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The Impacts of Cooking and an Assessment of Indoor Air Quality in Colorado Passive and Tightly Constructed Homes

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THE IMPACTS OF COOKING AND AN ASSESSMENT OF INDOOR AIR QUALITY IN COLORADO PASSIVE AND TIGHTLY CONSTRUCTED HOMES

by

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B.S., Mechanical Engineering

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written by Ryan Edward Militello-Hourigan
has been approved for the Department of Mechanical Engineering

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Dr. Shelly L. Miller

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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.

Abstract

Militello-Hourigan, Ryan Edward (M.S., Mechanical Engineering)

The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes

Thesis directed by Professor Shelly L. Miller

Low-energy home design is becoming more common in new and retrofitted homes, and energy-efficient designs often sell at a premium [1]. This perceived and realized value of reducing energy use in homes is important as the need to reduce fossil fuel use becomes increasingly critical. Energy efficiency measures, like tightening the envelope of a home saves energy, but can impact the indoor air quality. We monitored the indoor air quality of nine tightly constructed homes, one tightly constructed public library, and one conventionally constructed home, and performed a repeatable cooking activity to observe the impact and response to the resulting fine particulate matter ($PM_{2.5}$) emissions. We compared the $PM_{2.5}$ concentrations from the cooking activity while operating the mechanical ventilation systems at default rates (~0.1-0.3 h^{-1}) and in a temporary boost mode (~0.3-0.8 h^{-1}). We also measured the concentrations of total volatile organic compounds (TVOCs), formaldehyde, radon, and bedroom carbon dioxide (CO_2) levels. Results show that fine particulate matter concentrations are generally low indoors, but a cooking event drastically increases concentrations and levels are slow to decay. Median time above 35 $\mu g/m^3$ after cooking was 4.7 hours. Overall, there was not a significant difference between operating the ventilators at standard rates and utilizing the temporary boost. Completely-mixed flow reactor models of select tested homes show that installing and using a directly-exhausting range hood could reduce peak $PM_{2.5}$ concentrations by 75% or more. Current ventilation practices in these buildings may not be adequate for these common polluting events. TVOC concentrations were generally low with a median average of 459 $\mu g/m^3$. Formaldehyde was above the California Office of Environmental Health Hazard Assessment (OEHHA) chronic limit of 9 $\mu g/m^3$ across all tight buildings with a median value of 30 $\mu g/m^3$. Carbon dioxide levels in bedrooms were high at night (>1000 ppm) in six of the homes, indicating that current bedroom ventilation practices are not consistent nor adequate. Bedroom air exchange rates (AER) determined from carbon dioxide decay ranged from 0.08 to 0.30 h^{-1} with a median value of 0.12 h^{-1}.

Acknowledgements

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Chapter 1: Introduction

Passive houses are an important concept: construct a building that is tight and well-insulated, with ventilation by clean air and by energy-efficient means, and the result is a very energy-efficient and well-ventilated home. The term “passive” refers to the *goal* of eliminating active space heating or space cooling, so to achieve this low-energy status, there are several features that these buildings usually have in common. Along with the tight envelope and thick, high-efficiency insulation (wall R-values vary, but often range from 30 to 60 [2]), these homes feature high-performance windows and continuous or automatic mechanical ventilation with filtration of outdoor supply air [3]. A common proclaimed benefit of these homes, in addition to the energy efficiency, is improved indoor air quality because outdoor air is supplied and filtered [4], and improved environmental quality due to minimal variation in indoor temperature and relative humidity. Filtering the incoming ventilation air only solves one issue, however. Many pollutants in the home come from occupant activities, cooking being a major source [5]. Additionally, the unique characteristics of these homes can be a double-edged sword in regards to indoor air quality; the same features that can improve the air quality can easily prove to be a detriment if not properly designed and operated [6]. The process of installing a dedicated exhausting range hood over the stove for use during cooking in these homes is typically more complex than in a conventional home, due to a desire to minimize design openings and thermal bridges. As a result, most homeowners opt to rely on zone ventilation to dilute and remove the pollutants. Some homeowners also opt to install a recirculating, or “ductless”, hood. The effectiveness of this type of range hood is considered questionable [7].

Previous studies have looked at the indoor air quality of passive and tightly constructed houses. Five Scottish passive houses were monitored for one year to investigate thermal comfort and indoor air quality. Occasional overheating (>25°C) was an issue for all four of the five homes. High levels of CO_2 were observed in two of the homes, exceeding 1000 ppm for over 10% of the year [8].

Swedish passive houses were studied and compared to conventional houses and data from the Swedish housing stock. Median AERs in the passive houses were found to be 0.68 h^{-1}, higher than the 0.3-0.4 h^{-1} typically recommended for passive houses [9]. The conventional homes tested were found to have AERs of 0.60 h^{-1}. The Swedish building code requires rates that typically correspond to 0.5 h^{-1} in most houses. The passive houses were found to have lower formaldehyde and ozone concentrations than the conventional homes, but higher levels of TVOCs. High CO_2 levels were also found in these passive houses, but the conventional homes experienced it as well. Most passive and conventional houses that exceeded 1000 ppm did so less than 10% of the time [3].

A study of high performance homes in California, many with passive house qualities, found that acceptable IAQ is achievable when good design is practiced. Design that includes adequate ventilation, low-emitting materials, particle filtration, and kitchen/bathroom exhaust. Homes with air filtration systems had roughly 50% less airborne PM. The tight, mechanically ventilated homes (median ACH_{50} = 1.1) had a median AER of 0.30 h^{-1}, while the less tight non-mechanically ventilated homes (median ACH_{50} = 6.1) had a median AER of 0.32 h^{-1} [6].

A comparison of two nearly-identical buildings in Austria (one with continuous ventilation and one with just windows) also highlights the importance of proper ventilation. The building that relied on natural ventilation experienced higher levels of CO_2, especially in the winter months [10].

The thermal comfort and indoor environmental quality of these homes has also been investigated. Rohdin, et al. found generally good thermal comfort in Swedish passive houses. Drafts were not likely in the homes, but overheating in the summer was sometimes an issue [11]. A recent review by Wang, et al. highlights some of the main factors that affect the thermal comfort and indoor air quality such as occupant behavior, like opening windows, changing the shading, or modifying control set points [12]. Blight et al. suggest that passive houses can be reasonably resilient to behavioral impacts, however [13].

In this study, we characterized the air quality of nine tightly constructed homes, one tightly constructed public library, and one conventional home. Passive and low-energy housing can be economically favorable [14], so with the growing number of energy-efficient homes, it is important to characterize them by their impacts to indoor air quality, and ultimately human health [15,16].

Cooking in the home has been shown to increase airborne pollutants [5], so an objective of this study was to observe and quantify how the indoor air quality of passive and high-performance houses are impacted by a common cooking activity. Due to differences in how occupants typically cook throughout their daily routine, we designed our study to feature a repeatable cooking event, done by the same person in every home. In addition to measuring the impact on $PM_{2.5}$ concentrations from this cooking event, we measured the TVOC and formaldehyde concentrations in the main living area for over 2 days. We also monitored the bedroom CO_2 levels over one nighttime period in which the occupant or occupants were sleeping in the bedroom.

Chapter 2: Materials and Methods

2.1 Building Selection

The ideal candidates for this study were homes that were constructed or retrofitted to “passive house” standards. The definition and standards for a Passive House vary by country or organization, but typically have similar characteristics. The Passivhaus Institut (PHI) from Germany and the Passive House Institute U.S. (PHIUS) are the two common standards used in the United States. These organizations have slightly differing requirements, but both have strict guidelines on the tightness and energy use of a home. To be certified as a passive house, the home must be commissioned and verified by an approved agent. This typically carries extra cost, so many homeowners opt to skip this process. Due to the limited number of officially certified passive houses in Colorado, homes that were tight compared to conventional buildings and also featured energy recovery ventilation were included in the study. Buildings that meet PHI tightness requirements of 0.6 air changes per hour at 50 pascals (ACH50) are considered “passive” in this paper (Building ID starting with PH). Prior to 2015, both PHI and PHIUS used this metric. Three homes and the library do not meet this strict tightness requirement and are simply referred to as “tight” structures (Building ID starting with TH). Additionally one home of conventional construction did feature energy recovery ventilation and a dedicated exhaust range hood, and was included for comparison (Building ID: CH110). See Table 1 for the list of all 11 tested buildings and their characteristics. All buildings tested in this study are located in Colorado and 70 miles (113 km) more or less from Denver.

2.1.1 Home Ventilation

Due to the tight construction and thus low infiltration rates, all buildings tested in this study had balanced energy recovery ventilators. Balanced, in this case, means that the flow rates of the supplied ventilation approximately matches the flow rate of the exhausted air. The energy recovery method varies across ventilator models, but fundamentally, there are three common types in the tested buildings. Heat recovery ventilators (HRV), and enthalpy recovery ventilators (ERV), and conditioning energy recovery ventilators (CERV®). The last type is produced by a company called Build-Equinox (Urbana, IL), and feature a heat pump to exchange heat between the two air streams.

All HRVs and ERVs in the tested buildings ran continuously, and all those installed in passive and tight homes featured a *boost* mode in which the ventilation air flow rate is temporarily increased. For the second cooking tests, the boost was set to 20 minutes. The CERV® units do not typically run continuously and instead provide ventilation air on a timed or automatic basis. The automatic approach measures CO_2 and VOC levels in the air and ventilates when concentrations exceed the user-defined set point. Users can also set the unit to provide 100% ventilation air for a specific amount of time. Since these ventilators do not have a boost mode, homes with these units were put into 100% ventilation mode in lieu of a boost mode during the second cooking test. These units only allow the ventilation mode to run in 15-minute increments, so a 30-minute ventilation mode was used during the second cooking test.

