer, L.A. (eds)]. Geneva, Switzerland, 151pp. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf (accessed March 22, 2019).

Jayaratne, R., Liu, X., Thai, P., Dunhabin, M., Morawska, L. 2018. The influence of humidity on the performance of a low-cost air particle mass sensor and the effect of atmospheric fog. Atmospheric Measurement Techniques. 11:4883-4890. https://doi.org/10.5194/amt-11-4883-2018

Kerimray, A., Rojas-Solórzano, L., Torkmahalleh, M.A., Hopke, P.K., Gallachóir, P.Ó. 2017. Coal use for residential heating: Patterns, health implications and lessons learned. Energy for Sustainable Development. 40: 19-30. https://doi.org/10.1016/j.esd.2017.05.005

Kleeman, M.J., Schauer, J. J., Cass, G.R. 1999. Size and Composition Distribution of Fine Particulate Matter Emitted from Wood Burning, Meat Charbroiling, and Cigarettes. Environmental Science and Technology. 33:3516-3523. doi: 10.1021/es981277q

Kim, J.Y., Magari, S.R., Herrick, R.F., Smith, T.J., Christiani, D.C., Christiani, D.C. 2004. Comparison of Fine Particle Measurements from a Direct-Reading Instrument and a Gravimetric Sampling Method. Occupational and Environmental Hygiene. 1:707-715. doi: 10.1080/15459620490515833

Kingham, S., Durand, M., Aberkane, T., Harrison, J., Wilson, J.G., Epton, M. 2006. Winter comparison of TEOM, MiniVol, and DustTrak PM_{10} monitors in a woodsmoke environment. Atmospheric Environment. 40(2): 338 – 347. https://doi.org/10.1016/j.atmosenv.2005.09.042

Lashof, D.A., Ahuja, D.R. Relative contributions of greenhouse gas emissions to global warming. Nature. 344:529-531. doi: 10.1038/344529a0

Lowe, A.A., Bender, B., Liu, A.H., Solomon, T., Kobernic, A., Morgan, W., Gerald, L.B. 2018. Environmental Concerns for Children with Asthma on the Navajo Nation. Annals of the American Thoracic Society. 15(6): 745-753. doi: 10.1513/AnnalsATS.201708-674PS

Lu, F., Xu, D., Cheng, Y., Dong, S., Guo, C., Jiang, X., Zheng, X. 2015. Systematic review and met-analysis of the adverse health effects of ambient $PM_{2.5}$ and PM_{10} pollution in the Chinese population. Environmental Research. 136: 196 – 204. https://doi.org/10.1016/j.envres.2014.06.029

MacCarty, N., Ogle, D., Still, D., Bond, T., Roden, C. 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy for Sustainable Development. 12(2):56 -65. https://doi.org/10.1016/S0973-0826(08)60429-9

McCracken, J.P., Wellenius, G.A., Bloomfield, G.S., Brook, R.D., Tolunay, H.E., Dockery, D.W., Rabadan-Diehl, C., Checkley, W., Rajagopalan, S. Household Air Pollution from Solid Fuel Use: Evidence for Links to CVD. *Global Heart*. 7(3): 223-234. doi:10.1016/j.gheart.2012.06.010

McNamara, M.L., C.W. Noonan, T.J. Ward. 2011. Correction factor for continuous monitoring of wood smoke fine particulate matter. *Aerosol Air Qual Res.* 11(3):315-322. doi: 10.4209/aaqr.2010.08.0072.

Mehal, J.M., Holman, R.C, Steiner, C.A., Bartholomew, M.L., Singleton, R.J. 2014. Epidemiology of Asthma Hospitalizations Among American Indian and Alaska Native People and the General United States Population. *Chest*. 146(3): 624-632. doi: 10.1378/chest.14-0183

Meng, Q.Y., Spector, D., Colome, S., Turpin, B. 2009. Determinants of indoor and personal exposure to $PM_{2.5}$ of indoor and outdoor origin during the RIOPA study. Atmospheric Environment. 43: 5750 – 5758. doi: 10.1016/j.atmosenv.2009.07.066.

Met One Instruments, Inc. 2008. E-BAM Particulate Monitor Operation Manual E-BAM-9800 Rev L. http://www.equipcoservices.com/pdf/manuals/met_one_e-bam.pdf (accessed March 17, 2019).

Miller, B.G., Tillman, D.A. 2008. Chapter 2 – Coal Characteristics. *Combustion Engineering Issues for Solid Fuel Systems*. https://doi.org/10.1016/B978-0-12-373611-6.00002-1. (Accessed February 3, 2019).

Mishra, V. 2003. Effect of Indoor Air Pollution from Biomass Combustion on Prevalence of Asthma in the Elderly. *Environmental Health Perspectives*. 111(1):71-77. doi: 10.1289/chp.5559

Morris, K., Morganalnder, M., Coulehan, J.L., Gahagen, S., Arena, V.C. 1990. Wood-Burning Stoes and Lower Respiratory Tract Infection in American Indian Children. American Journal of Diseases of Children. 144(1): 105 – 108.

Naeher, L.P., M. Brauer, M. Lipsett, J. T. Zelikoff, C.D. Simpson, J. Q. Koenig, K. R. Smith. 2007. Woodsmoke Health Effects: A Review. *Inhalation Toxicology*, 19(1):67-107. doi: 10.1080/08958370600985875

National Oceanic and Atmospheric Administration. 2019a. Global Greenhouse Gas Reference Network: Trends in Atmospheric Carbon Dioxide. https://www.esrl.noaa.gov/gmd/ccgg/trends/ (accessed March 20, 2019).

NOAA. 2019b. Weather Conditions for Window Rock, Window Rock Airport, AZ. https://www.wrh.noaa.gov/mesowest/getobext.php?sid=KRQE&wfo=fgz&num=72 (accessed April 6, 2019).

Navajo Housing Authority. 2011. Phase II Housing Needs Assessment and Demographic Analysis. Window Rock, AZ. http://www.navajohousingauthority.org/wp-content/uploads/2015/08/Navajo_Nation_Housing_Needs_Assessment_091311.pdf (accessed March 31, 2019).

Navajo Nation Department of Information Technology. 2011. History. http://www.navajo-nsn.gov/history.htm (accessed March 30, 2019).

Navajo Nation Environmental Protection Agency. 2008. Arizona Public Service (APS) Four Corners Steam Electric Station: No. NN-ROP-05-07.

http://navajonationepa.org/main/images/Four%20Corners%20Steam%20Electric%20Station%20Final%20Permit.pdf (accessed April 8, 2019).

NOAA. 2019. Global Summary of the Month Station Details: Farmington Four Coners Regional Airport, NM US. https://www.ncdc.noaa.gov/cdo-web/datasets/GSOM/stations/GHCND:USW00023090/detail (accessed March 31, 2019).

Noonan, C.W., Navidi, W., Sheppard, L., Palmer, C.P., Bergauff, M., Hooper, K., Ward, T.J. 2012. Residential indoor $PM_{2.5}$ in wood stove homes: follow-up of the Libby changeout program. Indoor Air. 22:492-500. doi:10.1111/j.1600-0668.2012.00789.x

Perera, I.E. and Litton, C.D. 2015. Quantification of Optical and Physical Properties of Combustion-Generated Carbonaceous Aerosols ($<PM_{2.5}$) Using Analytical and Microscopic Techniques). doi: 10.1007/s10694-013-0376-z.

Permentier, K., Vercammen, S., Soetaert, S., Schellemans, C. 2017. Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department. International journal of Emergency Medcine. 10: 1-4. doi: 10.1186/s12245-017-0142-y

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. Journal of American Medical Association. 287(9):1132-1141. doi:10.1001/jama.287.9.1132

Pope III, C.A., Dockery, D.W. 2006. Health Effects of Fine Particulate Air Pollution: Lines that Connect. Journal of the Air & Waste Management Association. 56(6); 709 – 742. doi: 10.1080/10473289.2006.10464485

Prockop, L. 2009. Chapter 45 – Carbon Monoxide. Clinical Neurotoxicology – Syndromes, Substances, Environments. pg 500-514. https://doi.org/10.1016/B978-032305260-3.50051-4 (accessed March 19, 2019).

Raub, J.A., Mathieu-Nolf, M., Hampson, N.B., Thom, S.R. 2000. Carbon monoxide poisoning – a public health perspective. Toxicology. 145:1-14. https://doi.org/10.1016/S0300-483X(99)00217-6

Robin, L.F., Lees, P.S.J., Winget, M., Steinhoff, M., Moulton, L.H., Santosham, M., Correa, A. 1996. Wood-burning stoves and lower respiratory illnesses in Navajo Children. Pediatric Infection Disease Journal. 15(10): 859 – 865. Accession: 00006454-199610000-00006

Rogalsky, D.K., P. Mendola, T.A. Metts, and W.J. Martin. 2014. Estimating the number of low-income americans exposed to household air pollution from burning solid fuels. Environ. Health Perspect. 122:806–10. doi: 10.1289/ehp.1306709.

Schauer, J. J., G. R. Cass. 2000. Source apportionment of winter-time gas-phase and particle-phase air pollutants using organic compounds as tracers. *Environ Sci Technol.* 34(9):1821-1832. doi: 10.1021/es981312t

Schweizer, D., Cisneros, R., Shaw, G. 2016. A comparative analysis of temporary and permanent beta attenuation monitors: The importance of understanding data and equipment limitations when creating $PM_{2.5}$ air quality health advisories. Atmospheric Pollution Research. 7:865-875. http://dx.doi.org/10.1016/j.apr.2016.02.003

Services Polytests Inc. 2017. Test of a Hybrid Wood Stove for Emissions and Efficiency Per EPA Methods 28R and ASTM E2515 and ASTM E2780, May 2015. St-jean-sur-Richelieu, QC. http://www.woodstove.com/images/editorial_support/Navajo-Survival%20Reports/4)%20Rap_EPA%20wood%20stove%20PI-20154%20NON-CBI.pdf (accessed April 8, 2019).

Semmens, E. O., Noonan, C.W., Allen, R.W., Weiler, E.C., Ward, T.J. 2015. Indoor particulate matter in rural, wood stove heated homes. Environmental Research. 138: 93 – 100. https://doi.org/10.1016/j.envres.2015.02.005

Shen, G., Wang, W., Yang, Y., Zhu, C., Min, Y., Xue, M., Ding, J., Li, W., Wang, B., Shen, H., Wang, R., Wang, X., Tao, S. 2010. Emission factors and particulate matter size distribution of polycyclic hydrocarbons from residential coal combustions in rural Northern China. Atmospheric Environment. 44:5237-5243. doi: 10.1016/j.atmosenv.2010.08.042

Singleton, R.J., Holman, R.C., Folkema, A.M., Wenger, J.D., Steiner, C.A., Redd, J.T. 2012. Trends in Lower Respiratory Tract Infection Hospitalizations among American Indian/Alaska Native Children and the General US Child Population. *Journal of Pediatrics*. 161(2): 296:302. doi: 10.1016/j.jpeds.2012.02.053

Singleton, R., Salkoski, A.J., Bulkow, L., Fish, C., Dobson, J., Albertson, L., Skarada, J., Kovesi, T., McDonald, C., Hennessy, T.W., Ritter, T. 2016. Housing characteristics and indoor air quality in households of Alaska Native children with chronic lung conditions. Indoor Air. 27:478 – 486. doi: 10.1111/ina.12315

Solomon, S., Plattner, G.K., Knutti, R., Friedlingstein, P. 2008. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences. 106(6): 1704 – 1709. www.pnas.orgcgidoi10.1073pnas.0812721106

SRP. 2019. Four Corners Power Plant. https://www.srpnet.com/about/stations/fourcorners.aspx (accessed April 18, 2019).

TSI Incorporated. 2012. DustTrak II Aerosol Monitor Theory of Operation. https://www.tsi.com/getmedia/293ead1a-764b-4294-8238-414e958d6886/EXPMN-001_DustTrakII_Theory_of_Operation?ext=.pdf (accessed April 9, 2019).

TSI Incorporated. 2013a. DustTrak II Aerosol Monitor Model 8530/8531/8532/8530EP Operation and Service Manual. http://www.tsi.com/getmedia/7c608b93-b6d1-459a-a6a8-2b0e2a55ba91/8530-8531-8532-DustTrak_II-6001893-web?ext=.pdf (accessed March 17, 2019).

TSI Incorporated. 2013b. Rehydration of TSI Carbon Monoxide (CO) Sensors – Application Notes TSI-158. http://www.tsi.com/getmedia/9775e4f0-42fc-4586-8869-bda07e8d0f32/TSI-158_Rehydration_of_CO_Sensors-A4?ext=.pdf (accessed March 17, 2019).

Torres-Duque, C., Maldonado, D., Pérez-Padilla, R., Ezzati, M., Viegi, G. 2008. Biomass Fuels and Respiratory Diseases: A Review of the Evidence. *Proc Am Thorac Soc* 5:577-590. doi: 10.1513/pats.200707-100RP

Trent, Andy. 2006. Smoke Particulate Monitors: 2006 Update. Technical Report. 0625-2842-MTDC. Missoula, MT: U.S. Department of Agriculture Forest Service, Missoula Technology and Development Center https://www.arb.ca.gov/carpa/toolkit/data/monitor-comparison.pdf (accessed March 18, 2019).

