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ABSTRACT

The U.S. Department of Housing and Urban Development (HUD) has identified a need to improve urban housing conditions to protect children's health through its Healthy Homes Initiative (HHI). One critical area within this program is indoor air quality (IAQ), for example, inadequate ventilation, moisture, combustion by-products, etc. and the identification of effective intervention strategies to address these issues. To evaluate the impact of different interventions on indoor contaminant concentrations and occupant exposures, a simulation study was conducted using the multizone airflow and contaminant dispersal model CONTAM. This study modeled the exposures of a family of five to concentrations of carbon dioxide, carbon monoxide, nitrogen dioxide, water vapor, 0.3 μm to 10 μm particles, radon, and volatile organic compounds in a three-story townhouse. To investigate the impacts of environmental conditions, the townhouse was modeled with weather conditions from all four seasons in Boston, MA, Miami, FL, and Seattle, WA. The model included outdoor and indoor sources of the contaminants as well as adsorption and deposition loss mechanisms. CONTAM predicted ventilation rates, contaminant concentrations and occupant exposures for a baseline case and eight different interventions in each city/season combination. The interventions included venting an otherwise unvented space heater, replacement of a faulty stove, upgrading a furnace filter, installation of air conditioning, operation of kitchen and bathroom exhaust fans, ceasing the practice of using a gas oven to heat the house, tightening the house's envelope, and installation of mechanical ventilation.

Intervention strategies were compared on an individual basis and a small sub-set of interventions were considered to demonstrate an intervention ranking system for identifying the best strategy. The key parameter utilized in evaluating the interventions is the concentration relative to the baseline rather than comparison of absolute concentrations to guideline values. Overall, a combination of mechanical ventilation, local exhaust, and an improved air filter was most effective for reducing the largest number of contaminants in the study.

Key Words: exposure, indoor air quality, modeling, residential building, ventilation, air cleaning, contaminants.

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EXECUTIVE SUMMARY

The U.S. Department of Housing and Urban Development's Healthy Homes Initiative (HHI) is addressing a wide range of indoor air quality (IAQ) concerns to improve urban housing conditions and protect the health of children. Residential indoor air pollutants of concern include combustion by-products, volatile organic compounds, radon, and bioaerosols (Tobin et al., 1992; Sherman, 1999). Many of these contaminants are often measured at higher concentrations in lower income urban housing (Laquatra et al., 2002; Brugge et al., 2002), and these residences are typically in the greatest need of remediation. As such, the U.S. Department of Housing and Urban Development (HUD) has made it a priority to identify wide-reaching intervention strategies that can be feasibly implemented to improve IAQ in lower income homes, and the HHI program is funding several demonstration projects to implement interventions that correct many of the IAQ problems found in these homes. Due to the costs of fieldwork, however, the demonstration projects are only able to implement a limited number of interventions in a small number of homes. A more feasible way to prioritize the intervention strategies is through modeling. A modeling approach allows the evaluation of many potential interventions under a wider variety of conditions to help provide a knowledge base for recommending the most effective strategies. Such modeling can also be used to evaluate the interventions for possible unintended negative impacts. Thus, model results have the potential to provide valuable insight toward the improvement of IAQ in urban housing with multiple deficiencies.

To evaluate the impact of potential interventions on indoor contaminant concentrations and occupant exposures, a simulation study was conducted using the multi-zone IAQ model CONTAM. A CONTAM model of an actual townhouse was used as a baseline building (Emmerich et al., 2002), with modifications to make it more representative of lower-income urban housing. Since ventilation and IAQ performance vary by climate, the house was modeled in Boston, MA, Seattle, WA, and Miami, FL for one week of each season. To account for occupant-generated contaminants and to account for occupant exposure to indoor contaminants, a family of five was assumed to occupy the townhouse. The occupants of the house included an adult male, adult female, and three children, with a schedule for each family member that specifies the time spent in each room of the house.

The model was used to predict air change rates, contaminant concentrations of carbon dioxide (CO_2), water vapor (H_2O), carbon monoxide (CO), nitrogen dioxide (NO_2), airborne particles in five size ranges (P1: 0.3 μm to 0.5 μm, P2: 0.5 μm to 1.0 μm, P3: 1.0 μm to 2.5 μm, P4: 2.5 μm to 5.0 μm, and P5: 5.0 μm to 10 μm), volatile organic compounds (VOCs) and radon (Rn), and occupant exposures to these contaminants. The modeled sources included occupant respiration (CO_2 and H_2O), bathing (H_2O), cooking (H_20, CO, NO_2, and particles), dishwashing (H_2O), changing kitty litter (particles), building materials (VOC1), cleaning (VOC2), unvented combustion appliances (CO and NO_2), the soil (Rn), and outdoor air (all contaminants). These modeled sources were not intended to be comprehensive, but rather representative of typical residential sources to provide insight into each of the individual contaminants. Also, some of the sources produce additional contaminants beyond the ones considered, e.g., unvented combustion appliances also produce CO_2, H_2O, and particles but were not included as a source of these contaminants in this study.

The loss of contaminants due to adsorption, deposition and decay were also included in the models. Reversible sink effects for H_2O and VOCs were modeled with sink elements based on the boundary layer diffusion controlled (BLDC) model available in CONTAM. Particles were also removed in the baseline cases by a typical furnace filter in the air handler system (AHS).

The HUD HHI interventions and the requirements of ASHRAE's new residential ventilation and IAQ standard 62.2-2004 were considered in selecting the eight interventions that were modeled. The interventions can be categorized as dilution ventilation (continuous mechanical whole-house ventilation and tightening the building envelope), local ventilation (intermittent operation of kitchen and bathroom exhaust fans), air cleaning (upgrading filter in the heating and air-conditioning (HAC) system and dehumidification through the operation of an air-conditioner), or source control (removal of unvented space heater, upgrading gas stove, and ceasing use of gas oven to heat home). Obviously, there are many other interventions that could be considered, including a host of possible source control actions.

This report presents detailed simulation results including air change rates, contaminant concentrations and occupant exposures for the baseline cases. Each modeled intervention was then evaluated based on its impact relative to the baseline case. Based on these evaluations, a summary of each intervention strategy is provided below:

Upgrading gas stove: Upgrading the gas stove results in lower NO_2 and CO concentrations year round. In fact, it was the single most effective intervention at reducing these contaminants in all climates. In general, older combustion appliances have lower efficiencies and tend to emit more pollutants. Although a gas stove was used to illustrate this point in this project, the intervention would be effective for reducing contaminants for any unvented combustion appliance.

Operation of gas oven to heat home: Educating occupants of the potential dangers of using a gas oven for heat is the least expensive intervention strategy examined. Operating a gas oven to heat a house can elevate concentrations of CO and NO_2 to unhealthful, even fatal, levels (see warning at http://www.epa.gov/iaq/pubs/combust.html). For this project, using the gas oven to heat the house resulted in the second highest average winter concentration of CO, assuming a properly operating oven was used. If a faulty oven had been used, the occupants' exposure to CO would have been much higher and may have exceeded fatal levels. Unfortunately, this practice does persist in lower income housing when the residents do not understand the risks involved. Stopping this practice is a source control option that would prevent excessive exposure to CO and NO_2 at little to no cost to the resident (unless faulty heating equipment needs to be replaced, which could entail significant cost).

Removal of unvented space heater: Using only properly vented space heaters also reduces indoor air concentrations of CO and NO_2. Venting the combustion products from space heaters to the outside would essentially remove these pollutants from the living space, thereby significantly reducing occupants' exposure to CO and NO_2 in cold climates. This intervention would involve both education of the occupants and the installation of an exhaust vent, if needed.

Enhanced particle air cleaner: Air cleaning reduces contaminants originating both indoors and outdoors with no negative impact on other contaminant concentrations. Most homeowners, however, generally have access only to air cleaners that remove particles, limiting the scope of the intervention. While an effective intervention for removing particles, such an air filter only works when the HAC system is operating. For this project, the HAC system was operated for cold seasons in Boston and Seattle and hot seasons in Miami. In the other seasons, the HAC system was off and the air filter was not removing any particles. As a result, this intervention was only useful in cold or hot climates. This intervention would also be effective in more temperate seasons; however, it is important to consider the balance between first and operating costs and benefit from reducing particle concentrations. Portable air cleaners are also an option but were not evaluated in this study.

Installation of air-conditioner: Despite a relatively short operation time assumed in the modeling effort, the air-conditioner significantly decreased average indoor humidity levels. In fact, the humidity reduction from operating an air-conditioner for one season in Boston and Seattle outweighed the impacts of other interventions operated year-round. Again, there is a need to consider both first and operation costs along with the benefits obtained by limiting relative humidity to levels low enough to prevent mold, allergens, and other indoor air problems.

Kitchen and bathroom exhaust fans: The exhaust fan was the most effective intervention strategy to reduce peak concentrations associated with cooking and showering. This reduction in concentration during source events had a significant impact on the occupants' exposure to CO, NO_2, P2, P3 and H_2O. It was the single most effective intervention for exposure to P2 and P3 in most climates. The increased air change rate due to exhaust fan operation also reduced the concentrations of contaminants from sources in other parts of the house (e.g., VOC1 and radon). The downside of this intervention was the increase in concentrations of contaminants originating outdoors. This negative impact was significant for P4, P5, and H_2O in Miami. The benefits of using an exhaust fan during source events, however, far outweighed the negative impacts. In fact, project results showed that using the exhaust fan during more source events (e.g., cleaning in kitchen or bathroom, or dishwasher operation) would have reduced concentrations and exposures even more. If there is no exhaust fan installed or if the current fan does not vent to the outside, there will be an installation cost in addition to an operating cost associated with this intervention. However, in some cases, it is a matter of educating the occupants to turn on the fan during source events.

Mechanical whole-house ventilation: Continuous mechanical ventilation is another intervention that affects all indoor air contaminants, but not always positively. Mechanical ventilation was most effective at reducing contaminants primarily originating indoors via a continuous source (e.g., CO_2, Rn, and VOC1). Mechanical ventilation also diluted concentrations from shorter term sources (e.g., CO, NO_2, and VOC2). Contaminants originating primarily outdoors were negatively impacted (e.g., H_2O in Miami and particles). The negative impacts of mechanical ventilation tended to be greater than those of the exhaust fan intervention, since the mechanical ventilation occurred continuously and the exhaust fan only operated during source events. Effective filtration could mitigate this impact. Adding mechanical ventilation using an exhaust fan is the least expensive option, whereas adding outdoor air supply is likely to be more expensive. There is also an incremental cost associated with cooling or heating the added outdoor air.

Tightening the envelope: Tightening the building envelope has long been recommended for improving energy efficiency, but the resulting reduction in air change rate has dramatic effects on pollutants originating indoors. In fact, it was the single worst intervention in terms of increasing the concentrations of CO, CO_2, NO_2, P2, Rn, VOC1, and VOC2. Although it was most effective at reducing H_2O in Miami, P1, and P4, tightening should not be implemented without considering the need for supplementary outdoor air.

In addition to investigating the impact of each intervention individually, a methodology was developed to rank combinations of interventions. The methodology involves a full factorial simulation design (Box et al., 1978), which tests the significance of individual interventions as well as ranks combinations of interventions. A full factorial design also has the advantage of being able to detect when variables do not act additively on a specific response. To demonstrate the value of the ranking system, a factorial simulation design was developed for the following four interventions: envelope tightening, exhaust fans, mechanical ventilation, and enhanced filtration. The fall season in Boston was chosen as the model season and city, respectively. The impact of each combination of interventions was assessed based on the sum of individual exposures of the five occupants living in the house.

Factorial results were also compared across all contaminants by calculating the average percent change in exposure. Based on this analysis, intervention combinations were ranked as shown in Table ES1. An ANOVA analysis on these results showed tightening the house to have the most significant impact on contaminant concentrations followed by using mechanical ventilation and exhaust fans. Using a more efficient air filter did not have a significant individual impact on the results, but becomes more significant when used in combination with other interventions (see discussion below). Although tightening the house was found to have the most significant impact, it is in the direction of increasing occupant exposures. The most effective individual interventions at reducing all contaminant concentrations are the use of mechanical ventilation and exhaust fans.

Table ES1. Rank of interventions with positive overall impact.

Rank	Intervention Combination	Average Reduction Over All Contaminants (%)	Negative Impact on Exposure to Contaminants Below:
1	exfan, filter, mv	15	P4
2	exfan, filter	13	
3	filter, mv	9.8	
4	exfan, mv	9.7	P1, P3, P4, P5
5	exfan	7.7	P1, P3, P4, P5
6	exfan, filter, mv, tight	7.4	CO_2, P5, Rn, VOC1, VOC2
7	filter	5.8	
8	mv	4.3	P1, P3, P4, P5
9	exfan, mv, tight	2.0	CO_2, P4, P5, Rn, VOC1, VOC2

exfan: exhaust fan
filter: improved particle filter
mv: mechanical ventilation
tight: envelope tightening

For the ranking evaluation, the combination with the largest reduction in exposure across all contaminants was operating exhaust fans, installing mechanical ventilation, and adding a more efficient air filter, without tightening the house. This strategy, however, did have a negative impact on the concentration of P4. The most effective intervention strategy across all contaminants with no negative impacts was operating exhaust fans and adding a more efficient air filter, followed by the installation of mechanical ventilation and a more efficient air filter. Individually, the interventions of exhaust fan and mechanical ventilation led to an overall reduction in contaminant concentrations, but both also led to increased exposures to particles. This result emphasizes the importance of considering combinations of interventions to achieve the most effective strategy. Another intervention combination, which has been recommended by ASHRAE (2001a) and others, is tightening the envelope and adding filtered mechanical ventilation. For this project, the combination of tightening, mechanical ventilation via exhaust fans, and adding a more efficient air filter resulted in an overall increase in occupant exposure. Thus, depending on the relative changes, tightening the envelope could overwhelm additional mechanical ventilation, which should be considered when implementing an intervention strategy.

INTRODUCTION

Several air contaminants measured indoors have been shown to have negative impacts on human health (Berglund et al., 1992; Samet, 1993; Roberts and Dickey, 1995; Jones, 1999). Residential indoor air pollutants of concern include: combustion byproducts, volatile organic compounds, radon, and bioaerosols (Tobin et al., 1992; Haghighat and Bellis, 1993; Sherman, 1999). Many of these contaminants are often measured at higher concentrations in lower income urban housing (Rotko et al., 2001; Rotko et al., 2000; Laquatra et al., 2002; Brugge et al., 2002). Although these residences are typically in the greatest need of remediation, they are the least likely to be fixed. As such, the U.S. Department of Housing and Urban Development (HUD) has made it a priority to identify wide-reaching intervention strategies that can be feasibly implemented to improve the indoor air quality (IAQ) in lower income homes. As part of this effort, the HHI program is funding several demonstration projects to implement interventions that correct many of the IAQ problems found in lower income urban homes. Due to the costs of fieldwork, however, the demonstration projects are only able to implement a limited number of interventions in a small number of homes. A more feasible way to prioritize the hazards and identify the farthest-reaching intervention strategies is through modeling. A modeling approach allows the evaluation of many potential interventions under a wider variety of conditions to help provide a knowledge base for recommending the most effective strategies. Such modeling can also be used to evaluate the interventions for possible unintended negative impacts. Thus, model results have the potential to provide tremendous insight toward the improvement of IAQ in urban housing with multiple deficiencies.

Previous experimental and simulation intervention studies have investigated the impacts of source reduction (Shaw et al., 1999), ventilation strategies (Emmerich and Persily, 1996; Kruger and Kraenzmer, 1996; Persily, 1998; Shaw et al., 1999; Takaro et al., 2002), and air cleaning (Emmerich and Nabinger, 2001; Howard-Reed et al., 2004) on indoor air concentrations of pollutants. This project expands on these studies by considering all three types of interventions for a variety of contaminants and sources. A methodology was developed to rank interventions individually and in different combinations on the basis of: 1) impact on room contaminant concentrations, 2) impact on occupant exposure, 3) number of contaminants impacted, and 4) any negative impacts. The key parameter utilized in evaluating the interventions is the concentration relative to the baseline rather than comparison of absolute concentrations to guideline values. Based on this analysis, this report identifies interventions with the most significant positive impact for reducing contaminants in lower income urban housing and provides a tool for future intervention evaluation.

SIMULATION METHOD

There are two general types of computer simulation techniques for studying airflow and contaminant transport in buildings – zonal modeling and multizone modeling. Zonal (or room airflow) modeling takes a microscopic view of IAQ by applying a computational fluid dynamics (CFD) program to predict the detailed flow fields and pollutant concentration distributions within a room or rooms. Multizone airflow and pollutant transport modeling takes a macroscopic view of IAQ by evaluating average pollutant concentrations in the different zones of a building as contaminants are transported through the building and its heating, ventilating and air-conditioning (HVAC) system. To identify the impact of an intervention on the whole house, a multizone model was selected for this study.

The multizone approach is implemented by constructing a building model as a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones, which are modeled at a uniform pressure, temperature, and pollutant concentration. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations to the zones, which may contain pollutant sources and/or sinks. Feustel and Dieris (1992) described a survey of multizone airflow models, including the CONTAM model developed in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). The most recent publicly available version of CONTAM is CONTAM 2.1 (Walton and Dols, 2003), which was used in this study.

The CONTAM simulations were conducted in three phases. The first phase involved the modification of an existing CONTAM model, populating the building with contaminant sources and occupants, and performing week-long baseline simulations for each of the three cities and four seasons (12 total simulations). The second phase involved adding one intervention at a time to the building model and re-running the simulation for each of the city and season combinations, with a total of eight interventions simulated. Finally, a third phase included a factorial analysis of four of the interventions in order to analyze the impact of combining interventions.

Baseline Building Model

A well-studied CONTAM model of a townhouse was used as a baseline building for this project (Emmerich et al., 2002). Most recently, the townhouse model was validated for its ability to predict air change rates and SF_6 concentrations based on measured data (Emmerich et al., 2002). Although the original model was based on a house not considered typical of lower income urban housing, it was modified to be more representative of this housing type. The model townhouse is a three-story, three bedroom, three bathroom end-unit townhouse with a floor area of approximately 35 m^2 per level and an approximate living space volume of 250 m^3. The unfinished basement is three-quarters underground with no outside access doors. The basement contains a gas furnace, gas hot water heater and dryer, all vented to the outside. The second level consists of a kitchen, living room, and bathroom. There is a sliding glass balcony door and fireplace in the living room. The third level includes three bedrooms, two bathrooms, and several closets. The fourth level is an attic, with a volume of 50 m^3. A floor plan of the house as entered into CONTAM is shown in Figure 1 with the features of each zone provided in Table 1.

To characterize the airflow between zones and the outdoors, CONTAM uses different types of flow elements. A summary of the flow elements used in this model is provided in Appendix A. As shown in Appendix A, most of the model flow elements use leakage area data from the literature for different types of openings (e.g., wall-to-wall joints, electrical outlets, window frames, etc.). Other flow element types used in this model include orifice area data for the attic vents and two-opening data for the open doorways between zones. Leakage area elements were also used for airflow between zones at interior walls and ceilings and floors.

A variable wind pressure coefficient was applied to the exterior envelope leakage elements. Wind pressure coefficients characterize the relationship between wind and surface pressures and depend on the wind direction, the building shape, the position on the building surface, and the presence of shielding near the building. Equations provided in the Fundamentals Handbook (2001a) were used to construct a wind pressure profile for the model house.

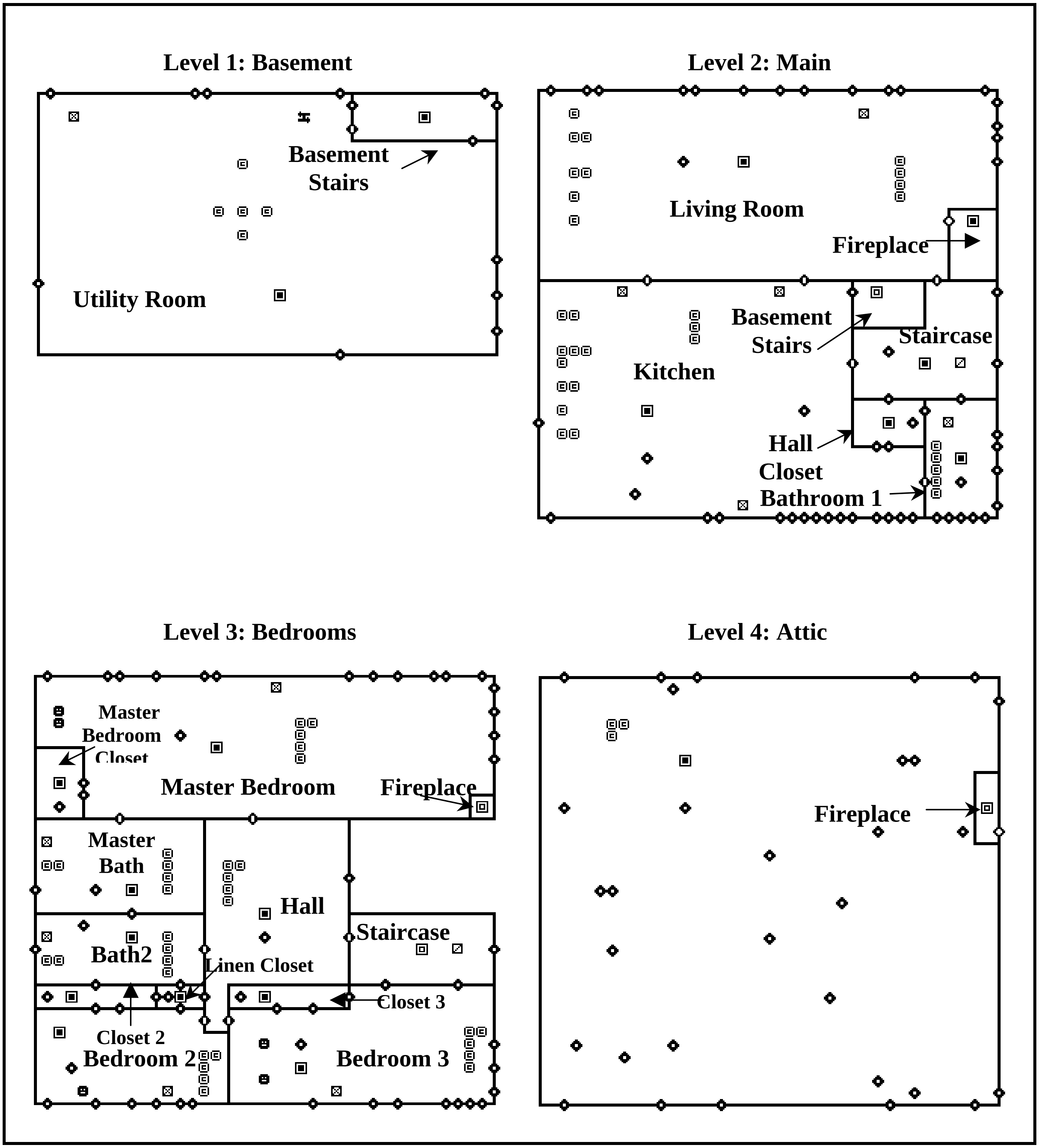

Figure 1. Floor plan of house in CONTAM.

A simple recirculating air handling system (AHS) was added to the model but was "operated" only during some weather conditions. The system ductwork does not enter the attic, resulting in insignificant duct leakage to the outside. The system was modeled as operating with a total volumetric airflow of 0.35 m^3/s. For baseline cases, the air handling system used a typical furnace filter that removed 7.5 % to 20 % of particles in a single pass, depending on particle size.

Table 1. CONTAM Model Zones.

Zone:	Description	Floor Area (m^2)	Volume (m^3)
LEVEL: Basement (1)			
util	Utility Room	20	55
basestr	Staircase	3.4	9.4
	Level Total	**23**	**64**
LEVEL: Main (2)			
lrdr	Living Room	17	47
kit	Kitchen	11	30
bath1	Bathroom	0.73	2.0
hcls	Hall Closet	0.36	0.99
fp	Fireplace	0.083	0.23
str2	Staircase	3.3	9.0
	Level Total	**32**	**89**
LEVEL: Bedrooms (3)			
mbr	Master Bedroom	11	30
mcl1	Master Bedroom Closet	0.78	2.1
mbth	Master Bathroom	2.5	6.9
bath2	Bathroom	1.5	4.1
hall	Hall	2.5	6.9
lncl	Linen Closet	0.37	1.0
br2	Bedroom	6.5	18
br2cls	Bedroom Closet	0.90	2.5
br3	Bedroom	8	22
br3cls	Bedroom Closet	0.99	2.7
	Level Total	**35**	**105**
LEVEL: Attic (4)			
attc	Attic	13	50
	Level Total	**13**	**50**

Since ventilation and IAQ performance vary by climate, the house was modeled in Boston, MA, Seattle, WA, and Miami, FL for one week of each season. While not covering all possible U.S. climates, these locations are representative of much of the climatic range of the United States. For each city-season combination, transient simulations were performed using TMY2 weather data (Marion and Urban, 1995). Since the three cities had a wide range of average ambient temperatures, different indoor heating and cooling schemes were used. Table 2 shows a summary of the baseline simulation files. For average weekly outdoor temperatures below 10 °C, which included Boston and Seattle winter and spring seasons, the central air heating system was assumed to operate for the first ten minutes of each hour. For average outdoor temperatures above 25 °C, which included Miami spring, summer, and fall, the air conditioning system was also assumed to operate for the first ten minutes of each hour. For all other cases where the average temperatures fell between 10 °C and 25 °C the AHS was assumed to be off.

Table 2. Baseline Simulation Cases

City	Season	Average Weekly Outdoor Temp. (°C)	Average Weekly Wind Speed (m/s)	Average Weekly Relative Humidity[1] (% RH)	Average Indoor Temp. by Level (°C)				Air Handler Status
					1	2	3	4	
Boston	Spring	10	4.2	72	20	20	20	20	None
Boston	Summer	19	4.5	69	22	24	26	34	None
Boston	Fall	7	5.6	72	20	20	20	20	Heat
Boston	Winter	1	6.0	59	18	20	22	12	Heat
Miami	Spring	25	2.8	60	22	22	22	36	A/C
Miami	Summer	27	4.0	75	22	24	26	36	A/C
Miami	Fall	26	3.1	75	22	22	22	36	A/C
Miami	Winter	19	3.9	72	22	24	26	34	None
Seattle	Spring	12	4.5	67	20	20	20	20	None
Seattle	Summer	17	3.6	74	22	24	26	34	None
Seattle	Fall	8	4.6	76	20	20	20	20	Heat
Seattle	Winter	6	3.8	72	18	20	22	12	Heat

[1]Based on average temperature and average humidity ratio.