Table 1. Building and ventilation properties

Building Properties											
Building ID	PH100	PH101	TH102	PH103	PH104	PH105	PH106	PH107	TH108	TH109	CH110
Building Type	House	House	House	Library	House	House	House	House	House	House	House
Building Age (yrs.)	3	4	37	1	4	6	5	2	1	1	39
# of Floors	1	2	2	1	2	3	2	4	3	3	3
# of Bedrooms	1	3	3	0	3	4	3	3	2	3	4
# Total Occupants	2A	1A	2A	Varies	1A	2A	2A	2A/1C	1A	2A	2A/2C
# Bedroom Occupants	1A	1A	2A	-	1A	2A	2A	2A	1A	2A	2A
Certification	PHI	No	No	No	PHIUS	PHIUS	PHIUS	No	No	No	No
Total Cond. Area (ft^2)	1250	2204	1982	3793	6632	2196	3648	3524	1648	2458	3091
Total Cond. Vol. (ft^3)	18850	21288	21068	51087	60592	23632	35666	28577	15056	22328	27185
Test Area (ft^2)	1057	941	939	3282	4566	1446	1770	1223	1141	1759	1356
Test Volume (ft^3)	15720	9290	12287	45977	40407	14308	15930	10334	10424	15972	9676
Bedroom Area (ft^2)	200	414	123	-	310	262	214	326	172	416	265
Bedroom Volume (ft^3)	2450	3726	981	-	2635	3734	2354	2771	1376	3536	2522
Tightness (ACH$_{50}$)	0.47	0.34	1.53	1	0.34	0.23	0.46	0.55	1.37	2.99	~4
Stove Type	Propane	Electric	Electric	N/A	Electric	Gas	Electric	Induction	Electric	Electric	Electric
Hood Type	None	Recirc.	Recirc.	-	Recirc.	Recirc.	Recirc.	None	Recirc.	Recirc.	Exhausting
Radon Mitigation	Passive	None	None	None	None	Active	None	None	None	None	Active
Ventilation Properties											
Ventilator Type	HRV	ERV	CERV	ERV	ERV	ERV	CERV	ERV	CERV	CERV	HRV
Ventilator Manufacturer	Air Pohoda	Air Pohoda	Build-Equinox	Life Breath	Air Pohoda	Zehnder	CERV	Ultimate Air	Build-Equinox	Build-Equinox	Carrier
Filter Rating	MERV-10	MERV-8	MERV-13	MERV-8	MERV-8	MERV-8	MERV-8	MERV-12	MERV-8	MERV-8	Unknown
Std. Design AER (h^{-1})	0.16	0.08	0.42	0.59	0.22	0.32	0.18	0.21	0.60	0.40	0.31
Boost Design (h^{-1})	0.48	0.51	-	1.17	0.40	0.76	-	0.34	-	-	-
Bedroom CO$_2$ AER (h^{-1})	0.15	0.08	0.12	-	0.08	0.15	0.12	0.11	0.30	0.32	0.13
ASHRAE 62 AER (h^{-1})	0.17	0.27	0.25	0.88	0.23	0.26	0.23	0.28	0.29	0.28	0.29
Est. Infiltration (h^{-1})	0.02	0.01	0.07	0.03	0.02	0.01	0.03	0.00	0.06	0.15	0.17

2.2 Data Collection

Air quality was monitored indoors and outdoors for all testing periods. Indoors, all equipment was placed at a height between 0.5 and 1.5 meters, typically in a main living area nearer to the kitchen, and at least 1 meter away from any doors, operable windows, vents, or obvious sources of pollutants. Outdoors, equipment was typically placed on a tripod at a height of 1.5 meters in the middle of the backyard.

Table 2. Air pollutant monitoring equipment and properties

Equipment	Pollutant	Measurement Period	Accuracy Notes
Outdoors			
Dylos DC1700	Particulate Matter (PM)	3-5 days	$R^2 = 0.778$ for mass conc. [17]
TSI Q-Trak	Carbon dioxide (CO_2)	10-15 min.	Max. of ± 3% or 50 ppm
Living Room			
Dylos DC1700	PM	3-5 days	$R^2 > 0.90$ for mass con. [18]
GrayWolf DirectSense TVOC	TVOC	3-5 days	Varies; Cal. 10-7500 ppb (C_4H_8)
SKC UMEx 100	Formaldehyde	3-5 days	+/- 22.7%
Bedroom			
TSI Q-Trak or	CO_2	3-5 days	Max. of ± 3% or 50 ppm
Telaire 7001			Max. of ± 5% or 50 ppm
Lowest Occ. Space			
Sun Nuclear Model 1027	Radon	3-5 days	Max. of ± 25% or 1 pCi/L

2.2.1 Fine Particulate Matter

Fine particulate matter (PM) was measured in the common living area and outdoors using optical particle counters (Dylos Corporation, DC1700). These units provide small (≥0.5 μm) and large (≥2.5 μm) particle counts. Subtracting the large from the small counts provides an approximate $PM_{2.5}$ particle count. Particle counts are not currently useful for determining health impacts as the National Ambient Air Quality Standards (NAAQS) used for comparison publishes limits in mass concentration (µg/m^3). To convert to mass concentration, the linear calibration coefficient for fresh particles determined by Dacunto, et al. [18], was applied. This calibration curve was determined by collocating the Dylos units with a more costly and gravimetrically-calibrated laser photometric unit (TSI Inc., SidePak AM510) and showed good agreement ($R^2 \geq 0.90$) for fresh particles of known sources. For outdoor measurements, the sources are typically unknown and likely not fresh, so this calibration curve is less applicable. Han, et al. also tested Dylos units for outdoor urban sources and found a reasonable linear curve ($R^2 = 0.778$) for concentrations under 100 µg/m^3 and relative humidity under 60% [17]. The curve reports negative concentrations at low outdoor concentrations, however, so the direct indoor to outdoor ratio was used instead.

2.2.2 Total Volatile Organic Compounds

TVOCs were measured in the living room at a height of approximately 1.5 meters using a photo-ionization detector (Gray Wolf Inc., DirectSense TVOC, TG-502). This monitor continuously measures TVOC levels, logging every minute. Data from the TVOC monitor is reported in parts per billion (ppb) based on isobutylene as a reference molecule. Many standards for VOCs report in mass concentration (µg/m^3). To convert from ppb to these units, the mole fraction was multiplied by a correction factor of 0.5 (isobutylene to toluene), as specified by the manufacturer, then converted to mass concentration using the ideal gas law and toluene as the new reference molecule [19]. An average barometric pressure of 0.83 atm was assumed for this conversion. The monitoring probe was factory calibrated approximately ten months before the start of this study.

2.2.3 Formaldehyde

Formaldehyde was measured using a passive diffusive sampler (SKC Inc., UMEx-100). Samplers were placed in the main living area at a height of approximately 1 meter. These samplers contain paper treated with 2,4-dinitrophenylhydrazine (DNPH). Samplers were sent to ALS Environmental in Salt Lake City for analysis using high performance liquid chromatography following the OSHA 1007 method. Precision for these samplers are +/- 22.7% [20].

2.2.4 Carbon dioxide (CO_2)

Carbon dioxide was measured in the master bedroom of all homes. If the bedroom had a door, residents were asked to sleep with it closed for one or more nights. Levels were measured using a portable non-dispersive infrared (NDIR) CO_2 monitor, (Telaire, Model 7001 and TSI, Q-trak) placed 0.5 to 1 meter above the floor and at least 1 meter away from the bed. The Telaire 7001 was used with good results for the first six homes, but then began to malfunction. The TSI Q-trak was then used for the remaining homes. Coincidental collocation in the previous homes show good agreement between the two instruments. The Q-trak was field calibrated one day before the first home was tested. Outdoor concentrations were determined by placing the Q-trak outside for ten to fifteen minutes and calculating the average. The first and last 15 minutes of indoor measurements were discarded in calculations to account for instrument warm-up and stabilization.

AERs in the bedrooms were determined from the carbon dioxide decay profiles. Profiles were selected to avoid times when the door was opened after a night of sleeping. All bedroom AER values were calculated from the average of three different decay profiles except for PH104, which only used two. The AER was calculated using a continuously-mixed flow reactor (CMFR) model accounting for outdoor concentrations.

2.2.5 Radon

Radon was measured using a continuous radon monitor (Sun Nuclear, Model 1027) in the lowest occupiable space of the building. Unfinished basements were not considered occupiable for this study. The continuous monitor logged hourly averages over the test period. Only the final EPA Protocol average, calculated internally by the instrument, is reported here. At the start of this study, the radon monitor was within one year of its factory calibration. Although some homes were tested up to a month after the annual recommended calibration, error is likely minimal and within the bounds of radon risk uncertainty [21].

2.3 Experiment Design

Homes were tested over periods of three to five days between October 2017 and March 2018. Cooler temperatures in the late fall and winter allowed for the homes to be tested with windows closed during testing periods.

The tests in each home were conducted on two different days, with two visits per day. During the first visit, all equipment was set up. This included the air monitoring equipment in the living room, bedroom, outdoors, and two air cleaners (Honeywell HPA200, Morris Plains, NJ) set apart in the main living area. The main living area defined here includes the living room and adjacent dining or common areas. Measuring equipment in the main living area varied from home to home, but ranged from about 5 to 15 meters away from the cooking setup in the kitchen. The two air cleaners were turned on to their highest setting and left to run for approximately three hours. During this time residents were asked to either leave as well or remain minimally active (i.e. no cooking, cleaning, or vigorous activity). The minimum clean air delivery rate (CADR) of each cleaner is listed by the manufacturer at 180 ft^3/min, providing a minimum of 0.36 h^{-1} (median of 0.91 h^{-1}) in addition to the installed mechanical ventilation. The three-hour cleaning period provided at least one air change of effective PM removal in every building before cooking.

After the air in the homes was cleaned for this period of time, we returned to the home to perform the cooking activity (described in 2.3.1). Immediately before cooking, both air cleaners were turned off, the ventilation was verified to be in its standard mode, and bedroom and bathroom doors were closed. The doors were closed to reduce the effective mixing volume and more closely approximate a completely mixed flow reactor. After cooking, the researcher left the home with all equipment in place in the home and monitoring the air over the following days.

Three to five days later, the same cleaning process and cooking activity was repeated, but the mechanical ventilation system was put into a short-term boost mode immediately before cooking (continuous mode for CERV units). After cooking, we left the home for roughly three hours while the monitors were recording the home’s response to the cooking event, then returned to collect all the equipment.

2.3.1 Cooking Activity

A repeatable prescribed cooking activity was performed in each house to test the performance of the home and its ventilation system. One large Grade AA white egg was fried in one tablespoon of canola oil in a 10-inch induction-ready stainless steel skillet for a duration of six minutes (three minutes on each side). The oil was preheated for one minute prior to cooking the egg. Cooking was done on an induction hot plate (Duxtop Model 8100 MC, Brookfield, WI) set to a power level 4. From the manufacturer's manual, this corresponds to a power of 1000 watts. During cooking, the pan was covered with a wire-mesh splatter screen that was only removed briefly to flip the egg after three minutes of cooking time. After six minutes of cooking, the egg was removed from the pan and covered. The pan was wiped down with a paper towel and allowed to cool briefly before rinsing with cold tap water. It should be noted that is a long time to cook a fried egg, and the emissions from this activity are likely higher than a normal fried egg. The goal was to produce substantial emissions that are within the range normal cooking. Cooking events by the occupants often exceeded the emissions produced by this prescribed cooking.

2.3.2 Modeling

PM concentrations from the cooking event were modeled in select homes by treating each building as a CMFR. The mass balance equation shown in Eq. (1) was solved analytically for the concentration as a function of time, *t*, as shown in Eq. (2).

$$\frac{dC}{dt} = \frac{E}{V} + \lambda C_{OA} - \lambda C - C\frac{A_f}{V}v_d \qquad \textit{Eq. (1)}$$

$$C(t) = C(0)\exp\Big(-\Big(\lambda + \frac{A_f}{V}v_d\Big)t\Big) + \frac{E}{\lambda V + A_f v_d}(1 - \exp\big(-\Big(\lambda + \frac{A_f}{V}v_d\Big)t\big) \qquad \textit{Eq. (2)}$$

C = *Indoor Concentration* ($\mu g/m^3$)
E = *Cooking Emissions* ($\mu g/hr$)
V = *Effective Volume* (m^3)
λ = *Air Exchange Rate* (h^{-1})
C_{OA} = *Outdoor Air Concentration* ($\mu g/m^3$)
A_f = *Floor Area* (m^2)
v_d = *Effective Deposition Velocity* (m/hr)

Area and volumes of the home were determined from the plans or by in-home measurements if plans were not available. The test area and test volume from Table 1 were used. These values do not include any rooms that were closed during the cooking test. PM emissions were modeled as a fixed rate for six minutes. The emission rate was adjusted in the model to match the peak concentration before smooth decay.

