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Pilot Study for Multifamily Building Ventilation and Indoor Air Quality

Zachary Merrin
Paul W. Francisco

Date 9/30/2022

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy and Transportation Science Division

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EXECUTIVE SUMMARY

Weatherization Program Notice (WPN) 17-7 issued by the US Department of Energy (DOE) Weatherization Assistance Program (WAP) requires that buildings have ventilation in accordance with ASHRAE Standard 62.2-2016 (entitled *Ventilation and Indoor Air Quality in Residential Buildings*) in dwelling units weatherized under the program. The 2016 version of the standard expanded its scope of application to include all multifamily dwelling units. This has resulted in concerns for buildings where installing ventilation in individual units is costly or otherwise logistically difficult. Also, excessive ventilation rates could significantly increase energy costs, and may cause indoor air quality issues within the buildings. One deficiency that is noted is that the standard does not provide a credit for existing infiltration in multifamily buildings that reduces the required mechanical ventilation levels.

This report details findings from a field study investigating envelope air-tightness, inter-unit connectivity, and indoor air quality in centrally ventilated high-rise multifamily buildings with central ventilation systems serving individual units in the state of New York. As allowed under WPN 17-7, the State of New York has a variance in the application of ASHRAE Standard 62.2-2016 in select types of multifamily buildings to provide time to determine how best to implement the standard.

The purpose of this pilot study is to characterize the impact that weatherization and feasible ventilation improvements have on the indoor air quality of large, multifamily buildings with centrally ventilated apartments, as currently performed under WAP in the State of New York under their variance request (i.e., to implement ASHRAE Standard 62.2-2016 "to the greatest extent possible" in this type of multifamily building). A major goal is to determine if these practices improve or at least "do no harm" to the indoor air quality of the weatherized multifamily buildings and to the occupants themselves.

Eligible buildings that were in or had recently completed the DOE Weatherization process were identified. Owing to administrative related delays during the preliminary planning stages and fieldwork interruptions due to the COVID-19 pandemic, field tests were successfully completed in 8 buildings in New York State and one building in Upstate NY, starting in 12/2018 and concluding in early 2022. In each building, nominally 6-8 units were selected for investigation, intentionally chosen to capture the potential influences of stack effect and envelope leakage. A variety of passive samplers and real-time data loggers were used to evaluate the indoor air quality (IAQ) within each unit. In order to determine airtightness of individual units, and connectivity to neighboring units, a series of pressure diagnostic tests was conducted on each main unit and any directly adjoining units. However, pressure diagnostic testing was not conducted for buildings tested during the COVID-19 pandemic (after 3/2020) in compliance with New York state guidance. Weatherization work including the changes made to the building's ventilation systems, and any envelope or air-sealing work that was done within the units themselves were noted, which would have a direct impact on the IAQ and air tightness in the individual units.

The results showed that the attempts made to comply with ASHRAE 62.2 were generally sufficient at achieving the desired ventilation rates. Instances of as-found IAQ issues that exceeded established guidelines were rare and never excessive. There was no evidence gathered in this study that suggests that that the weatherization work done on these sites had a detrimental impact on the IAQ in the units, complying with the "do-no-harm" philosophy of the weatherization program.

This research does not support prohibiting weatherization work on these buildings which in the scope of this project largely consisted of building system improvements (external to the individual units) and plug load efficiency measures. In buildings where major changes are made to the envelopes in individual units, special attention should be paid to ensure that there is sufficient ventilation to avoid creating IAQ issues, such as insufficient ventilation.

Given that some air leakage reduction does occur, it is reasonable to continue to have ventilation be a consideration in multifamily buildings. However, given the results of this report – including measures installed, airflow results, and IAQ results – it is also reasonable to support interventions at the scale that were implemented in these buildings rather than additionally require individual-unit ventilation installations.

1. INTRODUCTION

1.1 BACKGROUND

Weatherization Program Notice (WPN) 17-7 issued by the US Department of Energy (DOE) Weatherization Assistance Program (WAP) requires that buildings have ventilation in accordance with ASHRAE Standard 62.2-2016 (entitled *Ventilation and Indoor Air Quality in Residential Buildings*) in dwelling units weatherized under the program. The 2016 version of the standard expanded its scope of application to include all multifamily dwelling units. Some WAP practitioners are concerned that the updated standard requires excessive ventilation rates in existing multifamily buildings undergoing weatherization that are difficult and costly to achieve, could significantly increase energy costs, and may cause indoor air quality issues within the buildings. One deficiency that is noted is that the standard does not provide a credit for existing infiltration in multifamily buildings that reduces the required mechanical ventilation levels. A lack of data on the indoor air quality levels in typical multifamily dwelling units before and after weatherization and the benefits of different ventilation approaches makes it difficult to recommend changes to the standard regarding its multifamily building requirements. A lack of data also makes it difficult for WAP to provide guidance on how the standard should best be implemented in multifamily buildings weatherized under the program.

As allowed under WPN 17-7, the State of New York has a variance in the application of ASHRAE Standard 62.2-2016 in select types of multifamily buildings to provide time to determine how best to implement the standard. The State of New York will be implementing ASHRAE 62.2-2016 “to the greatest extent possible” in two distinct types of multifamily buildings (naturally ventilated multifamily buildings and large, centrally ventilated buildings) to study the results of this implementation approach.

1.2 Purpose

The purpose of this pilot study is to characterize the impact that weatherization and feasible ventilation improvements have on the indoor air quality of large, multifamily buildings with centrally ventilated apartments, as currently performed under WAP in the State of New York under their variance request (i.e., to implement ASHRAE Standard 62.2-2016 “to the greatest extent possible” in this type of multifamily building). A major goal is to determine if these practices improve or at least “do no harm” to the indoor air quality of the weatherized multifamily buildings and to the occupants themselves.

Results from the pilot study will be used in a broader effort to determine feasible, doable, and standard approaches for improving the ventilation systems and implementing ASHRAE 62.2-2016 in large, centrally ventilated multifamily buildings in New York with respect to local codes. These approaches will provide a pathway for achieving improved indoor air quality in large, centrally ventilated multifamily buildings undergoing weatherization. This broader effort will:

1. ***Develop a consistent approach to ventilation system improvements that can be implemented state-wide.***
2. ***Develop ventilation system assessment, retrofit, and verification protocols and procedures that can be standardized and applied state-wide.***
3. ***Develop a sampling protocol for measurement and verification.***
4. ***Develop a ventilation rate tolerance for testing, adjusting, and balancing.***
5. ***Develop a methodology for calculating an infiltration credit for vertically stacked dwelling units.***

A primary beneficiary of this pilot study and the broader effort described above will be DOE and the weatherization community. DOE will be able to provide updated and additional guidance on how ASHRAE Standard 62.2-2016 should best be implemented in multifamily buildings weatherized under the program. Entities like ASHRAE and other researchers will also benefit because published data on ventilation and infiltration rates and their impacts on indoor air quality in large, centrally ventilated multifamily buildings will now be available. This guidance will also help all owners and operators of multifamily buildings as they remodel and otherwise update their buildings. These data will help inform the ASHRAE 62.2 Ventilation Standard for further amendments related to ventilation systems in multifamily buildings.

1.3 Acknowledgements

This project would not have been possible without the participation and contributions from multiple parties, and the authors would like to thank the following people, groups, and entities: Oak Ridge National Lab staff for providing guidance and support through every stage of this research, including Mini Malhotra, Mark Ternes, Jason DeGraw, and Bill Eckman; the Association for Energy Affordability (AEA) staff for leading the building recruitment and interaction and being instrumental in every aspect of the field work, including David Hepinstall, Peter Hoyle, El Niang, Melanie Seymour, Francis Rodriguez, Adam Romano, and several others; the New York State Homes and Community Renewal staff and other WAP employees for assisting on the building recruitment and fieldwork in the Upstate New York sites, including Wayne Miller, Kevin O'Connell, and William Gregg; the administrative and maintenance staff from the participant buildings for granting us access and facilitating our interactions with the tenants; and U.S. DOE WAP staff for their continuing support for this project through the challenges presented by the COVID-19 pandemic. Most importantly, we would like to thank the tenants themselves who allowed us into their homes and permitted us to conduct our tests and deploy our instrumentation.

2. METHODS

2.1 BUILDING SELECTION

2.1.1 Timeline

Initially the field-testing portion of the study was intended to occur November 2018 through February 2020. This schedule was delayed by administrative issues during the preliminary planning stages, and by fieldwork interruptions due to the COVID-19 pandemic. Field testing started in 12/2018 and concluded in early 2022 according to the schedule in Table 1.

Table 1- Building Testing Dates

Building Location	Building ID	Pre-Wx Date	Post-Wx Date
New York City	Bldg1	12/2018	1/2020
	Bldg2	1/2019	1/2020
	Bldg3	7/2019	9/2021*
	Bldg4	1/2020	2/2021*
	Bldg5	1/2020	2/2021*
	Bldg6	9/2020*	5/2021*
	Bldg7	NA *(Post-Wx only)*	1/2020
	Bldg8	NA *(Post-Wx only)*	2/2021*
Upstate NY	BldgA	2/2020	NA§
	BldgB	2/2020	NA§
	BldgX	2/2020	3/2022*
*Blower door diagnostics not conducted due to COVID-19 restrictions			
§Weatherization work on these sites has been postponed indefinitely and they were subsequently dropped from the study			

2.1.2 Number of Buildings

A goal was set for a total of 12-16 buildings with the following breakdown.

- 8-12 buildings in New York City
    - 2 buildings that had been weatherized recently for post-only testing
- 4 buildings in Upstate New York
    - 2 buildings that had been weatherized recently for post-only testing
        - Due to recruitment issues related to the small quantity of eligible buildings weatherized during a suitable recent timeframe, this goal was abandoned, and replaced by an additional pre and post building, "BldgX".
            - Two site visits, pre & post on a single building, instead of two site visits post-only on two buildings.

All eight buildings in New York City were successfully recruited and tested. Only one of the Upstate New York buildings (BldgX) was completed; the Weatherization work at the other two buildings (BldgA & BldgB) was postponed indefinitely shortly after the pre-testing concluded, eliminating the possibility of completing post-testing before the project deadline.

2.1.3 Recruitment

2.1.3.1 Buildings

Buildings that were in or had recently completed the DOE Weatherization process were identified as potential candidates. AEA utilized their network of weatherization agencies to identify eligible buildings. From those buildings, sites were selected that met the following criteria.

1. Having an existing central ventilation system (that at a minimum serves the individual units).
2. Four or more stories (NYC buildings) or three or more stories (Upstate NY)
3. No dwelling units that span multiple stories.
4. Less than 50% vacancy.

2.1.3.2 Units

In each building, nominally 6-8 units were selected for investigation, intentionally chosen to capture the potential influences of stack effect and envelope leakage. For all buildings, two units on the highest floor and two units on the lowest floor were selected, ideally with one middle unit and one end/corner unit on each floor. In buildings with less than six stories, a total of six units were selected including two on a middle floor. In buildings with six or more stories, a total of eight units were selected, including two from the middle of the top-half (~75% of the building height) and two from the middle of the bottom half (~25% of the building height) of the building. Figure 1 shows a profile view depiction of two hypothetical buildings, a shorter 5-story building (left) and a taller 13-story building (right), and the potential unit selection, including "main units" shown in orange, and "neighboring units" shown in blue. Neighboring units needed to be accessed to measure main unit leakiness and connectivity using blower door and pressure diagnostics. Units can be intentionally selected to minimize the number of neighboring units needed (i.e., the same neighboring units can be reused for multiple main units, minimizing blower door setup, and the number of units requiring interaction). In the Figure 1-left example, both horizontal and vertical neighboring units are reused; in Figure 1-right, only the horizontal neighboring units are reused. Issues including apartment vacancies, amenability of tenants, and logistics of building configuration sometimes resulted in deviations from preferred or ideal unit selection.

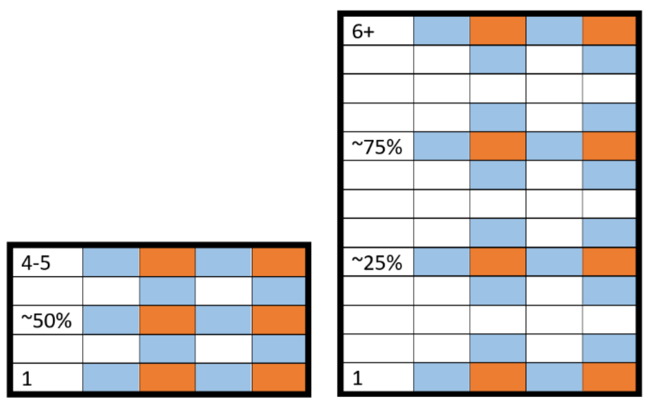

Figure 1 - Example unit selection, including "main units" (orange) and "neighboring units" (blue)

Issues with Individual Units

Because of the voluntary nature of involvement in the project and minimal incentive for participants, there were some issues with individual units. Some occupants initially agreed to participation, but later changed their mind and either (intentionally or unintentionally) unplugged the instruments (detailed in Figure 6 and Figure 7) or refused to participate in post-weatherization testing. Of the total 89 total main-units interacted with, 13 were tested in post only buildings, 16 were pre-tested but the building weatherization work was indefinitely delayed resulting in no post-testing, and 45 were tested during both the pre-weatherization and post-weatherization phases. The remaining 15 units were for various reasons only tested during one of the pre/post phases.

Due to delays in testing brought upon by weatherization schedules, seasonal changes, and COVID-19 related work stoppages, some occupants may have relocated between pre and post testing. Since this project investigated buildings instead of occupants in compliance with the IRB exemption, occupant details were intentionally not collected, and it is unknown how many units had a change in occupancy between the two testing phases. It is possible that new occupants, or altered behaviors due to the pandemic or otherwise, could result in lifestyle changes that would affect the measured IAQ metrics.

2.2 AIR QUALITY MONITORING

2.2.1 Indoor Air Quality Monitoring

A variety of passive samplers and real-time data loggers were used to evaluate the indoor air quality (IAQ) within each unit. A plastic shoebox sized container with the loggers and samplers was deployed in each selected unit and stayed in place for nominally two weeks. The sensor package is pictured in Figure 2 (with each sensor labeled with its target contaminant) and described in Table 2.

Efforts were made to place the sensor package in an appropriate location, but there were several practical limitations due to the size, contents, and configuration of the apartments. The most important placement criteria was that the unit was placed in a location that would not unduly inconvenience the occupant(s), and was within reachable distance (using a ~10’ extension cord) to a working, non-switched electrical outlet. Beyond that minimum requirement, sensors were never placed in bathrooms, and were only rarely placed in kitchens (in cramped efficiency apartments). When possible, sensors were placed out of direct sunlight, away from exterior walls and heat sources, away from air moving devices (HVAC registers, fans, dehumidifiers), and at least 2’ above/below the floor/ceiling.

Figure 2 - IAQ Sensor Package

Table 2 - IAQ Sensors and Measurements

Device (label in Figure 2)	Sensor	Contaminant(s)	Readings	Accuracy	Passive (sampling period)/Active (sample rate)
PurpleAir PA-II-SD (“PM”)	PMS5003 (qty: 2)	Particulate Matter	Concentrations of: PM_1, $PM_{2.5}$, PM_{10},	Greater of: ±10µg/m³ ±10%	Active (90s)
	BME280	Temperature*	°F	±1 °F	
		Relative Humidity*	%RH	±3 %RH	

Rotronic CL11 (“CO2”)	Senseair K30 (NDIR)	Carbon dioxide (CO_2)	Parts Per Million (ppm)	Greater of: ±30 ppm ±5 %	Active (5min)
	Thermistor**	Temperature	°C	±0.3 °K (±0.54 °F)	
	Hygromer IN-1**	Relative Humidity	%RH	<2.5 %RH	
Lascar EL-USB-CO300 (“CO”)	Nemoto NAP-505S	Carbon monoxide (CO)	ppm	±5ppm	Active (5min)
UME^x 100 (“HCHO”)	2,4-DNPH	Formaldehyde	mg/m^3	±25%	Passive (1 or 2 weeks)
Ogawa PS-100 (“NO_2”)	Ogawa PS-134	Nitrogen dioxide (NO_2)	Parts Per Billion (ppb)	Unknown***	Passive (2 weeks)
*Typically not used because internal device-generated heat affects measurements **These sensors are located in the “mast” to minimize effects of device generated heat ***A 3rd party study found an internal coefficient of variation of 6.4%, see Ogawa in section 2.2.4					

Initially, the schedule involved returning to the site in the middle of the two-week sampling period to collect the formaldehyde samplers, which are only rated for deployments between 15-minutes and 7-days, and to deploy a fresh set. In an effort to reduce field tech burden, minimize disturbance to occupants, and decrease contact during the pandemic, experiments were conducted on the validity of ~2-week tests at two buildings (including one done as part of a sister study in Chicago, “BldgII”). Figure 3 shows the result of the one vs two-week tests; the results from the first and second 1-week tests (red and green) show good alignment with the 2-week tests (blue). The 2-week long tests were on average ~11% lower than the mean of the individual 1-week tests. Given the relatively low results from the formaldehyde tests comparted to the WHO guideline and the sensors validation range (Figure 4), it is not thought that this potential bias had any meaningful impact on the results. The second 1-week data point for “bldgX_G4_pre” that is marked with an “*” was reported as “<0.003 mg/m3” (<3 µg/m^3), which is near the lower detection limit (LDL) of the sampler and was assumed to be 0.

The sampled residential environments generally have much lower formaldehyde levels than the commercial or industrial environments where these sensors are predominantly employed. The manufacturer has validated the sensors at levels from 0.06-3 ppm (~74-3680 µg/m^3). As seen in Figure 4, which shows the distribution of all the formaldehyde measurements (including those taken as part of the Chicago sister study), measured values were never above the minimum of the validation range, and were on average about an order of magnitude lower. The 7-day maximum deployment is limited by the expected exposure, and total sensor capacity, at lower concentrations the device should be capable of measuring longer. The sensors have a manufacturer rated capacity of 29 µg and a sampling rate of 28.6ml/min, meaning the samplers should be capable of measuring for 14-days in concentrations slightly over 50 µg/m^3; none of the sensors exceeded this level, and most of the longer tests (redder points in Figure 4) were at less than half of this level.

As a result of this experiment the mid-sampling formaldehyde swap visit was discontinued and starting spring of 2020 all sensors were deployed for 2-weeks.

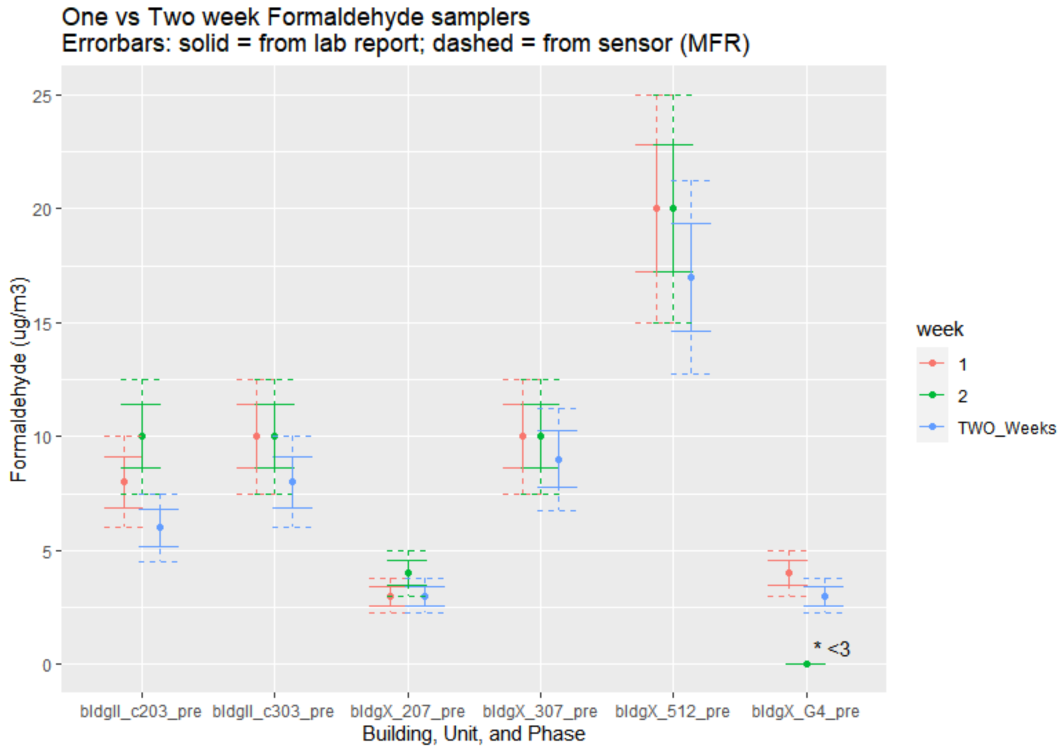

Figure 3 – One-week vs two-week formaldehyde comparison

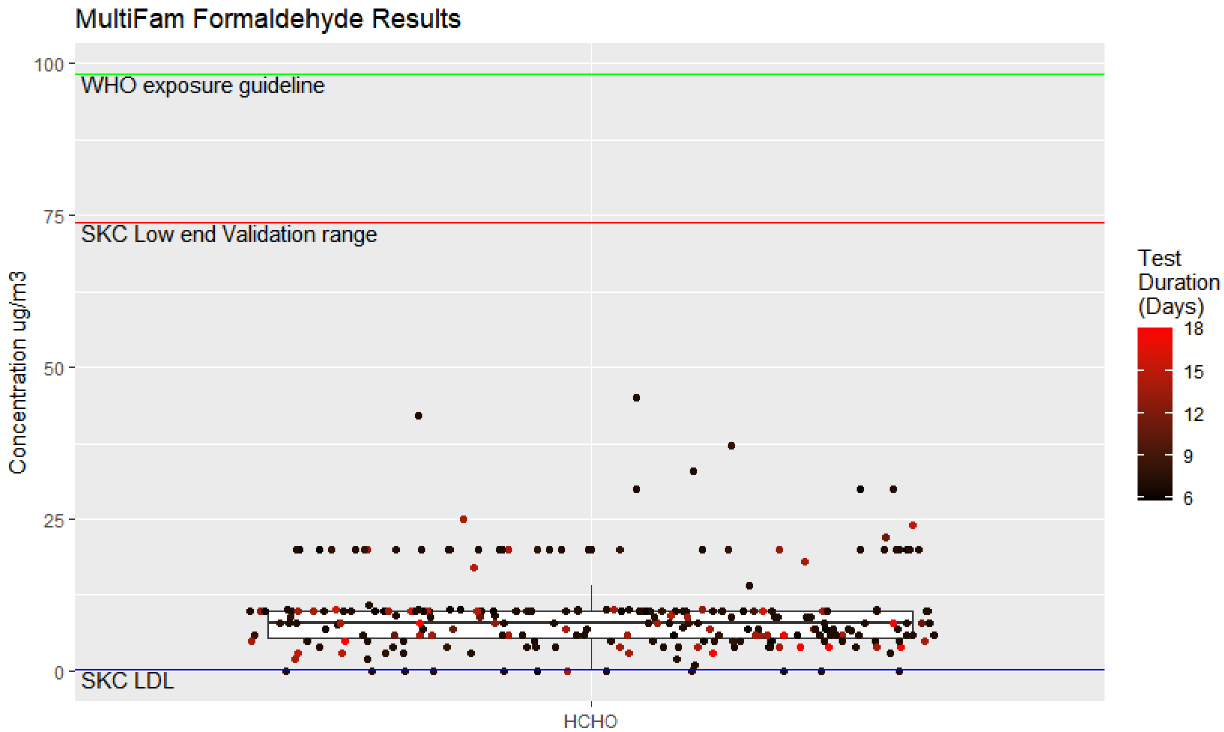

Figure 4 - Formaldehyde measurements from all tests (includes Chicago buildings)

2.2.2 Outdoor Air Quality Monitoring

All of the contaminants measured in the units except for formaldehyde and CO were also monitored in the outside ambient air to account for the potential influence of outdoor concentrations. A partly open enclosure was constructed out of a 5-gallon bucket and some wooden "legs" (Figure 5), to protect the instruments and power supplies from inclement weather while still allowing air exposure to the sensors. This apparatus was typically placed on the building's rooftop and secured in place with zip-ties to prevent blowing over. An extension cord coming from the apparatus was plugged into building power either through an available rooftop outlet or by routing the cord into a nearby utility room. The instruments' moderate power consumption, the length of deployment, and the expected cold temperatures prevented the use of alternative power sources such as batteries and solar panels.

Figure 5 - Outdoor Air Monitoring Station

2.2.3 Data Loss Issues

There were a few instances of individual sensors failing or reporting unrealistic data, and a few more-widespread issues with sensors or procedures on individual buildings. Outdoor sensors were especially problematic. Issues encountered included vandalism or unplugging by building workers or trespassers on the roof, inability to locate a usable power source, or failures of logger internal storage. The main issues encountered, and solutions elected are listed below.

- For the second half of pre-testing at building 1 and for all of pre-testing at building 2, data was not recorded on the outdoor PM sensor internal storage.
    - PurpleAir sensors (optionally) report data to an open-source web repository. The nearest outdoor sensor with consistent and high-quality data (based on agreement of the sensor's two internal channels) was located and substituted for the missing data. The substitute sensor was 8.5 mi away from Building 1, and 3.2 mi away for building 2. This should account for large-scale trends in PM but may miss local effects such as from heavy traffic.
    - The non-PM sensors at these sites did not exhibit any issues.
- The outdoor CO_2 logger at building 4 lost power ~1 day after launch.
    - Another nearby (~2.3 mi away) building was being tested concurrently. Data from this building's outdoor CO_2 sensor was used for both buildings.
- The roof at building 5 was trespassed, and the sensors were unplugged and vandalized after ~12 hours of data collection. The NO_2 sampler was located nearby in a puddle of water, and as such was not sent in for lab analysis, because according to the manufacturer "Moisture is the enemy of the coated pad"
    - As a result of the trespassing, the power source used for the pre-testing could not be used for the post testing at this site without risking additional trespassing and vandalism. No

alternative power sources could be located, so an outdoor sensor set was not used at this building. Alternative nearby options were explored, but nothing satisfactory materialized.

- There were several instances of missing data from the CO_2 loggers which required a multi-step setup and launch process. The most widespread instance of this was at the Building 8 post-test where none of the sensors were initialized correctly, and none recorded usable data (Figure 7).

2.2.3.1 Data Loss by Individual Unit

Figure 6 and Figure 7 show the amount of time that each of the plug-in sensors recorded data in each individual unit for the pre-weatherization and post-weatherization periods respectively. Ideally, all sites would have a clustering of points around ~14 days (solid black horizontal line) indicating that all sensors recorded data for the entire ~2 week period (such as building 3 in Figure 6). A data point significantly below the solid line indicates the data set was cut short, with points at zero (dotted black line) indicating no data recorded. Points of interest are called out with letters (capital for pre-weatherization and lowercase for post-weatherization) and described below each graph.

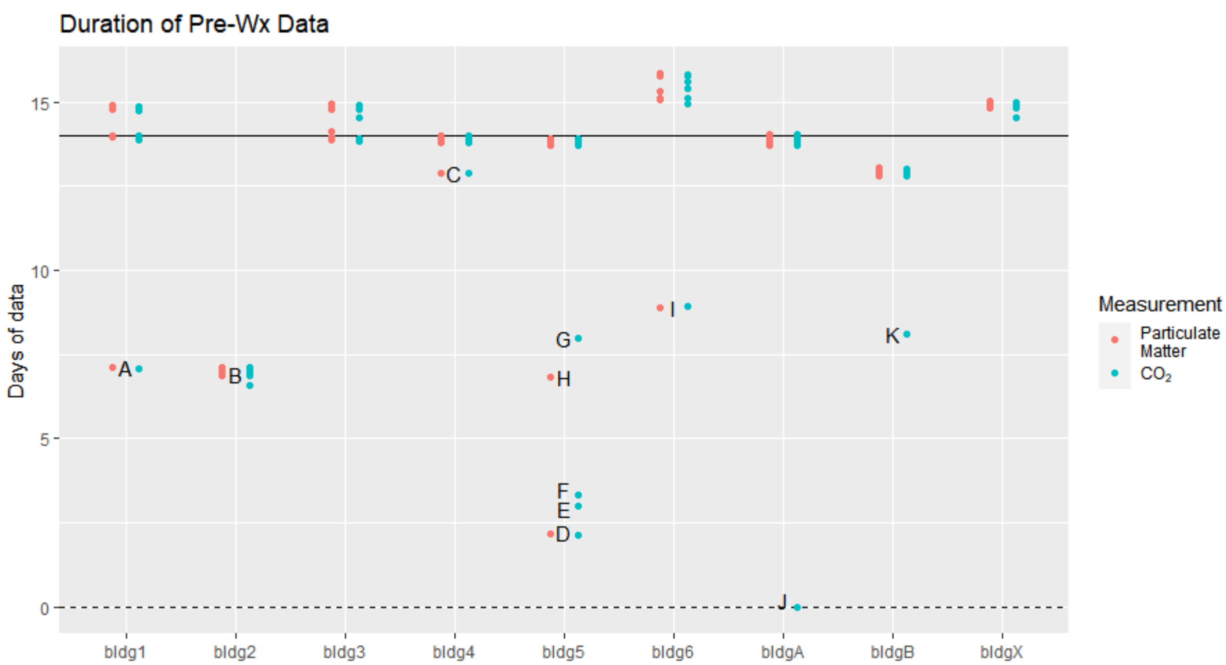

Figure 6 - Duration of Pre-Wx Data with Issues Highlighted

<u>A: Building 1, Unit 12F</u> – Participant withdrew from study during the mid-sampling visit.
<u>B: Building 2</u> – All sensors were pulled at ~1 week because the testing schedule conflicted with the weatherization work schedule, and the retrofit activates commenced shortly after retrieval of the sensors.
<u>C: Building 4, Unit 5E</u> – Plug-in sensors had a ~5-hour gap in the data, starting ~24-hours before the sensors in the other units were retrieved. When the sensors resumed data recording, the subsequent data was distinctly different from the previous data, and extended beyond the building pickup window. It is believed that these sensors were picked up a day early, transported back to the office, and were plugged back in there where they continued to collect data. The data following the gap has been discarded.
<u>D: Building 5, Unit 8J</u> – These sensors were unplugged by the occupant a little over 2 days after being installed.
<u>E, F, G: Building 5, three units (7J, 14D, 2T)</u> – A tight testing schedule where five buildings were tested during January 2020, combined with a limited quantity of measurement equipment, meant that some

sensors needed to be deployed in quick succession without a chance to download data in between sites. This resulted in a few CO_2 sensors exceeding their data storage capacity, and some lost data. This was not an issue for the PM logger, which has significantly more storage space.
H: Building 5, Unit 14D – Due to the availability of the occupant, these sensors needed to be pulled after one week resulting in an abbreviated testing period.
I: Building 6, Unit 15D - Due to the availability of the occupant, these sensors needed to be pulled after one week resulting in an abbreviated testing period.
J: Building A, Unit 5P – The CO_2 sensor in this unit was not started correctly and did not store any data.
K: Building B, Unit 1A – During the retrieval visit, the CO_2 sensor was found unplugged on the ground.

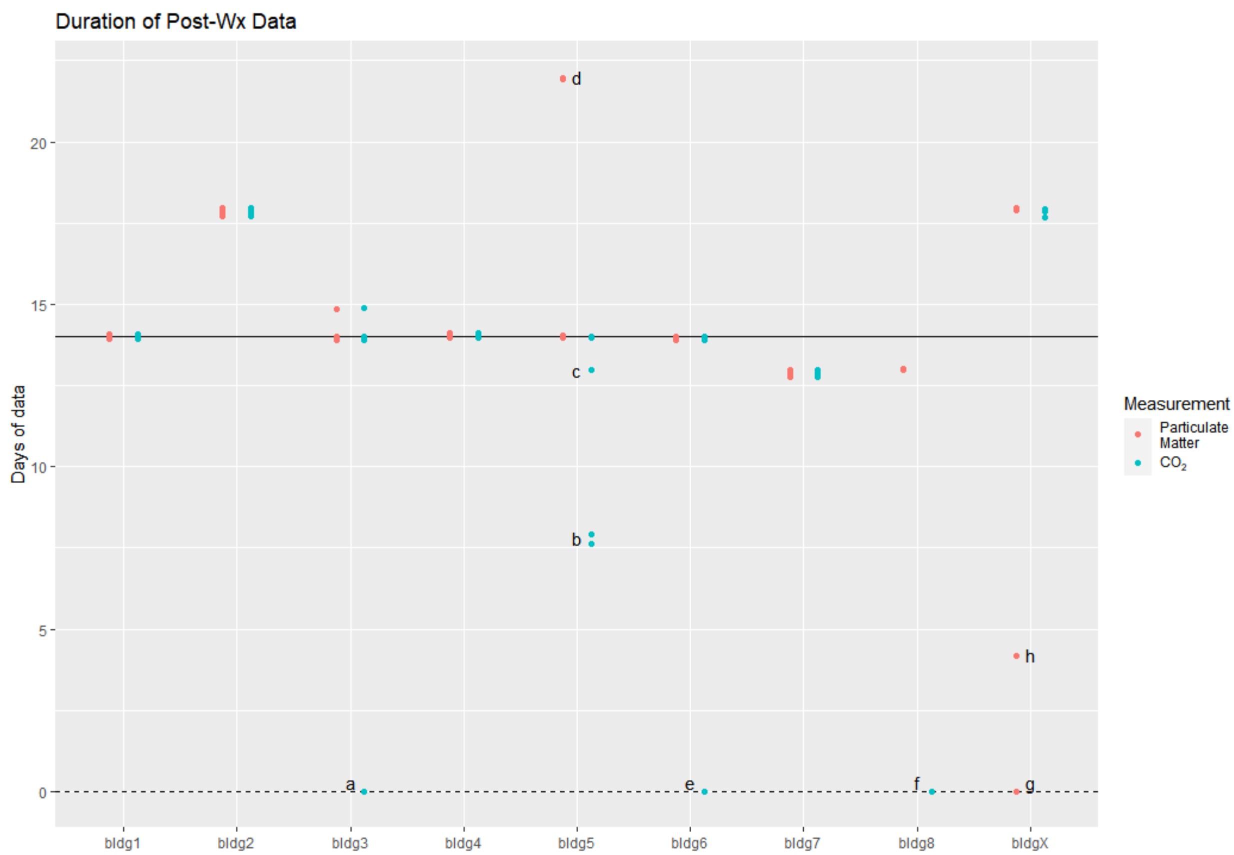

Figure 7 – Duration of Post-Wx Data with Issues Highlighted

a: Building 3, unit 15H – Only two data points recorded on sensor, presumed loose power cable.
b, c: Building 5, three units (7J, 7K, 2S) – At the retrieval visit, it was discovered that the CO_2 sensors were not logging, probably a result of them being initialized incorrectly. The occupants allowed us to leave the sensors in place for an additional week. The other real-time sensors remained in place during this testing extension; the passive sensors were removed.
d: Building 5, three units (7J, 7K, 2S) – As a result of the extended testing period (see b & c above), the sampling time for the PM sensors (which were initially launched correctly) was extended resulting in additional data.
e: Building 6, Unit 2J – The CO_2 sensor in this unit was not started correctly and did not store any data.
f: Building 8, All units – The CO_2 sensors at this building were not started correctly and did not store any data.
h: Building X, unit G4 – No PM data saved to SD card, presumed connection issue.

g: Building X, unit 503 – Only ~1 week of PM data stored, possibly unplugged or disturbed by occupant.