Occupants

To account for occupant-generated contaminants and to determine the exposure of building occupants to indoor contaminants, a family of five was assumed to occupy the townhouse. The occupants of the house included an adult male, adult female, and three children of ages 4, 10, and 13 years. A weekend (Saturday and Sunday) and weekday (Monday – Friday) schedule was created for each family member that specifies the time spent in each room of the house, as well as time outside of the house (see Appendix B). During the time spent outside of the house, the occupant exposure was assumed to be zero. Based on these schedules CONTAM accounts for the contaminant generated by each individual in the room where they are located at a given time and keeps track of the contaminant concentrations to which they are exposed. CONTAM then calculates the mean concentration over a given period of time as a measure of exposure.

Contaminants and Sources

The contaminants that were considered in the simulations include carbon dioxide (CO_2), water vapor (H_2O), carbon monoxide (CO), nitrogen dioxide (NO_2), airborne particles (in 5 sizes ranging from 0.3 μm to 10 μm), volatile organic compounds (VOCs) and radon (Rn). The sources of these contaminants were not intended to be comprehensive, but rather representative of some typical residential sources and to provide insight into each of the individual contaminants. Also, some of the sources produce additional contaminants beyond the ones considered (e.g., unvented combustion appliances produce CO_2, H_2O, and particles but were not included as a source of these contaminants in this study).

Carbon Dioxide

In general, concentrations of carbon dioxide (CO_2) do not reach harmful levels indoors; however, these concentrations have often been used as an indicator of ventilation. The only indoor source of CO_2 considered for this study was the respiration of the occupants. The generation rate of CO_2 from a person is a function of body size and physical activity. Table 3 shows the occupant CO_2 generation rates used for awake and sleeping time periods based on ASHRAE Fundamentals Handbook (2001a). The locations of these CO_2 sources depend on the occupant schedules discussed above (see Appendix B). Another important source of CO_2 was the outdoor air which was assumed to have a constant concentration of 630 mg/m^3 (all outdoor concentrations are presented in a later section in Table 10).

Table 3. Occupant generation rates of CO_2

Occupant	**Weight (kg)**	**CO_2 generation rate – awake (mg/s)**	**CO_2 generation rate – sleeping (mg/s)**
Adult Male	81	11	6.6
Adult Female	67	9.8	6.2
Child #1 (13 years old)	50	8.6	5.2
Child #2 (10 years old)	36	6.8	4.1
Child #3 (4 years old)	17	3.8	2.3

Water Vapor

Water itself is not considered a harmful contaminant, but, rather, it is the microorganisms (e.g., mold, dust mites, etc.) that can grow at higher relatively humidity that are of interest. There are numerous potential sources of water vapor in homes. A representative subset of water vapor sources was chosen for this project and includes respiration and perspiration of occupants, bathing, cooking, and dishwashing. As with occupant generation of CO_2, water vapor generation rates depend on body size and activity level. Table 4 shows the occupant water vapor generation rates used for awake and sleeping time periods based on Trechsel (1994). The locations of these H_2O sources depend on the occupant schedules discussed above (see Appendix B).

Table 4. Occupant generation rates of H_2O

Occupant	**H_2O generation rate – awake (mg/s)**	**H_2O generation rate – sleeping (mg/s)**
Adult Male	15.3	9.2
Adult Female	15.3	9.2
Child #1 (13 years old)	12.5	7.5
Child #2 (10 years old)	11.1	6.7
Child #3 (4 years old)	6.0	3.6

The water vapor generation rates and schedules for bathing, cooking and dishwashing are based on an earlier NIST study (Persily, 1998). Table 5 shows the rates, locations and schedules of these sources. In order to prevent the relative humidity from exceeding 100 %, CONTAM's cutoff concentration model was used. This model used the constant coefficient generation rates in Table 5 until the room concentration reached 100 % relative humidity, *i.e.*, a saturation point of 14.8 g/kg to 21.5 g/kg depending on the room temperature. At the saturation point, the source would stop emitting H_2O until the concentration fell below the saturation point again.

Table 5. H_2O generation rates and schedules for bathing, cooking, and dishwashing.

Activity	H_2O generation rate (g/s)	Location	Weekday schedule	Weekend schedule
Adult male shower	0.67	Master Bathroom	6:00 a.m. – 6:10 a.m.	9:00 a.m. – 9:10 a.m.
Adult female shower	0.67	Master Bathroom	6:30 a.m. – 6:40 a.m.	9:10 a.m. – 9:20 a.m.
Child #1 shower	0.67	Bathroom #2	7:00 a.m. – 7:10 a.m.	10:00 a.m. – 10:10 a.m.
Child #2 shower	0.67	Bathroom #2	7:20 a.m. – 7:30 a.m.	9:10 a.m. – 9:20 a.m.
Child #3 shower	0.67	Bathroom #2	7:10 a.m. – 7:20 a.m.	9:40 a.m. – 9:50 a.m.
Cooking – breakfast	0.14	Kitchen	6:30 a.m. – 7:00 a.m.	9:30 a.m. – 10:00 a.m.
Cooking – lunch	0.42	Kitchen	12:00 p.m. – 12:30 p.m.	12:00 p.m. – 12:30 p.m.
Cooking – dinner	0.28	Kitchen	5:00 p.m. – 6:00 p.m.	5:00 p.m. – 6:10 p.m.
Dishwashing - breakfast	0.085	Kitchen	7:40 a.m. – 8:00 a.m.	10:20 a.m. – 10:40 a.m.
Dishwashing - dinner	0.17	Kitchen	7:00 pm – 7:30 pm	7:00 pm – 7:30 pm

Carbon Monoxide and Nitrogen Dioxide

The indoor sources of CO and NO_2 included a gas stove and an unvented space heater. Table 6 shows the generation rates and schedules for the gas stove (Persily 1998) and unvented space heater (Emmerich and Persily 1996), which are based on values in the literature. The unvented space heater was only operated during the winter seasons in Boston and Seattle.

Table 6. Sources of CO and NO_2

Source	CO generation rate (mg/s)	NO_2 generation rate (mg/s)	Location	Weekday schedule	Weekend schedule
Gas stove – breakfast	0.21	0.028	Kitchen	6:30 a.m. – 7:00 a.m.	9:30 a.m. – 10:00 a.m.
Gas stove - lunch	0.42	0.056	Kitchen	12:00 p.m. – 12:30 p.m.	12:00 p.m. – 12:30 p.m.
Gas stove - dinner	0.42	0.056	Kitchen	5:00 p.m. – 5:30 p.m.	5:00 p.m. – 5:30 p.m.
Gas stove – dinner	0.83	0.11	Kitchen	5:30 p.m. – 6:00 p.m.	5:30 p.m. – 6:00 p.m.
Unvented space heater	0.28	0.070	Living Room	8:00 a.m. – 10:00 a.m. 7:00 p.m. – 10:40 p.m.	10:40 a.m. – 12:00 p.m. 7:00 p.m. – 11:40 p.m.

Airborne Particles

Combustion and mechanical processes generate airborne particles of many different sizes and composition. Although many different properties of airborne particles can impact human health, this study only addressed particle size as it impacts generation rates and removal. The model included 5 particle size ranges (0.3 μm to 0.5 μm, 0.5 μm to 1.0 μm, 1.0 μm to 2.5 μm, 2.5 μm to 5.0 μm, 5.0 μm to 10 μm), which correspond to size ranges commonly measured in the field (Wallace and Howard-Reed, 2002; Howard-Reed et al., 2003; Wallace et al., 2004). Indoor particle sources included cooking (for generation of smaller particles) and changing of kitty litter twice a week (for generation of larger particles). As with the other contaminants, many other potential sources of particles may exist in any given residence. These sources were chosen as examples based on the availability of source strength data. The source strengths for these events were based on measurements in previous studies (Wallace et al., 2004; Howard-Reed et al., 2003) and are summarized in Tables 7 and 8.

Table 7. Particle generation rates and schedules for cooking.

Source	**Particle Generation Rate (number per hour)**			**Location**	**Weekday Schedule**	**Weekend Schedule**
	0.3-0.5 μm	**0.5-1.0 μm**	**1.0-2.5 μm**			
Cooking – Breakfast	6.4×10^{10}	1.6×10^{10}	8.0×10^{9}	Kitchen	6:30 a.m. – 6:40 a.m.	9:30 a.m. – 9:40 a.m.
Cooking – Lunch	4.0×10^{10}	1.0×10^{10}	5.0×10^{9}	Kitchen	12:00 p.m. – 12:10 p.m.	12:00 p.m. – 12:10 p.m.
Cooking – Dinner	8.0×10^{10}	2.0×10^{10}	1.0×10^{9}	Kitchen	5:00 p.m. – 5:10 p.m.	5:00 p.m. – 5:10 p.m.

Table 8. Particle generation rates and schedules for changing kitty litter.

Source	**Particle Burst Amount (number of particles)**	**Location**	**Weekday Schedule**	**Weekend Schedule**
Kitty Litter: 0.5 – 1.0 μm	5.6×10^{8}	Living Room	Wednesday @ 9:20 a.m.	Saturday @ 9:20 a.m.
Kitty Litter: 1.0 – 2.5 μm	5.0×10^{8}			
Kitty Litter: 2.5 – 5.0 μm	6.8×10^{8}			
Kitty Litter: 5.0 – 10 μm	7.9×10^{8}			

Volatile Organic Compounds

Volatile organic compounds (VOCs) include a broad class of compounds with wide variations in physical and chemical properties, health impacts, and sources. The study includes two nonspecific VOCs as surrogates for two general classes of sources. The first VOC (VOC1) was generated in each room of the house with a generation rate proportional to the floor area. A continuous generation rate of 0.2 $mg/h \cdot m^2$ was used, based on an average of approximately 50 published flooring emission rates for toluene (U.S. EPA, 1999). The second VOC was generated by a burst source in different rooms of the house. Based on an emission rate for floor cleaning, a mass of 0.08 g was used for the burst (Wallace, 1987). The release location and schedule of the burst VOC source is shown in Table 9.

Table 9. Location and schedule for burst VOC sources.

Location	Day of Week	Time
Kitchen	Monday - Friday	7:30 a.m.
	Saturday and Sunday	10:30 a.m.
Bathroom #1	Saturday	11:00 a.m.
Living Room	Saturday	11:20 a.m.
Master Bedroom	Saturday	11:30 a.m.
Master Bathroom	Saturday	11:40 a.m.
Hall	Saturday	3:40 p.m.
Bedroom #2	Saturday	3:50 p.m.
Bedroom #3	Saturday	4:00 p.m.
Bathroom #2	Saturday	4:40 p.m.

Radon

A pressure dependent radon source described in an earlier NIST report (Fang and Persily, 1995) was included in the basement zone of the model. The source equation is as follows:

$$S = G\Delta P^n \tag{1}$$

where:

S = contaminant source strength ($Bq/s\cdot m^2$)

G = generation rate coefficient ($Bq/s\cdot m^2\cdot Pa$)

ΔP = pressure difference (Pa)

n = pressure exponent

With little information available in the literature for model inputs, the value of G was determined based on it yielding reasonable concentrations in the house. Exact values were not critical, since analysis for this project is based on relative concentrations. Based on these trial simulations a generation rate of 0.004 $Bq/s\cdot m^2\cdot Pa$ and a pressure exponent of 1 were chosen.

Outdoor Concentrations

Outdoor concentrations of water vapor were based on the humidity ratios in the TMY2 weather data. Outdoor concentrations of CO, NO_2, CO_2, and VOCs were based on those used in earlier NIST studies (Persily 1998 and Emmerich and Persily 1995) and are presented in Table10. Outdoor particle concentrations were based on average concentrations measured outside a research townhouse in Reston, VA (Wallace and Howard-Reed, 2002). It should be noted that Reston is considered a suburban location where outdoor pollutant levels may not be as high as an urban location. Nonetheless, a constant value for each particle size range was used (see Table 10).

Table 10. Outdoor Concentrations of CO, NO_2, CO_2, VOCs, and Particles.

Time Contaminant	12:00 a.m. – 7:00 a.m.	7:00 a.m. – 9:00 a.m.	9:00 a.m. – 5:00 p.m.	5:00 p.m. – 7:00 p.m.	7:00 p.m. – 12:00 a.m.
CO (mg/m^3)	1.1	2.3	1.7	3.4	1.7
NO_2 (mg/m^3)	0.038	0.075	0.038	0.075	0.038
CO_2 (mg/m^3)	630	630	630	630	630
VOC (mg/m^3)	0.10	0.10	0.10	0.10	0.10
P1: 0.3 – 0.5 μm (#/cm^3)	64	64	64	64	64
P2: 0.5 – 1.0 μm (#/cm^3)	3.7	3.7	3.7	3.7	3.7
P3: 1.0 – 2.5 μm (#/cm^3)	0.39	0.39	0.39	0.39	0.39
P4: 2.5 – 5.0 μm (#/cm^3)	0.11	0.11	0.11	0.11	0.11
P5: 5.0 – 10 μm (#/cm^3)	0.020	0.020	0.020	0.020	0.020

Removal Mechanisms

Contaminant Sinks

The loss of contaminants due to adsorption, deposition and decay were also included in the models as follows. Reversible sink effects for H_2O and VOCs were modeled with sink elements based on the boundary layer diffusion controlled (BLDC) model. The BLDC adsorption model is described in detail by Axley (1990). The parameters required for this sink model are the film mass transfer coefficient, the adsorbent mass and the partition coefficient. Sink values for H_2O and VOCs are given in Table 11. It was assumed that these values would apply to all living areas of the house, except for closets and stairways.

Table 11. Boundary Layer Diffusion Controlled Model Parameters

Parameter Sink:	H_2O	VOC
Film Transfer Coefficient	0.25 m/h	0.08 m/h
Film Density	1.2 kg/m^3	1.2 kg/m^3
Surface Mass	550 kg	550 kg
Partition Coefficient	1.5	5

Nitrogen dioxide decay and particle deposition were modeled as single-reactant first order reactions with a single, constant value in all rooms of the houses. The kinetic rate coefficient used for NO_2 decay was 0.86 h^{-1} and is based on the average of measurements in a contemporary research house reported by Leslie et al. (1988). Particle deposition rates were measured in a research townhouse and reported elsewhere (Howard-Reed et al., 2003). A summary of the deposition rates is given in Table 12.

Table 12. Deposition Rates for NO_2 and Particles

Contaminant	Deposition Rate (h^{-1})
NO_2	0.86
P1: 0.3 μm to 0.5 μm	0.30
P2: 0.5 μm to 1.0 μm	0.42
P3: 1.0 μm to 2.5 μm	0.78
P4: 2.5 μm to 5.0 μm	1.4
P5: 5.0 μm to 10 μm	2.7

The half-life of Radon-222 is 3.8 days, which corresponds to a decay rate of 0.0076 h^{-1}.

Air Cleaning
Particles were also removed in the baseline cases with a central HAC system by a typical furnace filter. Removal rates were based on experimental results of a previous NIST study (Emmerich and Nabinger, 2001). The specific removal rates for each particle size were as follows: 7.5 % for 0.3 μm to 0.5 μm, 14 % for 0.5 μm to 1.0 μm, 20 % for 1.0 μm to 2.5 μm, 20 % for 2.5 μm to 5.0 μm, and 20 % for 5.0 μm to 10 μm. Note that these removal rates also account for losses through deposition to the ductwork.

Scenarios/Interventions
Baseline models were created in order to provide a benchmark for determining the impact of various housing repairs/interventions and other scenarios of interest. The housing repairs/interventions included some being performed by HUD's NOFA grant awardees, recommendations of ASHRAE 62.2-2004, and additional alternative IAQ strategies. Other possible interventions such as dehumidification were not modeled. The interventions/scenarios were as follows:

- **Removal of space heater or properly venting it to the outside.**
  For winter baseline simulations in Boston and Seattle, an unvented space heater was used in the living room and constituted a source of NO_2 and CO (see Table 6). The intervention of removing the space heater emissions was modeled by not including the space heater in the winter simulations.

- **Replacement of the faulty stove.**
  A gas stove releases NO_2 and CO with an emission rate dependent on several characteristics of the stove. For the baseline case, a relatively high emission rate was assumed based on values in a previous report (Emmerich and Persily, 1995). In this intervention, lower stove emission rates associated with a more efficiently operating stove was modeled for each city and season and compared with the baseline values (from Persily 1998). A comparison of the stove emission rates is provided in Table 13.

Table 13. Baseline and Intervention CO and NO_2 emission rates for a gas stove.

	Baseline Generation Rates (mg/s)		Reduced Generation Rates (mg/s)	
Source	**CO**	**NO_2**	**CO**	**NO_2**
Gas stove – breakfast	0.21	0.028	0.0070	0.0043
Gas stove - lunch	0.42	0.056	0.014	0.0085
Gas stove - dinner	0.42	0.056	0.014	0.0085
Gas stove – dinner high	0.83	0.11	0.028	0.017

- **Replace typical furnace filter with enhanced particle air filter.**
  For the baseline simulations, a typical furnace filter was used in the HAC system (see Table 2). For the intervention, the furnace filter was replaced with a higher efficiency air filter. The particle removal efficiencies for the improved air filter were based on a study by Emmerich and Nabinger (2001) and are given in Table 14.

Table 14. Comparison of Removal Efficiencies of Typical Furnace Filter and Intervention Air Filter.

Particle Size	Typical Furnace Filter Removal Efficiency (%)	Enhanced Air Filter Removal Efficiency (%)
0.3 – 0.5	0.075	0.36
0.5 – 1.0	0.135	0.49
1.0 – 2.5	0.20	0.62
2.5 – 5.0	0.20	0.62
5.0 – 10	0.20	0.62

- **Installation of air conditioner.**
  The impact on humidity of adding an air conditioner was investigated for the summer simulations in Boston and Seattle. Due to high outdoor temperatures (average temperature > 25 °C) in Miami, an air conditioner was included in the Miami baseline cases in spring, summer and fall. As a result, Miami was not included in this intervention. For the Boston and Seattle summer simulations, an air conditioner was added to the model and operated the first 10 min of every hour. While operating, the air conditioner removed moisture at a rate of 17 % (based on the value used in Persily 1998) and particles at a rate equivalent to the typical furnace filter values in Table 14.

- **Inclusion of kitchen and bathroom exhaust fans.**
  All the baseline cases did not include local exhaust fans. This intervention involved the inclusion of intermittent kitchen and bathroom exhaust fans that meet the requirements of ASHRAE Standard 62.2 (2004). The kitchen exhaust fan has airflow of 47 L/s and was operated during cooking events (see Table 6). The bathroom exhaust fans each had airflow of 24 L/s and were operated during showers.

- **Operation of a gas oven to heat the house.**
  In addition to using gas ovens for cooking, some residents use them as a heat source in the winter (Brugge et al. 2002). This practice can result in elevated concentrations of CO and NO_2. This would also increase H_2O and particle concentrations in practice but this effect was not modeled. In order to assess the impact of ceasing this practice, separate simulations were performed for each city using a stove to heat the house for 4 h every evening in the winter. The oven emission rates are equivalent to those for breakfast cooking in Table 6. Results were then compared with the baseline case where the gas stove was only operated for cooking.

- **Tighten the exterior envelope**
  A common suggestion to reduce residential energy consumption is to tighten a house's exterior envelope. Tightening a building results in lower infiltration rates, which in turn reduces the number of outdoor contaminants entering the building, but also increases the indoor concentration of contaminants generated inside the building. As a result, this recommendation may actually have a negative impact on indoor air quality. To model this intervention, all exterior envelope leakage area elements were reduced by 40 % from the baseline case.

- **Installation and operation of a mechanical ventilation system that meets the requirements of ASHRAE Standard 62.2-2004.**
  ASHRAE Standard 62.2 requires the installation of a mechanical exhaust system and/or supply system to provide outdoor air to a dwelling (ASHRAE 2004). The amount of outdoor ventilation air is based on the house's floor area and number of bedrooms. The continuous outdoor air requirement may be adjusted to an intermittent value based on the ventilation effectiveness and fractional time on. There are also some special stipulations for extreme climates. For all seasons in Boston and Seattle, an exhaust fan continuously operating at 24 L/s was installed in the master bathroom to meet the mechanical ventilation requirement. Due to Miami's hot and humid climate, a mechanical supply system was used instead of an exhaust system. Since the outdoor air was provided on the same schedule as the air-conditioner operation (i.e., 10 min of every hour), the outdoor air was supplied at a rate of 142 L/s to provide the equivalent of 24 L/s continuous ventilation.

Factorial Intervention Simulations

In addition to investigating the impact of each intervention individually, a methodology was developed to rank combinations of interventions. The methodology involves a full factorial simulation design (Box et al., 1978), which tests the significance of individual interventions as well as ranks combinations of interventions. A full factorial design also has the advantage of being able to detect when variables do not act additively on a specific response. To demonstrate the value of the ranking system, a factorial simulation design was developed for the following four interventions: tightening, exhaust fans, mechanical ventilation, and enhanced filtration (see Table 15). The fall season in Boston was chosen as the model season and city, respectively. The impact of each combination of interventions was assessed based on the sum of individual exposures of the five occupants living in the house.

Table 15. Factorial design for four intervention combinations.

Simulation Number	Tightened	Exhaust Fan	Mechanical Ventilation	Upgraded Filter
1	no	no	no	no
2	yes	no	no	no
3	no	yes	no	no
4	yes	yes	no	no
5	no	no	yes	no
6	yes	no	yes	no
7	no	yes	yes	no
8	yes	yes	yes	no
9	no	no	no	yes
10	yes	no	no	yes
11	no	yes	no	yes
12	yes	yes	no	yes
13	no	no	yes	yes
14	yes	no	yes	yes
15	no	yes	yes	yes
16	yes	yes	yes	yes

SIMULATION RESULTS

The results have been divided into three sections. The first section contains a discussion of the baseline results in terms of infiltration rates and contaminant concentrations for each city and season combination. Next, the individual intervention results are presented with impacts on air change rates, contaminant concentrations for specific zones, and occupant exposures for each city and season combination. Finally, results are presented for the factorial simulation methodology.

Baseline Results

A total of 12 baseline city/season combinations were simulated. For each city and season a two week simulation was conducted with the second week being used to determine the resultant impacts. Based on the second week of data, minimum, average, and maximum air change rates and contaminant concentrations were reported for each case. Airflow rates and concentrations are available for all 19 zones of the house, however, for reporting purposes a representative set of zones was chosen.

Infiltration Rates

A fan pressurization test was simulated for the baseline model and resulted in an air change rate at 50 Pa of 12.5 h^{-1} and an effective leakage area at 4 Pa of 640 cm^2. The normalized leakage area for this house is approximately 0.92 which is tighter than the national average of 1.72 but within its standard deviation of 0.84 (Sherman and Dickerhoff, 1998). Compared to the national average this house appears tight, however, many individual states were found to have average leakage areas below 1.0. For example, Sherman and Dickerhoff (1998) reported the average values for Massachusetts and Washington to be 0.53 and 0.44, respectively (an average value was not reported for Florida).

Seasonal average whole house air change rates were determined for each baseline case and are reported in Table 16. The house's air change rate directly impacts the indoor concentrations of each contaminant as well as contributing contaminants from outdoors. Since the same house was used for each city, the difference in air change rates was due solely to each city's weather. Realistically, the house's characteristics would likely vary based on geography, thereby also affecting air change rates. However, such building differences are not critical to this study due to the analysis being based on results relative to baseline values. As shown in Table 16, Boston had the highest air change rates followed by Seattle and then Miami. For each city, the highest air change rates occurred during the winter season. Boston and Seattle had the lowest air change rates in the summer, whereas Miami's lowest values were in the fall.

A metric to put these air change rates into context has been provided by ASHRAE Standard 62.2. Currently, the standard requires a house to have mechanical ventilation, which is not included in any of the baseline cases. In fact, most homes in America do not meet this requirement of ASHRAE Standard 62.2. Previously, ASHRAE Standard 62 (2001b) included a recommendation of a minimum air change rate of 0.35 h^{-1} in low-rise residential buildings, but did not specifically require mechanical ventilation. For the purposes of comparison, a benchmark air change rate value of 0.35 h^{-1} was used in this study. As shown in Table 16, air change rates in Boston and Seattle were generally greater than 0.35 h^{-1}, with the exception of summer in both cities and spring in Seattle. In contrast, the weather in Miami resulted in air change rates below 0.35 h^{-1}

more than 60 % of the time in the fall and summer and at least 20 % to 30 % of time in the winter and spring, respectively.

The results shown in Table 16 show that a moderately leaky house may have low infiltration during mild weather, which can compromise IAQ yet, have high infiltration during the winter, which can have a steep energy penalty. As a result, some recommend for tighter building envelopes with mechanical ventilation (Persily 1998, ASHRAE 2001a).

Table 16. Air change rates for baseline cases.

City	Season	Minimum (h^{-1})	Average (h^{-1})	Maximum (h^{-1})	% < 0.35 h^{-1}
Boston	Fall	0.32	0.76	1.1	2
	Winter	0.72	0.98	1.5	0
	Spring	0.36	0.66	0.96	0
	Summer	0.24	0.47	0.73	13
Miami	Fall	0.14	0.31	0.52	67
	Winter	0.16	0.45	0.75	23
	Spring	0.15	0.42	0.82	32
	Summer	0.13	0.33	0.66	61
Seattle	Fall	0.53	0.75	1.0	0
	Winter	0.65	0.80	1.1	0
	Spring	0.17	0.57	0.96	12
	Summer	0.13	0.49	0.70	20

Contaminant Concentrations

Although efforts were made to achieve realistic contaminant concentrations in the house, the baseline concentrations should be considered reference values with which to evaluate the impact of the different interventions. In the statistical analysis that follows, the key parameter utilized in evaluating the interventions is the concentration relative to the baseline rather than comparison of absolute concentrations to guideline values. A summary of the total living area (utility room, living room, kitchen, bathrooms, and bedrooms) contaminant concentrations is provided for each city and season in Tables 17 – 19. The minimum, average and maximum values in these tables are based on one week of each season.

In general, the contaminants from primarily indoor sources (CO, CO_2, NO_2, Rn, VOC1 (constant source), VOC2 (burst)) were highest during the seasons with lower air change rates. Likewise, contaminants with significant outdoor sources (particles, H_2O) were highest during the seasons with higher air change rates. However, typical households may have additional sources of these contaminants that were not included in the model, which would impact this relationship. In that same vein, the average concentrations of CO, CO_2, Rn, and VOCs were highest in Miami, the city with the lowest air change rates. Miami also has the highest outdoor relative humidity, resulting in the highest indoor concentrations of H_2O. NO_2 and particles were highest in Seattle and Boston due to the higher air change rates and the presence of a space heater in winter.

The baseline concentrations were also used to characterize where contaminants are distributed in the house. For example, Figures 2 – 5 show a representative 24 h profile of CO concentrations in

Boston for each season. In general, the CO concentrations tend to be higher than typical values, but again, it is the relative concentrations between cases that are the important metrics. As shown in these figures, the CO concentration has the highest peaks in the zones with a CO source – the gas stove in the kitchen and the space heater in the living room during the winter. The CO concentrations in the remaining zones are dictated by the model's airflow pattern, which is seasonally dependent. For example, in the summer, CO emissions in the kitchen result in high peaks in the living room and basement stairway. Whereas, in the spring, the living room concentrations of CO are relatively low with the higher peaks predicted in the second level stairway and third level hall and bathroom. The bedroom CO concentrations, where the occupants spend the most time, are typically in the middle for all seasons.

