Contribution of Liquid Fuel-Fired Heating Equipment on Indoor Particulate Pollution

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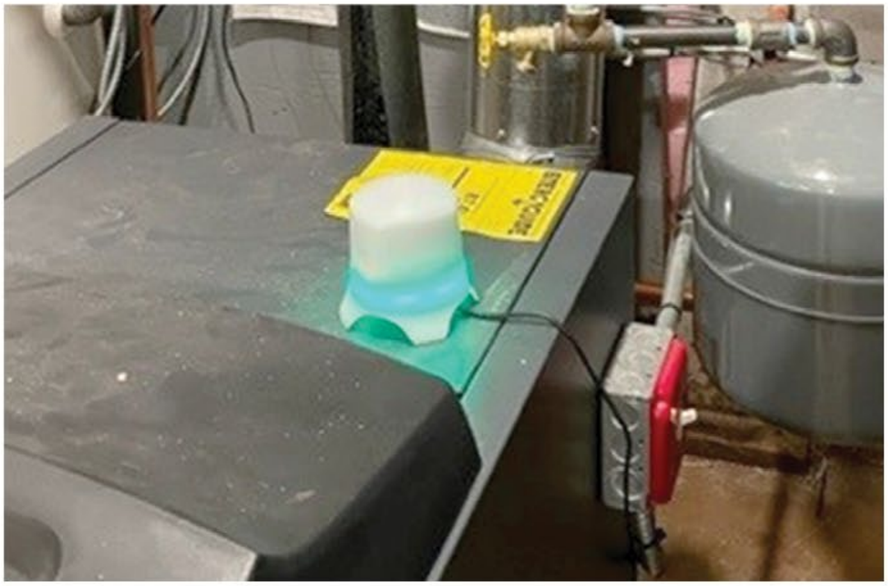

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Abstract

Indoor particulate air pollution is a significant public health concern, and fuel-fired heating equipment has been identified as a potential contributor. This study focused specifically on liquid fuel-fired heating systems and whether they meaningfully contribute to indoor particulate matter (PM), particularly through flue barometric dampers that could release particulates during normal burner cycling.

Low-cost PM sensors were installed in eight homes, positioned near the heating appliance as well as in other key locations such as kitchens, near fireplaces, and outdoors. The primary objective was to assess the relative contribution of the liquid fuel-fired heater compared to other common PM sources.

The findings showed that indoor particulate levels were strongly influenced by cooking activities (especially frying), indoor wood combustion, and elevated outdoor PM events. In contrast, liquid fuel-fired heating systems were not identified as a significant source of indoor particulate matter.

Acknowledgements

The authors would like to thank Michael Persch, former mechanical engineering intern at NORA, who was immensely helpful in assembling the monitoring devices key to the study and analyzing the data. We would also like to thank the homeowners for participating in and accommodating their homes for this study, as well as for keeping detailed logs of their activities that provided us with added insight into the data.

Introduction

Fine particulate matter (PM) is known to have human health and environmental impacts (U.S. Environmental Protection Agency n.d., Pope 2009, Seals and Krasner 2020, Schwartz, Dockery and Neas 2012). A range of PM sources of indoor origin contribute specifically to indoor air quality including smoking, cooking, and heating (U.S. Environmental Protection Agency n.d., Li, Wen and Zhang 2017, Nassikas, et al. 2022). Outdoor sources and infiltration also significantly impact indoor air quality (San Jose and Perez-Camanyo 2023). An estimated 5 million homes and smaller commercial buildings in the U.S. use liquid fuels for heating. The focus of this study was in improving understanding of the potential of these systems to contribute to indoor emissions and their relative importance compared to cooking and wood use.

Chimney venting is most commonly used with liquid-fuel heating systems although direct and side-wall vent systems are also available. With chimney vent systems a barometric damper is used to avoid excessive draft levels in the vent which can cause changes in burner air/fuel ratio and potentially lead to flame instability. Flue gas flow out of these dampers and into the living space, particularly during startup and cold chimney conditions could be a source of PM (Fugler 1989). Figure 1 provides an illustration of a barometric damper. These devices close when the flue pressure exceeds the pressure in the surrounding room although these are designed to have a small open area even when fully closed.

In this study, low-cost ambient PM sensors were installed in 8 homes with liquid-fuel heating. The sensors were located close to the heating system barometric damper and in other home locations. The objective of this work was to collect data on PM concentrations near the liquid fuel heating source relative to other common home sources.

Figure 1: Example of a barometric damper commonly used to control draft in liquid-fuel fired boilers and furnaces. Source: Field Controls, used with permission.

Low-cost ambient air particulate matter (PM) measurement devices have become very popular as tools to evaluate regional impacts of air quality events such as wildfires, track air quality trends in municipalities, and evaluate indoor air quality (Higgins, Kumar and Morawska 2024). Over the past several years, vast improvements in sensor and wireless technologies have allowed for more widespread recording and sharing of air quality data and essentially real-time, which has provided a massive paradigm shift as compared to traditional instruments for air quality measurement that are higher-cost and stationary (Snyder, et al. 2013). In this study, one family of these low-cost devices, PurpleAir products, were used. In most of this work the PurpleAir Flex model was used although in a few cases the PurpleAir Zen model was used. These devices use dual laser-based particle counters from Plantower (Model PMS S6003). From the manufacturer's data, these can measure particles larger than 0.3 microns. Particle counting efficiency is reported to be 50% at 0.3 microns and 98% at > 0.5 microns [https://www2.purpleair.com/products/purpleair-flex]. Each of the two Plantower sensors includes a fan which draws air through the measurement chamber at 0.1 L/min. The measurement principle is 90-degree laser scattering (Sayahi, Butterfield and Kelly 2018). The PurpleAir devices store all data locally on an SD card and can also upload data via Wi-Fi to a popular on-line map application. The data provided by the PurpleAir sensor is in the form of particulates smaller than 1, 2.5, and 10 microns (PM_1, $PM_{2.5}$, PM_{10}) in units of $\mu g/m^3$. The output data also includes a count-based measure of particles in 5 size divisions.

Considerable effort has been put into the correlation of PurpleAir reported PM mass concentrations and those measured with true mass-based filter sampling systems. Correction factors have been developed for specific environments and locations. In a recent study, the U.S. EPA has reviewed these correction factors and developed a United States-wide correction factor which includes the effects of local relative humidity (Barkjohn, Gantt and Clements 2021).

The PurpleAir units can be installed to perform standalone, offline measurements or connected to the internet to view the $PM_{2.5}$ concentration at its location on a worldwide map of increasingly expanding network of other such connected devices. For this study, only offline measurements were performed for houses primarily with a liquid-fuel-fired heating appliance. Several sites with such a system were selected as part of the study, some of which also utilized alternative heating methods such as wood stoves or fireplaces. Also analyzed for the sites were the PM emissions from other activities such as cooking.

Paulin et al. used Purple Air monitors in a recent study as part of an evaluation of the impact of heating fuel type on indoor air quality in New England, although separation of the heating system from other sources of particulate matter was not done (Paulin, et al. 2025).

Methods

Sites for this study were chosen and distinguished with a few considered criteria. Firstly, every site except one utilizes a liquid fuel fired appliance for heating. The mode of heating, hydronic or forced air, was not a considered factor. Some sites were specifically chosen because the homeowners also utilized a secondary heating system, either in the form of a wood stove or a fireplace. This enabled a direct comparison of the effects of these systems on indoor air quality. Once a site was selected, a plan was formed for installing the sensors. For the sites that were located near the NORA laboratory in Plainview, NY, a member of the NORA team installed the sensors. For the others, a package of sensors along with instructions on how to install them was mailed to each of the homeowners.

Table 1 shows the site location, sensor locations for all eight selected sites and number of days that data was recorded. It must be noted that partial data, as opposed to a full day of data, was recorded on the first and last days of data collection for all sites. Five of the eight chosen sites were in New York State. Out of the eight, seven sites were specifically chosen because they were primarily heated using a liquid-fuel-fired appliance. Of those, four sites – 1, 5, 6 and 8 – were equipped with a temperature sensor in the flue pipe of the liquid-fuel-fired appliance to capture information on when the heating system was operating. Site 3 was chosen to only record data in the kitchen area when the homeowners planned to cook on multiple occasions. All these sources used blends of fossil heating oil and biodiesel ranging from 5% to 100% biodiesel.

