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Indoor Air Quality Impacts of Residential HVAC Systems Phase II.B Report: IAQ Control Retrofit Simulations and Analysis

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Abstract

The National Institute of Standards and Technology (NIST) performed a preliminary study of the potential for using central forced-air heating and cooling system modifications to control indoor air quality (IAQ) in residential buildings. The objective of this effort was to provide insight into the use of state-of-the-art IAQ models to evaluate such modifications, the potential of these modifications to mitigate residential IAQ problems, the pollutant sources they are most likely to impact, and their potential limitations. This study was not intended to determine definitively whether the IAQ control options studied are reliable and cost-effective. This report summarizes the results of Phase II.B of this project, which consisted of three main efforts: computer simulations of contaminant levels with IAQ control retrofits, evaluation of the effectiveness of the IAQ control retrofits, and development of recommendations for future research.

In Phase II.A of the project, NIST used the multizone airflow and pollutant transport program CONTAM93 to simulate the pollutant concentrations due to a variety of sources in eight buildings with typical HVAC systems under different weather conditions. In Phase II.B, the simulations were repeated after modifying the HVAC systems with three IAQ control technologies -- an electrostatic particulate filter, a heat recovery ventilator, and an outdoor air intake damper on the forced-air system return. The impact of these IAQ control technologies on indoor pollutant levels was evaluated by comparing average and peak pollutant concentrations for the modified cases to the concentrations determined for the baseline cases.

Simulation results indicate that the system modifications reduced pollutant concentrations in the houses for some cases. However, the heat recovery ventilator and outdoor air intake damper increased pollutant concentrations in certain situations involving a combination of weak indoor sources, high outdoor concentrations, and indoor pollutant removal mechanisms. In cases where the IAQ controls reduced pollutant concentrations, they led to larger relative reductions in the tight houses than in the houses with typical levels of airtightness, though the typical houses still had lower post-control concentrations. The controls had the largest impact on concentrations of a non-decaying pollutant from a constant source. Limited system run-time under mild weather conditions was identified as a limitation of IAQ controls that operate in conjunction with forced-air systems.

Another important objective of the project was to identify issues related to the use of multizone IAQ models and to identify areas for follow-up work. Recommendations for future research include: additional simulations for other buildings, pollutants, and IAQ control technologies; model validation; model sensitivity analysis; and development of a database of model inputs.

Key Words: air change rates, airflow modeling, building technology, computer simulation, filtration, heat recovery ventilation, indoor air quality, infiltration, modeling, outdoor air, residential buildings, ventilation

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Table of Contents

1 Introduction

Central forced-air heating and cooling systems can have both negative and positive impacts on residential indoor air quality (IAQ). Negative impacts can arise because these systems circulate large volumes of air throughout houses, spreading pollutants generated in one room to the rest of the house. Forced-air systems also can act as a source of indoor air pollution, for example, due to damp or dirty ductwork and filters. However, modifications to forced-air systems have the potential to improve indoor air quality (IAQ) through the addition of air cleaners or devices to introduce and distribute outdoor air in the house. Evaluating the impacts of HVAC systems, as well as the effectiveness of modifications to these systems would require extensive field testing. Alternatively, computer modeling may provide insight into the effectiveness without the time and effort required to perform field tests.

A literature review of both experimental and simulation studies on the IAQ impacts of residential HVAC systems and components was reported in the Phase I report of this project (Emmerich and Persily 1994). The literature review indicated that the interactions between buildings, HVAC systems, pollutant sources, and ambient conditions are significant; that whole building analysis is essential for studying these interactions; and that multizone airflow and pollutant transport models are appropriate tools for such an analysis. This review found that many residential IAQ studies employed simplified approaches to modeling buildings and their HVAC systems. For example, some studies have ignored the multizone nature of the problem (Hamlin and Cooper 1992, Novosel et al. 1988) and others have not rigorously modeled building airflow (Owen et al. 1992, Sparks et al. 1989). However, a few studies have employed a whole building modeling approach (Li 1993, Yuill et al. 1991).

In this effort, a multizone airflow and pollutant transport model was used to conduct a preliminary assessment of the potential for using central forced-air heating and cooling systems to control IAQ in residential buildings. The objective was to provide insight into the use of state-of-the-art IAQ models to evaluate such modifications, the potential of these modifications to mitigate residential IAQ problems, the pollutant sources they are most likely to impact, and their potential limitations. This effort was preliminary in that it was not intended to determine definitively whether the modifications are reliable and cost-effective. Another important objective was to identify key issues related to the use of multizone airflow and pollutant transport models to study IAQ and IAQ control in residential buildings.

This report consists of three main sections: Modeling Method, Results, and IAQ Modeling Issues and Follow-Up Activities. The first section summarizes the modeling of the houses with the program CONTAM93 (Walton 1994). This section includes a description of the program, a discussion of both building and pollutant related inputs to the program, and a description of the IAQ control technologies. More detailed modeling information is included in the Phase II.A report of this project (Emmerich and Persily 1995). The next section of this report presents the results of the simulations performed with and without the IAQ control retrofits. This section includes transient pollutant concentration results for selected cases and a summary of peak and average concentrations for all cases. The third section discusses issues related to the use of multizone IAQ models and identifies several important follow-up activities.