2.2.4 Calibration and Data Quality

Most of the sensors employed in this study were not designed to be calibrated by the end user using traditional methods. Despite this, efforts were made to regularly assess the sensors for the highest possible data credibility.

- PurpleAir PA-II-SD, PM logger – These units lack the ability to be recalibrated. Instead, in an effort to confirm data quality, the instruments contain duplicate PM sensors, which both report their measurements. When the two channels were plotted against each other, most showed high agreement between the two channels having trend lines with slopes of ~1 and high R-squared values (Figure 8, left). Several sensors did exhibit inconsistencies between the two channels (Figure 8, right) indicating that one or both of the channels was generating erroneous data.

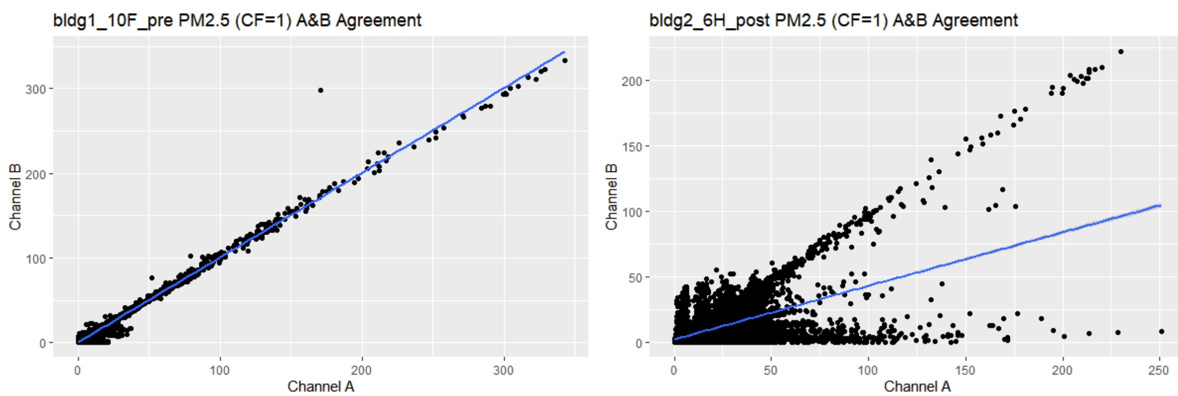

Figure 8 - PM2.5 Agreement between 2 Channels, good agreement (left), and poor agreement (right)

Test data with slopes or R-squared values below 0.85 were flagged for further investigation to try to salvage accurate data. Figure 10 shows the channel agreement for all tests completed by each sensor. A first attempt at data quality assurance was to simultaneously run flagged sensors alongside sensors with demonstrated agreement between the two channels. The intention was to determine which channel deviated from the rest of the group, and then discard that channel's data from field-collected data sets with high disagreement. This method was based on the assumption that only one of the channels was defective, and that it was performing consistently that way. Unfortunately, the results did not align with this hypothesis; several of the flagged sensors performed well, and a few of the "good" sensors exhibited disagreement between their two channels, indicating that this issue is inconsistent. In the 8-sensor test, all of the R-squared values were above 0.85, but two of the slopes were outside the 15% acceptable range, one was at 0.81, and another was at 1.21, both of these inconsistencies were from sensors previously thought to be performing well. Closer investigation into the data revealed that most of the sites that had poor agreement had relatively low levels of $PM_{2.5}$ (Figure 9 – which shows the $PM_{2.5}$ channel agreement vs the maximum concentration measured), suggesting this was not exclusively a result of sensor failure, but rather had to do with sensitivity to low concentrations. Although it is known that low cost PM sensors are sensitive to effects from high relative humidity (Tryner, et al. 2020), it does not appear that high humidity exposure resulted in increased discrepancy between the two sensor channels (Figure 11), likely because both channels were simultaneously exposed to the same environmental conditions, and would have experienced similar bias.

Figure 12 shows the time series data (left) and the channel correlation (right) for the $PM_{2.5}$ measurements at the site with the worst performing PM sensor. It is clear from the two graphs that the disagreement between the two channels was intermittent. Based on the data trends during the times when the sensors agreed and when they disagreed, it is most likely that the channel A sensor (red in Figure 12 left) malfunctioned. In this instance, only the data from channel B was used. Additional $PM_{2.5}$ quality checks (for sensors outside of the 15% range) and decisions are listed in Appendix C – PM2.5 Quality Checks.

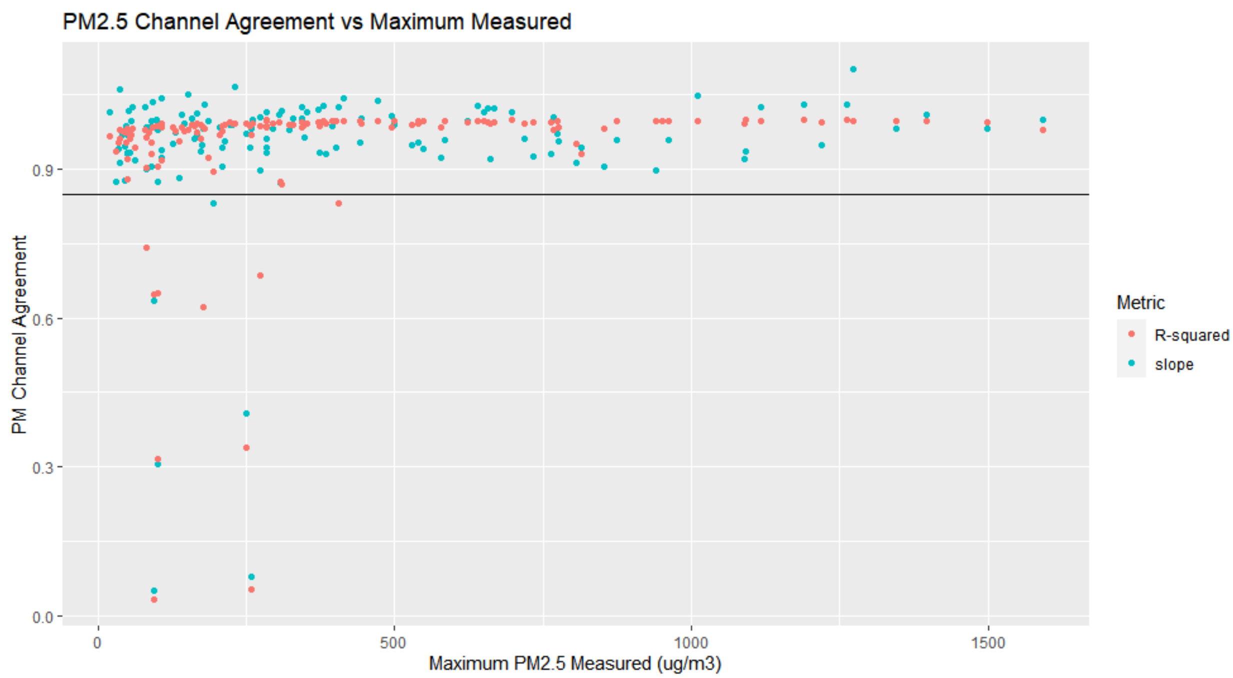

Figure 9 - PM2.5 channel agreement vs maximum measured

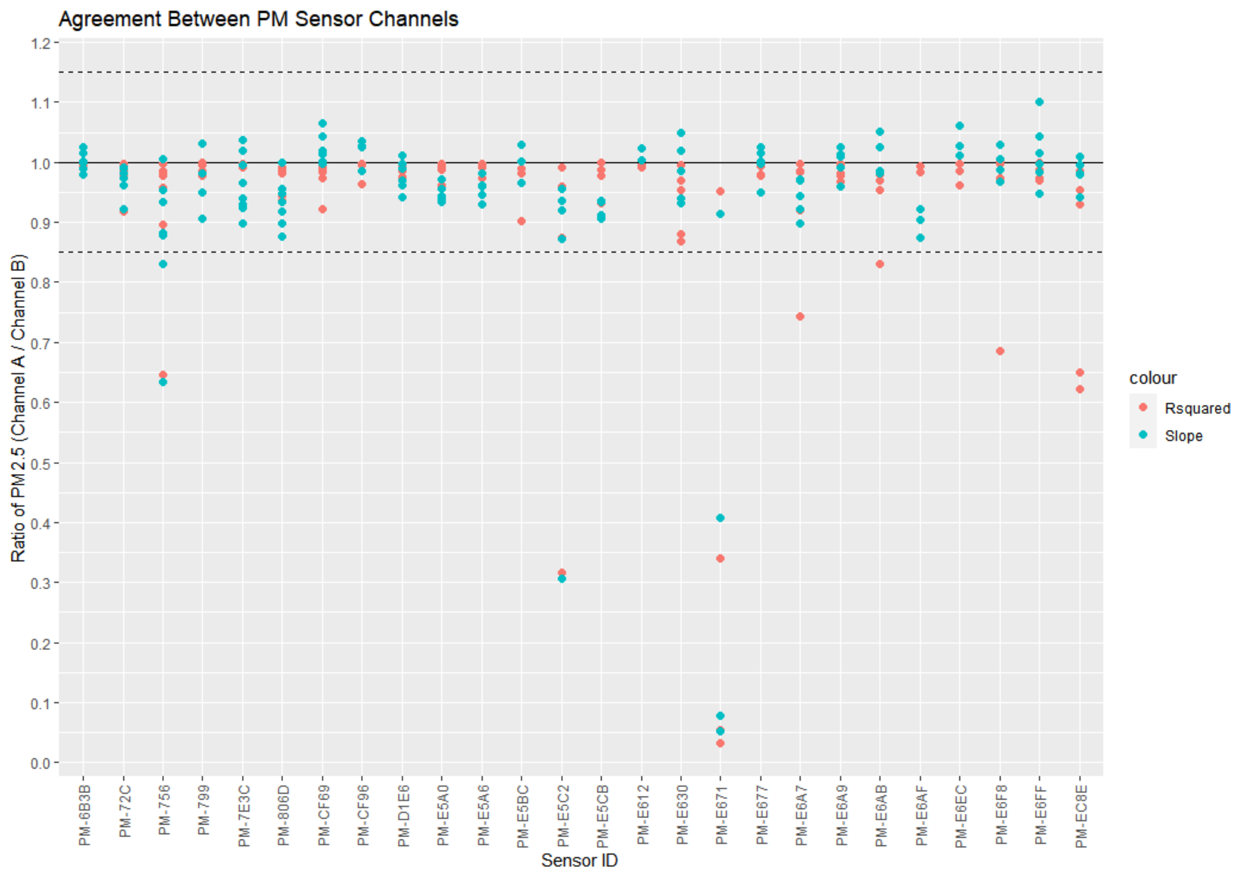

Figure 10 - PM2.5 agreement by sensor

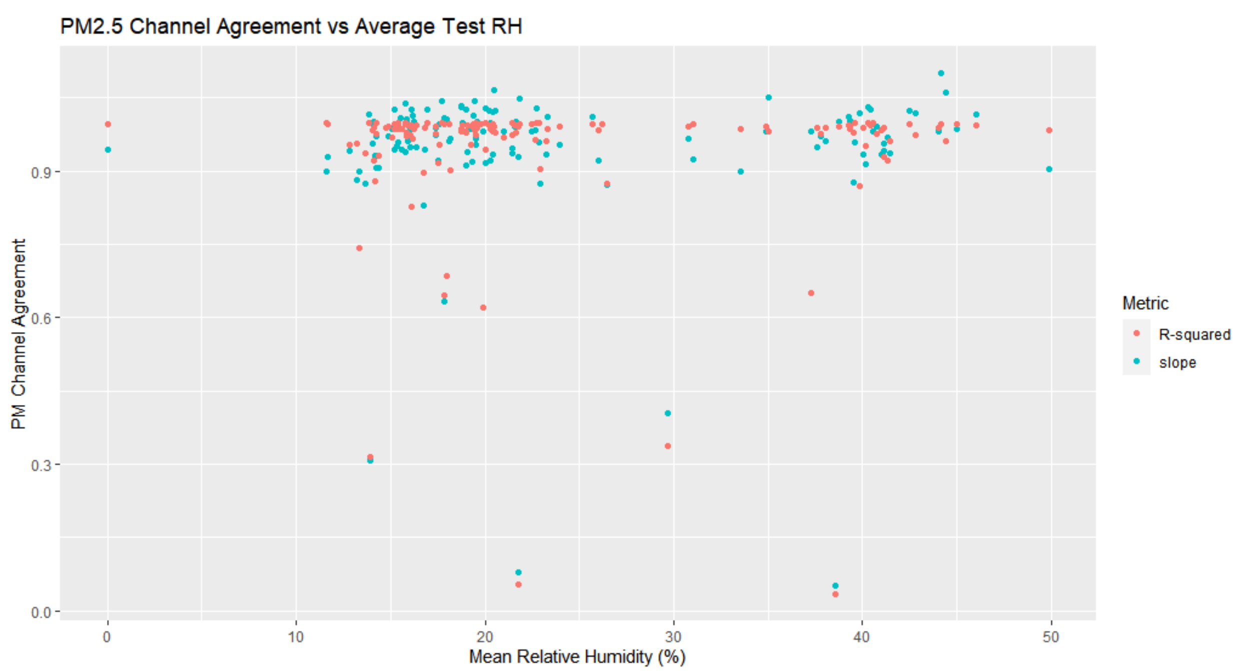

Figure 11 - PM2.5 channel agreement vs average test relative humidity

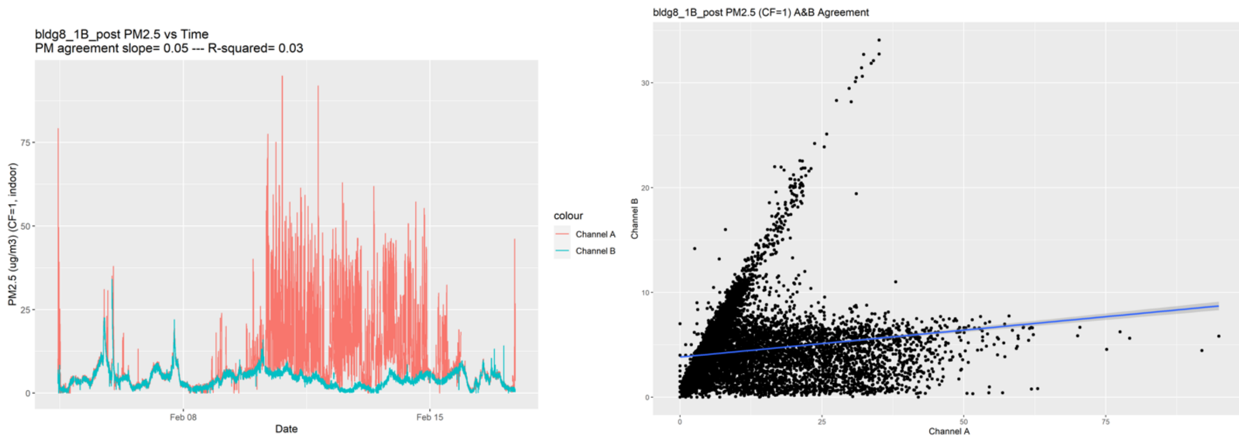

Figure 12 - Example PM2.5 data from site with worst performing sensor

- Rotronic CL11, CO_2 logger – These units have a built a in Automatic Baseline Correction (ABC) feature, where the instrument will detect the lowest stable concentration and automatically recalibrate the data to assign that minimum to 400 ppm. This feature was disabled during testing so that different sections of the data were not based on different correction factors, and to avoid mis-calibrating the sensor to non-ambient air (indoor air with levels above 400ppm). Instead, sensors were manually ABC'd simultaneously in fresh outdoor air (Figure 13) regularly and following any lengthy breaks in testing.

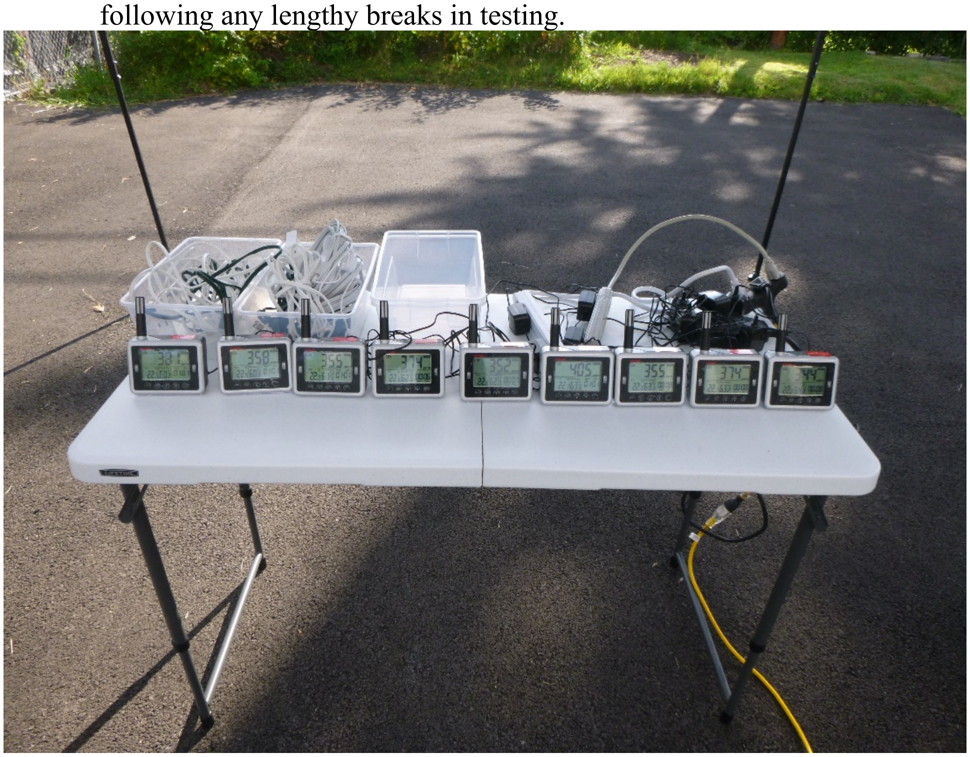

Figure 13 - CO2 Logger Calibration

- Lascar EL-USB-CO300, CO logger – These loggers lack any options for adjustment or calibration. Loggers were periodically intercalibrated against each other using CO generated from vehicle emissions. Any loggers that deviated significantly from the others were retired.
- Ogawa PS-134 with PS-100, NO_2 – The sensor is made of a single-use coated pad inside a reusable housing (Figure 14). To ensure accuracy a field blank from the same sensor batch and exposed to the same transportation and storage conditions was included with each deployment. Following each deployment, all sensor housings and screens were washed with ultrapure type 1 deionized water and allowed to air dry before reassembling.

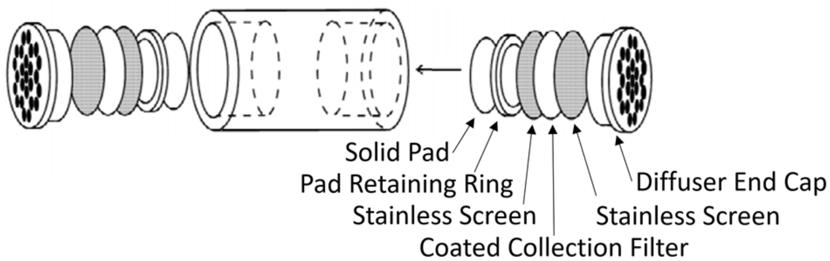

Figure 14 - NO2 filter and housing exploded view – modified from OgawaUSA.com image

  - The fieldwork stop brought upon by the COVID-19 pandemic resulted in some NO_2 sensor pads which exceeded their expiration date (unopened pack, 1 year when stored in freezer) before they had a chance to be used. These pads were used in an informal experiment to investigate the sensitivity that they have to aging. A set of four pads that were ~100 days beyond "expiration" were deployed alongside fresh pads. One was deployed as a blank, and the remaining three were deployed to measure in units. The results from this experiment are listed in Table 3. Although there was a moderate (27.3%) relative percent difference (RPD) between the blanks from the two groups, the corrections from those blanks are so small that they had a minimal impact on the measurements, and the average RPD between the fresh and expired pads were slightly over 3% regardless of whether the raw or corrected values were considered. Ogawa does not publish accuracy claims for their sensors; however, a research study which measured 53 Ogawa samplers against a reference monitor found that they underestimated concentrations by 9.1% and had an internal coefficient of variation of 6.4% (Hagenbjörk-Gustafsson, et al. 2010) ***(see Table 2).

Table 3 – Results from expired NO_2 pad comparison

Unit in Bldg6	Uncorrected NO_2 measurement (and corrected)		Relative Percent Difference	
	Fresh pad	Expired pad	Based on raw	Based on corrected
BLANK (7M)	60.3 ng	79.4 ng	27.3%	NA
7M	29.0 (28.8) ppb	27.8 (27.6) ppb	4.2%	4.3%
2E	33.2 (33.0) ppb	32.9 (32.6) ppb	0.9%	1.2%
15D	31.6 (31.4) ppb	30.3 (30.1) ppb	4.2%	4.2%

- SKC UMEx 100 Passive Sampler, Formaldehyde (HCHO) – The UMEx 100 sampler is a single use passive sampler that uses tape treated with 2,4-dinitrophenylhydrazine (DNPH) which collects formaldehyde. The sensors include a built in blank to validate that no contamination has occurred.

2.2.5 Results Reporting

Providing results reports to occupants was intentionally excluded from the procedure. The study was intended to assess weatherization impacts on building IAQ, not the influence of resident activities on IAQ. Potential participant building's administrative staff voiced concerns about disseminating individual results to occupants could potentially be used to levy complaints against building staff even if the problem was due to resident activities. Project participation could then have become a financial or legal liability. However, out of concern for the participant's safety, it was determined that we would alert individual occupants and take corrective action if pre and/or post conditions exceeded the thresholds listed in Table 4. None of these thresholds for alerting or taking corrective action were breached during this research.

Since many of the contaminants can be generated from occupant activity, it is plausible that one or a few actions (e.g. cooking) performed during the short measurement period could significantly skew the mean concentrations. For the results reporting and action-level threshold calculations, baseline levels (lowest stable concentrations) are used instead of averages for some contaminants.

Table 4 - IAQ Action Thresholds

Contaminant	Threshold	Correction Action
CO_2	Post-baseline levels above 1500 ppm and 50% higher than the pre-baseline levels	Investigate the source of the increase, and recommend or supply solutions on a case-by-case basis
Formaldehyde	Post levels above 0.15ppm (184 μg/m^3) and 50% higher than pre levels	Return for subsequent testing in ~1 month. If levels are still elevated at that time, we will provide/suggest additional ventilation or investigate the potential sources of formaldehyde
$PM_{2.5}$	Baseline levels are above 35 ug/m^3 and 50% higher than the pre baseline levels	Investigate the source of the increase, and recommend or supply solutions on a case-by-case basis
NO_2	Post levels above 0.25 ppm and more than 50% higher than pre levels	If the occupants voluntarily use unvented non-cooking combustion appliances (fireplaces, space heaters, etc.), information about proper use and safety.
		If the only unvented combustion appliances are cooking, we will educate the clients regarding the importance of using ventilation.
CO	Average concentrations above 9 ppm during any phase	Send information (after all testing is completed) to the occupants about possible sources/solutions and the risks from that exposure
	Average CO levels are above 35 ppm during any phase	Notify the occupants as soon as possible
	post CO levels are above 9 ppm and 25% higher than pre levels	Investigate possible sources and inform the homeowner. If the CO is determined to be caused by any weatherization or study activities, replacements or repairs will be made, and a no-cost low-level CO alarm will be provided.

2.3 PRESSURE DIAGNOSTICS

In order to determine airtightness of individual units, and connectivity to neighboring units, a series of pressure diagnostic tests was conducted on each main unit and any directly adjoining units. Only units sharing a surface were considered (highlighted in Figure 15); diagonally connected units were not included (grayed out in Figure 15). Non-residential spaces (e.g. stairwells, utility/storage rooms, public shared spaces, or exterior spaces) that adjoined target units were not included in the pressure diagnostics testing. One or multiple blower doors and digital manometers were setup depending on the test configuration. Manual instrument reading and recording was used instead of computerized logging to simplify the procedure due to the large number of tests and equipment necessary. Three tests were conducted:

- Test 1 – "Standard blower door test"
    - All windows and exterior/corridor doors on main unit and neighboring units closed.
    - Multiple manometers in main unit measuring in-unit pressure with respect to (WRT) neighboring units.
    - Blower door installed in main unit, and depressurized by ~-50 Pa.
    - Pressure and flow of blower door fan recorded, as well as pressure difference to all neighboring units.
- Test 2 – "Open blower door test"
    - All windows in main unit closed. Neighboring units opened to outside with exterior doors/windows or corridor doors. Corridor opened directly to outside if possible.
    - Blower door installed in main unit, and depressurized by ~-50 Pa.
    - Pressure and flow of blower door fan recorded.
- Test 3 – "Guarded test"
    - All windows and exterior/corridor doors on main unit and neighboring units closed.
    - Blower doors set up in main unit and all neighboring units (either concurrently or sequentially).
    - Main unit blower door depressurized by ~-50 Pa WRT the corridor
    - Neighboring units depressurized to 0 Pa WRT main unit, one at a time.
    - Pressure and flow of main unit blower door recorded.

$U_{i+1,j-1}$ ***Above-left***	$U_{i+1,j}$ ***Above***	$U_{i+1,j+1}$ ***Above-right***	Floor i+1
$U_{i,j-1}$ ***Left***	$U_{i,j}$ ***Main-unit***	$U_{i,j+1}$ ***Right***	Floor i
$U_{i-1,j-1}$ ***Below-left***	$U_{i-1,j}$ ***Below***	$U_{i-1,j+1}$ ***Below-right***	Floor i-1

Figure 15 - Main and Adjacent Unit Notation

Figure 16 through Figure 18 show graphic representations of the testing configurations using two manometers and two blower doors. When more equipment was available more efficient configurations could be used, by pressure testing all neighboring units simultaneously in Test 1 or having multiple blower doors set up (but all but 1 closed, capped, and off at any given time) in Test 3.

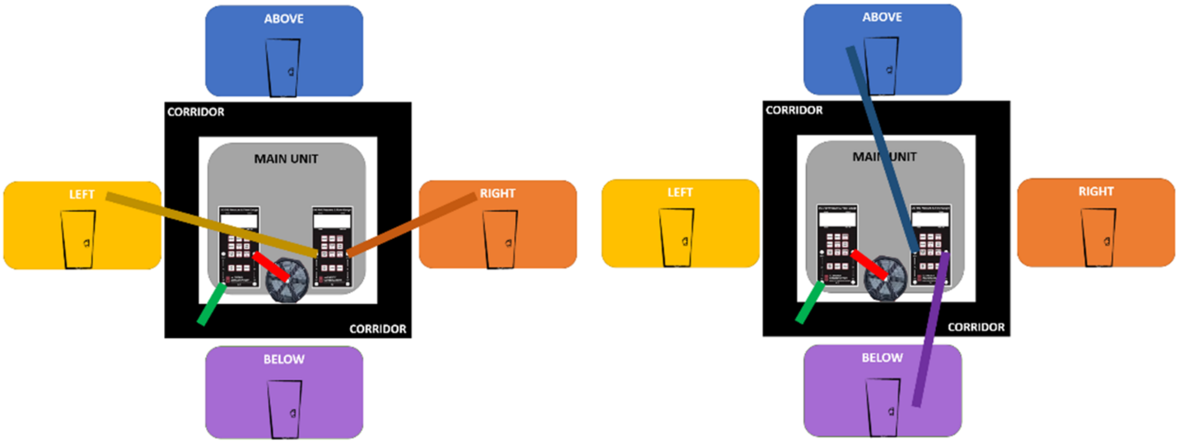

Figure 16 – Test 1 ("Standard blower door test") Configuration

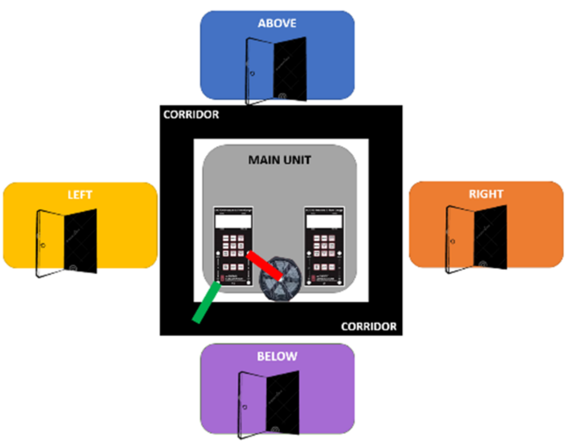

Figure 17 – Test 2 ("Open blower door test") Configuration

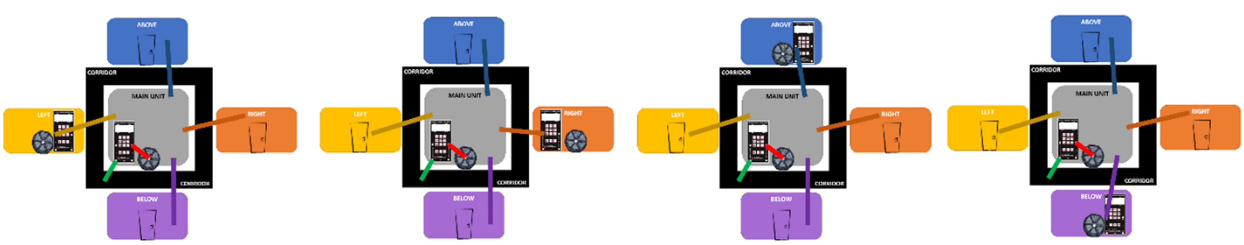

Figure 18 – Test 3 ("Guarded test") Configuration

In an effort to minimize risk to the field staff and building occupants, and in accordance with NYSHCR guidance (Moriarta 2020), pressure diagnostic testing was not conducted for buildings tested during the COVID-19 pandemic (after 3/2020), since this testing:

- increased the required quantity of on-site field-techs
- significantly increased the number of residents interacted with due to need to engage with adjoining units
- substantially added to the amount of time required in each unit
- would distribute large quantities of air from apartments with potentially infected occupants into common building spaces and adjoining units

3. RESULTS

3.1 BUILDING WEATHERIZATION RESULTS

Although extensive retrofit work was done on the building during weatherization process, this research only focuses on the work that was done which would have a direct impact on the IAQ and air tightness in the individual units. This section describes the changes made to the building's ventilation systems, and any envelope or air-sealing work that was done within the units themselves. Additional non-relevant upgrades were made to the buildings (e.g. lighting, refrigerators), which are not mentioned here.

Table 5 – Summary of air sealing and ventilation retrofits completed at each building

Building	In-unit air tightness modification	Ventilation system changes
Bldg1	• Caulk AC sleeve • Weatherstrip Un-caulked Apt Windows • Install Weatherstrip and Door Sweeps	• Replace Roof Top Fans • Clean Bathroom and Kitchen Vent Registers • Install CAR Dampers
Bldg2	• Replace w/LowE argon-filled Thermal Pane (Apartment and Common Area) • Install Weatherstrip and Door Sweeps	• Replace Roof Top Fans • Install CAR Damper • Replace Bathroom and Kitchen Vent Registers
Bldg3	• Install Weatherstrip and Door Sweeps • Install AC Sleeve Covers.	• Clean Bathroom and kitchen Vent Registers
Bldg4	• Replace w/LowE argon-filled Thermal Pane (Apartment and Common Area) • Install Weatherstrip and Door Sweeps	• Replace Roof Top Fans • Clean Bathroom and Kitchen Vent Registers
Bldg5	• None	• Replace Roof Top Fans • Clean Bathroom and Kitchen Vent Registers
Bldg6	• Install Weatherstrip and Door Sweeps • Install AC Sleeve Covers.	• Replace Roof Top Fans • Clean and replace Bathroom and Kitchen Vent Registers
Bldg7	• Install Weatherstrip and Door Sweeps	• Clean Bathroom and Kitchen Vent Registers
BldgX	• None	• Installed 20 local ventilation fans with run time switches in corner units (which previously did not have any ventilation) o Including four of the tested units

Table 5 describes the retrofit measures relevant to ventilation and in-unit air sealing that were completed at each site. The most common ventilation measures were cleaning/replacing registers (7 out of 8) and replacing rooftop fans (5 out of 8), the rooftop fans at building X had been progressively replaced in the years leading up to the weatherization retrofit and were sufficiently modern when audited to not justify replacement. Two sites had Constant Airflow Regulators ("CAR Dampers") installed, which are mechanical devices that modulate the opening size to provide a consistent ventilation rate at a range of pressures. The most common air sealing retrofit was installing weatherstrip and door sweeps, which occurred at 6 out of 8 sites. Two sites had the windows in the units replaced, an intervention with the potential to drastically change unit-to-outdoor leakiness depending on the condition of the original windows.