Table 1: Location, Sensor Placement Location, and Number of Data Collection Days for all Sites

Site #	Site Location	Sensor Locations	Days of Data Collection
1	Stony Brook, NY	Boiler room, Outside	63
2	Ridge, NY	Boiler room, Den, Kitchen, Outside	14
3	Port Jefferson, NY	Kitchen	6
4	Lebanon, NJ	Boiler room, Den, Outside	5
5	Northborough, MA	Furnace room, Kitchen, Outside	10
6	Muttontown, NY	Boiler room, Kitchen, Outside	10
7	North Andover, MA	Boiler room, Den, Outside	14
8	Mount Sinai, NY	Boiler room, Kitchen, Outside	10
9	Cherry Creek, NY	Den	28

Two different models of PurpleAir sensors were used for this study – the Purple Air Flex Air Quality Monitor and the PurpleAir Zen Air Quality Monitor. Both have the same measurement method. The monitor manufacturer recommends having some spacing between the bottom of the sensor and the surface on which it is placed to provide proper airflow for the device to perform measurements. This is made easier by a base stand that the Zen sensor is packaged with. The Flex model, however, must be placed on a support to facilitate the spacing since it is not equipped with a base stand. Some of the sites were provided with a temperature measurement sensor for measuring the flue gas temperature of their liquid-fuel-fired appliance. Attached to this sensor was a Thermoworks TC101A temperature logger for recording the temperatures. The temperature data provided the ability to determine when the burner in a liquid-fuel-fired appliance was operating.

For sites that received PurpleAir Zen sensors, the package of sensors also included the mounting stand pre-installed. For the sites that received PurpleAir Flex sensors, mounting brackets and zip ties were provided to secure these sensors. Figure 2 and Figure 3 show examples of PurpleAir sensors after installation in the field.

Figure 2: PurpleAir Zen sensor mounted on base stand on top of the boiler in Site 6 (left) and PurpleAir Flex sensor secured to a pole using zip ties and a mounting bracket outdoor in Site 1 (right)

Figure 3: A PurpleAir Zen sensor installed in the den area in Site 7

Data collection for the sites was performed between December 2022 and August 2023. The collection period varied between five and 63 days depending on the site, as noted in Table 1. Each PM sensor contained a preinstalled SD card for storing data. Once a group of sensors was returned from a site after data collection was performed, the data was combined, processed, and plotted using data processing software. During the processing of the $PM_{2.5}$ data, a correction factor depending only on the ambient relative humidity (referred to as EPA CF for the remainder of this report) developed by the US Environmental Protection Agency was utilized to account for errors in the measurement made by the PurpleAir sensors (Barkjohn, Gantt and Clements 2021). The validity of this correction factor has been examined in a study by comparing data from these sensors from various PM-generating events corrected using the EPA CF against readings from local regulatory PM2.5 monitors (Jaffe, et al. 2023). This study found the correction factors to be effective for the type and magnitude of PM generation observed in this study. Therefore, all $PM_{2.5}$ data presented in the remainder of this study has been corrected using the US EPA method. An important point of note is that some PurpleAir units deployed in the field, one of the two internal sensors recorded single elevated points of $PM_{2.5}$. All such data points of this type have been regarded as erroneous and are not presented in the data. Furthermore, data from Site 9 could not be corrected using the EPA correction factor because the relative humidity data was not available. PM data from Site 8 was initially found to be incomplete because of power loss to the outside sensor. All sensors were then returned to the homeowner, and another set of data was collected. Outside sensor data from Sites 4 and 5 were also affected because of power loss during the testing period, but the sensors were not returned to these sites for more data collection. The temperature loggers have internal storage capabilities, which can be downloaded using the Thermoworks LogMaster4 software. Following the download of temperature data, for sites where such a sensor was installed, a data processing software was used for analysis. A detailed analysis of the data from all nine sites is provided in the Results and Discussion section.

Results and Discussion

Site 1

This is the first site where sensors were installed, and the site with the longest period of data collection. A total of two PurpleAir sensors were installed for Site 1, one indoor and one outdoor. The indoor sensor was placed in the boiler room, approximately 8 feet away from the boiler flue pipe. The boiler room is located in the basement of this site. The outdoor sensor was installed on the back deck of the home, a few feet away from a gas-fired grill. Site 1 was also equipped with a flue temperature sensor and logger. The combined and corrected data from the two PurpleAir sensors over the entire data collection period is shown in Figure 4.

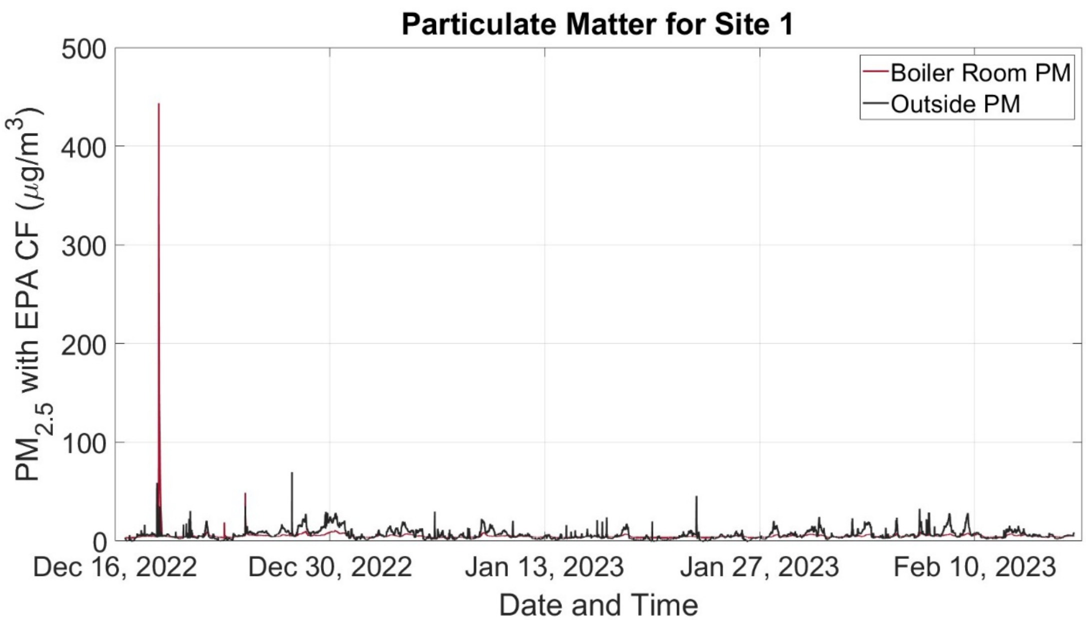

Figure 4: $PM_{2.5}$ data from boiler room and outside locations during the entire collection period for Site 1

Figure 4 indicates there are numerous local increases in PM for both the inside and outside sensors in Site 1 throughout the data collection period. However, one such increase in the PM for the inside sensors skews the remainder of the data. During this period, the $PM_{2.5}$ concentration rises close to 450 $\mu g/m^3$. The homeowner stated that he was soldering metal piping during that time. A closer look at the flue gas temperature at that time can verify if the burner was firing and, hence, releasing flue gases. This is shown in Figure 5, which is a plot of the boiler room PM and flue gas temperature data in a 24-hour time period during which the soldering was performed. For figures containing flue gas temperature data, any sudden rise in that parameter above 200°F can be assumed as a time when the burner is operating. In this figure, it is seen that the burner only fired ~4 hours before and ~13 hours after the soldering event, but not at any time in between.

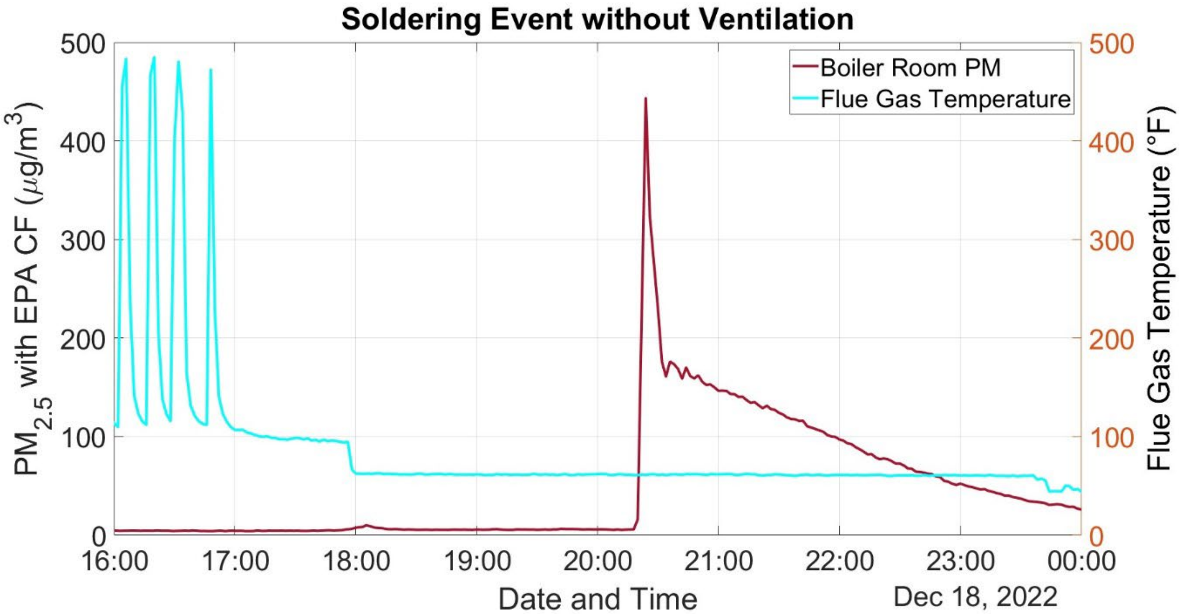

Figure 5: Boiler room $PM_{2.5}$ and flue gas temperature data in a 24-hour period where a high rise in PM is observed.