2 Modeling Method

The program CONTAM93 (Walton 1994) was used to simulate the pollutant levels due to a variety of sources in eight buildings under different weather conditions. These simulations were performed with "baseline" forced-air HVAC systems that were based on standard design approaches. The baseline HVAC systems were then modified with three IAQ control technologies including an electrostatic particulate filter, a heat recovery ventilator, and an outdoor air intake damper. Altogether, ninety-six simulations were performed to evaluate the performance of these controls when challenged by constant volatile organic compound (VOC) sources, burst (short-duration) VOC sources, scheduled combustion pollutant sources and elevated outdoor pollutant concentrations.

2.1 CONTAM93

CONTAM93 is a multizone airflow and pollutant transport model employing a graphic interface for data input and display. Multizone models take a macroscopic view of airflow and IAQ by calculating average pollutant concentrations in the different zones of a building as contaminants are transported through the building and its HVAC system. The multizone approach is implemented by assembling a network of elements describing the airflow paths between the zones of a building. The network nodes represent the zones that contain pollutant sources and sinks and are modeled at a uniform temperature and pollutant concentration. A number of other multizone models have been developed based on the same approach (Feustel and Dieris 1992).

2.2 Building-Related Factors

Calculating airflow rates and contaminant concentrations with CONTAM93, or any other multizone model, requires the following input: configuration and volume of the building zones, air leakage paths through the building envelope and interior walls, wind pressure profile on the building envelope, pollutant source strengths and temporal profiles, HVAC system flows, filter efficiencies, pollutant sink characteristics, pollutant decay or deposition rates, and ambient weather and pollutant concentrations. Some models eliminate the need for one or more of these inputs by using a simplified, though not necessarily technically sound, approach to specific mechanisms of airflow and pollutant transport. This section describes the building-related input data used in the CONTAM93 simulations.

The study included eight building models - a ranch and a two-story house, located in two sites (Miami and Minneapolis), with typical and low values of envelope air leakage. The houses are not based on real buildings but are intended to be representative of typical buildings. All rooms of the houses, even some closets, were modeled as separate zones. The ranch and two-story house floorplans and zone labels are shown in Figures 1 and 2, respectively. The houses all have attics, and the Minneapolis houses have basements (zone label BMT) not shown in the figures.

Simulations were performed under three sets of weather conditions (cold, mild, and hot) for each building. The weather conditions were chosen by selecting a cold, mild, and hot day for each location from Weather Year for Energy Calculation (WYEC) data (Crow 1983) and are specified in Tables 5 and 6 of the Phase II.A report. There were a total of 24 baseline simulation cases. Table 1 lists the baseline simulations by house type, location, airtightness and weather condition. Each simulation was performed for a one-day cycle that was repeated until concentrations converged to a specified tolerance.

Table 1 - Baseline Simulations

Simulation	House type	Location	Airtightness	Weather
SIM1FLC	ranch	Miami	typical	cold
SIM1FLM	ranch	Miami	typical	mild
SIM1FLH	ranch	Miami	typical	hot
SIM1FTC	ranch	Miami	tight	cold
SIM1FTM	ranch	Miami	tight	mild
SIM1FTH	ranch	Miami	tight	hot
SIM1MLC	ranch	Minneapolis	typical	cold
SIM1MLM	ranch	Minneapolis	typical	mild
SIM1MLH	ranch	Minneapolis	typical	hot
SIM1MTC	ranch	Minneapolis	tight	cold
SIM1MTM	ranch	Minneapolis	tight	mild
SIM1MTH	ranch	Minneapolis	tight	hot
SIM2FLC	two-story	Miami	typical	cold
SIM2FLM	two-story	Miami	typical	mild
SIM2FLH	two-story	Miami	typical	hot
SIM2FTC	two-story	Miami	tight	cold
SIM2FTM	two-story	Miami	tight	mild
SIM2FTH	two-story	Miami	tight	hot
SIM2MLC	two-story	Minneapolis	typical	cold
SIM2MLM	two-story	Minneapolis	typical	mild
SIM2MLH	two-story	Minneapolis	typical	hot
SIM2MTC	two-story	Minneapolis	tight	cold
SIM2MTM	two-story	Minneapolis	tight	mild
SIM2MTH	two-story	Minneapolis	tight	hot

