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Effects of Outdoor Smoking Areas and Weather Conditions on Indoor Air Quality

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ABSTRACT

At the Research Support Building at Brookhaven National Laboratory building occupants complained of second hand smoke from people smoking outdoors. This building consists of two wings (North and South) joined by an Atrium. Tests were conducted to quantify the in-leakage from outdoor smoking using five gaseous perfluorocarbon tracers (PFTs) released at the two designated and two 'unofficial' outdoor smoking areas, and one in the building. Two test campaigns were conducted (Fall and Winter). The Fall test data supports an increased likelihood of noticing cigarette smoke from the outdoors by the occupants in the North wing as compared to other areas of the building. Concentrations of tracers released outdoors were a few percent of the tracer released indoors. The second campaign in the Winter used Brookhaven Atmospheric Tracer Samplers (BATS) to sample hourly over the PFTs over a 2 day period. During the day, in-leakage was similar to the fall test. However, a temperature inversion occurred during the evening and the winds were calm for a six hour period. During this period three tracers showed a substantial (a factor of 10) increase in concentration as compared to their values in the day when the temperature inversion was not present. The tracer PDCB released from an 'unofficial' smoking area had a peak concentration of 19% when normalized to the tracer released indoors during this period.

INTRODUCTION

In 1993, EPA released a report (EPA, 1993) that evaluated the respiratory health effects from breathing secondhand smoke (also called environmental tobacco smoke (ETS)) and concluded that ETS is a carcinogen. This prompted many companies to ban smoking in the work site consistent with the ASHRAE position (ASHRAE, 2013) that the only effective means to protect against ETS is to ban smoking .Concerns about second hand smoke from smoking outside but near buildings are increasing. In 2011 the City of Great Neck, New York passed a law prohibiting smoking outside in their main business district. A study (Bohac, 2011) examined the exposure to second hand smoke from interior sources in an apartment building. At Brookhaven National Laboratory (BNL) complaints on second hand smoke from outdoor smoking areas were received by occupants of a new LEED compliant office building.

The Research Support Building (RSB, also known as Building 400) houses frequently visited administrative and support functions in a single location to provide more efficient administrative services to Brookhaven employees and visiting scientists (Figure 1). Construction of the $13- Million RSB, which houses 170 employees, was finished in the fall of 2006. The building features a glass atrium-style lobby connecting two wings of offices covered by a metal panel facade. The

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Research Support Building tops New York State requirements for energy efficiency by 15 percent, and was awarded a Leadership in Energy and Environmental Design (LEED) silver rating by the U.S. Green Building Council.

Figure 1 Research Support Building (Bldg. 400) view from the southeast. The south wing is to the left and the glass atrium in the middle joins with the north wing to the right.

The building was designed to ensure low energy and maintenance costs. To preserve indoor environmental quality, ductwork was kept clean and dry during installation, and each building was flushed with 100 percent of outside air for two weeks prior to occupancy. Ventilation rates are based on carbon-dioxide sensors. Air intake locations for ventilation are the screened areas at the top level of each wing, Figure 1. Water-based paint and other low volatile organic compound-emitting materials were used in construction. In the RSB, 90 percent of building occupants have a view of the outdoors. Occupancy sensors in all office and circulation areas control efficient lighting, and thermostats are located throughout the buildings, so that occupants can readily control the interior temperature for comfort, within certain limits. All BNL buildings including the RSB are smoke free. There are, however, designated smoking area outside the building located both north and south of the atrium.

TEST BACKGROUND

In the fall test period the BNL Tracer Technology Group (TTG) performed an indoor building air flow test on the RSB. This test consisted of releasing gaseous perfluorocarbon tracers (PFTs) in the building and then following the movement of the tracers in the various areas of the building. In discussions with the building occupants prior to the testing, several employees expressed concerns about the smell of cigarette smoke that allegedly was entering the building, especially in the north wing. Based on these concerns, a small scoping study using a tracer released outdoors was added. This additional study was designed specifically to determine if cigarette smoke from outdoor smoking could infiltrate the building in concentrations that might be discernible to the occupants.