Filtering out the PM data from the soldering event allows visualization of local peaks in PM for both boiler room and outside data. This is shown in Figure 6.

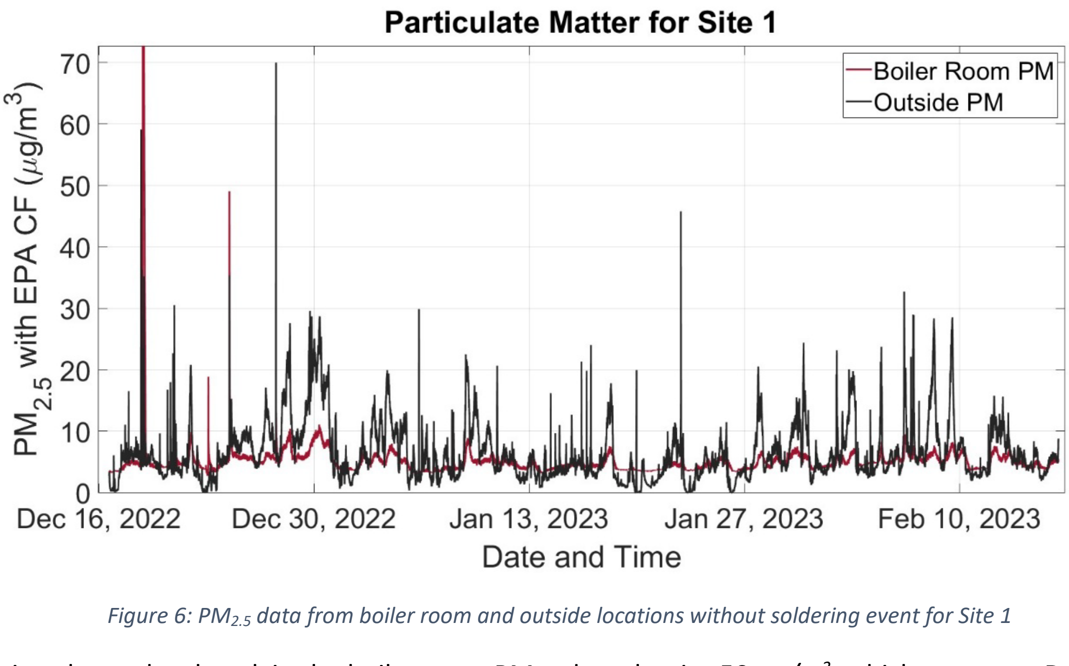

Figure 6: $PM_{2.5}$ data from boiler room and outside locations without soldering event for Site 1

There is only one local peak in the boiler room $PM_{2.5}$ data that is ~50 *μg/m³*, which occurs on December 24th, 2022, at ~1100 hours. The flue gas temperature data during that peak show that the burner fired once every 10 minutes or less. A negative pressure in the home may have drawn particulates out of the flue pipe but that it highly unlikely to cause a peak of this magnitude. During that time, elevated PM of up to ~35 *μg/m³* was captured in the outside sensor. It is also likely that a local outdoor PM spike that was not adequately captured by the outside sensor affected the air quality in the boiler room. There are also several $PM_{2.5}$ peaks from the outside data, some of which may have been caused by a recreational firepit located ~20 feet from the outside PurpleAir sensor. Outdoor PM was found to frequently peak in the evenings at times when woodstoves or fireplaces were being used in the area.

Site 2

PM sensors were installed in four locations in this site – boiler room, kitchen, fireplace and outside. The boiler room sensor was placed ~6 feet away from the boiler flue pipe. The location of this room is in the basement of the home. The kitchen sensor was placed on a countertop in close vicinity of the propane range. The fireplace sensor was placed in the den area, close to the fireplace. Both kitchen and Den sensors were located on the first floor of the home. The outside sensor was placed in the backyard area. The $PM_{2.5}$ data from this site for all measurement points during the entire data collection period is shown in Figure 7.

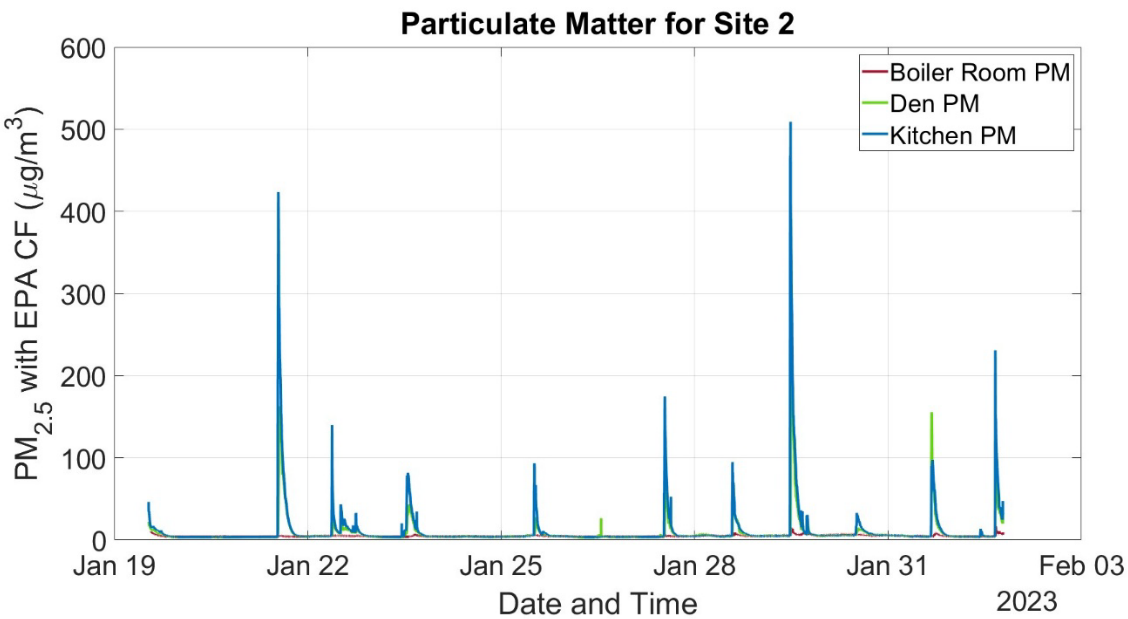

Figure 7: $PM_{2.5}$ data from all measurement locations during the entire data collection period for Site 2

There are several major peaks of at least ~80 $\mu g/m^3$ and as high as ~500 $\mu g/m^3$ in Figure 7, all of which occur in the den and kitchen areas. As a result of these peaks, the behavior of the boiler room $PM_{2.5}$ data cannot be properly distinguished in this figure. Figure 9 shows $PM_{2.5}$ data from the boiler room exclusively in order to show the characteristics of the data from that location. All $PM_{2.5}$ peaks observed in this figure occur shortly after high PM-producing events in either the kitchen or fireplaces areas and are much lower than those in Figure 7. For example, the cooking event on January 29 which produced a peak of ~500 $\mu g/m^3$ in the kitchen results only in a local peak of ~15 $\mu g/m^3$ in the boiler room ~9 minutes later. This is shown in Figure 8. It is worth nothing from the figure that PM concentrations in the kitchen only decrease to ~70 $\mu g/m^3$ more than three hours after the greatest peak in that area is recorded, demonstrating that high levels of PM in the home can linger for several hours and do not dissipate immediately. All other such events at this site share a similar rate of PM dissipation.