Urch, B., Silverman, F., Corey, P., Brook, J.R., Lukic, K.Z., Rajagopalan, S., Brook, R.D. 2005. Acute Blood Pressure Responses in Health Adults During Controlled Air Pollution Exposures. Environmental Medicine. 113(8): 1052 – 1055. doi: 10.1289/ehp.7785

United States Census Bureau. 2014. Census Data: Profile of General Population and Housing Characteristics: Shiprock, CDP, New Mexico. Suitland, MD. http://factfinder.census.gov/bkmk/table/1.0/en/DEC/10_SF1/SF1DP1/1600000US3572770 (accessed March 22, 2019).

U.S. Census Bureau. 2015. Navajo Nation House Heating Fuel 2011–2015 American Community Survey Estimate: Shiprock, CDP, New Mexico. Suitland, MD. https://factfinder.census.gov/bkmk/table/1.0/en/ACS/ 15_5YR/B25040/2500000US2430 (accessed October 19, 2017).

U.S. Census Bureau. 2015b. American Community Survey 2011–2015 5-Year Estimates: Navajo Nation Reservation and Off-Reservation Trust Land, AZ-NM-UT, Poverty Status in the Past 12 Months. Suitland, MD. http://factfinder.census.gov/bkmk/table/1.0/en/ACS/14_5YR/S1701/2500000US2430 (accessed Oct 21, 2017).

U.S. Census Bureau. 2017a. 2013 – 2017 American Community Survey 5-Year Estimates: ACS Demographic and Housing Estimates: Shiprock, CDP, New Mexico. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed March 31, 2019).

U.S. Census Bureau. 2017b. 2013 – 2017 American Community Survey 5-Year Estimates: Selected Housing Characteristics: Shiprock, CDP, New Mexico. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed March 31, 2019).

U.S. Census Bureau. 2017c. 2013 – 2017 American Community Survey 5-Year Estimates: ACS Demographic and Housing Estimates: Navajo Nation Reservation and Off-Reservation Trust Land, AZ—NM--UT. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk (accessed March 31, 2019).

U.S. Census Bureau. 2017d. 2013 – 2017 American Community Survey 5-Year Estimates: Poverty Status in the Past 12 Months: Shiprock, CDP, New Mexico. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed March 31, 2019).

U.S. Census Bureau. 2017e. 2013 – 2017 American Community Survey 5-Year Estimates: Selected Economic Characteristics: Shiprock, CDP, New Mexico. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed March 31, 2019).

U.S. Census Bureau. 2017f. 2013 – 2017 American Community Survey 5-Year Estimates: Selected Economic Characteristics: United States. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed March 31, 2019).

U.S. Census Bureau. 2017g. 2013 – 2017 American Community Survey 5-Year Estimates: Poverty Status in the Past 12 Months: United States. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed March 31, 2019).

U.S. Census Bureau. 2017h. 2013 – 2017 American Community Survey 5-Year Estimates: Poverty Status in the Past 12 Months: Navajo Nation Reservation and Off-Reservation Trust Land, AZ—NM--UT. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk (accessed March 31, 2019).

U.S. Census Bureau. 2017i. 2013 – 2017 American Community Survey 5-Year Estimates: Year Structure Built: Universe: Housing Units: Navajo Nation Reservation and Off-Reservation Trust Land, AZ—NM--UT. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_14_5YR_B25034&prodType=table (accessed March 31, 2019).

U.S. Census Bureau. 2017j. 2013 – 2017 American Community Survey 5-Year Estimates: Poverty Status in the Past 12 Month: United States. Suitland, MD. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF (accessed April 1, 2019).

U.S. Environmental Protection Agency. 1995. The Inside Story: A Guide to Indoor Air Quality. https://nepis.epa.gov/Exe/ZyPDF.cgi/000003M1.PDF?Dockey=000003M1.PDF (accessed April 9, 2019).

U.S. Environmental Protection Agency. 2000. Update: $PM_{2.5}$ Monitoring Implementation. https://www3.epa.gov/ttn/amtic/files/ambient/pm25/exec.pdf (accessed March 17, 2019).

U.S. Environmental Protection Agency. 2007. 40 CFR Part 49: Source-Specific Federal Implementation Plan for Four Corners Power Plant; Navajo Nation. 72(87) https://www.govinfo.gov/content/pkg/FR-2007-05-07/pdf/E7-8530.pdf (accessed April 8, 2019).

U.S. Environmental Protection Agency. 2010. 40 CFR Part 49: Source Specific Federal Implementation Plan for Implementing Best Available Retrofit Technology for Four Corners Power Plant: Navajo Nation. https://www.regulations.gov/document?D=EPA-R09-OAR-2010-0683-0065 (accessed April 9, 2019).

U.S. Environmental Protection Agency. 2012. President's Task Force on Environmental Health Risks and Safety Risks to Children: Coordinated Federal Action Plan to Reduce Racial and Ethnic Asthma Disparities. https://www.epa.gov/sites/production/files/2014-08/documents/federal_asthma_disparities_action_plan.pdf (accessed April 3, 2019).

U.S. Environmental Protection Agency. 2015a. Standards of Performance for New Residential Wood Heaters, New Residential Hydronic Heaters and Forced-Air Furnaces. 40 CFR Part 60. https://www.govinfo.gov/content/pkg/FR-2015-03-16/pdf/2015-03733.pdf (accessed March 13, 2019).

U.S. Environmental Protection Agency. 2015b. Four Corners Power Plant Clean Air Act Settlement. https://www.epa.gov/enforcement/four-corners-power-plant-clean-air-act-settlement (accessed April 3, 2019).

U.S. Environmental Protection Agency, 2015c. Revised NSPS for New Residential Wood Heaters. https://www.federalregister.gov/documents/2015/03/16/2015-03733/standards-of-performance-for-new-residential-wood-heaters-new-residential-hydronic-heaters-and (accessed April 22, 2019).

U.S. Environmental Protection Agency. 2016. NAAQS Table. https://www.epa.gov/criteria-air-pollutants/naaqs-table (accessed March 19, 2019).

U.S. Environmental Protection Agency. 2018. Indoor Air Quality (IAQ): Carbon Monoxide's Impact on Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/carbon-monoxides-impact-indoor-air-quality (accessed March 21, 2019).

von Klot, S., Wolke, G., Tuch, T., Heinrich, J., Dockery, D.W., Schwartz, J., Kreyling, W.G., Wichmann, H.E., Peters, A. 2002. Increased asthma medication use in association with ambient fine and ultrafine particles. European Respiratory Journal. 20:691-702. doi: 10.1183/09031936.02.01402001

Ward, T., Noonan, C. 2008. Results of a residential indoor $PM_{2.5}$ sampling program before and after a woodstove changeout. Indoor Air. 18:408-415. doi: 10.1111/j.1600-0668.2008.00541.x

Weinert, B.A., Edmonson, M.B. 2016. Hospitalizations at Nonfederal Facilities for Lower Respiratory Tract Infection in American Indian and Alaska Native Children Younger than 5 Years of Age, 1997 – 2012. *Journal of Pediatrics*. 175:33-39. doi: 10.1016/j.peds.2016.03.019

Williams, C. 2009. A Comparison of Medical, Clinical, and Spiritual Adolescent Suicide Interventions on the Navajo Nation, Arizona State University, Ann Arbor. ProQuest, https://colorado.idm.oclc.org/login?url=https://search.proquest.com/docview/304843832?accountid=14503 (accessed April 11, 2019).

Wilson, W.E., Suh, H.H. 1997. Fine Particles and Coarse Particles: Concentration Relationships Relevant to Epidemiologic Studies. Journal of the Air & Waste Management Association. 47(12): 1238 – 1249. doi: 10.1080/10473289.1997.10464074

Woodstock Soapstone Company. R2015. Navajo Hybrid Combination Wood/Coal Stove Model 212 Owner's Manual. https://www.woodstove.com/images/Navajo-Manual-PDFs/Navajo_Covers_Specs1802.pdf (accessed March 13, 2019).

World Health Organization. 2006. Air Quality Guidelines: Global Update 2005. Copenhagen, Denmark. http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1 (accessed March 20, 2019).

World Health Organization. 2010. WHO guidelines for indoor air quality: selected pollutants. http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf (accessed March 20, 2019).

World Health Organization. 2014. WHO Guidelines for Indoor Air Quality: Household Fuel Combustion. http://www.who. int/indoorair/guidelines/hhfc/en (accessed January 26, 2019).
World Health Organization. 2015. Residential heating with wood and coal: health impacts and policy options in Europe and North America. http://www.euro.who.int/__data/assets/pdf_file/0009/271836/ResidentialHeatingWoodCoalHealthImpacts.pdf (accessed February 5, 2019).

World Health Organization. 2016. Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children. http://apps.who.int/iris/bitstream/10665/204717/1/9789241565233_eng.pdf?ua=1(accessed January 26, 2019).

Wu, W., Jin, Y.J., Carlsten, C. 2018. Inflammatory health effects of indoor and outdoor particulate matter. J Allergy Clin Immunol. 141: 833 – 844.
Zhang, J., Smith, K.R. 2007. Household Air Pollution from Coal and Biomass Fuels in China: Measurements, Health Impacts, and Interventions. *Environmental Health Perspectives*. 115(6): 848-855. doi: 10.1289/ehp.9479

Yanosky, J.D., Williams, P.L., MacIntosh, D.L. 2001. A comparison of two direct-reading aerosol monitors with the federal reference method for PM2.5 in indoor air. Atmospheric Environment. 36:107-113. https://doi.org/10.1016/S1352-2310(01)00422-8

Zhou, Z., Liu, Y., Yuan, J., Zuo, J., Chen, G., Xu, L., Rameezdeen, R. 2016. Indoor PM2.5 concentrations in residential buildings during a severely polluted winter: A case study in Tianjin, China. Renewable and Sustainable Energy Reviews. 64: 372 – 381. doi: 10.1016/j.rser.2016.06.018.

Appendix A: Linear Regression Plots for Fort Defiance and Shiprock

Figures A-1 to A-4 are the linear regression plots for the DustTraks at Fort Defiance and A-5 to A-10 are the plots for Shiprock.