The CO concentrations were distributed in a similar fashion in the townhouse located in Seattle with the peak concentrations slightly higher due to lower air change rates. The Miami townhouse CO concentrations, however, were distributed quite differently during the various seasons and reached higher peaks due to the lower air change rates. For example, in the fall, the highest peak CO concentrations in Boston and Seattle reached 10 mg/m^3 to 30 mg/m^3 and were highest in the kitchen, living room and upstairs zones. In Miami, the highest peak of about 35 mg/m^3 was also in the kitchen, but the CO tended to move down through the house to the basement stairs and utility room. Miami's mild weather resulted in smaller air change rates and a reverse stack flow of air in the townhouse. These differences in CO distribution show the importance of air change rates and source location on occupant exposure and reveal important information regarding the effectiveness of different interventions.

Although radon originates outdoors, it behaves like an indoor pollutant source due to its entry location in the basement. However, unlike CO from indoor sources, radon is emitted on a continuous basis. Figure 6 shows the radon concentration for each zone in the house in Seattle in the fall. The outdoor temperatures during this season resulted in the air handling system operating for heating purposes resulting in an influx of radon directly from the basement every hour to all zones with supply registers. The utility room and basement stairs had the highest concentrations followed by the kitchen on the next level up. Interestingly, concentrations in the third level rooms reached higher concentrations than in the living room and middle level bathroom. The stairway appears to serve as a conduit that bypasses these zones for certain weather conditions.

Radon concentration levels are a function of the pressure difference across the basement floor and the air change rate in the house. So the greater pressure difference caused by increased indoor/outdoor temperature differences in cold seasons is counterbalanced by the associated increase in air change rate. For this house, the radon concentrations were highest in the summer when air change rates were the lowest (see Figure 7). This contaminant illustrates the impact of the HAC system on contaminant distribution in the house. When a contaminant source is located in a less occupied zone of the house (e.g., basement), the HAC system serves to distribute the contaminant, often increasing the contaminant concentrations in more frequently occupied areas of the house (e.g., bedrooms). Conversely, when a contaminant source is generated in more frequently occupied areas of the house, the HAC system can serve to dilute the indoor contaminant concentrations. This potential benefit can be further enhanced when an effective air cleaner of the contaminant is used in the HAC system.

Table 17. Boston Baseline Results – Living area averages

	Winter			Spring			Summer			Fall		
Contaminant	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**
CO (mg/m^3)	1.1	2.9	9.0	1.1	2.4	10	1.1	2.9	11	1.1	2.4	10
CO_2 (mg/m^3)	630	700	795	630	729	855	630	765	972	630	723	887
H_2O (%RH)	6.1	18	50	24	39	52	33	51	66	14	33	68
NO_2 (mg/m^3)	0.021	0.16	0.64	0.016	0.073	0.75	0.015	0.081	0.86	0.012	0.071	0.75
P1 ($\#/cm^3$)	44	51	84	42	51	96	36	48	98	33	49	90
P2 ($\#/cm^3$)	2.2	3.2	11	2.2	3.5	14	1.8	3.5	16	1.5	3.2	13
P3 ($\#/cm^3$)	0.17	0.24	1.6	0.16	0.25	2.0	0.13	0.24	2.1	0.11	0.23	1.8
P4 ($\#/cm^3$)	0.034	0.052	1.7	0.026	0.054	2.2	0.024	0.051	2.4	0.021	0.050	2.1
P5 ($\#/cm^3$)	0.0039	0.012	1.7	0.0027	0.016	2.2	0.0030	0.017	2.4	0.0023	0.014	2.0
Rn (pCi/L)	0.99	1.5	1.9	1.9	2.5	3.8	2.0	3.7	5.4	1.3	2.1	4.2
VOC1 (mg/m^3)	0.14	0.17	0.18	0.18	0.20	0.25	0.25	0.21	0.31	0.19	0.16	0.29
VOC2 (mg/m^3)	0.10	0.14	0.90	0.10	0.16	1.2	0.10	0.20	1.4	0.10	0.16	1.0

Note: VOC1 is a continuous VOC source and VOC2 is a burst VOC source

Table 18. Miami Baseline Results – Living area averages

	Winter			Spring			Summer			Fall		
Contaminant	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**
CO (mg/m^3)	1.1	3.0	12	1.1	3.0	11	1.4	3.2	11	1.3	3.3	12
CO_2 (mg/m^3)	630	774	1029	630	866	1316	635	925	1253	630	936	1314
H_2O (%RH)	29	54	78	39	55	75	50	64	79	50	65	85
NO_2 (mg/m^3)	0.012	0.083	0.90	0.009	0.071	0.85	0.007	0.077	0.83	0.006	0.077	0.81
P1 ($\#/cm^3$)	33	47	93	24	41	87	24	38	83	21	36	84
P2 ($\#/cm^3$)	1.7	3.5	16	1.1	2.9	12	1.0	2.9	12	0.88	2.8	13
P3 ($\#/cm^3$)	0.10	0.23	2.0	0.062	0.18	2.1	0.065	0.17	2.1	0.055	0.16	2.0
P4 ($\#/cm^3$)	0.016	0.049	2.4	0.011	0.043	2.5	0.010	0.036	2.5	0.0085	0.035	2.4
P5 ($\#/cm^3$)	0.0016	0.017	2.3	0.0011	0.016	2.4	0.0012	0.014	2.4	0.00091	0.015	2.4
Rn (pCi/L)	2.1	4.3	6.7	1.2	3.0	6.0	1.4	3.1	6.8	1.5	3.2	5.9
VOC1 (mg/m^3)	0.19	0.26	0.37	0.18	0.28	0.41	0.21	0.31	0.41	0.22	0.32	0.45
VOC2 (mg/m^3)	0.10	0.19	1.1	0.10	0.21	1.2	0.10	0.23	1.2	0.10	0.24	1.3

Note: VOC1 is a continuous VOC source and VOC2 is a burst VOC source

Table 19. Seattle Baseline Results – Living area averages

	Winter			Spring			Summer			Fall		
Contaminant	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**
CO (mg/m^3)	1.1	3.1	9.6	1.1	2.6	11	1.1	3.0	13	1.1	2.4	9.8
CO_2 (mg/m^3)	630	707	813	630	738	997	630	752	993	630	716	833
H_2O (%RH)	23	30	41	33	42	58	41	49	63	15	37	58
NO_2 (mg/m^3)	0.019	0.19	0.72	0.016	0.077	0.85	0.016	0.087	0.92	0.017	0.073	0.73
P1 ($\#/cm^3$)	44	51	90	36	50	98	34	49	98	41	50	92
P2 ($\#/cm^3$)	2.2	3.3	13	1.9	3.6	15	1.8	3.7	16	2.0	3.3	13
P3 ($\#/cm^3$)	0.17	0.24	1.9	0.12	0.25	2.0	0.11	0.24	2.0	0.15	0.24	1.9
P4 ($\#/cm^3$)	0.035	0.055	2.1	0.016	0.051	2.2	0.019	0.050	2.3	0.030	0.053	2.1
P5 ($\#/cm^3$)	0.0041	0.016	2.1	0.0017	0.015	2.2	0.0024	0.016	2.3	0.0035	0.015	2.1
Rn (pCi/L)	1.3	1.8	2.2	1.5	2.7	5.6	2.2	3.4	6.4	1.3	1.9	2.6
VOC1 (mg/m^3)	0.16	0.18	0.20	0.17	0.22	0.34	0.19	0.24	0.38	0.16	0.18	0.21
VOC2 (mg/m^3)	0.10	0.15	1.0	0.10	0.18	1.2	0.10	0.19	1.2	0.10	0.16	0.98

Note: VOC1 is a continuous VOC source and VOC2 is a burst VOC source

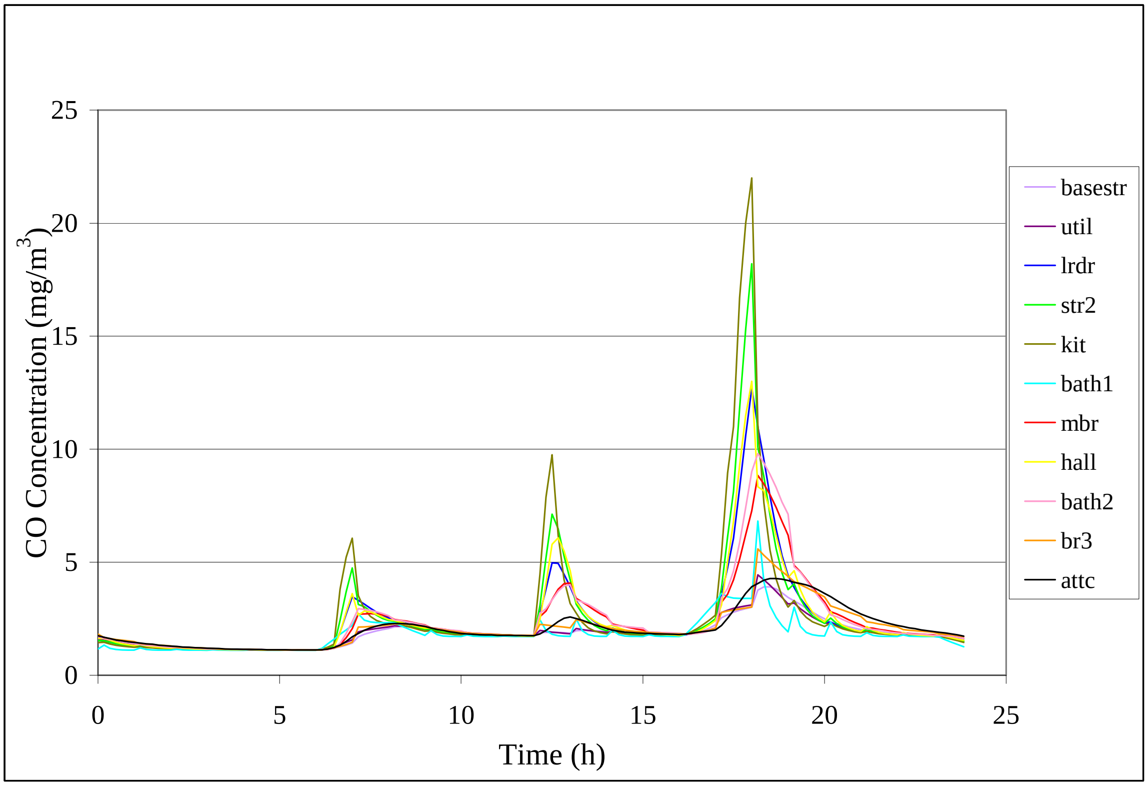

Figure 2. 24 h CO concentrations in Boston in fall.

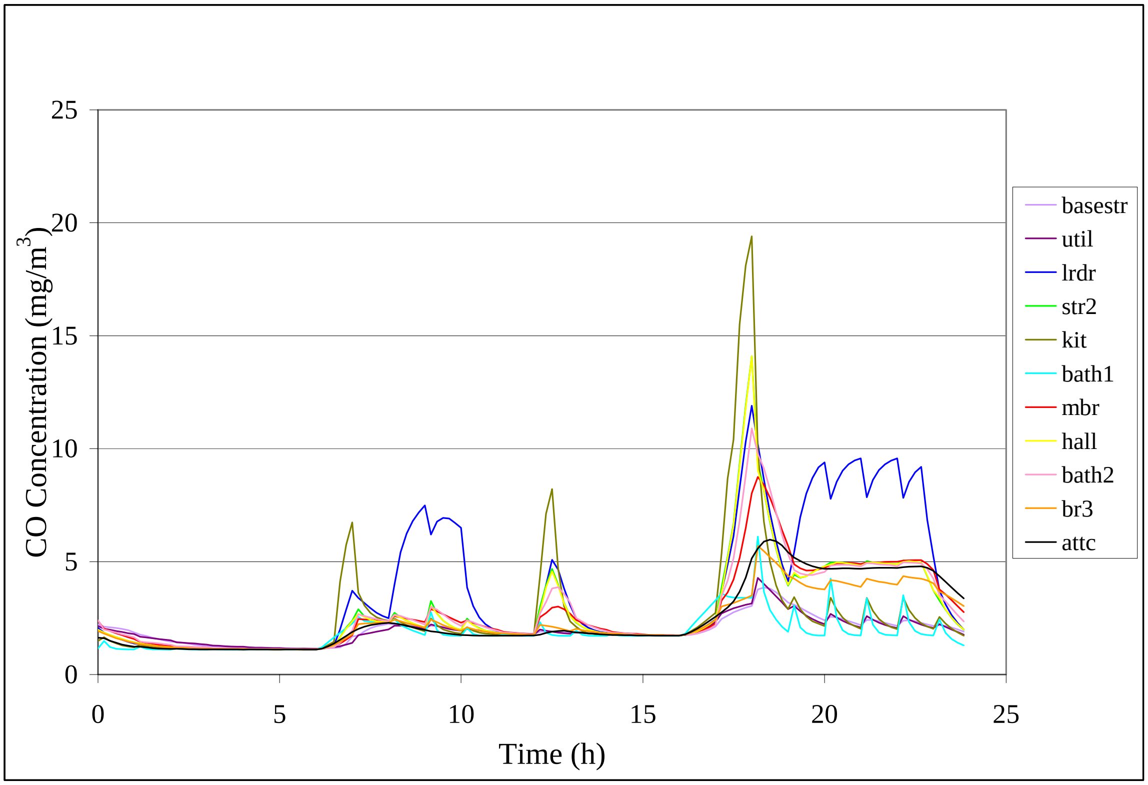

Figure 3. 24 h CO concentrations in Boston in winter.

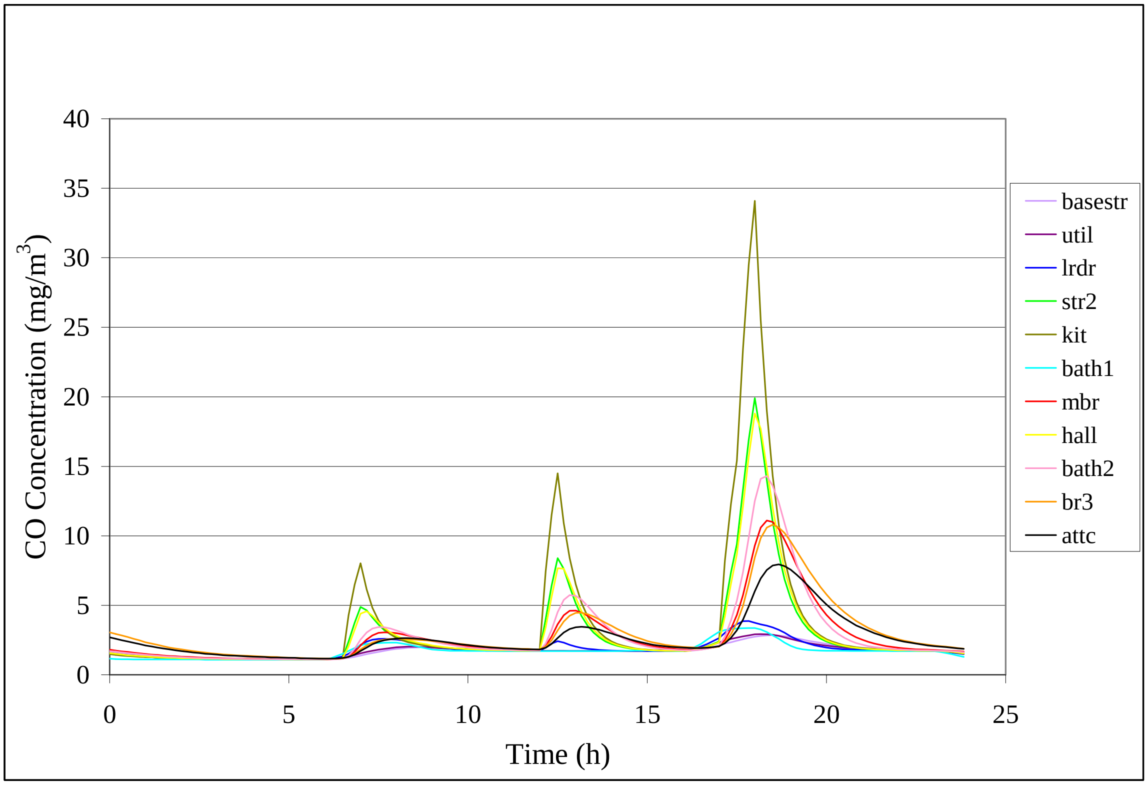

Figure 4. 24 h CO concentration in Boston in spring.

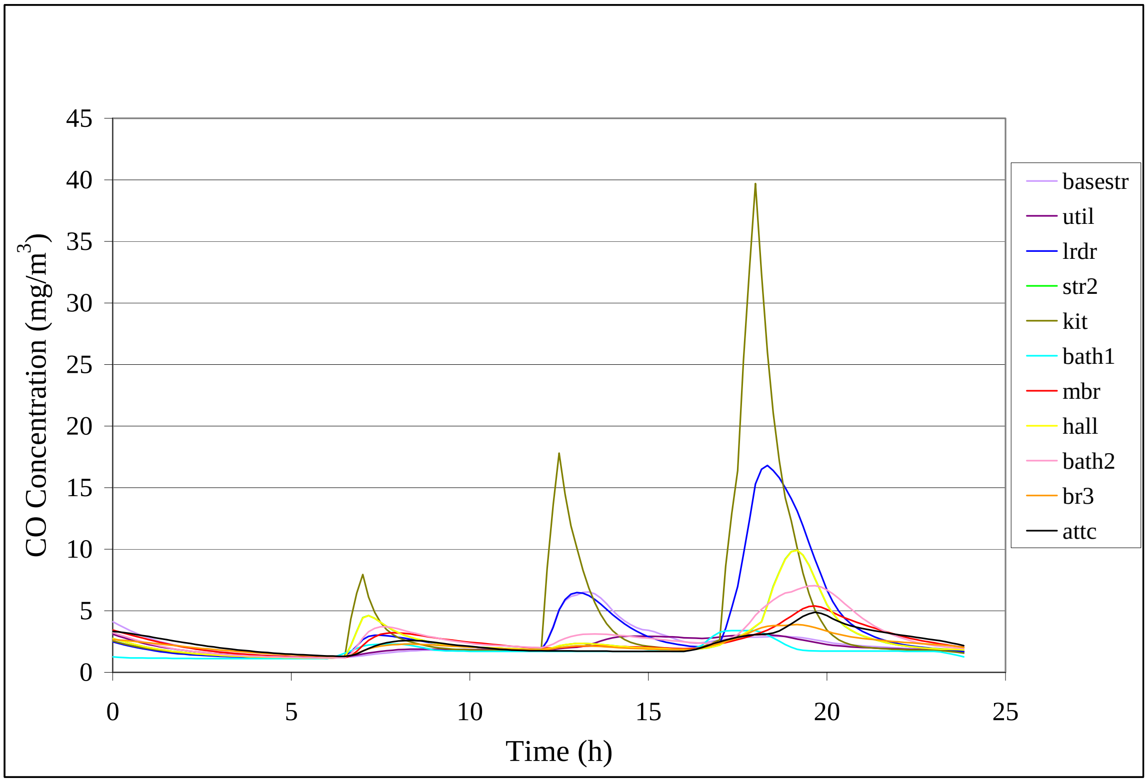

Figure 5. 24 h CO concentration in Boston in summer.

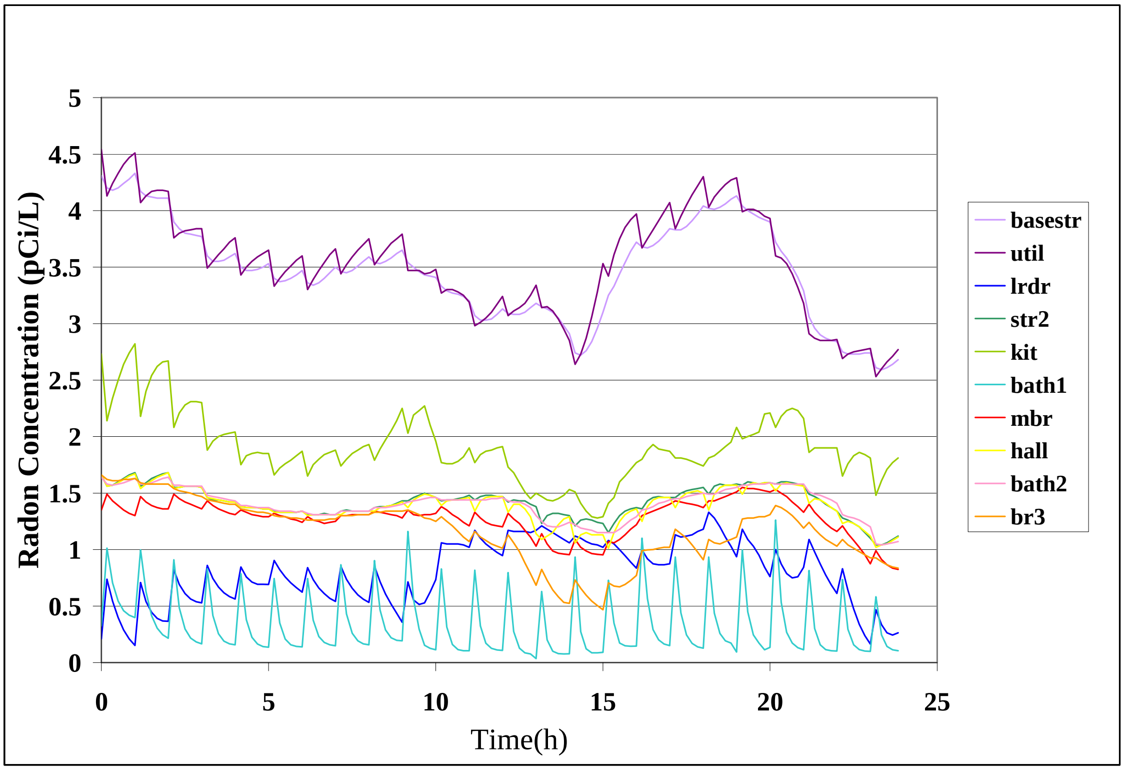

Figure 6. 24 h Radon concentration in Seattle in fall.

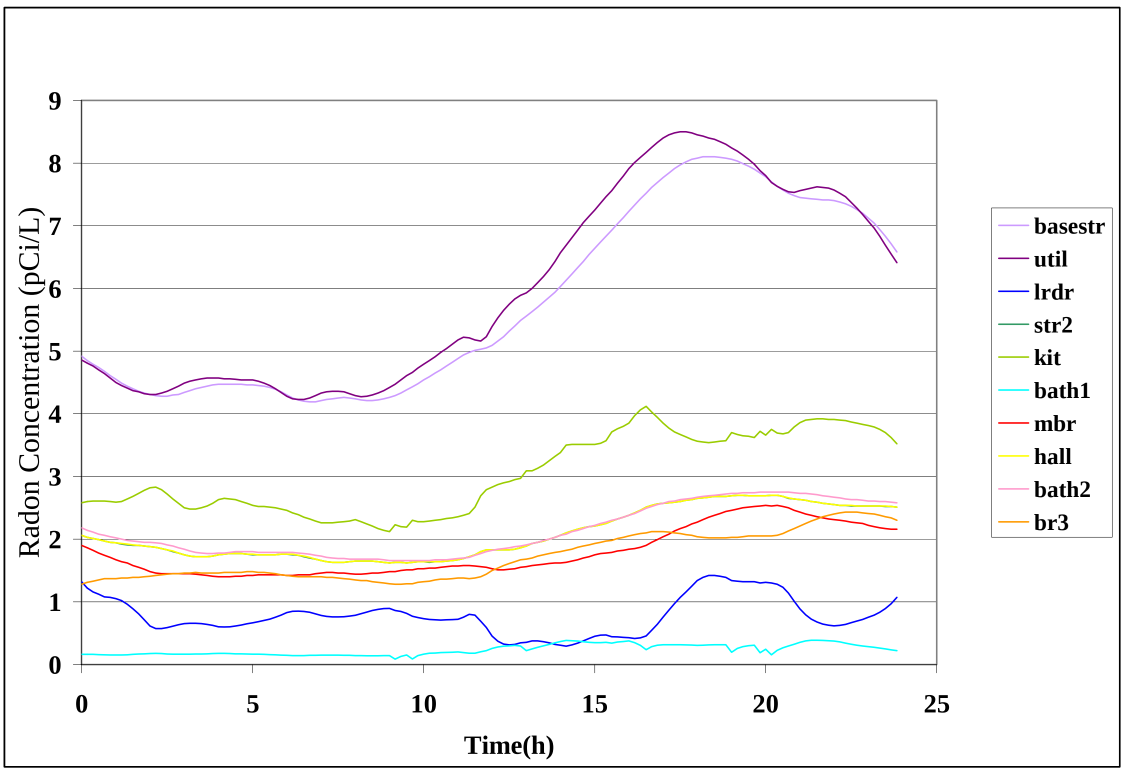

Figure 7. 24 h Radon concentration in Seattle in summer.

A pollutant primarily brought indoors from outside was P4 (2.5 μm to 5 μm particles). Figures 8 – 10 show the concentration profile of P4 in each zone of the townhouse in Boston, Miami, and Seattle, respectively. To show the distribution of P4 in the townhouse for each city, a season was chosen that did not require the use of the air handling system. As shown in Figures 8 – 10, the zone with the highest concentration of P4 for all cities was the middle level bathroom. The zones with the next highest P4 concentrations, however, varied from city to city. This result illustrates the impact of weather on the penetration and distribution of outdoor contaminants. In general, particle concentrations were reduced during seasons with the air handling system operating due to removal by the furnace filter.

Water vapor is another contaminant with both indoor and outdoor contribution. Figure 12 shows the concentration of H_2O in the townhouse zones in Miami in winter. Peaks are associated with the shower and cooking events. In general, H_2O concentrations in all zones of the house are of similar magnitude and follow the same pattern throughout the day. Contaminants with just an indoor source decay back to near zero, whereas the outdoor contribution of H_2O results in a relatively high background level.