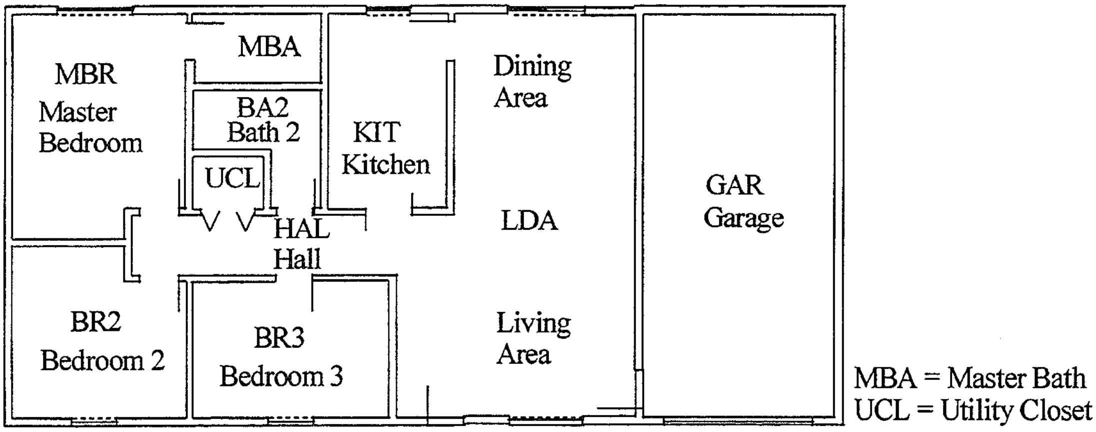
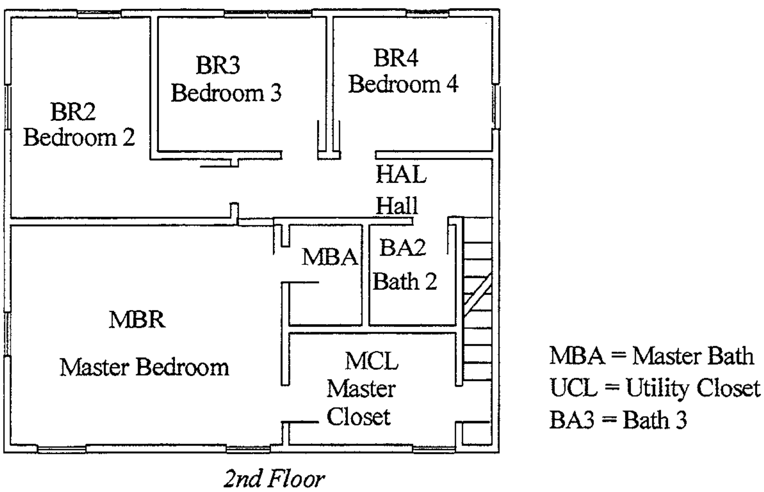


Figure 1 - Ranch House Foorplan and Zones



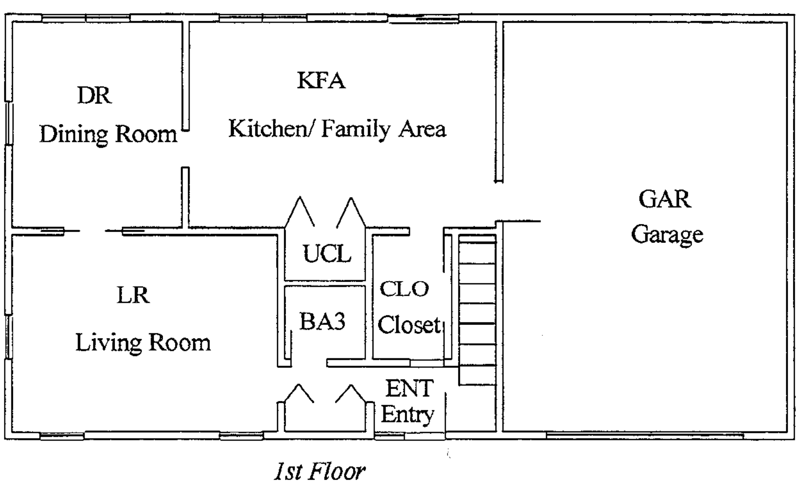


Figure 2 - Two-story House Floorplan and Zones

The air leakage of the house envelopes and interior partitions was modeled by including elements for leakage paths typically found in residential buildings. Table 2 of the Phase II.A report shows all of the leakage paths between the zones of the Miami ranch house. Table 3 of the Phase II.A report lists the values used for those leakage paths. The leakage values were input as effective leakage areas for a reference pressure difference of 4 Pa. Most of the values used for the leakage paths are from Table 23-3 of the ASHRAE Handbook of Fundamentals (ASHRAE 1993).

The infiltration through a building's envelope also depends on the static pressure distribution created by the wind on the building's exterior surfaces. The relationship between wind and surface pressures is characterized by wind pressure coefficients which depend on the wind direction, the building shape, the position on the building surface, and the presence of shielding near the building. The surface pressure coefficients for the building walls were based on Equation 23-8 of ASHRAE (ASHRAE 1993). The coefficient for the flat garage roof was based on Figure 14-6 of ASHRAE. No modifier for shielding effects was used.

Fan pressurization tests in the houses were simulated with CONTAM93 by including a constant flow element in the door of each house and adjusting the flow until pressure differences of 4 and 50 Pa were achieved. The airflow rates at 50 Pa were divided by the interior volumes of the houses to determine the 50 Pa air change rates, and the 4 Pa flows were converted to effective leakage areas. As shown in Table 2, the results of the fan pressurization simulations show that the tight houses are about 66% tighter than the typical houses. Additional airflow simulations performed on the houses to evaluate the building air change rates under a variety of conditions are described in Emmerich et al. 1994 and in Appendix A of the Phase II.A report.