Fort Defiance

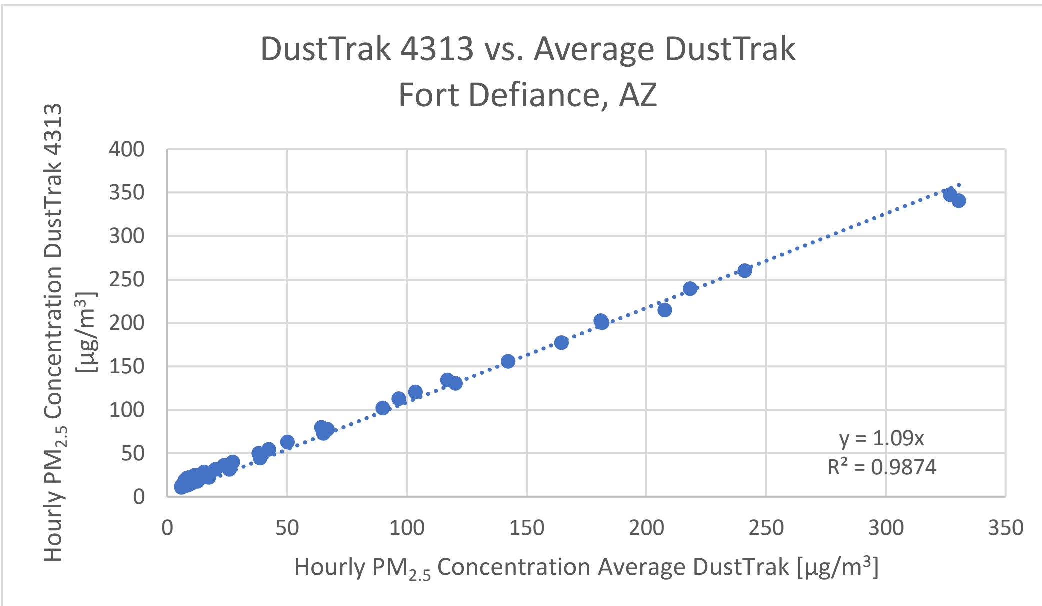

Figure A-1. Fort Defiance - DustTrak 4313 vs. Average DustTrak

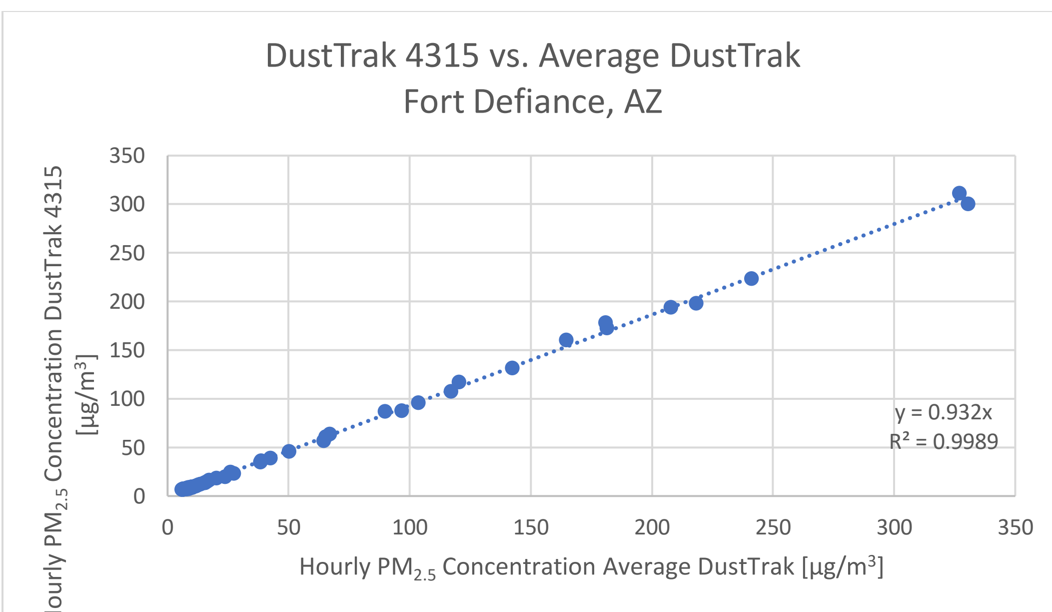

Figure A-2. Fort Defiance – DustTrak 4315 vs. Average DustTrak

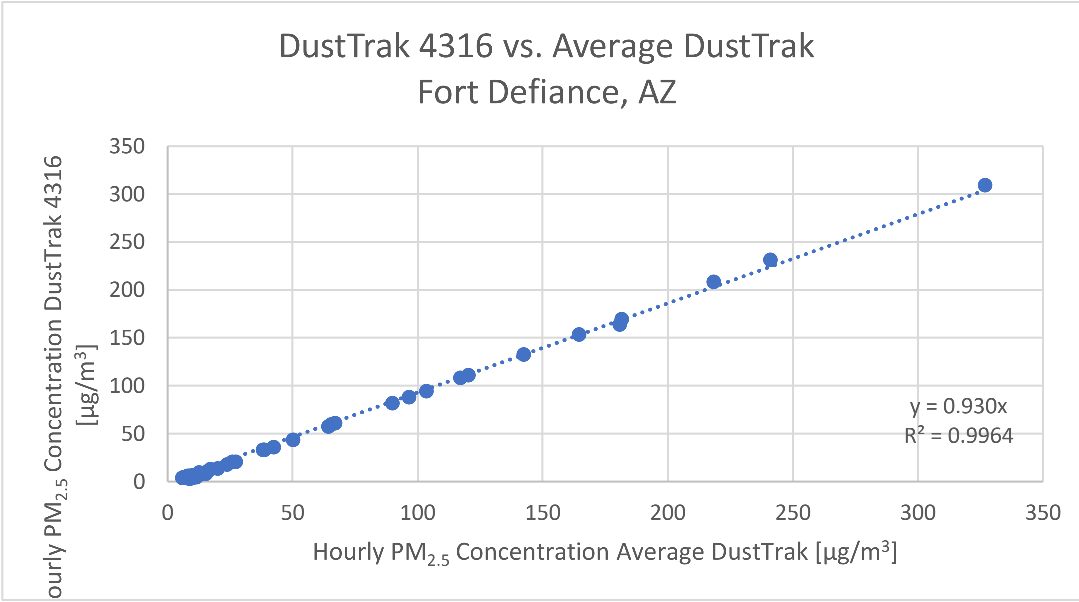

Figure A-3. Fort Defiance – DustTrak 4316 vs. Average DustTrak

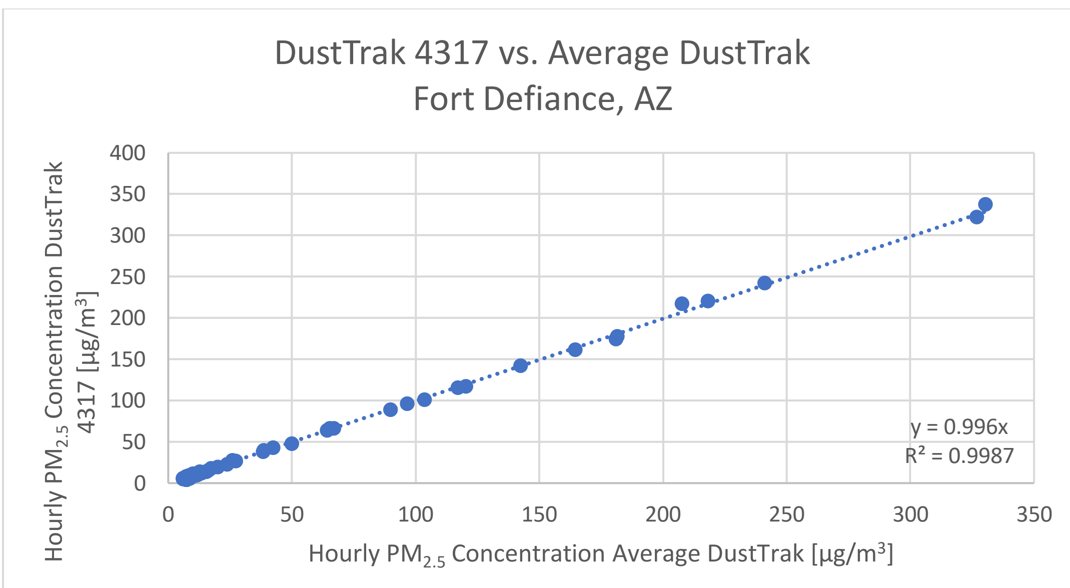

Figure A-4. Fort Defiance – DustTrak 4317 vs. Average DustTrak

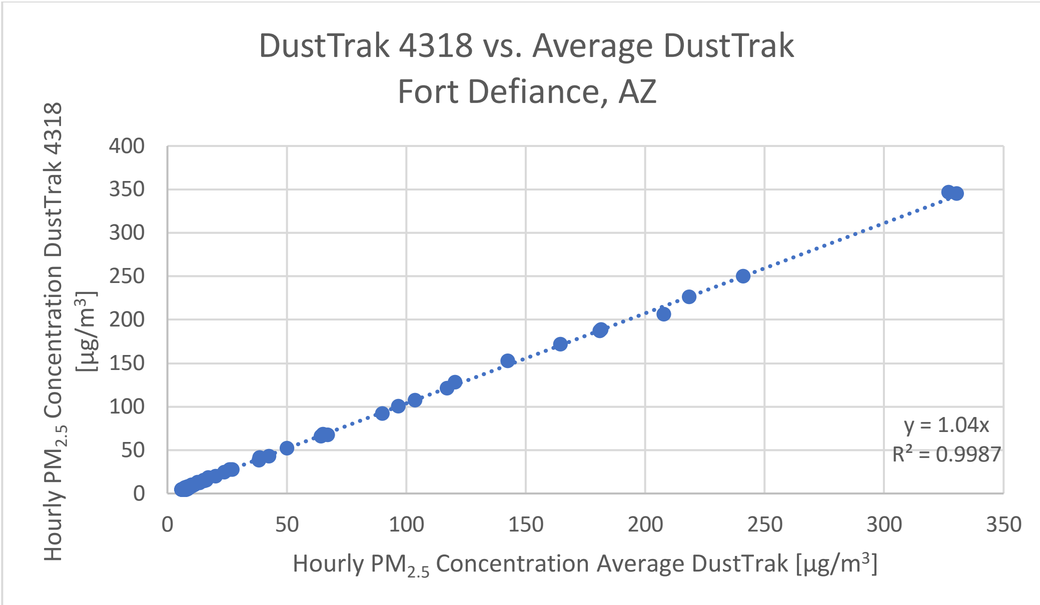

Figure A-5. Fort Defiance – DustTrak 4318 vs. Average DustTrak

Shiprock

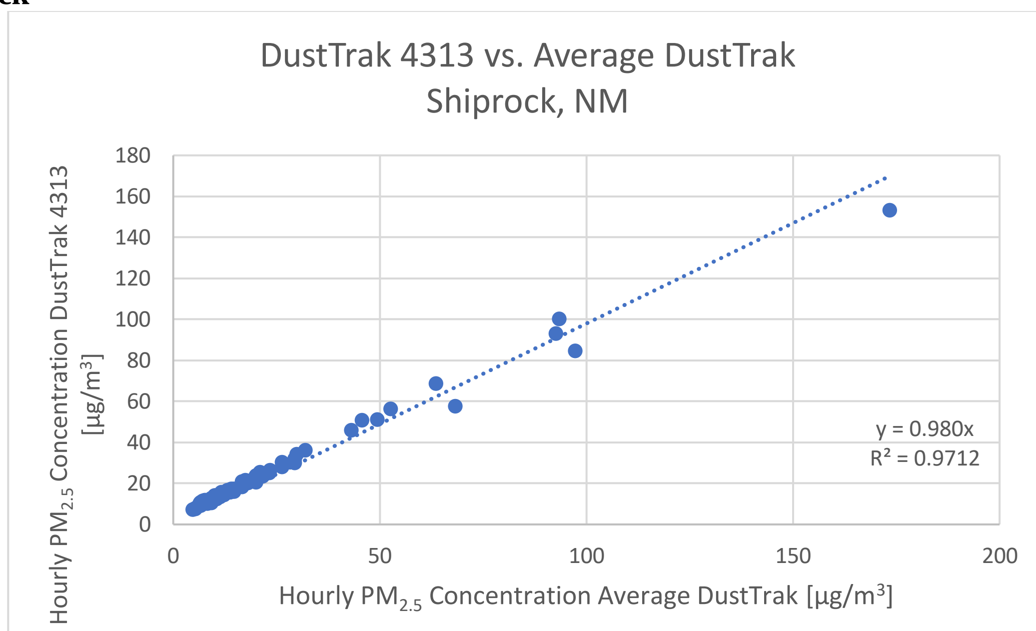

Figure A-6. Shiprock – DustTrak 4313 vs. Average DustTrak

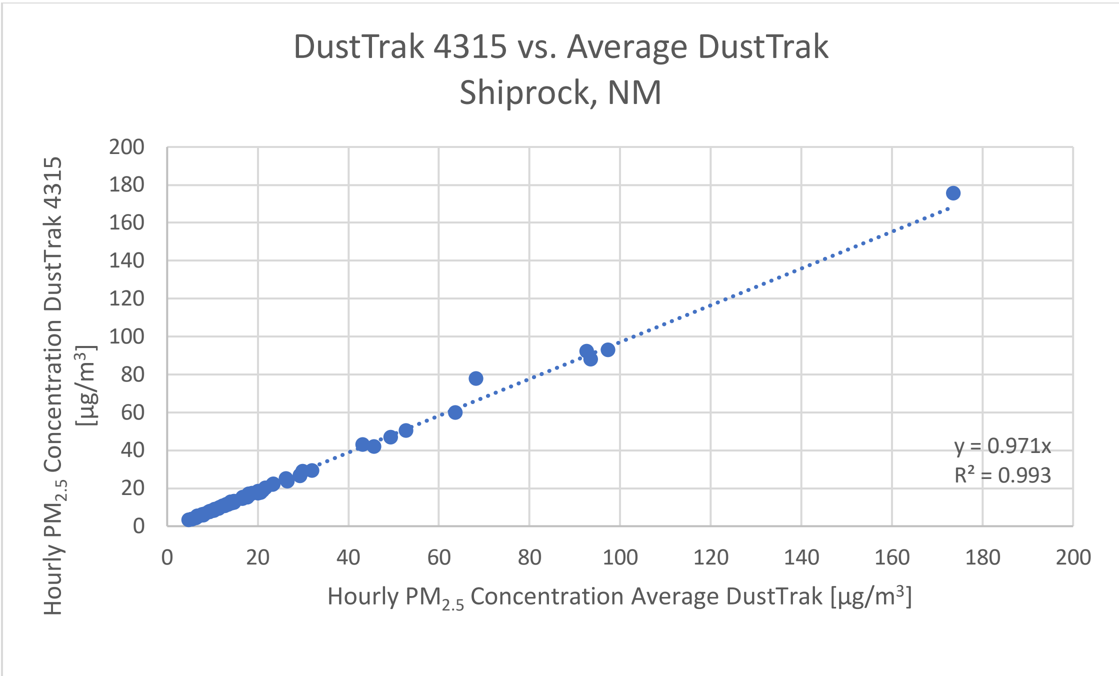

Figure A-7. Shiprock – DustTrak 4315 vs. Average DustTrak

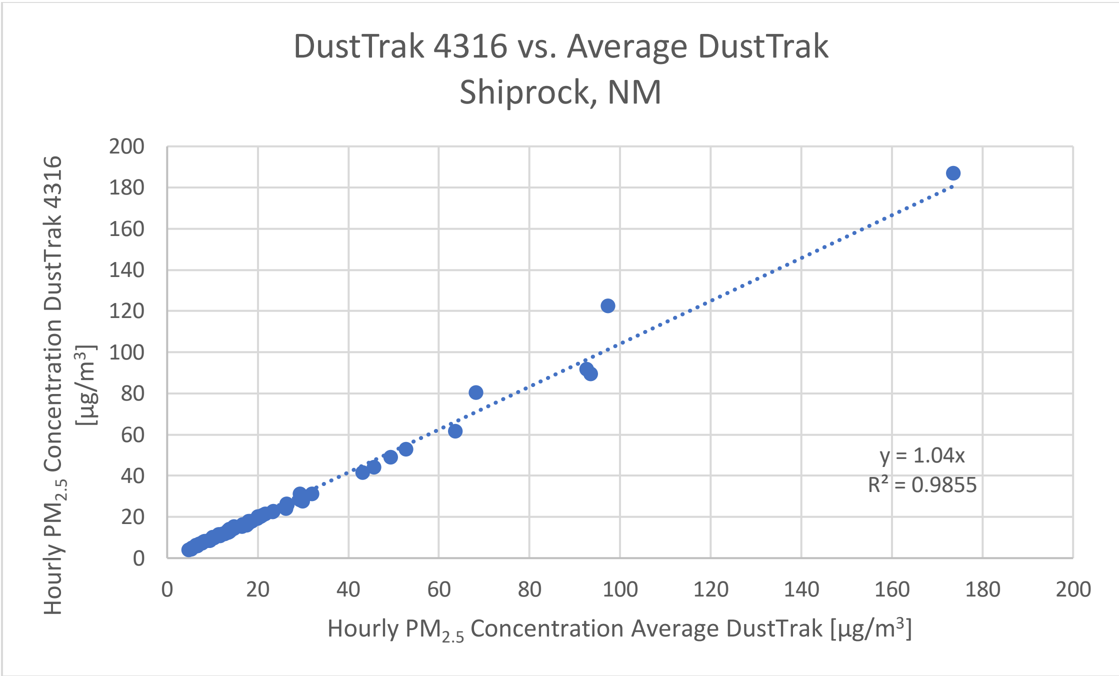

Figure A-8. Shiprock – DustTrak 4316 vs. Average DustTrak