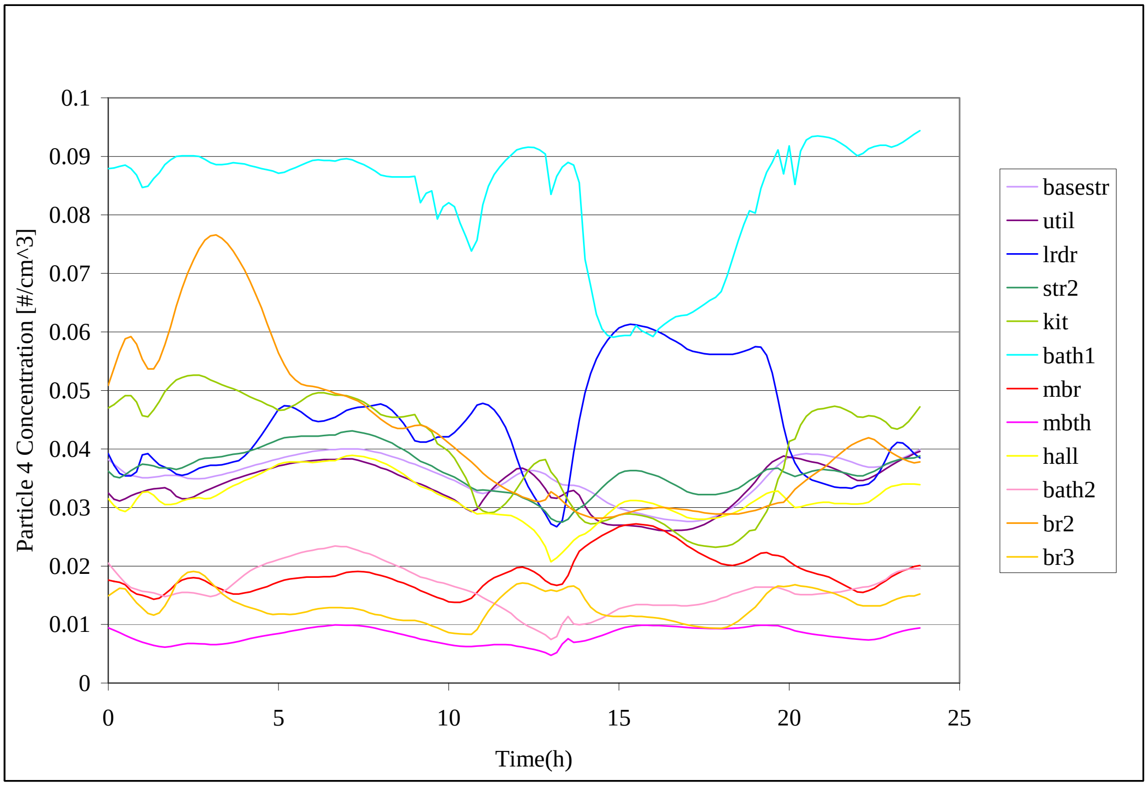

Figure 8. 24 h Particle 4 concentration in Boston in spring

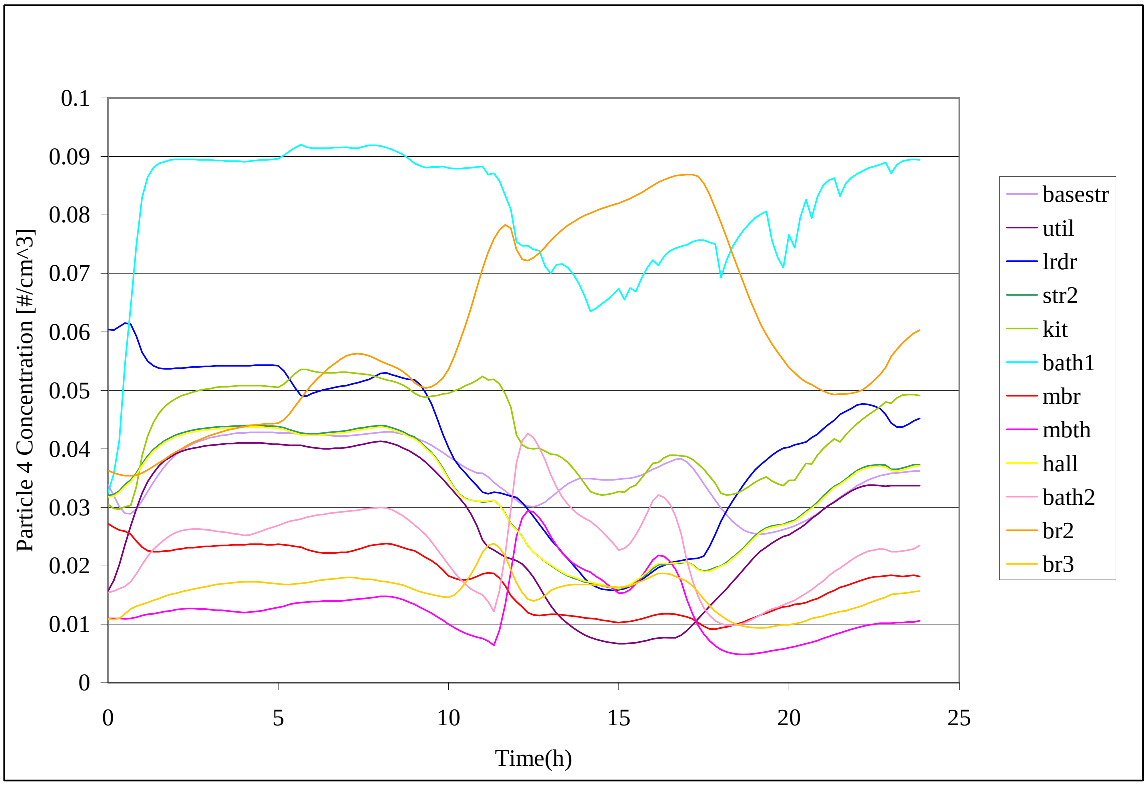

Figure 9. 24 h Particle 4 concentration in Miami in winter

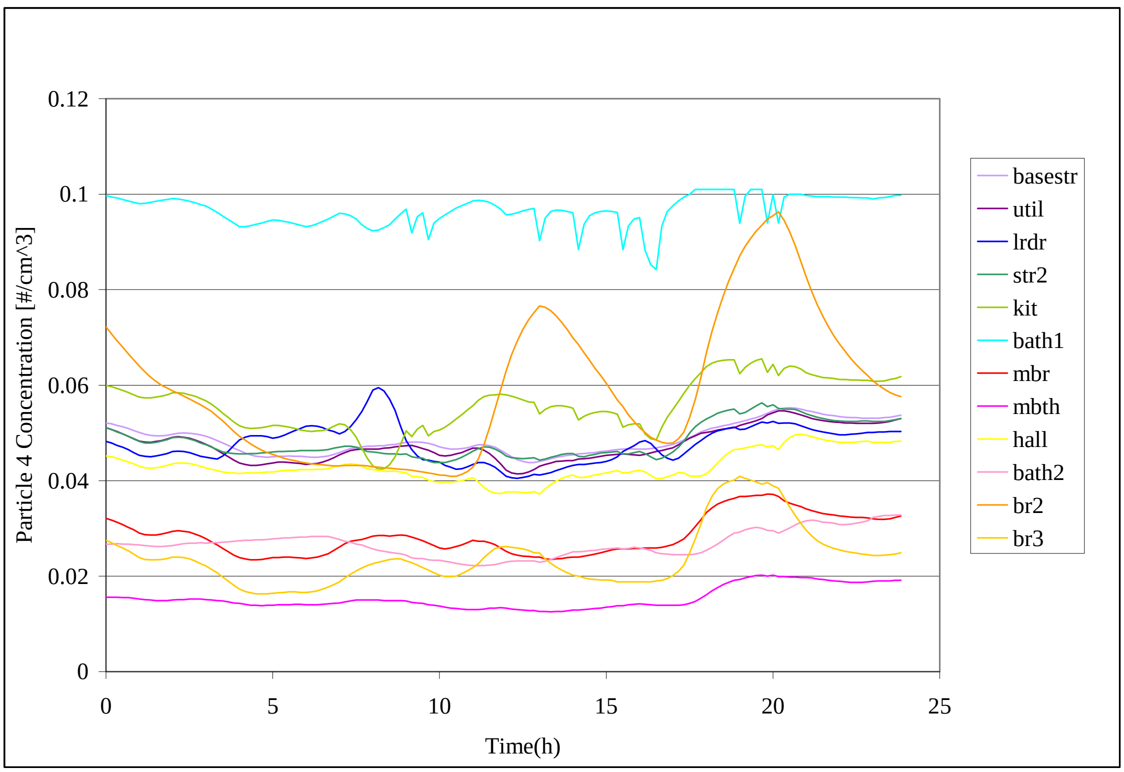

Figure 10. 24 h Particle 4 concentration in Seattle in spring

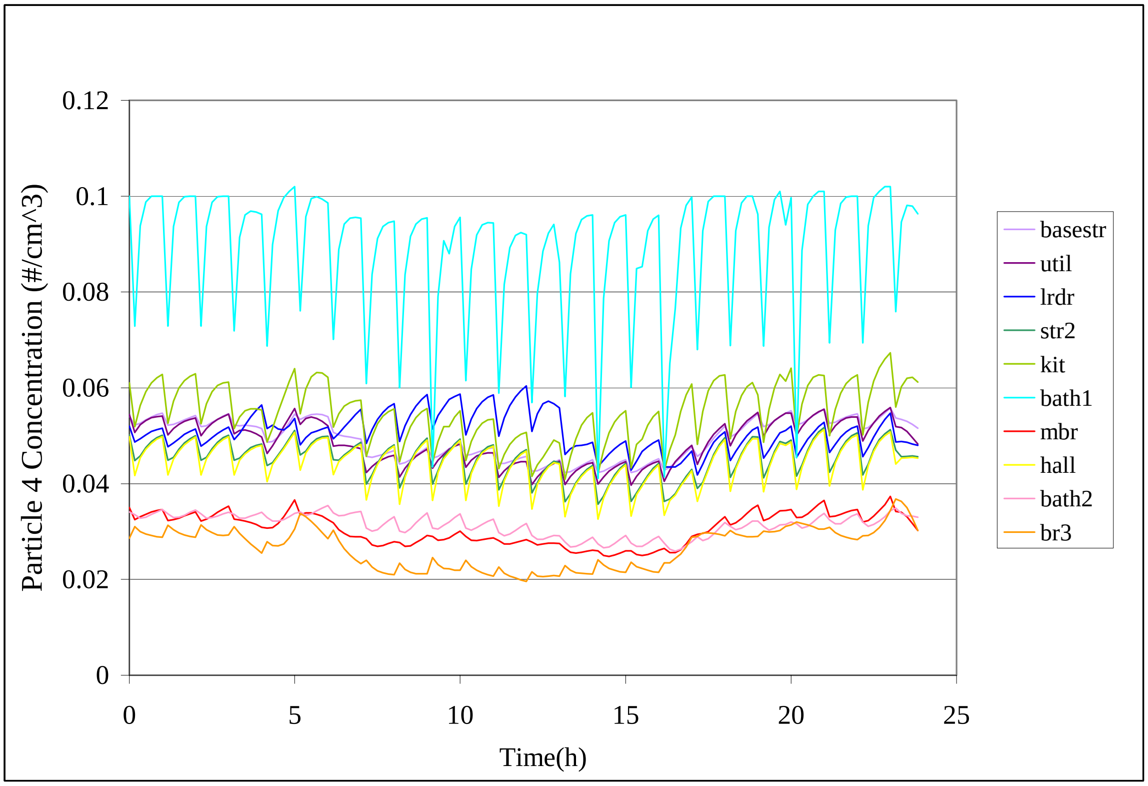

Figure 11. 24 h Particle 4 concentration in Seattle in winter.

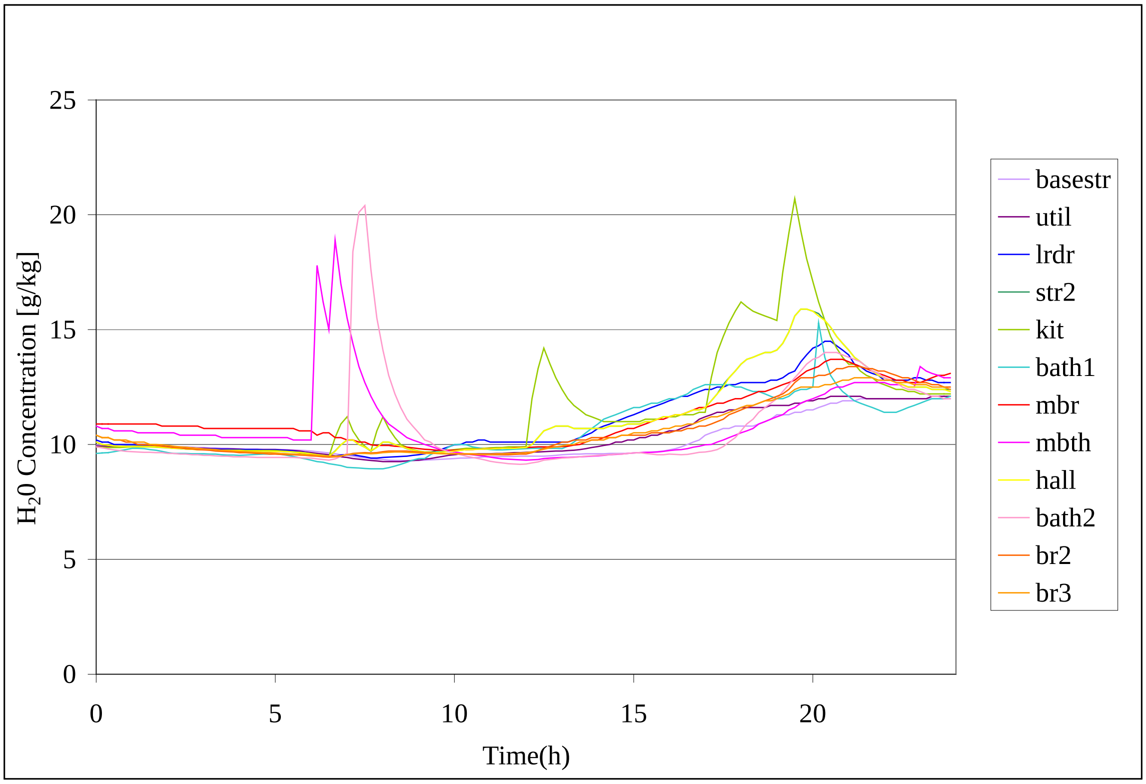

Figure 12. 24 h H_2O concentration in Miami in winter.

Intervention Results

A total of eight interventions were implemented in the different cities, with the intervention simulations run in the same manner as the baseline cases. The impact of each intervention is presented in terms of its effect on air change rates and the concentrations of each of the 12 contaminants.

Infiltration Rates

The interventions that affected air change rate included: intermittent exhaust fans, mechanical ventilation, envelope tightening, and air conditioner operation. A summary of the minimum, average, and maximum air change rates for these interventions in each city and season is provided in Table 20. The intervention with greatest positive impact on air change rates was the addition of mechanical ventilation, increasing the average air change rate by as much as a factor of 2. With mechanical ventilation, the air change rates in all cities were never below the value of 0.35 h^{-1} (see Table 21). Mechanical ventilation using a central HAC system (intervention in Miami) was more effective at increasing the air change rate than the method using exhaust fans (interventions in Boston and Seattle).

The intermittent exhaust fans and air conditioner had a small but positive impact on the air change rates. The exhaust fan pulled more outdoor air through the building's envelope and the air conditioner led to pressure differences also causing more outdoor air to enter. Tightening the house without any mechanical ventilation, however, dramatically reduced the air change rate and resulted in values less than 0.35 h^{-1} nearly 100 % of the time in all climates and cities.

Contaminant Concentrations

The impact of each intervention was determined by comparing weeklong average contaminant concentrations with baseline simulation results for each city and season. Results are presented in Tables C1 – C36 of Appendix C by contaminant and by city. Not all interventions had an impact on every contaminant. For each contaminant, three zones were identified as the most important in terms of contaminant source location and occupant exposure time. For each city and contaminant, the relevant interventions were ranked based on the total difference between the intervention average concentrations and the baseline average concentrations for all seasons. Interventions resulting in a negative impact were also identified.

Carbon monoxide (CO) concentrations in the house were primarily associated with the gas stove in the kitchen and the space heater in the living room during the winter. Based on these sources and the time occupants spent in their bedrooms, the following zones were chosen for comparison: the kitchen, living room, and average of the three bedrooms. Summaries of the weekly minimum, average, and maximum concentrations are provided in Tables C1 – C3 in Appendix C. For all three cities, the source removal intervention of repairing the faulty stove had the biggest overall impact on CO concentrations. In terms of a ventilation strategy, the intermittent exhaust fan was the most effective due to its reduction of peak concentrations during cooking events. Even operating the air conditioner in summer in Boston and Seattle caused a slight reduction in CO concentration, due to its slight impact on air change rates in the house (see earlier discussion). For all three cities, tightening the building envelope increased the CO concentrations.

Table 20. Intervention air change rates (h^{-1}).

City	Season	Baseline			Exhaust Fan			Mech. Ventilation			Tightening			Air Conditioning		
		Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
Boston	**Fall**	0.32	0.76	1.1	0.32	0.80	1.5	0.53	0.94	1.3	0.13	0.26	0.36	N/A	N/A	N/A
	Winter	0.72	0.98	1.5	0.72	1.0	1.6	0.90	1.2	1.7	0.24	0.33	0.51	N/A	N/A	N/A
	Spring	0.36	0.66	0.96	0.42	0.70	1.2	0.54	0.84	1.1	0.12	0.22	0.31	N/A	N/A	N/A
	Summer	0.24	0.47	0.73	0.24	0.51	1.0	0.45	0.66	0.91	0.079	0.15	0.24	0.25	0.49	0.73
Miami	**Fall**	0.14	0.31	0.52	0.16	0.36	0.83	0.49	0.65	0.86	0.056	0.12	0.18	N/A	N/A	N/A
	Winter	0.16	0.45	0.75	0.16	0.49	1.0	0.50	0.81	1.1	0.051	0.15	0.25	N/A	N/A	N/A
	Spring	0.15	0.42	0.82	0.15	0.46	0.97	0.49	0.76	1.2	0.056	0.15	0.28	N/A	N/A	N/A
	Summer	0.13	0.33	0.66	0.15	0.37	0.86	0.47	0.67	1.0	0.051	0.12	0.23	N/A	N/A	N/A
Seattle	**Fall**	0.53	0.75	1.0	0.53	0.79	1.2	0.72	0.94	1.2	0.18	0.25	0.35	N/A	N/A	N/A
	Winter	0.65	0.80	1.1	0.65	0.84	1.3	0.85	0.99	1.2	0.21	0.27	0.37	N/A	N/A	N/A
	Spring	0.17	0.57	0.96	0.21	0.61	1.2	0.42	0.76	1.2	0.057	0.19	0.32	N/A	N/A	N/A
	Summer	0.17	0.49	0.71	0.18	0.54	0.95	0.37	0.69	0.88	0.055	0.16	0.23	0.18	0.51	0.74

Table 21. Percentage of hours during one week period of each season with air change rates < 0.35 h^{-1}.

City	Season	Baseline	Exhaust Fan	Mechanical Ventilation	Tightening	Air Conditioning
Boston	**Fall**	2	2	0	98	N/A
	Winter	0	0	0	69	N/A
	Spring	0	0	0	100	N/A
	Summer	13	11	0	100	11
Miami	**Fall**	67	61	0	100	N/A
	Winter	23	20	0	100	N/A
	Spring	32	29	0	100	N/A
	Summer	61	55	0	100	N/A
Seattle	**Fall**	0	0	0	99	N/A
	Winter	0	0	0	99	N/A
	Spring	11	7.7	0	100	N/A
	Summer	20	15	0	100	20

Figure 13 shows the impact of air change rate on CO concentrations in the kitchen and bedrooms. There appears to be a nonlinear relationship between air change rate and CO concentration. CO concentrations dramatically decrease as the air change rate increases until approximately 0.4 h^{-1}, at which point the effect levels off. Thus, an air change rate of 1.2 h^{-1} does not have a significant impact on CO concentration over an air change rate of 0.4 h^{-1}. Figure 13 also shows that using an exhaust fan to reduce source peaks is most effective at reducing CO exposure.

Carbon dioxide (CO_2) concentrations are reported for zones of high occupancy (living room, master bedroom, and children's bedrooms) in Tables C4 – C6 of Appendix C. Since the only source of CO_2 considered for this project was occupant respiration, source control was not an intervention option, and neither was air cleaning. Comparing ventilation strategies, it is not surprising that the results are similar to those reported for air change rates (see Table 20). As expected, mechanical ventilation, which provided the highest air change rates, also resulted in the lowest concentrations of CO_2, followed by the exhaust fan and air conditioner in the summer of Boston and Seattle. Tightening the building envelope reduced the supply of outdoor air to the house and therefore increased the CO_2 concentrations.

The non-occupant sources of water vapor were located in the kitchen, master bathroom, and children's bathroom. The resulting concentrations in these three zones are presented in Tables C7 – C9 of Appendix C. No source control options were modeled for this contaminant. The addition of air conditioning to Boston and Seattle in the summer was the most effective intervention at reducing average concentrations, even when compared to the impact of exhaust fans and mechanical ventilation for the entire year. While the use of exhaust fans and mechanical ventilation was a positive intervention for Boston and Seattle, they were found to have a negative impact in Miami. Due to the higher outdoor humidity and removal of indoor humidity by the baseline air-conditioning system, the Miami house benefited more from tightening the building envelope rather than adding more outdoor air.

Unlike other contaminants, reducing average relative humidity may not be a good measure of effectiveness since problems such as mold may be associated with high local relative humidity, and the CONTAM model does not account for such local gradients. Therefore, the interventions were also ranked based on the reductions in maximum zone water vapor concentrations. Using this ranking method, exhaust fans become the clear leader in effectiveness for both Boston and Seattle followed by mechanical ventilation, and summer air-conditioning. Envelope tightening still results in a negative impact for these climates. In Miami, the order of effectiveness does not change, however, exhaust fans have a net positive effectiveness (i.e., exhaust fans lower peak relative humidity levels).

Additionally, the effectiveness of the kitchen exhaust fans at reducing peak relative humidity could be greatly improved by extending the fan operation time. The original intervention simulations included kitchen fan operation only when during cooking. As seen in Tables C7 to C9, this operation schedule resulted in reductions of peak kitchen relative humidity of 5 % RH or less. However, a simulation was performed for the Seattle spring case with the kitchen exhaust fan operation time extended to include the period of dishwashing time, which is another significant source of water vapor in the kitchen. Extended exhaust fan operation improved the effectiveness, reducing the peak kitchen humidity by 21 % RH.

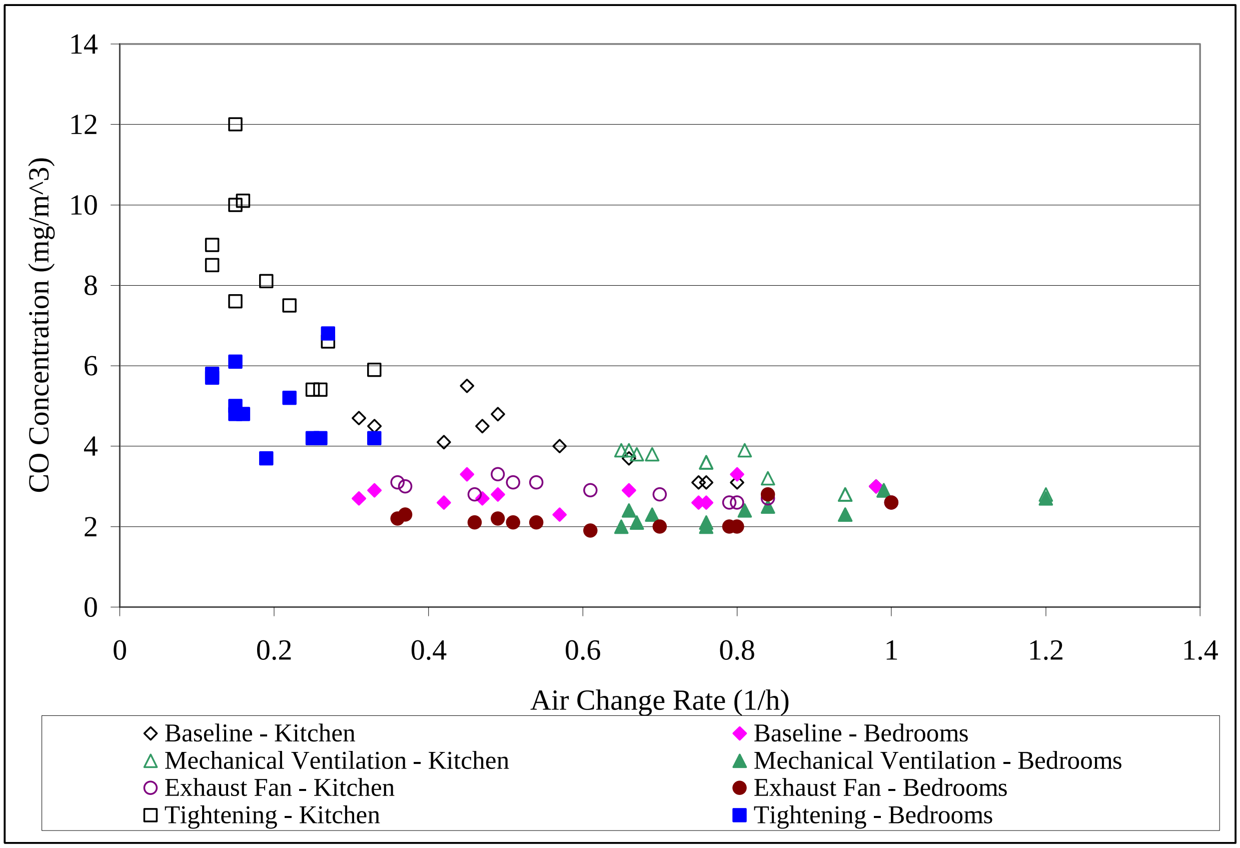

Figure 13. Impact of air change rate on CO concentration in kitchen and bedrooms.

The zones where occupants spent a majority of their time (*i.e.*, kitchen, living room, and bedrooms) were chosen for analysis of the NO_2 results (see Tables C10 – C12 of Appendix C). Source control through repair of the faulty stove and removal of the space heater were the most effective interventions for NO_2. Due to low NO_2 outdoor concentrations, exhaust fans and mechanical ventilation also reduced the concentrations of NO_2, whereas tightening the building's envelope had a negative impact.

There were two primary sources of Particle 1 (P1: 0.3 μm to 0.5 μm) – outdoor air and indoor cooking events. As a result, the interventions tended to either reduce concentrations due to one source or the other, with the exception of the mechanical air filter, which applied to both. Results are presented in Tables C13 – C15 of Appendix C for the highest occupancy zones. In terms of average concentrations, tightening the house's envelope was the most effective overall. However, tightening did result in higher peak concentrations in the kitchen source zone. For seasons during which the HAC system was operated, the improved filter was the second most effective intervention followed by the exhaust fan. The exhaust fan was effective at reducing peak concentrations, however, this removal was offset by its introduction of outdoor particles through increased negative pressure. The air conditioner also had a positive impact on the Particle 1 concentrations in Boston and Seattle summer due to the furnace filter in the system, which is not active when the system is off (baseline Boston and Seattle summers). The outdoor air introduced by mechanical ventilation did not successfully dilute the indoor concentrations of Particle 1, resulting in a negative impact.