Table 6 - Changes in ventilation rate (only units with both pre and post ventilation measurements)

Bldg	Unit	Ventilation location	Ventilation (∑CFM)		Change in ventilation rate (CFM)	ASHRAE 62.2 ventilation rate (CFM)	Deficiency relative to 62.2	
			Pre-Wx	Post-Wx			Pre-Wx	Post-Wx
Bldg1	10F	bathroom	0	50.3	50.3	15.6	**15.6**	-34.7
	11L	bathroom	16.9	55.3	38.4	39.5	**22.6**	-15.8
	12K	bathroom	14.1	58.8	44.7	50.6	**36.5**	-8.2
	4J	bathroom	12.8	15.5	2.7	39.1	**26.3**	**23.6**
Bldg2	1H	kitchen + bathroom	52.2	58.5	6.3	31.8	-20.4	-26.7
	1J	kitchen + bathroom	32.6	57.5	24.9	31.7	-0.9	-25.8
	3P	kitchen + bathroom	55.3	75.5	20.2	31.7	-23.6	-43.8
	3Q	kitchen + bathroom	77	57.5	-19.5	32.8	-44.2	-24.7
	4E	kitchen + bathroom	34.6	78.2	43.6	20.0	-14.6	-58.2
	4H	kitchen + bathroom	51.3	70.7	19.4	31.8	-19.5	-38.9
	6E	kitchen + bathroom	54	68.8	14.8	20.0	-34	-48.8
	6H	kitchen + bathroom	45.7	55.1	9.4	31.8	-13.9	-23.3
Bldg3	12F	bathroom	118	63.4	-54.6	21.8	-96.2	-41.6
	12G	bathroom	43.1	58.9	15.8	50.0	**6.9**	-8.9
	15H	bathroom	12.3	62.7	50.4	50.0	**37.7**	-12.7
	15I	bathroom	93.7	66.4	-27.3	37.5	-56.2	-28.9
	1G	bathroom	21.9	52.9	31	50.0	**28.1**	-2.9
	5D	bathroom1 + bath2	12.4	79.6	67.2	66	**53.6**	-13.6
	5I	bathroom	59.8	74.9	15.1	37.5	-22.3	-37.4
BldgX	G5	bathroom (added)	0	43.9*	43.9	15	**15**	-28.9
	208	bathroom (added)	0	94*	94	15	**15**	-79
	308	bathroom (added)	0	56.4*	56.4	15	**15**	-41.4
	512	bathroom (added)	0	52.7*	52.7	15	**15**	-37.7
	G4	bathroom	68	69.5	1.5	15	-53	-54.5
	207	bathroom	67.6	93.1	25.5	7.5	-60.1	-85.6
	307	bathroom	53	173	120	7.5	-45.5	-165.5
	503	bathroom	121.8	72	-49.8	15	-106.8	-57
*These fans were newly installed as part of the weatherization retrofit with "run time switches", it is unknown how regularly or frequently they were operating.								

Table 6 describes the ventilation rates at all units where both pre-Weatherization and post-Weatherization flow rates are available. The column "ASHRAE 62.2 ventilation rate (CFM)" shows the prescribed ventilation rate based on ASHRAE 62.2-2016 using Equation 1 (where studio apartments are treated as having zero bedrooms). The columns "Deficiency relative to 62.2" shows the difference between the flow rate during a phase, and the required flow rate, with a positive number indicating a deficiency and a negative number indicating excess flow; Only 1 site out of 23 with data available had a deficiency relative to the 62.2 rate following weatherization, despite having a slight increases in flow rate relative to pre-weatherization.

$$Q_{total} = 0.03 * Floor\ Area\ (sqft) + 7.5 * (Quantity_{bdrms} + 1)$$

Equation 1 - ASHRAE 62.2-2016 Required Flow Rate Calculation For Existing Buildings

3.2 IAQ RESULTS

The following sections describe the results from the IAQ measurements. Table 7 provides the sample wide summary of results across units showing average values of all collected data. The Pre/Post-median columns represent the sample wide mean of the real-time data median values at the individual sites; for some event based contaminants medians can be a better representation of typical levels since they are less susceptible to short term event driven spikes. Due to inconsistencies in the availability of outdoor ambient measurements, these results are not presented as elevations above outdoor conditions. Each contaminant is discussed individually in the following subsections.

Table 7 - IAQ Results Summary

Contaminant (units)	Pre-mean (SD)	Post-mean (SD)	Pre-median (SD)	Post-median (SD)
Formaldehyde (ppb)	7.8 (±6.3)	7.7 (±5.5)	NA*	NA*
PM2.5 (µg/m^3)	18.5 (±23.6)	28.1 (± 57.0)	10.3 (±15.4)	16.8 (±43.9)
CO (ppm)	0.5 (±1.1)	0.6 (±1.2)	0.1 (±0.4)	0.2 (±0.7)
CO_2 (ppm)	638 (±217)	583 (±127)	587.4 (±177.1)	547.7 (±112.3)
NO_2 (ppb)	29.0 (±23.3)	24.1 (±10.9)	NA*	NA*
* Not real-time data, so no way to calculate individual median values.				

3.2.1 Carbon Dioxide

Carbon Dioxide (CO_2) occurs naturally in ambient air. Current outdoor concentrations are near 400 ppm, although global concentrations vary seasonally, and local concentrations can vary daily (Imasu and Tanabe 2018). Because CO_2 is generated by human respiration, indoor levels can be much higher than outdoor levels and are often used as a metric for evaluating ventilation levels. Another common source of CO_2 in residential settings is unvented combustion, including gas-cooking appliances. Ideally, indoor levels are kept close to outdoor concentrations, because elevated CO_2 levels have been associated with lower cognitive ability (Du, et al. 2020). A common recommendation is to keep CO_2 levels at no greater than 700 ppm above outdoor, which is about 1100 ppm. This metric is often used to classify a space as having adequate ventilation (ASHRAE 2018).

Figure 19 shows the distribution and sample wide median of mean CO_2 levels in each unit differentiated by phase and by cooking fuel. Overall mean levels were comparable pre and post-weatherization, and with overlapping standard deviations (Table 7). In the pre-weatherization sample, the median CO_2 levels were noticeable higher in the sites with gas kitchens (666 ppm ±237) vs those with electric (505 ppm ±54). The difference between gas and electric is much less substantial during the post testing (gas: 566±134, electric: 527±35), but it is important to caveat that there is only one site with electric kitchens that has data from the post-testing period.

Looking at individual buildings (Figure 20), of the seven buildings that have pre and post CO_2 data, three of them (bldg1, bldg2, bldg6) had significant reductions in CO_2 concentrations, while the remaining four (bldg3, bldg4, bldg5, bldgX) stayed essentially the same. All three of the buildings with substantial CO_2 reductions had their roof top fans replaced; only two out of the four with minimal change in the CO_2 levels had their roof top fans replaced, although one of those did have additional bathroom exhaust fans installed in the units previously lacking mechanical ventilation.

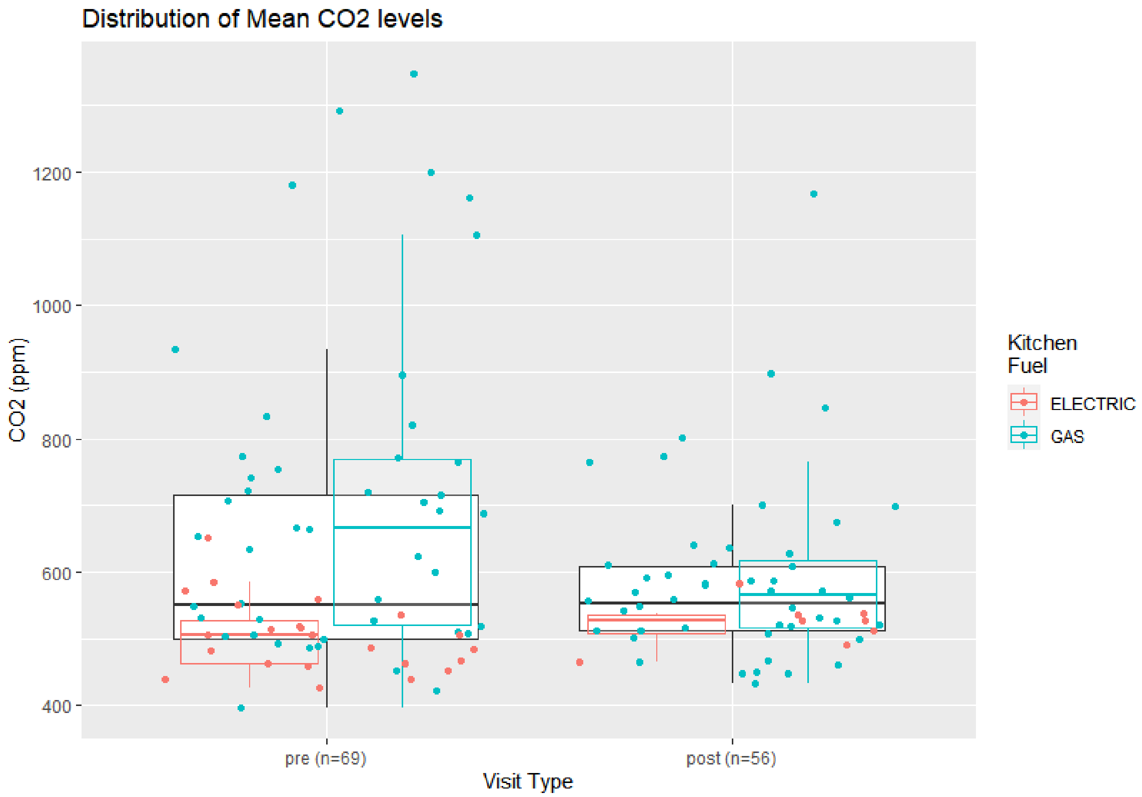

Figure 19 - Distribution of mean CO2 levels

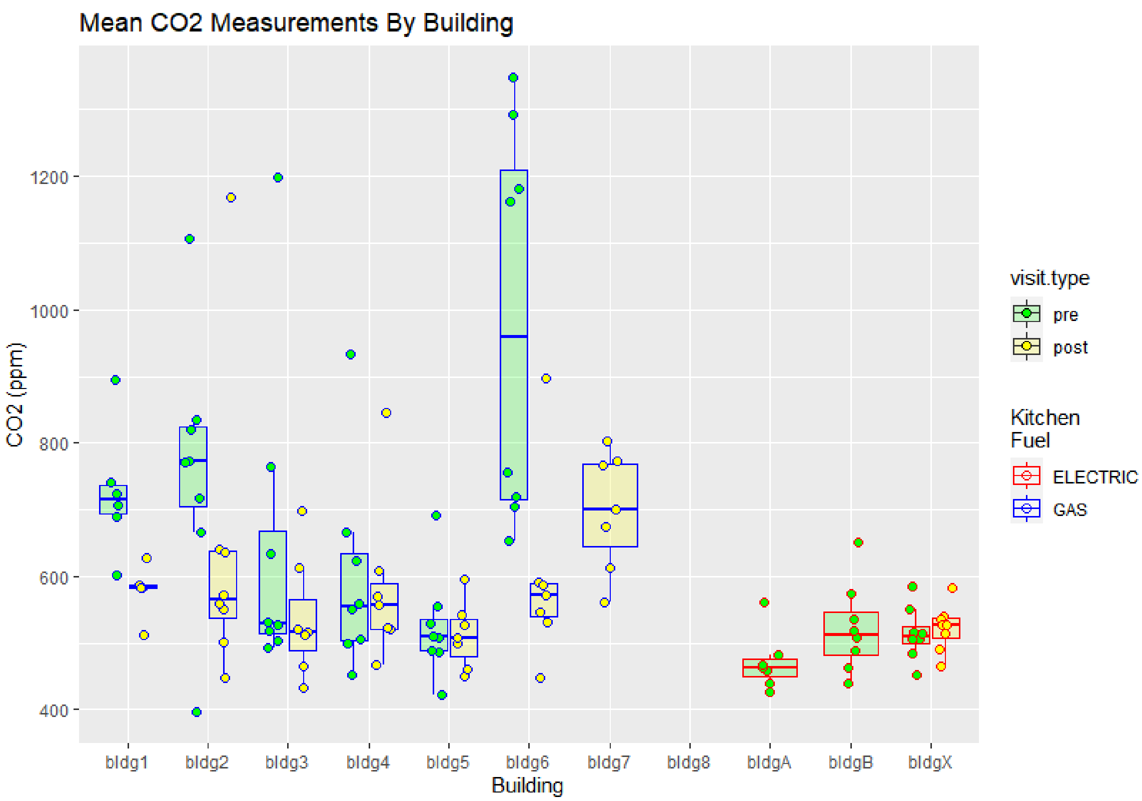

Figure 20 - Mean CO_2 concentration by building and phase

Figure 21 shows the mean real-time CO_2 concentrations minus the real-time outdoor measurements. As expected (with very few exceptions) the indoor concentrations were above the outdoor levels. The sites where the levels were near the dotted line at zero, suggest those buildings had good ventilation and/or high leakage rates to the outdoors.

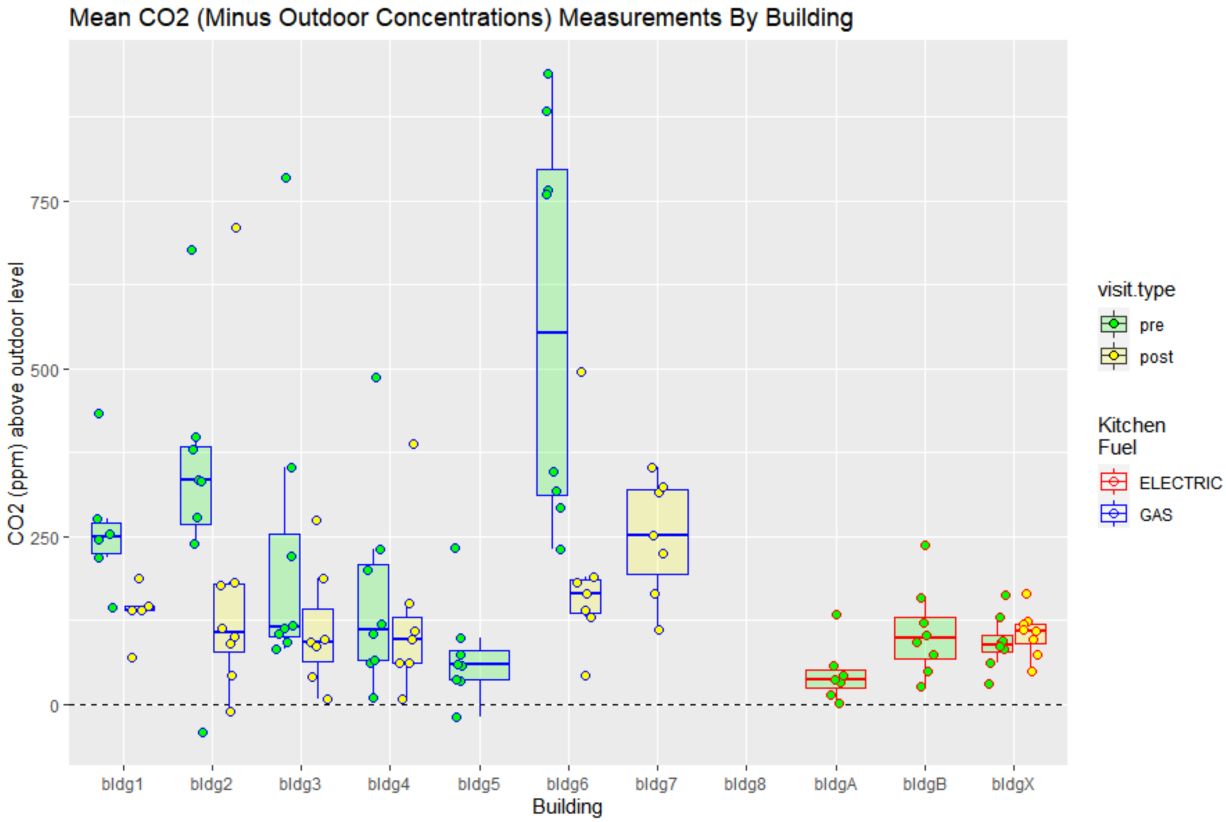

Figure 21- Mean CO_2 concentration by building and phase minus outdoor concentration

3.2.2 Carbon Monoxide

Carbon monoxide (CO) is a poisonous gas that is generated as a result of incomplete combustion. Ideally, indoor CO concentrations are close to zero. Figure 22 shows the distribution and sample wide median of mean CO measurements for all sites differentiated by phase and by kitchen fuel. One site exceeded the WHO's 24-hr guideline for CO by ~15%. CO concentrations in sites without gas kitchens were consistently low, with the highest mean value at ~0.77ppm, and an overall median value near zero. Sites with gas kitchens had a median CO value of 0.25ppm. None of the weatherization retrofits included upgrading the kitchen stoves or other potential sources of CO generation in the apartments.

Figure 23 shows the maximum measured 8-hour average CO levels in the same format as Figure 22. No sites with non-gas kitchens exceeded the EPA NAAQS (an outdoor standard) 8-hr maximum of 9 ppm, and the sample wide median levels were below the EPA NAAQS for both the pre and post phase. Many sites with gas kitchens exceeded the EPA NAAQS, but only one exceeded the OSHA 8-hr PEL. It seems clear that gas cooking is a major contributor to indoor CO levels at these sites. Because there were similar elevations in homes with gas cooking both before and after retrofit, the elevations are unlikely due to weatherization but rather to occupant behavior and unused or unavailable kitchen ventilation.

Figure 24 shows CO measurements split up for individual buildings. The lack of post-weatherization data from buildings 3, A, B, and X where pre-weatherization CO measurements were relatively low is likely a strong contributor to the higher overall post-weatherization CO numbers.

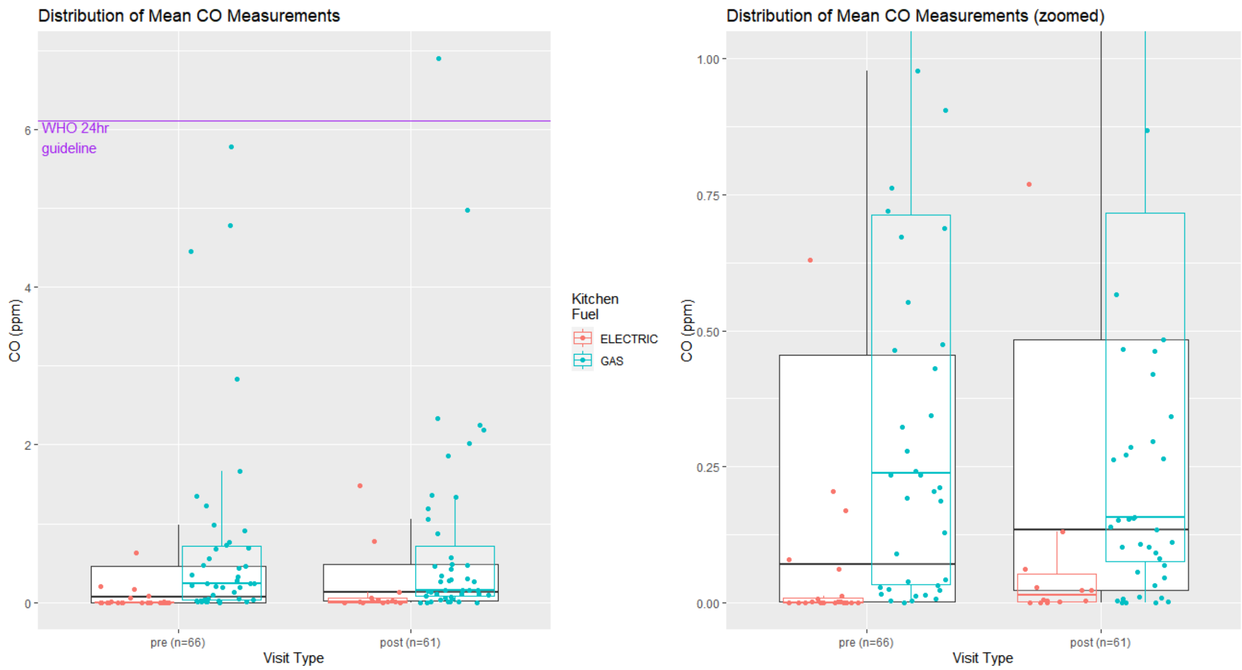

Figure 22 – Mean CO concentrations by phase (left all data, right detailed zoom with outliers excluded)

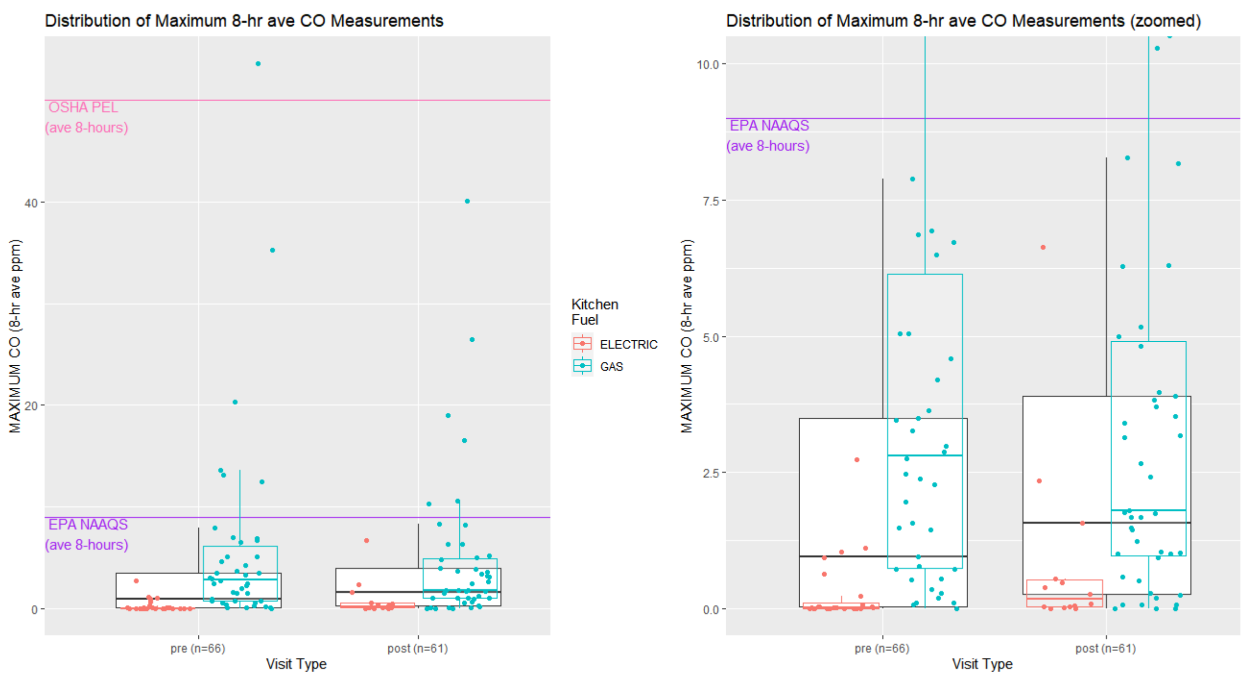

Figure 23 – Maximum 8-hr CO concentration by phase

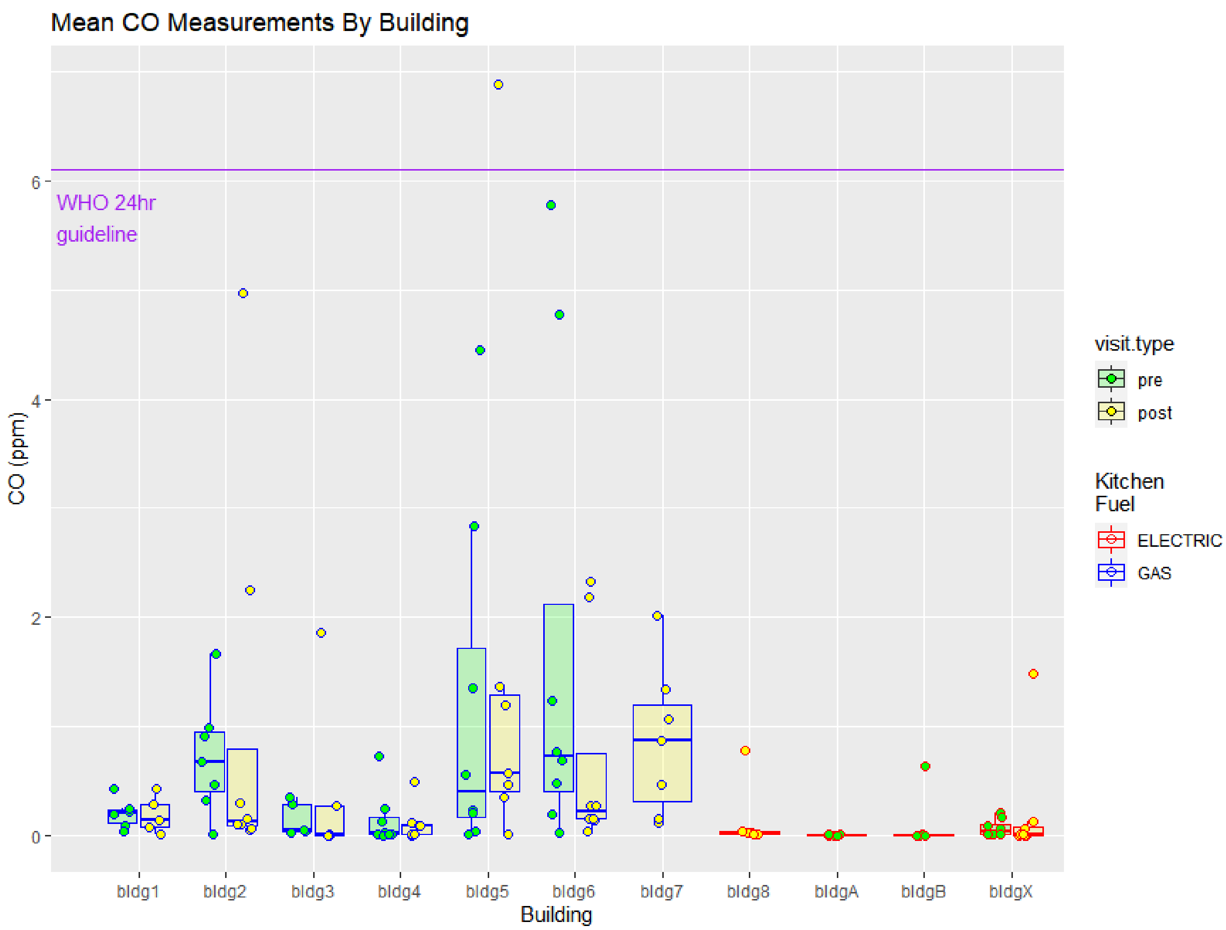

Figure 24 – Mean CO concentration by building and phase

3.2.3 Particulate Matter

Figure *25* shows the distribution of $PM_{2.5}$ measurements by testing phase (left=all data, right= zoomed in for detail), and Figure 26 shows the same data broken down by building (outliers are not shown for better visibility). On average the levels were reasonably low, with sample-wide median levels near the WHO annual mean air quality guideline of 10 µg/m^3, regardless of phase or cooking fuel. Although this guideline is intended for outdoor ambient levels, "the WHO AQG for PM can also be applied to the indoor environment" (WHO 2006).

Figure 25 – Distribution of mean $PM_{2.5}$ levels by phase (left = all data, right = detailed view)

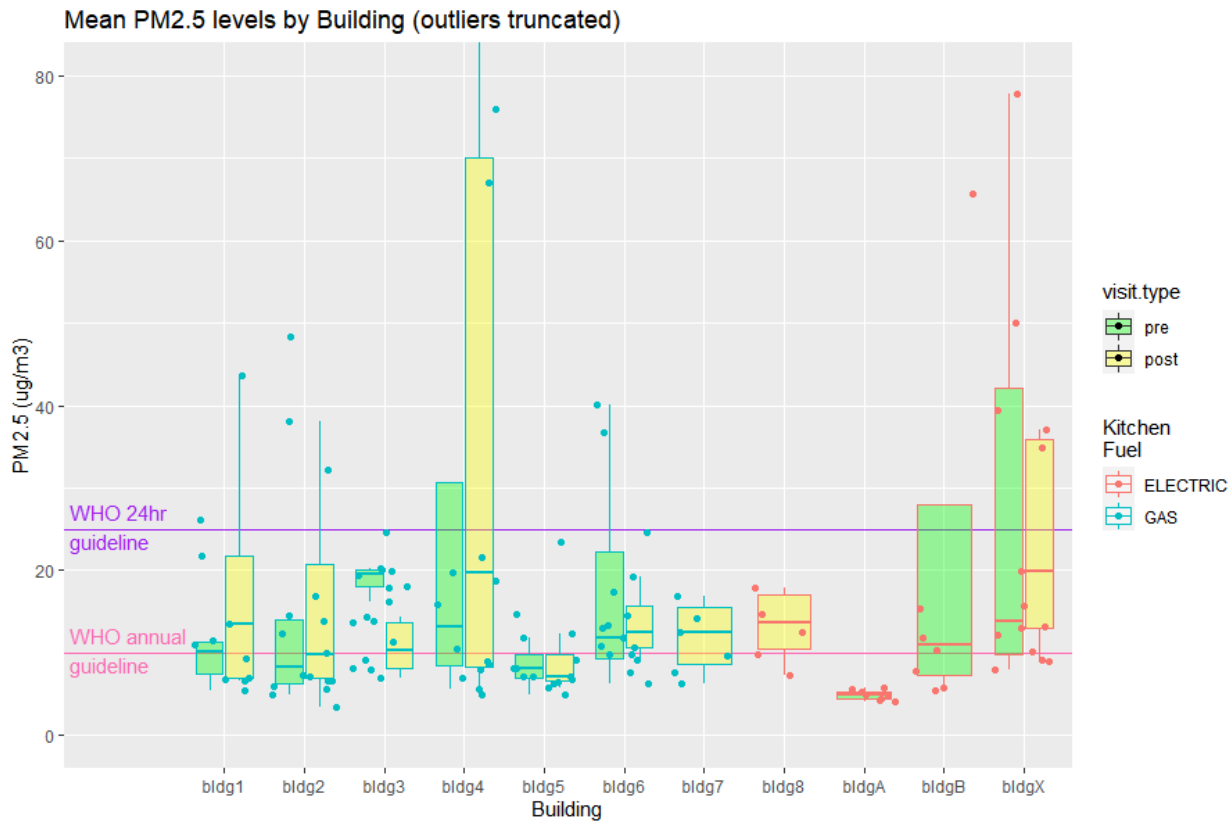

Figure 26 - Distribution of Mean $PM_{2.5}$ Levels by Building

Similar to the WHO, the US EPA does not have a set guideline for $PM_{2.5}$ levels in indoor air, but they do have an Air Quality Index based on concentration for outdoor air. Most of the tests (~86%) fell into the "Good" or "Moderate" range, but some tests had concerning levels of $PM_{2.5}$; the highest tested unit had $PM_{2.5}$ concentrations in the "Hazardous" range, and nine tests (6.7%) were within the "Very Unhealthy" or Unhealthy" range on the EPA scale. Breakpoints and number of units within each category are shown in Table 8. Given the similar distribution and averages for both the pre-weatherization and post-weatherization measurements, it is not suspected that the weatherization process resulted in a significant change in $PM_{2.5}$ levels. Further evidence that high levels are not due to weatherization is that high readings are relegated to individual units, not entire buildings.

Table 8 - EPA Air Quality Index and distribution

Air Quality Label	AQI Range	# of tests*	Percentage
Good	0 - 12	70	52.63%
Moderate	12.1 - 35.4	45	33.83%
Unhealthy for Sensitive Groups	35.5 - 55.4	8	6.02%
Unhealthy	55.5 - 150.4	6	4.51%
Very Unhealthy	150.5 - 250.4	3	2.26%
Hazardous	250.5 - 350.4	0	0.00%
Hazardous	350.5 - 500	1	0.75%
*Note this column refers to the total number of tests completed, a unit with both a pre and post-test would be counted twice, whereas a post-only or incomplete building will only be represented once, potentially skewing the numbers.			

Figure 27 shows the $PM_{2.5}$ concentrations minus the real-time outdoor to correct for $PM_{2.5}$ in the ambient outdoor air. Values below the dashed line at zero indicate that concentrations indoors are lower than those outdoors, and in these situations additional ventilation has the potential to degrade the IAQ conditions by bringing in dirtier outdoor air. On average, most units had $PM_{2.5}$ concentrations that approximated outdoor conditions; concentrations that exceeded ambient levels were likely a result of occupant activities (e.g. cooking).