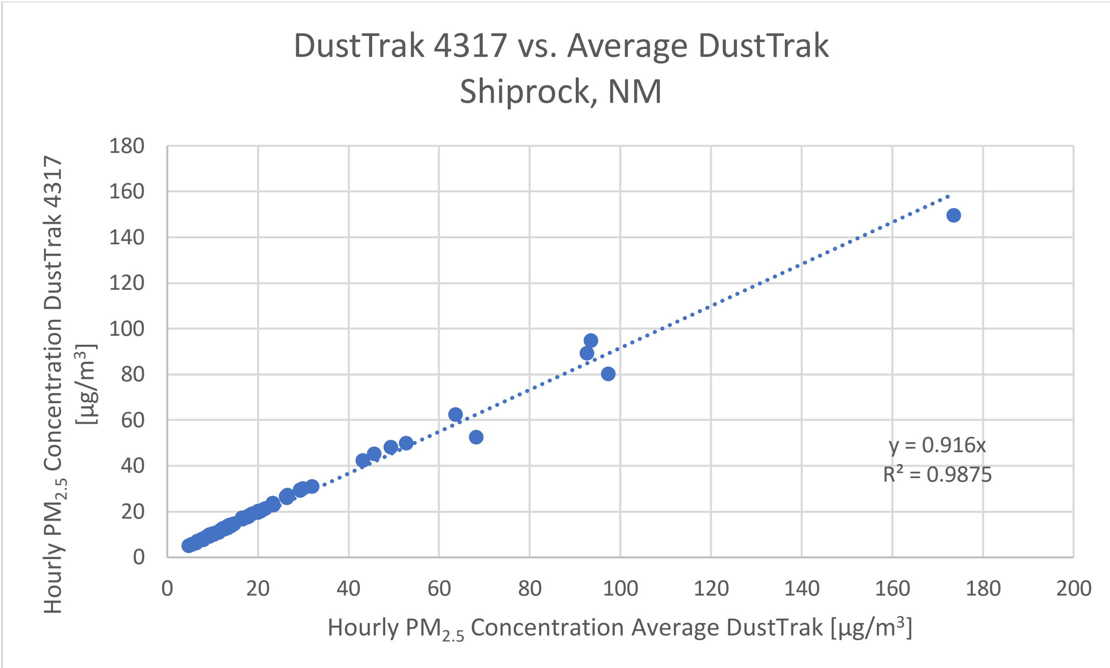

Figure A-9. Shiprock – DustTrak 4317 vs. Average DustTrak

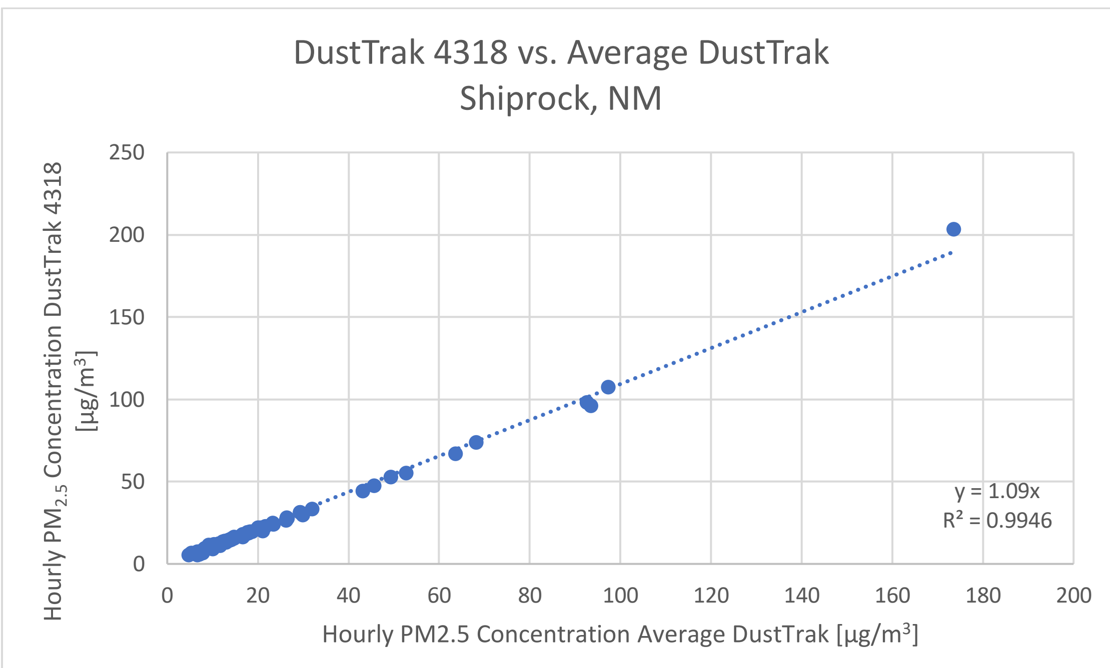

Figure A-10. Shiprock – DustTrak 4318 vs. Average DustTrak

Appendix B: Pre and Post Flow Calibrations

Pre-Experiment

Table B-1. MiniVol 5420 and 5421 Pre-Experiment Flow Calibration

Rotameter	C3PO(2) Serial No. 5420	R2D2 Serial No. 5421
	Mini-Buck Average	Mini-Buck Average
Lpm	Lpm	Lpm
3.5	3.786	3.679
4	4.463	4.360
4.5	5.043	4.949
5	5.714	5.644
5.5	6.225	6.167
6	6.935	6.783
6.5	7.478	7.369

Post-Experiment

Table B-2. MiniVol 5420 and 5421 Post Experiment Flow Calibration

Rotameter	C3PO(2) Serial No. 5420	R2D2 Serial No. 5421
	Mini-Buck Average	Mini-Buck Average
Lpm	Lpm	Lpm
3.5	3.727	3.724
4	4.348	4.292
4.5	4.919	4.882
5	5.573	5.530
5.5	6.111	6.069
6	6.722	6.717
6.5	7.320	7.272