In contrast to Particle 1, the indoor sources of Particle 2 (P2: 0.5 μm to 1.0 μm) are more significant than the outdoor contribution changing the relative impact of the different interventions (see Tables C16 – C18 of Appendix C). For this contaminant, the exhaust fan was the most effective intervention followed by the mechanical air filter and mechanical ventilation, respectively. Given the indoor sources, the reduced air change rate caused by tightening the house's envelope results in a negative impact.

The intervention impacts on Particle 3 (P3: 1.0 μm to 2.5 μm) are shown in Tables C19 – C21 of Appendix C. The model sources of P3 are significant both outdoors as well as indoors (e.g., cooking and changing kitty litter). As a result, the intervention rankings varied from city to city. For example, in Boston, tightening the house's envelope was the most effective followed by the exhaust fan and filter. In Miami, the exhaust fan and filter were more effective than tightening. And for Seattle, the order was exhaust fan, tightening and filter. In all three cities, however, the mechanical ventilation resulted in a negative impact. Since the indoor and outdoor source strengths are the same for all three cities, the varying air change rates are impacting which intervention is the most effective at reducing P3. Higher air change rates in Boston promoted envelope tightening, whereas lower air change rates in Miami supported local indoor source control.

As discussed earlier, Particle 4 (P4: 2.5 μm to 5.0 μm) is primarily an outdoor pollutant that penetrates indoors, with a small fraction of indoor sources. As such, the most effective interventions for reducing indoor concentrations of P4 are tightening and air cleaning (see Tables C22 – C24 of Appendix C). However, once again, tightening also has a negative impact by increasing peak concentrations. Peak concentrations are particularly high in the living room where the kitty litter is changed. Exhaust fans and mechanical ventilation also had a negative impact for this contaminant.

Figure 14 further demonstrates the impact of ventilation on P4 concentrations in the kitchen and bedrooms. In Figure 14, an air change rate greater than 0.4 h^{-1} results in doubling the P4 concentration after tightening for bedroom concentrations. In the living room, where there is an indoor source, increasing the air change rate has little impact on P4 concentrations.

Particle 5 (P5: 5.0 μm to 10 μm) is the one contaminant where neither exhaust fans, mechanical ventilation, nor tightening reduced indoor concentrations (see Tables C25 – C27 of Appendix C). The kitty litter source of P5 overwhelmed the average concentration values such that only air cleaning had a positive impact. Although not included as an intervention for this project, source control would clearly be a more effective intervention.

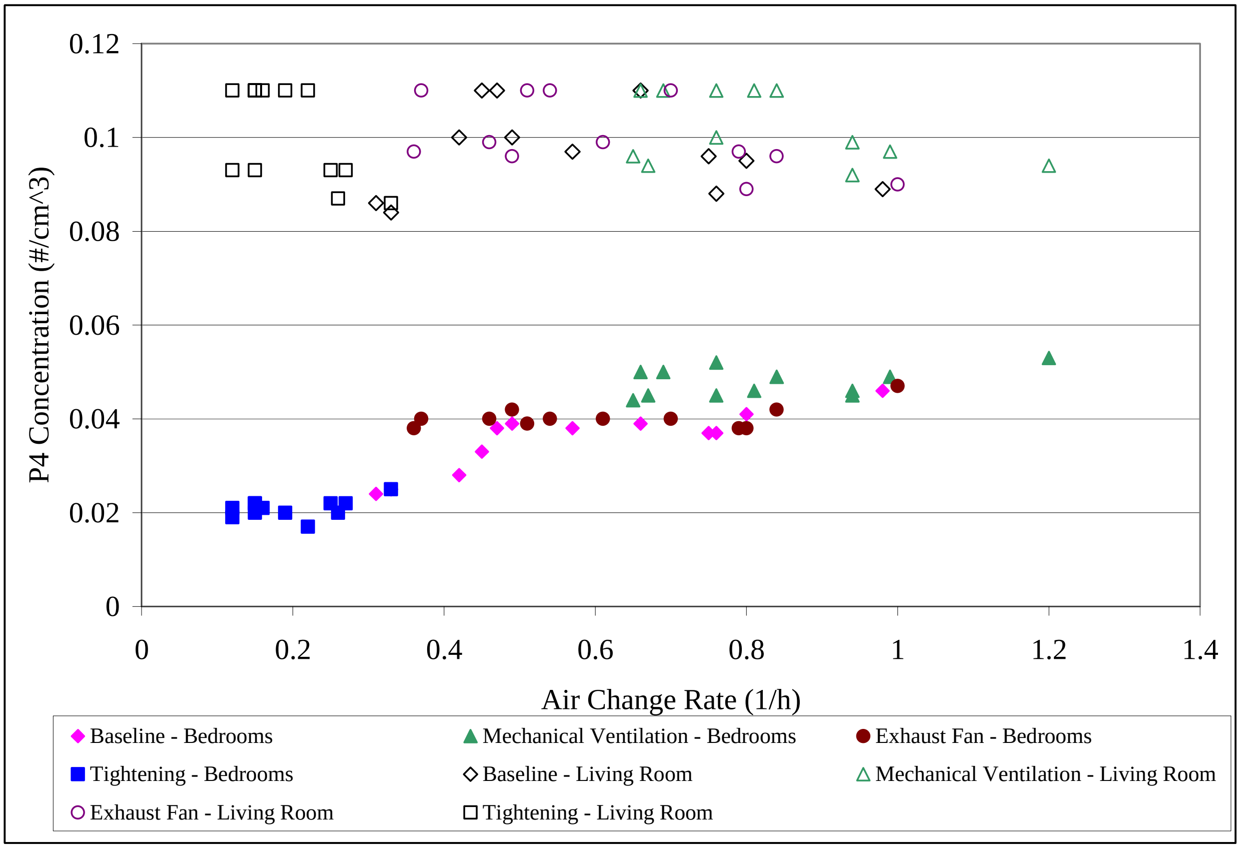

Figure 14. Impact of air change rate on P4 concentration in kitchen and bedrooms.

Concentrations of radon were compared in the utility room, living room, and average of the bedrooms (see Tables C28 – C30 of Appendix C). Radon is a complicated contaminant to control due to the counteracting effects of negative pressure and air change. For all three cities, mechanical ventilation was the most effective intervention. Although it distributes the radon from the basement more efficiently to other rooms in the house, it also dilutes the concentration with outdoor air. The exhaust fans increase the negative pressure differential, drawing in more radon, but also result in more outdoor air ventilation, which ultimately resulted in lower indoor concentrations. Tightening had a negative impact on both the average and peak concentrations.

The continuous VOC (VOC1) is another contaminant of indoor origin where ventilation strategies were the only options considered. Again, mechanical ventilation, exhaust fans and air conditioning reduced concentrations and tightening the building envelope had a negative impact (see Tables C31 – C33 of Appendix C). Other potential intervention options that were not evaluated include using lower emitting products and gaseous air cleaning.

Tables C34 – C36 of Appendix C show the resulting concentrations for VOC2 in the higher occupancy zones. The burst source of VOC2 resulted in higher peak concentrations than VOC1, but the average concentrations were of similar magnitude. Mechanical ventilation, exhaust fans and air conditioning reduced both the peak concentrations and average values, whereas tightening increased both the peak and average values.

Occupant Exposure

Another way to analyze intervention impacts is in terms of occupant exposure. Exposure to a contaminant is a function of room air concentration and exposure time. Thus, the occupants who were in the house the longest had the highest exposure values. For this project, the mother and 4-year old child were in the house 22 h per day and thus had the greatest exposure to all contaminants. The mother's total exposure was higher than the child's due to her proximity to indoor sources of contaminants (e.g., cooking, cleaning, etc.). In contrast, the father was only in the house 14 h per weekday, resulting in a lower total exposure.

The impact of the interventions on occupant exposure did not deviate significantly from the results for the zone concentrations, although there were some differences between occupants. Tables D1 – D21 of Appendix D show the impact of each intervention on the average exposure of the father, mother, and 4-year old child for each contaminant. Impact was divided into 5 categories of percent reduction or increase of contaminant exposure, ranging from greater than 25 % reduction to greater than 25 % increase (see Figure 1D for legend). H_2O was not included in the analysis as direct exposure to H_2O is not an IAQ concern.

Operating the kitchen exhaust fan during a source event had the most significant impact for all of the occupants. This intervention was particularly effective at reducing the exposure of the mother and highlights the importance of local ventilation during source events. Several combinations of city and season resulted in negative impact on zone concentrations, but only Miami/fall was negative for the mother and no conditions were negative for the 4-year old child. This result highlights the importance of considering people's exposure, not just zone concentrations.

Tightening the building envelope led to greater than 25 % increase in exposure to CO, CO_2, NO2, P2, Rn, VOC1, and VOC2. Tightening did reduce exposure to P4 and P5, more so for the father than the mother or 4-year old child. The other intervention with negative impacts on exposure was mechanical ventilation, which tended to increase these particle exposures for all residents.

Interventions with no negative impact on occupant exposure included source control (e.g., repairing the faulty stove, removal of space heater, etc.) and using a more efficient air filter. These interventions, however, were more limited in the number of contaminants reduced.

Table 22. Change in Family Exposure for Factorial Simulation Design

Intervention #	Tight	Exh. Fan	Mech. Vent.	Filter	CO (%)	CO_2 (%)	NO_2 (%)	P1 (%)	P2 (%)	P3 (%)	P4 (%)	P5 (%)	Rn (%)	VOC1 (%)	VOC2 (%)
1	no	no	no	no	0	0	0	0	0	0	0	0	0	0	0
2	yes	no	no	no	83	38	53	-20	5.5	-18	-25	12	180	88	83
3	no	yes	no	no	-19	-1.5	-33	-4.5	-16	-8.2	2.3	1.4	-8.7	-1.5	-0.7
4	yes	yes	no	no	4.4	30	-27	-32	-34	-36	-21	13	130	73	73
5	no	no	yes	no	-10	-7.4	-12	4.5	0	6.6	12	3.6	-27	-9.4	-9.8
6	yes	no	yes	no	24	5.8	24	-6.4	3.4	-4.2	-2.8	18	34	24	18
7	no	yes	yes	no	-22	-8.3	-36	1.0	-12	0.2	14	4.5	-32	-10	-10
8	yes	yes	yes	no	-12	3.0	-29	-14	-22	-17	0.4	19	15	19	14
9	no	no	no	yes	0	0	0	-17	-18	-16	-12	-5.9	0	0	0
10	yes	no	no	yes	83	38	53	-42	-21	-35	-35	5.2	180	88	83
11	no	yes	no	yes	-19	-1.5	-33	-21	-31	-23	-9.7	-4.8	-8.7	-1.5	-0.7
12	yes	yes	no	yes	4.4	30	-27	-50	-50	-49	-31	7.1	130	73	73
13	no	no	yes	yes	-10	-7.4	-12	-11	-16	-9.1	-0.7	-2.6	-27	-9.4	-9.8
14	yes	no	yes	yes	24	5.8	24	-26	-18	-21.4	-15	10	34	24	18
15	no	yes	yes	yes	-22	-8.3	-36	-14	-26	-14	1.2	-1.6	-32	-10	-10
16	yes	yes	yes	yes	-12	3.0	-29	-31	-37	-31	-11	12	15	19	14

Shaded cells indicate largest reduction in family exposure to that contaminant.

Factorial Simulation Design

If there is a single specific contaminant of concern, it is rather straightforward to determine the most effective intervention. However, typically there are several indoor air contaminants of concern that cannot all be addressed with a single intervention. As a result, combinations of interventions may be needed to address overall indoor air quality. To examine this issue, four interventions (mechanical ventilation, exhaust fans, improved filter, and envelope tightening) were identified for use in a factorial simulation design to determine the most effective combination of interventions for each contaminant based on occupant exposure. The impact on family exposure (sum of all 5 occupant's individual exposures) for each contaminant is shown in Table 22. In general, intervention combinations that include the use of exhaust fans and mechanical ventilation result in the greatest reduction in contaminant concentrations. Whereas intervention combinations that include tightening tend to increase contaminant concentrations.

Factorial results were also compared across all contaminants by calculating the average percent change in concentration. Based on this analysis, intervention combinations were ranked as shown in Table 23. The combination with the largest decrease across all contaminants was operating exhaust fans, installing mechanical ventilation, and adding a more efficient air filter, without tightening the house. An ANOVA analysis on these results showed tightening the house to have the most significant impact on contaminant concentrations ($p < 0.001$) followed by using mechanical ventilation ($p < 0.01$) and exhaust fans ($p < 0.01$). Adding a more efficient air filter did not have a significant impact on the results and would be considered a much lower priority for these particular sources and building features. Although tightening the house was found to have the most significant impact, it is not a desirable intervention because the impact is in the direction of increasing contaminant concentrations. Thus the most effective individual interventions at reducing all contaminant concentrations are the use of mechanical ventilation and exhaust fans.

Table 23. Rank of Interventions with Positive Overall Impact on Average Percent Change in Family Exposure.

Rank	Intervention Combination	Average Reduction Over All Contaminants (%)	Negative Impact on Exposure to Contaminants Below:
1	exfan, filter, mv	15	P4
2	exfan, filter	13	
3	filter, mv	9.8	
4	exfan, mv	9.7	P1, P3, P4, P5
5	exfan	7.7	P1, P3, P4, P5
6	exfan, filter, mv, tight	7.4	CO2, P5, Rn, VOC1, VOC2
7	filter	5.8	
8	mv	4.3	P1, P3, P4, P5
9	exfan, mv, tight	2.0	CO2, P4, P5, Rn, VOC1, VOC2

exfan: exhaust fan
filter: improved particle filter
mv: mechanical ventilation
tight: envelope tightening

SUMMARY AND DISCUSSION

One of HUD's objectives for its Healthy Homes Initiative was to improve the indoor air quality of residential environments, particularly those of lower income housing. Health studies have shown the negative impact of elevated contaminant levels in such homes and indicate a need for improvement. There are many factors to consider when developing an IAQ intervention strategy for lower income housing including: cost, skill level of those performing interventions, climate, ratio of indoor/outdoor pollutant source contributions, and building characteristics. This project focused on a single lower income house with given envelope and HAC system characteristics and subjected it to a range of climate conditions, outdoor pollutants, and indoor pollutant sources. This project also focused its analysis on IAQ impacts rather than energy consumption. A select list of interventions were chosen based on recommendations from HUD, ASHRAE 62.2-2004, common residential IAQ control strategies, and ease of implementation. Due to the possibility that only a single intervention could be put into practice, each intervention was analyzed individually for its impact on the concentrations of twelve common indoor air contaminants and associated occupant exposures. A small subset of interventions based on ASHRAE 62.2 requirements, were analyzed in different combinations to demonstrate a method to develop a total strategy for a given house. Based on these analyses, a summary of each intervention strategy is provided below:

Upgrading gas stove:

Upgrading the gas stove by either tuning it or replacing it with a newer model is a source control intervention. For specific contaminants, source control interventions were always the most effective and had no negative impacts on concentration levels of other contaminants. Many indoor sources of contaminants, however, cannot be removed or reduced and there is no source control over contaminants originating outdoors. In the case of the gas stove, source control results in lower NO_2 and CO concentrations year round. In fact, it was the single most effective intervention at reducing these contaminants in all climates.

In general, older combustion appliances have lower efficiencies and tend to emit more pollutants. Although a gas stove was used to illustrate this point in this project, the intervention would be effective for reducing contaminants for any combustion appliance (e.g., furnace, gas dryer, etc.).

Educating occupants of dangers of using gas oven for heat:

Educating occupants of the potential dangers of using a gas oven for heat is the least expensive intervention strategy examined for this project. Operating a gas oven to heat a house is a dangerous practice that can elevate concentrations of CO and NO_2 to unhealthful, even fatal, levels (see U.S. Consumer Product Safety Commission, U.S. Environmental Protection Agency and the American Lung Association warning at http://www.epa.gov/iaq/pubs/combust.html).

For this project, using the gas oven to heat the house resulted in the second highest average winter concentration of CO, assuming a properly operating oven was used. If a faulty oven had been used, the occupants' exposure to CO would have been much higher and may have exceeded fatal levels. In a field study involving 60 apartments, Tsongas and Hader (1994) found that most gas ovens resulted in steady-state CO concentrations of 11 mg/m^3 (10 ppm(v)) or less but a few resulted in steady-state CO concentrations exceeding 230 mg/m^3 (200 ppm(v)). Unfortunately, this practice does persist in lower income housing when the residents do not fully understand the risks involved. Stopping this practice is a source control option that would prevent excessive exposure to CO and NO_2 in cold climates at little to no cost to the resident (unless faulty heating equipment needs to be replaced, which would entail significant cost).

Properly venting space heater to the outside:
Providing proper exhaust venting for space heaters would have a similar impact on indoor air concentrations of CO and NO_2 that were realized for ceasing the use of a gas oven for heat. Venting the combustion products from space heaters to the outside would essentially remove these pollutants from the living space, thereby significantly reducing occupants' exposure to CO and NO_2 in cold climates. This intervention strategy would require both education for the occupants and the installation of only vented space heaters.

Installing a more efficient air filter in HAC system:
Air cleaning is a positive intervention that reduces contaminants originating indoors and outdoors with no negative impact on other contaminant concentrations. Most homeowners, however, only have access to air cleaners that remove particles, limiting the scope of the intervention. While an effective intervention for removing particles, an air filter only works when the HAC system is operating. For this project, the HAC system was operated for cold seasons in Boston and Seattle and hot seasons in Miami. In the other seasons, the HAC system was off and the air filter was not removing any particles. As a result, this intervention was only available in cold or hot climates. This intervention would also be effective in more temperate seasons, however, it is important to determine the balance between costs of operating the HAC system and removal of particles. ASHRAE 62.2-2004 recommends using an air filter with a MERV rating of 6 with supply mechanical ventilation. As discussed below, this recommendation helps to mitigate the impact of outdoor contaminants that are introduced by mechanical ventilation.

Operating an air conditioner in hot and humid seasons:
An air conditioner is essentially working like an air filter that removes moisture from the air stream. Many lower income homes do not have air conditioning resulting in elevated relative humidity levels in the summer. For this project, the air conditioner was added to operate 10 min of every hour. Even this relatively short operation time resulted in significant decreases in humidity levels in the house. In fact, the benefit of operating an air conditioner for one season in Boston and Seattle outweighed the benefits of other interventions operated year-round. Again, there is a need to consider electricity costs of operation along with the benefits obtained by limiting relative humidity to levels low enough to prevent mold, allergens, and other indoor air problems. Air conditioning primarily reduces the concentration of water, but central air conditioning also has the side benefit of pulling the air through a filter, thereby reducing particle concentrations.

Exhaust fan:
The exhaust fan was the most effective intervention strategy to reduce peak concentrations associated with cooking and showering. This reduction in concentration during source events had a significant impact on the occupants' exposure to CO, NO_2, P2, P3 and H_2O. It was the single most effective intervention for year-round exposure to P2 and P3 in most climates, and the most effective ventilation intervention strategy for CO, H_2O, NO_2, P2 and P3 in most climates.

Exhaust fans had a broader impact on contaminant concentrations than just for NO_2, CO, P2, P3 and H_2O. During operation, the exhaust fan increased the house's negative pressure causing more outdoor air to enter through leakage paths. As a result, the concentrations of contaminants from continuous sources in other parts of the house (e.g., VOC1 and radon) were also diluted by the increased air change rate. The downside of this intervention strategy was the increase in concentrations of contaminants originating outdoors. This negative impact was significant for P4, P5, and H_2O in Miami. The benefits of using an exhaust fan during source events, however, far outweighed the negative impacts. In fact, project results showed that using the exhaust fan during more source events (e.g., cleaning in kitchen or bathroom, or dishwasher operation) would have reduced concentrations and exposures even more.

If there is no exhaust fan installed or if the current fan does not vent to the outside, there will be an installation cost associated with this intervention. However, in some cases, it is a matter of educating the occupants to turn on the fan during source events. There is also an electricity cost associated with operating the exhaust fan on a regular basis that should also be considered. As shown by the project results, there is a potential negative impact from continuously operating an exhaust fan in areas with higher concentrations of contaminants outdoors.

Continuous mechanical ventilation:
Continuous mechanical ventilation is another intervention that affects all indoor air contaminants, but not always positively. There are different ways to implement this intervention based on climate. For this project, mechanical ventilation was achieved using a continuous exhaust fan in Boston and Seattle, and supply air in Miami. Adding mechanical ventilation using an exhaust fan is the least expensive option, whereas adding outdoor air supply is likely to be more expensive. There is also an incremental cost associated with cooling or heating the added outdoor air.

Mechanical ventilation was effective at reducing contaminants primarily originating indoors via a continuous source (e.g., CO_2, Rn, and VOC1). Mechanical ventilation also effectively diluted concentrations from contaminants primarily from indoor burst sources (e.g., CO, NO_2, and VOC2). Contaminants originating primarily outdoors were negatively impacted (e.g., H_2O in Miami and particles). The negative impacts of mechanical ventilation tended to be greater than those of the exhaust fan intervention, since the outdoor air was continuously added with mechanical ventilation and only added during source events with the exhaust fan intervention. Effective filtration of the incoming air or recirculation air could reduce this impact.

Mechanical ventilation is most beneficial during mild weather when conditions result in lower air change rates due to infiltration.

Tightening the envelope:
Tightening the building envelope has long been recommended for improving energy efficiency, but the resulting reduction in air change rate has dramatic effects on pollutants originating indoors. In fact, it was the single worst intervention in terms of increasing the concentrations of CO, CO_2, NO_2, P2, Rn, VOC1, and VOC2. Although it was most effective at reducing H_2O in Miami, P1, and P4, tightening should not be implemented without considering the need for

supplementary outdoor air. For example, ASHRAE (2001a) has recommended tightening the envelope and adding properly designed mechanical ventilation. For this project, the combination of tightening and mechanical ventilation via exhaust fans showed that tightening can still overwhelm the additional ventilation.

Of all the intervention strategies analyzed for this project, the operation of an exhaust fan during source events had the broadest effect (i.e., a beneficial impact on multiple contaminants). This benefit would have been extended even further if it were operated during more of the source events. If only two interventions can be implemented, then the exhaust fan and more efficient air filter should be used, with the assumption that the HAC system is operating at least 15 % of the time. However, considering the possible large impact on a single contaminant that is possible through source control, any intervention effort should include a review of sources, particularly large or unusual ones.

These recommendations are based on results for a specific house and do not account for cost or contaminant toxicity. Future recommended research includes broadening the scope of the building type, incorporating an economic analysis of the options, and perhaps assigning a ranking of contaminants based on human health effects.

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Appendix A: Flow Elements
Exterior Leakage Elements

Flow Element	Element Name	No. of elements in zone	Leakage data	Relative Elevation	Multiplier
Utility					
wall-wall junction	walltowall	10	1.5 cm^2/m	1.22 m	2.74 m
sliding door	slidingdoor	1	60 cm^2	1 m	
exterior door frame	extdoorframe	1	1.7 cm^2/m^2	1 m	2.92 m^2
window	window	1	1.1 cm^2/m	1.24 m	5.94 m
window frame	windowframe	1	1.7 cm^2/m^2	1.24 m	1.19 m^2
floor-wall interface	floorwall	4	4 cm^2/m	0 m	
electrical outlet	elecoutlet	1	2.5 cm^2	0.43 m	
ceiling-wall joint	celngwalljnt	4	1.5 cm^2/m	2.74 m	
fuse box	fusebox	1	10 cm^2	2 m	
furnace	furnace	1	50 cm^2	1.22 m	
hot water heater	hotwtrheater	1	20 cm^2	1.37 m	
dryer vent	dryervent	1	15 cm^2	1.37 m	
Kitchen					
wall-wall junction	walltowall	4	1.5 cm^2/m	1.22 m	2.74 m
Kitchen exhaust	kitexhaust	1	40 cm^2	2.4 m	
ceiling-wall joint	celngwalljnt	2	1.5 cm^2/m	2.74 m	
floor-wall interface	floorwall	2	4 cm^2/m	0 m	
window	window	1	1.1 cm^2/m	1.23 m	7.05 m
window frame	windowframe	3	1.7 cm^2/m^2	1.23 m	2 m^2
single window	singlewindow	2	0.87 cm^2/m	1 m	2.4 m
front door	frontdoor	1	21 cm^2	1 m	
exterior door frame	extdoorframe	1	1.7 cm^2/m^2	1 m	1.86 m^2
Living/Dining Room					
floor-wall interface	floorwall	3	4 cm^2/m	0 m	
ceiling-wall joint	celngwalljnt	3	1.5 cm^2/m	2.74 m	
wall-wall junction	walltowall	4	1.5 cm^2/m	1.22 m	2.74 m
sliding door	slidingdoor	1	60 cm^2	1 m	
exterior door frame	extdoorframe	1	1.7 cm^2/m^2	1 m	2.96 m^2
window	window	2	1.1 cm^2/m	1.24 m	5.94 m
window frame	windowframe	2	1.7 cm^2/m^2	1.24 m	1.19 m^2
electrical outlet	elecoutlet	3	2.5 cm^2	0.43 m	
Bathroom 1					
ceiling-wall joint	celngwalljnt	2	1.5 cm^2/m	2.74 m	
piping penetration	pipingpenet	1	6 cm^2	1 m	3
electrical outlet	elecoutlet	1	2.5 cm^2	1.12 m	
floor-wall interface	floorwall	2	4 cm^2/m	0 m	
wall-wall junction	walltowall	2	1.5 cm^2/m	1.22 m	2.74 m
bath exhaust	bathexhaust	1	20 cm^2	2.4 m	
Stair2					
ceiling-wall joint	celngwalljnt	2	1.5 cm^2/m	2.74 m	

floor-wall interface	floorwall	2	4 cm^2/m	0 m	
Bedroom 2					
floor-wall interface	floorwall	2	4 cm^2/m	0 m	
ceiling-wall joint	celngwalljnt	2	1.5 cm^2/m	2.74 m	
wall-wall junction	walltowall	2	1.5 cm^2/m	1.22 m	2.74 m
electrical outlet	elecoutlet	1	2.5 cm^2	0.43 m	
window	window	1	1.1 cm^2/m	1.25 m	7.2 m
window frame	windowframe	1	1.7 cm^2/m^2	1.25 m	2.1 m^2
Bedroom 3					
wall-wall junction	walltowall	2	1.5 cm^2/m	1.22 m	2.74 m
ceiling-wall joint	celngwalljnt	2	1.5 cm^2/m	2.74 m	
floor-wall interface	floorwall	2	4 cm^2/m	0 m	
window	window	1	1.1 cm^2/m	1.24 m	6.6 m
window frame	windowframe	1	1.7 cm^2/m^2	1.24 m	1.6 m^2
electrical outlet	elecoutlet	1	2.5 cm^2	0.3 m	
Bathroom 2					
bath exhaust	bathexhaust	1	20 cm^2	2.4 m	
Master Bath					
bath exhaust	bathexhaust	1	20 cm^2	2.4 m	
Master Bedroom					
wall-wall junction	walltowall	4	1.5 cm^2/m	1.22 m	2.74 m
window	window	3	1.1 cm^2/m	1.24 m	7.2 m
window frame	windowframe	3	1.7 cm^2/m^2	1.24 m	2.1 m^2
electrical outlet	elecoutlet	3	2.5 cm^2	0.33 m	
ceiling-wall joint	celngwalljnt	2	1.5 cm^2/m	2.74 m	
floor-wall interface	floorwall	2	4 cm^2/m	0 m	
Hall					
ceiling-wall joint	celngwalljnt	1	1.5 cm^2/m	1.22 m	2.74 m
Stair2					
ceiling-wall joint	celngwalljnt	1	1.5 cm^2/m	1.22 m	2.74 m
Attic					
wall-wall junction	walltowall	8	1.5 cm^2/m	1.22 m	2.74 m
attic vent	atticvent2	6	0.002 m^2 (orifice area data)	0 m	5
piping penetration	pipingpenet	3	6 cm^2	3.8 m	
attic fan	atticfan	1	0.152 m^2	3 m	