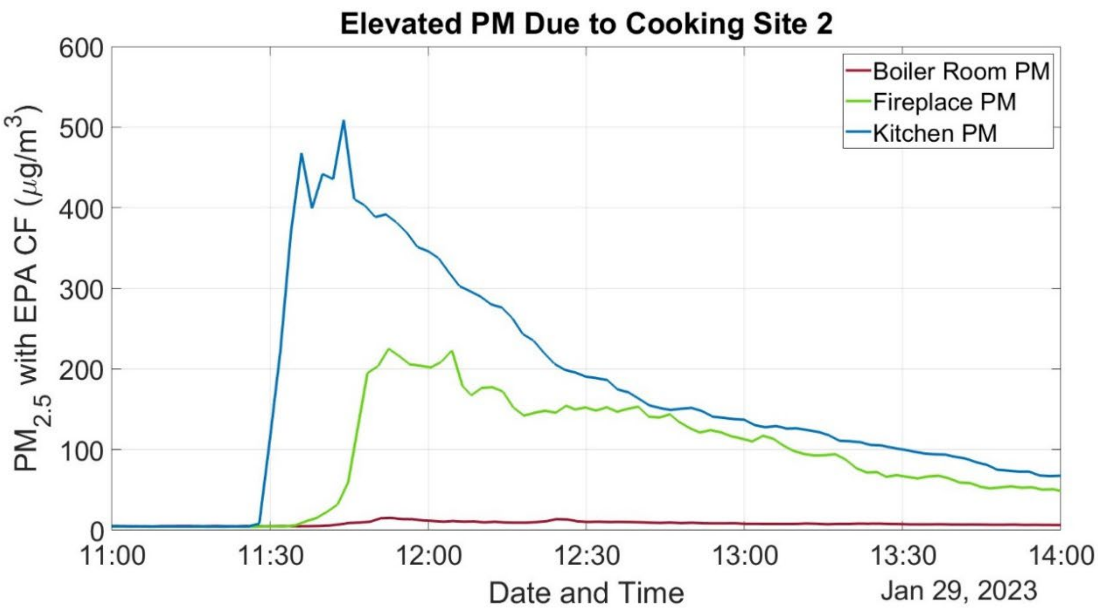

Figure 8: $PM_{2.5}$ concentrations in the boiler room, kitchen, and den areas during a cooking event.

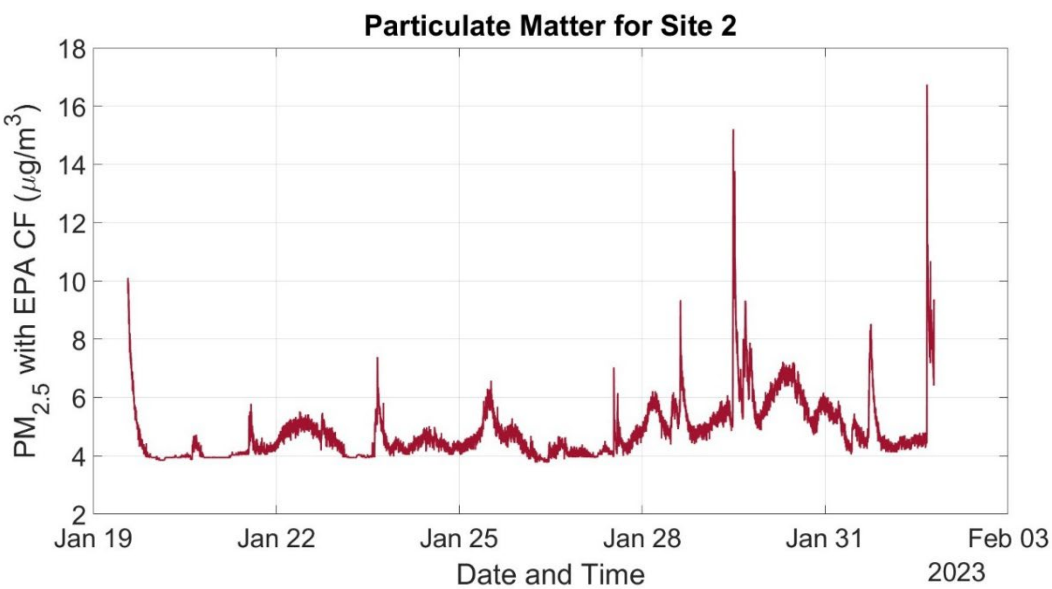

Figure 9: $PM_{2.5}$ data from boiler room during the entire data collection period for Site 2

Site 3

The only sensor installed for this site was in the kitchen. This sensor was placed ~3 ft away from the range on a countertop. The $PM_{2.5}$ data for the entire data collection period is shown for this sensor in Figure 10. Each of the peaks observed in the figure is a specific cooking event. The specific cooking event that was performed on each day was identified by the homeowner. Sometime between the two localized peaks on February 18 and February 19, the homeowner also had a fire in their wood fireplace, but this event did not cause elevated $PM_{2.5}$ in the area.

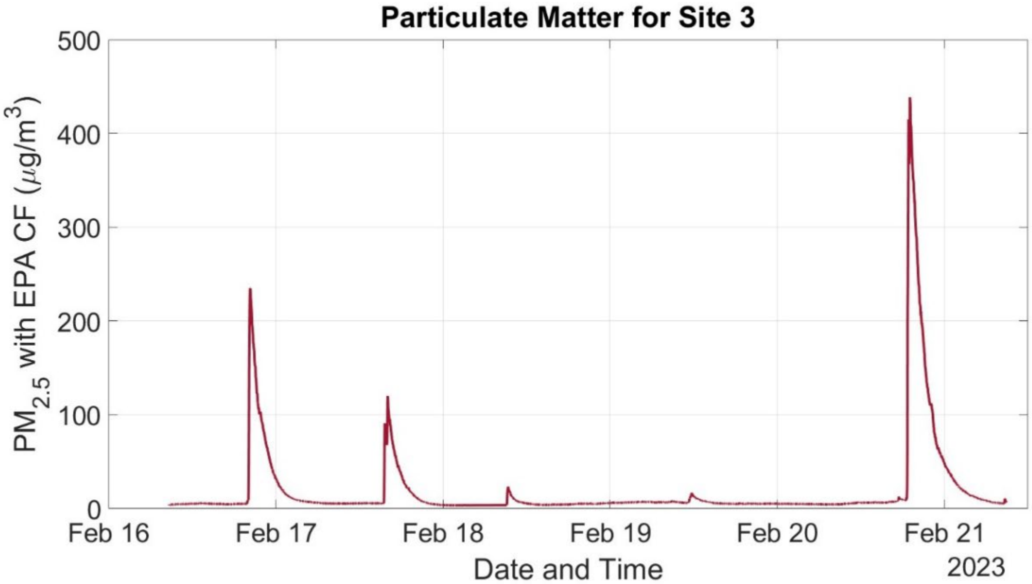

Figure 10: $PM_{2.5}$ data from the kitchen area during the entire data collection period for Site 3

Site 4

PM sensors were placed in three different locations for this site – boiler room, den and outside. A boiler room sensor was installed ~6 feet away from the liquid-fuel-fired boiler located in the basement. A den sensor was placed in the living room on the first floor, which is adjacent to the kitchen. The outside sensor was placed in the backyard area and as mentioned previously, did not record data continuously due to power loss. Due to the substantial loss of data and lack of any interesting $PM_{2.5}$ peaks from the available data, the data from that sensor is not used for discussion here. Instead, Figure 11 is presented with only data from the boiler room and den sensors.

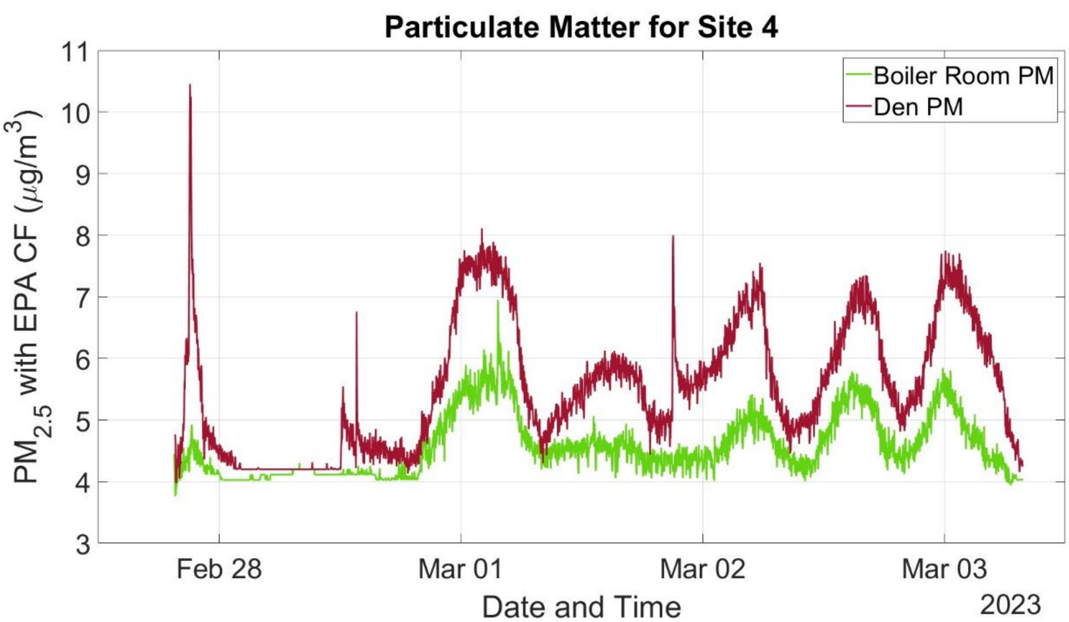

Figure 11: $PM_{2.5}$ data from the kitchen and boiler room areas during the entire data collection period for Site 4

There are multiple peaks observed in this figure in both the den and boiler room, which only exceed 10 *μg/m³* on one occasion in the den. All $PM_{2.5}$ peaks in the boiler room appear to be a direct result of an event in the den/kitchen area – same as the behavior observed in the data from Site 2. The homeowners cooked almost every day during the data collection period, but the $PM_{2.5}$ peaks are much smaller in magnitude than other sites (Sites 2, 3, 5,6, and 8) where cooking activities caused substantial PM-generating events. This is most likely because the homeowners of Site 4 exclusively utilize boiling or baking, as opposed to frying, broiling, or grilling used by the other homeowners, as their cooking methods.