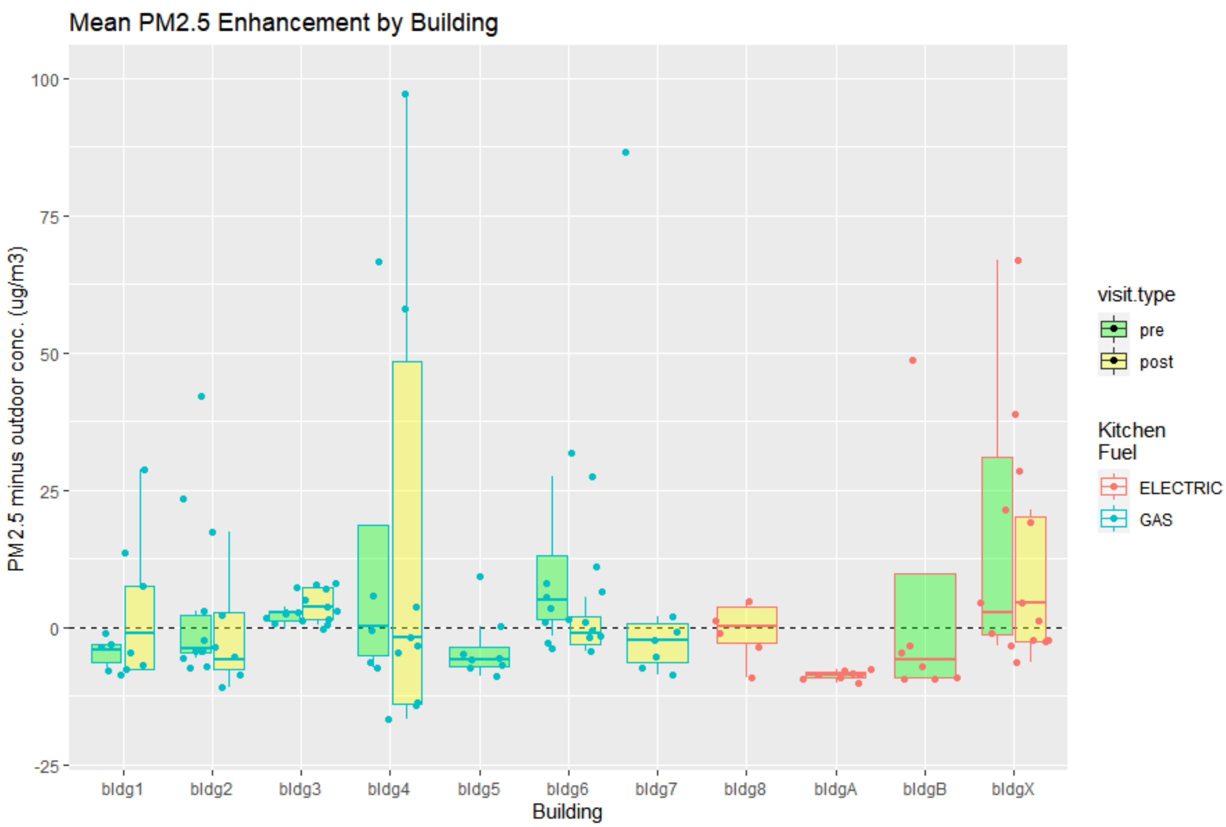

Figure 27 – Mean Real-Time $PM_{2.5}$ Concentration Elevation above Outdoor Measured Levels

3.2.4 Nitrogen Dioxide

The following figures show the distribution of NO_2 concentrations measurements by phase (Figure 28) and by building (Figure 29). Superimposed on each graph are two purple horizontal lines: the solid line labeled "NAAQS" denotes the US EPA's annual NO_2 National Ambient Air Quality Standard of 53ppb, and the dashed line labeled "WHO" denotes the World Health Organization's guideline for annual NO_2 levels of 21.3ppb (40 µg/m^3). It is important to note that both of these levels are intended for outdoor ambient air. WHO does have a 1-hour NO_2 guideline for indoor air of 106 ppb (200 µg/m^3), although we were not able to measure for that short of a duration, only 1 unit exceeded that level during any phase of testing.

Only 8 of the 107 measurements exceeded the EPA's NAAQS level, and half of those were from a single building (building 2 – pre-weatherization) (Figure 29). This building was the only instance where median levels exceeded the NAAQS; however, during the post-weatherization testing the levels were much lower with the median below the NAAQS, and nearly down to the WHO annual guideline level.

For a variety of reasons, outdoor measurements were not conducted or successfully completed at several sites. Outdoor measurements exceeded the WHO annual guideline at 4 of the 8 instances where they were successfully completed and analyzed. For all sites with outdoor NO_2 measurements, the outdoor level was outside of the interquartile range (IQR) of the indoor measurements. For both of the sites with non-gas kitchens and outdoor NO_2 data, the outdoor level was above the IQR. For all but one of the sites with gas kitchens, the outdoor level was below the IQR, except for building 4 post-weatherization where it was above.

Similar to CO, NO_2 levels were noticeably higher at sites with gas kitchens compared to those with electric kitchens. This is not surprising since gas-cooking emissions are a known source of NO_2. None of the individual units with electric kitchens exceeded the WHO annual guideline.

Building A had the lowest overall NO_2 levels for any building (median = 2.2 ppb). In addition to the absence of gas-cooking appliances, this building (along with building B which did not have NO_2 tested due to an equipment supply issue), is located in upstate New York near the Canadian border in a relatively low population density area where outdoor NO_2 levels are presumably low (although they were not tested due to equipment supply issues). This combination of factors likely resulted in the low levels. In contrast, building X also lacks gas kitchens, but it is located in a much more populated part of upstate New York; building X had significantly higher NO_2 levels with a median of 10.7 ppb, which was very close to the building X outdoor measurement of 12.0 ppb.

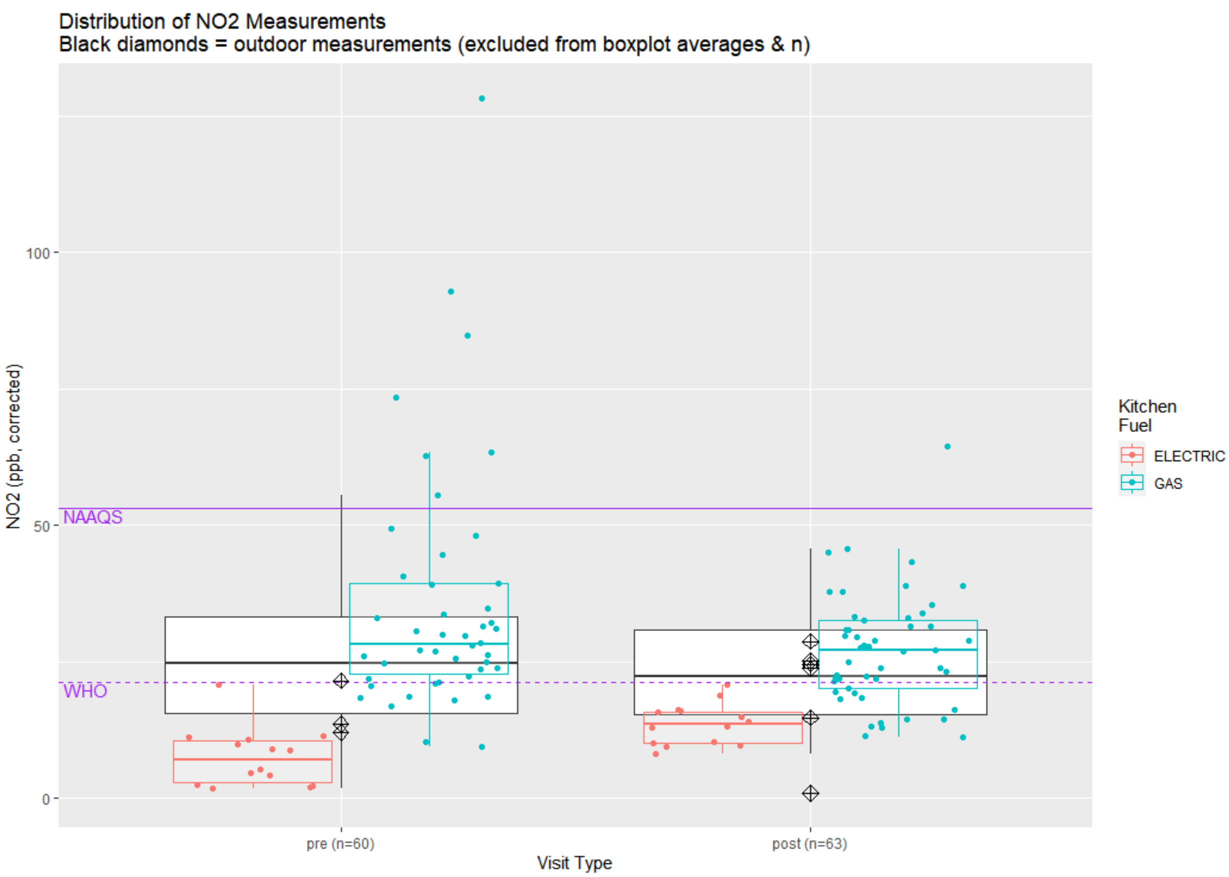

Figure 28 –NO_2 measurement distribution by phase

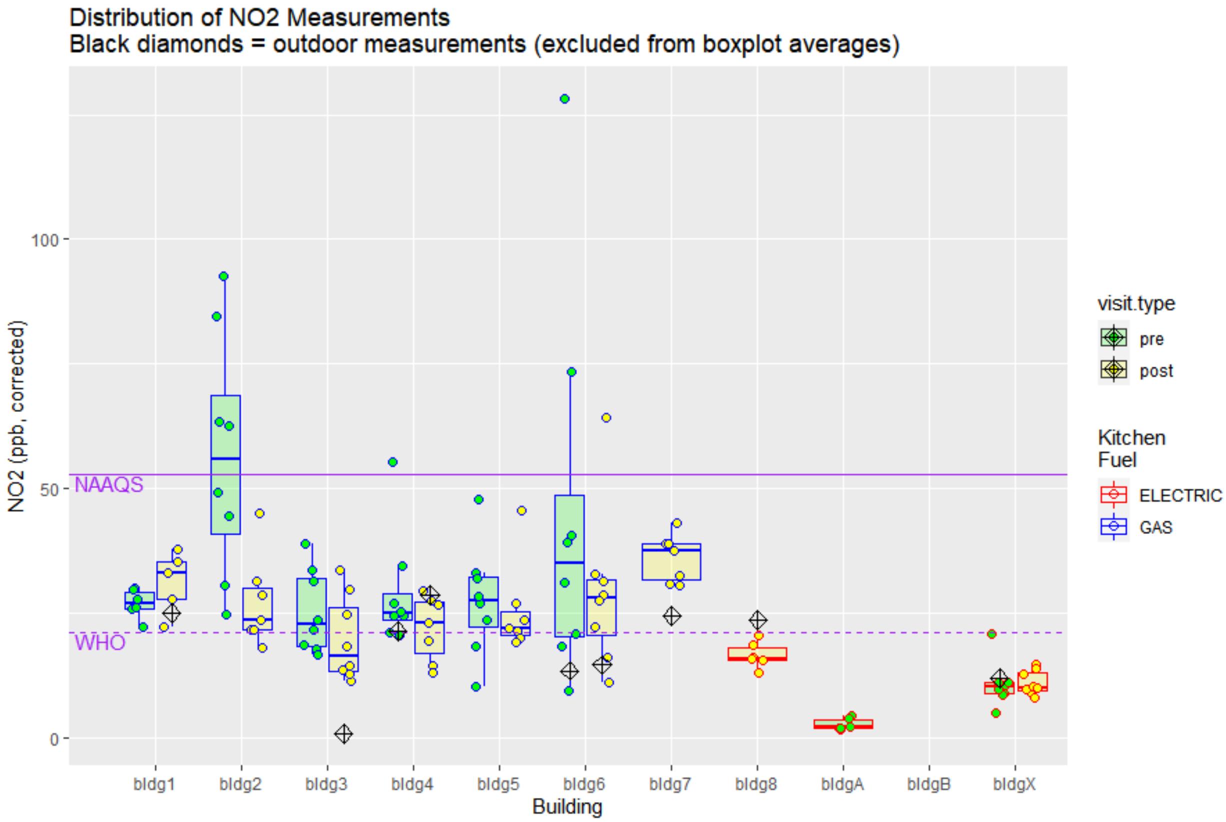

Figure 29 – NO_2 measurements distribution by building

Figure 30 shows the NO_2 concentrations less the outdoor measured values for buildings and units that have both measurements. Readings near the dotted line at zero indicate that the indoor and outdoor levels are similar. For the units where data is available, only one apartment with electric cooking appliances had a measured NO_2 concentration that exceeded the outdoor level. At the sites with gas cooking, in general the indoor levels were higher than the outdoor levels. One interesting exception is at building 4, where the pre-weatherization concentrations were near or slightly above the outdoor levels, but the post-weatherization levels were all at or below the outdoor levels.

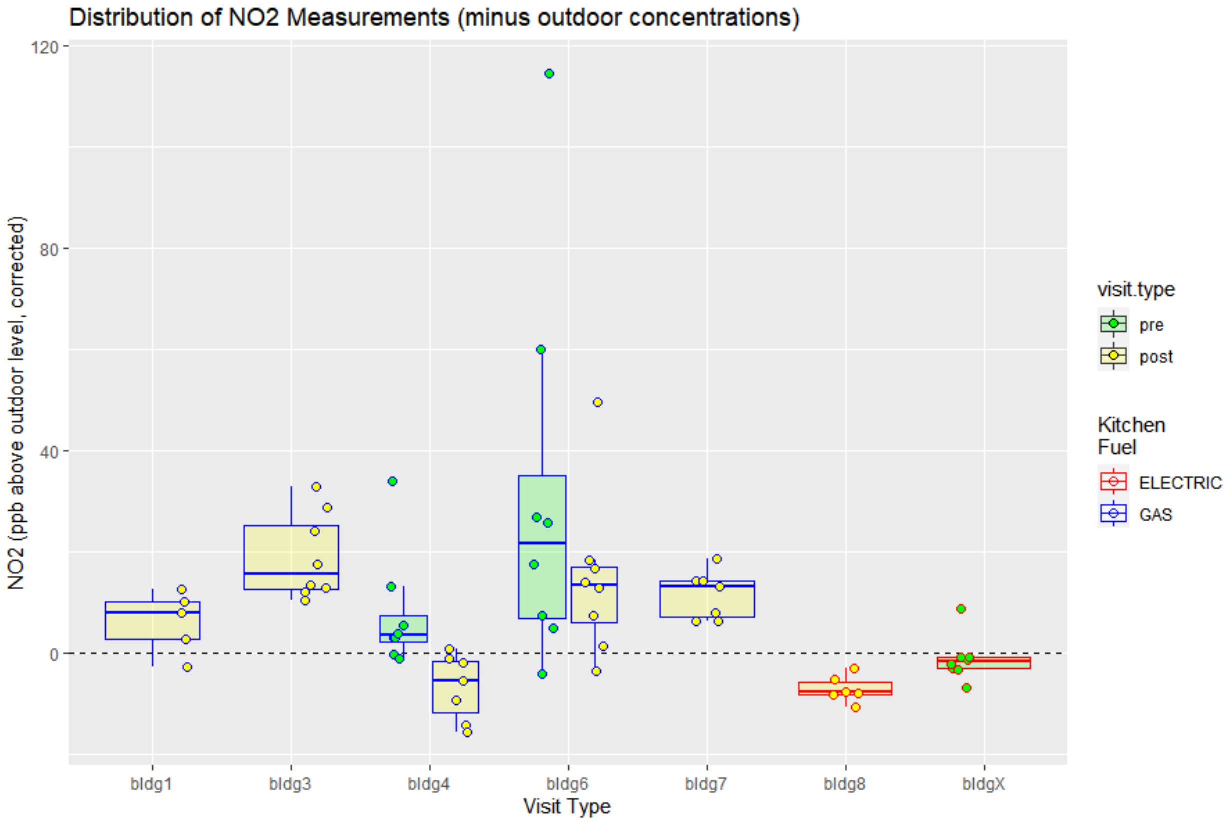

Figure 30- NO2 measurements above outdoor concentrations distribution by building

3.2.5 Formaldehyde

Measured formaldehyde concentrations were generally low. The median concentration was 6.4 ppb for both pre-weatherization and post-weatherization tests (Figure 31) which is an order of magnitude lower than the WHO guideline of ~80 ppb (0.1 mg/m^3, 30-minute average concentration). The highest individual test measured 36 ppb, which is still less than half of the WHO guideline. There is not a statistically significant difference between the pre-weatherization (7.8 ppb) and post-weatherization (7.7 ppb) results ($p=0.92$).

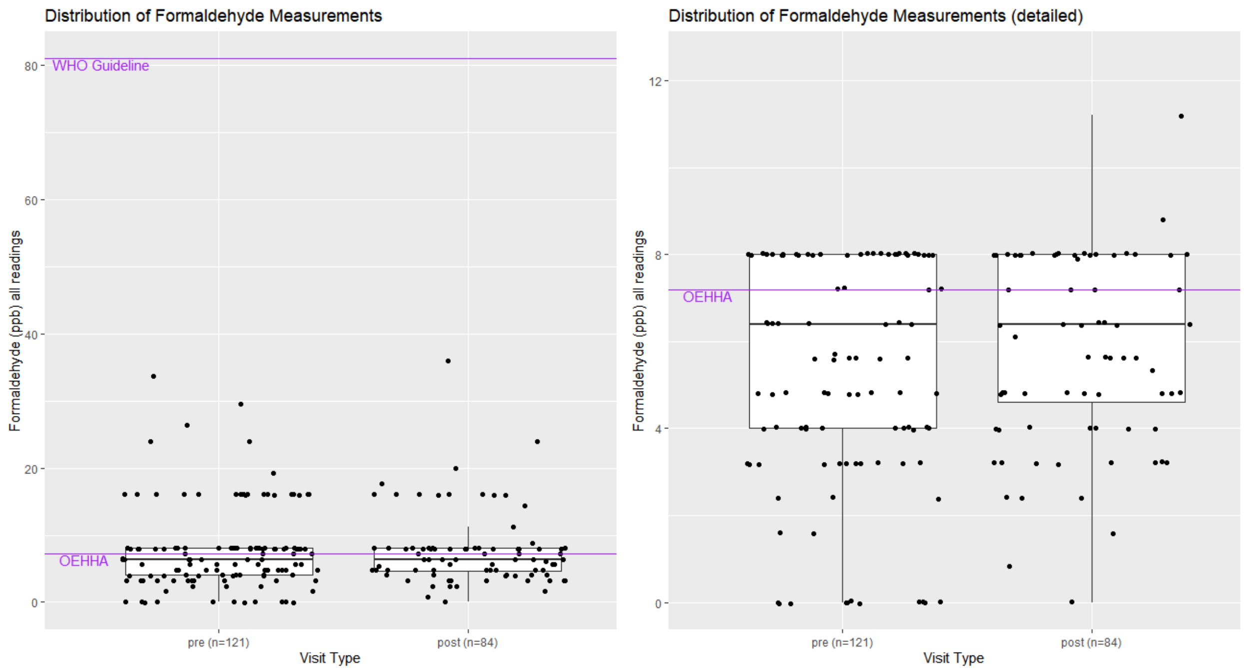

Figure 31 - Formaldehyde distribution by phase (left= all data, right = detailed zoom with outliers removed)

3.3 BLOWER DOOR DIAGNOSTICS RESULTS

Blower door diagnostics in large multifamily buildings is complicated. In addition to the multiple manometers, fans, hoses, doors, and apartment configurations that need to be set up and operated correctly, interference from external sources, such as changing wind conditions, elevator movement, and toggling of uninvolved exterior building doors/windows, can generate noise in the pressure diagnostics data.

In an attempt to visualize the abundance of data collected from the series of blower door tests performed on a unit, the following graphs were generated. Figure 32 shows all the blower door data for two example units, on a polar graph where zero is at the center. For all metrics represented, teal represents pre-data, and pink represents post-data. In the graph, the solid circles represent the CFM50 from the standard blower door test, and the dotted circles represent the CFM50 from the blower door test with the neighboring units open to outside. The diamonds represent the guarded test results for individual units where both the main unit and a neighboring unit are depressurized to the same level, negating airflow between those units.

Graphs that are all teal indicate that only pre-weatherization blower door testing was done, those that are all pink indicate that only post-weatherization blower door testing was done. Tests with a gray-ish circle in the middle indicate that both pre-weatherization and post-weatherization blower door testing was conducted; those with a teal ring around them indicate that the pre-testing was leakier, and those with a pink ring indicate that post testing was leakier, with the size of the ring proportional to the difference between tests.
Equivalent graphs for the rest of the units are included in Appendix D – Blower door results.

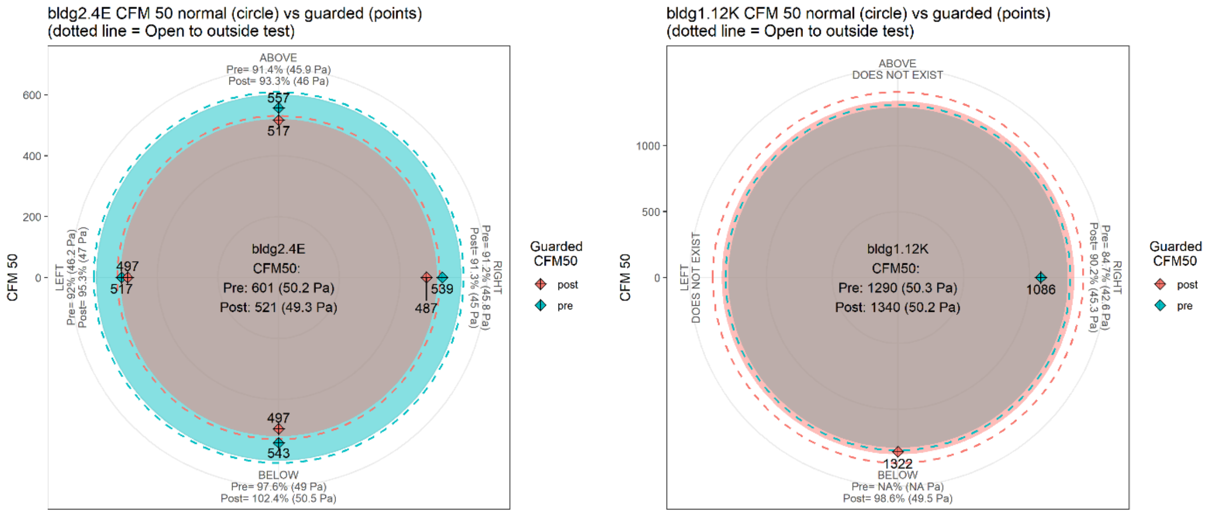

Figure 32- Example Blower Door Visualizations

Of the 69 units where blower door testing was completed, only twelve had both pre and post testing, all of which were from building 1 and building 2. Of those twelve, eight suggested that the unit was less leaky following weatherization, and 4 suggested that the unit was more leaky (Table 9). All seven of the building 2 units that had both pre- and post-weatherization blower door data indicated less leakage following weatherization; this was one of only two buildings where windows were replaced as part of the weatherization process, suggesting that this is likely a real change in unit tightness and not a result of equipment of procedure issues.

In contrast, at building 1, four of the units indicated an increase in leakiness, and one indicated a reduction. Windows were not replaced on this building, and minimal changes to the individual units occurred (caulking AC sleeve, and weatherstrip installed on windows and doors) which were likely to affect unit tightness and connectivity.

Table 9 - Blower door results at sites with pre and post testing

Site	CFM50 Pre	CFM50 Post	% Change
bldg1_10F	551	599	9%
bldg1_11L	907	1273	40%
bldg1_12F	516	588	14%
bldg1_12K	1290	1340	4%
bldg1_4J	1835	1557	-15%
bldg2_1H	815	670	-18%
bldg2_3P	724	601	-17%
bldg2_3Q	744	693	-7%
bldg2_4E	601	521	-13%
bldg2_4H	474	358	-24%
bldg2_6E	1238	797	-36%
bldg2_6H	904	640	-29%

Figure 33 - Figure 41 show the leakage for all units in each individual building. In the graphs, the gray bar represents the total amount of leakage measured during the standard blower door test, and the bar with the dashed outline represents the overall leakage measured during the test where the neighboring units were open-to-outside. It is to be expected that the open-to-outside test would yield higher flow rates than the standard test since there is less resistance on the airflow coming through the neighboring units. However, that is not uniformly the case in the results, with a mixture of the open-to-outside tests being higher or lower than the standard tests, suggesting that the noise and inherent variation in this test is larger than the signal coming from the change in resistance.

The small colored bars stacked within each larger bar indicate the amount of leakage that is coming from the neighboring unit as measured during the individual guarded tests, and assuming that neighboring units are not connected to each other. The absence of a colored bar indicates that the unit did not exist (e.g. no units above a top floor unit), or that we were not granted access by the neighboring unit to access their apartment to conduct the test, or the amount of leakage from that unit is too small to register on the graph scale. A negative bar in the negative direction indicates that the guarded test result was higher than the standard test suggesting either an issue with the test or that the difference is within the noise of blower door testing. At sites 1 and 2 where both pre and post testing were completed, both of those results are included in the graph. The graphs indicate that there is large variation in the amount of leakage between units in different buildings, and even amongst different units in the same building.