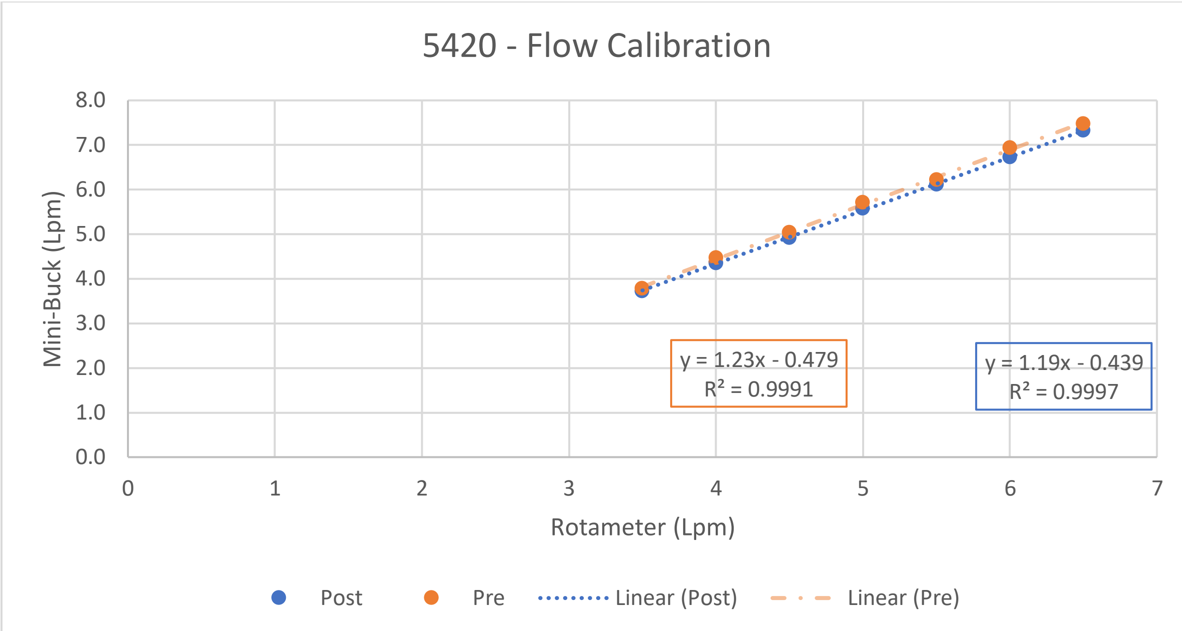

Figure B-1. Pre and Post Experiment Flow Calibrations for MiniVol 5420

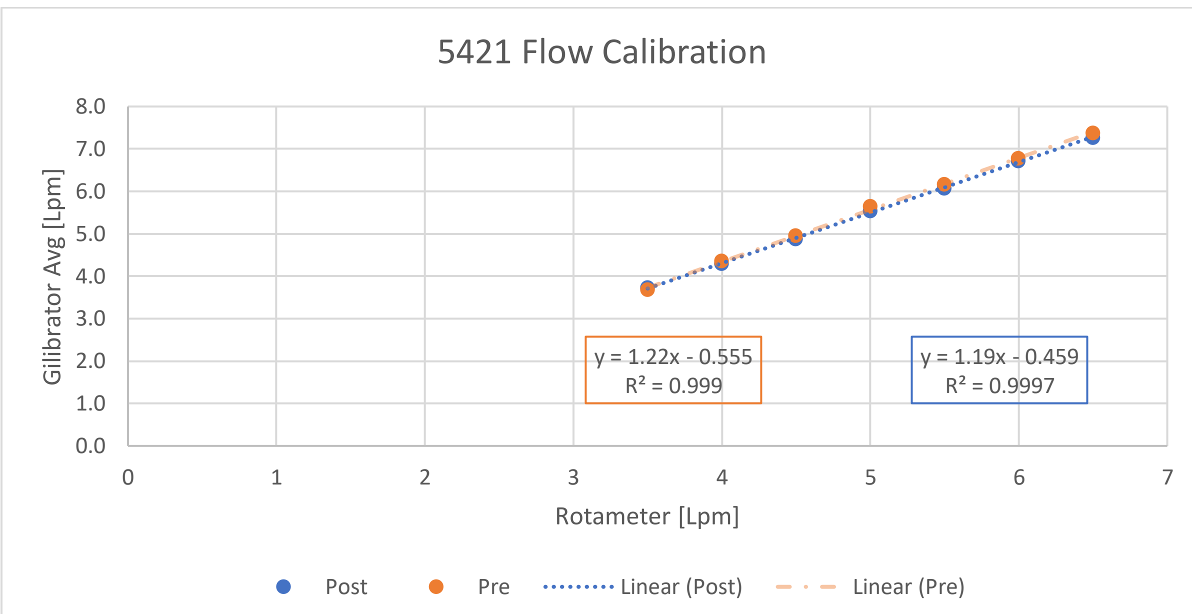

Figure B-2. Pre and Post Experiment Flow Calibrations for MiniVol 5421

Appendix C: E-BAM and DustTrak Linear Regression with Fixed Intercept

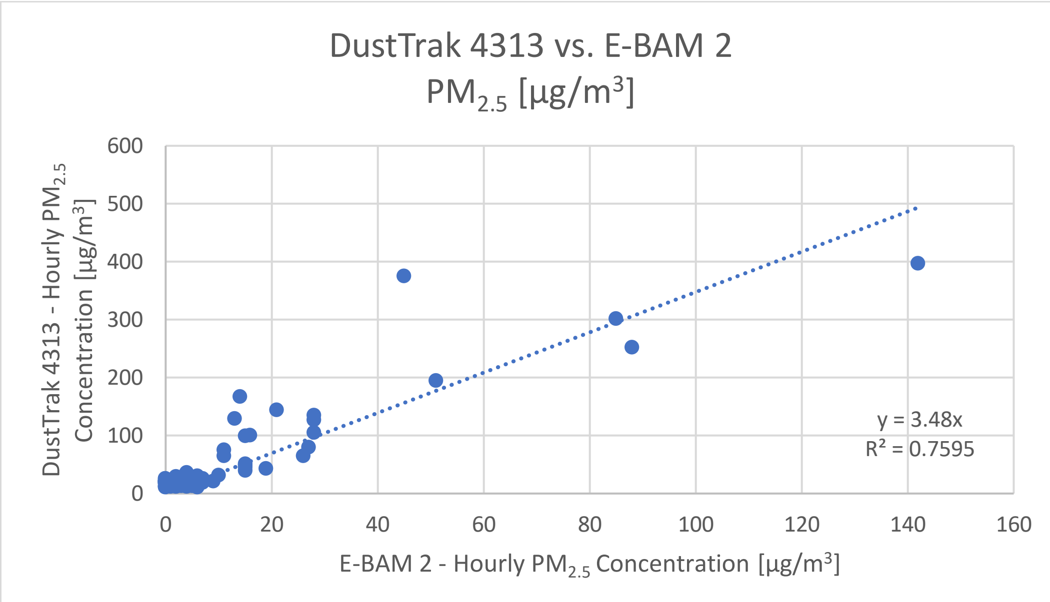

Figure C-1. DustTrak 4313 vs. E-BAM 2

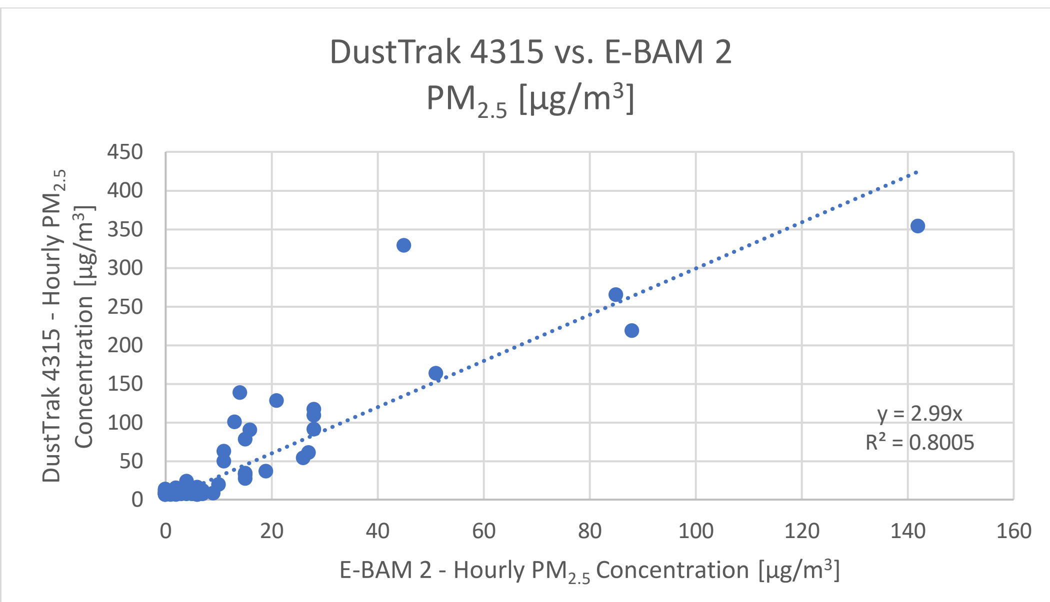

Figure C-2. DustTrak 4315 vs. E-BAM 2

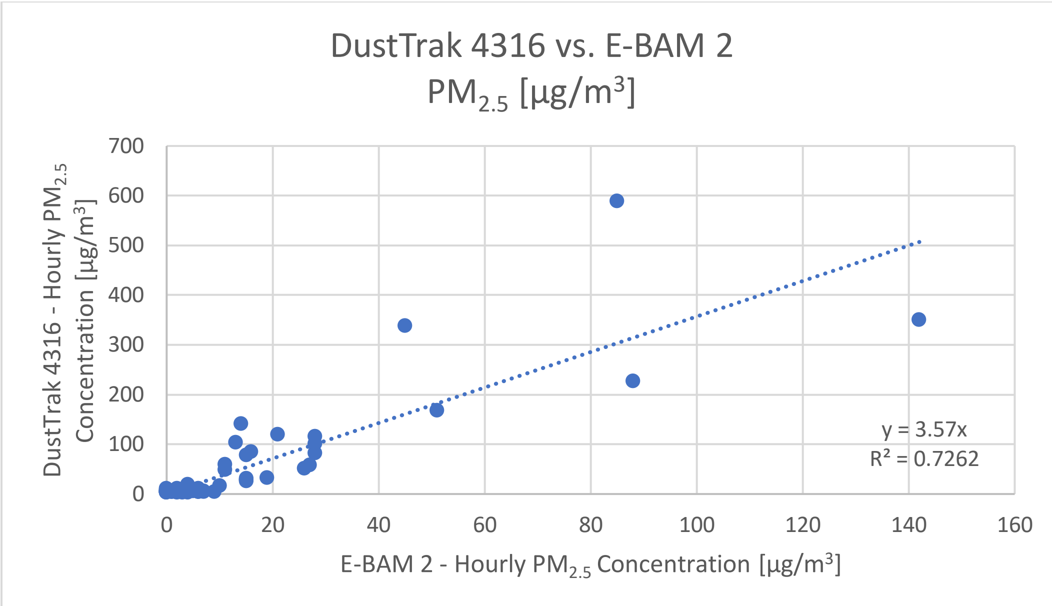

Figure C-3. DustTrak 4316 vs. E-BAM 2

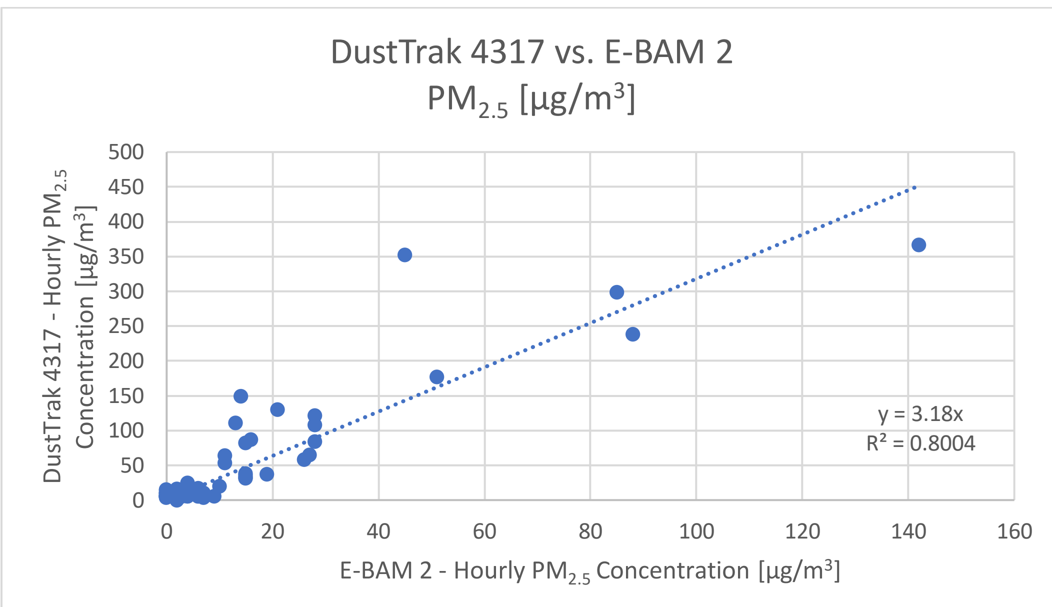

Figure C-4. DustTrak 4317 vs. E-BAM 2

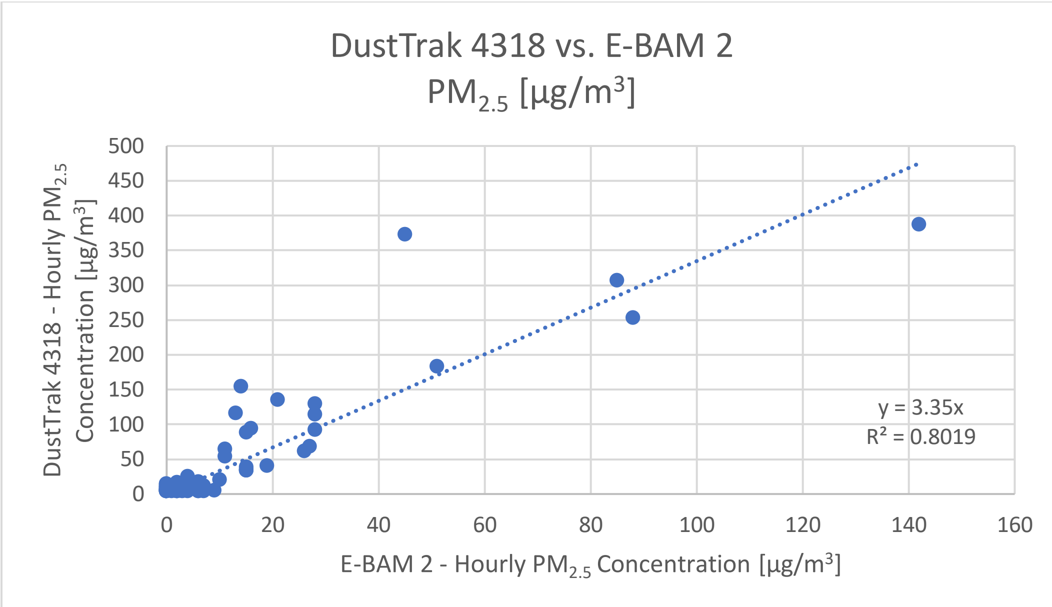

Figure C-5. DustTrak 4318 vs. E-BAM 2

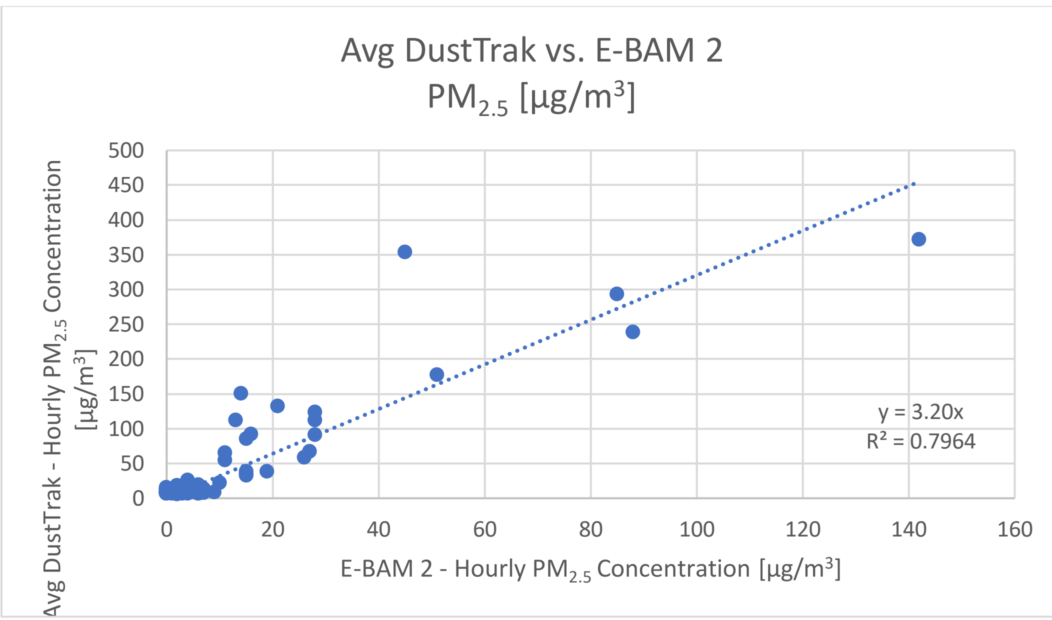

Figure C-6. Average DustTrak vs. E-BAM 2

Appendix D: Home Temperature vs. Stove Temperature

The linear regression plots and the correlation (R^2) for the Navajo Hybrid Stove temperature and home temperature are provided below from Figure C-1 to C-7.