The ventilation rate was determined using rates from reports provided by the owner or building's design consultant. These reports were typically the Home Energy Rating System (HERS) or passive house certification report. The deposition rate was then adjusted in the model to match the PM decay curve. It was assumed that particle deposition occurred only on the floor, so the resulting deposition velocity is an effective velocity based on net floor area. Coagulation was assumed to be negligible during this 3-6 hour period after cooking [22].

The tuned models were used to investigate the ventilation rates required to reduce $PM_{2.5}$ concentrations to healthy levels within one hour. The effects of using a dedicated exhaust hood were also explored. Two exhaust hood flow rates were modeled: a low setting of 108 ft^3/min (51 l/s) and a high setting of 171 ft^3/min (81 l/s). These correspond to the rates of the low cost hood tested by Lunden et al. [5]. Capture efficiencies of 75% and 90%, respectively, were used, and are reasonable for rear-burner cooking.

Chapter 3: Results & Discussion

3.1.1 Ventilation

Ventilation flow rates taken from commissioning documents were used to determine the AERs for the overall home. System pressures and losses can vary over time, so these rates were also compared to the rates required by ASHRAE 62.2 and to those determined from carbon dioxide decay profiles in the bedrooms. Overall rates ranged from 0.08 to 0.42 h^{-1} for homes and 0.59 h^{-1} for the library. The median value, determined from balanced rates, was 0.31 h^{-1}, which is within the typical 0.3-0.4 h^{-1} recommendation [9]. These design rates are similar to the 0.30 h^{-1} found by Less, et al. [6], but much lower than the 0.62 h^{-1} found by Langer et al. in Sweden [3]. Since the library is a commercial building, ASHRAE Standard 62.1 was used for comparison. It is important to note that homes with CERV units have systems capable of the AER listed, but because they are typically operated in the automatic mode, the time-averaged rate is likely much lower. CERV units operating in standard mode may have ventilated automatically during the first cooking test. Though in the one home with a CERV that recorded the ventilation times, it was noted that the ventilation did not turn on in response to the large increase in PM. Although data to observe this was only available in one home, it may indicate a “blind spot” in the units’ sensing capabilities, since only CO_2 and VOC sensors are used.

3.1.2 Fine Particulate Matter

The fine particle counts from the optical particle counters were converted to mass concentration to compare to the NAAQS $PM_{2.5}$ 24-hour limit of 35 $\mu g/m^3$ [23]. Several approaches were taken to quantify severity of the impact from cooking, as well as to compare the standard ventilation with the boost or continuous mode.

After the cooking emissions raise the concentration of PM in these tight homes, the rate of decay is a primarily a function of ventilation rate and particle deposition [22]. Filtration is not a factor since only one home, TH102, had a filter in the return line of the CERV unit that would filter particles in the recirculation mode. Incoming particles from the ventilation or from infiltration would slow down the effective decay rate, but the only building that appeared to experience substantial penetration from the outdoors was the public library. High outdoor levels raised the indoor concentrations over time (see Figure B-1 in Appendix).

The total fine particle decay rates after cooking across all homes were estimated and ranged from 0.24 h^{-1} to 1.1 h^{-1} with a median value of 0.47 h^{-1}. These do not include the decay from the first cook test in PH101; one of the air cleaners was accidentally turned on about 30 minutes after cooking and remained on for about 2 hours. The highest decay rate was found in the home with the least tight construction, indicating that exfiltration was an important factor in that case.

For both cooking activities in each home, the $PM_{2.5}$ concentration was averaged for the length time that the ventilator boost mode operated. This corresponded to 20 minutes for continuous HRV and ERVs and 30 minutes for CERV units. A volume-normalized 20-minute average for each cooking test type was calculated for all homes and the 95% confidence interval was found. This interval was applied to each home to determine the variability in cooking emissions. The bars in Figure 1 represent the probable range of each average due to the variability in cooking the eggs.

The high variability in cooking emissions from each test make it difficult to determine the effectiveness of the boost, but the trend suggests that using the temporary boost is ineffective at reducing this initial 20 or 30-minute average. No significant difference ($p<0.05$) was found between the standard and enhanced ventilation modes. Four of the nine homes show a reduction while using the boost, while five show an increase or no decrease. The conventional home showed an 85% decrease while using their direct exhaust hood.

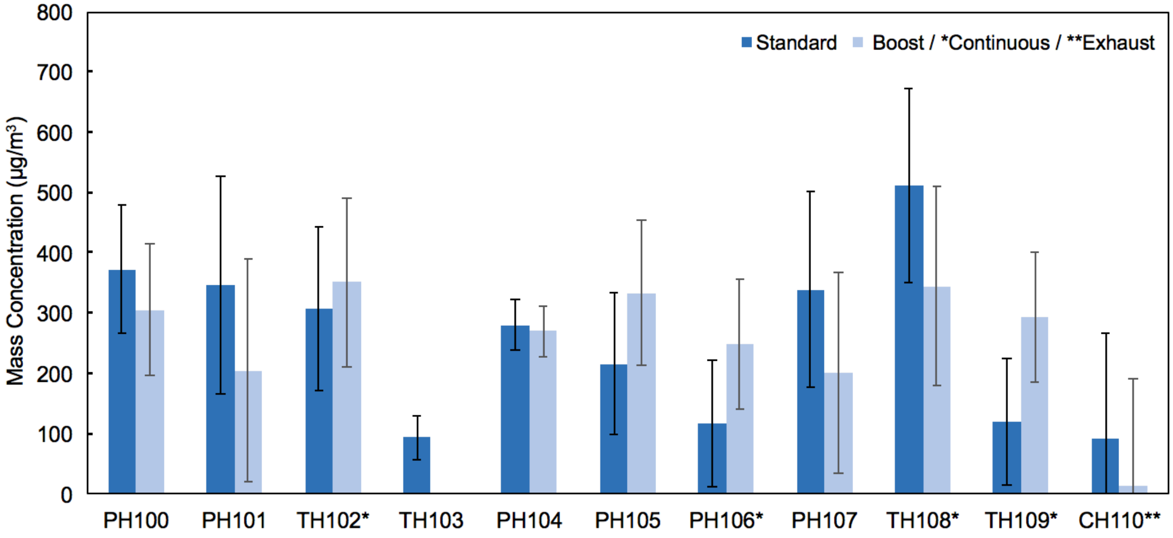

Figure 1. Short-term (20 or 30 minute) $PM_{2.5}$ average concentration after cooking for under each ventilation modes. Boost and Exhaust ventilators ran for 20 minutes, Continuous mode ventilators ran for 30 minutes. Bars represent a 95% confidence interval for concentration averages in each ventilation mode.

Long-term averages in between the prescribed cooking events are shown in Table 3 below. These were converted from particle count to mass concentration using the calibration curve [18] for fresh particles. These long term averages are not from fresh particles and are not always from a known source, so should be used for approximate comparisons only.

Table 3. Long term (3-5 day) $PM_{2.5}$ averages

	PH100	**PH101**	**TH102**	**TH103**	**PH104**	**PH105**	**PH106**	**PH107**	**TH108**	**TH109**	**CH110**
Indoor* (μg/m^3)	2.3	2.8	18.8	16.8	18.3	12.5	3.3	32.6	2.8	7.3	20.1
I/O Ratio**	0.22	0.44	1.36	0.22	0.11	1.01	0.16	2.26	0.12	0.66	3.23

*Indoor average is taken in between repeatable cooking events.
**Outdoor average is calculated from the same corresponding times for determining the indoor/outdoor (I/O) ratio.

In regards to fine PM, the indoor air quality of this group of buildings was reasonably good outside of the prescribed cooking activity. For all but the library (TH103), filtered supply air was sufficient in preventing most outdoor PM from penetrating the indoor space. The increased foot traffic in and out of the building or high winds may explain the increased penetration in the library. Homes with higher I/O ratios experienced increased cooking events, and do not appear to be due to an outdoor source.

The prescribed cooking events tell a different story. None of the passive or tight homes tested had range hoods that exhaust directly to the outdoors and instead relied on ventilator exhaust grilles in the kitchen area to remove the pollutants. This strategy, in general, did not prove to be effective. The particulate emissions from the cooking overwhelmed any exhaust removal and spread to the rest of the house. Concentrations remained high for several hours under both normal ventilation and boost conditions. As shown in Figure 2, one home experienced concentrations above 35 μg/m^3 for nearly 10 hours after cooking. One would hope that residents would notice the diminished air quality and open a window to increase the ventilation rate, but this may not be realistic or feasible. In the winter months, cold temperatures may prevent residents from doing this. If cooking events like this were a regular occurrence, there could be potential health risks from repeated exposure to high $PM_{2.5}$.

The conventional home, CH110, experienced much lower PM concentrations, and this is likely a combination of the higher infiltration rate and also the living room was not adjacent to the kitchen. Though ideally well-mixed, some of the particles may have been diluted or settled as they spread to the living room.

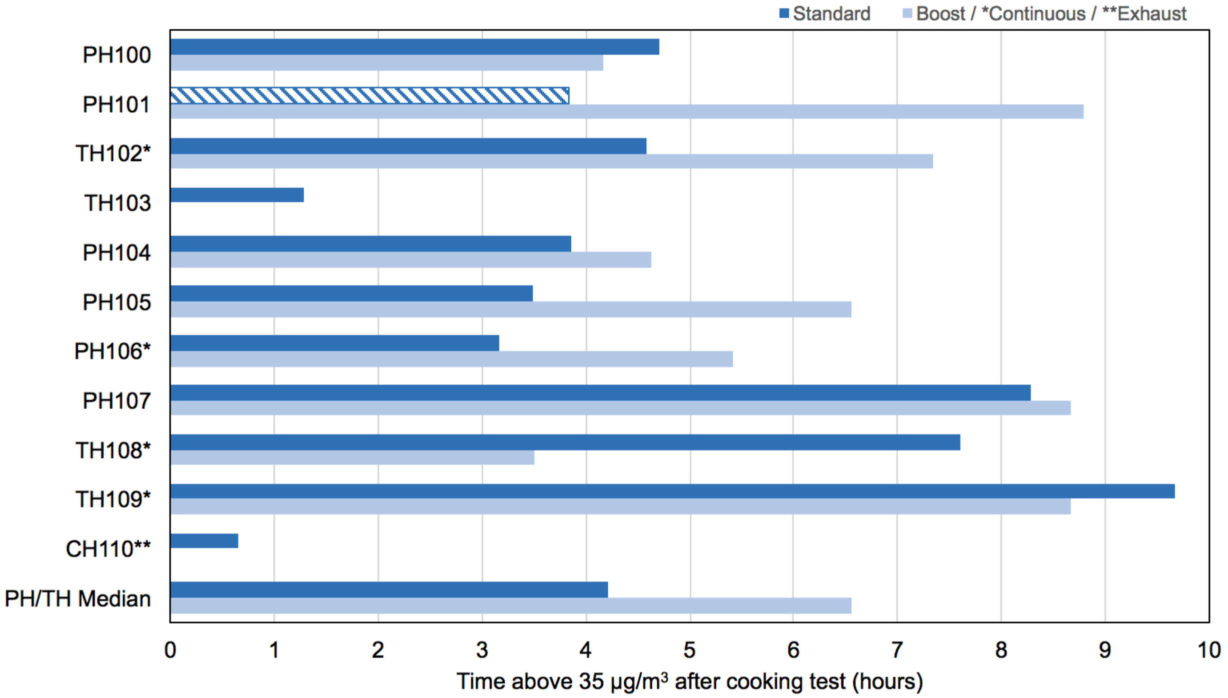

Figure 2. Number of hours each building exceeded NAAQS 24-hr limit after cooking test. Time under standard mode was directly measured. Time under boost/continuous/exhaust is extrapolated after ~ 3 hours. Diagonal-patterned bar reflects an artificially low time when one air cleaner was turned on about 30 minutes after cooking.