Table 2 - Fan Pressurization Simulation Results

House	ach_{50} (h^{-1})	Leakage area (cm^2)
Typical Miami ranch	13.2	680
Tight Miami ranch	4.1	220
Typical Minneapolis ranch	6.6	710
Tight Minneapolis ranch	2.2	230
Typical Miami 2 story	12.9	1,120
Tight Miami 2 story	4.6	390
Typical Minneapolis 2 story	8.8	1,180
Tight Minneapolis 2 story	3.1	410

2.3 HVAC System Factors

The buildings were modeled with typical central forced-air heating and cooling systems. Cooling and heating load calculations were performed using the method described in the ASHRAE Handbook of Fundamentals, and commercially-available equipment was selected to meet these design loads. The air distribution system layouts were designed based on guidelines published by the National Association of Home Builders (Yingling et al. 1981). For the baseline simulations, the HVAC systems included standard furnace filters with constant efficiencies of 5% for fine particles (diameter less than 2.5 μm) and 90% for coarse particles (diameter greater than 2.5 μm). No outdoor air intake was included for the baseline HVAC systems. Table 3 summarizes HVAC system design information. More detailed descriptions of the systems including the heating and cooling load calculations and distribution system drawings are included in the Phase I report.

Table 3 - HVAC Systems

House	System description	Heating supply airflow (L/s)	Cooling supply airflow (L/s)	Equipment location	Main duct location	Return type
Miami ranch	Split-system ac and direct expansion fan coil with electric heater	222	356	1st floor utility closet	Attic	Central
Miami 2-story	Split-system ac and direct expansion fan coil with electric heater	222	356	1st floor utility closet	Internal	Central
Minneapolis ranch	Split-system ac and cased coil with gas furnace	271	425	Basement	Basement	Distributed
Minneapolis 2-story	Split-system ac and cased coil with gas furnace	271	425	Basement	Basement	Distributed

Duct leakage can have an important impact on building airflows and IAQ by affecting pressure relationships across the building envelope and between zones. It was modeled by including an additional supply or return point in the zone of the duct leakage and reducing the other supply and return flows. Based on a study of 160 Florida houses (Cummings et al. 1991), a duct leak equal to 10% of the total system flow was included. In the Minneapolis houses, a 10% return leak was located in the basement. A 10% supply leak was included in the Miami ranch house attic because the system has a central, unducted return. No leaks were included in the Miami two-story house because all ducts are internal.

CONTAM93 also requires an operation schedule for the systems. The schedules were determined by calculating the fractional on-time required to meet the cooling or heating load for each 3-hour period of the day. Table 4 summarizes the average percent run-time of the systems.

Table 4 - HVAC System Run-time

House	Weather	HVAC system % run-time
Miami ranch	Cold	16
Miami ranch	Mild	5
Miami ranch	Hot	61
Miami 2-story	Cold	24
Miami 2-story	Mild	8
Miami 2-story	Hot	68
Minneapolis ranch	Cold	77
Minneapolis ranch	Mild	23
Minneapolis ranch	Hot	43
Minneapolis 2-story	Cold	74
Minneapolis 2-story	Mild	21
Minneapolis 2-story	Hot	47

2.4 Pollutant Factors

This section describes the pollutant-related inputs used in the simulations. Based on the Interagency Agreement between CPSC and NIST (CPSC 1993), the pollutants simulated in this study were nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, and volatile organic compounds (VOCs). Table 1 of the Interagency Agreement lists these pollutants with maximum design burden concentrations and reduced concentrations as reference points. The values listed for NO_2 are initial/maximum design burden of 1000 ppb, reduced long-term level of 52 ppb, and reduced short-term peak of 300 ppb. The values for CO are an initial/maximum design burden of 200 ppm, reduced 8-hour average of 15 ppm, and reduced 1-hour average of 25 ppm. The values for particulates (with diameters of 2.5 μm and less) are initial/maximum design burden of 500 $\mu g/m^3$, and reduced 24-hour average of 100 $\mu g/m^3$. The only value listed for TVOCs is a reduced level of 300 $\mu g/m^3$. These values are not specified as health-based limits and are not used as definitive criteria for evaluating the effectiveness of the IAQ controls but are merely points of reference to use in the analysis of the results. The table in the Interagency Agreement also listed biologicals as a pollutant of interest, but they were not included in the study due to a lack of data for required model inputs, in particular source strengths.

A literature review of reports quantifying residential sources of these pollutants was summarized in the Phase I report. The pollutant sources used in the simulations included several VOC short-duration or burst sources (medium strength source based on a polish and high strength source based on a spray carpet cleanser (Colombo et al. 1990)), a constant VOC area source (based on a PVC flooring material with high emissions (Saarela and Sandell 1991)), and combustion sources (based on medium source strengths for an oven and an unvented gas space heater (DOE 1990)) of CO, NO_2, and fine particles. A total of eight burst sources was included in each simulation, and the TVOC concentrations due to each one was calculated separately by CONTAM93. The source strength used for the flooring material is based on the high end of a range reported by Saarela and Sandell (1991) for a variety of flooring materials. The flooring material emission rate is also somewhat higher than the range of 0.17 to 2.11 $mg/m^2 \cdot h$ recently reported in 5-day emission tests of finished particleboard (Hoag and Cade 1994). Table 5 lists information on these sources including the zones (see Figures 1 and 2 for zone labels; BMT is the basement zone) in which they are located, source strengths, and schedules.