The BNL Perfluorocarbon Tracer (PFT) Technology provides a rapid, unobtrusive, and accurate technique to evaluate building air infiltration, circulation, and exhaust to provide information for air quality and emergency response. Only a small amount of odorless, colorless, and non-toxic tracer material is used and concentrations of the tracer are then measured using samples collected throughout the building for laboratory analysis to evaluate complex air flows to determine air flow patterns and air exchange rates. BNL's unique analytical capabilities can detect the presence of specific PFTs at atmospheric background levels (Watson, et. al., 2007), i.e., concentrations as low as parts per quadrillion (10^{-15}). With the use of six or more distinct tracers, specific internal flow patterns as well as air exchange with outside air can be examined simultaneously under the same conditions. In addition, tracers can be used as surrogates for toxic materials so personal exposure dose can be measured directly (using portable pocket-sized personal samplers) to estimate an upper bound on potential human health effects and determine the variability in dose as a function of movement and location.

TIME INTEGRATED STUDY

In the Fall in-leakage study unique PFT sources were placed at the two designated outdoor smoking areas for the RSB as well as three "unofficial" smoking areas that some building occupants have been observed to use out of convenience. These "unofficial" areas are within 5 - 10 feet of a door. Also, another unique PFT source was placed at one indoor location. The indoor tracer would be compared to the concentrations of the PFTs released outdoors. The atrium area was chosen for the indoor release as it is centrally located and exchanges air with both the north and south wings. A separate type of PFT tracer with a unique signature was used at each location so that any measured indoor concentration was traceable to its outdoor release point (i.e., smoking location). Outdoor source release rates were nominally set at three times the indoor release rate to compensate for dispersion and dilution of the tracer and ensure detection if present inside the building. Three permeation sources were placed at each outdoor location and one at the indoor location. Table 1 and Figure 2 show which tracers were used, release locations and release rates.

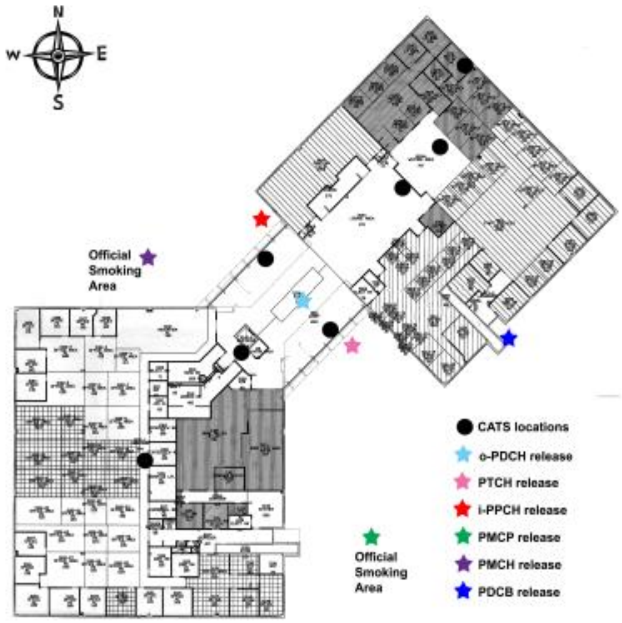
Table 1 Perfluorocarbon Tracers used in the Preliminary Building 400 Cigarette Smoke Infiltration Study. (rates given as nL vapor per min).

Tracer	ID	Location	Release Rate (nL/min)	Normalized Rate*
Ortho-perfluoro, dicyclohexane	o-PDCH	Indoor atrium	1.5	1
Perfluoro, methyl, cyclohexane	PMCH	North designated smoking area	7.1	4.6
Perfluoro, methyl, cyclopentane	PMCP	South designated smoking area	11.4	7.4
Iso-perfluoro, propyl, cyclohexane	i-PPCH	North unofficial Smoking area	2.6	1.7
Perfluoro, trimethyl, cyclohexane	PTCH	South unofficial smoking area #1 – outdoor seating	2.0	1.3
Perfluoro, dimethyl, cyclobutane	PDCB	South unofficial smoking area #2 – north wing exit	10.4	6.8

* The emission rate from the different sources is normalized to the rate of the indoor source o-PDCH. Dividing the measured concentrations by the normalized release rate allows direct comparison between the different PFTs.

Capillary adsorption tube samplers (CATS) were used to sample the air. These are passive diffusion type samplers. Sample tubes were placed in various locations throughout the building (see Figure 2a, 2b). The samplers were left in place for 24 hours and thus are composite samples for the whole day. The results are given in Figures 3a and 3b. Figure 3a shows the measured tracer concentrations for all tracers. Figure 3b shows the concentrations normalized by the ratio of their release rate to the release rate of the tracer released indoors (ocPDCH for all tracers released outdoors. All values for tracer concentration have an estimated error of ± 10%.