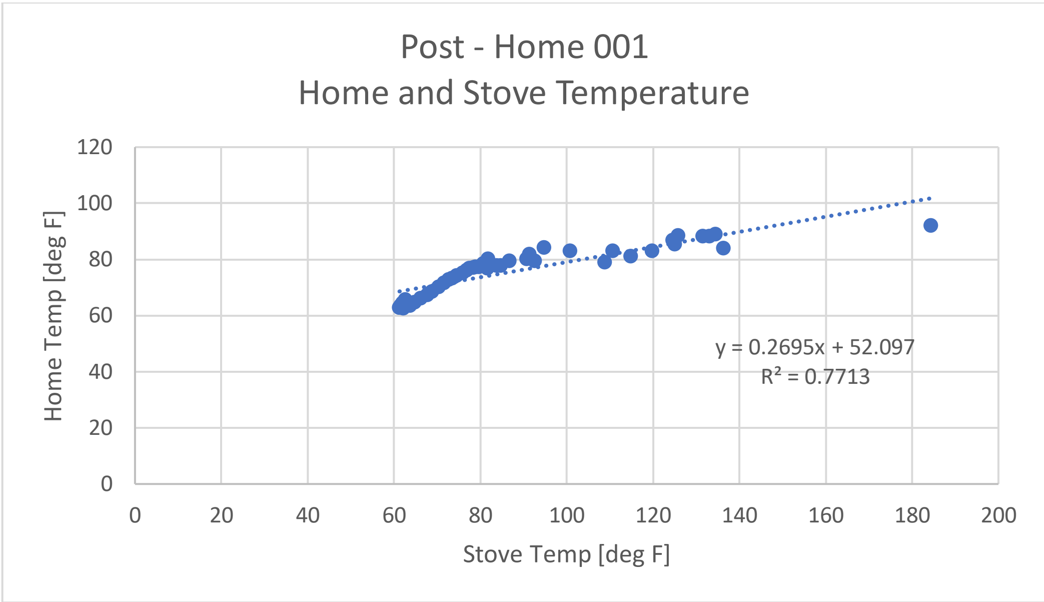

Figure D-1. Home 001 Home and Stove Temperature

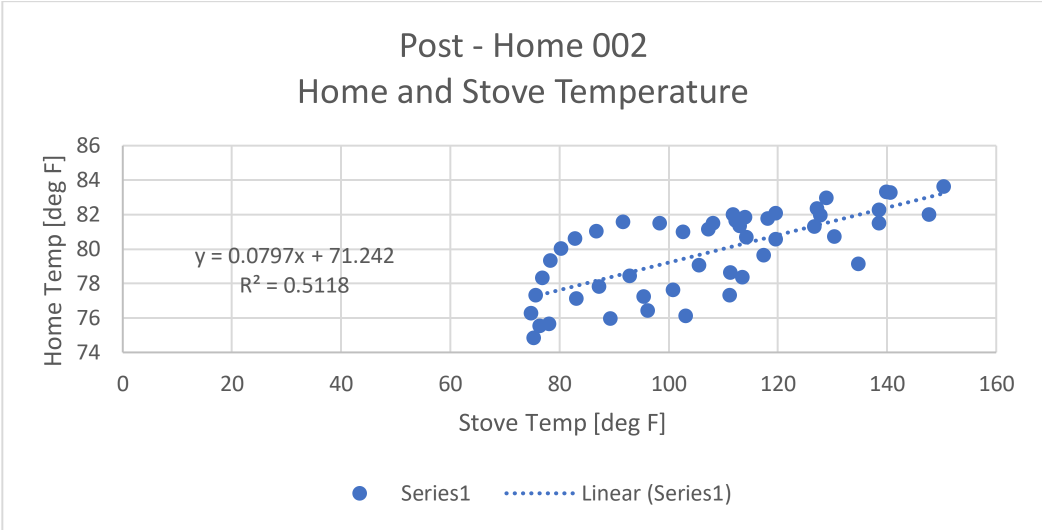

Figure D-2. Home 002 Home and Stove Temperature

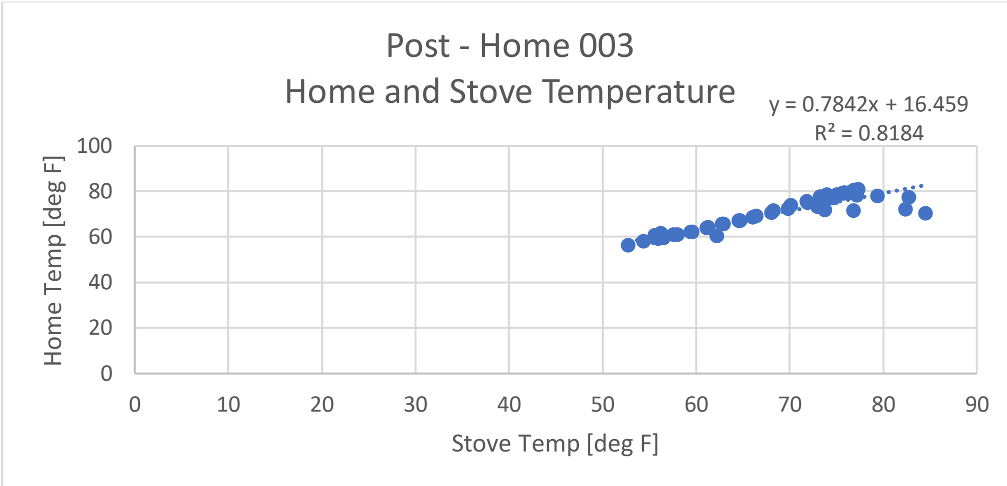

Figure D-3. Home 003 Home and Stove Temperature

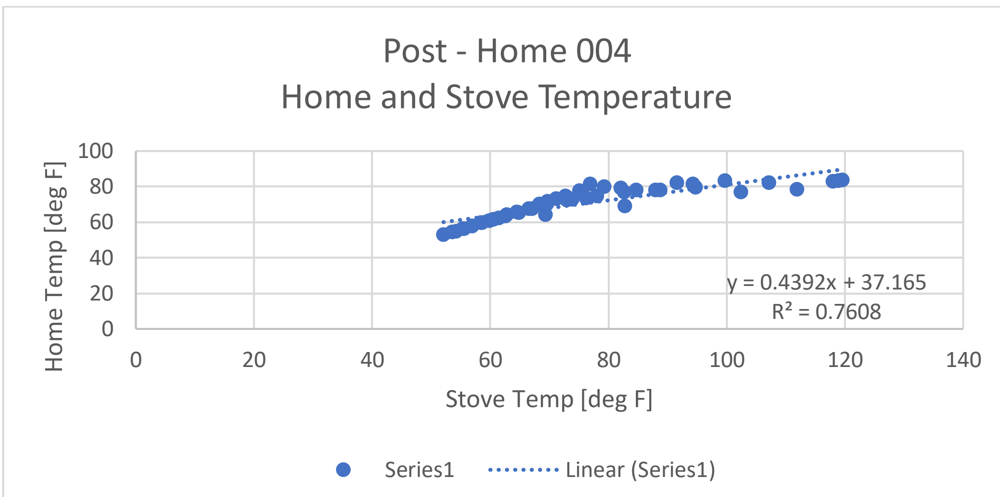

Figure D-4. Home 004 Home and Stove Temperature

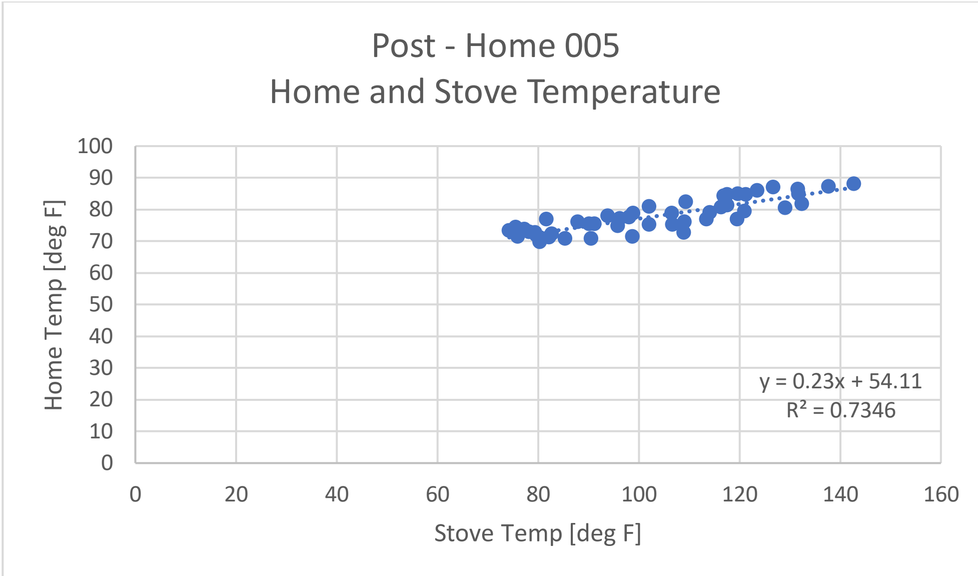

Figure D-5. Home 005 Home and Stove Temperature

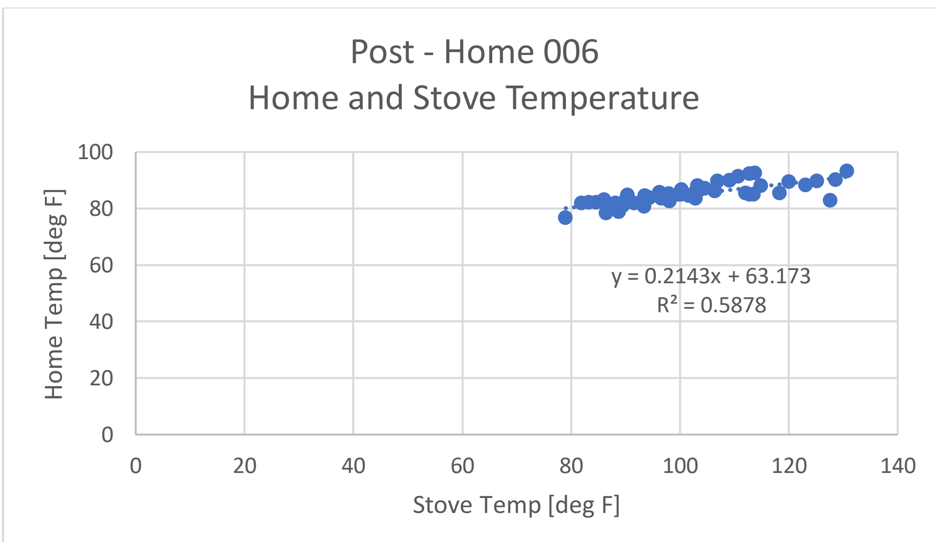

Figure D-6. Home 006 Home and Stove Temperature

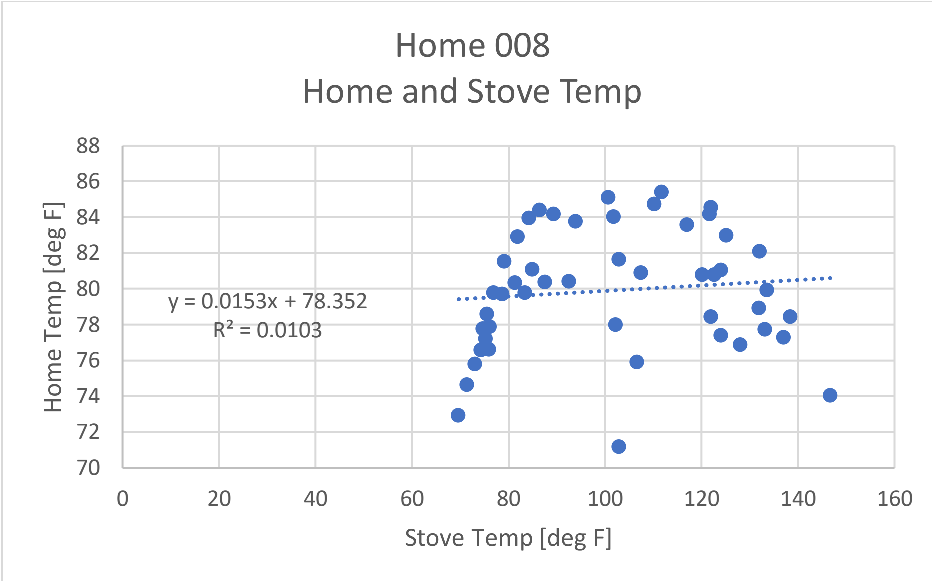

Figure D-7. Home 008 Home and Stove Temperature

Appendix E: IRB Process

IRB approval was obtained from three institutions, Diné College, the University of Colorado – Boulder, and the Navajo Nation Human Research Review Board (NNHRRB). IRB approval was obtained first at the two colleges, then by the NNHRRB as was mandated by their process. The appropriate materials (the application for NNHRRB can be found online) must be submitted one month in advance to the actual meeting. The dates for submission and IRB meetings are also online.

Prior to using the collected data for this thesis, NNHRRB approval was obtained. Ten hard copies of the application were submitted February 22^{nd} for the March 19^{th} meeting in Window Rock, and the abstract was emailed to the IRB Administrator on February 22^{nd}. Support letter(s) from the PI and collaborators were instrumental in securing approval. A short, ten-minute presentation on the research was also presented to the committee members of the NNHRRB, who then asked questions afterwards. Following questions, the members voted and approved the study. A hard copy letter, along with the IRB number, was mailed a few weeks later.