Table 5 - Pollutant Sources

Source	Pollutant	Zone(s)	Source strength	Schedule
Burst (medium)	TVOCs	Several	300 mg/h	9 - 9:30 a.m. 7 - 7:30 p.m.
Burst (high)	TVOCs	GAR and BMT	1100 mg/h	9 - 10 a.m. 7 - 8 p.m.
Flooring material	TVOCs	All but GAR, ATC	7.0 mg/h•m²	constant
Oven	CO	KIT (ranch house), KFA (two-story house)	1900 mg/h	7 - 7:30 a.m. 6 - 7 p.m.
Oven	NO_2	KIT (ranch house), KFA (two-story house)	160 mg/h	7 - 7:30 a.m. 6 - 7 p.m.
Oven	Fine particles	KIT (ranch house), KFA (two-story house)	0.2 mg/h	7 - 7:30 a.m. 6 - 7 p.m.
Heater	CO	GAR and BMT	1000 mg/h	7 - 10 a.m. (GAR) 7 - 9 p.m. (BMT)
Heater	NO_2	GAR and BMT	250 mg/h	7 - 10 a.m. (GAR) 7 - 9 p.m. (BMT)
Heater	Fine particles	GAR and BMT	2 mg/h	7 - 10 a.m. (GAR) 7 - 9 p.m. (BMT)

Outdoor pollutant concentrations vary by location and over time at any one location. The concentrations used as boundary conditions for the indoor sources in the simulations were selected as typical outdoor conditions and were specified per the schedules in Table 6. The CO and NO_2 concentrations were chosen based on review of US EPA air quality documents (EPA 1991, EPA 1993a, EPA 1993b). The selected CO and NO_2 concentration schedules have a diurnal pattern with morning and afternoon peaks that are very similar to values measured outside a research house in Chicago (Figure 3.2 of Leslie et al. 1988). The outdoor fine particle and TVOC concentrations were assumed to be constant throughout the day. The ambient fine particle concentration was chosen based on the average of reported measurements for four US cities (Table 4 of Sinclair et al. 1990). The TVOC concentration chosen is in the middle of the reported range of 10 to 211 μg/m³ measured at 68 sites in the US (Shields and Fleischer 1993).

Table 6 - Outdoor Pollutant Concentrations

Hour of day	0 - 7	7 - 9	9 -17	17 - 19	19 - 24
CO (ppm)	1	2	1.5	3	1.5
NO_2 (ppb)	20	40	20	40	20
Fine particles (μg/m³)	13	13	13	13	13
TVOCs (μg/m³)	100	100	100	100	100

In addition to the ambient concentrations that served as the boundary conditions for the indoor sources, elevated levels of CO, NO_2 and coarse particles were simulated in order to evaluate the effect of the IAQ control technologies on pollutants brought into residences from the outdoors. These elevated pollutant concentrations were selected based on review of US EPA air quality documents (EPA 1991, EPA 1993a, EPA 1993b) and were specified per the schedules in Table 7.

Table 7 - Elevated Outdoor Pollutant Concentrations

Hour of day	0 - 7	7 - 9	9 -17	17 - 19	19 - 24
CO (ppm)	4	8	7	12	6
NO_2 (ppb)	200	400	200	400	200
Coarse particles ($\mu g/m^3$)	75	75	75	75	75

Reversible sink effects for the VOCs were modeled with sink elements based on a boundary layer diffusion controlled (BLDC) model with a linear adsorption isotherm described by Axley (1991). The parameters required for this sink model are the film mass transfer coefficient, the adsorbent mass, and the isotherm partition coefficient. Little data is available for these parameters which depend on factors such as gas diffusion properties, airflow rates, and adsorbent material. The values used were 35 μm/s for the film mass transfer coefficient, 0.5 g-air/g-sorbent for the partition coefficient, and 3 kg per m^2 of zone interior surface area for the adsorbent mass. The basis for the values is described in the Phase II.A report.

Nitrogen dioxide decay and particle deposition were modeled as single-reactant first order reactions with a single, constant decay rate in all rooms of the houses. Nitrogen dioxide decay depends strongly on the materials present in a house (e.g., floor and wall coverings, furnishings, etc.), and a wide range of measured values have been reported including a range of 0.09 - 13.74 h^{-1} by Lee et al. 1993. Average NO_2 decay rates of 0.17, 0.29, 0.65, 0.8, 0.82, and 2.07 h^{-1} have been reported (Leslie and Billick 1990, Ozkaynak et al. 1982, Borazzo et al. 1987, Spicer et al. 1989, Tamura 1987, Lee et al. 1993). The kinetic rate coefficient used for NO_2 decay was 0.87 h^{-1} based on the average of measurements in a contemporary research house (Leslie et al. 1988).

Particle deposition depends on the size and type of particles, particle concentration, airflow conditions, and surfaces available for deposition. The fine particle deposition rate used was 0.08 h^{-1} and is based on combustion products from a wood-burning stove in a test house (Traynor et al. 1987). The coarse particle deposition rate used was 1.5 h^{-1} and is based on the lower value reported for 4 μm particles in a test room (Byrne et al. 1993).

2.5 IAQ Control Technologies

The IAQ control technologies considered for the study were limited to commercially available equipment that can be used with conventional forced-air systems. The three IAQ control technologies included were electrostatic particulate filtration, heat recovery ventilation, and an outdoor air intake damper on the forced-air system return. This section discusses only the important modeling details of the devices. More information including detailed descriptions, duct drawings, cost estimates, and thermal loads is in the Phase II.A report of this project.