Site 5

Three PM sensors were installed at this site. One was installed in the furnace room, located in the basement, ~6 feet away from the liquid-fuel-fired furnace flue pipe. The kitchen sensor was installed on a kitchen countertop ~4 feet away from the electric range. The location of the kitchen is on the first floor of the home. The outside sensor was located in the backyard area, ~6 feet away from the building. Due to lack of continuous data from that sensor, the data is not being presented for discussion here. Figure 12 contains the $PM_{2.5}$ concentration data from the furnace room and kitchen during the entire data collection period.

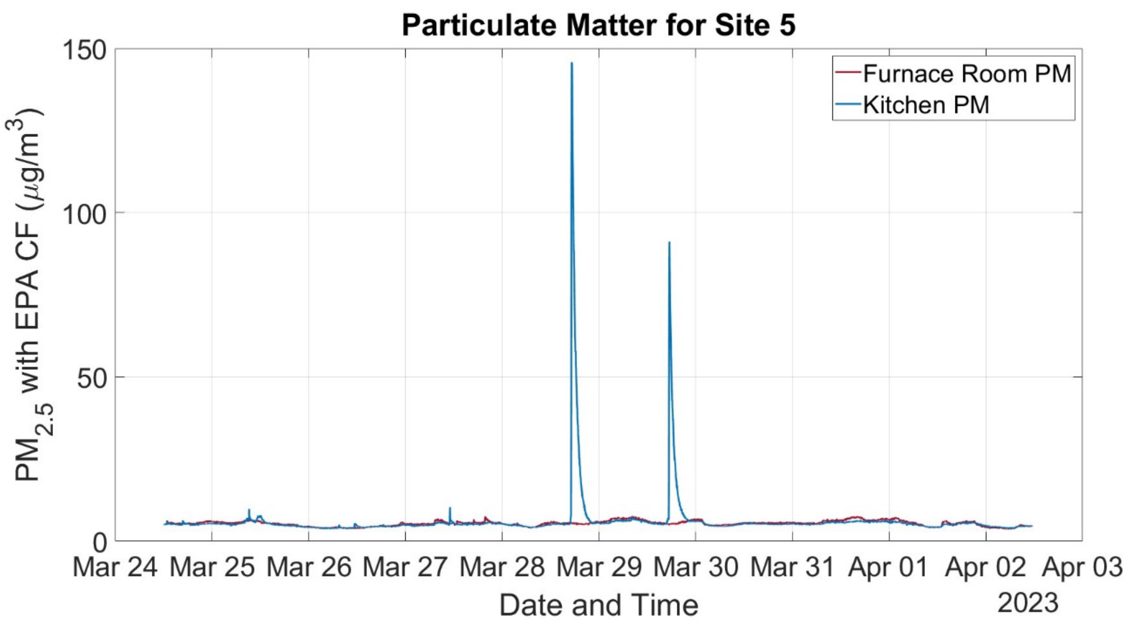

Figure 12: $PM_{2.5}$ data from the furnace room and kitchen during the entire data collection period for Site 5

There are two notable peaks for the data from the kitchen area observed in Figure 11, both of which correspond to cooking events as logged by the homeowner. There are two other observable peaks for that data, but both are below 10 *μg/m³*. Due to the nature of the larger peaks, it is not possible to discern the behavior of the PM levels in the furnace room from the combined plot. Therefore, an exclusive view of the furnace room data is provided in Figure 13. As observed in this figure, the $PM_{2.5}$ concentration remains at very low levels between ~4 *μg/m³* and ~7.5 *μg/m³*. $PM_{2.5}$ from the kitchen and furnace room sensors during the first of the two cooking events are also provided in Figure 14. Here, a peak is observed in the kitchen area but none in the furnace room. The same behavior was identified during the second cooking event in Figure 12.

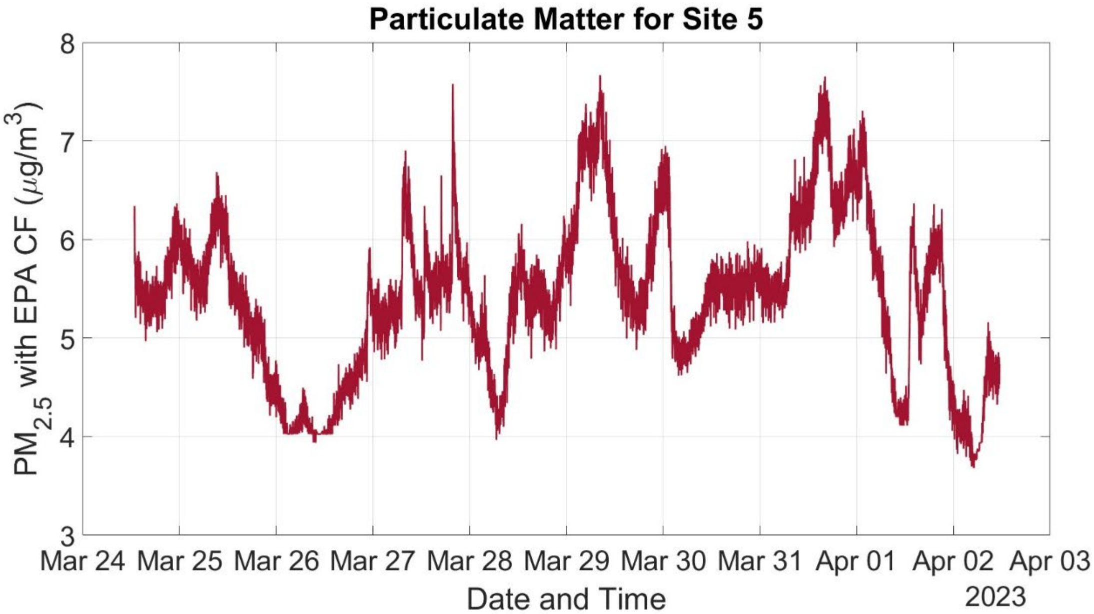

Figure 13: $PM_{2.5}$ data from the furnace room during the entire data collection period for Site 5

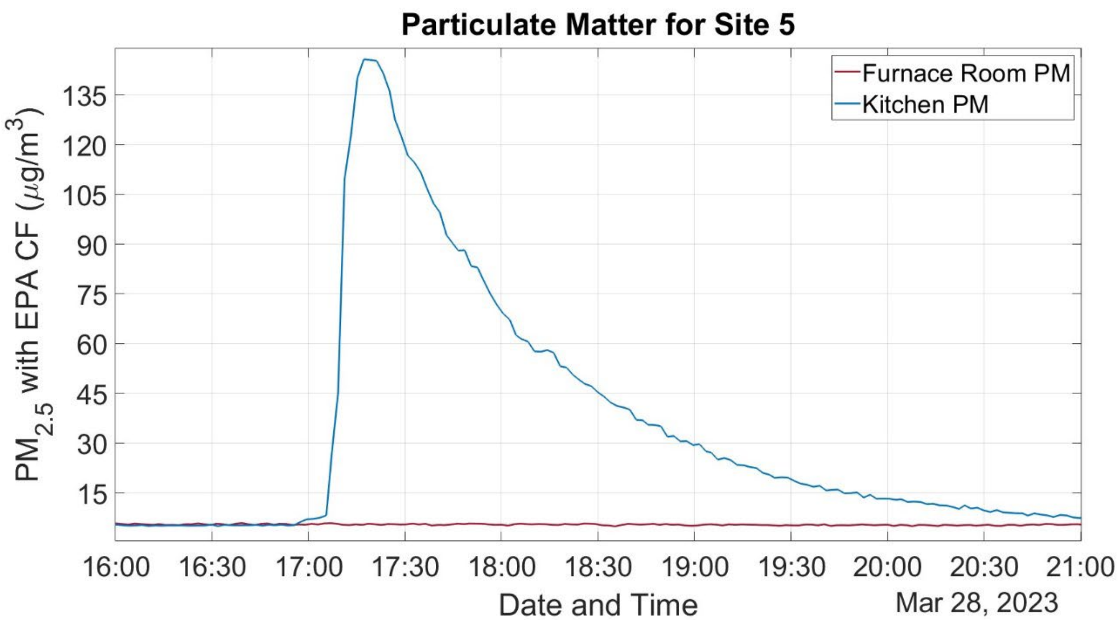

Figure 14: $PM_{2.5}$ data from the kitchen and furnace room areas during one of the cooking events at Site 5

Site 6

Three PM sensors were installed at this site. The boiler room sensor was placed ~6 feet away from the flue pipe of the liquid-fuel-fired boiler located in the basement of the home. The kitchen sensor was placed on a countertop close to the stove. The outdoor sensor was placed in the backyard area. Despite loss of power for prolonged periods of time, this sensor captured some data that is useful for discussion in this section. A flue gas temperature sensor was also installed to monitor operation of the boiler unit. Figure 15 shows $PM_{2.5}$ data from all sensors for the entire data collection period.