Figure 3 shows the results of modeling PH100. The standard condition was tuned to the measured data and shows good agreeability. The boost mode was modeled as currently designed and estimates the concentrations while using the 20-minute boost, and then a one-hour boost. The ventilation rates required to reduce concentrations to 35 µg/m^3 in one hour were calculated and shown as the (ideal) cases. It was found that the ventilation boost would need to provide 2025 ft^3/min (7.84 h^{-1}) if only run for 20 minutes, and 640 ft^3/min (2.44 h^{-1}) if run for the full hour. If the boost, as designed, were left on, the home would still need about three hours to reach 35 µg/m^3. The effects of using an exhaust hood for 20 minutes at low and high flow rates are also shown. The exhaust hood on its high setting would reduce concentrations to 35 µg/m^3 in just under 30 minutes.

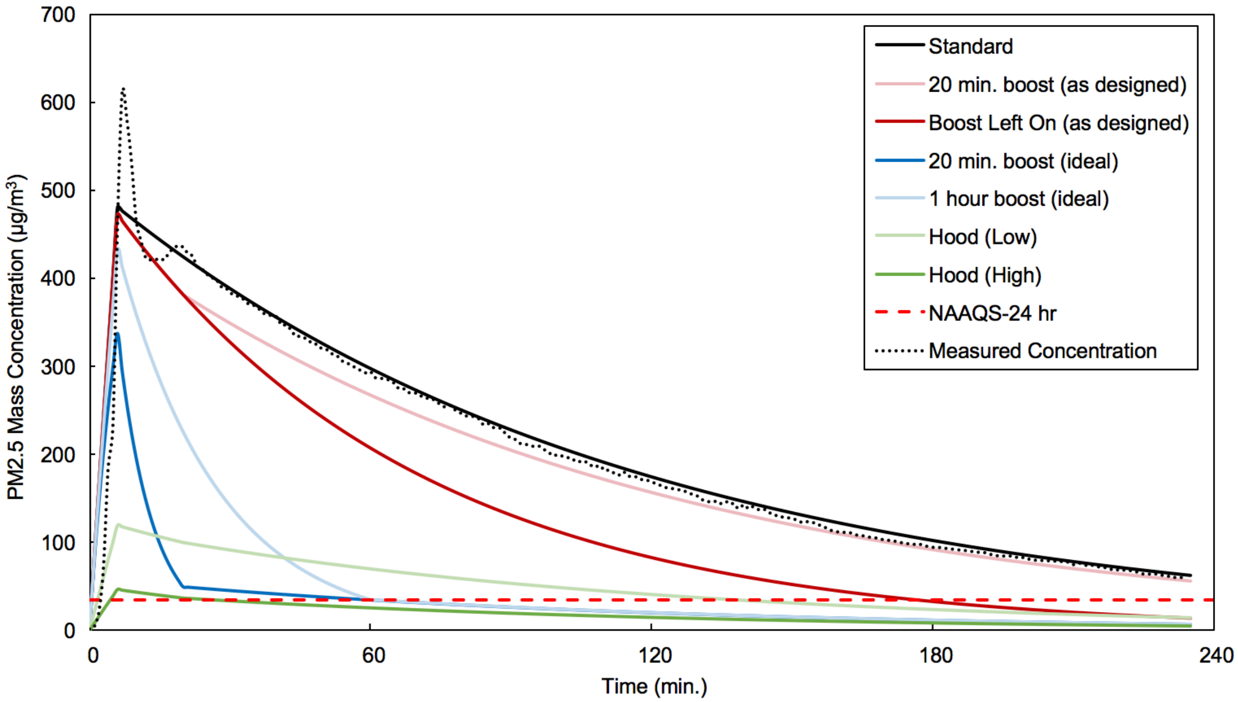

Figure 3. Modeled PM$_{2.5}$ concentrations in PH100 under multiple ventilation conditions

It should be acknowledged that the model has limitations due to the assumptions made. The ventilation rate is assumed to be accurate for the determination of the deposition rate. Many of the homes experience a spike in PM$_{2.5}$ right after the cooking even, but quickly drop. This is attributed to a parcel of highly polluted air that reached the instruments before mixing throughout the house. These spikes were ignored when tuning the model to determine the emission rates. As mentioned in Section 2.3.2, the peak concentration right before the concentration began to decay more smoothly was used. The emission lasting for six minutes is another idealization. Although we removed the egg from the pan, the oil in the pan smoked up to a minute after. By assuming the emission lasts for only six minutes, the calculated emission rate is likely larger than the actual average. The actual emission rate of the eggs was not the focus of the study, rather the impacts of the emissions, so this assumption is not critical.

Another large assumption in the model is that it is completely mixed flow reactor. The mechanical ventilation likely helps to mix the air within the space, but the large size and multiple levels in some of these homes likely reduces the accuracy. Doors that were closed before cooking may have been opened and then closed as residents moved around the house after, so the actual effective mixing volume is somewhere between test volume and the home’s full volume. For these reasons, only select homes where the assumptions were reasonable were modeled.

3.1.3 Total Volatile Organic Compounds (TVOC)

TVOC concentrations can be used as a good indicator of general air quality and for controlling ventilation rates, but there are no guidelines or regulations currently set in the U.S. for concentrations measured with a PID. The reported results were compared to the mass concentration limit for new commercial buildings set by the U.S. Green Building Council (USGBC), which dictates a maximum concentration of 500 µg/m^3 [24]. Converting from a mole fraction to mass concentration, average TVOC levels ranged from 221 to 677 µg/m^3. Only three homes had average concentrations higher than the USGBC limit. The median value for all passive and tight buildings was 459 µg/m^3. This is much higher than the median value of 272 µg/m^3 found in Swedish passive houses by Langer et al. [3].

During a first visit to TH102, numerous items did not go as planned, including an improperly operated hot plate and a malfunctioning TVOC logging software. The TVOC monitor stopped logging after about 18 hours. The home was later revisited to collect data with the fixed equipment and proper protocol. This second visit, however, occurred about 1 week after some remodeling in the home. Finishes and materials used in the remodel appeared to increase the TVOC concentrations during the second visit and is reflected in Figure 4 below (TH102V1 and TH102V2 correspond to Visit #1 and Visit #2). The median and range described in the paragraph above are from Visit #1.

Focusing on individual buildings, it appears that location may be a factor. The three buildings with the smallest range over the measurement period (PH100, TH103, PH104) were located in the least populated locations. These locations also had lower averages, but not exclusively. Average concentrations were found to be independent of building age and ventilation rate, and is likely a result of other factors including occupant behavior and furnishings.

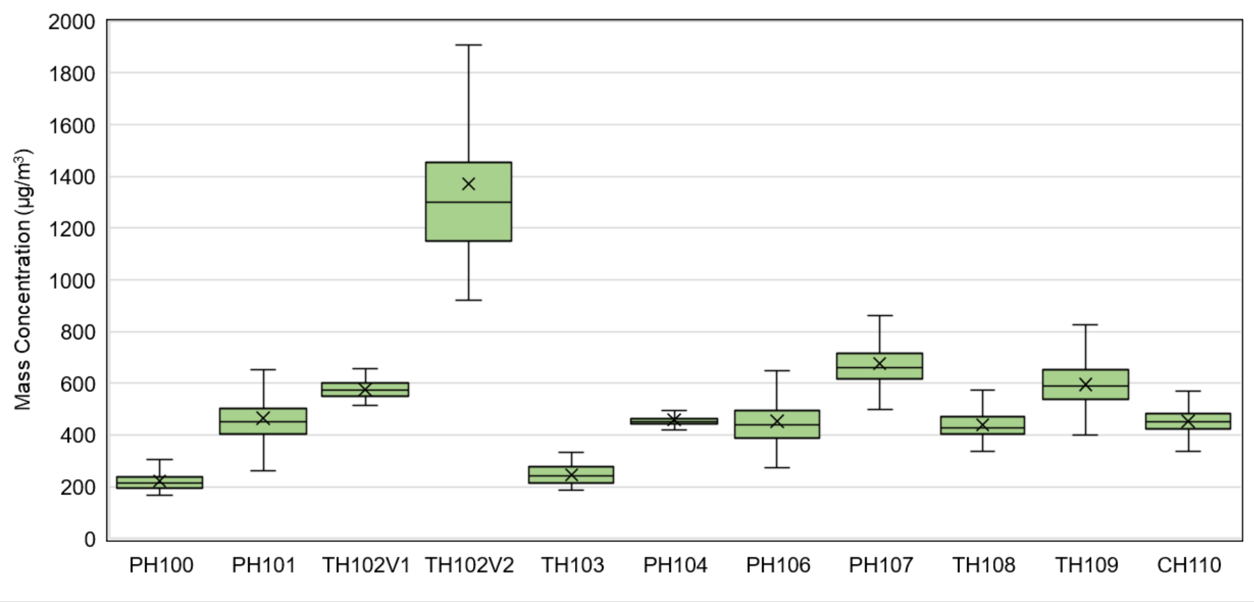

Figure 4. TVOC concentrations in all tested buildings.

3.1.4 Formaldehyde

Formaldehyde concentrations in these homes were generally higher than expected. Results for each building are shown in Figure 5. Values ranged from 14 to 67 μg/m^3. All buildings were above the California Office of Environmental Health Hazard Assessment (OEHHA) chronic limit of 9 μg/m^3. The median concentration of 30 μg/m^3 in the passive and tight buildings (32 μg/m^3 for all) is similar to concentrations found in new California homes by Offermann et al. [25] at 36 μg/m^3. Though passive houses in Sweden [3] and high performance homes in California [6] had lower concentrations with a median of 11.1 μg/m^3, and 20.1 μg/m^3, respectively. Only two homes (TH102 & CH110) were much older than the rest, so there is insufficient data to determine if age was a factor.