The electrostatic particulate filter (EPF) selected for the study has a filter efficiency of 30% for fine particles (emitted by the combustion sources in these simulations) and 95% for coarse particles (associated with the elevated outdoor air concentrations). The EPF was modeled by replacing the standard furnace filters in the baseline HVAC systems. The filter efficiency was modeled as constant over time, and impacts on airflow through the system were neglected.

The heat recovery ventilator (HRV) draws air from the return side of the forced-air system and replaces it with outdoor air drawn through the heat exchanger. Figure 3 shows a schematic of the HRV. The outdoor airflow rate in each house was selected to correspond to an air change rate of 0.35 ach. The HRV was modeled by setting the outdoor airflow rate for the HVAC system to the appropriate fraction of the total system supply airflow rate. Thus, the desired amount of outdoor air will be supplied whenever the HVAC system is operating. Other control options (such as constant operation or demand control) were not studied. A standard furnace filter was included in the outdoor air intake path of the HRV. The actual HRV employs a defrost cycle that periodically closes the outdoor air damper in cold weather. However, the defrost cycle was not modeled.

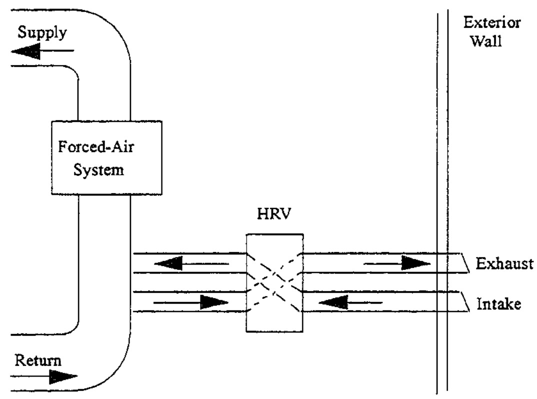


Figure 3 - Schematic of Heat Recovery

The outdoor air intake damper (OAID) draws outdoor air into the return side of the forced-air system. Figure 4 shows a schematic of the OAID. The OAID was modeled similarly to the HRV. The baseline HVAC system was modified to include a constant fraction of outdoor air to provide an air change rate of 0.35 ach whenever the HVAC system is operating. A standard furnace filter was included in the outdoor air intake path. The primary difference between the OAID and the HRV is that the outdoor air intake damper does not include an exhaust duct. Therefore, the outdoor airflow will tend to pressurize the house. This effect was modeled by reducing the HVAC return flows from the house by an amount equal to the outdoor air supplied to the system.

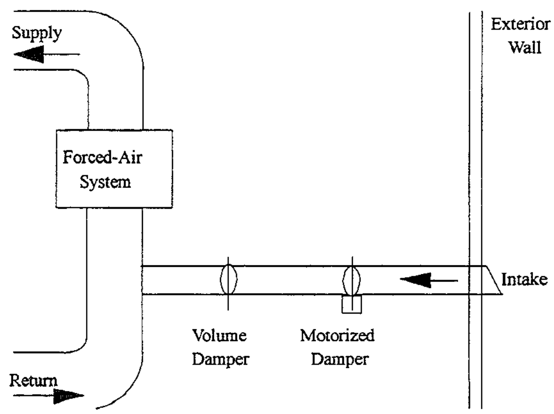


Figure 4 - Schematic of Outdoor Air Intake Damper

3 Results

Each simulation yields pollutant concentrations for up to 18 pollutants in each of up to 18 building zones for each 15-minute time step of the 24-hour simulation period. The complete transient simulation results are not presented in this report but are available in spreadsheet files. This section presents sample transient results, a summary of peak and 24-hour average results for each source, and 24-hour average air change rates for the baseline, HRV and OAID cases. The percent reductions in concentration due to the IAQ controls are summarized in tables at the end of this section. Appendix A contains tables summarizing the baseline average and peak concentrations and percent reductions due to each IAQ control for all individual cases.

3.1 TVOC Sources

This subsection presents the simulation results for the TVOC burst and floor sources. Medium strength burst sources were located in several building zones and operated for 30 minutes at 9 a.m. and 7 p.m. High strength burst sources were located in the garage and basement zones and operated for 1 hour at 9 a.m. and 7 p.m. As mentioned previously, a total of eight burst sources was included in each simulation and the concentrations in all building zones due to each were calculated separately by CONTAM93. The floor source was located in all zones of the houses with a constant source strength that depended on the zone floor area. Transient results for both burst and floor sources for selected cases are presented first. Summaries of average and peak concentrations due to the floor and the burst sources follow for all simulation cases.

3.1.1 Transient - TVOC

Figure 5 shows the TVOC concentrations in the living and dining area (LDA), kitchen (KIT), and master bedroom (MBR) zones resulting from a burst source in the LDA for the tight Miami ranch house with a baseline HVAC system on the cold day. The simulations were performed with calculations at 5 minute steps and output was reported at 15 minute steps. Two concentration peaks (1870 and 2040 $\mu g/m^3$) are seen in the source zone LDA, corresponding to the burst-source events. The adjacent zone KIT also shows two peaks, however, the KIT concentration peaks (490 and 560 $\mu g/m^3$) are significantly lower than the LDA peaks and occur from one to two hours after the LDA peaks. The peaks are not clearly distinguishable in the MBR that is located on the opposite end of the house from the LDA. When the HVAC system is off, the concentration in all three zones decays gradually due to infiltration. When the HVAC system turns on (e.g. 10:15 a.m.), the concentration in the LDA zone decreases abruptly and the concentration in the other two zones increases as the system mixes the contaminant from the source zone into the rest of the house.