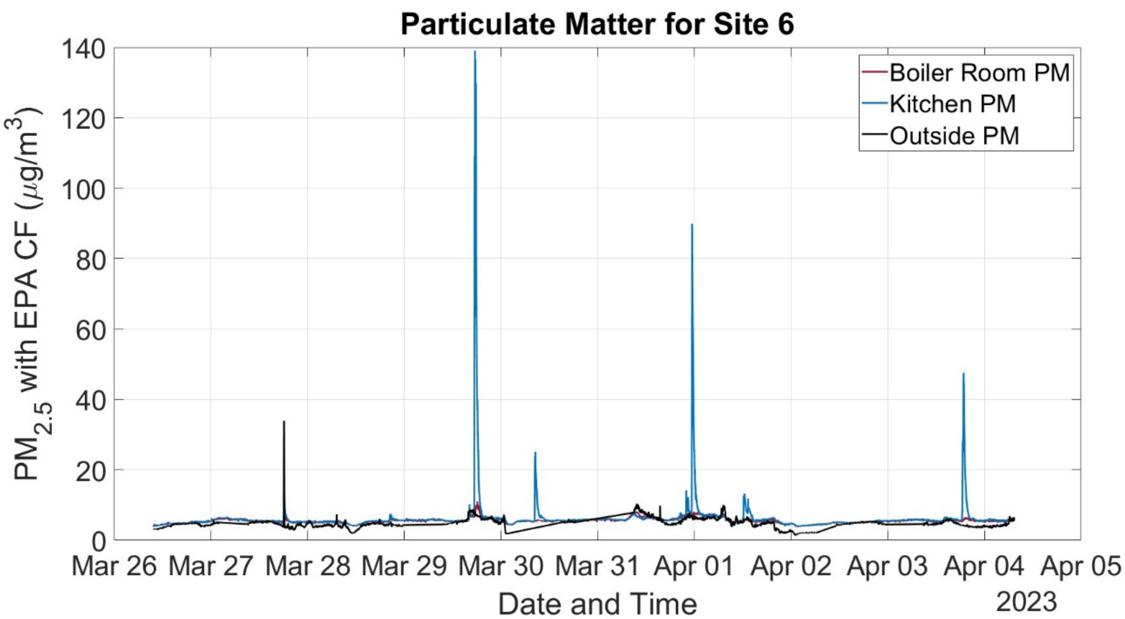

Figure 15: $PM_{2.5}$ data from all measurement locations during the entire data collection period for Site 6

The homeowner stated that during the data collection period, there were at least five separate cooking events, four of which cause a $PM_{2.5}$ concentration above ~25 *μg/m³* in the kitchen area observed in Figure 13. $PM_{2.5}$ from these events dissipate at a rate similar to or faster than the dissipation rates seen in the kitchen area at Site 5. The peak observed on March 29th in this area of 139 *μg/m³* does not cause any elevation in PM in the boiler room.

There is one major peak of 34 *μg/m³* in the outside area during this time, but there is no documented cause for it. This peak in the outside area coincides with very short peaks of 15 *μg/m³* and 11 *μg/m³* in the boiler room and kitchen, respectively. This event is shown in Figure 16. The homeowners did not document any activities that correspond to this event, so it is likely that there was PM-generating activity such as woodstove or firepit operation in the vicinity.

The PM generated from cooking events at this site dissipates at faster rates than PM generated by cooking events at other sites. $PM_{2.5}$ from the kitchen and boiler room for the cooking event on March 29 is shown in Figure 17 to demonstrate the fast rate of dissipation. Here, the $PM_{2.5}$ concentrations fall below 10 *μg/m³* within 80 minutes, compared to at least three to five hours following cooking events at other locations. The faster dissipation rate of PM in Site 6 can most likely be attributed to better ventilation during cooking activities.

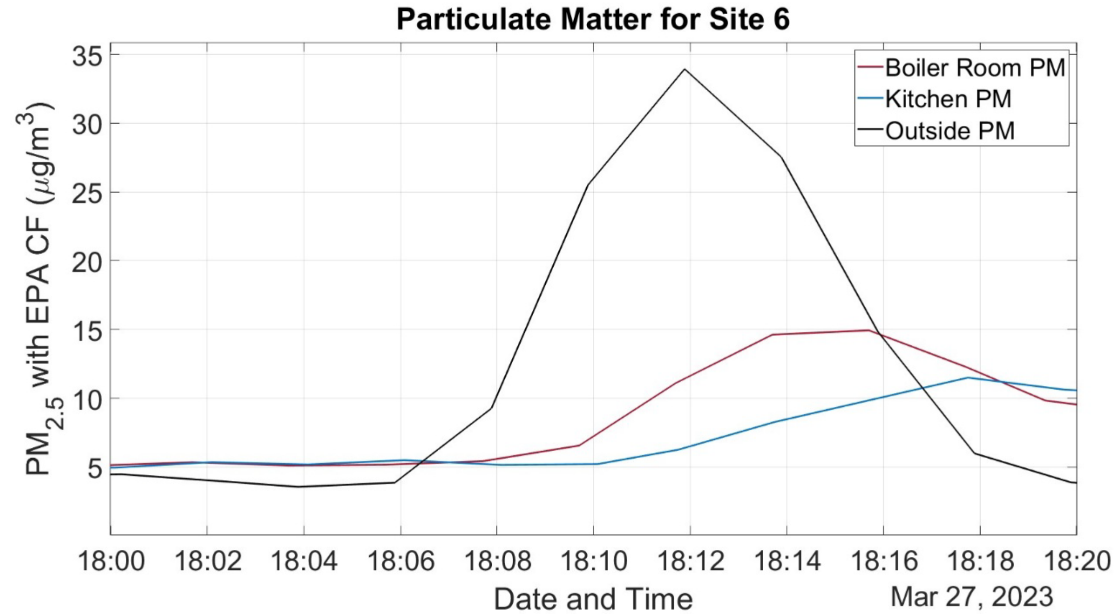

Figure 16: $PM_{2.5}$ data from all measurement locations during an elevated PM event outside.

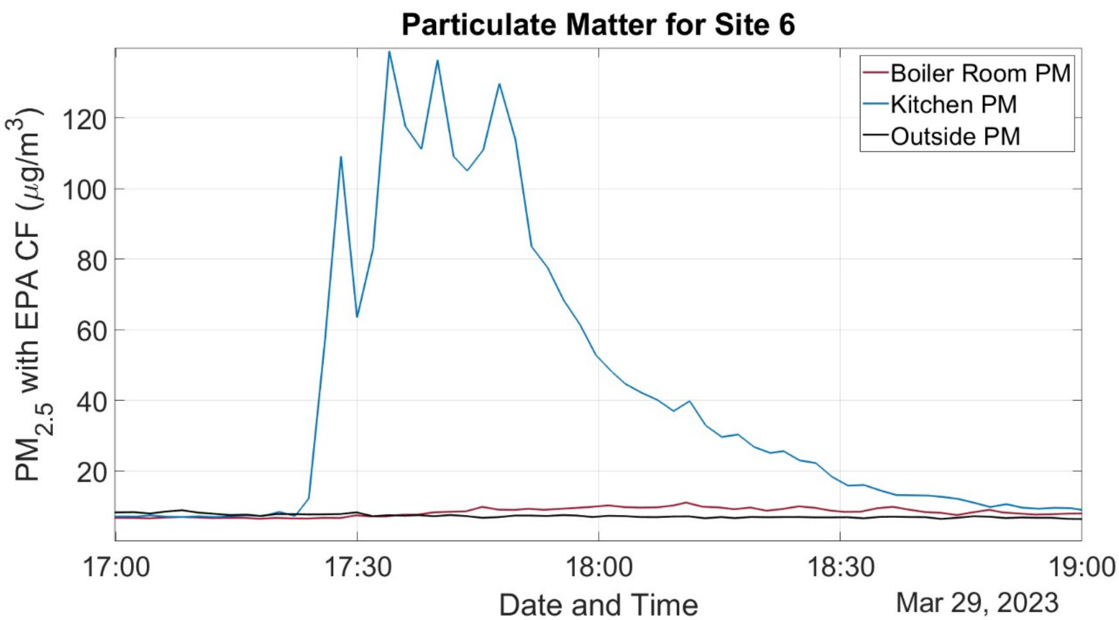

Figure 17: $PM_{2.5}$ data from all measurement locations during a cooking event.