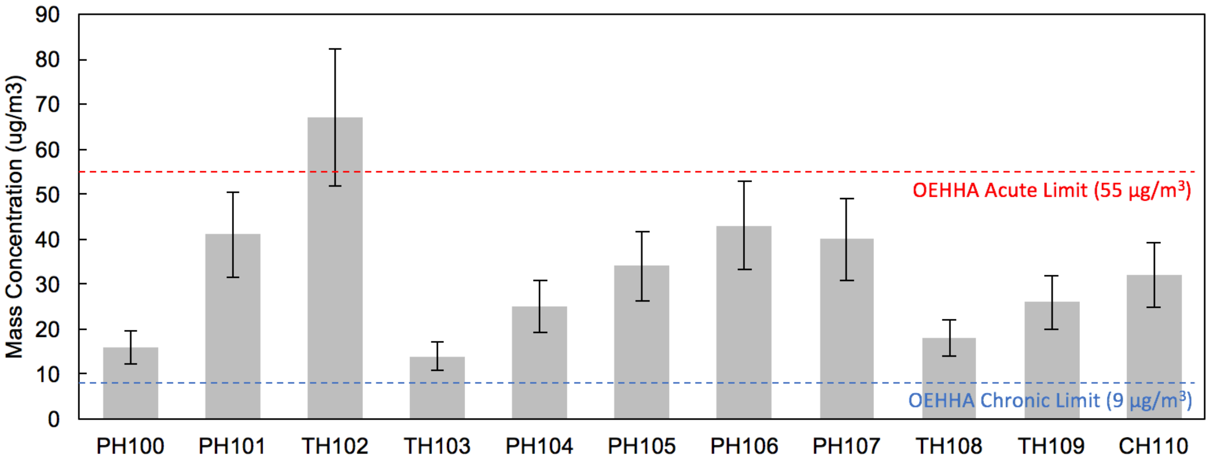

Figure 5. Formaldehyde concentrations in all tested buildings

3.1.5 Radon

Radon in Colorado homes and buildings can reach very high levels. Most counties in Colorado are designated as Zone 1 by the Environmental Protection Agency (EPA). Zone 1 counties have a predicted average radon level exceeding 4 pCi/L. Tight homes are at an additional risk for high radon unless appropriate action is taken [26]. Heat or energy recovery ventilation may be a viable option to reduce concentrations, but is not recommended as the primary method, as systems must be sized appropriately and may fail to due improper installation or maintenance [26].

Our results vary from home to home likely due to the location. Most buildings tested did not have a radon mitigation system (n=7). Of those that did, two were active (fan-powered) and two were passive (pipe running from soil to atmosphere). Table 4 below shows the radon concentrations measured in each home.

*Table 4. Average radon levels in each building**

	PH100	**PH101**	**TH102**	**TH103**	**PH104**	**PH105**	**PH106**	**PH107**	**TH108**	**TH109**	**CH110**
Avg. Radon (pCi/L)	2.7	0.9	**13.6**	1.1	**6.6**	0.4	**17.4**	**16.3**	0.9	2.2	0.5
Mitigation	P	N	N	N	N	A	N	N	N	N	A
Base-ment	N	N	P/F	N	F	U	F	F	F	N	F

*Bold indicates levels are above the EPA recommended level.
Mitigation Types: N = None; P = Passive; A = Active
Basement Types: N = None; F = Finished; U = Unfinished; P = Partially below grade

All buildings without a basement had levels under the actionable limit, whether or not a mitigation system was installed. All buildings with a mitigation system were under this level as well. Only four homes exceeded the actionable limit and these all had basements, though one was only below grade on one side of the home. One building (TH108) with a basement and without mitigation did not have high levels. Though this home is less airtight than most of the others, the difference is most likely due to its location; TH109 is very closely located and experienced higher levels even though its ACH50 value is double that of TH108. All homes that tested above the EPA action level were told that radon mitigation was recommended.

3.1.6 Carbon dioxide

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommends a concentration 1000 ppm as guideline for occupant comfort, though this is not a required limit in either Std 62.1 or Std. 62.2 [27,28]. Based on this comfort guideline, bedroom CO_2 was elevated in over half of the homes (n=7). Of the homes that experienced this issue, only two experienced it less than one-third of the total test period (three to five days). Figure 6 shows the time fraction that the bedrooms were above this limit. Unexpectedly, the two homes with the highest bedroom AERs experienced elevated CO_2 for more than 30% of the time.

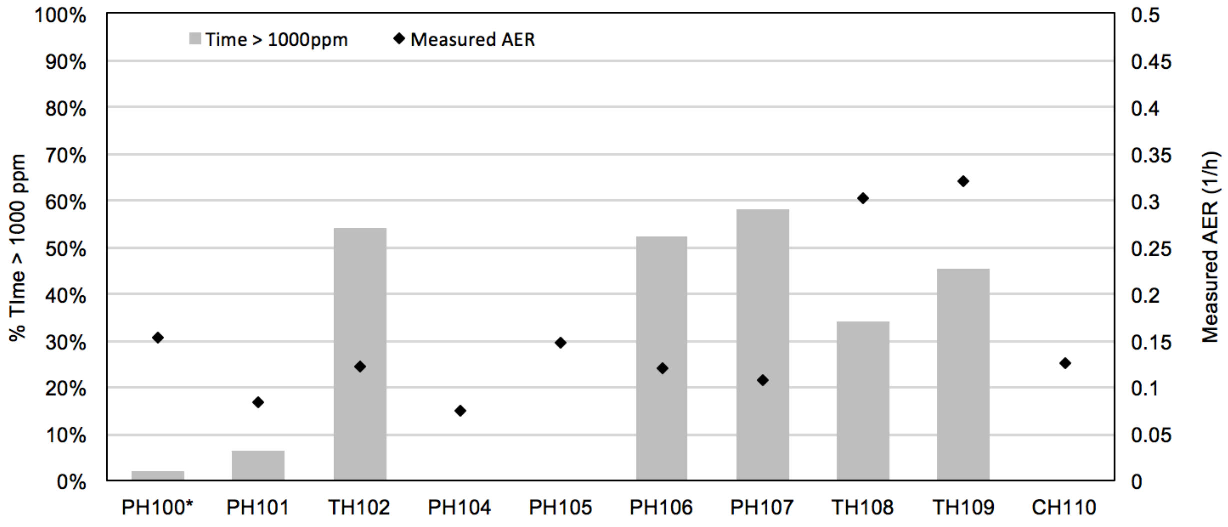

*Figure 6. Time fraction that bedrooms spent above the ASHRAE comfort guideline. *During the final testing period, PH100 was not occupied at night, so CO_2 data from a previous test in November 2016 is shown.*

The CO_2 concentrations in the bedrooms of these homes are slightly higher than those found in the Swedish passive houses. 60% of the Swedish passive houses exceeded 1000 ppm, though typically less than 10% of the time [3]. Likewise, 60% of the passive and tight homes here exceeded 1000 ppm. Though those that did experienced the elevated concentration with median of 49% of the time. Scottish passive houses also experienced high levels, though not as severe. Two of the five homes tested exceeded 1000 ppm over 25% of the year [8].

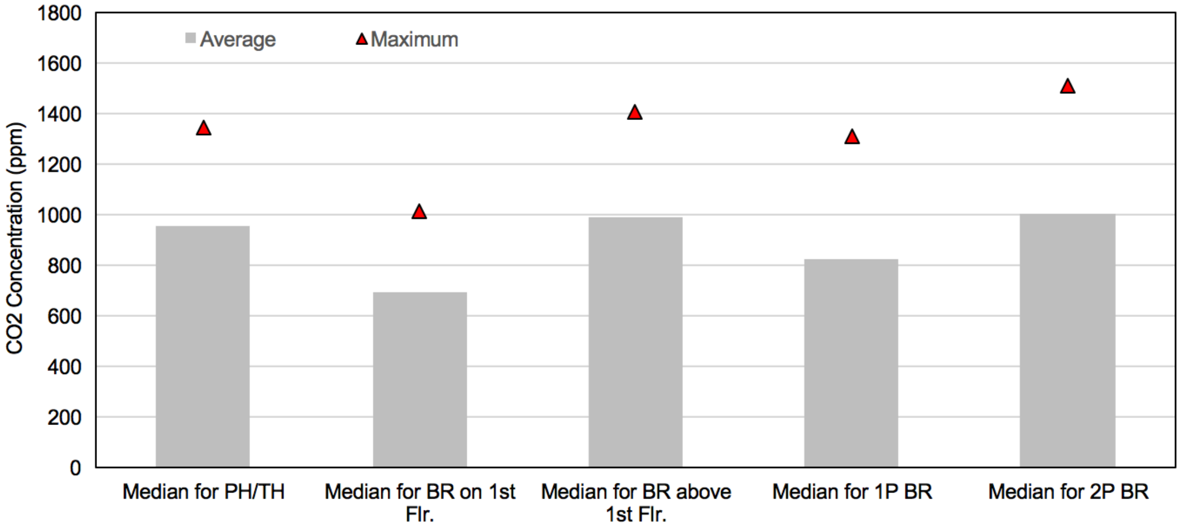

Figure 7. Median CO_2 concentrations for homes with various properties: all passive and tight homes, bedrooms on 1st floor, bedrooms above 1st floor, one-person bedrooms, and two-person bedrooms

As shown in Figure 7, homes with bedrooms above the first floor had average and peak concentrations higher than those with bedrooms on the first floor. Thermal stratification was initially thought to be a contributing factor, but temperatures between the floors in these homes were approximately the same. Unsurprisingly, bedrooms with two people experienced higher concentrations than those with one, indicating that ventilation rates are not always adjusted for the increased occupancy.

Chapter 4: Conclusions

The passive house concept can be an effective design approach to reduce energy use and improve thermal comfort, but it should not be assumed that this type of building has inherently good indoor air quality. These severe, but not atypical, cooking events drastically reduced the indoor air quality for many hours, and the temporary boost mode that many of the mechanical ventilators feature was ineffective at reducing PM emissions from the cooking activities. The conventional home that featured a dedicated exhaust hood experienced lower $PM_{2.5}$ concentrations that did not exceed 35 $\mu g/m^3$ when used. However, this home also reached much lower concentrations under standard ventilation conditions. Outside of the cooking tests, the fine particle concentrations were reasonably low and were mostly affected by indoor activities rather than outdoor levels. TVOC concentrations were generally acceptable. Only three buildings, on average, exceeded the USGBC limit for new construction. One home had excessively high levels due to a recent remodel. Formaldehyde concentrations were above the OEHHA chronic limit in all homes, but levels were similar to new California homes [25]. Radon varied by location and four of the homes exceeded the EPA actionable limit. It is important to note that radon testing is critical and even very tight homes are not immune to this issue in areas where soil concentration is high. At least two of those homes have since installed active mitigation systems. Carbon dioxide levels exceeded the ASHRAE recommended comfort limit in seven of the ten homes. In general, the indoor air quality of these homes is acceptable, but increased bedroom ventilation is important to consider, and a directly exhausting range hood is highly recommended for frequent cookers, as these hoods are very effective at reducing fine particulate matter concentrations.