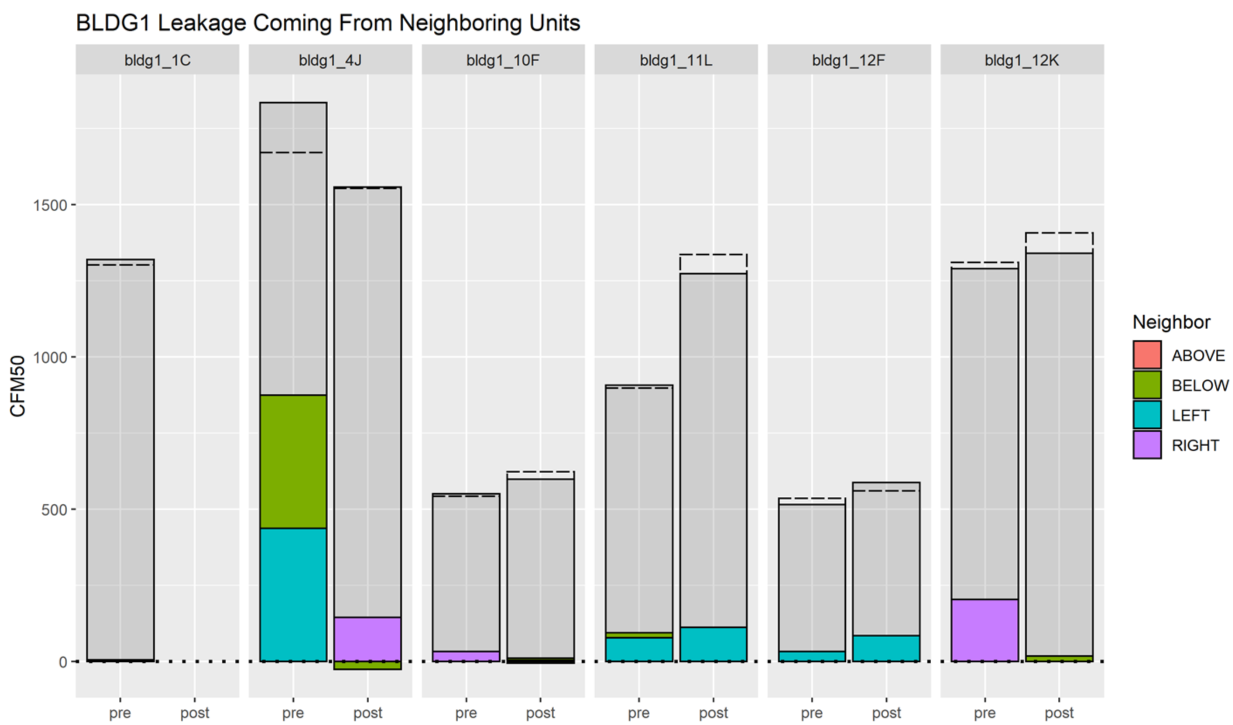

Figure 33 – Building 1 leakage coming from neighbors

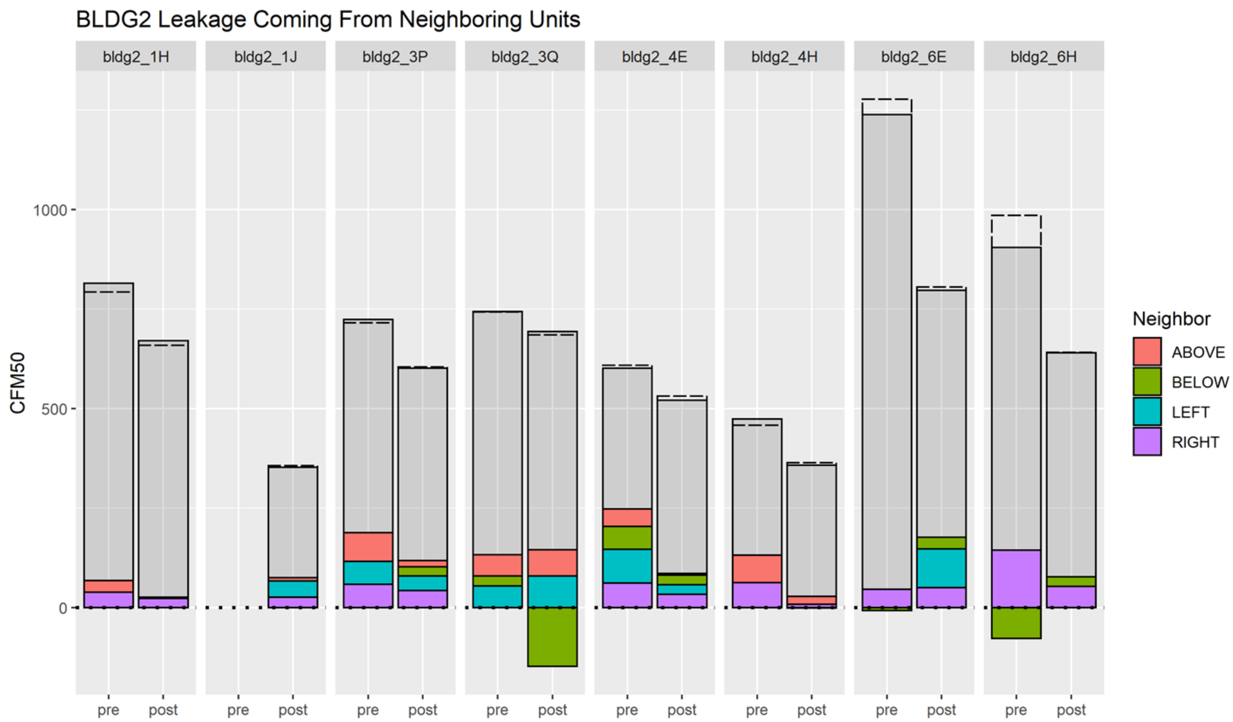

Figure 34 – Building 2 leakage coming from neighbors

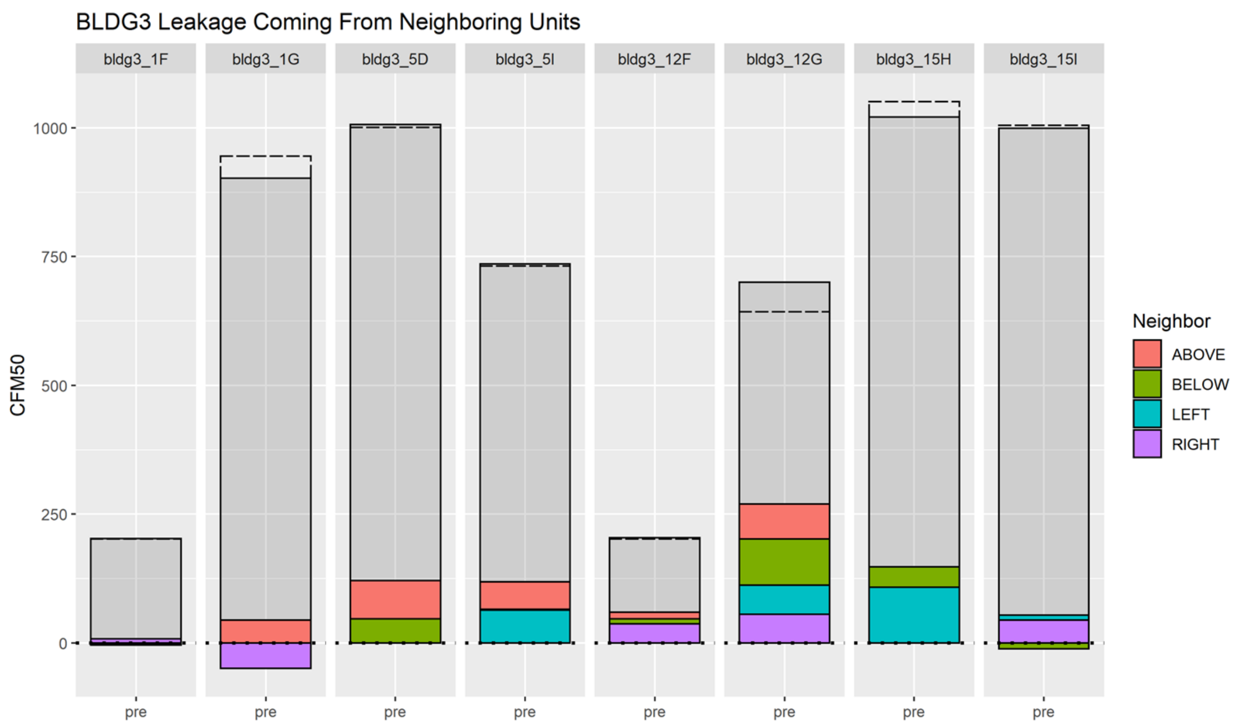

Figure 35 – Building 3 leakage coming from neighbors

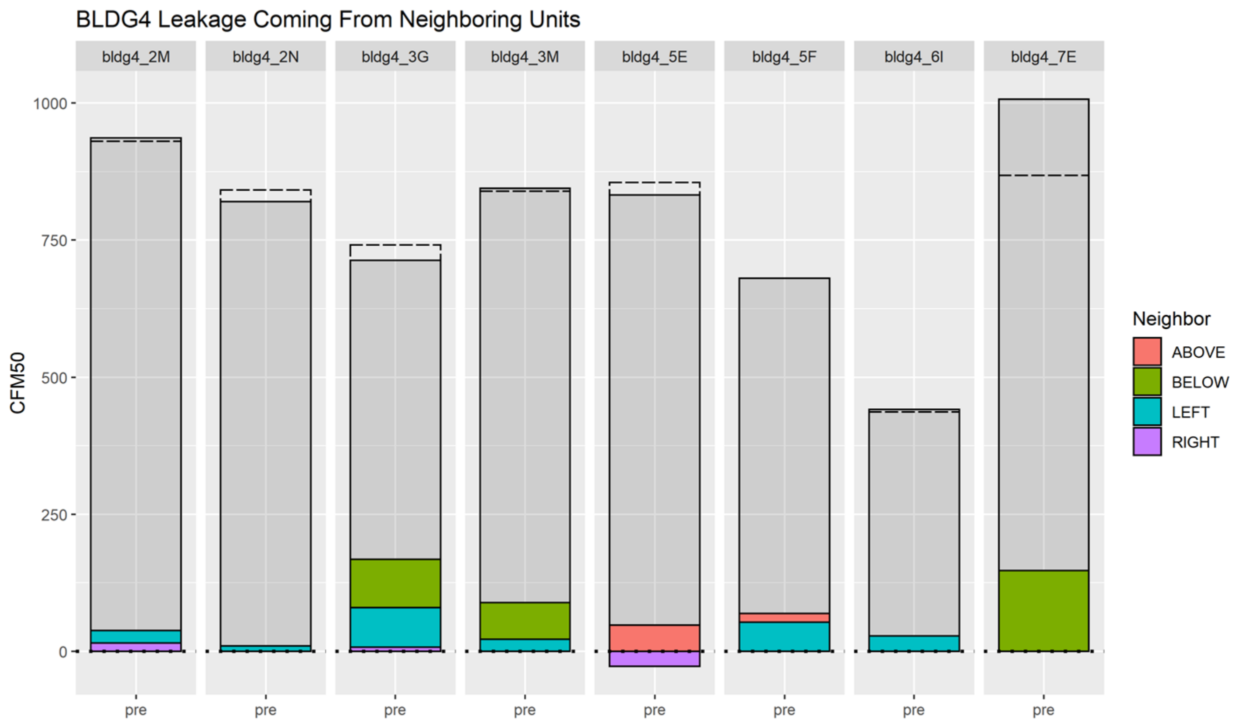

Figure 36 – Building 4 leakage coming from neighbors

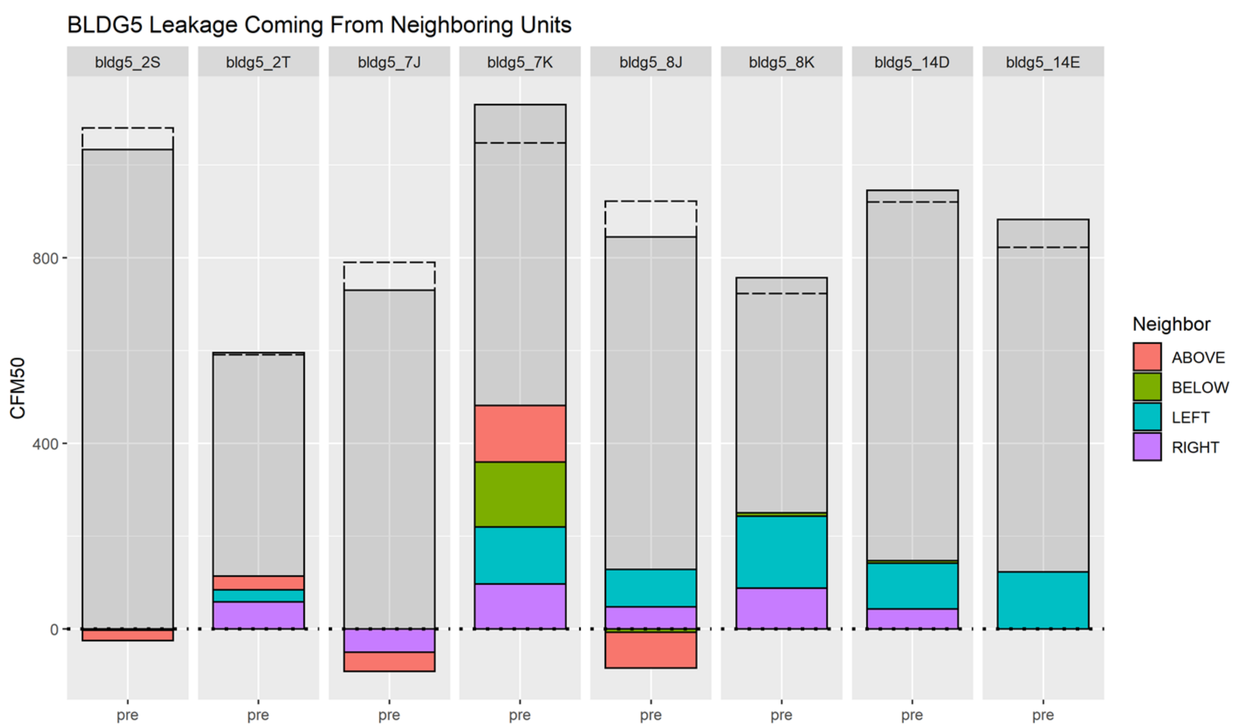

Figure 37 – Building 5 leakage coming from neighbors

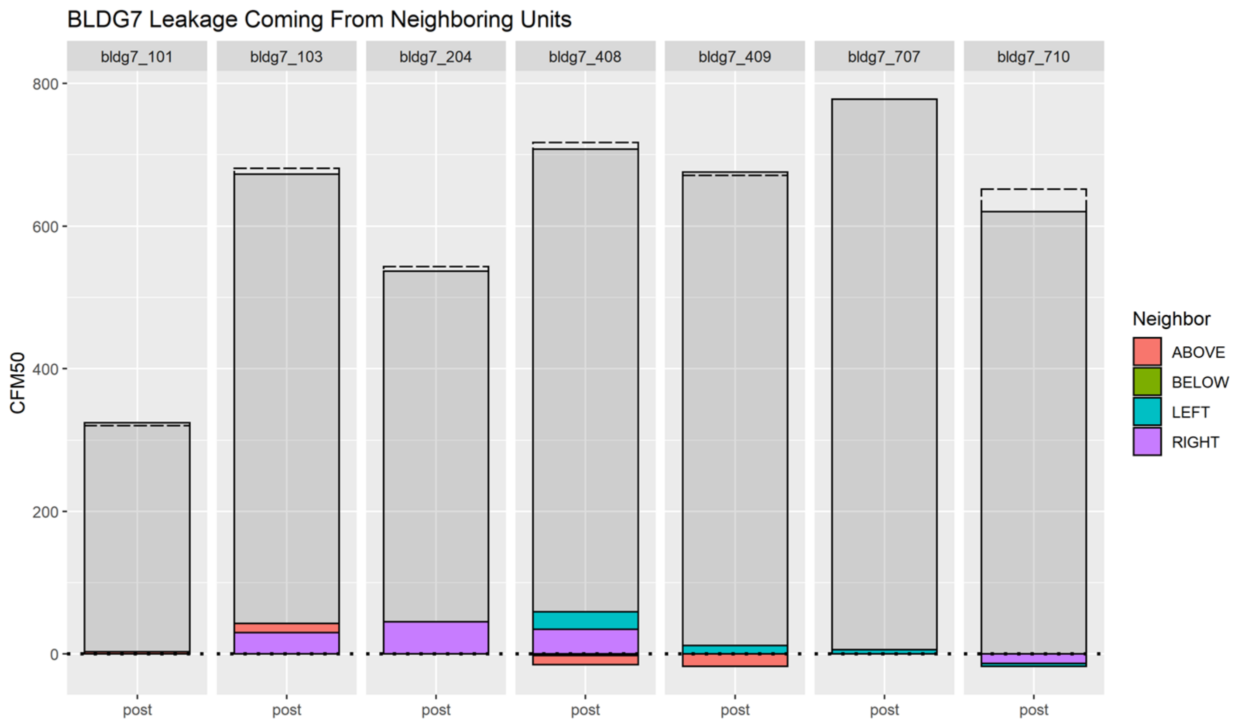

Figure 38 – Building 7 leakage coming from neighbors

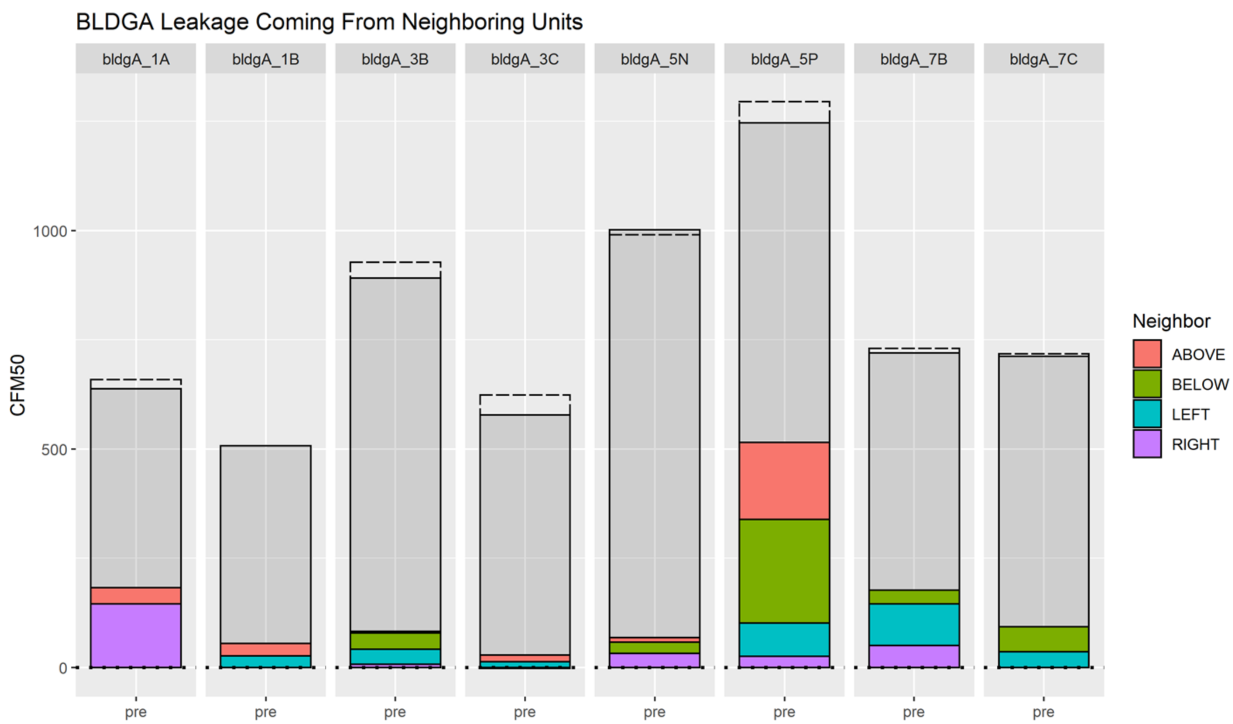

Figure 39 – Building A leakage coming from neighbors

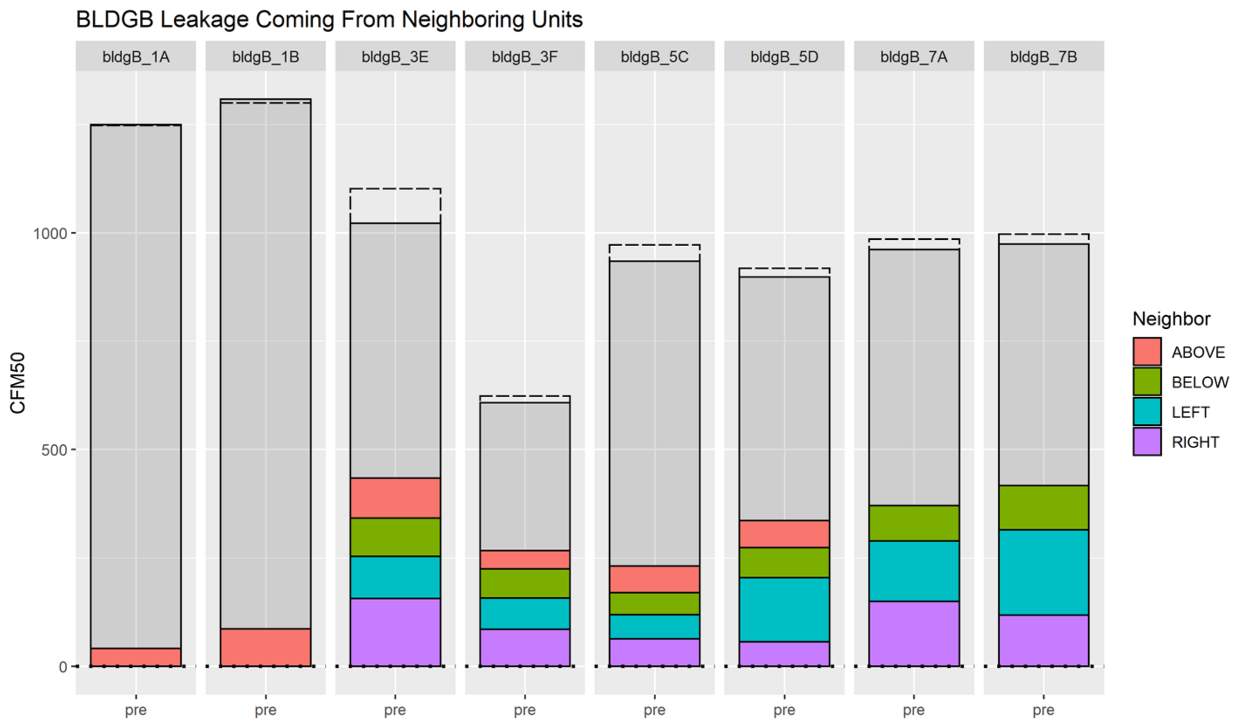

Figure 40 – Building B leakage coming from neighbors

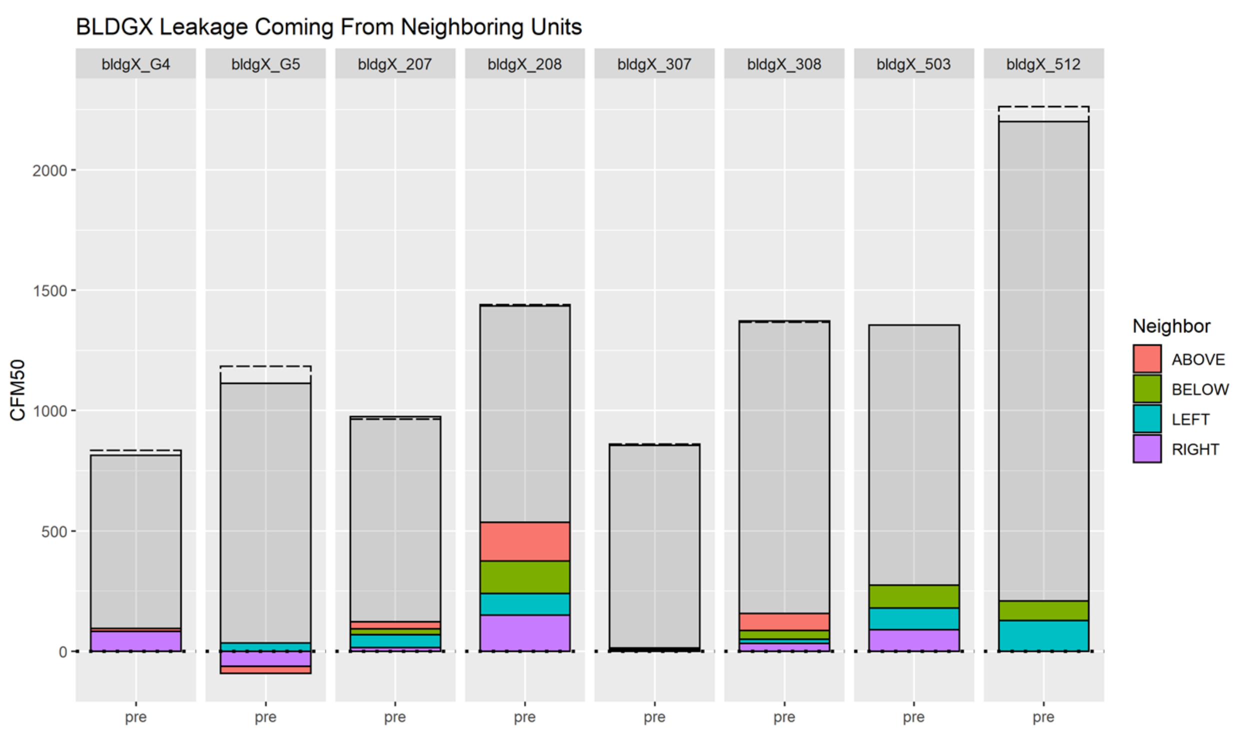

Figure 41 – Building X leakage coming from neighbors

4. DISCUSSION

Most of the measured IAQ contaminants were not observed at widespread concerning levels, with the possible exceptions of $PM_{2.5}$ and NO_2, which had sample wide averages approximating WHO annual guidelines for outdoor air. NO_2 levels were significantly higher in units with gas cooking appliances, but $PM_{2.5}$ levels were similar between units with and without gas cooking appliances.

One possible explanation for the apparent increases in $PM_{2.5}$ was lifestyle changes related to the COVID-19 pandemic. Only one out of ten of the pre-tests was conducted during the pandemic, compared to six out of the nine post tests. Some known consequences of the pandemic were people spending more time at home (Zhang, et al. 2021) and cooking more meals there (Gerritsen, et al. 2021). Since cooking is a major source of $PM_{2.5}$ in residential environments, it is plausible that at least some of the increase in $PM_{2.5}$ is a higher prevalence of cooking events. If the increased in $PM_{2.5}$ were due to increased cooking one would expect a similar trend in NO_2 levels at sites with gas cooking. The only site that exhibited an increase in NO_2 levels post-weatherization was Bldg1, one of only two sites where both the pre and post testing occurred pre-pandemic. The absence of these increases does not support the hypothesis that the increases in $PM_{2.5}$ levels were a result of increased cooking at home.

Bldg2 was the only building where building-wide mean NO_2 measurements were above the NAAQS during any phase. Following weatherization, it also exhibited the most substantial reduction in NO_2 of 29 ppb (equating to a 52% reduction relative to pre levels). This building had the rooftop fans replaced, in-unit CAR dampers installed, and had an average increase of 14.9 CFM of ventilation per unit.

In three of the buildings there was a substantial decrease in mean CO_2 levels, all of these buildings had their rooftop fans replaced during weatherization; in contrast, the CO_2 levels at the remaining four buildings with pre and post data stayed approximately the same, only two of these buildings had their rooftop fans replaced. Improving ventilation systems in these buildings is an essential task for increasing IAQ, and replacing inadequate or outdated mechanical ventilation equipment seems to be an important step in that process.

One concern that motivated this project was that the ventilation rates prescribed by ASHRAE 62.2 would be costly to achieve. In this study, most units achieved ASHRAE 62.2 rates without unit-specific ventilation installed, but rather were able to exceed ASHRAE 62.2 rates through some combination of replacement rooftop fans, cleaning/replacing of intakes, and CAR dampers. This suggests that, at least in similar buildings, more costly installations of unit-specific ventilation systems are not needed to achieve ASHRAE 62.2 prescribed airflow rates.

The absence of an infiltration credit in the ventilation calculation for multifamily buildings means that overventilation is expected when implementing 62.2. Whether ASHRAE 62.2 will, at some point, adopt other considerations is unknown. Additionally, since airflow rates tended to exceed 62.2 rates with the measures implemented, it is not possible to determine whether rates below those required by 62.2 would have achieved similar aims.

All else being equal, it is inevitable that operation of mechanical ventilation will result in greater energy use than not using ventilation. In single-family homes, increases in energy due to ventilation can be offset by good air sealing; however, air sealing between the building and outside is usually not a major focus in these types of multifamily buildings. Nominally, energy savings from other retrofits such as space conditioning system upgrades and increased ventilation fan efficiency, will offset any increases from additional ventilation and will be satisfactory to the residents and building management.

One interesting case study within the data is building X. Four of the units within building X did not have any ventilation during the initial visit, but as part of the retrofit, individual bathroom exhaust fans were installed in these units “with run time switches” (it is unknown how frequently the ventilation was used during the post testing). Additionally among the four tested units that had ventilation previously, the flow rate in individual units: increased substantially, increased slightly, stayed approximately the same, or decreased moderately.

Changes in the ventilation rate and contaminant concentration are described in Table 10. CO is not included in Table 10 because the levels were often at or near zero, generating meaningless and confusing ratios. The ratios for $PM_{2.5}$ are shown for both the mean and median levels since a spike/decay from a single or a few cooking events can greatly skew the mean; CO_2 is calculated as mean only, and the formaldehyde and NO_2 are single values from passive samplers.

There were no major differences in the CO_2 levels in any of the units; three of the four units that started without ventilation had lower CO_2 levels by 2~10%, while the one with the most powerful fan installed (94 CFM) had a 4% increase. The only unit where the ventilation rate reduced (- ~50 CFM) had the largest increase in CO_2 levels at ~17%, and the unit with the largest increase in ventilation rate (+120 CFM), had nearly identical CO_2 levels before and after (+ ~6ppm).

Two of the units that started without ventilation saw reductions in their $PM_{2.5}$ levels, and two saw increases (consistent across both the mean and median calculations). The unit with the most added ventilation saw a substantial reduction in mean $PM_{2.5}$ levels, but only a slight reduction in median levels. The unit with reduced ventilation flow rate saw a substantial increase in mean levels, but no change in median levels.

Formaldehyde levels reduced substantially in three of the four units with newly installed ventilation, and the unit with the largest increase in existing ventilation, but increased in all the others units, doubling in the unit where the ventilation rate was largely unchanged.

NO_2 levels increased in all the units with newly installed ventilation, and decreased in three of the four units that had pre-existing ventilation, including the one where the ventilation rate was reduced.

The inconsistent relationship between pollutants levels and changes in the ventilation rate are consistent with the notion that, although ventilation is important, occupant behaviors play a major role in contaminant generation and concentrations.

Table 10 - Building X Changes in Ventilation and Selected Contaminants

Unit #	Ventilation flow rate (CFM)			Post/pre ratio of average measurement (unitless)				
	Pre-Wx	Post-Wx	Delta (post-pre)	Mean CO_2	$PM_{2.5}$ Mean	$PM_{2.5}$ Median	Mean Formaldehyde	Mean NO_2
512	0	52.7	52.7	0.90	0.50	0.61	0.40	1.58
308	0	56.4	56.4	0.92	0.58	0.65	0.60	1.41
G5	0	43.9	43.9	0.98	1.28	1.76	0.57	1.39
208	0	94	94	1.04	1.07	1.81	1.20	1.05
307	53	173	120	1.01	0.48	0.93	0.50	0.92
207	67.6	93.1	25.5	1.13	3.90	2.68	1.14	1.08
G4	68	69.5	1.5	1.02			2.00	0.62
503	121.8	72	-49.8	1.17	3.15	1.00	1.45	0.90

The measured IAQ data does not suggest that the weatherization process resulted in a significant change in contaminant levels. In three of the buildings, the average CO_2 levels went down substantially, and in the remaining four buildings with both pre and post data, the levels were approximately the same (Figure 20). Only one building exhibited an increase in the mean CO_2 levels (bldgX), and that was only by 1.4% or 7ppm. With CO_2 levels frequently used as an indication of general indoor air and sufficient ventilation, these improvements and lack of increases can be interpreted as compliance with the "do no harm" Weatherization policy.

CO levels were generally low, with only 1 unit exceeding the WHO 24-hour guideline. The apparent slight increase in overall mean CO levels from pre to post testing (Figure 22) is due to artificial inflation by building 7 which was a post-only building, and the building with the highest average CO levels; and artificial deflation by buildings A and B which had electric kitchens and low CO levels but were not post tested.

Given the limited amount of pressure diagnostics data collected (primarily due to the COVID-19 pandemic), and the apparent noise within that data, it is difficult to make any conclusive claims about the connectivity between units and any changes that may have resulted from the weatherization activities. Assuming the limited amount of air sealing work that was done on individual units in this study is representative, it is unlikely that weatherization work will create or exacerbate an issue related to inter-unit connectivity.

5. CONCLUSION

The attempts made to comply with ASHRAE 62.2 were generally sufficient at achieving the desired ventilation rates. Instances of as-found IAQ issues that exceeded established guidelines were rare and never excessive. There was no evidence gathered in this study that suggests that that the weatherization work done on these sites had a detrimental impact on the IAQ in the units, complying with the "do-no-harm" philosophy of the weatherization program. This research does not support prohibiting weatherization work on these buildings which in the scope of this project largely consisted of building system improvements (external to the individual units), and plug load efficiency measures. In buildings where major changes are made to the envelopes in individual units, special attention should be paid to ensure that there is sufficient ventilation to avoid creating IAQ issues, such as insufficient ventilation.

Given that some air leakage reduction does occur, it is reasonable to continue to have ventilation be a consideration in multifamily buildings. However, given the results of this report – including measures installed, airflow results, and IAQ results – it is also reasonable to support interventions at the scale that were implemented in these buildings rather than additionally require individual-unit ventilation installations.

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APPENDIX A – IN-UNIT DATA COLLECTION SHEET

Apartment Profile Summary (*one per unit*)

(When applicable, labeled photos should be included in the appropriate sections)

Building Name and Address:	Apt #:
Date: Time:	
Number of bedrooms:	Number of bathrooms:
Horizontal location (circle one): middle, corner , ___________	
Vertical location (circle one): bottom, lower-half, middle, upper-half, top, _________________	
Kitchen venting type:	Cooking fuel: ☐ Electricity ☐ Gas
HVAC SYSTEMS (if individual for unit)	
Heating system make, model, type and age of equipment. Photos if relevant	
Cooling system make, model, type and age of equipment. Photos if relevant	
Window AC: Present? ☐ Installed? ☐ Describe window opening behavior when cooling:	
Ventilation systems type, measured or rated capacity (note which). Photos if relevant	
APARTMENT VENTILATION	
Fan quantity (#):	Location(s): ☐ Rooftop ☐ In-unit ☐ Attic ☐ Other:
Were windows open on arrival? _________________	Are they usually open? _________________
Apartment central exhaust inlet location: ☐ Kitchen exhaust hood ☐ Kitchen wall or ceiling inlet ☐ Bathroom ☐ Other:	
CFM:	
Mold and/or mildew noticed? ☐ Yes (describe and photograph) ☐ No	
APARTMENT SIZE	
Floor area (ft^2) : Ceiling height (ft):	Conditioned volume (ft^3):
Floor plan:	

Building Address: ____ **Apartment #:** _______________

Instrumentation Deployment Information			
Date & Time:	Field Tech(s):		
Stay in place until end of measurement period		Date/time start	Date/time stop
$PM_{2.5}$ (PurpleAir)	device ID: PM-____ ____ ____ ____		
CO_2: (Rotronic CL11)	device ID: CD-		
Place these devices if they are available and if there are gas appliances in the kitchen			
iButton (on stove, if avail.)	device ID: IB-		
CO (if available)	device ID: CO-		
Place these passive sensors and record time opened/closed		Date/time opened	Date/time closed
NO_2	device ID:		
NO_2 Blanks (3 per building)	device ID: QTY:	KEEP CLOSED	
Formaldehyde badges are replaced after 7 days – Do NOT use sharpies to label samplers.			
Formaldehyde week1	device ID:		
Formaldehyde week2	device ID:		

Building Address: ____ **Apartment #:** _______________

Blower-door Test Results

Date & Time: Field Tech(s):

Test Mode	Unit	color	Actual Pressure WRT Corridor/Outside	CFM$_{50}$	Notes
Test 1 – All units closed. Install the Blower door (BD) in main unit (MU), with all neighboring units (NU) closed. Run tubing to each NU to measure pressure difference (ΔP). Record baseline (MU-corridor), and outside-corridor, turn BD to 50 Pa, record pressure, CFM$_{50}$, and all ΔP's.					
CFM$_{50}$(C-O) Close all windows/doors on neighboring units Baselines (fan off & closed): $\Delta P_{unit\text{-}corridor}$ = _________Pa $\Delta P_{corridor\text{-}outside}$ = ________Pa			Pa	CFM$_{50}$	
ΔP, U_{i-1j} (below)			Pa		
ΔP, U_{ij-1} (left)			Pa		
ΔP, U_{ij+1} (right)			Pa		
ΔP, U_{i+1j} (above)			Pa		
Test 2 – NUs open. Open doors between NU and corridor/outside (*make sure pets will not escape & non-residents will not enter*). Turn MU BD to 50 Pa and record pressure & flow.					
CFM50(O-O) Open neighboring units to outside (or corridor)			Pa	CFM$_{50}$	
Test 3 – Guarded tests. Install BD at NU's one at a time cruise BD to 0 Pa NU-MU. Turn MU BD to 50Pa, record pressure and CFM$_{50}$.					
CFM$_{50}$(G-U_{i-1j} (below)) Install blower door in neighboring unit and cruise to ΔP = 0 (WRT main unit)			Pa	CFM$_{50}$	
CFM$_{50}$(G-U_{ij-1} (left))			Pa	CFM$_{50}$	
CFM$_{50}$(G-U_{ij+1} (right))			Pa	CFM$_{50}$	
CFM$_{50}$(G-U_{i+1j} (above))			Pa	CFM$_{50}$	

Ventilation Measurement Information ← DO THIS!

Date & Time: Field Tech(s):

Fan Location	**CFM**	**Fan Location**	**CFM**
Bathroom #1		Kitchen	
Bathroom #2		Other #1:	
Bathroom #3		Other #2:	

$U_{i+1,j-1}$ *Above-left*	$U_{i+1,j}$ ***Above***	$U_{i+1,j+1}$ *Above-right*	Floor *i*+1
$U_{i,j-1}$ ***Left***	$U_{i,j}$ ***Main-unit***	$U_{i,j+1}$ ***Right***	Floor *i*
$U_{i-1,j-1}$ *Below-left*	$U_{i-1,j}$ ***Below***	$U_{i-1,j+1}$ *Below-right*	Floor *i*-1

APPENDIX B – IN-UNIT ABBREVIATED DATA COLLECTION SHEET (COVID-19)

Abbreviated Apartment Summary

Complete before going in unit:

Building Address: ______________________________ Apartment #: _______________

Horizontal location (circle one): middle, corner, __________

Vertical location (circle one): bottom, lower-half, middle, upper-half, top, ________________

Complete inside unit:

Number of bedrooms: _______________ Number of bathrooms: _________________

Kitchen fuel (circle one): Electricity / Gas

Date and time sensors placed: ___________ / ___________ / 2021 _________:________

Instrumentation Deployment Information		
Plug-in sensors		
$PM_{2.5}$ (PurpleAir)	device ID: PM-____ ____ ____ ____	Plug in device with white USB cable, make sure internal red/blue lights turn on. Velcro to top of box
CO_2: (Rotronic CL11)	device ID: CD- _____ _____ _____	Plug in. Set date/time (hold "set", press down to "rtc", enter, up/down to set year/date/time. "esc" to exit, hold "start" for 3 sec to start, make sure "REC" is flashing (mid left side)
Battery powered sensors		
CO (if available)	device ID: CO-	Place on top of sensor box
NO_2 sensors		
NO_2	device ID:	Remove sensor from bag and jar and clip to outside of box
NO_2 Blanks (3 per building)	device ID: QTY:	DO NOT OPEN (if present), leave inside jar, inside box.
Formaldehyde badges		
Formaldehyde	device ID:	Open foil envelope, write apt# in pen (NOT SHARPIE), slide green cover down to open. Clip to top of box.

APPENDIX C – $PM_{2.5}$ QUALITY CHECKS

Figure 42 through Figure 51 show the channel agreement (left) and the time series data for the PM sensors at the sites where the PM sensors performed poorly. The table at the end of this appendix described the decision and justification for each data set.