Site 7

Three PM sensors were installed at this site. The boiler room sensor was located ~3 feet away from the boiler flue pipe. The den sensor was installed ~5 feet away from the fireplace. The outside sensor the placed in the backyard area, ~3 feet away from the house. The $PM_{2.5}$ concentrations from all the measurement locations are shown in Figure 18.

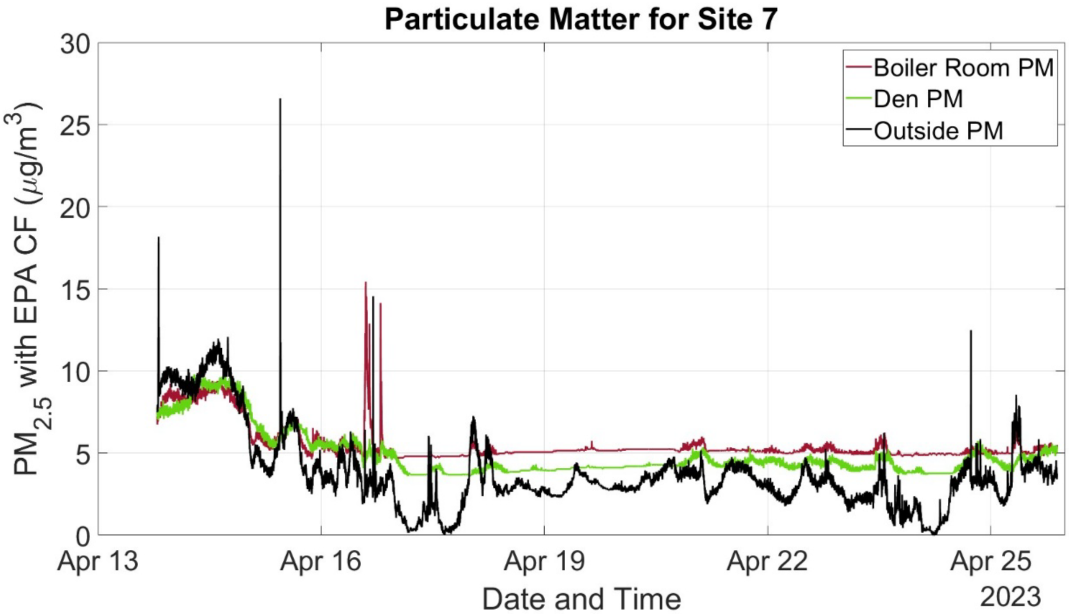

Figure 18: $PM_{2.5}$ data from all measurement locations during the entire data collection period for Site 7

According to the log maintained by the homeowner, wood fires were started in the fireplace on two separate occasions, once at 9:15 PM on April 15 and again at 7:00 PM on April 24. The fires ended 3.5 hours and 4.5 hours after they were started, respectively. Neither of the fires caused a rise in $PM_{2.5}$ levels for any of the measurement locations, as seen in Figure 15. The most notable peak occurs in the outside location where $PM_{2.5}$ concentrations rise to 26 $\mu g/m^3$. There are two other peaks of 15 $\mu g/m^3$ and 12 $\mu g/m^3$ observed at the same location. While the homeowner did not document any PM-generating activities during those events, other sources of PM from neighbors may have caused them. There is also a cluster of three peaks observed on the afternoon of April 17 in the boiler room location, the highest of which only reaches 15 $\mu g/m^3$. There are no documented causes for any of these peaks.

Site 8

Three PM sensors were installed at this site. The boiler room sensor was installed ~3 ft from the boiler flue pipe. The kitchen sensor was installed ~2 ft on a countertop from the electric range. The outdoor sensor was installed in the backyard area, ~15 ft from the gas-fired grill. The grill is situated ~2 ft away from the back door of the home. This placed the grill at a closer distance to the kitchen PM sensor than to the outside PM sensor. Also placed at this site was a flue gas temperature sensor. The homeowners cooked food on their grill multiple times during the data collection period. They also cooked in the kitchen on their gas range and oven. Those activities can be observed in the $PM_{2.5}$ data, which is shown in Figure 19.

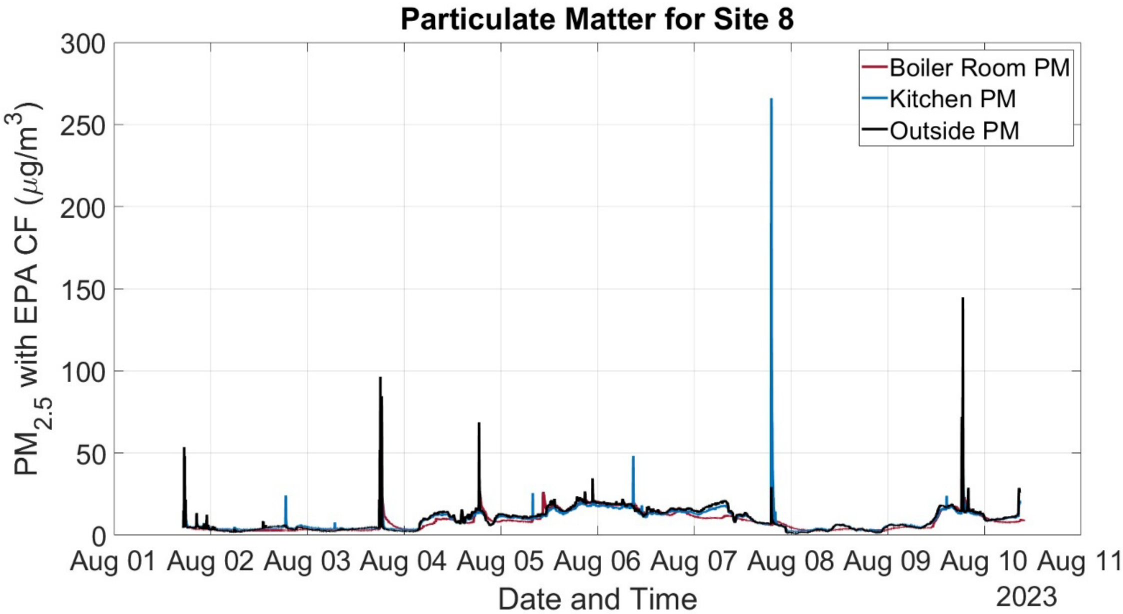

Figure 19: $PM_{2.5}$ data from all measurement locations during the entire data collection period for Site 8

The largest peak of 266 *µg/m³* was observed in the kitchen area on August 7, where a peak of 315 *µg/m³* was recorded during a time that the grill was fired, and the back door was left open. This event caused a much smaller peak of 29 *µg/m³* in the outdoor sensor. Other grilling events occurred on August 1, 3, 4, and 9, causing a peak in the outdoor sensor of at least 50 *µg/m³* on each occasion. On August 3, 4, and 9, there are much shorter peaks observed in the kitchen and boiler room between 15 and 30 minutes after a peak in the outdoor sensor due to grilling. To illustrate the peaks in the boiler room, Figure 20 shows only the $PM_{2.5}$ concentrations in that area along with flue gas temperatures at that time.