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Appendices

Appendix A: PM$_{2.5}$ concentrations after cooking

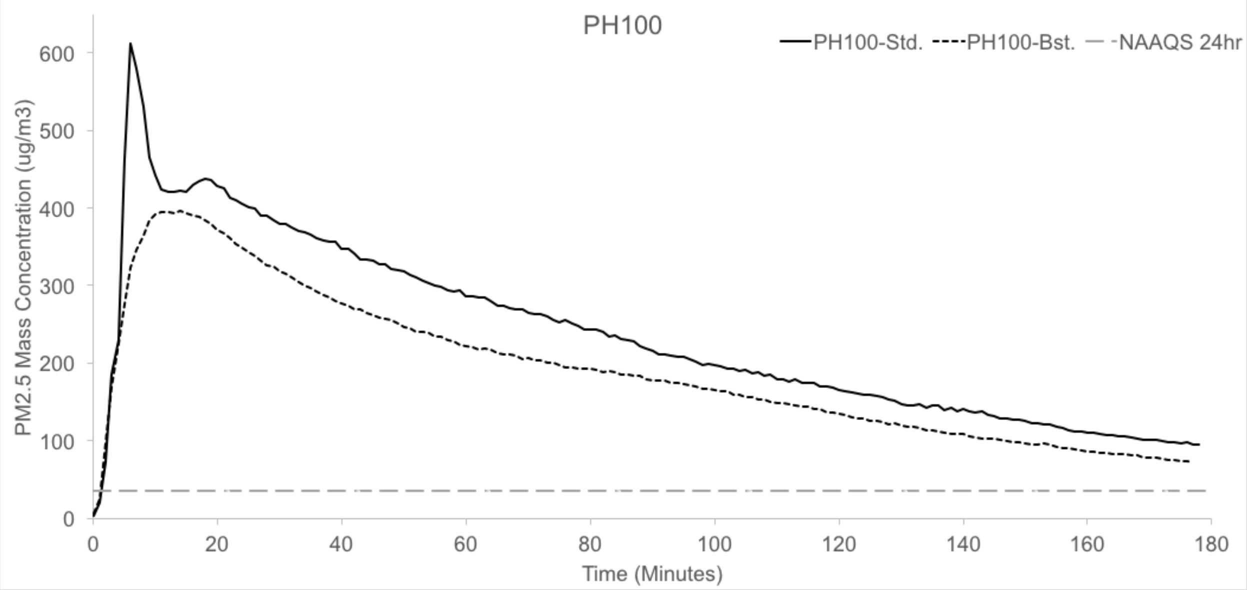

Figure A-1. PH100 PM$_{2.5}$ concentrations after cooking in both ventilation modes

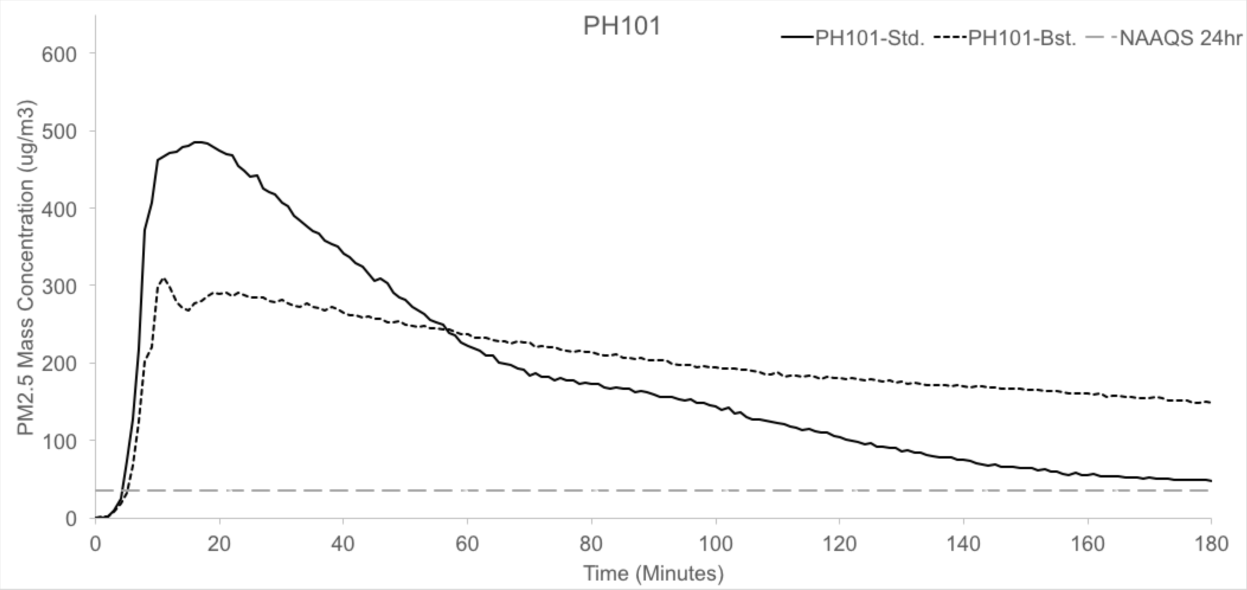

Figure A-2. PH101 PM$_{2.5}$ concentrations after cooking in both ventilation modes

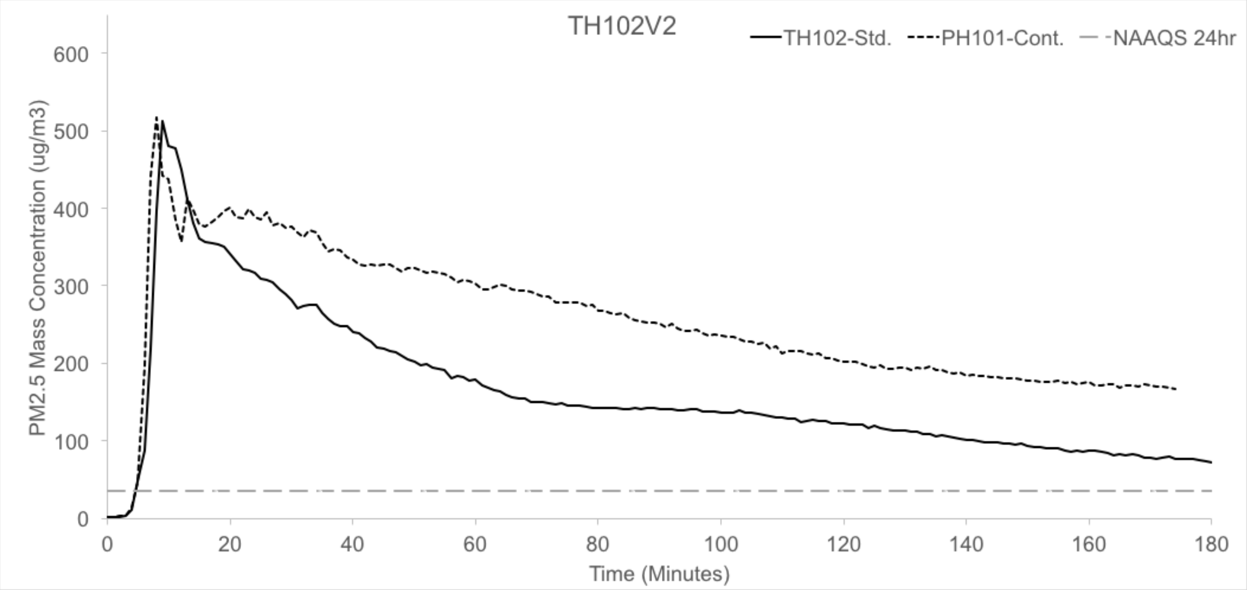

Figure A-3. TH102 $PM_{2.5}$ concentrations after cooking in both ventilation modes

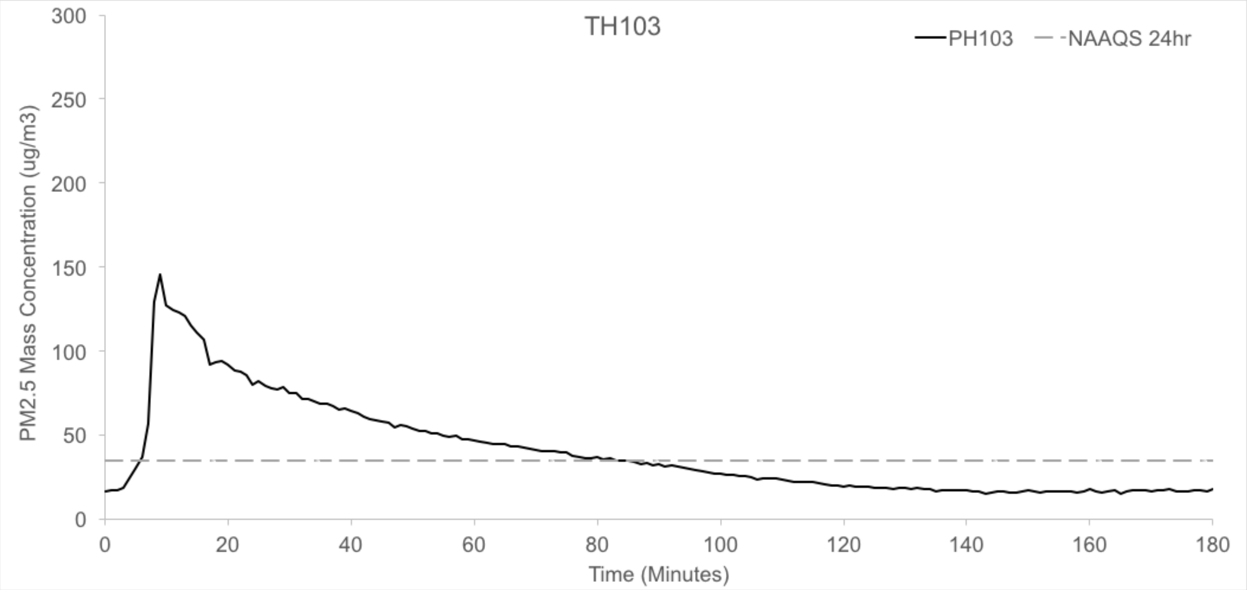

Figure A-4. TH103 $PM_{2.5}$ concentrations after cooking

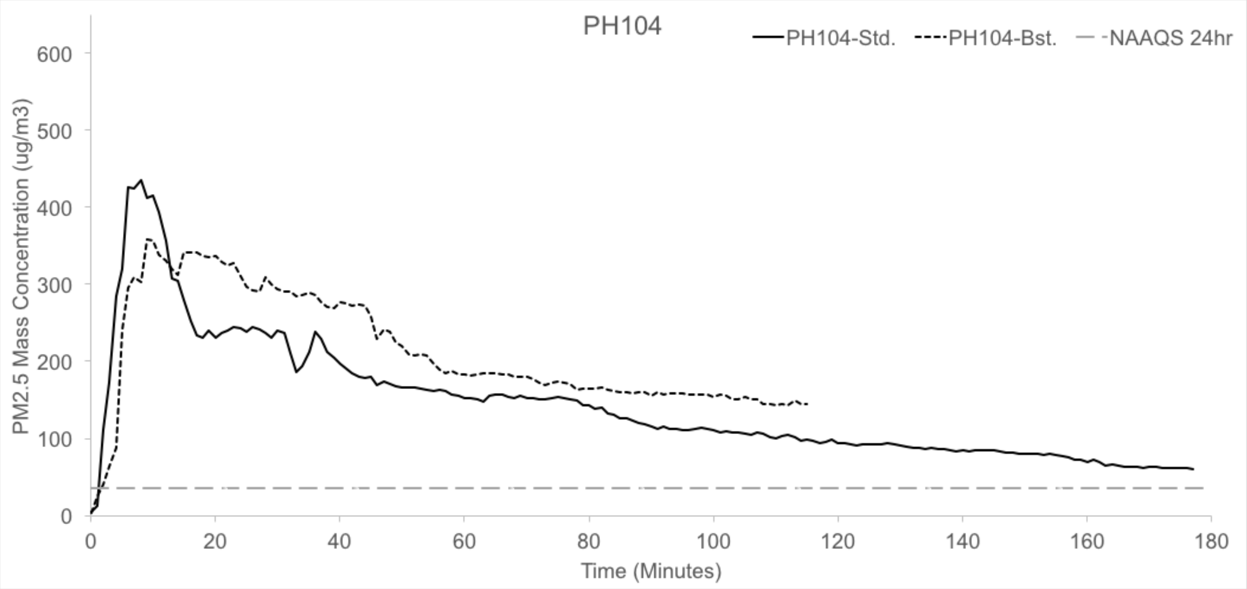

Figure A-5. PH104 PM$_{2.5}$ concentrations after cooking in both ventilation modes