The tracer released indoors in the atrium redistributed to the North and South wings in a roughly 2:1 ratio, as shown in Figure 3a. The normalized concentrations of most of the outdoor tracers were reasonably low inside the building, running 1 to 2 percent of the indoor tracer concentration. In other words, a person smoking outdoors results in a concentration of smoke that is 1-2% of the smoke level inside the building compared with a person smoking indoors in the atrium area. A noticeable exception to this was the PDCB tracer concentration in the North wing. PDCB was released at the South unofficial smoking area #2 (Figure 2a) just outside of the North wing. The PDCB concentration in the North wing was 3% of the indoor tracer concentration (o-PDCH) seen in the Atrium and 8% of the indoor tracer concentration seen in the North wing. While sensitivity to smell is highly variable, these data suggest that outdoor smoking near the building can impact the air quality of the building.



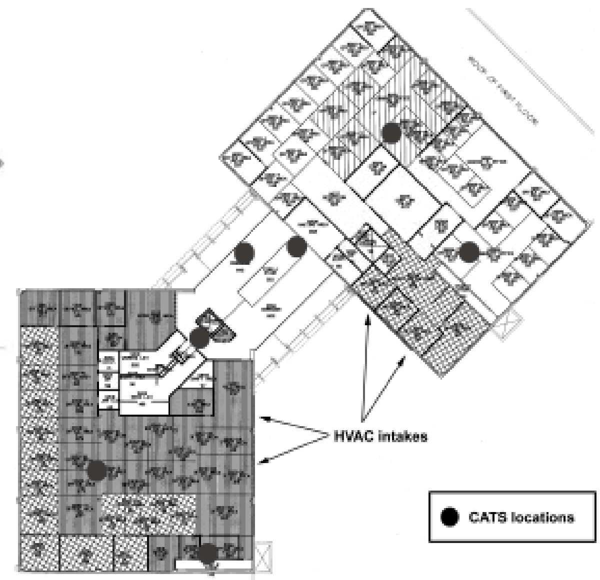


Figure 2a: Research Support Building showing release locations (stars) and 1st floor sample locations (circles) for the Fall test.

Figure 2b Research Support Building showing 2nd Floor sample locations

Time Resolved Study

One limitation of the results from the fall study is that the data represented a 24 hour composite of the concentrations. As a means of removing this limitation, a second experiment was designed that included time resolved sampling. In this study two PFTs were placed indoors and four PFTS were released outdoors. The indoor releases used i-PPCH in the Atrium and PTCH in the South wing, as shown in Table 2. Each location had two permeation sources. The outdoor releases had six permeation sources at each location to compensate for both the high dilutions expected and the colder temperature occurring in January (Table 2). This resulted in normalized (outdoor to indoor) release rates that were very similar to the fall study.

PMCP was placed at the south official smoking area, o-PDCH was placed at the south unofficial smoking area closest to the atrium, PDCB was placed at the unofficial smoking area located at the south exit of the north wing and PMCH was placed at the north official smoking area. Table 2 gives the release rates, in mL/min vapor, as well as the normalized rates. The release rates in Table 3 have been adjusted using a temperature dependent calibration curve. The indoor rates are at 21°C and the outdoor rates at -2°C. The outdoor sources were placed out 24 hours prior to air sampling to allow the building to reach equilibrium. Indoor sources were placed to coincide with the start of air sampling so that the concentration rise rate could be measured as well. The latter, along with measurement of the decay curve, was completed for BNL Emergency Operations to obtain a better understanding of the building dynamics and shelter-in-place requirements.

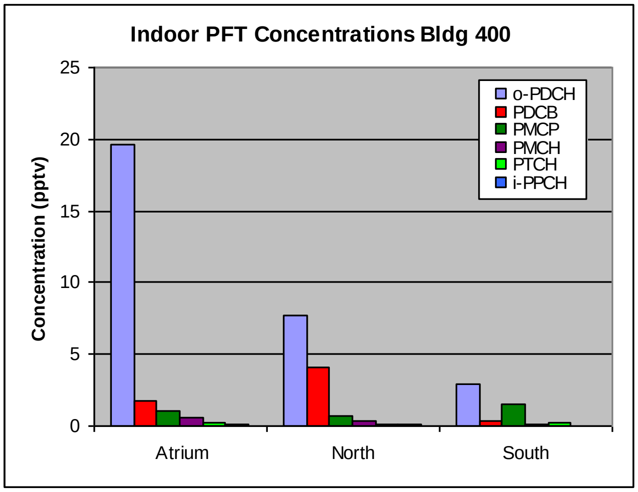


Figure 3a: RSB interior tracer concentrations.