Appendix B: Occupancy Schedule Tables

Weekday Occupancy Schedules (Monday – Friday)

Time	Father	Mother	Child (13 yr old)	Child (10 yr old)	Child (4 yr old)
0:00	Master Bedroom	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #2
6:20	Master Bedroom	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #2
6:25	Master Bedroom	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #2
6:30	Kitchen	Master Bathroom	Bedroom #3	Kitchen	Bedroom #2
6:45	Kitchen	Master Bathroom	Bedroom #3	Kitchen	Bedroom #2
6:50	Kitchen	Bedroom 2	Bedroom #3	Kitchen	Bedroom #2
7:00	Out	Bathroom 2	Bedroom #3	Kitchen	Bathroom #2
7:05	Out	Bathroom 2	Bedroom #3	Kitchen	Bathroom #2
7:10	Out	Bedroom 2	Bathroom #2	Kitchen	Bedroom #2
7:15	Out	Bathroom 2	Bathroom #2	Kitchen	Bedroom #2
7:20	Out	Kitchen	Bedroom #3	Bathroom #2	Kitchen
7:30	Out	Kitchen	Kitchen	Bedroom #3	Kitchen
7:40	Out	Kitchen	Kitchen	Bedroom #3	Kitchen
7:55	Out	Kitchen	Kitchen	Bedroom #3	Kitchen
8:00	Out	Living Room	Out	Out	Living Room
8:05	Out	Living Room	Out	Out	Living Room
8:20	Out	Living Room	Out	Out	Living Room
8:30	Out	Living Room	Out	Out	Living Room
9:00	Out	Living Room	Out	Out	Bathroom #1
9:10	Out	Living Room	Out	Out	Living Room
9:30	Out	Bathroom 1	Out	Out	Living Room
9:40	Out	Living Room	Out	Out	Living Room
10:00	Out	Out	Out	Out	Out
12:00	Out	Kitchen	Out	Out	Kitchen
12:50	Out	Kitchen	Out	Out	Bathroom #1
13:00	Out	Bedroom 2	Out	Out	Bedroom #2
13:10	Out	Living Room	Out	Out	Bedroom #2
14:00	Out	Bathroom 1	Out	Out	Bedroom #2
14:10	Out	Living Room	Out	Out	Bedroom #2
15:00	Out	Living Room	Living Room	Living Room	Living Room
15:05	Out	Master Bathroom	Living Room	Living Room	Living Room
15:10	Out	Master Bathroom	Living Room	Living Room	Living Room
15:20	Out	Kitchen	Living Room	Bathroom #1	Living Room
15:25	Out	Kitchen	Living Room	Bathroom #1	Living Room
15:30	Out	Kitchen	Kitchen	Kitchen	Kitchen
15:50	Out	Living Room	Bathroom #2	Living Room	Living Room
16:00	Out	Living Room	Bedroom #3	Living Room	Bathroom #1
16:30	Out	Bathroom 1	Bedroom #3	Living Room	Bathroom #1
16:40	Out	Living Room	Bedroom #3	Living Room	Bathroom #1
17:00	Kitchen	Kitchen	Bedroom #3	Living Room	Bathroom #1
17:50	Kitchen	Kitchen	Bedroom #3	Living Room	Bathroom #1
18:00	Kitchen	Kitchen	Kitchen	Kitchen	Kitchen
18:50	Kitchen	Kitchen	Kitchen	Bathroom #1	Kitchen
18:55	Kitchen	Kitchen	Kitchen	Bathroom #1	Kitchen
19:00	Living Room	Kitchen	Living Room	Living Room	Living Room
19:15	Living Room	Kitchen	Living Room	Living Room	Living Room
19:30	Living Room	Kitchen	Bathroom #2	Living Room	Living Room
19:40	Living Room	Bathroom 1	Bedroom #3	Living Room	Living Room
19:50	Living Room	Living Room	Bedroom #3	Living Room	Bathroom #2

20:00	Bathroom 1	Bedroom 2	Bedroom #3	Living Room	Bedroom #2
20:10	Living Room	Bedroom 2	Bedroom #3	Living Room	Bedroom #2
20:30	Living Room	Living Room	Bedroom #3	Living Room	Bedroom #2
21:00	Kitchen	Master Bathroom	Living Room	Living Room	Bedroom #2
21:10	Living Room	Living Room	Bedroom #2	Living Room	Bedroom #2
21:20	Living Room	Living Room	Bedroom #2	Bathroom #2	Bedroom #2
21:30	Living Room	Bedroom 3	Bedroom #2	Bedroom #3	Bedroom #2
21:40	Living Room	Living Room	Bedroom #2	Bedroom #3	Bedroom #2
22:40	Living Room	Master Bathroom	Bedroom #3	Bedroom #3	Bedroom #2
22:50	Master Bathroom	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #2

Week-end Occupancy Schedules (Saturday and Sunday)

Time	Father	Mother	Child (13 yr old)	Child (10 yr old)	Child (4 yr old)
0:00	Master Bedroom	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #4
9:10	Master Bedroom	Master Bathroom	Bedroom #3	Bathroom #2	Bedroom #4
9:20	Master Bedroom	Master Bathroom	Bedroom #3	Bathroom #3	Bedroom #4
9:30	Kitchen	Bedroom 2	Bedroom #3	Kitchen	Bedroom #4
9:40	Kitchen	Bedroom 2	Bedroom #3	Kitchen	Bathroom #2
10:00	Out	Kitchen	Bathroom #2	Out	Kitchen
10:10	Out	Kitchen	Bedroom #3	Out	Kitchen
10:15	Master Bedroom	Kitchen	Bedroom #3	Out	Kitchen
10:20	Master Bedroom	Kitchen	Kitchen	Out	Kitchen
10:40	Master Bedroom	Living Room	Kitchen	Out	Living Room
10:50	Master Bedroom	Living Room	Bedroom #3	Out	Living Room
11:00	Master Bedroom	Bathroom #1	Bedroom #3	Out	Living Room
11:10	Master Bedroom	Living Room	Bedroom #3	Out	Living Room
11:30	Master Bedroom	Master Bedroom	Bedroom #3	Out	Living Room
12:00	Kitchen	Kitchen	Kitchen	Kitchen	Kitchen
12:40	Kitchen	Kitchen	Living Room	Kitchen	Bathroom #1
12:50	Living Room	Kitchen	Living Room	Bathroom #1	Living Room
13:00	Living Room	Bathroom #2	Out	Out	Bathroom #2
13:10	Living Room	Out	Out	Out	Bathroom #2
14:00	Bath 1	Out	Out	Out	Bathroom #2
14:10	Living Room	Out	Out	Out	Bathroom #2
15:00	Out	Living Room	Living Room	Bathroom #1	Out
15:10	Out	Living Room	Living Room	Living Room	Out
15:20	Out	Living Room	Bathroom #1	Bathroom	Out
15:30	Out	Living Room	Living Room	Living Room	Out
15:40	Out	Hall	Living Room	Living Room	Out
15:50	Out	Bathroom #2	Living Room	Living Room	Out
16:00	Living Room	Bathroom #3	Living Room	Living Room	Bathroom #1
16:10	Living Room	Living Room	Living Room	Living Room	Living Room
16:40	Living Room	Bathroom #2	Living Room	Living Room	Living Room
17:00	Kitchen	Kitchen	Bedroom #3	Living Room	Living Room
17:50	Kitchen	Kitchen	Kitchen	Bathroom #1	Living Room
18:00	Kitchen	Kitchen	Kitchen	Kitchen	Kitchen
18:30	Kitchen	Kitchen	Kitchen	Living Room	Kitchen
18:50	Kitchen	Kitchen	Kitchen	Bathroom #1	Kitchen
19:00	Living Room	Kitchen	Living Room	Living Room	Living Room
19:20	Living Room	Kitchen	Living Room	Living Room	Bathroom #1
19:30	Living Room	Kitchen	Bathroom #1	Living Room	Living Room
19:40	Living Room	Bathroom #1	Living Room	Living Room	Living Room
19:50	Living Room	Living Room	Living Room	Living Room	Living Room

20:00	Bath 1	Living Room	Living Room	Living Room	Living Room
20:10	Living Room	Living Room	Living Room	Living Room	Living Room
20:30	Living Room	Living Room	Living Room	Bathroom #1	Living Room
20:40	Living Room	Living Room	Living Room	Living Room	Living Room
20:50	Living Room	Living Room	Living Room	Living Room	Bathroom #2
21:00	Kitchen	Bedroom #2	Living Room	Living Room	Bedroom #2
21:10	Living Room	Bedroom #2	Living Room	Living Room	Bedroom #2
21:20	Living Room	Bedroom #2	Bathroom #1	Living Room	Bedroom #2
22:40	Living Room	Living Room	Living Room	Bathroom #2	Bedroom #2
22:50	Bath 1	Master Bathroom	Bathroom #2	Bedroom #3	Bedroom #2
23:00	Living Room	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #2
23:40	Living Room	Master Bath	Bedroom #3	Bedroom #3	Bedroom #2
23:50	Master Bathroom	Master Bedroom	Bedroom #3	Bedroom #3	Bedroom #2

Appendix C: Intervention Results – Contaminant Concentrations

Table C1. Boston Carbon Monoxide

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	1.1	3.1	40	1.1	2.3	13	1.1	2.6	12
		Winter	1.1	3.0	29	1.1	3.9	12	1.1	3.0	11
		Spring	1.1	3.7	44	1.1	1.9	7.9	1.1	2.9	12
		Summer	1.1	4.5	45	1.1	2.8	17	1.1	2.7	12
1	Repair Faulty Stove	Fall	1.1	1.8	3.9	1.1	1.7	3.5	1.1	1.8	3.2
		Winter	1.1	2.0	3.9	1.1	3.4	11	1.1	2.4	5.1
		Spring	1.1	1.8	3.9	1.1	1.7	3.3	1.1	1.8	3.1
		Summer	1.1	1.8	4.3	1.1	1.8	3.3	1.1	1.8	3.0
2	Exhaust Fan	Fall	1.1	2.6	19	1.1	1.9	7.3	1.1	2.0	5.8
		Winter	1.1	2.6	19	1.1	3.6	11	1.1	2.6	5.8
		Spring	1.1	2.8	19	1.1	1.8	4.4	1.1	2.0	5.4
		Summer	1.1	3.1	19	1.1	2.0	6.2	1.1	2.1	5.1
3	Mechanical Ventilation	Fall	1.1	2.8	32	1.1	2.1	12	1.1	2.3	12
		Winter	1.1	2.8	25	1.1	3.6	11	1.1	2.7	12
		Spring	1.1	3.2	34	1.1	1.9	6.6	1.1	2.5	14
		Summer	1.1	3.9	43	1.1	2.6	15	1.1	2.4	14
4	Removal of Space Heater	Winter	1.1	2.8	29	1.1	2.2	12	1.1	2.3	11
5	Gas Oven for Heat	Winter	1.1	3.9	29	1.1	4.3	15	1.1	3.5	11
6	Air Conditioner	Summer	1.1	4.0	44	1.1	2.8	15	1.1	2.9	11
Neg. Impact	Tightening	Fall	1.2	5.4	59	1.2	3.7	14	1.3	4.2	14
		Winter	1.5	5.9	50	1.5	7.8	26	1.5	5.8	13
		Spring	1.2	7.5	63	1.1	2.5	9.0	1.3	5.2	14
		Summer	1.2	10	64	1.2	4.9	20	1.7	4.8	14

Table C2. Miami Carbon Monoxide

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	1.2	4.7	51	1.2	2.5	8.0	1.2	2.7	9.7
		Winter	1.1	5.5	56	1.1	2.2	11	1.1	3.3	13
		Spring	1.1	4.1	49	1.1	2.3	13	1.1	2.6	9.0
		Summer	1.3	4.5	51	1.2	2.4	9.2	1.3	2.9	10
1	Repair Faulty Stove	Fall	1.2	1.8	3.8	1.1	1.8	3.0	1.2	1.8	2.8
		Winter	1.1	1.8	4.3	1.1	1.7	3.3	1.1	1.8	2.9
		Spring	1.1	1.8	4.1	1.1	1.8	3.3	1.1	1.8	3.0
		Summer	1.2	1.8	4.1	1.2	1.8	3.2	1.2	1.8	2.9
2	Exhaust Fan	Fall	1.2	3.1	20	1.1	2.1	4.5	1.2	2.2	5.0
		Winter	1.1	3.3	19	1.1	1.9	3.9	1.1	2.2	5.2
		Spring	1.1	2.8	19	1.1	2.0	5.0	1.1	2.1	4.8
		Summer	1.2	3.0	19	1.2	2.0	4.7	1.2	2.3	5.1
3	Mechanical Ventilation	Fall	1.1	3.9	50	1.1	2.0	5.4	1.1	2.0	5.6
		Winter	1.1	3.9	54	1.1	2.1	9.3	1.1	2.4	8.6
		Spring	1.1	3.6	49	1.1	2.0	11	1.1	2.0	5.6
		Summer	1.1	3.8	51	1.1	2.0	5.9	1.1	2.1	7.0
4	Gas Oven for Heat	Winter	1.1	8.0	56	1.1	2.7	11	1.1	4.6	16
Neg. Impact	Tightening	Fall	3.2	9.0	67	2.6	5.3	12	3.1	5.7	14
		Winter	1.2	12	71	1.3	3.1	11	1.6	6.1	15
		Spring	1.9	7.6	65	1.5	4.3	14	1.9	5.0	13
		Summer	2.9	8.5	66	2.4	5.0	13	2.7	5.8	15

Table C3. Seattle Carbon Monoxide

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	1.1	3.1	35	1.1	2.3	13	1.1	2.6	11
		Winter	1.1	3.1	27	1.1	4.2	12	1.1	3.3	11
		Spring	1.1	4.0	50	1.1	2.9	15	1.1	2.3	12
		Summer	1.1	4.8	56	1.1	3.2	15	1.1	2.8	12
1	Repair Faulty Stove	Fall	1.1	1.8	3.9	1.1	1.7	3.3	1.1	1.8	3.2
		Winter	1.1	2.0	3.8	1.1	3.6	11	1.1	2.5	5.5
		Spring	1.1	1.8	4.3	1.1	1.7	3.4	1.1	1.7	2.9
		Summer	1.1	1.8	4.5	1.1	1.7	3.3	1.1	1.7	2.9
2	Exhaust Fan	Fall	1.1	2.6	20	1.1	1.9	5.7	1.1	2.0	5.7
		Winter	1.1	2.7	19	1.1	3.8	11	1.1	2.8	5.8
		Spring	1.1	2.9	19	1.1	2.0	7.4	1.1	1.9	4.6
		Summer	1.1	3.1	19	1.1	2.1	5.6	1.1	2.1	4.8
3	Mechanical Ventilation	Fall	1.1	2.8	28	1.1	2.1	11	1.1	2.3	12
		Winter	1.1	2.9	24	1.1	3.8	11	1.1	2.9	12
		Spring	1.1	3.6	53	1.1	2.6	14	1.1	2.1	14
		Summer	1.1	3.8	46	1.1	2.5	12	1.1	2.3	14
4	Removal of Space Heater	Winter	1.1	2.9	27	1.1	2.3	12	1.1	2.5	11
5	Gas Oven for Heat	Winter	1.1	4.1	27	1.1	4.6	15	1.1	3.9	11
6	Air Conditioner	Summer	1.1	4.2	54	1.1	3.1	13	1.1	3.1	12
Neg. Impact	Tightening	Fall	1.4	5.4	55	1.3	3.6	14	1.4	4.2	13
		Winter	1.7	6.6	49	1.7	8.6	26	2.0	6.8	14
		Spring	1.1	8.1	69	1.1	4.7	18	1.3	3.7	14
		Summer	1.2	10	73	1.2	5.1	17	1.6	4.8	15

Table C4. Boston Carbon Dioxide

Rank	Intervention	Season	Living Room Conc. (mg/m^3)			Master Bedroom Conc. (mg/m^3)			Children Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	630	740	1100	630	850	1600	630	720	960
		Winter	630	720	1000	630	800	1200	630	680	850
		Spring	630	730	1300	630	930	1600	630	710	940
		Summer	630	810	1700	630	1000	2300	630	700	950
1	Mechanical Ventilation	Fall	630	720	1000	630	770	1000	630	690	860
		Winter	630	700	980	630	750	960	630	670	800
		Spring	630	720	1200	630	780	1000	630	680	850
		Summer	630	780	1600	630	810	1100	630	670	850
2	Exhaust Fan	Fall	630	730	1100	630	840	1600	630	700	880
		Winter	630	710	1000	630	790	1200	630	680	810
		Spring	630	730	1300	630	910	1600	630	690	850
		Summer	630	800	1600	630	980	2100	630	680	920
3	Air Conditioner	Summer	630	810	1500	630	920	1600	630	750	970
Neg. Impact	Tightening	Fall	640	980	1800	650	1200	2200	650	940	1400
		Winter	640	890	1600	640	1000	1800	640	840	1100
		Spring	630	950	2300	650	1500	3000	650	850	1300
		Summer	630	1200	3100	700	1800	4400	650	830	1300

Table C5. Miami Carbon Dioxide

Rank	Intervention	Season	Living Room Conc. (mg/m^3)			Master Bedroom Conc. (mg/m^3)			Children Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	630	930	1800	640	1100	2200	640	850	1200
		Winter	630	790	1700	630	1000	1900	630	730	1100
		Spring	630	850	1900	630	1000	2100	630	830	1200
		Summer	630	900	1600	640	1100	2400	640	870	1200
1	Mechanical Ventilation	Fall	630	820	1700	630	910	2000	630	690	810
		Winter	630	760	1500	630	840	1600	630	700	840
		Spring	630	780	1600	630	890	1800	630	700	830
		Summer	630	800	1500	630	910	2100	630	710	830
2	Exhaust Fan	Fall	630	900	1800	630	1000	2100	640	810	1200
		Winter	630	780	1700	630	1000	1900	630	710	990
		Spring	630	840	1900	630	980	2000	630	800	1100
		Summer	630	880	1600	640	1000	2000	640	840	1100
Neg. Impact	Tightening	Fall	760	1400	2700	810	1600	2800	850	1300	1800
		Winter	630	1100	2700	730	1800	4100	690	930	1500
		Spring	650	1300	2900	670	1500	3000	700	1200	1900
		Summer	710	1400	2400	770	1600	3000	820	1300	1700

Table C6. Seattle Carbon Dioxide

Rank	Intervention	Season	Living Room Conc. (mg/m^3)			Master Bedroom Conc. (mg/m^3)			Children Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	630	730	1100	630	840	1300	630	710	890
		Winter	630	730	1000	630	820	1200	630	700	870
		Spring	630	780	1700	630	930	1900	630	670	930
		Summer	630	810	1700	630	950	1600	630	690	1000
1	Mechanical Ventilation	Fall	630	710	1000	630	760	990	630	680	810
		Winter	630	710	1000	630	760	990	630	680	800
		Spring	630	770	1800	630	780	1100	630	650	820
		Summer	630	760	1400	630	800	1100	630	650	850
2	Exhaust Fan	Fall	630	720	1000	630	830	1400	630	700	840
		Winter	630	720	1000	630	810	1300	630	690	820
		Spring	630	760	1600	630	900	1700	630	660	880
		Summer	630	790	1600	630	930	1700	630	680	990
3	Air Conditioner	Summer	630	800	1500	630	890	1500	630	740	1000
Neg. Impact	Tightening	Fall	650	950	1600	650	1100	2000	660	930	1200
		Winter	640	930	1600	660	1100	1900	660	900	1200
		Spring	630	1100	3000	650	1500	3500	640	770	1200
		Summer	630	1100	2800	660	1600	3100	660	820	1400

Table C7. Boston H_2O

Rank	Intervention	Season	Kitchen Conc. (% RH)			Master Bathroom Conc. (% RH)			Child Bathroom Conc. (% RH)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	13	34	91	14	35	95	14	35	98
		Winter	6	20	67	5	19	83	5	19	92
		Spring	24	42	77	25	43	94	25	42	99
		Summer	32	54	90	28	48	95	27	47	97
1	Air Conditioner	Summer	24	45	71	18	32	64	18	34	69
2	Exhaust Fan	Fall	13	33	89	14	34	87	14	33	85
		Winter	6	19	67	5	18	64	5	17	67
		Spring	24	40	75	23	41	79	22	40	81
		Summer	32	53	87	27	47	78	27	45	80
3	Mechanical Ventilation	Fall	13	33	85	14	34	87	13	34	99
		Winter	6	19	65	5	17	65	5	18	93
		Spring	24	41	69	24	40	77	22	41	98
		Summer	32	53	82	28	47	76	28	47	98
Neg. Impact	Tightening	Fall	14	39	100	17	40	95	15	39	99
		Winter	8	25	81	8	23	87	8	23	97
		Spring	26	48	100	28	50	97	28	47	100
		Summer	37	61	100	34	53	96	31	50	99

Table C8. Miami H_2O

Rank	Intervention	Season	Kitchen Conc. (% RH)			Master Bathroom Conc. (% RH)			Child Bathroom Conc. (% RH)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	50	66	100	45	65	91	48	69	93
		Winter	29	57	100	26	50	95	25	49	99
		Spring	40	59	95	34	54	86	35	57	88
		Summer	51	66	93	39	55	73	41	57	77
1	Tightening	Fall	34	48	88	32	47	84	33	50	88
		Winter	31	64	100	30	54	97	27	51	100
		Spring	30	46	86	24	41	84	25	43	88
		Summer	34	48	80	27	39	67	28	42	70
Neg. Impact	Exhaust Fan	Fall	51	67	100	45	67	94	48	70	97
		Winter	28	55	100	24	48	84	24	47	84
		Spring	40	59	97	34	54	85	35	57	85
		Summer	52	67	94	39	56	75	41	58	77
Neg. Impact	Mechanical Ventilation	Fall	64	83	100	64	82	97	64	83	98
		Winter	28	56	99	24	48	92	24	48	99
		Spring	49	68	100	46	65	88	46	66	88
		Summer	73	81	100	61	70	79	61	70	81

Table C9. Seattle H_2O

Rank	Intervention	Season	Kitchen Conc. (% RH)			Master Bathroom Conc. (% RH)			Child Bathroom Conc. (% RH)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	15	39	72	16	39	91	15	39	97
		Winter	22	32	59	21	29	87	20	29	94
		Spring	32	45	91	34	45	97	32	44	99
		Summer	41	52	93	38	46	92	36	45	96
1	Air Conditioner	Summer	29	43	69	21	31	64	21	33	68
2	Exhaust Fan	Fall	15	38	72	16	38	80	15	38	82
		Winter	22	31	56	21	28	71	20	28	71
		Spring	32	44	87	32	43	81	31	42	83
		Summer	41	51	88	37	44	74	36	43	76
3	Mechanical Ventilation	Fall	15	38	70	16	38	78	15	39	98
		Winter	22	31	56	20	28	71	20	29	95
		Spring	32	44	87	32	43	80	31	43	99
		Summer	41	51	82	37	45	74	34	45	97
Neg. Impact	Tightening	Fall	18	44	89	21	44	94	19	44	99
		Winter	26	37	75	24	34	90	23	34	98
		Spring	35	51	100	36	51	98	33	48	99
		Summer	42	58	100	38	50	95	36	48	98

Table C10. Boston Nitrogen Dioxide

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.014	0.16	4.0	0.012	0.06	0.98	0.0066	0.071	0.76
		Winter	0.021	0.17	3.0	0.022	0.39	1.7	0.015	0.15	0.76
		Spring	0.015	0.22	4.3	0.017	0.04	0.45	0.0073	0.082	0.79
		Summer	0.015	0.26	4.4	0.013	0.07	1.1	0.0072	0.064	0.81
1	Repair Faulty Stove	Fall	0.014	0.05	0.63	0.012	0.03	0.19	0.0065	0.028	0.14
		Winter	0.020	0.07	0.49	0.021	0.36	1.7	0.014	0.110	0.54
		Spring	0.015	0.05	0.67	0.016	0.03	0.11	0.0072	0.027	0.15
		Summer	0.014	0.06	0.70	0.013	0.03	0.19	0.0072	0.025	0.14
2	Exhaust Fan	Fall	0.014	0.12	2.0	0.012	0.04	0.47	0.0065	0.039	0.30
		Winter	0.020	0.14	1.9	0.022	0.36	1.7	0.015	0.123	0.54
		Spring	0.015	0.14	2.0	0.017	0.03	0.16	0.0073	0.033	0.25
		Summer	0.014	0.15	2.0	0.013	0.03	0.27	0.0072	0.034	0.24
3	Removal of Space Heater	Winter	0.021	0.14	3.0	0.021	0.07	0.93	0.014	0.068	0.76
4	Gas Oven for Heat	Winter	0.021	0.26	3.0	0.022	0.43	2.0	0.015	0.19	0.90
5	Mechanical Ventilation	Fall	0.018	0.14	3.2	0.015	0.06	0.90	0.0098	0.067	0.87
		Winter	0.023	0.15	2.5	0.023	0.36	1.6	0.016	0.133	0.84
		Spring	0.018	0.18	3.4	0.019	0.04	0.35	0.0086	0.077	0.93
		Summer	0.018	0.23	4.2	0.015	0.07	0.98	0.0078	0.067	0.89
6	Air Conditioner	Summer	0.015	0.21	4.3	0.013	0.07	1.1	0.0088	0.070	0.77
Neg. Impact	Tightening	Fall	0.007	0.25	5.4	0.006	0.08	0.93	0.0032	0.080	0.75
		Winter	0.015	0.31	4.8	0.013	0.68	3.0	0.0073	0.22	0.91
		Spring	0.008	0.39	5.7	0.008	0.03	0.38	0.0018	0.086	0.57
		Summer	0.007	0.45	5.8	0.006	0.06	0.80	0.0015	0.069	0.54