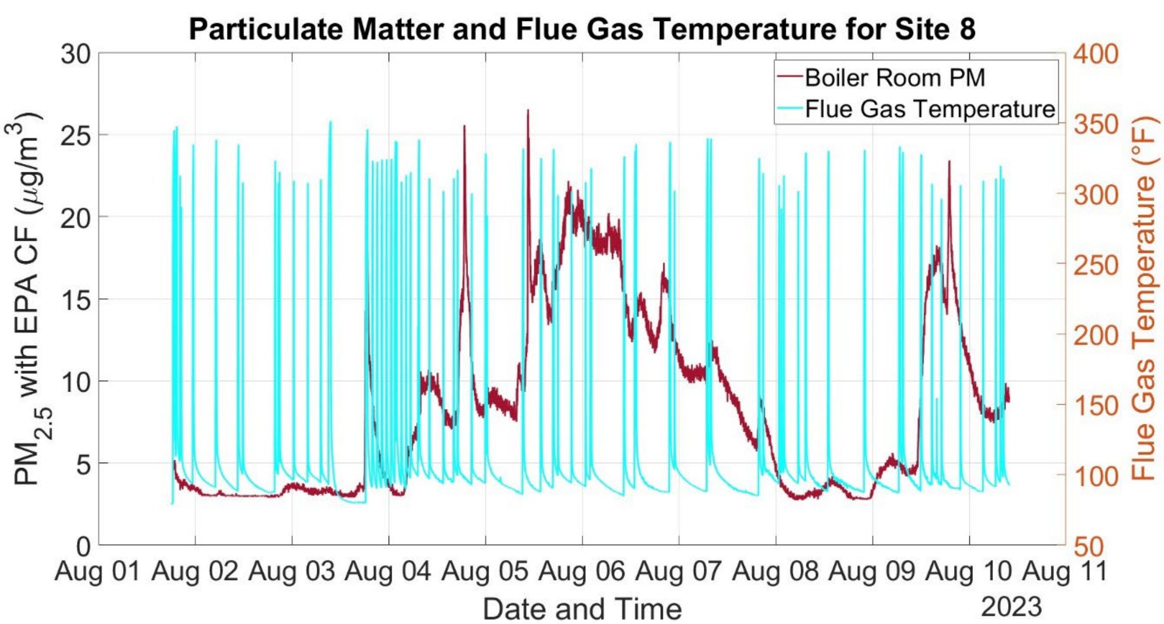

Figure 20: Boiler room PM2.5 and flue gas temperature data during the entire collection period for Site 8

All the peaks in the boiler room $PM_{2.5}$ concentrations shown in Figure 20 occur following a grilling event, except for one on August 5, for which there is no documented reason. The boiler is most likely not the cause of this peak since it occurred ~70 minutes after the last time the burner was operating.

Site 9

One PM sensor was installed at this site in the den area to capture any PM generating activity from the cordwood stove, which the homeowner utilizes as the primary source of heating when he is home. While data collection occurred for 28 days at this site, two periods of regular PM-generating events were used for analysis. Figure 21 shows $PM_{2.5}$ data the den sensor at this site for a 10-day period in April 2023 (period 1). Additionally, Figure 22 contains data from the same source during a 7-day period in May 2023 (period 2).

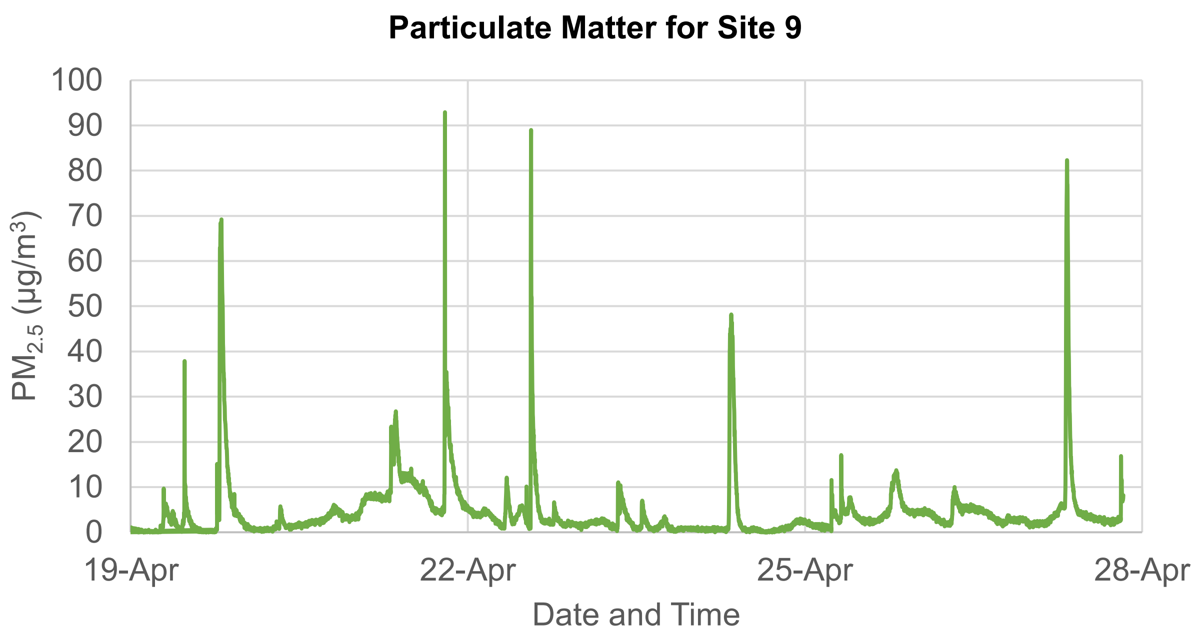

Figure 21: Den $PM_{2.5}$ during period 1 for Site 9

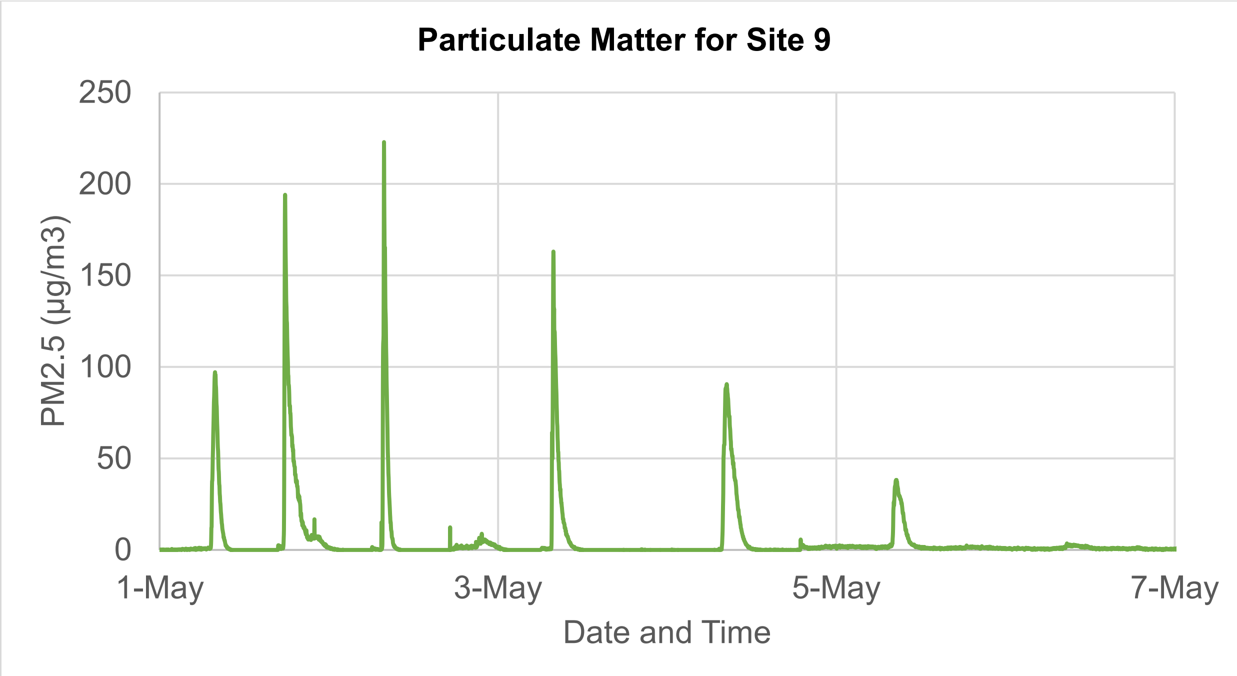

Figure 22: Den $PM_{2.5}$ during period 2 for Site 9

There are several instances of elevated $PM_{2.5}$ during both periods. In period 1, there are 6 distinct spikes observed. Three of these occur during the morning to early afternoon hours, when the homeowner typically opens the wood stove door and starts or stokes a fire. The remaining three spikes during this period are in the late evening hours for which there are no documented events, but these could be either attributed to wood stove activity or cooking. Five of the 6 notable elevated $PM_{2.5}$ events during period 2 occur in the early morning hours and are most likely due to wood stove activity, while the other event occurs in the evening for no documented reason but are likely, once again, due to either wood stove activity or cooking.

Conclusion

PM2.5 concentrations indoors can rise for a variety of reasons. Elevated levels were most commonly associated with everyday activities such as cooking and operating a fireplace. Short-term spikes also occurred during specific events, including soldering without ventilation and instances where parchment paper ignited while cooking. In one case, indoor PM2.5 levels increased sharply when an exterior door was left open near an operating outdoor grill. High outdoor PM2.5 concentrations were also shown to negatively impact indoor air quality.

Several unexplained PM2.5 increases were observed, including some in boiler or furnace rooms. In those cases, flue gas temperature measurements were used to confirm that the heating system was not actively firing at the time of the spike. Based on the data collected at these locations, the liquid fuel–fired heating system was not identified as a significant source of indoor fine particulate matter.

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