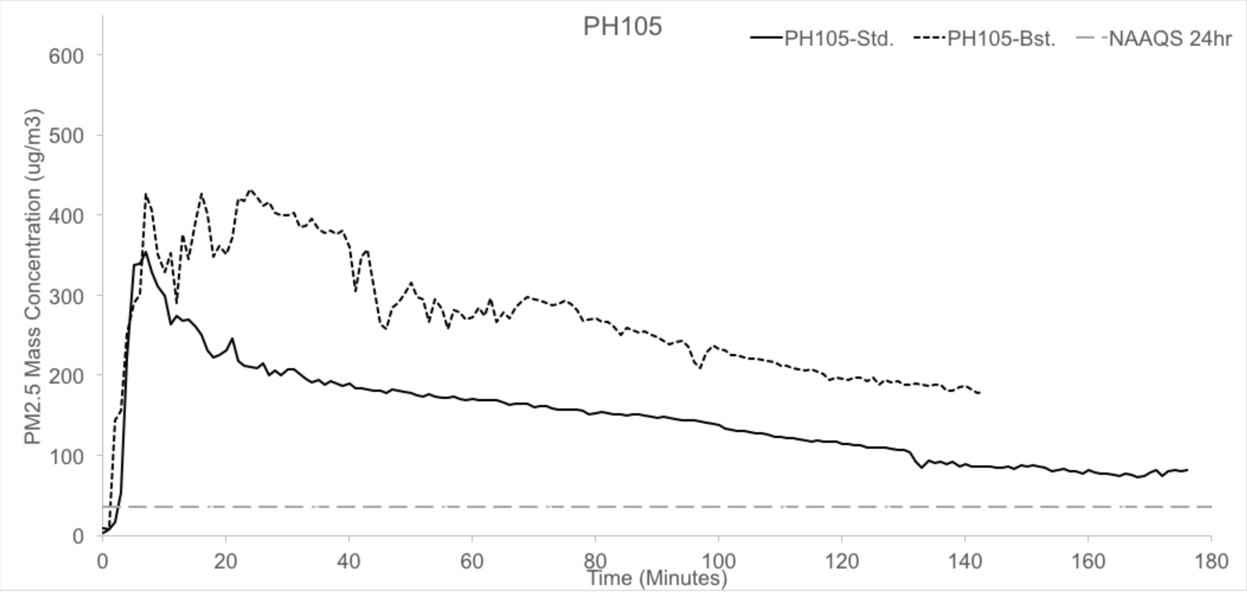

Figure A-6. PH105 PM$_{2.5}$ concentrations after cooking in both ventilation modes

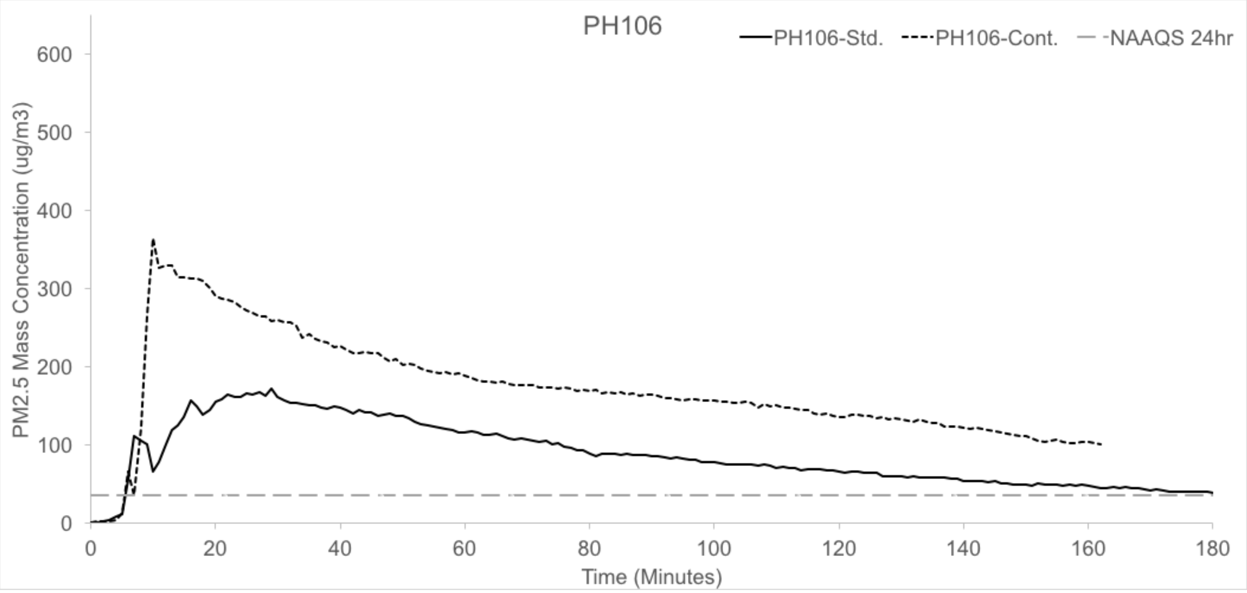

Figure A-7. PH106 $PM_{2.5}$ concentrations after cooking in both ventilation modes

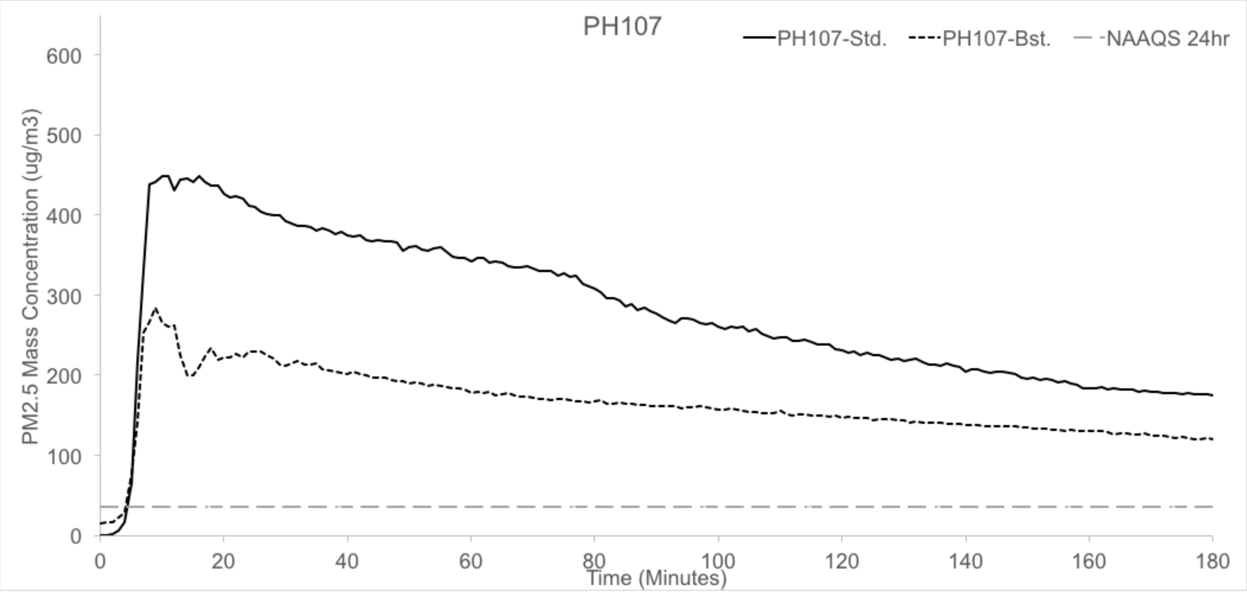

Figure A-8. PH107 $PM_{2.5}$ concentrations after cooking in both ventilation modes

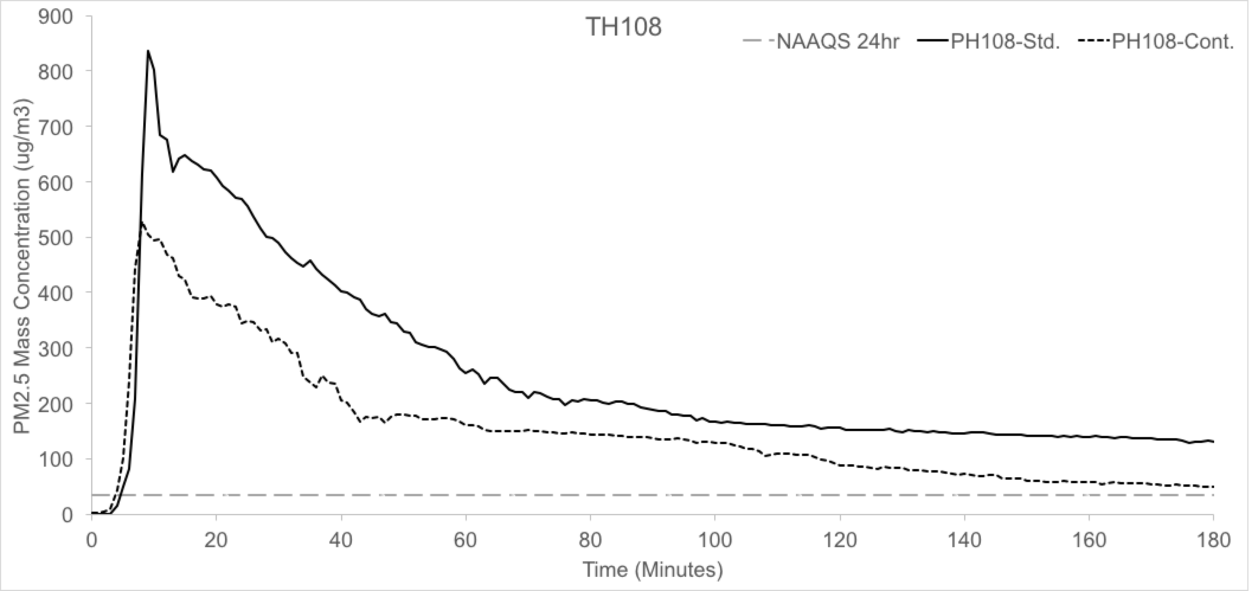

Figure A-9. TH107 $PM_{2.5}$ concentrations after cooking in both ventilation modes