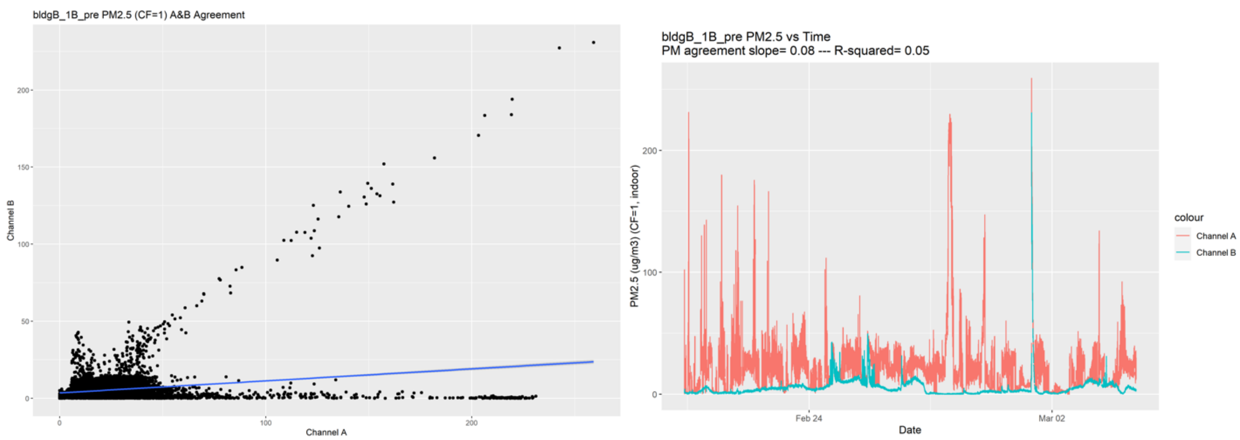


Figure 42 - Building B, Unit 1B, Pre

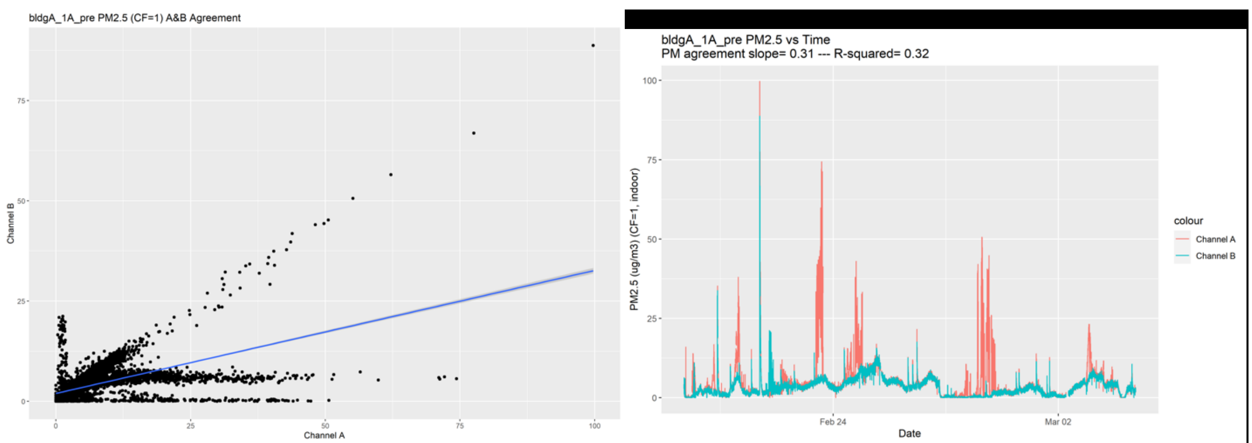


Figure 43 - Building A, Unit 1A, Pre

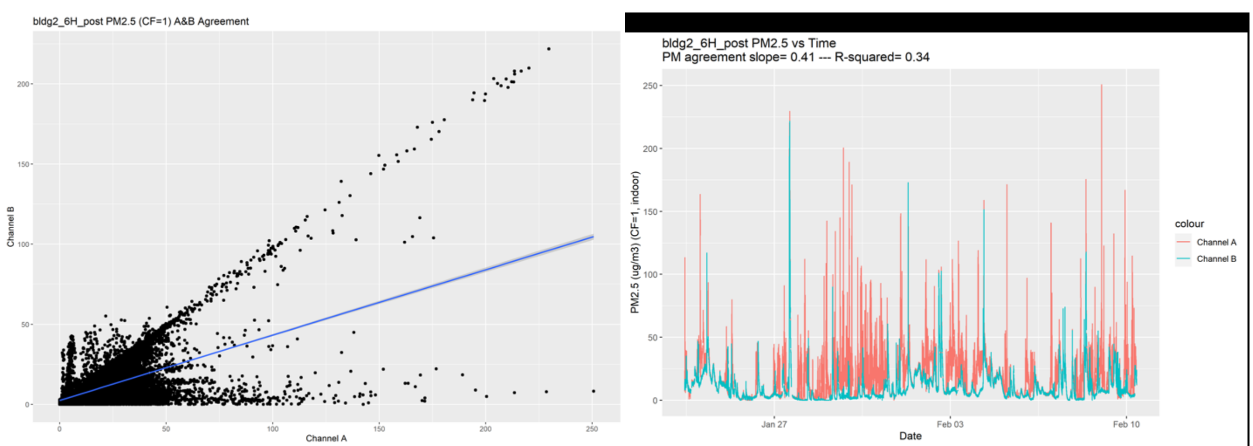


Figure 44 - Building 2, Unit 6H, Post

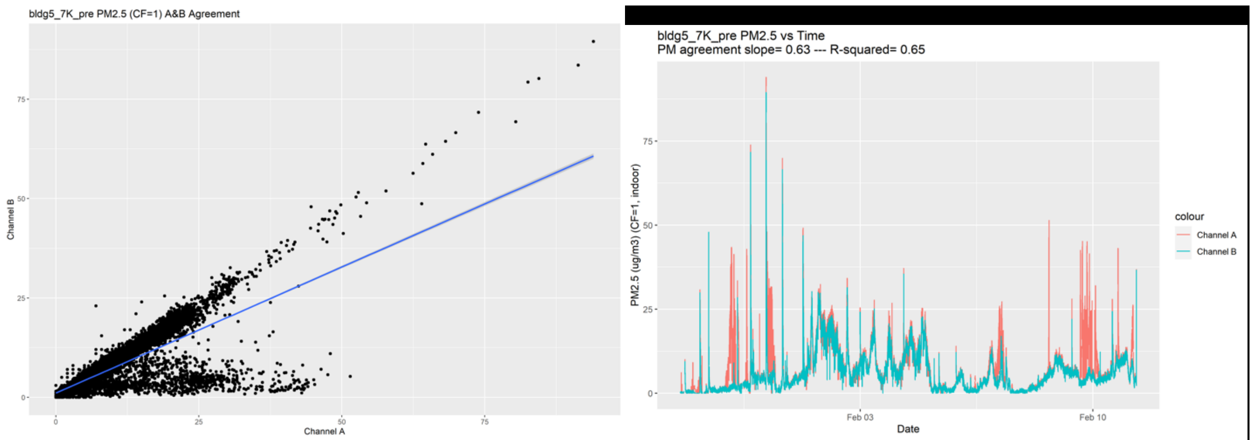


Figure 45 - Building 5, Unit 7K, Pre

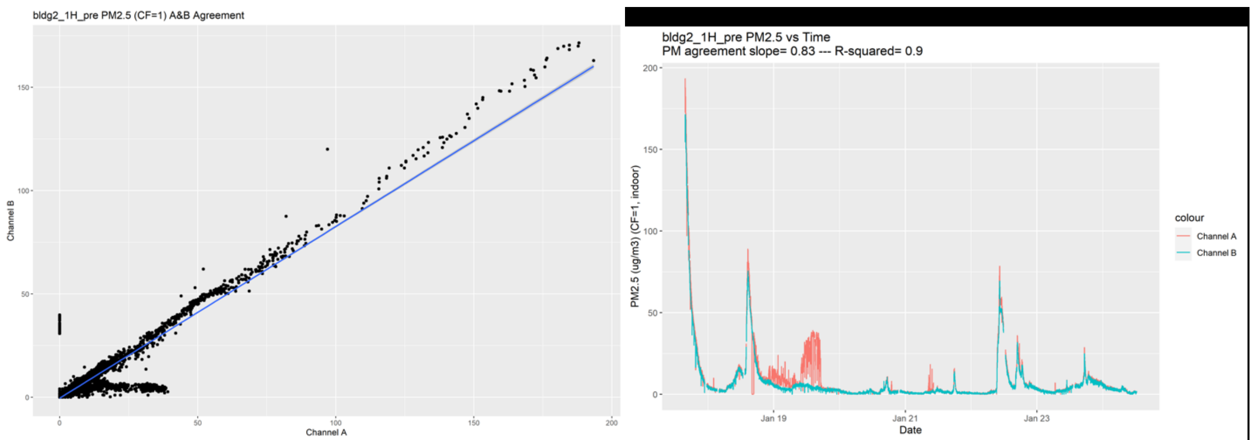


Figure 46 - Building 2, Unit 1H, Pre

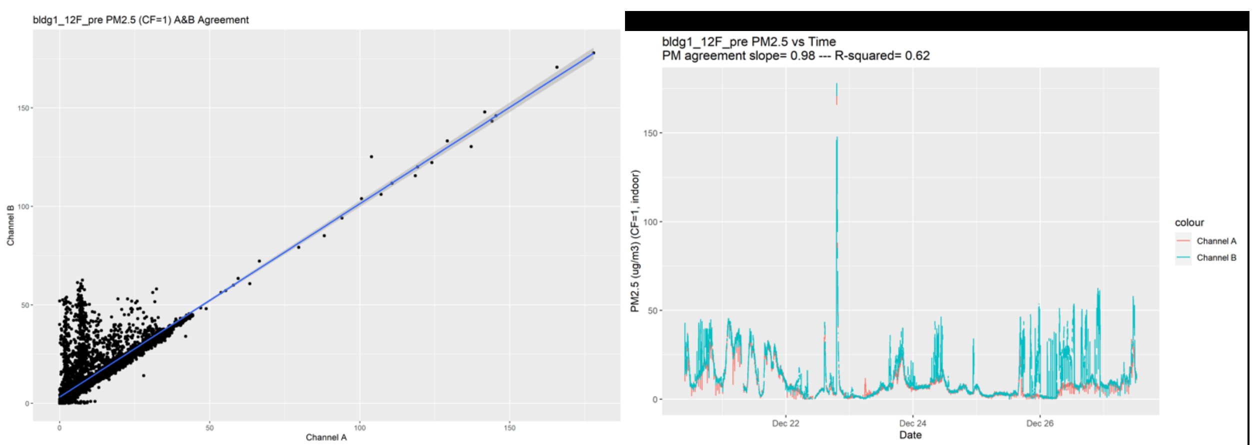


Figure 47 - Building 1, Unit 12F, Pre

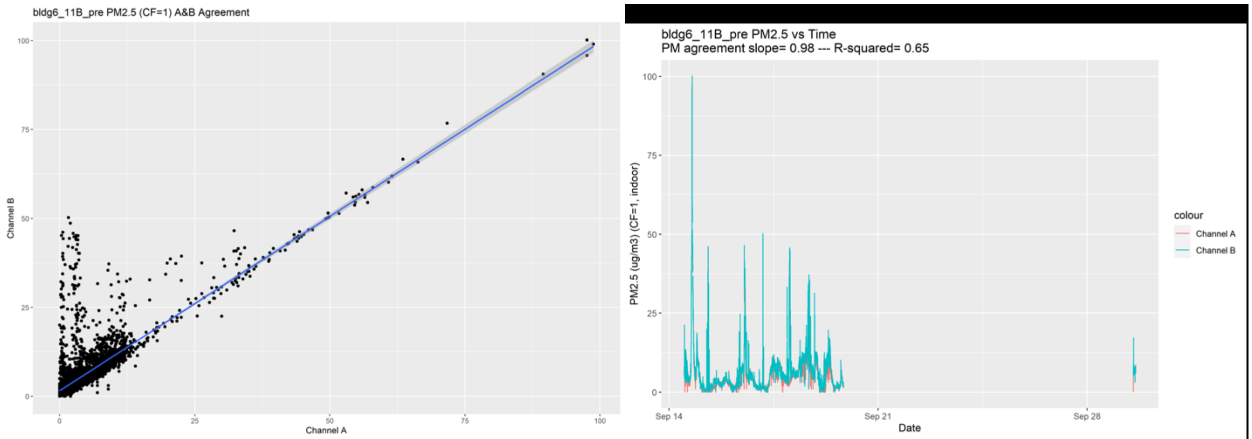


Figure 48 - Building 6, Unit 11B, Pre

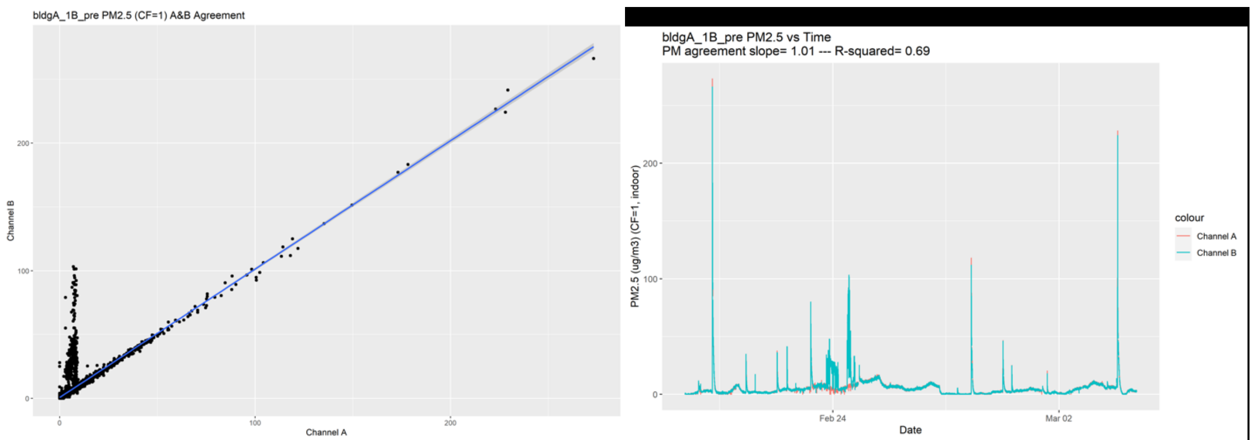


Figure 49 - Building A, Unit 1B, Pre

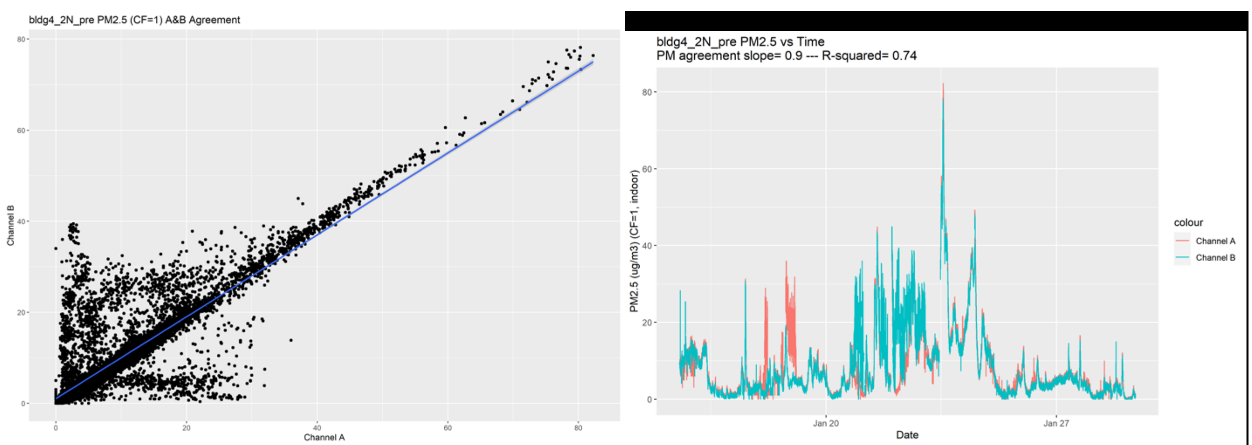


Figure 50 - Building 4, Unit 2N, Pre

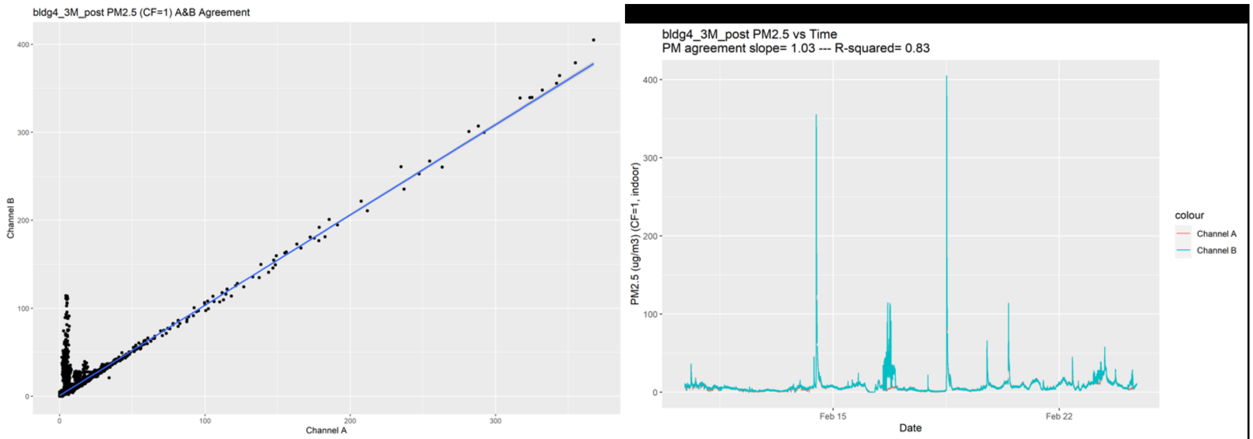
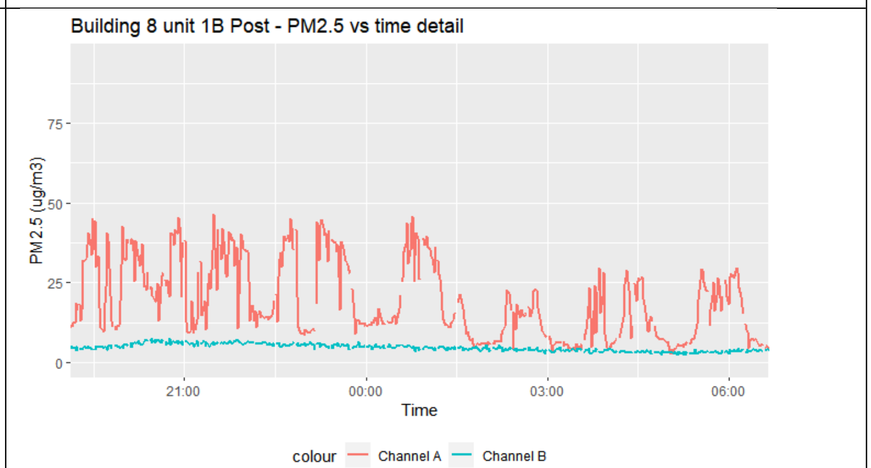
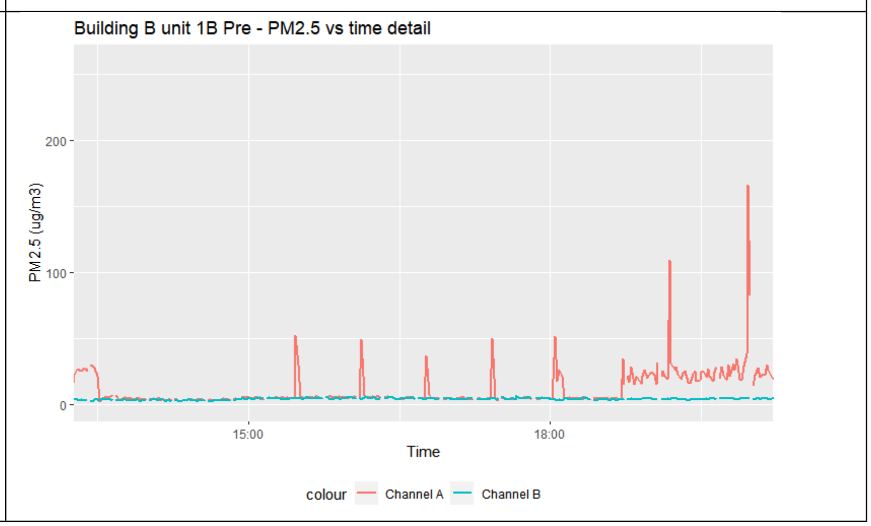
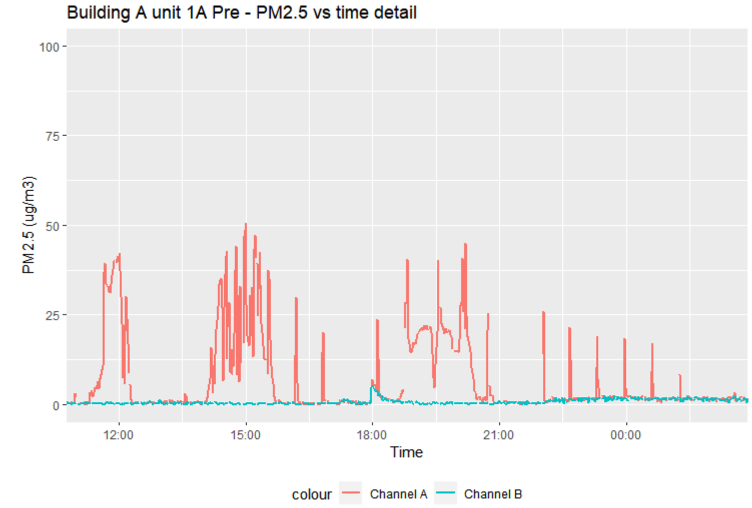
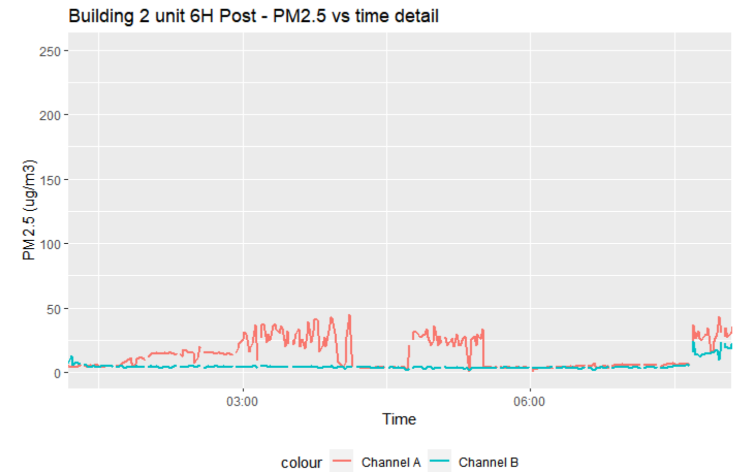
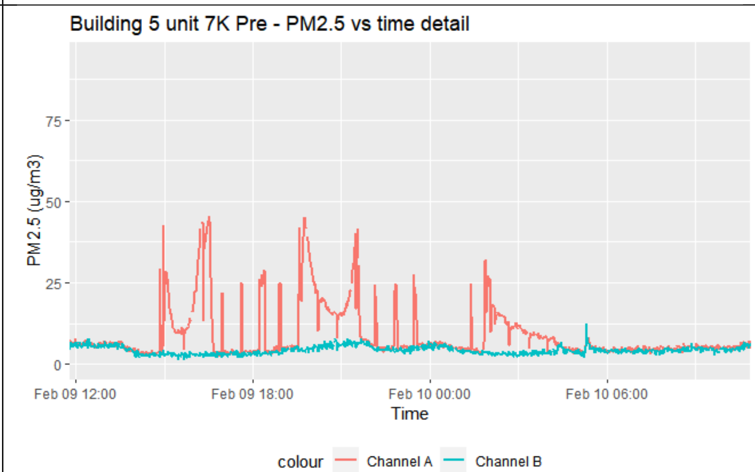
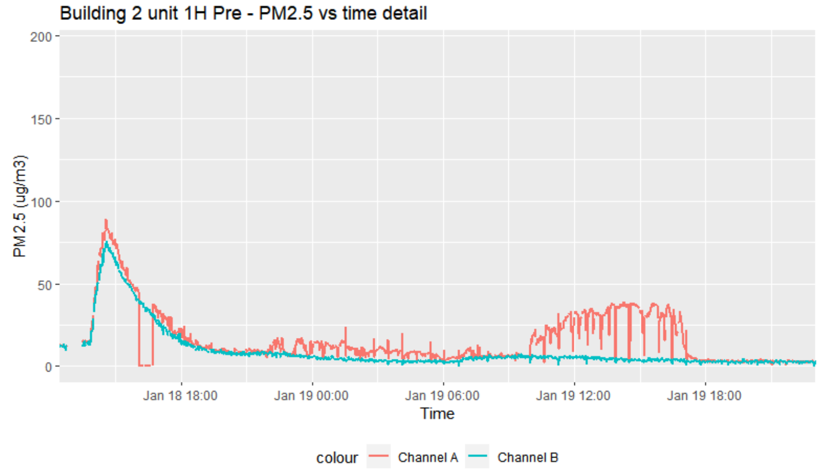
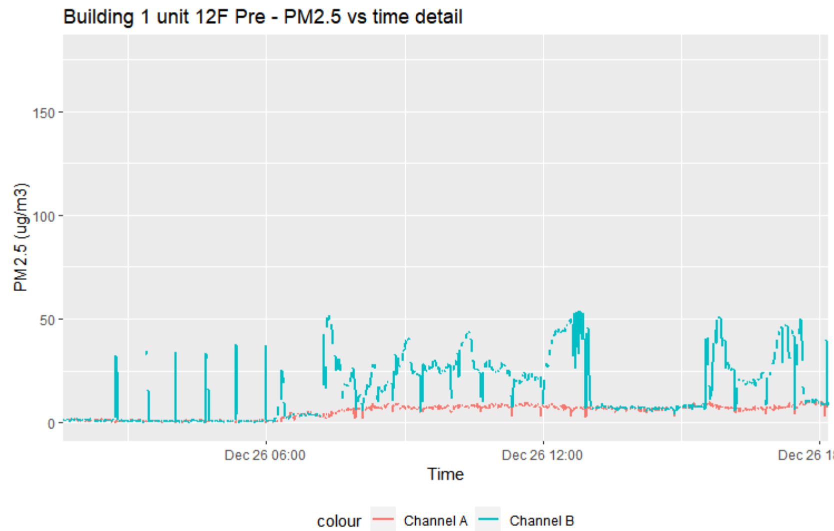
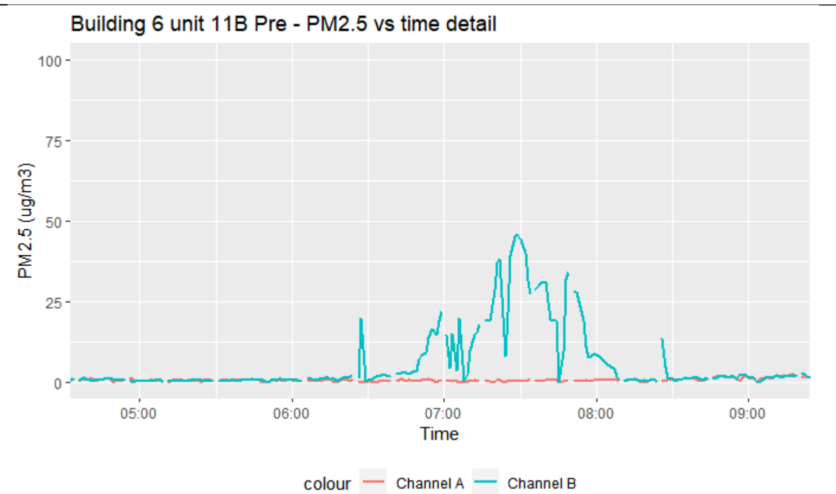


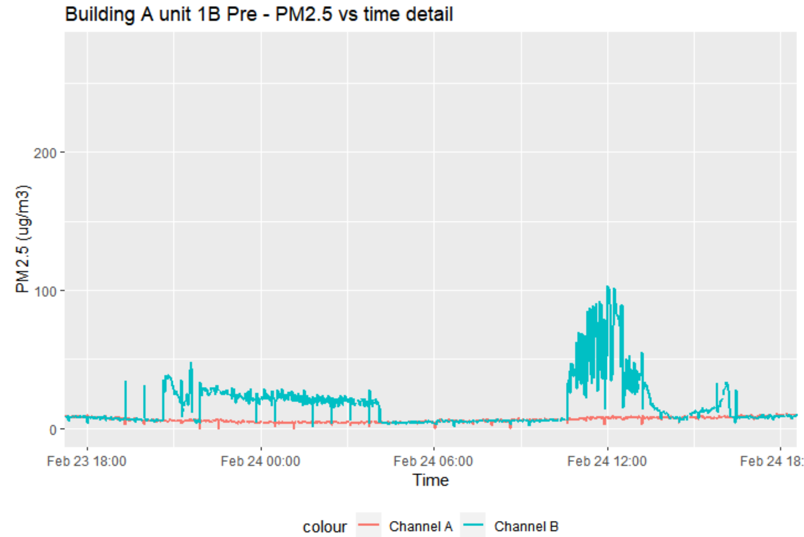
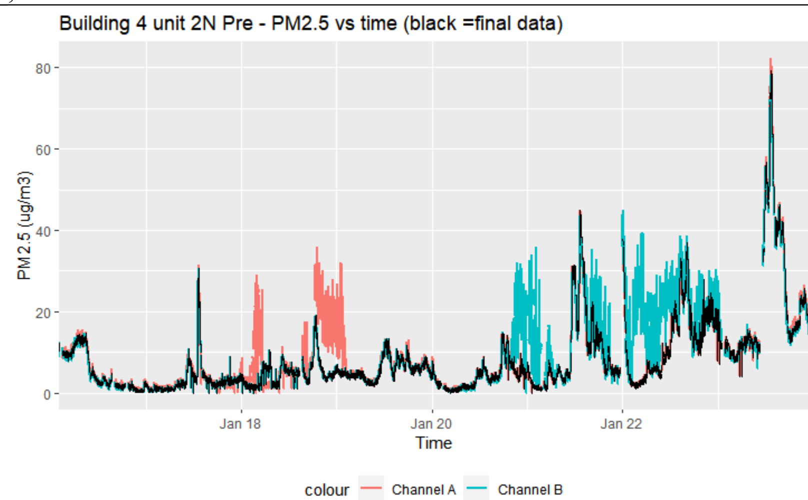
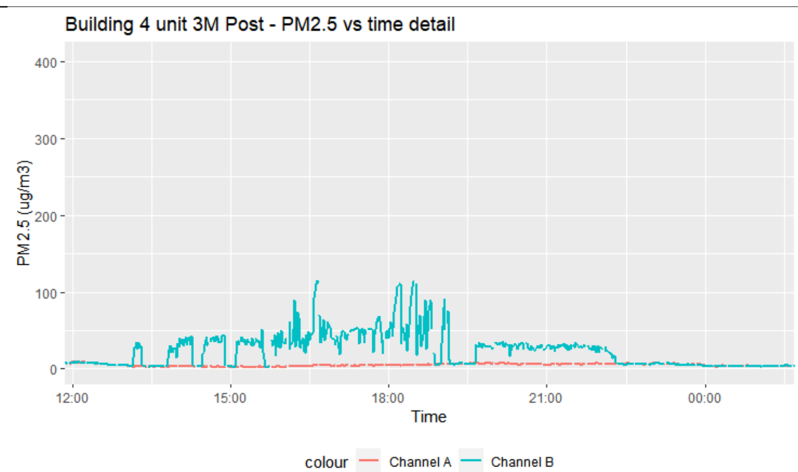
Figure 51 - Building 4, Unit 3M, Post

Table 11 - $PM_{2.5}$ erroneous data identification and justifications

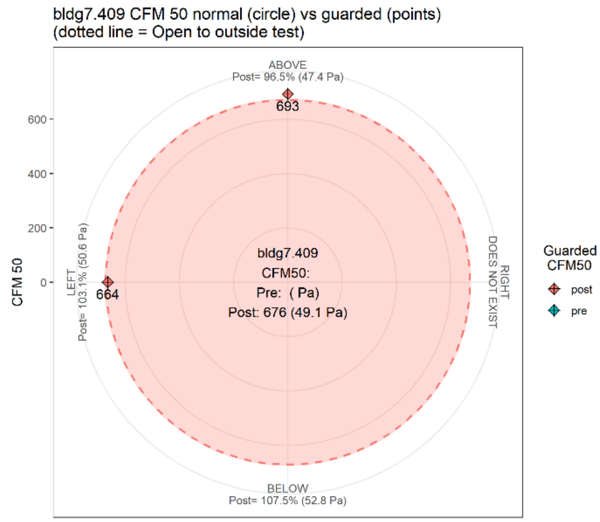
Data Set	Erroneous channel & Justification	Visualization
Bldg8 Unit 1B Post	When channels report different levels, channel A differs from the trend of when both channels align, channel B's trend is consistant.	
BldgB Unit 1B Pre	Channel A exhibited unrealistic cycling.	

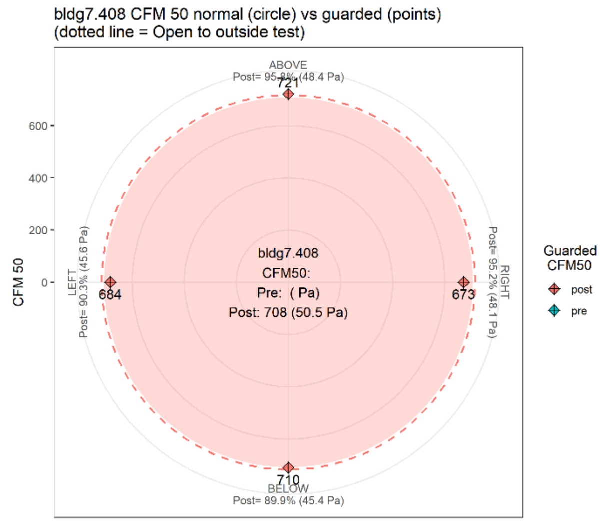
BldgA Unit 1A Pre	Channel A exhibited unrealistic cycling.	
Bldg2 Unit 6H Post	Channel A exhibits unrealistic jumps from moderate concentrations to zero and back.	
Bldg5 Unit 7K Pre	Channel A exhibited unrealistic cycling.	

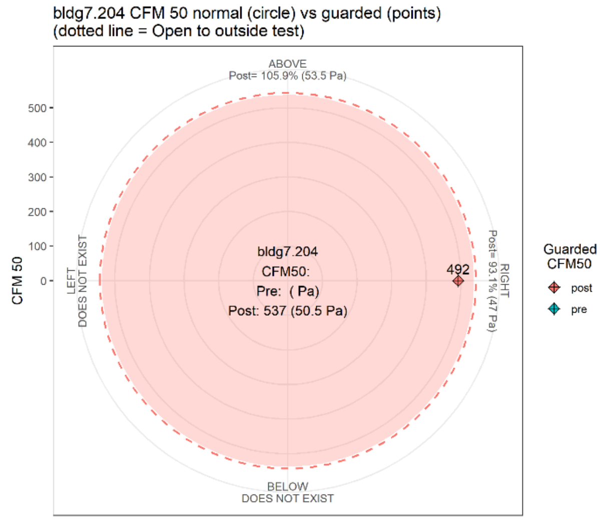
Bldg2 Unit 1H Pre	Channel A exhibited unrealistic cycling.	
Bldg1 Unit 12F Pre	Channel B exhibited unrealistic cycling.	
Bldg6 Unit 11B Pre	Channel B exhibited unrealistic cycling.	