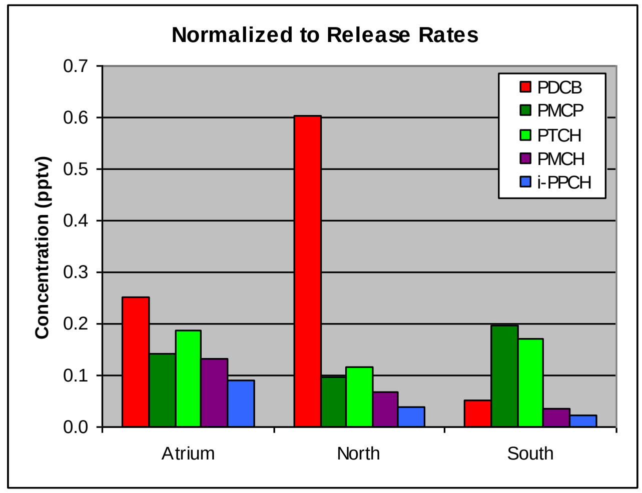


Figure 3b. RSB interior concentrations of tracers released outdoors normalized to ocPDCH release rate

Sampling was accomplished using Brookhaven Atmospheric Tracer Samplers (BATS), which are automated, programmable air samplers. Each sampler had a lid with 22 adsorption tubes and was programmed to take 60 minute samples at 50 cc/min. Samplers were placed in the atrium on the ground floor and on both floors of the north and south wings. Sampling was performed over a two day period starting at 1000 hrs. on January 6th. Twenty two consecutive one-hour samples were taken, ending at 0800 January 7th. The BATS sampling tubes were changed on the 7th and a second set of sampling started at 1000 hrs. on January 7th. This sampling period also collected 22 one-hour samples. The indoor sources were removed at 1000 hrs. on January 7th to allow measurement of the decrease in tracer concentration over time (decay curve) for the building. The decay curve can be used to determine the number of air changes per hour in the building.

Table 2 Perfluorocarbon Tracers used in the two-day, Time-resolved, Building 400 Cigarette Smoke Infiltration Study. (rates given as nl vapor per min).

Tracer	ID	Location	Release Rate (nl/min)	Normalized Rate*
Ortho-perfluoro, dicyclohexane	o-PDCH	South unofficial smoking area #1 – outdoor seating	3.4	3.1
Perfluoro, methyl, cyclohexane	PMCH	North designated smoking area	5.2	4.6
Perfluoro, methyl, cyclopentane	PMCP	South designated smoking area	8.0	7.2
Iso-perfluoro, propyl, cyclohexane	i-PPCH	Indoor atrium – 1st floor	1.1	1.0
Perfluoro, trimethyl, cyclohexane	PTCH	Indoor in North Wing- 1st floor	0.9	0.8
Perfluoro, dimethyl, cyclobutane	PDCB	South unofficial smoking area #2 – north wing exit	7.2	6.4

* The emission rate from the different sources is normalized to the rate of the indoor source i-PPCH. Dividing the measured concentrations by the normalized release rate allows direct comparison between the different PFTs.

TIME RESOLVED RESULTS

On the first test day, January 6th, the tracers released indoors were at much higher concentrations (by a factor of 10 or more) than the tracers released outdoors. The two tracers used indoors (iPPCH and PTCH) on January 6th were removed at the start of the data collection on the 7th and had a concentration near background within an hour.

The time resolved data shows a distinct day/night change in the tracer equilibrium concentration. The RSB has a complex HVAC control system. Sensors monitor humidity, temperature, outside air temperature and CO_2 levels. In addition, the system has sensors to estimate the number of occupants and has a programmed night cycle that maintains a lower temperature and lower ventilation rate than in the daytime. Some day-to-night variation in tracer concentrations is expected due to this. The indoor tracers rise for the first hour then reach a daytime equilibrium concentration and remain fairly constant until 2100 hrs.; around the time the buildings night set back begins. This results in a reduced air exchange rate (less outside air being brought in) and the tracer concentration rises for two to three hours and reaches the night equilibrium concentration until the morning (~0600 hrs.) when the daytime HVAC settings are re-established.