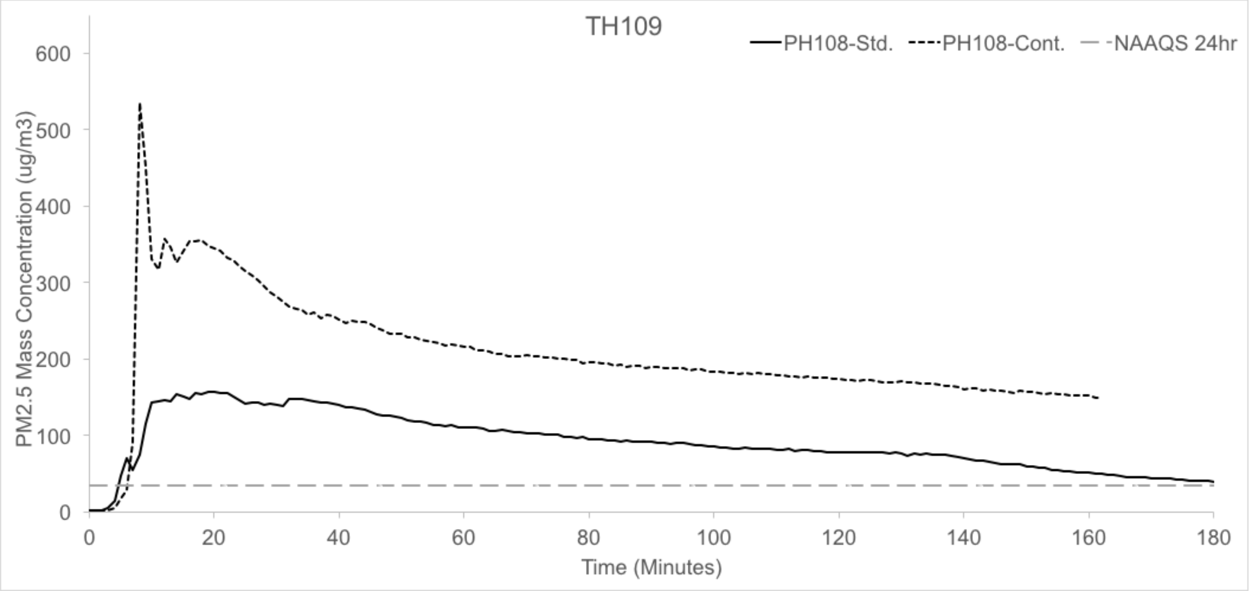

Figure A-10. TH109 $PM_{2.5}$ concentrations after cooking in both ventilation modes

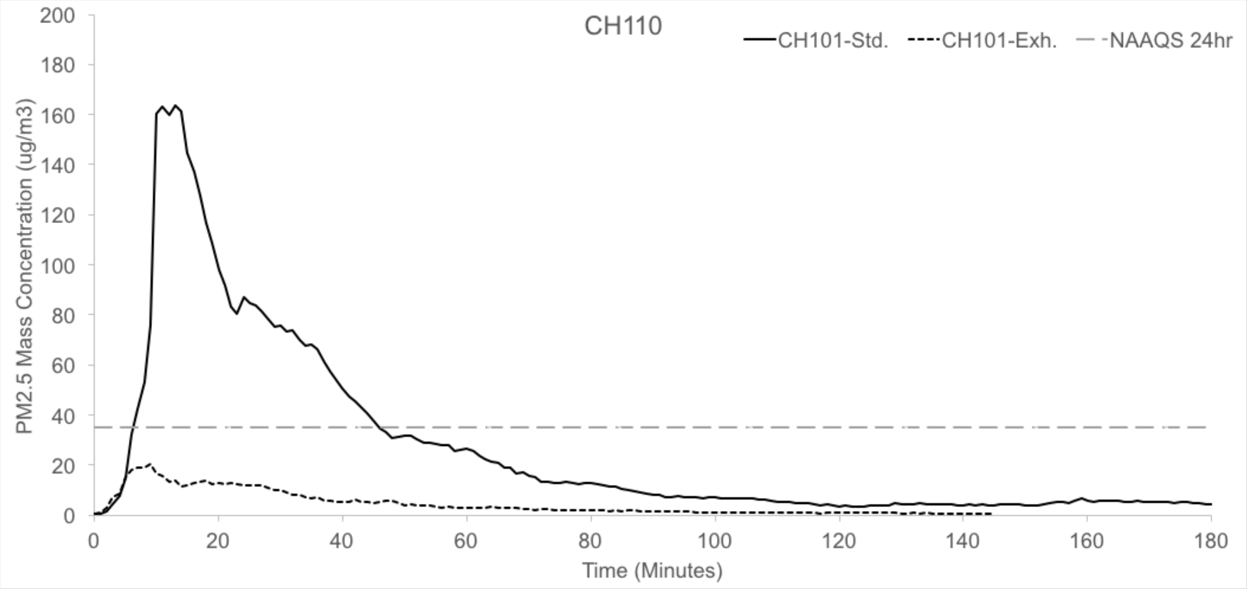

Figure A-11. CH110 $PM_{2.5}$ concentrations after cooking in both ventilation modes

Appendix B: Appendix B: Select Indoor and Outdoor Fine Particle Counts (PN>0.5μm - PN>2.5μm)

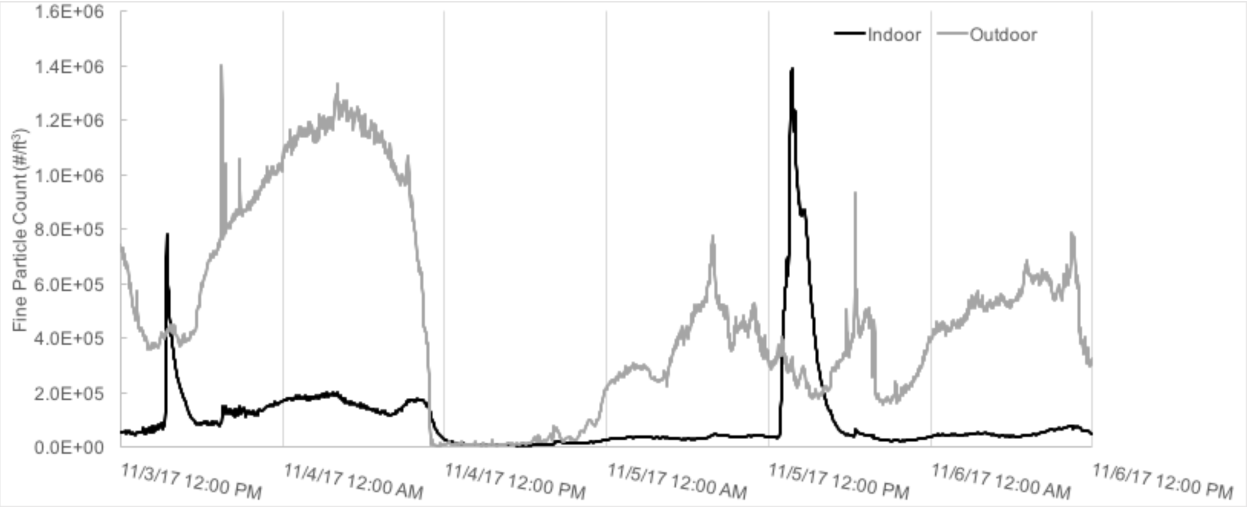

Figure B-1. Indoor and outdoor fine particle counts for TH103. Note the rise in indoor concentrations when outdoor concentrations are high.

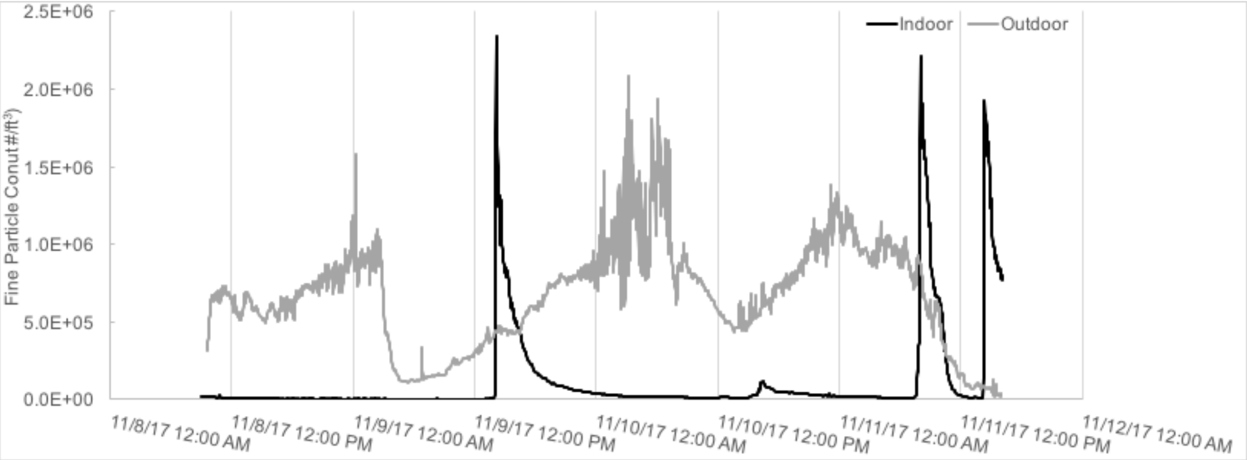

Figure B-2. Indoor and outdoor fine particle counts for PH104. Note that indoor concentrations appear to be independent of outdoor concentrations.

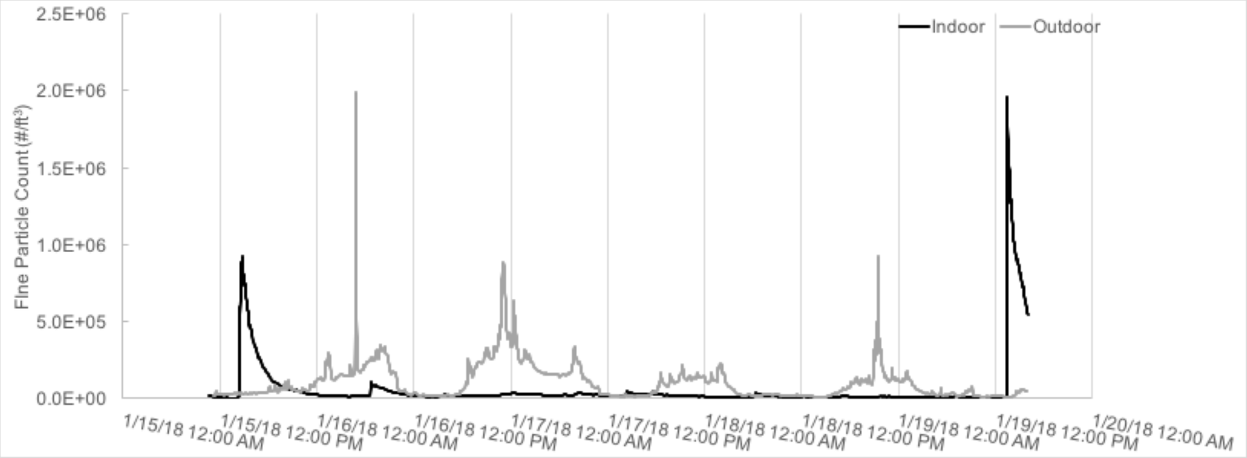

Figure B-3. Indoor and outdoor fine particle counts for PH106. Note that indoor concentrations appear to be independent of outdoor concentrations