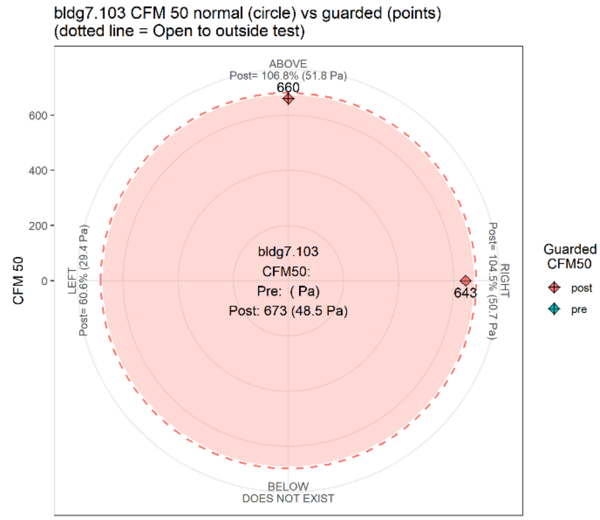
BldgA Unit 1B Pre	Channel B exhibited unrealistic cycling.	 ,
Bldg4 Unit 2N Pre	Both channels exhibited unrealistic cycling at different times, a manually customized data set was generated that maintained the best looking data during diverging periods (black line)	
Bldg4 Unit 3M Post	Channel B exhibited unrealistic cycling.	

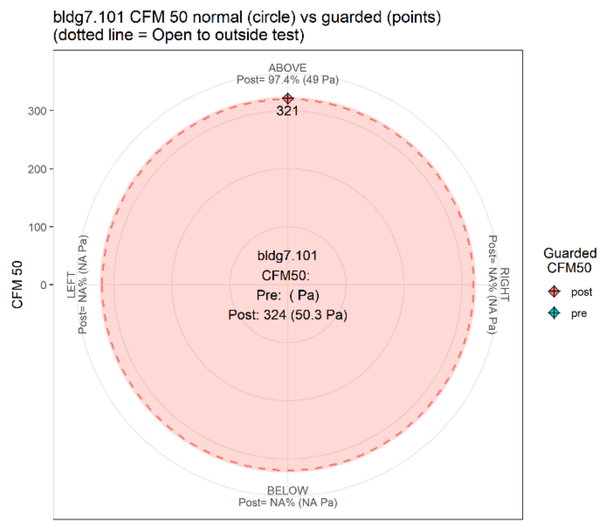
APPENDIX D – BLOWER DOOR RESULTS

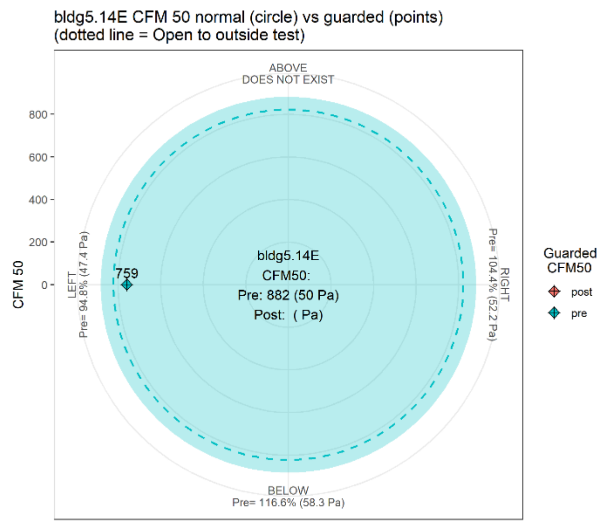




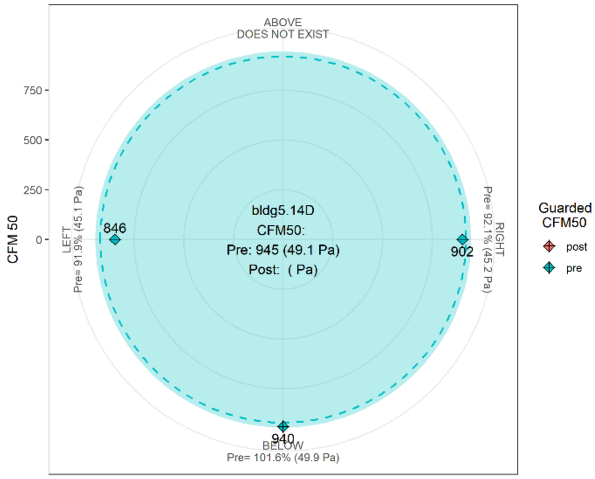




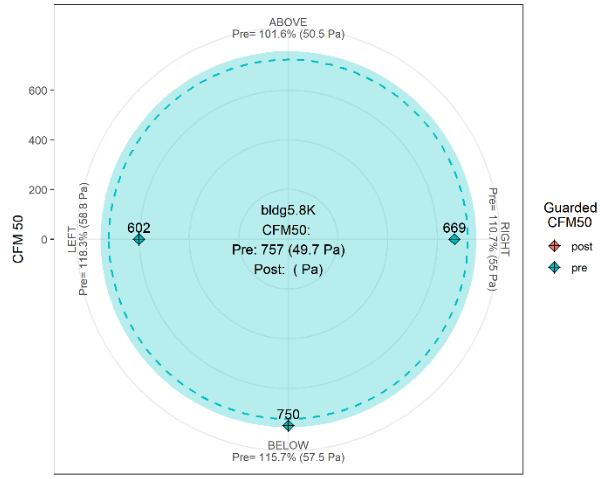




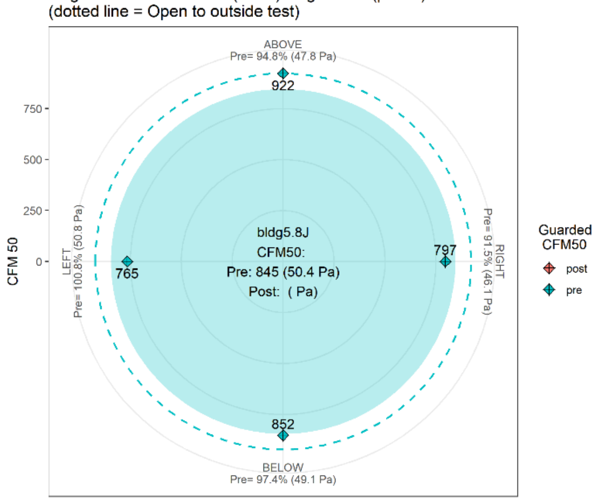
bldg5.14D CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



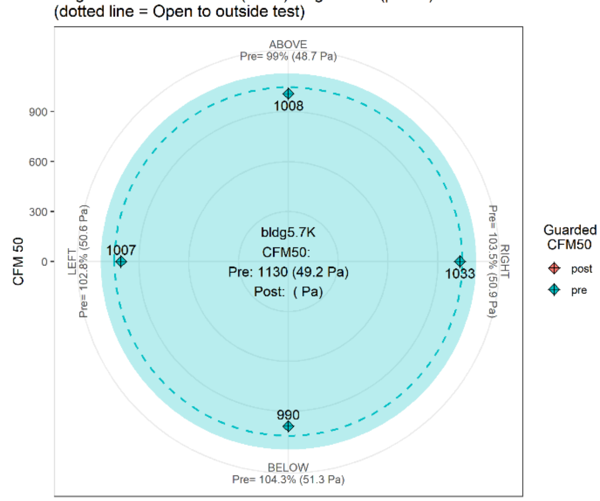
bldg5.8K CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



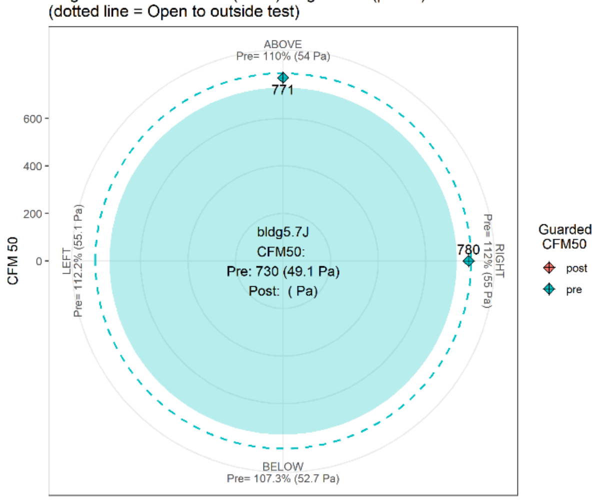
bldg5.8J CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



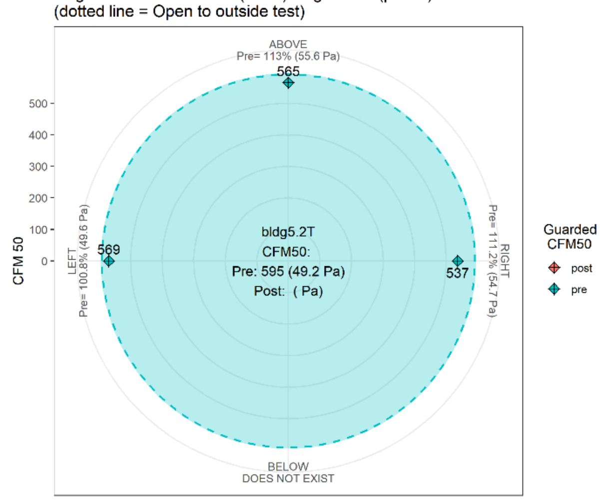
bldg5.7K CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



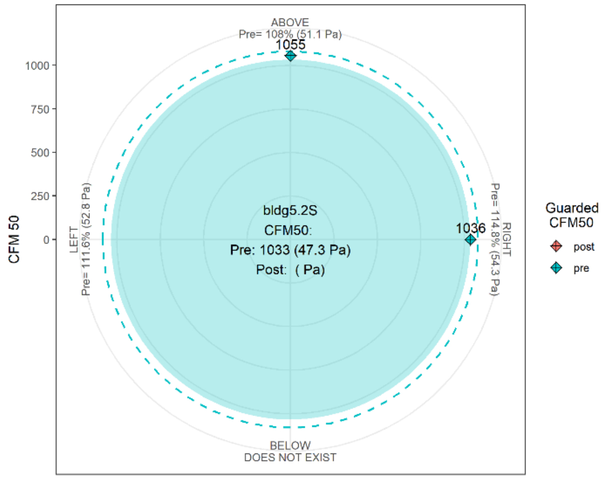
bldg5.7J CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



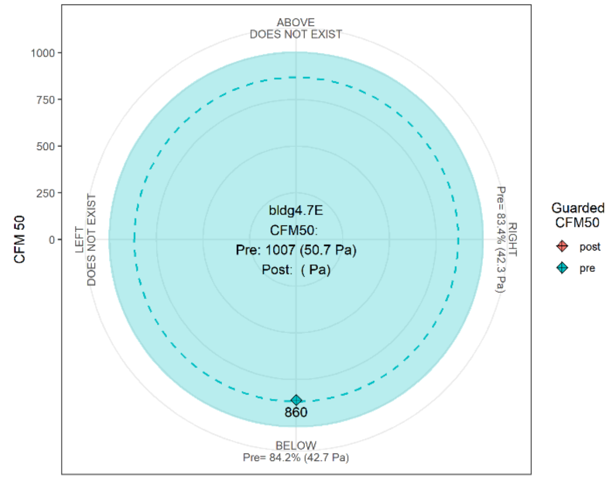
bldg5.2T CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



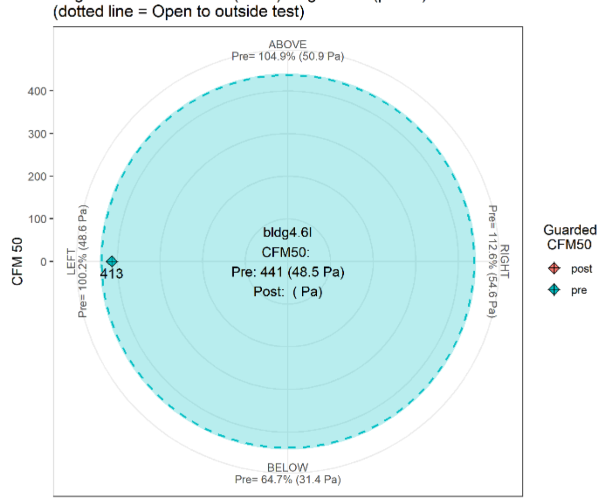
bldg5.2S CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



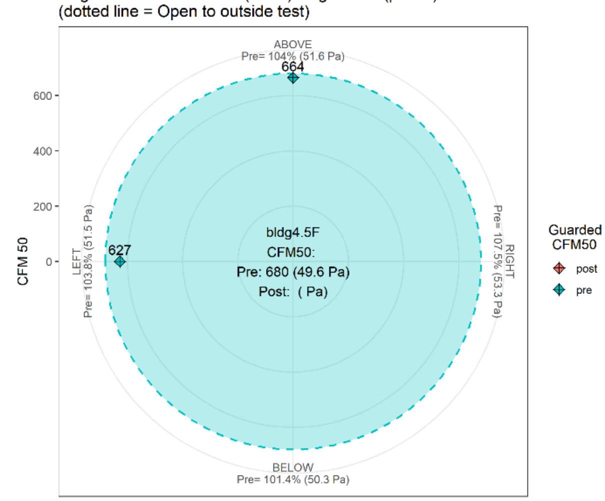
bldg4.7E CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



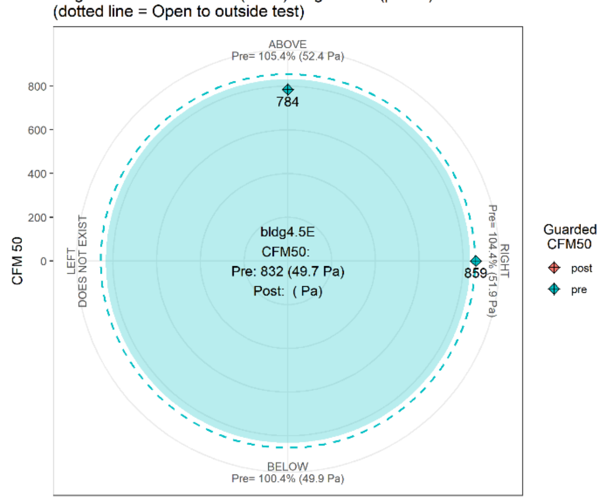
bldg4.6I CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



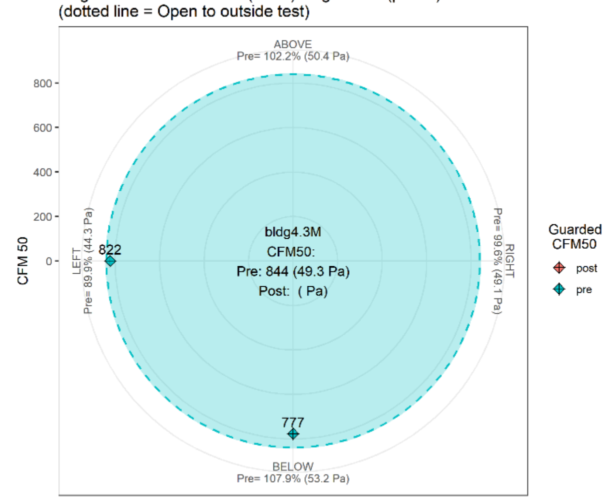
bldg4.5F CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



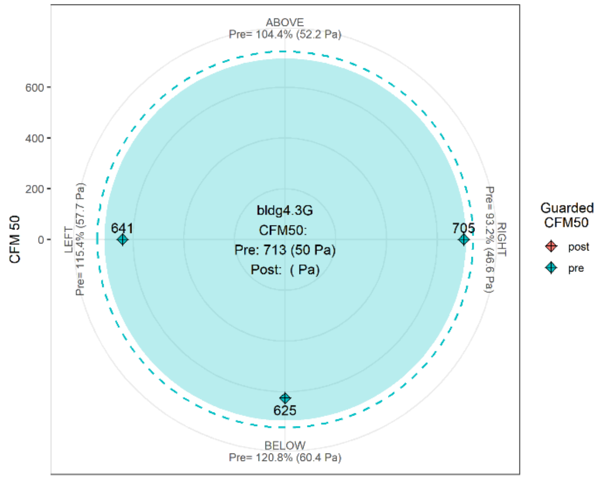
bldg4.5E CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



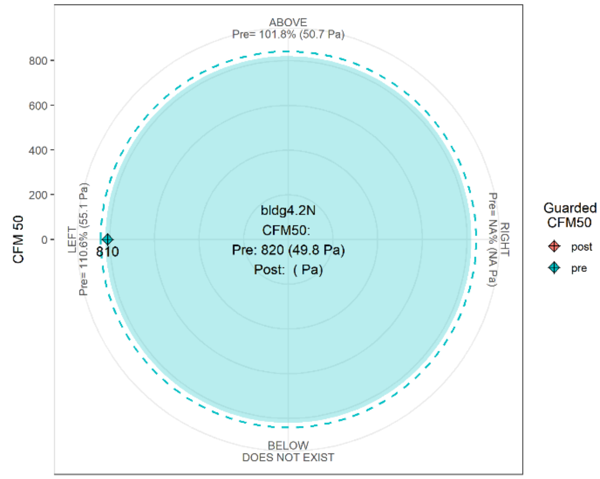
bldg4.3M CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



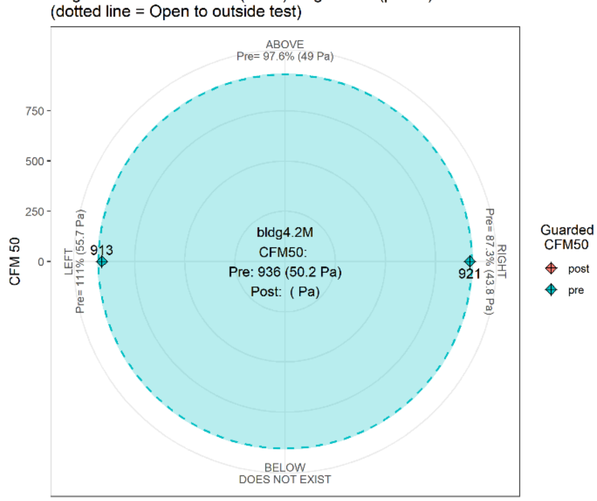
bldg4.3G CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



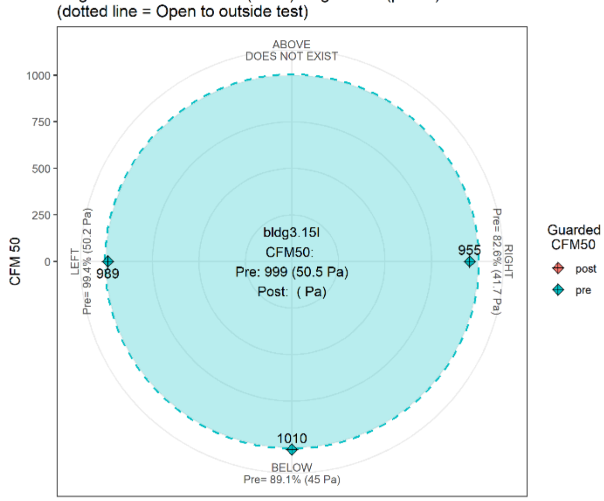
bldg4.2N CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



bldg4.2M CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



bldg3.15I CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



bldg3.15H CFM 50 normal (circle) vs guarded (points)
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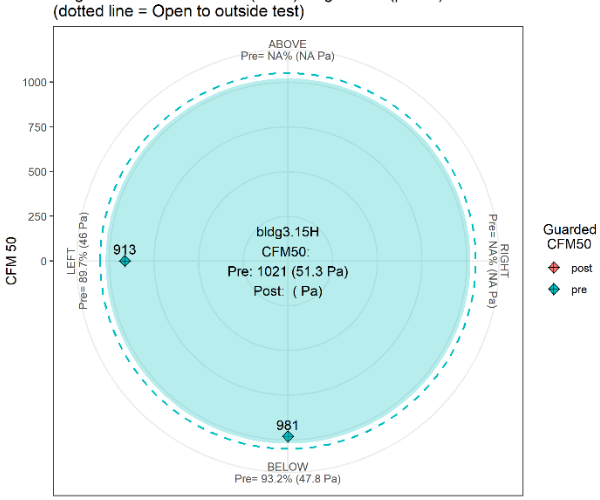

bldg3.12G CFM 50 normal (circle) vs guarded (points)
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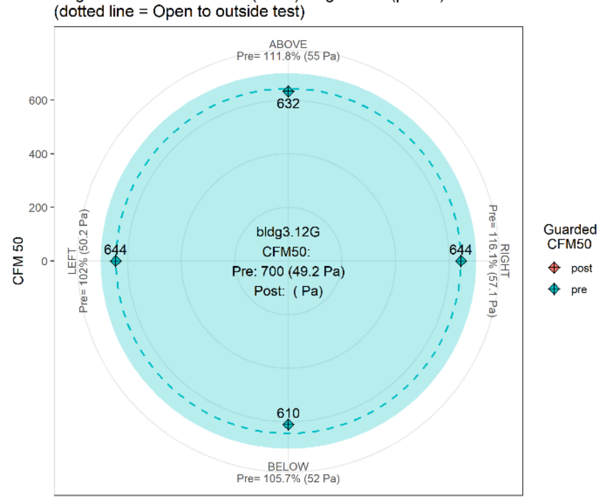
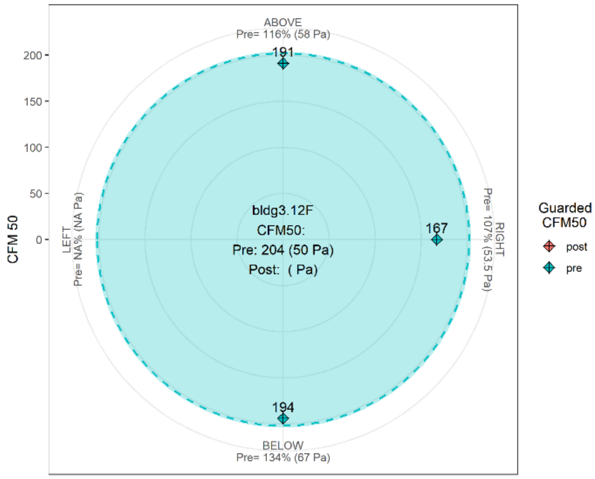
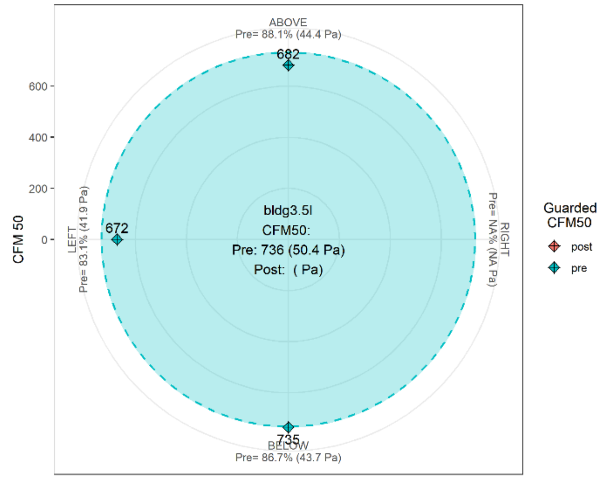


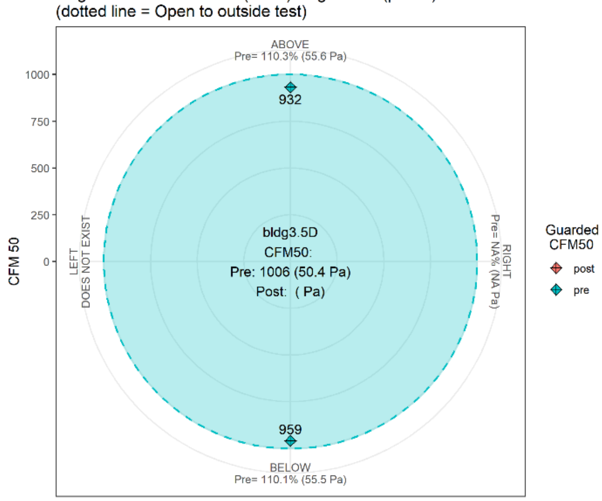
bldg3.12F CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



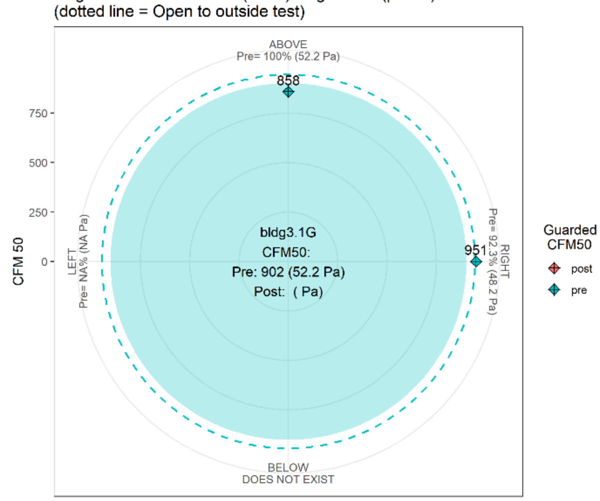
bldg3.5I CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



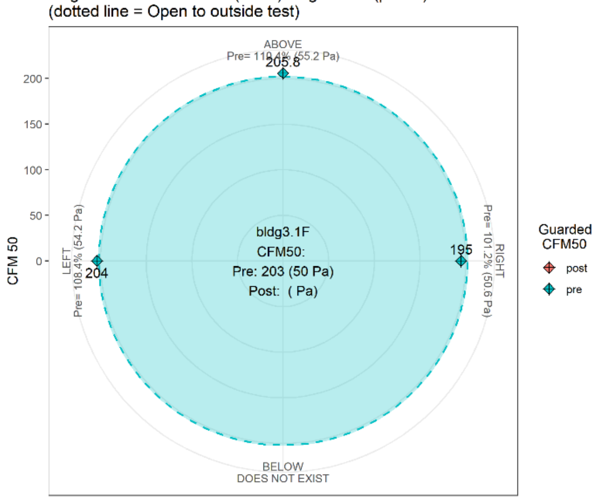
bldg3.5D CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



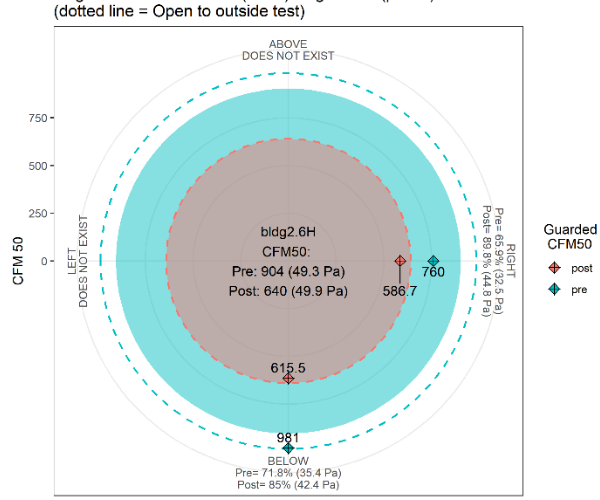
bldg3.1G CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



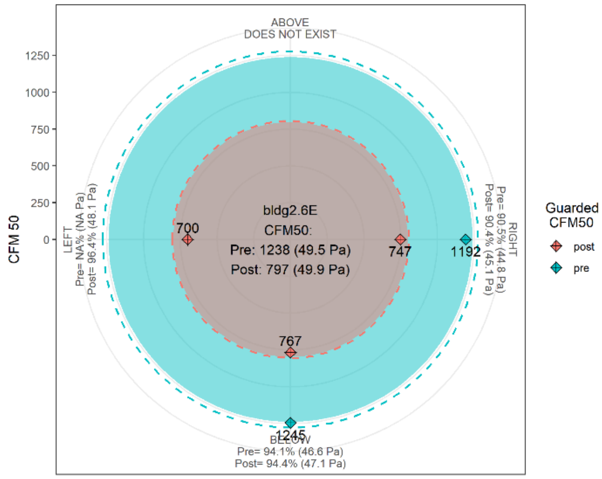
bldg3.1F CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



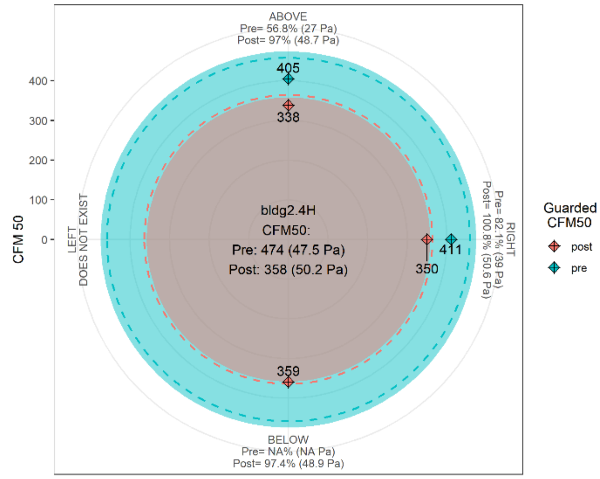
bldg2.6H CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



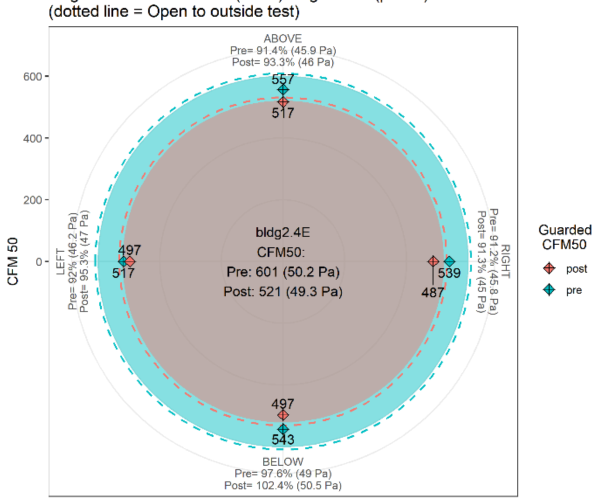
bldg2.6E CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



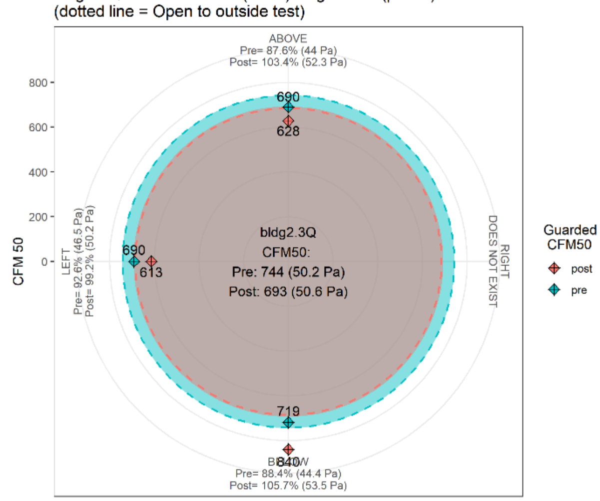
bldg2.4H CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



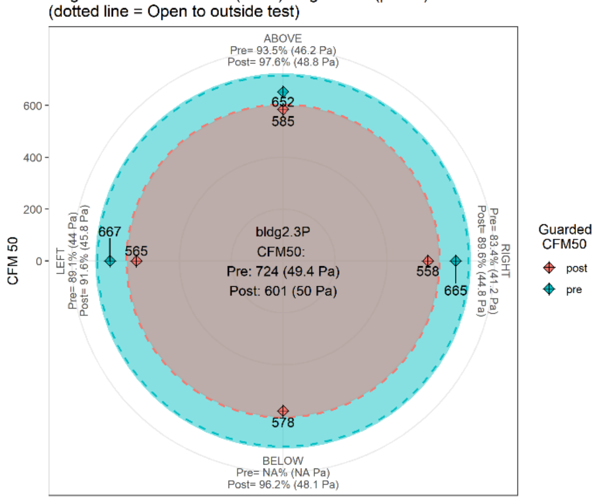
bldg2.4E CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



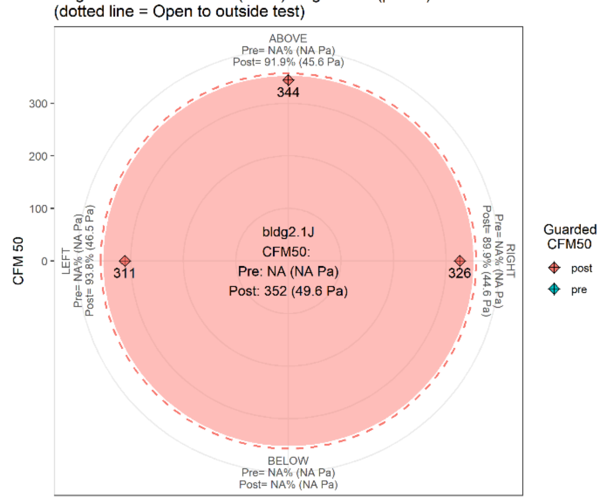
bldg2.3Q CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



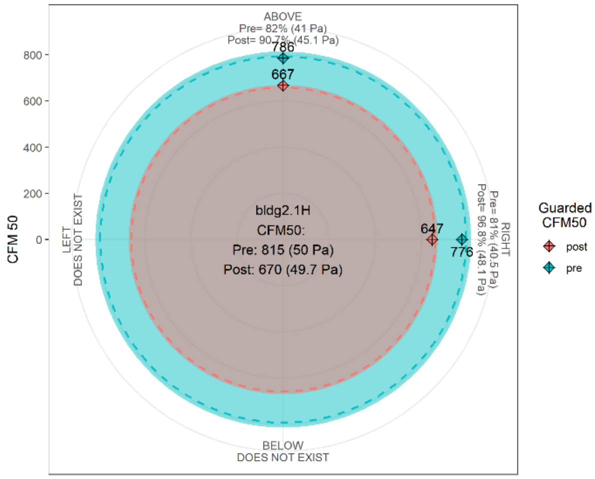
bldg2.3P CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