On the first day the indoor tracer i-PPCH, released in the atrium, redistributed slightly differently than what was observed in the fall study for o-PDCH (released in the atrium in the first study). It was seen in roughly equal amounts (10 to 12 ppt) in the North and South wings (peak value in the atrium was ~30 ppt). The fall study was completed under mild conditions when heat and cooling requirements were minimal. The winter study was completed under colder outdoor temperatures which would change heat and air exchange rates. This might explain the differences seen between fall and winter testing.

PTCH, released in the South wing, was seen at low levels (< 5 ppt) during the day and had a very large rise at night (40 ppt). In fact, the daytime levels of PTCH were similar to the concentration levels for the outdoor tracers PMCP (released closest to the South wing air intakes). However, the source strength for PMCP was approximately 9 times greater than for PTCH. During the day the PTCH levels in the atrium were similar to the south wing concentrations. After the night set back went into effect, the PTCH equilibrium concentration in the south wing reached about 30 ppt, reached a max of 5 ppt in the atrium and still was not seen above 0.1 ppt in the North wing.

The first day outdoor tracer concentrations in the RSB were significantly different from the second day concentration profiles. On the first day the outdoor tracers were barely seen in the North wing with PMCH having the maximum concentration of 1.4 ppt of all outside tracers. The tracer released at the unofficial smoking area near the North wing of the building (PDCB) was not seen at the concentrations consistent with the Fall study. The overall response to the outdoor sources was quite different from the Fall study. As mentioned, during the day the South wing saw levels of PMCP (outdoor tracer) equal to the indoor concentrations of PTCH (indoor tracer south wing release). PMCP remained at a constant level throughout the first day and did not show the nighttime rise as seen for the indoor tracers. PDCB and PMCH were seen at fairly low levels in the south wing during the day and showed a slight rise during the night; eventually reaching levels equal to the PMCP. The atrium showed only minor levels of o-PDCH, low levels of PMCH and PMCP, and PDCB was highest of the outdoor tracers. The PDCB peaked at levels of about 15% of the peak i-PPCH level in the atrium or 3% of the normalized concentration. Over all, the outdoor tracers were seen in minor levels throughout the first day study. The PDCB level in the atrium indicates some infiltration from the unofficial smoking area #2 near the north wing exit. Similarly, the PMCP levels in the south wing seem to indicate some infiltration of air from the south official smoking area.

The second day showed a marked increase of in-leakage from the outside sources. The indoor tracers were removed to measure the decay curve for the building. For the most part the indoor tracers reached very low to insignificant levels within the first hour after source removal. So comparison of indoor to outdoor concentrations for the second day is not valuable.

The pattern of much higher concentrations at night when the ventilation rate is reduced was observed again. However, the magnitude of the effect was much greater on the second day. As seen on the first day, the PMCP released from the south official smoking area infiltrated the south wing and atrium. The levels were about the same as on the first day and indicate the possibility of smoke being detectable by occupants. The PMCP level was slightly higher on the 2nd floor of the south wing than the 1st floor. PDCB, released at the unofficial smoking area #2 near the north wing exit, was at low levels (< 5 ppt) for the beginning of the day, started rising slightly at sunset (~1630) reaching a constant low level until approximately 2230 when the concentrations started to rise to very high levels. In the North wing, the PDCB levels of 56 ppt surpassed the maximum tracer concentration for the tracer released in the atrium (i-PPCH) in the North wing on the first day (12 ppt). The PDCB concentration in the North wing even exceeded the maximum first day concentration (31 ppt) for indoor tracer i-PPCH in the Atrium where it was released. The PDCB concentration in the atrium peaked at 30 ppt, the same level as the equilibrium concentration of iPPCH released at that location. Even though the source strength of PDCB was 6.4 times greater than for i-PPCH, it is clear that there was a large rate of in-leakage during the evening of January 7th. The normalized peak concentration of PDCB in the North wing was 35% of the atrium level of i-PPCH seen on the first day. The atrium saw 31 ppt PDCB or 19% of the normalized i-PPCH day one level, while the South wing peaked at 11 ppt (6% of the day one level). Around 0430 the PDCB concentration began to decrease but remained high until sampling ended at 0800.