Appendix F: Time Series for $PM_{2.5}$ and CO

Home 001

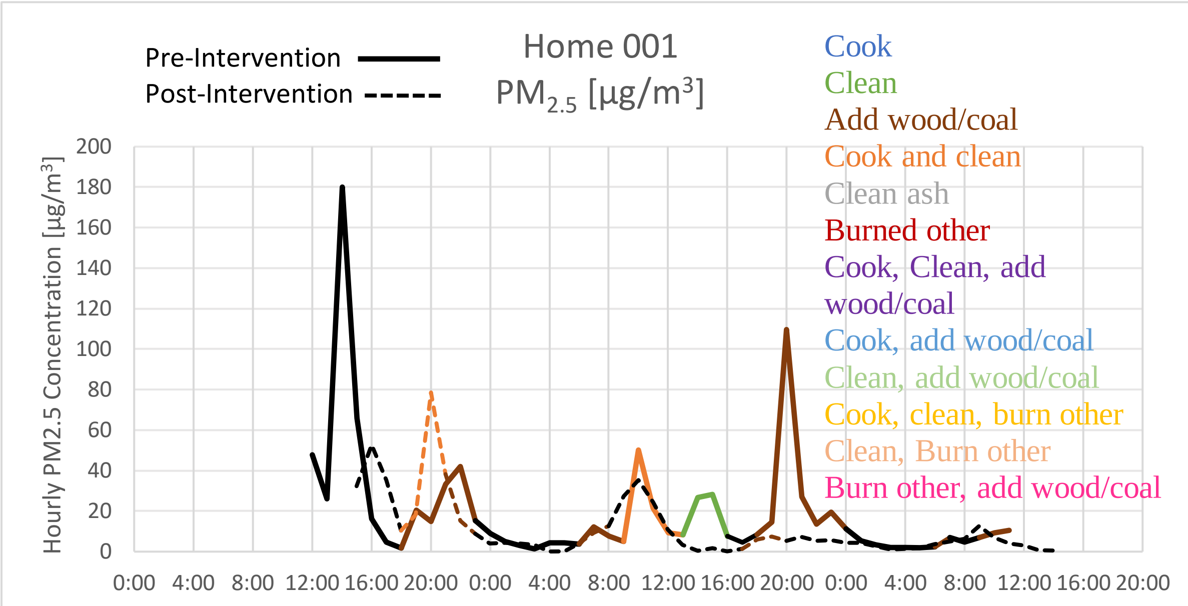

Figure E-1. Home 001 $PM_{2.5}$ Time Series

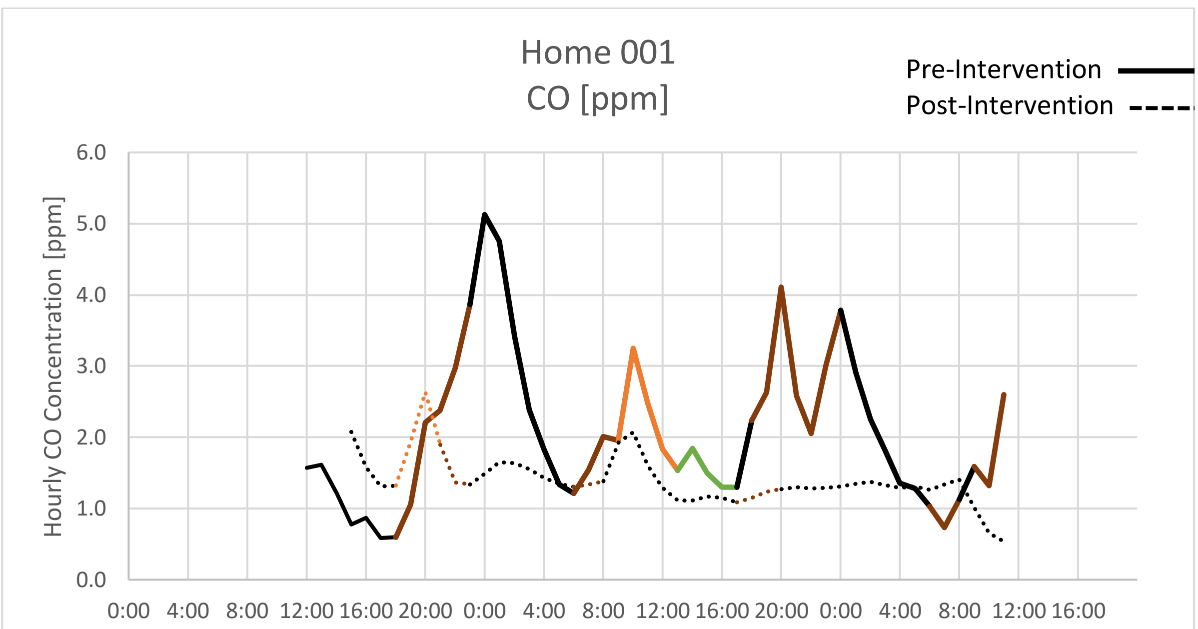

Figure E-2. Home 001 CO Time Series

Home 002

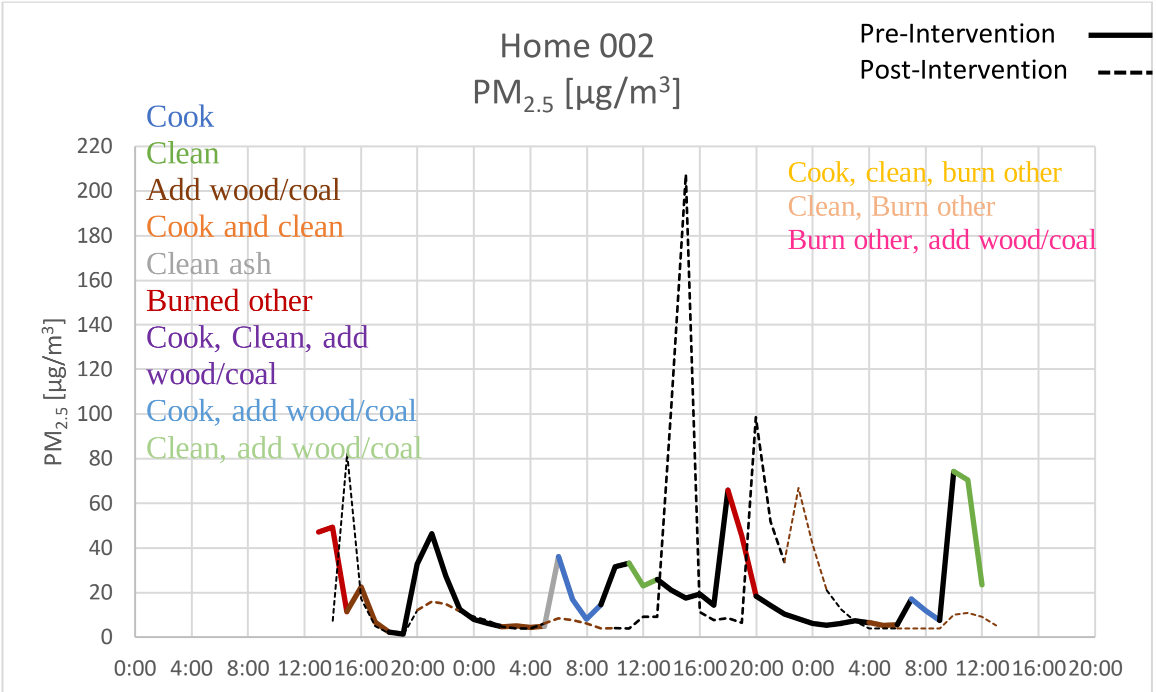

Figure E-3. Home 002 PM2.5 Time Series

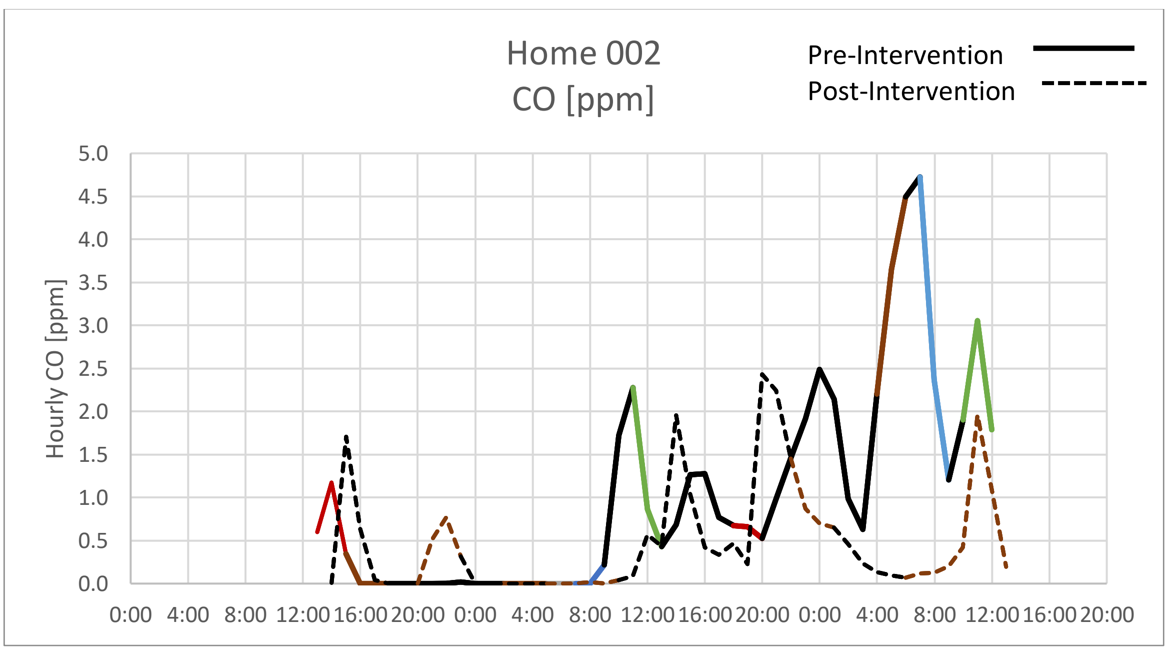

Figure E-4. Home 002 CO Time Series

Home 003

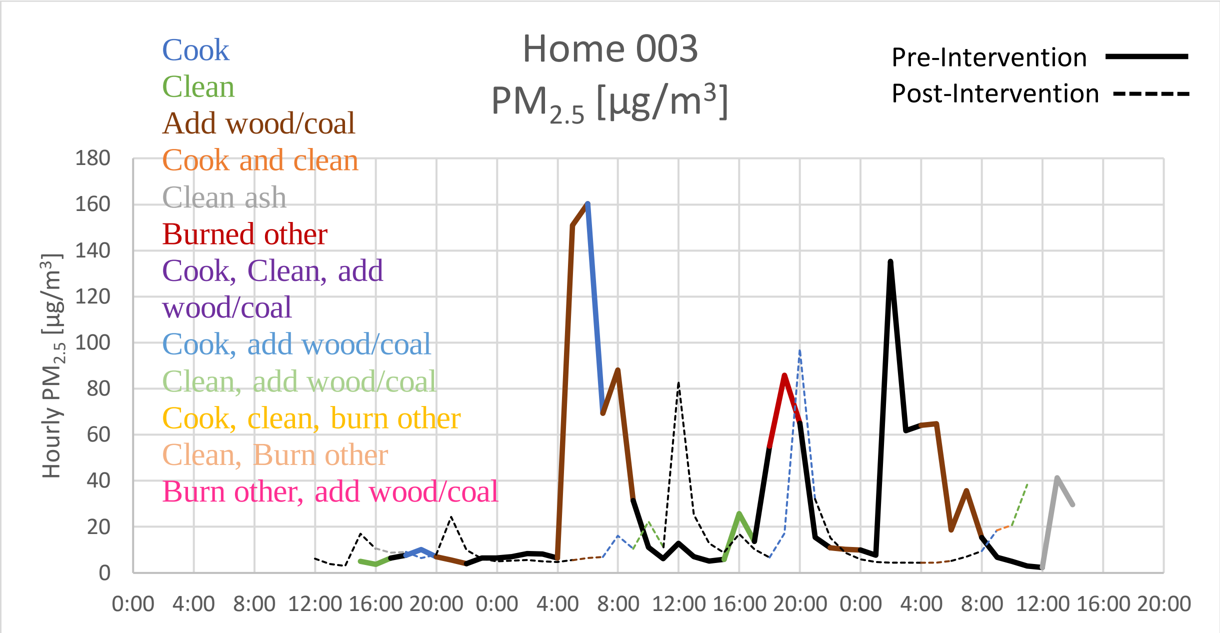

Figure E-5. Home 003 PM2.5 Time Series

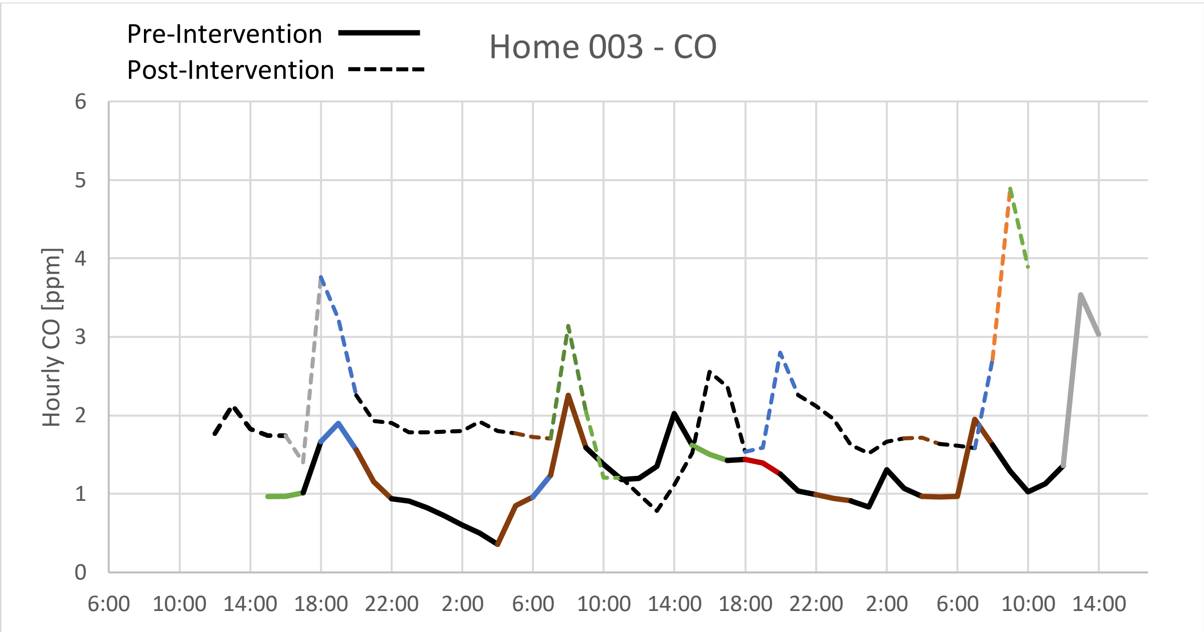