Table C11. Miami Nitrogen Dioxide

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**	**Ave**	**Max**
0	Baseline	Fall	0.006	0.23	4.8	0.007	0.04	0.41	0.0041	0.048	0.54
		Winter	0.010	0.31	5.3	0.014	0.04	0.52	0.0050	0.080	0.81
		Spring	0.009	0.20	4.7	0.008	0.04	0.82	0.0044	0.048	0.53
		Summer	0.008	0.22	4.9	0.008	0.04	0.49	0.0060	0.060	0.66
1	Repair Faulty Stove	Fall	0.006	0.04	0.75	0.007	0.02	0.08	0.0041	0.019	0.10
		Winter	0.010	0.06	0.83	0.012	0.03	0.09	0.0048	0.024	0.14
		Spring	0.007	0.05	0.74	0.007	0.03	0.14	0.0043	0.020	0.10
		Summer	0.008	0.04	0.77	0.008	0.02	0.10	0.0044	0.021	0.12
2	Exhaust Fan	Fall	0.006	0.12	2.0	0.007	0.03	0.19	0.0041	0.031	0.23
		Winter	0.010	0.16	1.9	0.014	0.03	0.10	0.0049	0.035	0.24
		Spring	0.008	0.12	2.0	0.007	0.03	0.22	0.0043	0.032	0.23
		Summer	0.008	0.12	1.9	0.008	0.03	0.21	0.0051	0.036	0.26
3	Gas Oven for Heat	Winter	0.010	0.53	5.3	0.014	0.07	0.52	0.0057	0.14	0.82
4	Mechanical Ventilation	Fall	0.011	0.22	4.8	0.011	0.03	0.26	0.0082	0.036	0.26
		Winter	0.014	0.22	5.2	0.016	0.05	0.54	0.0101	0.060	0.54
		Spring	0.013	0.20	4.7	0.012	0.04	0.71	0.0082	0.036	0.26
		Summer	0.012	0.21	4.9	0.012	0.03	0.30	0.0089	0.046	0.43
Neg. Impact	Tightening	Fall	0.003	0.31	5.9	0.004	0.05	0.54	0.0025	0.068	0.65
		Winter	0.005	0.49	6.3	0.007	0.03	0.23	0.0014	0.075	0.48
		Spring	0.005	0.30	5.8	0.004	0.05	0.75	0.0025	0.067	0.64
		Summer	0.004	0.31	5.9	0.004	0.05	0.56	0.0033	0.075	0.67

Table C12. Seattle Nitrogen Dioxide

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.018	0.16	3.5	0.019	0.07	0.93	0.010	0.074	0.75
		Winter	0.022	0.18	2.8	0.022	0.42	1.7	0.012	0.17	0.74
		Spring	0.011	0.23	4.8	0.013	0.09	1.2	0.0072	0.047	0.61
		Summer	0.016	0.28	5.3	0.014	0.09	1.0	0.0081	0.064	0.55
1	Repair Faulty Stove	Fall	0.017	0.05	0.56	0.019	0.03	0.17	0.0097	0.028	0.14
		Winter	0.022	0.07	0.46	0.021	0.39	1.7	0.012	0.12	0.58
		Spring	0.009	0.06	0.75	0.013	0.03	0.21	0.0071	0.023	0.12
		Summer	0.016	0.06	0.83	0.009	0.03	0.18	0.0074	0.024	0.10
2	Exhaust Fan	Fall	0.017	0.12	2.0	0.019	0.04	0.29	0.0099	0.040	0.29
		Winter	0.022	0.14	1.9	0.022	0.39	1.7	0.012	0.14	0.59
		Spring	0.010	0.14	2.0	0.013	0.04	0.47	0.0074	0.026	0.18
		Summer	0.016	0.15	2.0	0.012	0.04	0.26	0.0076	0.034	0.19
3	Removal of Space Heater	Winter	0.020	0.15	2.8	0.021	0.07	0.88	0.012	0.074	0.74
4	Mechanical Ventilation	Fall	0.021	0.14	2.8	0.021	0.06	0.82	0.012	0.069	0.87
		Winter	0.024	0.16	2.5	0.023	0.39	1.6	0.014	0.15	0.85
		Spring	0.020	0.20	5.0	0.017	0.08	1.1	0.0087	0.046	0.95
		Summer	0.019	0.22	4.5	0.015	0.07	0.90	0.0094	0.064	0.89
5	Gas Oven for Heat	Winter	0.022	0.28	2.8	0.022	0.46	2.0	0.012	0.21	0.97
6	Air Conditioner	Summer	0.017	0.22	5.1	0.014	0.09	0.98	0.0095	0.076	0.74
Neg. Impact	Tightening	Fall	0.010	0.26	5.2	0.010	0.08	0.90	0.0045	0.082	0.77
		Winter	0.014	0.32	4.6	0.013	0.71	3.0	0.0065	0.24	0.94
		Spring	0.009	0.40	6.1	0.007	0.09	1.1	0.0016	0.038	0.41
		Summer	0.009	0.46	6.3	0.009	0.07	0.81	0.0022	0.061	0.38

Table C13. Boston Particle 1

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	34	57	290	35	53	98	24	47	83
		Winter	46	59	250	47	55	110	38	50	86
		Spring	40	64	380	45	55	78	30	49	94
		Summer	41	65	390	37	52	120	30	47	91
1	Tightening	Fall	20	49	310	21	40	84	13	34	69
		Winter	31	52	310	31	44	85	23	38	72
		Spring	27	70	420	29	43	62	13	36	79
		Summer	25	76	430	21	40	93	12	35	80
2	Exhaust Fan	Fall	34	54	210	35	51	84	24	44	71
		Winter	46	57	210	47	54	80	38	49	74
		Spring	40	57	270	45	53	60	29	43	60
		Summer	38	54	270	36	48	59	29	43	65
3	Filter	Fall	26	51	280	27	47	95	15	35	75
		Winter	35	54	250	37	50	100	26	40	77
4	Air Conditioner	Summer	35	54	290	34	48	94	30	43	82
Neg. Impact	Mechanical Ventilation	Fall	41	58	280	42	55	99	30	50	91
		Winter	48	60	240	49	57	100	40	52	92
		Spring	45	63	360	48	56	75	29	51	110
		Summer	44	65	390	41	54	110	30	51	110

Table C14. Miami Particle 1

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	23	47	320	25	41	77	18	36	75
		Winter	35	67	400	38	51	85	25	44	92
		Spring	25	53	320	26	48	78	20	39	81
		Summer	26	49	320	27	44	69	20	37	78
1	Tightening	Fall	13	41	330	15	29	63	11	25	64
		Winter	19	79	440	27	38	67	10	32	76
		Spring	15	44	330	14	35	67	12	28	69
		Summer	15	42	330	16	31	63	11	27	66
2	Filter	Fall	13	36	310	16	32	55	9	24	51
		Spring	15	43	310	17	41	63	11	25	49
		Summer	16	38	320	21	36	54	11	24	50
3	Exhaust Fan	Fall	23	39	200	25	39	61	17	35	65
		Winter	35	52	270	35	49	58	24	39	64
		Spring	24	46	210	26	46	66	19	37	70
		Summer	26	41	200	27	43	63	19	35	67
Neg. Impact	Mechanical Ventilation	Fall	35	57	330	36	48	72	30	46	68
		Winter	39	58	310	41	53	86	34	49	77
		Spring	37	59	330	36	52	78	31	48	70
		Summer	38	58	340	37	49	67	31	47	74

Table C15. Seattle Particle 1

Rank	Intervention	Season	Kitchen Conc. ($\#/cm^3$)			Living Room Conc. ($\#/cm^3$)			Bedrooms Conc. ($\#/cm^3$)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	42	57	270	45	54	98	33	47	83
		Winter	46	58	270	46	54	96	36	48	85
		Spring	33	66	390	38	55	130	26	46	83
		Summer	43	68	430	33	54	110	28	47	83
1	Tightening	Fall	28	49	310	29	42	81	19	34	69
		Winter	31	50	310	31	42	80	20	35	70
		Spring	25	74	430	25	44	110	11	33	72
		Summer	28	78	450	24	43	90	14	34	76
2	Exhaust Fan	Fall	42	54	220	45	52	79	32	44	72
		Winter	46	56	220	46	52	77	36	46	73
		Spring	33	57	280	35	49	74	27	44	64
		Summer	39	56	280	30	48	57	27	42	65
3	Filter	Fall	31	51	260	36	48	92	22	35	72
		Winter	35	52	260	37	48	86	25	36	72
4	Air Conditioner	Summer	33	55	290	28	50	93	27	43	77
Neg. Impact	Mechanical Ventilation	Fall	47	58	250	48	55	97	35	50	92
		Winter	49	59	250	49	56	96	39	51	92
		Spring	45	66	420	42	56	120	29	51	110
		Summer	46	66	410	37	55	110	31	51	110

Table C16. Boston Particle 2

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	1.6	4.5	64	1.7	3.4	14	1.0	3.1	11
		Winter	2.3	4.4	51	2.3	3.5	16	1.8	3.2	12
		Spring	2.0	6.2	86	2.3	3.3	13	1.4	3.7	13
		Summer	2.1	6.9	87	1.8	3.7	21	1.4	3.3	13
1	Exhaust Fan	Fall	1.6	3.8	43	1.7	2.9	11	1.0	2.5	8
		Winter	2.3	3.9	40	2.3	3.1	11	1.8	2.8	9
		Spring	2.0	4.4	58	2.3	3.0	12	1.3	2.3	5
		Summer	2.1	4.3	58	1.8	2.6	12	1.4	2.4	5
2	Filter	Fall	1.2	4.0	64	1.3	2.9	14	0.6	2.1	10
		Winter	1.6	4.0	51	1.8	3.1	15	1.1	2.4	11
3	Air Conditioner	Summer	1.8	4.9	64	1.6	3.3	15	1.4	3.0	11
4	Mechanical Ventilation	Fall	2.0	4.4	60	2.0	3.4	14	1.3	3.2	13
		Winter	2.5	4.3	48	2.5	3.5	15	1.9	3.3	13
		Spring	2.3	5.6	79	2.5	3.3	12	1.5	3.6	17
		Summer	2.4	6.3	86	2.1	3.7	18	1.5	3.5	17
Neg. Impact	Tightening	Fall	0.9	5.3	72	0.9	3.1	15	0.5	2.7	10
		Winter	1.5	5.2	67	1.5	3.3	15	1.0	2.8	10
		Spring	1.4	10	98	1.4	2.8	14	0.5	3.6	12
		Summer	1.2	12	99	0.9	3.4	17	0.5	3.1	12

Table C17. Miami Particle 2

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.94	5.3	73	1.1	2.6	14	0.68	2.4	10
		Winter	1.7	7.7	91	2.0	3.2	13	1.1	3.5	14
		Spring	1.1	5.1	71	1.1	2.9	13	0.78	2.5	10
		Summer	1.1	5.2	74	1.2	2.7	12	0.79	2.6	11
1	Exhaust Fan	Fall	0.94	3.1	43	1.1	2.2	12	0.69	1.9	7
		Winter	1.7	4.2	57	1.8	2.7	13	1.0	2.2	5
		Spring	1.0	3.4	43	1.1	2.6	13	0.78	2.1	8
		Summer	1.1	3.2	43	1.2	2.4	12	0.77	2.0	8
2	Filter	Fall	0.60	4.4	73	0.80	2.0	13	0.34	1.4	5
		Spring	0.62	4.4	71	0.79	2.5	13	0.40	1.4	5
		Summer	0.73	4.3	74	0.96	2.1	12	0.43	1.5	7
3	Mechanical Ventilation	Fall	1.7	5.6	74	1.7	2.8	13	1.4	2.7	7
		Winter	1.9	5.1	68	2.1	3.3	13	1.6	3.1	10
		Spring	1.8	5.3	71	1.7	3.1	13	1.4	2.7	7
		Summer	1.8	5.4	75	1.8	2.9	12	1.4	2.8	8
Neg. Impact	Tightening	Fall	0.50	6.1	77	0.62	2.5	15	0.39	2.2	10
		Winter	0.85	13	100	1.3	2.6	14	0.40	3.2	12
		Spring	0.66	6.0	76	0.59	2.6	15	0.43	2.3	10
		Summer	0.60	6.0	77	0.67	2.5	14	0.42	2.4	10

Table C18. Seattle Particle 2

Rank	Intervention	Season	Kitchen Conc. ($\#/cm^3$)			Living Room Conc. ($\#/cm^3$)			Bedrooms Conc. ($\#/cm^3$)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	2.1	4.5	56	2.3	3.5	14	1.5	3.1	11
		Winter	2.3	4.4	56	2.4	3.5	14	1.7	3.2	12
		Spring	1.6	6.5	90	2.0	4.2	21	1.1	3.0	11
		Summer	2.2	7.2	98	1.8	4.1	18	1.4	3.4	11
1	Exhaust Fan	Fall	2.1	3.8	43	2.3	3.0	12	1.4	2.5	9
		Winter	2.3	3.9	44	2.3	3.0	12	1.7	2.6	9
		Spring	1.6	4.4	58	1.8	2.8	12	1.2	2.3	4
		Summer	2.2	4.4	59	1.5	2.7	12	1.3	2.4	5
2	Filter	Fall	1.5	4.0	56	1.7	3.0	14	0.9	2.2	10
		Winter	1.8	4.0	56	1.8	3.0	12	1.1	2.2	10
3	Air Conditioner	Summer	1.7	4.9	62	1.3	3.5	14	1.3	3.1	11
4	Mechanical Ventilation	Fall	2.4	4.4	53	2.4	3.5	14	1.6	3.2	13
		Winter	2.5	4.3	52	2.5	3.5	13	1.8	3.2	13
		Spring	2.4	6.1	95	2.2	4.0	20	1.3	3.1	17
		Summer	2.5	6.2	91	1.9	3.7	17	1.5	3.5	17
Neg. Impact	Tightening	Fall	1.3	5.3	69	1.3	3.1	16	0.8	2.7	10
		Winter	1.4	5.2	70	1.5	3.2	16	0.8	2.8	10
		Spring	1.4	10	100	1.1	4.1	20	0.4	2.6	10
		Summer	1.3	12	110	1.6	3.8	19	0.6	3.2	9

Table C19. Boston Particle 3

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.12	0.31	3.1	0.12	0.28	7.2	0.05	0.20	0.88
		Winter	0.18	0.32	2.6	0.19	0.30	7.1	0.12	0.23	0.89
		Spring	0.14	0.38	4.2	0.17	0.31	7.8	0.07	0.22	1.0
		Summer	0.15	0.40	4.2	0.12	0.30	8.2	0.08	0.21	0.83
1	Tightening	Fall	0.06	0.27	3.5	0.05	0.22	8.7	0.02	0.13	0.85
		Winter	0.09	0.28	3.3	0.09	0.24	8.7	0.05	0.15	0.87
		Spring	0.06	0.44	4.6	0.08	0.26	8.9	0.02	0.15	0.75
		Summer	0.07	0.49	4.7	0.05	0.25	9.2	0.02	0.15	0.54
2	Exhaust Fan	Fall	0.12	0.28	2.2	0.12	0.27	7.2	0.05	0.18	0.86
		Winter	0.18	0.30	2.1	0.19	0.29	7.1	0.12	0.21	0.88
		Spring	0.14	0.30	2.9	0.17	0.30	7.7	0.07	0.18	0.92
		Summer	0.15	0.30	2.9	0.11	0.27	8.2	0.08	0.18	0.63
3	Filter	Fall	0.09	0.28	3.1	0.10	0.26	7.2	0.03	0.14	0.56
		Winter	0.13	0.29	2.6	0.15	0.27	7.1	0.07	0.17	0.62
4	Air Conditioner	Summer	0.12	0.30	3.1	0.10	0.27	8.2	0.07	0.18	0.89
Neg. Impact	Mechanical Ventilation	Fall	0.16	0.32	3.0	0.15	0.30	6.9	0.08	0.22	0.99
		Winter	0.20	0.33	2.5	0.20	0.31	6.9	0.13	0.25	1.0
		Spring	0.18	0.37	3.9	0.20	0.32	7.5	0.08	0.25	1.2
		Summer	0.19	0.40	4.2	0.14	0.32	8.0	0.08	0.25	1.2

Table C20. Miami Particle 3

Rank	Intervention	Season	Kitchen Conc. (#/cm³) Min	Ave	Max	Living Room Conc. (#/cm³) Min	Ave	Max	Bedrooms Conc. (#/cm³) Min	Ave	Max
0	Baseline	Fall	0.05	0.26	3.5	0.07	0.22	8.6	0.03	0.13	0.67
		Winter	0.11	0.42	4.4	0.12	0.29	8.6	0.05	0.20	1.2
		Spring	0.06	0.30	3.4	0.07	0.27	8.8	0.04	0.15	0.77
		Summer	0.07	0.28	3.5	0.08	0.23	8.1	0.03	0.14	0.60
1	Exhaust Fan	Fall	0.05	0.19	2.2	0.07	0.21	8.5	0.03	0.13	0.65
		Winter	0.11	0.29	2.9	0.11	0.28	8.6	0.05	0.16	1.1
		Spring	0.06	0.23	2.4	0.07	0.26	8.8	0.04	0.14	0.75
		Summer	0.07	0.20	2.2	0.08	0.22	8.1	0.03	0.13	0.55
2	Filter	Fall	0.03	0.22	3.5	0.04	0.19	8.5	0.01	0.08	0.29
		Spring	0.04	0.25	3.4	0.05	0.24	8.8	0.02	0.09	0.31
		Summer	0.04	0.23	3.5	0.06	0.20	8.1	0.02	0.09	0.35
3	Tightening	Fall	0.02	0.26	3.7	0.04	0.18	9.3	0.01	0.10	0.77
		Winter	0.05	0.51	4.7	0.06	0.24	9.3	0.01	0.13	0.76
		Spring	0.02	0.27	3.6	0.03	0.21	9.4	0.02	0.10	0.79
		Summer	0.03	0.26	3.7	0.04	0.19	9.1	0.01	0.10	0.70
Neg. Impact	Mechanical Ventilation	Fall	0.11	0.32	3.6	0.11	0.26	8.6	0.08	0.20	0.49
		Winter	0.14	0.33	3.3	0.14	0.30	8.6	0.10	0.23	0.88
		Spring	0.12	0.34	3.5	0.12	0.30	8.9	0.08	0.21	0.54
		Summer	0.12	0.33	3.6	0.12	0.26	8.1	0.08	0.21	0.51

Table C21. Seattle Particle 3

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.16	0.30	2.8	0.18	0.30	7.6	0.09	0.20	0.88
		Winter	0.19	0.31	2.8	0.19	0.30	7.4	0.11	0.21	0.90
		Spring	0.10	0.39	4.3	0.13	0.32	8.1	0.06	0.20	0.58
		Summer	0.17	0.41	4.7	0.09	0.31	8.2	0.07	0.21	0.76
1	Exhaust Fan	Fall	0.16	0.28	2.2	0.18	0.28	7.5	0.09	0.18	0.84
		Winter	0.19	0.29	2.2	0.19	0.28	7.4	0.11	0.19	0.88
		Spring	0.09	0.31	2.9	0.11	0.27	8.1	0.07	0.18	0.58
		Summer	0.16	0.30	3.0	0.08	0.27	8.2	0.07	0.18	0.74
2	Tightening	Fall	0.08	0.27	3.3	0.09	0.23	8.9	0.03	0.12	0.85
		Winter	0.10	0.28	3.4	0.10	0.24	8.9	0.04	0.13	0.87
		Spring	0.04	0.46	4.7	0.06	0.27	9.3	0.02	0.13	0.39
		Summer	0.09	0.48	4.9	0.04	0.26	9.3	0.02	0.15	0.56
3	Filter	Fall	0.11	0.27	2.8	0.14	0.27	7.6	0.05	0.14	0.54
		Winter	0.14	0.28	2.8	0.15	0.27	7.4	0.07	0.15	0.85
4	Air Conditioner	Summer	0.11	0.30	3.0	0.07	0.27	8.2	0.07	0.18	0.81
Neg. Impact	Mechanical Ventilation	Fall	0.19	0.31	2.6	0.20	0.31	7.4	0.10	0.22	1.0
		Winter	0.21	0.32	2.6	0.21	0.31	7.2	0.13	0.23	1.2
		Spring	0.17	0.39	4.6	0.16	0.32	8.0	0.08	0.24	1.1
		Summer	0.20	0.39	4.4	0.12	0.32	7.9	0.09	0.25	1.2

Table C22. Boston Particle 4

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.019	0.051	0.55	0.021	0.088	8.9	0.0067	0.037	0.82
		Winter	0.036	0.059	0.52	0.040	0.089	8.8	0.0196	0.046	0.84
		Spring	0.023	0.047	0.42	0.027	0.11	9.5	0.0083	0.039	0.75
		Summer	0.025	0.054	1.9	0.016	0.11	10	0.0089	0.038	0.39
1	Tightening	Fall	0.007	0.028	0.63	0.008	0.087	11	0.0017	0.020	0.78
		Winter	0.015	0.033	0.62	0.016	0.086	11	0.0053	0.025	0.80
		Spring	0.007	0.023	0.25	0.010	0.11	11	0.0011	0.017	0.36
		Summer	0.008	0.029	1.0	0.004	0.11	11	0.0012	0.022	0.16
2	Filter	Fall	0.013	0.046	0.23	0.019	0.084	8.9	0.0046	0.028	0.46
		Winter	0.026	0.054	0.22	0.033	0.085	8.8	0.0133	0.037	0.51
3	Air Conditioner	Summer	0.023	0.046	1.4	0.014	0.093	10	0.0093	0.034	0.83
Neg. Impact	Exhaust Fan	Fall	0.022	0.052	0.55	0.021	0.089	8.9	0.0070	0.038	0.82
		Winter	0.037	0.060	0.52	0.040	0.090	8.8	0.0196	0.047	0.84
		Spring	0.024	0.049	0.42	0.030	0.11	9.5	0.0084	0.040	0.75
		Summer	0.027	0.055	1.9	0.016	0.11	10	0.0090	0.039	0.39
Neg. Impact	Mechanical Ventilation	Fall	0.031	0.057	0.55	0.029	0.092	8.6	0.0087	0.046	0.93
		Winter	0.044	0.064	0.52	0.045	0.094	8.5	0.0233	0.053	0.95
		Spring	0.035	0.054	0.26	0.034	0.11	9.2	0.0120	0.049	1.0
		Summer	0.035	0.063	2.0	0.023	0.11	9.9	0.0104	0.050	0.90

Table C23. Miami Particle 4

Rank	Intervention	Season	Kitchen Conc. ($\#/cm^3$)			Living Room Conc. ($\#/cm^3$)			Bedrooms Conc. ($\#/cm^3$)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.007	0.029	2.0	0.010	0.086	11	0.0025	0.024	0.61
		Winter	0.015	0.049	2.1	0.016	0.11	11	0.0042	0.033	0.90
		Spring	0.009	0.046	2.3	0.011	0.10	11	0.0030	0.028	0.72
		Summer	0.010	0.037	2.1	0.012	0.084	10	0.0038	0.025	0.48
1	Tightening	Fall	0.002	0.018	1.2	0.004	0.090	11	0.0010	0.016	0.73
		Winter	0.005	0.028	1.3	0.005	0.11	11	0.0009	0.016	0.36
		Spring	0.003	0.025	1.4	0.004	0.097	12	0.0010	0.017	0.75
		Summer	0.003	0.022	1.3	0.005	0.088	11	0.0012	0.016	0.65
2	Filter	Fall	0.004	0.023	2.0	0.008	0.082	11	0.0014	0.017	0.23
		Spring	0.006	0.039	2.3	0.009	0.097	11	0.0017	0.017	0.27
		Summer	0.006	0.031	2.1	0.009	0.081	10	0.0024	0.017	0.23
Neg. Impact	Exhaust Fan	Fall	0.007	0.032	2.0	0.010	0.088	11	0.0026	0.027	0.62
		Winter	0.018	0.050	2.1	0.016	0.11	11	0.0063	0.035	0.90
		Spring	0.009	0.048	2.3	0.011	0.10	11	0.0039	0.029	0.72
		Summer	0.012	0.039	2.1	0.012	0.086	10	0.0038	0.027	0.48
Neg. Impact	Mechanical Ventilation	Fall	0.017	0.044	2.0	0.018	0.096	11	0.011	0.044	0.34
		Winter	0.023	0.053	1.8	0.022	0.11	11	0.013	0.046	0.67
		Spring	0.019	0.058	2.3	0.018	0.11	11	0.011	0.045	0.40
		Summer	0.020	0.051	2.1	0.019	0.094	10	0.011	0.045	0.29

Table C24. Seattle Particle 4

Rank	Intervention	Season	Kitchen Conc. (#/cm^3) Min	Kitchen Conc. (#/cm^3) Ave	Kitchen Conc. (#/cm^3) Max	Living Room Conc. (#/cm^3) Min	Living Room Conc. (#/cm^3) Ave	Living Room Conc. (#/cm^3) Max	Bedrooms Conc. (#/cm^3) Min	Bedrooms Conc. (#/cm^3) Ave	Bedrooms Conc. (#/cm^3) Max
0	Baseline	Fall	0.032	0.049	0.57	0.037	0.096	9.3	0.013	0.037	0.81
		Winter	0.038	0.054	0.55	0.038	0.095	9.2	0.017	0.041	0.84
		Spring	0.013	0.048	0.07	0.010	0.097	9.9	0.0093	0.038	0.42
		Summer	0.028	0.044	0.06	0.010	0.103	10	0.0079	0.039	0.57
1	Tightening	Fall	0.013	0.026	0.64	0.016	0.093	11	0.0029	0.019	0.79
		Winter	0.018	0.029	0.64	0.016	0.093	11	0.0047	0.022	0.80
		Spring	0.003	0.024	0.04	0.003	0.11	11	0.0015	0.020	0.13
		Summer	0.012	0.020	0.03	0.002	0.11	11	0.0015	0.021	0.20
2	Filter	Fall	0.023	0.044	0.23	0.029	0.091	9.3	0.0086	0.027	0.44
		Winter	0.030	0.049	0.22	0.031	0.090	9.2	0.012	0.031	0.75
3	Air Conditioner	Summer	0.021	0.042	0.54	0.009	0.092	10	0.0085	0.033	0.74
Neg. Impact	Exhaust Fan	Fall	0.032	0.050	0.57	0.037	0.097	9.3	0.013	0.038	0.81
		Winter	0.039	0.055	0.55	0.039	0.096	9.2	0.017	0.042	0.84
		Spring	0.013	0.050	0.11	0.014	0.099	9.9	0.0093	0.040	0.42
		Summer	0.028	0.046	0.13	0.010	0.11	10	0.0089	0.040	0.57
Neg. Impact	Mechanical Ventilation	Fall	0.039	0.056	0.57	0.043	0.099	9.2	0.016	0.045	0.94
		Winter	0.045	0.060	0.55	0.044	0.097	8.9	0.022	0.049	1.1
		Spring	0.032	0.056	0.07	0.020	0.10	9.8	0.014	0.052	0.91
		Summer	0.039	0.052	0.06	0.019	0.11	9.8	0.015	0.050	1.1