This behavior begged the question; what caused these high concentrations during the night hours? A possible explanation is found in the weather conditions. The Meteorological Services group at BNL records weather data at 2 meters, 10 meters and 85 meters. There is a clear temperature inversion on the second day and none on the first. Inversions are created when colder dense air displaces warm air near ground level, thus interrupting the natural air flow created when warm air rises and cooler air flows in to replace it. The calm winds at the ground elevation on the evening of January 7th are typical of a temperature inversion. This explains the sudden increase in the tracer concentrations seen late in the night on the second day. The inversion begins around 2200 hrs. and lasts until about 0400 hrs. these times correspond to the rise and fall times seen inside the building. Looking at wind speed it is clear the outside air movement/mixing becomes very small during this period, allowing less dilution and higher outdoor concentrations that leak into the RSB. It is very interesting that PDCB, PMCH, and o-PDCH interior concentrations are strongly affected by the inversion with all increasing by at least a factor of 10 while the PMCP remained fairly constant throughout the sampling period.

CONCLUSIONS

Indoor building air flow tests were conducted on the Research Support Building at Brookhaven National Laboratory. These tests used perfluorocarbon tracers released for a 24 hour period and measured the concentration of these tracers at several locations in the building to determine air flow patterns. As part of these tests PFT tracers were placed outside the building in designated and “unofficial” smoking areas with the goal of understanding whether cigarette smoke from outdoors could impact indoor air quality. Two test campaigns were conducted.

The first campaign used CATS to collect a composite average of concentration over the 24 hour test period. There were two unique tracers released inside the building and four unique tracers released outside. As a basis of comparison, the concentrations of the PFTs released outside were compared to the PFTs released inside after normalization for the different release rates. The results indicated that, for three of the tracers, the normalized concentrations of the outdoor tracers were approximately 1 to 2 percent of the indoor tracer concentration. That is a person smoking outdoors would result on average in 1-2% of the smoke level compared to a person smoking indoors in the atrium area. The fourth tracer, PDCB, was released at the unofficial smoking area #2 (Figure 2) just outside of the North wing. The PDCB concentration in the North Wing was 3% of the indoor tracer concentration (o-PDCH) seen in the Atrium and 8% of the indoor tracer concentration seen in the North wing. Coincidentally, this is the area in the building where BNL personnel complained of smoke odors. The data supports that there is an increased likelihood of noticing cigarette smoke from the outdoors by the occupants in the North wing as compared to other areas of the building.

The second campaign used BATS to sample the PFTs. This allowed one-hour composite data to be collected as opposed to the 24 hour composite in the fall campaign. This campaign had two days of testing. In the first day there were two interior tracers and four exterior tracers. The interior tracers quickly reached equilibrium in the day time. At night, the building temperature and ventilation flows are decreased. This caused the interior tracer concentrations to increase to a new equilibrium value. The exterior tracers did appear in the interior at levels consistent with the tests in the Fall. The second day test removed the interior tracers and used tracers at the four exterior locations. During these tests one tracer, PMCP released at the south designated smoking area, appeared to quickly reach a uniform level of about 4-5 ppt in all areas of the RSB and maintain this level over the 24 hour test period. The other three tracers showed an order of magnitude increase in concentration between 2200 and 0400 hours on the evening of January 7th.

The night of January 7th had a temperature inversion which is characterized by extremely calm winds. This temperature inversion phenomena could have a major impact on indoor air quality (the tracers act as surrogates for gaseous pollutants). This has implications for ventilation of buildings that are heavily occupied at night (i.e. residential buildings and spaces that have shift work). The impact of low winds on in-leakage has implications for Emergency Management decisions regarding shelter in place decisions. During temperature inversions the need to evacuate buildings increases.

The flow paths from the ground into the building are not obvious. However, it appears that in-leakage occurs primarily through the air intake vents on the east side of the building (Figures 1 and 2). During the evening, the building is unoccupied and the likely pathway for the outdoor sources into the building is through the air intake vents. These vents are directly above the o-PDCH source. However, the PDCB source around the corner and to the north enters the building at much higher concentrations. The temperature inversion had a major impact on the inside concentrations of three outside sources, but not the fourth. These findings are not intuitive and most likely cannot be determined without testing. Additionally, the importance of source location on indoor air quality is a function of wind direction as well as wind speed needs to be studied. Further testing would be needed to understand these effects.

These tests covered three days, one in fall and two in the winter. This does not cover the entire range of anticipated conditions. Additional studies could be performed to examine other conditions. For example, higher winds may lead to more dispersion of the pollutant, but higher air in-leakage into buildings. The net impact is not known. In summer, outdoor temperature may exceed indoor temperature which will impact on the amount of outside air used for ventilation and may impact in-leakage.

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