Figure E-6. Home 003 CO Time Series

Home 004

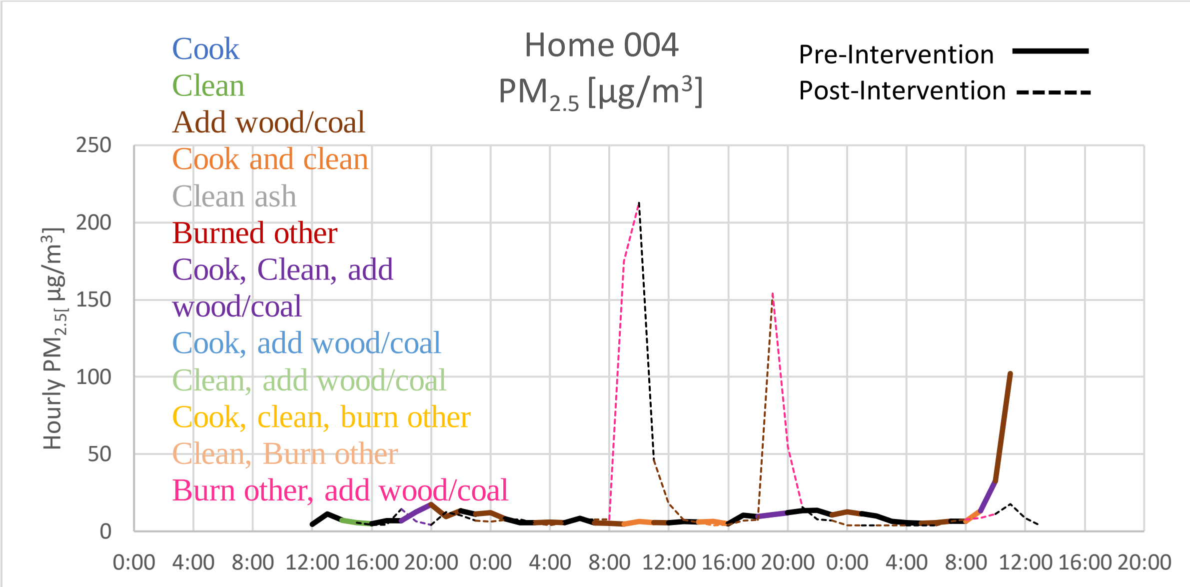

Figure E-7. Home 004 PM2.5 Time Series

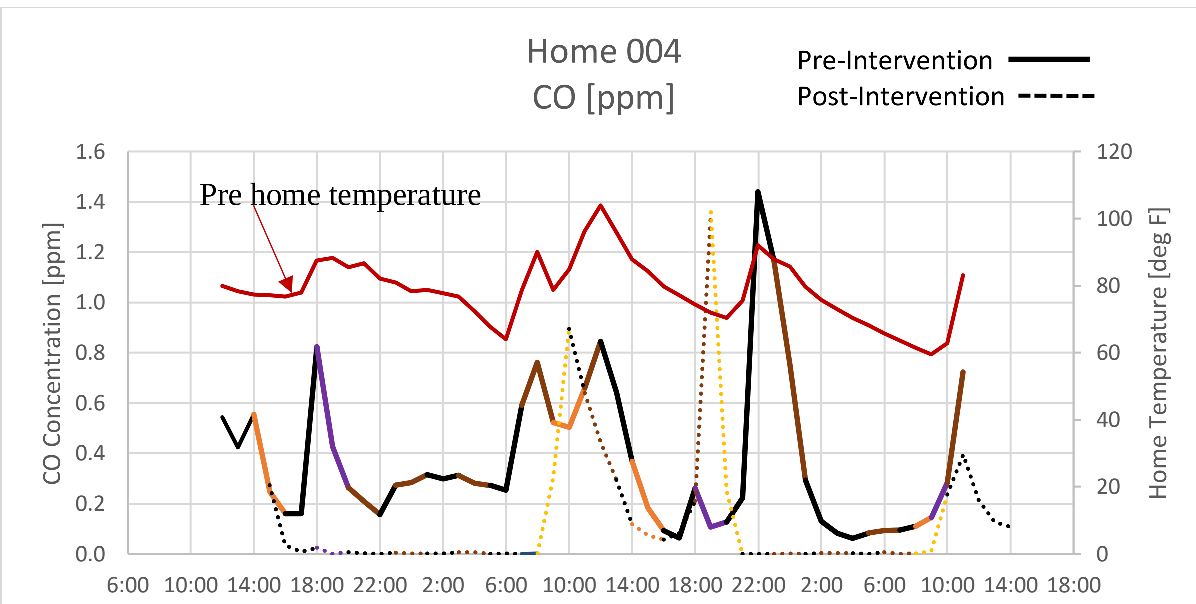

Figure E-8. Home 004 CO Time Series

Home 005

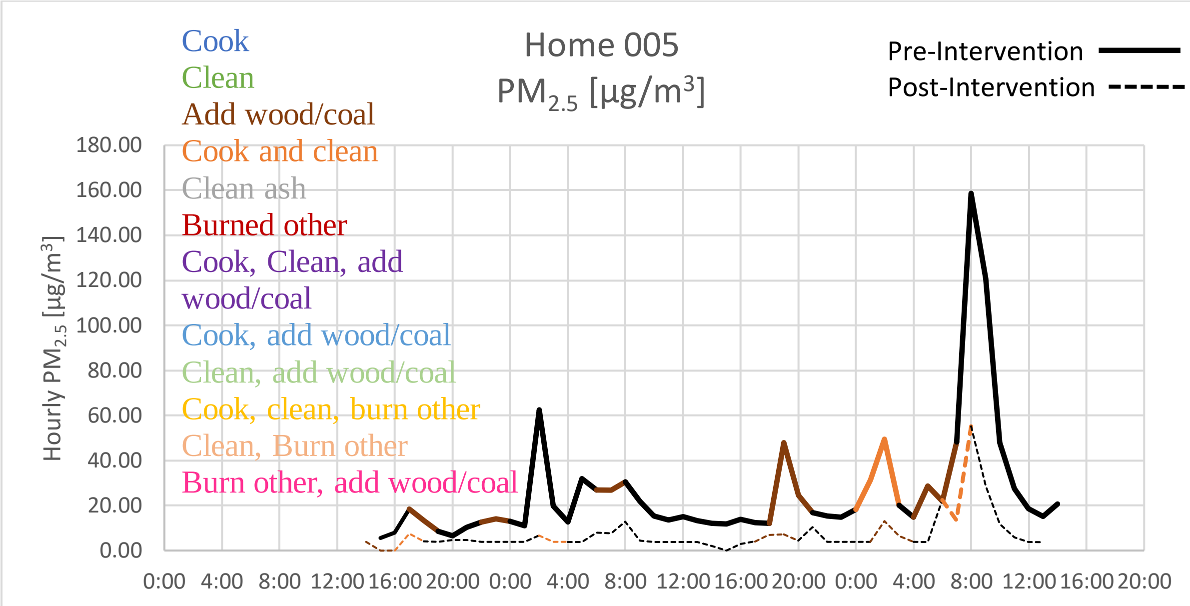

Figure E-9. Home 005 PM2.5 Time Series

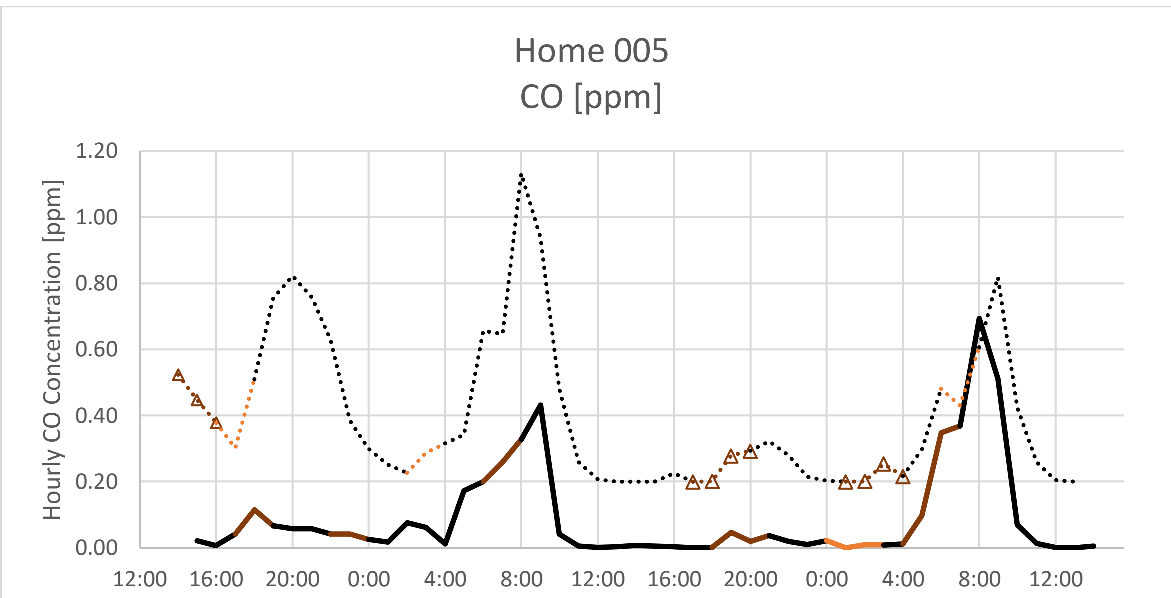

Figure E-10. Home 005 CO Time Series

Home 006

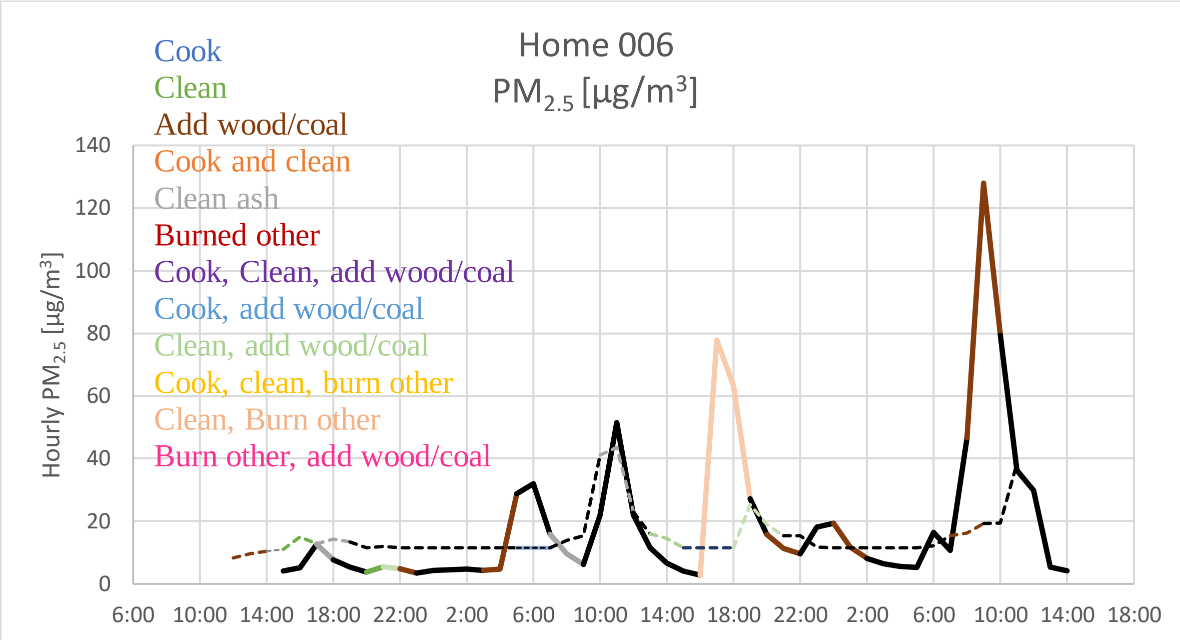

Figure E-11. Home 006 PM2.5 Time Series

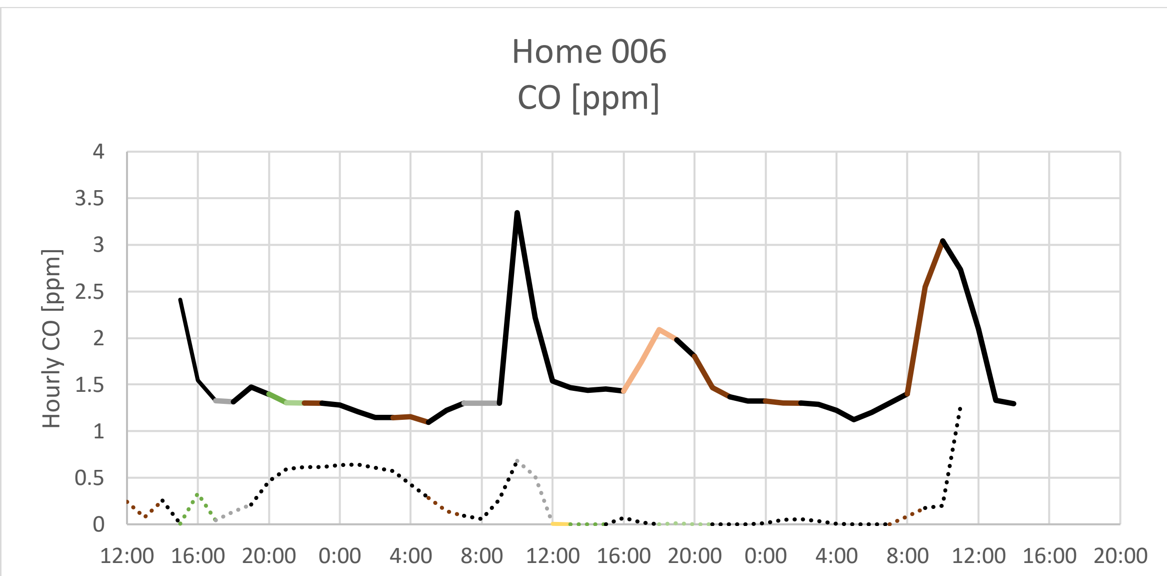

Figure E-12. Home 006 CO Time Series