Figure 6 shows the impact of the HRV and OAID on the living-space average TVOC concentrations due to the LDA burst source for the same case shown in Figure 5 (tight Miami ranch house in cold weather). The EPF results are not listed here or for any of the TVOC, CO, and NO_2 sources as the filter affects only the particle concentrations. The living-space average includes the kitchen, living room, dining room, and all bedroom zones. When the HVAC system comes on, the concentration drops suddenly due to the additional outdoor air brought in through the HRV and the OAID. When the system is off, the concentration decreases at a lower rate due to infiltration. Both the HRV and OAID had small impacts on the concentration peaks (reductions of 2.5% and 3.4%, respectively) but more substantial impacts on the 24-hour average concentrations as they reduced concentrations throughout the day (reductions of 14% and 17%, respectively). These concentration peak reductions refer to the maximum concentration in an *individual* zone and not to the living-space average peak concentration shown in Figure 6. The small reductions in peak concentrations indicate an inability of the modest increase in the ventilation rate to mitigate concentration spikes due to a short-term source. Despite the reductions, the 24-hour average living-space TVOC concentration remained above the reduced-level reference point of 300 $\mu g/m^3$ for both the HRV and OAID cases.

Figure 7 shows the living-space average concentration due to the floor TVOC source for the tight Miami ranch house in cold weather. Since the floor source is constant, the concentration changes are due entirely to changes in the building air change rate with the outdoor conditions and with HVAC system operation. In general, the TVOC concentration gradually increases when the system is off and then drops sharply when the system turns on due to the higher air change rate. Overall, the concentrations are higher during the latter part of the day because the infiltration driving forces are lower and the system operates less frequently, both resulting in a lower building air change rate. In this building, system operation increases the outdoor air change rate due to the supply duct leak in the attic. The HRV and the OAID reduced both peak (19% and 18%, respectively) and average TVOC concentrations (22% and 24%, respectively) for the floor source by a greater amount than for the burst source. As noted in the discussion of Figure 6, the reductions in peak concentrations refer to individual zone concentrations, not the living-space average concentration. The IAQ controls have a greater impact on the peak concentration for the floor source than for the burst sources because the floor-source peak is due to a gradual build-up of pollutant through the day rather than a short-term event.

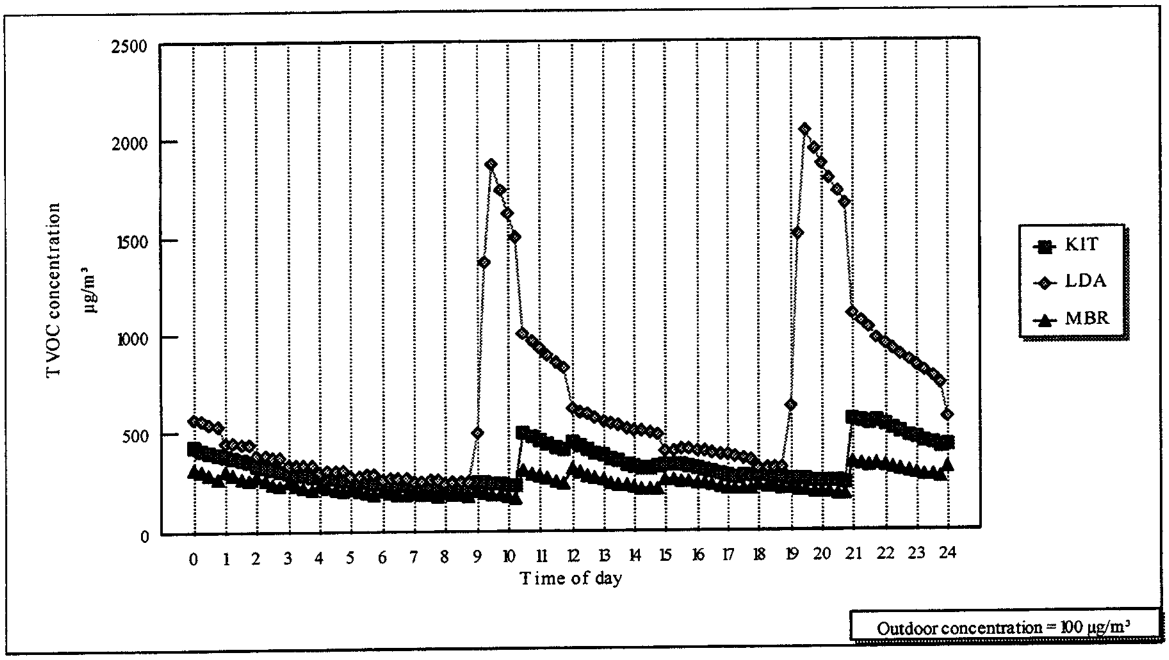


Figure 5 - Transient TVOC Concentration Due to LDA Burst Source (Tight Miami Ranch House on Cold Day)