Table C25. Boston Particle 5

Rank	Intervention	Season	Kitchen Conc. (#/cm³)			Living Room Conc. (#/cm³)			Bedrooms Conc. (#/cm³)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.0020	0.0075	0.43	0.0019	0.041	9.1	0.0003	0.0072	0.65
		Winter	0.0041	0.0088	0.41	0.0046	0.038	9.0	0.0015	0.0083	0.67
		Spring	0.0021	0.0067	0.29	0.0026	0.051	9.6	0.0004	0.0086	0.53
		Summer	0.0024	0.012	1.4	0.0012	0.055	10	0.0005	0.0063	0.22
1	Filter	Fall	0.0014	0.0065	0.17	0.0018	0.040	9.1	0.0003	0.0052	0.36
		Winter	0.0031	0.0078	0.16	0.0040	0.037	9.0	0.0011	0.0064	0.41
2	Air Conditioner	Summer	0.0023	0.010	1.2	0.0012	0.050	10	0.0005	0.0072	0.65
Neg. Impact	Exhaust Fan	Fall	0.0021	0.0077	0.43	0.0019	0.041	9.1	0.0004	0.0075	0.65
		Winter	0.0041	0.0089	0.41	0.0046	0.038	9.0	0.0015	0.0085	0.67
		Spring	0.0022	0.0071	0.29	0.0029	0.051	9.6	0.0004	0.0090	0.54
		Summer	0.0024	0.012	1.4	0.0012	0.055	10	0.0005	0.0064	0.22
Neg. Impact	Mechanical Ventilation	Fall	0.0036	0.0085	0.43	0.0029	0.041	8.8	0.0005	0.0089	0.75
		Winter	0.0052	0.0096	0.40	0.0054	0.039	8.7	0.0021	0.0094	0.76
		Spring	0.0036	0.0073	0.18	0.0034	0.049	9.4	0.0008	0.011	0.71
		Summer	0.0036	0.014	1.5	0.0019	0.054	10	0.0007	0.0086	0.54
Neg. Impact	Tightening	Fall	0.0006	0.0046	0.50	0.0006	0.052	11	0.0001	0.0055	0.62
		Winter	0.0014	0.0053	0.49	0.0015	0.050	11	0.0003	0.0060	0.63
		Spring	0.0006	0.0030	0.14	0.0009	0.064	11	0.0000	0.0040	0.18
		Summer	0.0007	0.0060	0.64	0.0002	0.067	11	0.0000	0.0038	0.05

Table C26. Miami Particle 5

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.0005	0.0098	1.6	0.0009	0.050	11	0.0001	0.0048	0.49
		Winter	0.0013	0.012	1.7	0.0013	0.055	11	0.0003	0.0072	0.60
		Spring	0.0007	0.014	1.7	0.0009	0.053	11	0.0001	0.0059	0.56
		Summer	0.0008	0.012	1.7	0.0010	0.046	10	0.0002	0.0053	0.38
1	Filter	Fall	0.0004	0.0084	1.6	0.0009	0.049	11	0.0001	0.0029	0.18
		Spring	0.0006	0.013	1.7	0.0008	0.052	11	0.0001	0.0032	0.21
		Summer	0.0006	0.011	1.7	0.0010	0.045	10	0.0002	0.0034	0.16
Neg. Impact	Exhaust Fan	Fall	0.0005	0.010	1.6	0.0009	0.051	11	0.0001	0.0051	0.49
		Winter	0.0016	0.012	1.7	0.0014	0.055	11	0.0004	0.0078	0.60
		Spring	0.0007	0.014	1.7	0.0009	0.053	11	0.0002	0.0060	0.56
		Summer	0.0009	0.012	1.7	0.0010	0.046	10	0.0002	0.0055	0.38
Neg. Impact	Mechanical Ventilation	Fall	0.0012	0.011	1.6	0.0014	0.051	11	0.0006	0.0070	0.25
		Winter	0.0020	0.011	1.6	0.0019	0.051	11	0.0008	0.0087	0.47
		Spring	0.0014	0.015	1.8	0.0014	0.053	11	0.0007	0.0074	0.29
		Summer	0.0014	0.013	1.7	0.0015	0.047	10	0.0007	0.0076	0.21
Neg. Impact	Tightening	Fall	0.0001	0.0065	0.76	0.0003	0.058	11	0.0000	0.0048	0.57
		Winter	0.0004	0.0069	0.89	0.0004	0.066	11	0.0000	0.0037	0.18
		Spring	0.0002	0.0081	0.83	0.0003	0.059	11	0.0000	0.0053	0.59
		Summer	0.0002	0.0077	0.82	0.0004	0.056	11	0.0001	0.0049	0.51

Table C27. Seattle Particle 5

Rank	Intervention	Season	Kitchen Conc. (#/cm^3)			Living Room Conc. (#/cm^3)			Bedrooms Conc. (#/cm^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.0035	0.0071	0.44	0.0042	0.045	9.5	0.0008	0.0079	0.64
		Winter	0.0047	0.0080	0.43	0.0045	0.044	9.4	0.0013	0.0092	0.67
		Spring	0.0009	0.0059	0.009	0.0007	0.050	10	0.0005	0.0065	0.24
		Summer	0.0030	0.0052	0.007	0.0007	0.054	10	0.0006	0.0078	0.34
1	Filter	Fall	0.0027	0.0060	0.17	0.0035	0.044	9.5	0.0007	0.0055	0.35
		Winter	0.0038	0.0068	0.17	0.0038	0.043	9.4	0.0011	0.0069	0.49
2	Air Conditioner	Summer	0.0024	0.0063	0.42	0.0007	0.049	10	0.0006	0.0074	0.59
Neg. Impact	Exhaust Fan	Fall	0.0035	0.0074	0.44	0.0042	0.045	9.5	0.0009	0.0080	0.64
		Winter	0.0048	0.0082	0.43	0.0046	0.044	9.4	0.0013	0.0094	0.67
		Spring	0.0009	0.0062	0.025	0.0009	0.050	10	0.0005	0.0067	0.24
		Summer	0.0030	0.0055	0.030	0.0007	0.054	10	0.0006	0.0081	0.34
Neg. Impact	Mechanical Ventilation	Fall	0.0048	0.0083	0.45	0.0050	0.045	9.4	0.0012	0.0095	0.75
		Winter	0.0059	0.0089	0.43	0.0053	0.043	9.1	0.0020	0.0104	0.85
		Spring	0.0033	0.0072	0.010	0.0018	0.050	9.9	0.0012	0.0085	0.62
		Summer	0.0045	0.0066	0.009	0.0017	0.052	9.9	0.0013	0.0088	0.72
Neg. Impact	Tightening	Fall	0.0012	0.0044	0.51	0.0014	0.055	11	0.0001	0.0056	0.62
		Winter	0.0018	0.0049	0.50	0.0017	0.055	11	0.0003	0.0064	0.63
		Spring	0.0002	0.0025	0.004	0.0002	0.064	11	0.0001	0.0034	0.05
		Summer	0.0011	0.0021	0.003	0.0001	0.067	11	0.0001	0.0045	0.09

Table C28. Boston Radon

Rank	Intervention	Season	Utility Conc. (pCi/L) Min	Ave	Max	Living Room Conc. (pCi/L) Min	Ave	Max	Bedrooms Conc. (pCi/L) Min	Ave	Max
0	Baseline	Fall	2.6	4.4	9.7	0.13	0.92	2.3	0.316	1.3	2.8
		Winter	2.5	3.5	6.4	0.028	0.69	1.3	0.036	0.9	1.5
		Spring	3.6	5.4	13	0.000	0.60	2.1	0.217	1.7	2.9
		Summer	5.5	9.2	17	0.000	1.2	3.4	0.014	1.5	3.4
1	Mechanical Ventilation	Fall	2.4	3.8	7.8	0.079	0.68	1.5	0.212	0.9	2.0
		Winter	2.3	3.2	6.3	0.020	0.55	1.0	0.040	0.7	1.1
		Spring	3.3	4.6	8.6	0.000	0.42	1.4	0.246	1.1	1.9
		Summer	4.8	7.8	16	0.000	0.86	2.6	0.006	1.0	2.5
2	Air Conditioner	Summer	4.6	7.1	12	0.070	1.3	2.6	0.108	1.7	2.8
3	Exhaust Fan	Fall	2.4	4.2	9.1	0.077	0.84	2.3	0.220	1.2	2.8
		Winter	2.5	3.4	6.4	0.026	0.63	1.3	0.039	0.8	1.5
		Spring	3.4	5.2	12	0.000	0.54	2.0	0.181	1.5	2.3
		Summer	5.1	9.0	17	0.000	1.1	3.3	0.011	1.4	3.4
Neg. Impact	Tightening	Fall	7.4	11	18	1.3	2.9	4.2	1.890	3.7	5.7
		Winter	7.3	9.0	13	0.59	2.2	3.2	0.544	2.7	3.7
		Spring	12	16	26	0	1.9	5.7	1.130	5.0	7.5
		Summer	18	28	46	0.001	3.8	9.9	0.378	4.9	9.5

Table C29. Miami Radon

Rank	Intervention	Season	Utility Room Conc. (pCi/L) Min	Ave	Max	Living Room Conc. (pCi/L) Min	Ave	Max	Bedrooms Conc. (pCi/L) Min	Ave	Max
0	Baseline	Fall	5.3	10	18	0.042	0.60	2.0	0.073	0.8	2.3
		Winter	4.3	11	20	0.000	0.75	2.1	0.027	2.2	4.7
		Spring	4.4	9.6	17	0.005	0.57	3.0	0.035	0.8	3.4
		Summer	4.9	9.6	18	0.023	0.55	3.0	0.076	0.8	3.5
1	Mechanical Ventilation	Fall	5.2	9.4	16	0.012	0.20	0.8	0.022	0.2	0.7
		Winter	3.4	7.3	12	0.017	0.58	1.2	0.129	0.9	1.8
		Spring	4.4	9.1	15	0.002	0.23	1.3	0.012	0.2	1.5
		Summer	4.7	9.0	16	0.005	0.19	1.2	0.022	0.3	1.2
2	Exhaust Fan	Fall	5.3	10	17	0.034	0.54	1.9	0.048	0.7	2.3
		Winter	3.9	10	19	0.000	0.65	2.0	0.021	1.8	4.3
		Spring	4.5	9.5	16	0.005	0.52	2.6	0.035	0.7	3.4
		Summer	4.9	9.6	17	0.021	0.50	2.7	0.044	0.7	3.3
Neg. Impact	Tightening	Fall	14	18	25	1.5	3.2	5.6	1.840	3.6	6.4
		Winter	15	30	48	0	2.4	5.9	0.740	6.6	11
		Spring	11	17	23	0.37	2.4	6.1	0.921	3.1	6.5
		Summer	13	18	25	0.96	2.8	6.4	1.560	3.5	7.1

Table C30. Seattle Radon

Rank	Intervention	Season	Utility Conc. (pCi/L)			Living Room Conc. (pCi/L)			Bedrooms Conc. (pCi/L)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	2.5	3.7	5.2	0.14	0.81	1.4	0.37	1.3	1.9
		Winter	2.2	3.5	4.5	0.39	0.83	1.4	0.41	1.2	1.6
		Spring	3.1	6.1	17	0	1.3	3.5	0.003	1.3	4.0
		Summer	4.2	7.9	20	0.004	1.3	2.8	0.23	1.7	4.1
1	Mechanical Ventilation	Fall	2.3	3.4	4.6	0.088	0.62	1.1	0.23	1.0	1.4
		Winter	2.1	3.2	4.0	0.28	0.62	1.1	0.27	0.9	1.2
		Spring	2.8	5.5	17	0.001	0.90	2.5	0	0.7	2.8
		Summer	3.8	6.7	19	0.002	0.78	1.5	0.11	1.0	3.1
2	Exhaust Fan	Fall	2.5	3.7	5.2	0.11	0.74	1.4	0.29	1.2	1.8
		Winter	2.2	3.4	4.3	0.086	0.75	1.2	0.35	1.1	1.5
		Spring	3.0	5.9	16	0	1.1	3.0	0.002	1.1	3.0
		Summer	3.9	7.6	18	0.004	1.1	2.4	0.15	1.5	3.7
3	Air Conditioner	Summer	3.6	6.3	14	0.20	1.4	2.8	0.75	1.8	3.3
Neg. Impact	Tightening	Fall	7.3	9.8	12	1.2	2.7	3.7	2.3	3.7	4.5
		Winter	6.9	9.3	11	1.6	2.7	3.8	2.2	3.5	4.3
		Spring	9.9	17.8	37	0.065	3.7	6.7	0.32	4.2	8.5
		Summer	14	22	42	0.43	3.6	5.7	1.9	5.5	9.1

Table C31. Boston VOC 1

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.14	0.17	0.28	0.14	0.17	0.26	0.17	0.22	0.35
		Winter	0.12	0.15	0.18	0.12	0.15	0.17	0.13	0.19	0.23
		Spring	0.15	0.18	0.25	0.12	0.15	0.22	0.18	0.25	0.34
		Summer	0.16	0.21	0.29	0.13	0.20	0.29	0.16	0.28	0.40
1	Mechanical Ventilation	Fall	0.13	0.16	0.22	0.13	0.15	0.21	0.15	0.20	0.31
		Winter	0.12	0.14	0.16	0.12	0.14	0.16	0.13	0.18	0.22
		Spring	0.14	0.16	0.20	0.12	0.14	0.20	0.16	0.24	0.36
		Summer	0.14	0.18	0.25	0.12	0.17	0.24	0.15	0.25	0.38
2	Exhaust Fan	Fall	0.13	0.17	0.28	0.13	0.16	0.26	0.16	0.22	0.35
		Winter	0.12	0.15	0.17	0.12	0.15	0.17	0.13	0.19	0.23
		Spring	0.14	0.17	0.24	0.12	0.15	0.21	0.17	0.24	0.34
		Summer	0.16	0.20	0.29	0.13	0.19	0.28	0.16	0.27	0.37
3	Air Conditioner	Summer	0.16	0.22	0.29	0.13	0.21	0.30	0.16	0.26	0.35
Neg. Impact	Tightening	Fall	0.23	0.33	0.53	0.23	0.31	0.46	0.30	0.41	0.61
		Winter	0.18	0.27	0.33	0.18	0.26	0.32	0.21	0.34	0.42
		Spring	0.27	0.34	0.51	0.17	0.26	0.41	0.35	0.53	0.75
		Summer	0.33	0.42	0.60	0.19	0.40	0.62	0.37	0.64	0.91

Table C32. Miami VOC 1

Rank	Intervention	Season	Kitchen Conc. (mg/m³)			Living Room Conc. (mg/m³)			Bedrooms Conc. (mg/m³)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.20	0.30	0.44	0.16	0.26	0.41	0.19	0.31	0.50
		Winter	0.15	0.23	0.34	0.13	0.19	0.30	0.20	0.31	0.45
		Spring	0.15	0.24	0.37	0.13	0.20	0.37	0.16	0.28	0.44
		Summer	0.18	0.28	0.41	0.14	0.24	0.38	0.19	0.31	0.46
1	Mechanical Ventilation	Fall	0.16	0.20	0.28	0.14	0.19	0.25	0.14	0.21	0.30
		Winter	0.14	0.19	0.25	0.13	0.17	0.23	0.14	0.21	0.28
		Spring	0.14	0.18	0.25	0.12	0.16	0.25	0.14	0.21	0.29
		Summer	0.15	0.20	0.26	0.13	0.18	0.25	0.14	0.22	0.30
2	Exhaust Fan	Fall	0.17	0.28	0.41	0.16	0.24	0.37	0.16	0.29	0.45
		Winter	0.14	0.22	0.31	0.13	0.18	0.29	0.19	0.31	0.43
		Spring	0.15	0.23	0.36	0.13	0.20	0.37	0.16	0.27	0.41
		Summer	0.17	0.26	0.38	0.14	0.22	0.35	0.17	0.29	0.44
Neg. Impact	Tightening	Fall	0.50	0.63	0.86	0.38	0.55	0.78	0.44	0.62	0.93
		Winter	0.28	0.47	0.67	0.19	0.35	0.56	0.44	0.72	0.94
		Spring	0.30	0.50	0.72	0.22	0.42	0.69	0.32	0.54	0.80
		Summer	0.44	0.59	0.78	0.32	0.51	0.70	0.42	0.61	0.85

Table C33. Seattle VOC 1

Rank	Intervention	Season	Kitchen Conc. (mg/m³)			Living Room Conc. (mg/m³)			Bedrooms Conc. (mg/m³)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.14	0.17	0.20	0.13	0.16	0.19	0.17	0.21	0.27
		Winter	0.14	0.16	0.18	0.14	0.16	0.18	0.17	0.21	0.25
		Spring	0.14	0.18	0.31	0.13	0.19	0.32	0.18	0.27	0.39
		Summer	0.16	0.20	0.30	0.14	0.20	0.36	0.20	0.29	0.43
1	Mechanical Ventilation	Fall	0.14	0.15	0.18	0.13	0.15	0.17	0.15	0.20	0.25
		Winter	0.13	0.15	0.17	0.13	0.15	0.17	0.15	0.19	0.23
		Spring	0.14	0.16	0.23	0.13	0.17	0.27	0.16	0.24	0.38
		Summer	0.15	0.17	0.24	0.14	0.17	0.28	0.17	0.25	0.34
2	Exhaust Fan	Fall	0.14	0.17	0.20	0.13	0.16	0.19	0.16	0.21	0.27
		Winter	0.14	0.16	0.18	0.13	0.16	0.18	0.17	0.21	0.25
		Spring	0.14	0.18	0.27	0.13	0.18	0.29	0.17	0.26	0.38
		Summer	0.15	0.19	0.29	0.14	0.19	0.34	0.19	0.28	0.39
3	Air Conditioner	Summer	0.17	0.21	0.32	0.14	0.21	0.36	0.19	0.26	0.39
Neg. Impact	Tightening	Fall	0.26	0.32	0.40	0.23	0.30	0.35	0.31	0.40	0.49
		Winter	0.24	0.30	0.34	0.25	0.29	0.35	0.31	0.39	0.46
		Spring	0.24	0.34	0.68	0.20	0.36	0.69	0.36	0.60	0.85
		Summer	0.29	0.38	0.57	0.24	0.38	0.68	0.43	0.65	0.88

Table C34. Boston VOC 2

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.10	0.19	2.3	0.10	0.14	1.5	0.10	0.18	4.4
		Winter	0.10	0.17	1.8	0.10	0.14	1.5	0.10	0.16	4.4
		Spring	0.10	0.22	2.2	0.10	0.13	1.4	0.10	0.20	4.6
		Summer	0.10	0.29	2.4	0.10	0.19	1.5	0.10	0.22	4.7
1	Mechanical Ventilation	Fall	0.10	0.17	2.1	0.10	0.13	1.4	0.10	0.16	4.3
		Winter	0.10	0.16	1.7	0.10	0.13	1.4	0.10	0.15	4.4
		Spring	0.10	0.20	2.1	0.10	0.12	1.4	0.10	0.17	4.4
		Summer	0.10	0.23	2.2	0.10	0.15	1.5	0.10	0.18	4.3
2	Exhaust Fan	Fall	0.10	0.19	2.3	0.10	0.14	1.5	0.10	0.18	4.4
		Winter	0.10	0.17	1.8	0.10	0.14	1.5	0.10	0.16	4.4
		Spring	0.10	0.22	2.2	0.10	0.13	1.4	0.10	0.20	4.6
		Summer	0.10	0.29	2.4	0.10	0.19	1.5	0.10	0.21	4.7
3	Air Conditioner	Summer	0.10	0.27	2.6	0.10	0.20	1.6	0.10	0.22	4.8
Neg. Impact	Tightening	Fall	0.10	0.36	2.8	0.10	0.26	2.0	0.10	0.33	5.4
		Winter	0.10	0.30	2.7	0.10	0.23	2.0	0.10	0.28	5.2
		Spring	0.10	0.47	2.7	0.10	0.18	1.7	0.10	0.39	5.4
		Summer	0.10	0.63	3.0	0.10	0.35	1.8	0.12	0.44	5.1

Table C35. Miami VOC 2

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.10	0.33	2.8	0.10	0.19	1.8	0.10	0.21	4.3
		Winter	0.10	0.30	2.5	0.10	0.14	1.3	0.10	0.24	4.6
		Spring	0.10	0.29	2.9	0.10	0.17	1.7	0.10	0.20	4.9
		Summer	0.10	0.30	2.6	0.10	0.16	1.6	0.10	0.22	5.0
1	Mechanical Ventilation	Fall	0.10	0.26	2.6	0.10	0.14	1.7	0.10	0.14	4.2
		Winter	0.10	0.23	2.5	0.10	0.13	1.4	0.10	0.16	4.6
		Spring	0.10	0.24	2.6	0.10	0.13	1.6	0.10	0.14	4.7
		Summer	0.10	0.24	2.6	0.10	0.13	1.5	0.10	0.15	4.8
2	Exhaust Fan	Fall	0.10	0.32	2.7	0.10	0.18	1.8	0.10	0.20	4.3
		Winter	0.10	0.31	2.5	0.10	0.14	1.3	0.10	0.24	4.6
		Spring	0.10	0.28	2.7	0.10	0.16	1.7	0.10	0.19	4.8
		Summer	0.10	0.29	2.6	0.10	0.16	1.6	0.10	0.21	4.9
Neg. Impact	Tightening	Fall	0.20	0.67	4.1	0.18	0.44	2.1	0.19	0.47	5.1
		Winter	0.10	0.71	3.1	0.10	0.22	1.6	0.11	0.50	5.2
		Spring	0.13	0.56	4.0	0.11	0.35	2.0	0.12	0.43	5.5
		Summer	0.17	0.61	3.8	0.14	0.37	2.0	0.16	0.47	5.7

Table C36. Seattle VOC 2

Rank	Intervention	Season	Kitchen Conc. (mg/m^3)			Living Room Conc. (mg/m^3)			Bedrooms Conc. (mg/m^3)		
			Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
0	Baseline	Fall	0.10	0.19	2.0	0.10	0.14	1.6	0.10	0.18	4.6
		Winter	0.10	0.18	2.0	0.10	0.14	1.6	0.10	0.17	4.5
		Spring	0.10	0.24	2.5	0.10	0.17	2.1	0.10	0.21	4.6
		Summer	0.10	0.26	2.4	0.10	0.19	2.0	0.10	0.22	4.6
1	Mechanical Ventilation	Fall	0.10	0.17	1.9	0.10	0.13	1.5	0.10	0.16	4.4
		Winter	0.10	0.17	1.8	0.10	0.13	1.5	0.10	0.16	4.4
		Spring	0.10	0.21	2.2	0.10	0.15	1.9	0.10	0.18	4.4
		Summer	0.10	0.21	2.1	0.10	0.15	1.8	0.10	0.17	4.4
2	Air Conditioner	Summer	0.10	0.25	2.4	0.10	0.19	1.9	0.10	0.22	4.6
3	Exhaust Fan	Fall	0.10	0.19	2.0	0.10	0.14	1.6	0.10	0.18	4.6
		Winter	0.10	0.18	2.0	0.10	0.14	1.6	0.10	0.17	4.5
		Spring	0.10	0.24	2.5	0.10	0.18	2.1	0.10	0.21	4.6
		Summer	0.10	0.26	2.4	0.10	0.19	2.0	0.10	0.22	4.6
Neg. Impact	Tightening	Fall	0.10	0.36	2.8	0.10	0.25	2.1	0.11	0.33	5.3
		Winter	0.10	0.34	2.8	0.10	0.25	2.0	0.10	0.31	5.3
		Spring	0.10	0.50	2.8	0.10	0.32	2.3	0.10	0.40	4.8
		Summer	0.10	0.60	3.0	0.10	0.34	2.3	0.10	0.45	5.1

APPENDIX D: Impact of Interventions on Occupant Exposure

This Appendix contains tables showing the impact of each intervention on the exposure of the model's father, mother, and 4-year old child to each contaminant. The impact of each intervention is calculated based on its reduction or increase in contaminant exposure relative to the baseline exposures. The results have been divided into 5 color classifications which are shown in Figure 1D. The color coding provides a relatively quick way to evaluate the impact of each intervention on occupant exposure.

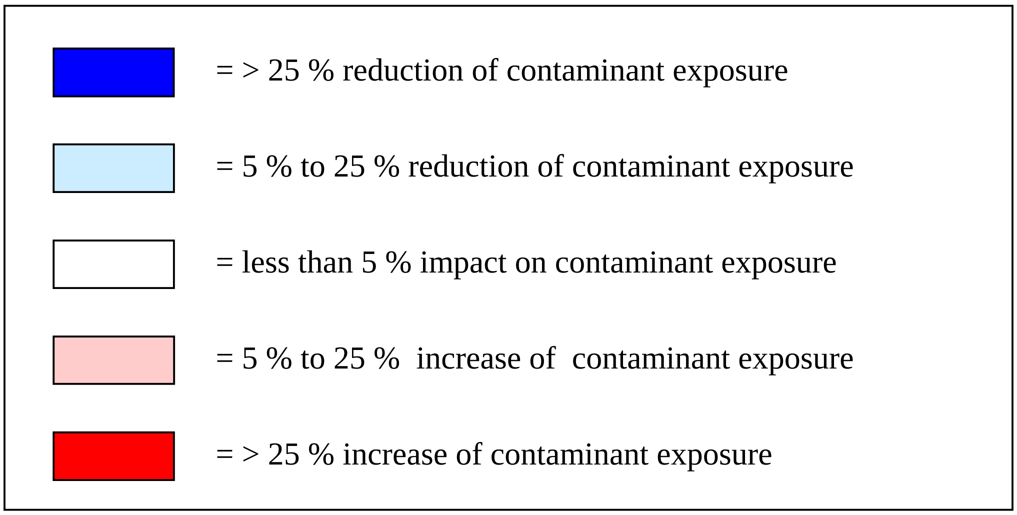

Figure 1D. Legend for Tables D

OCCUPANT #1: Father

Table D1. Exhaust Fan Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D2. Filter Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D3. Tightening Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D4. Mechanical Ventilation Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D5. Repair Faulty Stove Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D6. Restricting Use of Gas Oven for Heat in Winter Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D7. Removal of Winter Space Heater Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

OCCUPANT #2: Mother

Table D8. Exhaust Fan Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D9. Filter Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D10. Tightening Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D11. Mechanical Ventilation Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D12. Repair Faulty Stove Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D13. Restricting Use of Gas Oven for Heat in Winter Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D14. Removal of Winter Space Heater Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	**Fall**											
	Winter											
	Spring											
	Summer											
Seattle	**Fall**											
	Winter											
	Spring											
	Summer											

OCCUPANT #5: 4-year old child

Table D15. Exhaust Fan Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D16. Filter Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D17. Tightening Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D18. Mechanical Ventilation Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D19. Repair Faulty Stove Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D20. Restricting Use of Gas Oven for Heat in Winter Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Miami	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											

Table D21. Removal of Winter Space Heater Intervention

City	Season	CO	CO_2	NO_2	P1	P2	P3	P4	P5	Rn	VOC1	VOC2
Boston	Fall											
	Winter											
	Spring											
	Summer											
Seattle	Fall											
	Winter											
	Spring											
	Summer											