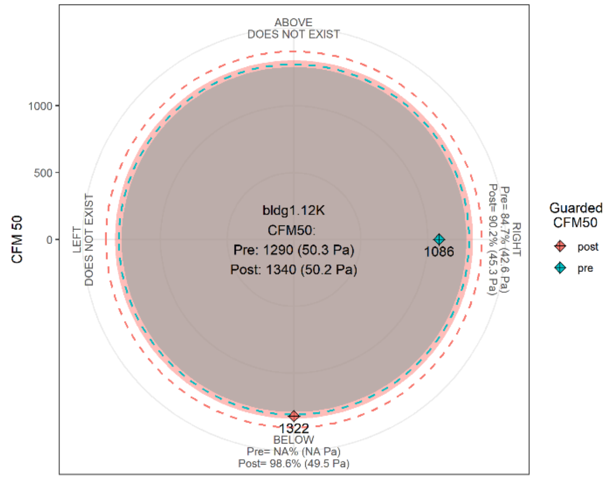
bldg2.1J CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



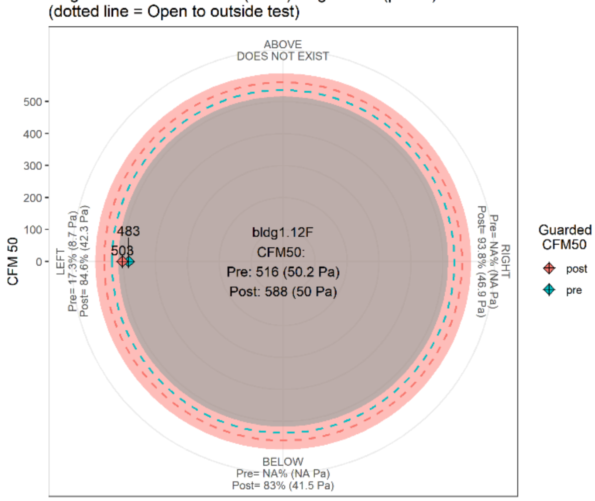
bldg2.1H CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



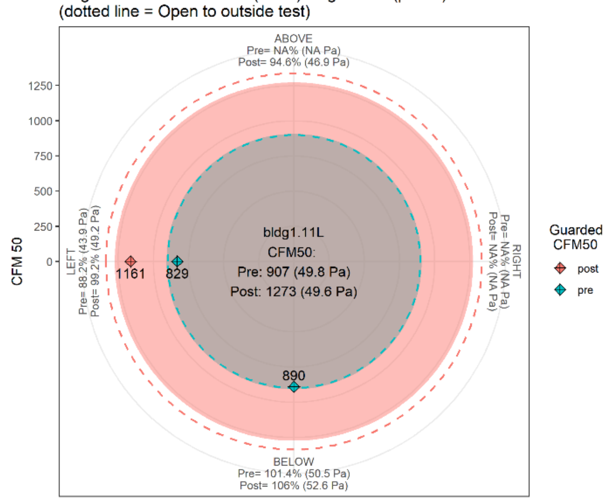
bldg1.12K CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



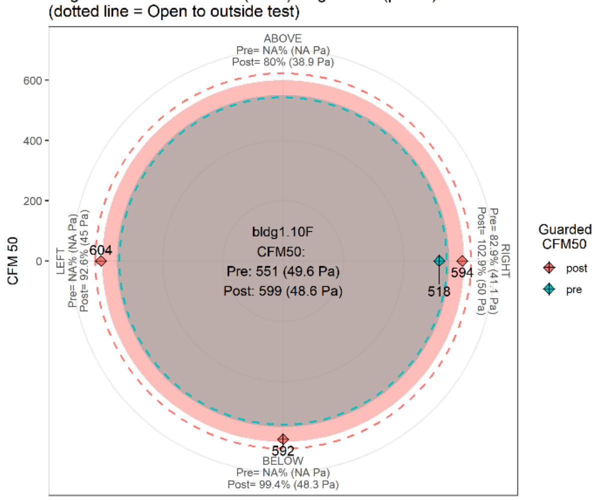
bldg1.12F CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



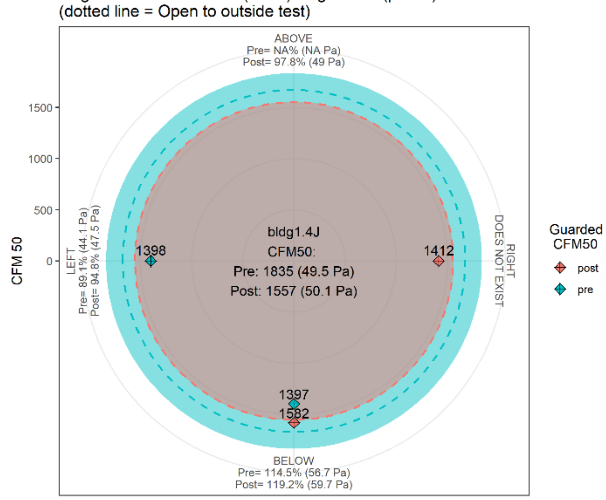
bldg1.11L CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



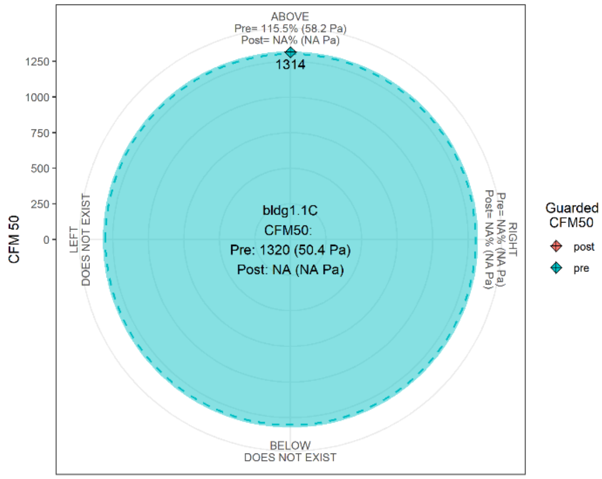
bldg1.10F CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



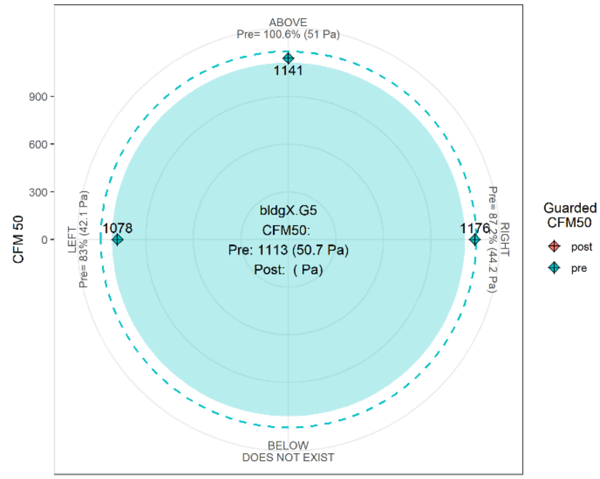
bldg1.4J CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



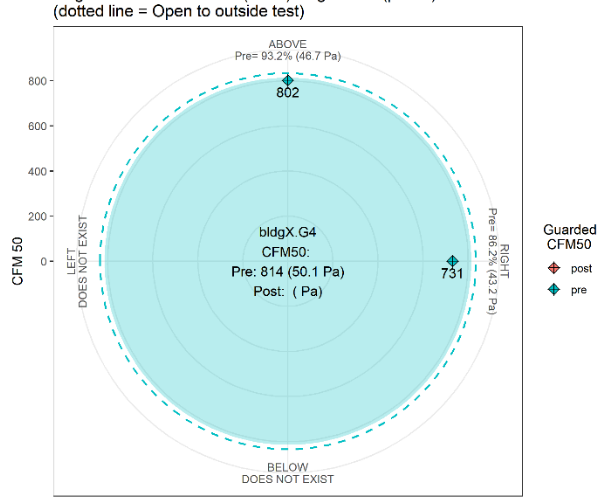
bldg1.1C CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



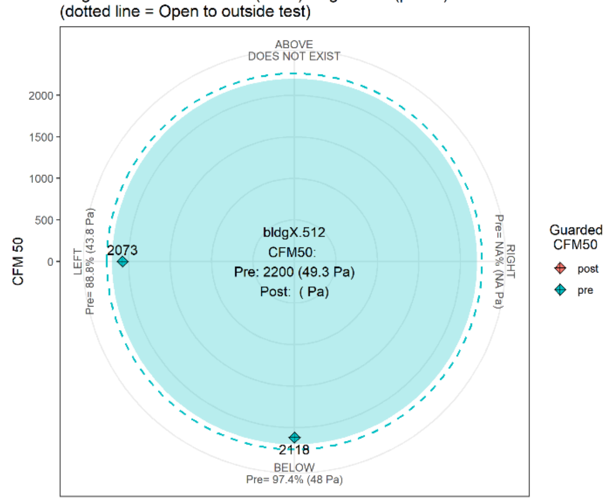
bldgX.G5 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



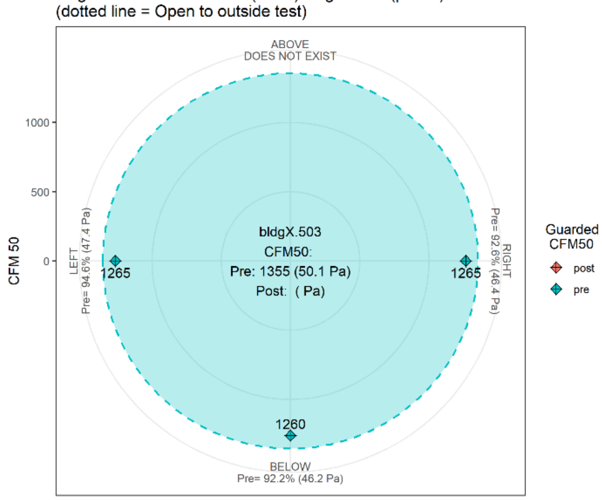
bldgX.G4 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



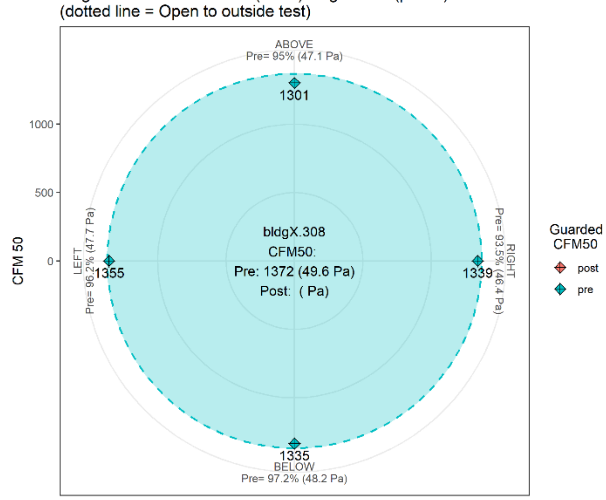
bldgX.512 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)

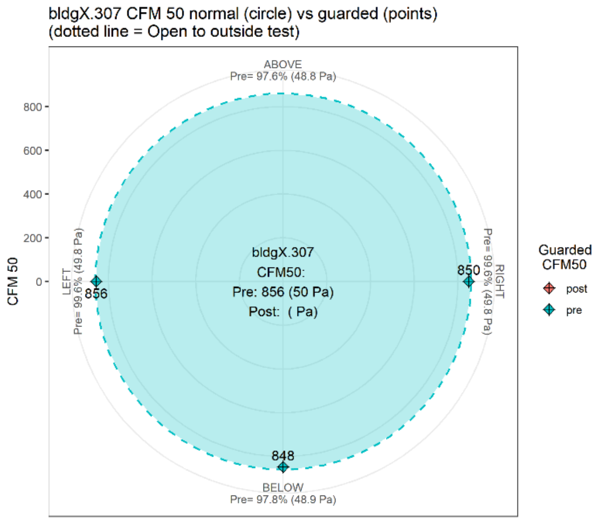


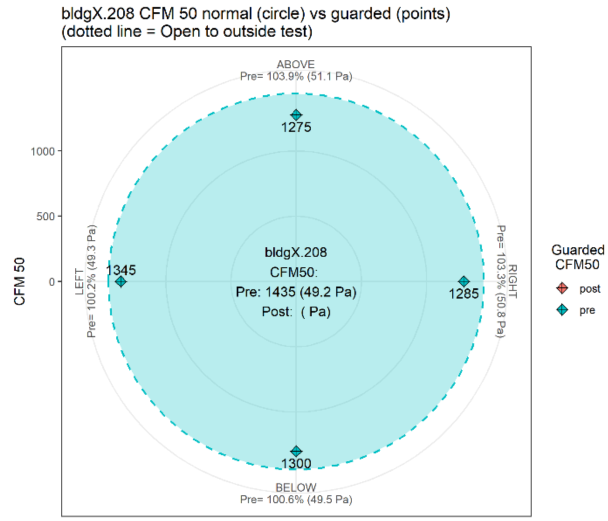
bldgX.503 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)

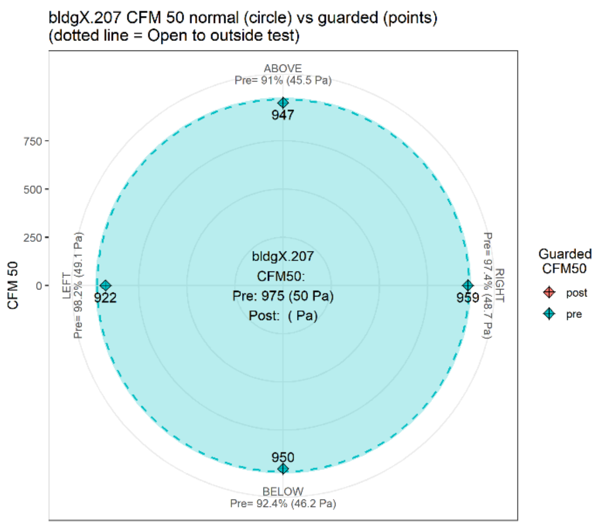


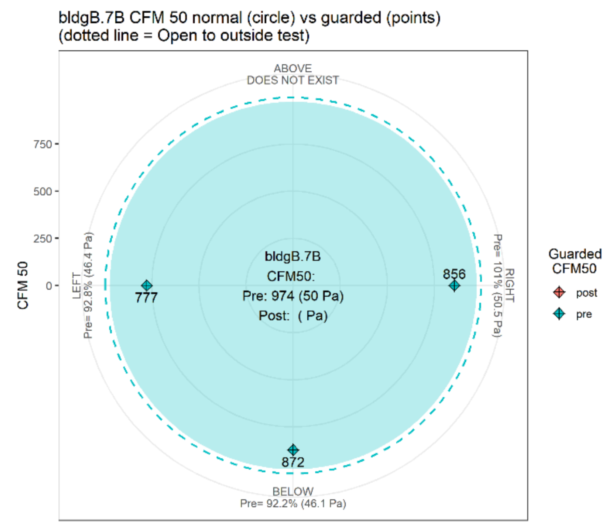
bldgX.308 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)

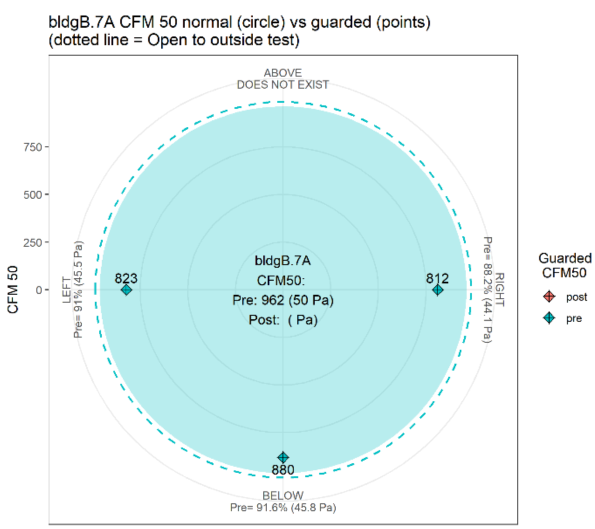


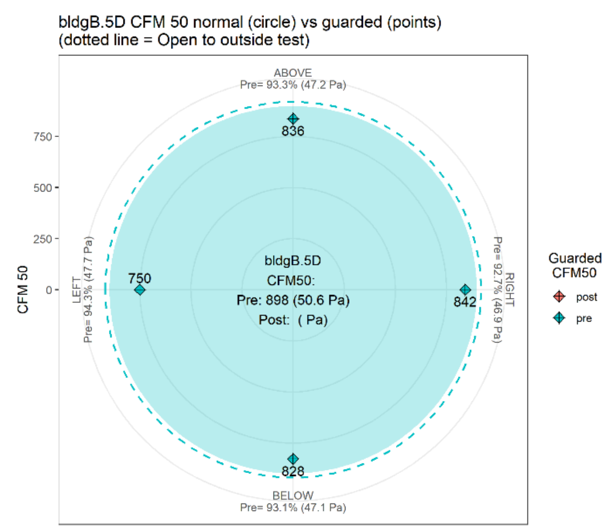

bldgX.307 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)
ABOVE
Pre= 97.6% (48.8 Pa)
LEFT
Pre= 99.6% (49.8 Pa)
RIGHT
Pre= 99.6% (49.8 Pa)
BELOW
Pre= 97.8% (48.9 Pa)
856
850
848
bldgX.307
CFM50:
Pre: 856 (50 Pa)
Post: (Pa)
CFM 50
Guarded
CFM50
post
pre


bldgX.208 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)
ABOVE
Pre= 103.9% (51.1 Pa)
LEFT
Pre= 100.2% (49.3 Pa)
RIGHT
Pre= 103.3% (50.8 Pa)
BELOW
Pre= 100.6% (49.5 Pa)
1275
1345
1285
1300
bldgX.208
CFM50:
Pre: 1435 (49.2 Pa)
Post: (Pa)
CFM 50
Guarded
CFM50
post
pre

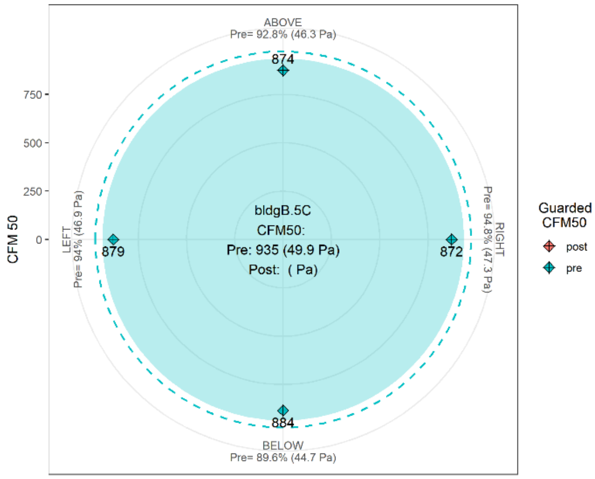

bldgX.207 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)
ABOVE
Pre= 91% (45.5 Pa)
LEFT
Pre= 98.2% (49.1 Pa)
RIGHT
Pre= 97.4% (48.7 Pa)
BELOW
Pre= 92.4% (46.2 Pa)
947
922
959
950
bldgX.207
CFM50:
Pre: 975 (50 Pa)
Post: (Pa)
CFM 50
Guarded
CFM50
post
pre


bldgB.7B CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)
ABOVE
DOES NOT EXIST
LEFT
Pre= 92.8% (46.4 Pa)
RIGHT
Pre= 101% (50.5 Pa)
BELOW
Pre= 92.2% (46.1 Pa)
777
856
872
bldgB.7B
CFM50:
Pre: 974 (50 Pa)
Post: (Pa)
CFM 50
Guarded
CFM50
post
pre

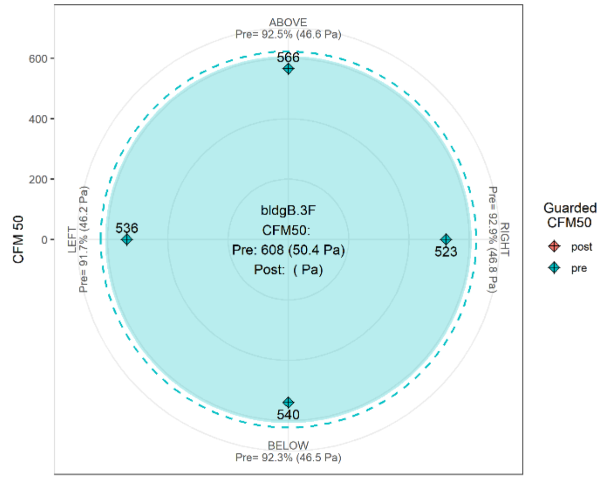

bldgB.7A CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)
ABOVE
DOES NOT EXIST
LEFT
Pre= 91% (45.5 Pa)
RIGHT
Pre= 88.2% (44.1 Pa)
BELOW
Pre= 91.6% (45.8 Pa)
823
812
880
bldgB.7A
CFM50:
Pre: 962 (50 Pa)
Post: (Pa)
CFM 50
Guarded
CFM50
post
pre


bldgB.5D CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)
ABOVE
Pre= 93.3% (47.2 Pa)
LEFT
Pre= 94.3% (47.7 Pa)
RIGHT
Pre= 92.7% (46.9 Pa)
BELOW
Pre= 93.1% (47.1 Pa)
836
750
842
828
bldgB.5D
CFM50:
Pre: 898 (50.6 Pa)
Post: (Pa)
CFM 50
Guarded
CFM50
post
pre

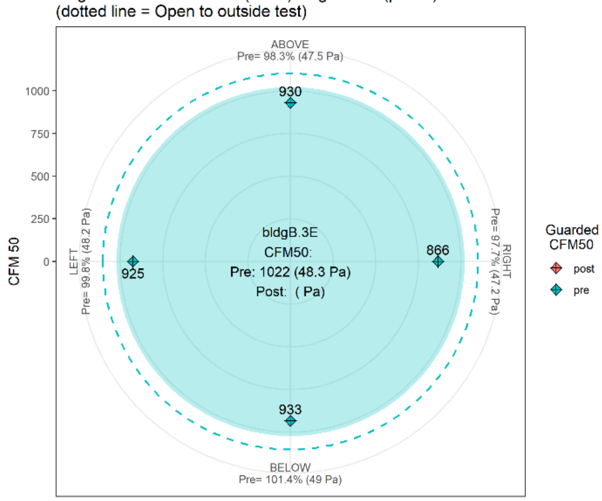
bldgB.5C CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



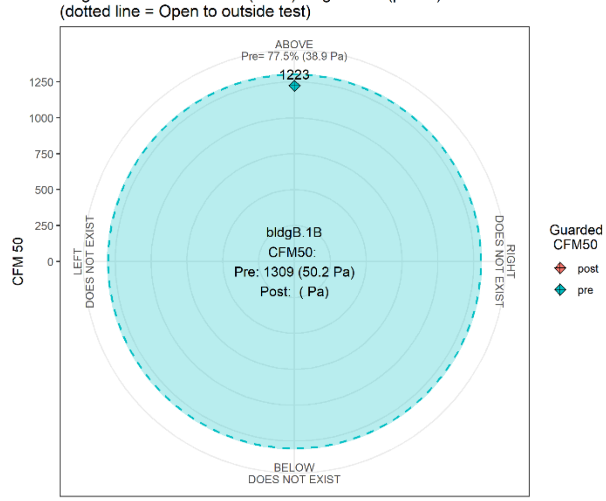
bldgB.3F CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



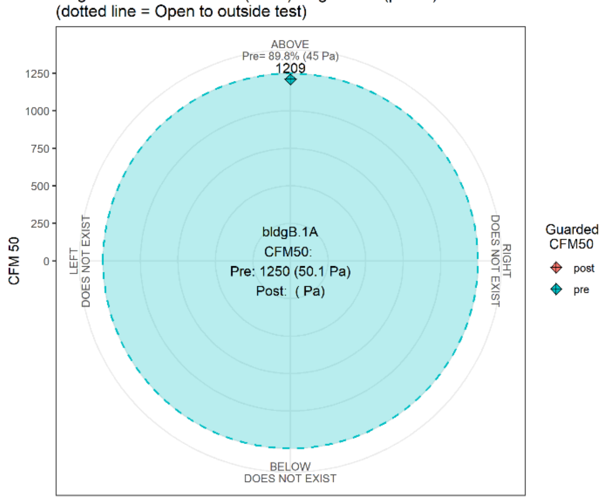
bldgB.3E CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



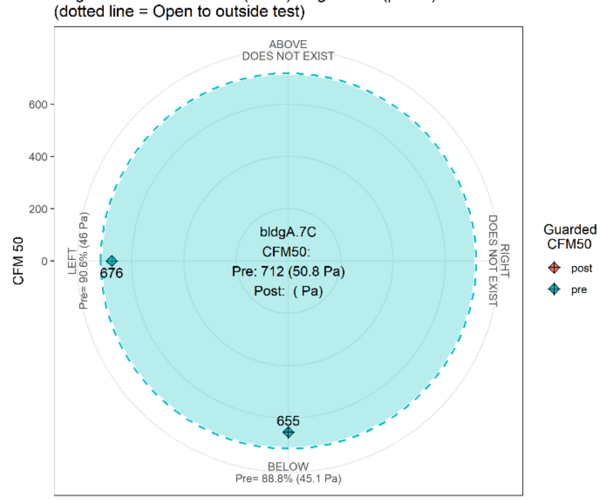
bldgB.1B CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



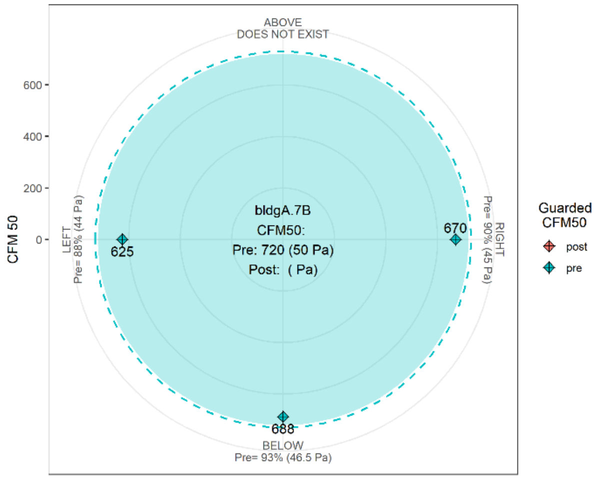
bldgB.1A CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



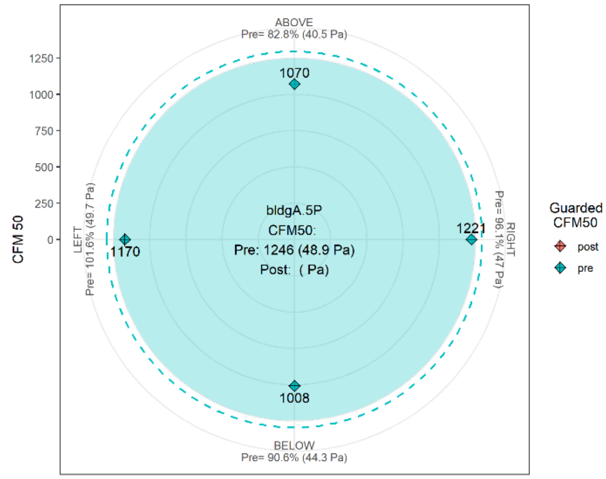
bldgA.7C CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



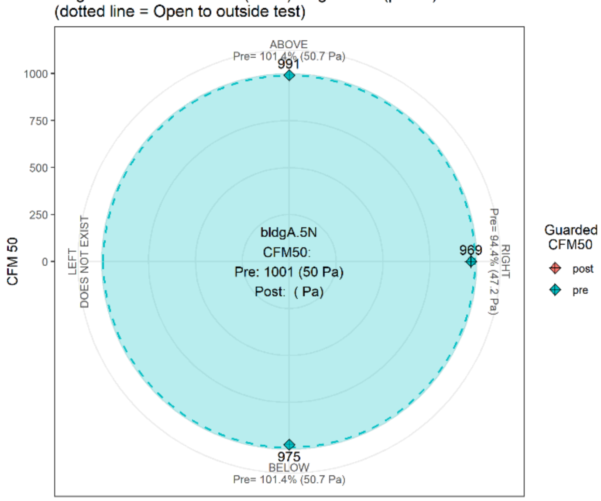
bldgA.7B CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



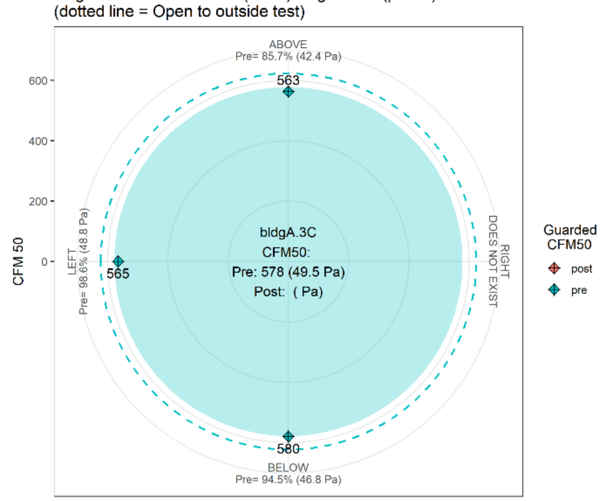
bldgA.5P CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



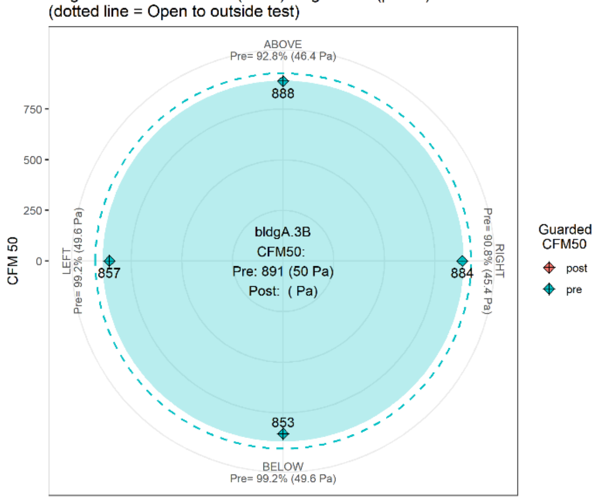
bldgA.5N CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



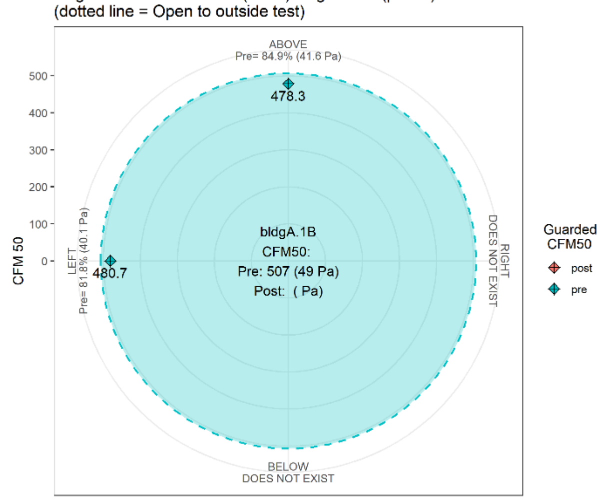
bldgA.3C CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



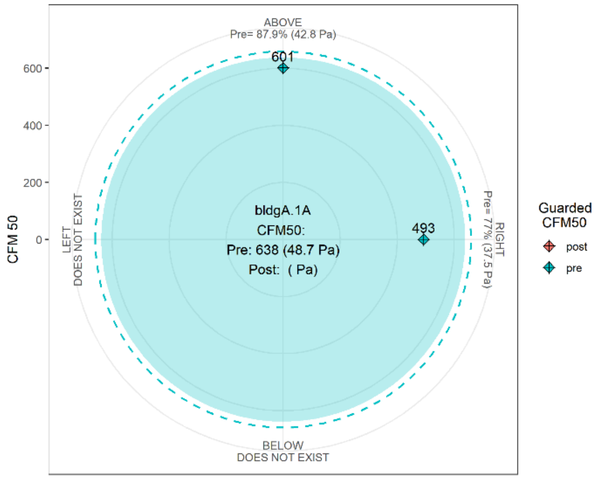
bldgA.3B CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



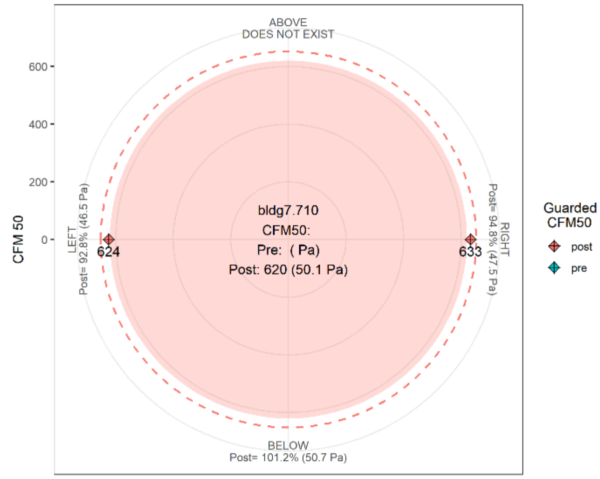
bldgA.1B CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



bldgA.1A CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



bldg7.710 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)



bldg7.707 CFM 50 normal (circle) vs guarded (points)
(dotted line = Open to outside test)