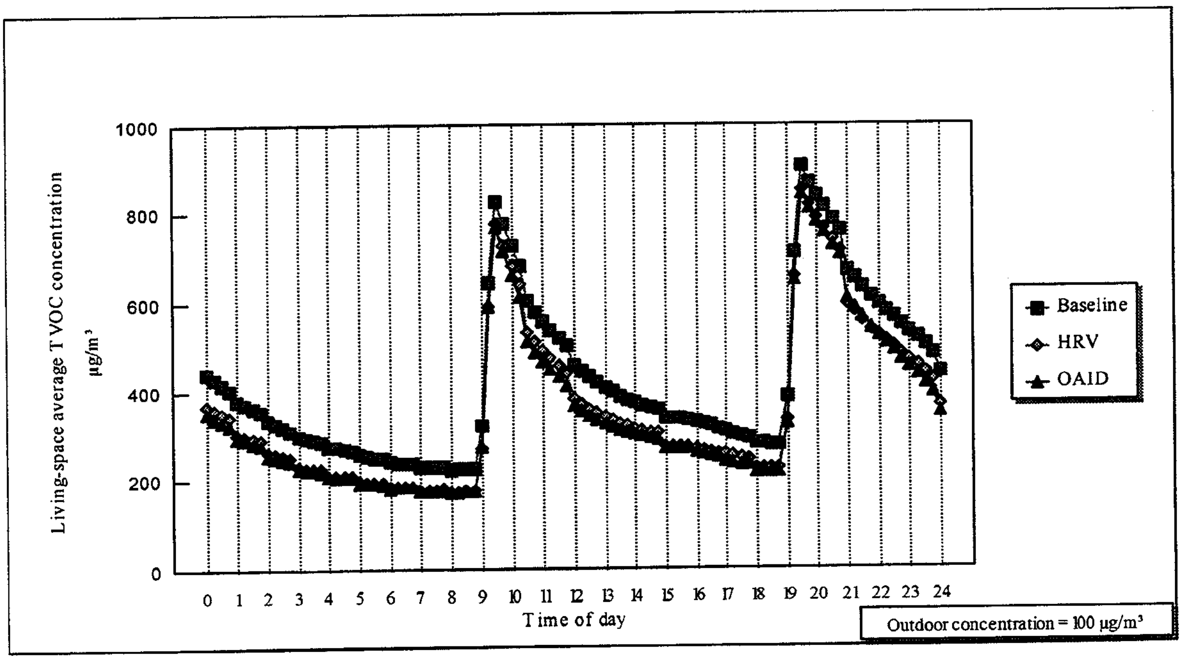


Figure 6 - Transient Living-space Average TVOC Concentration Due to LDA Burst Source (Tight Miami Ranch House on Cold Day)

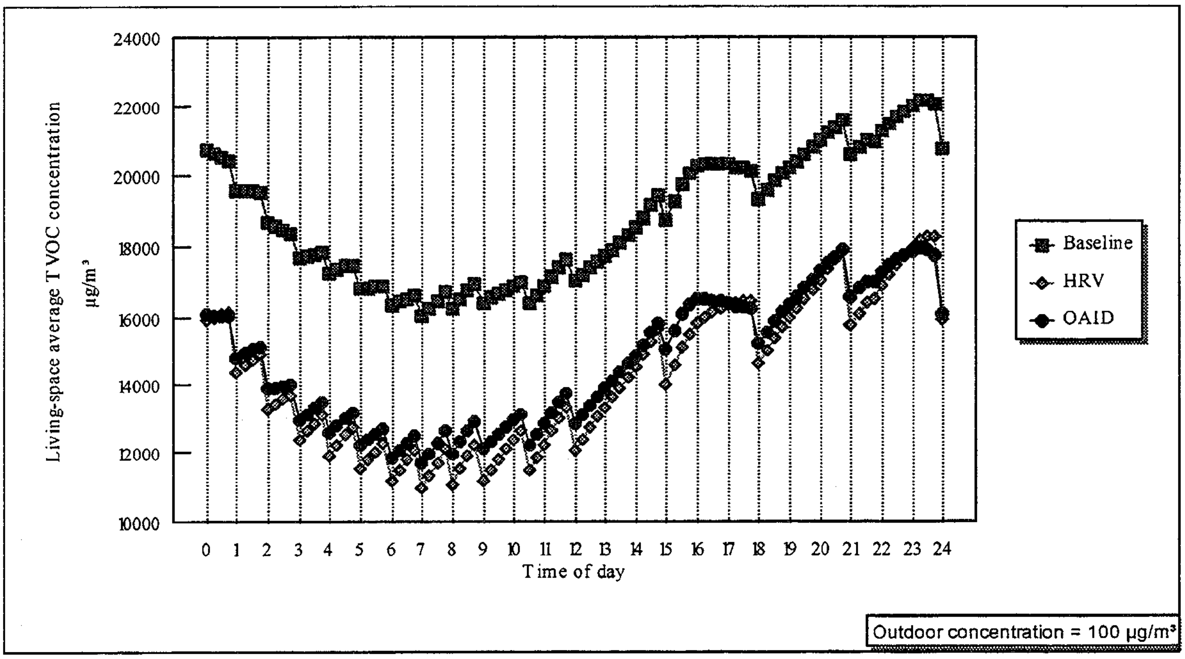


Figure 7 - Transient Living-space TVOC Concentration Due to Floor Source (Tight Miami Ranch House on Cold Day)

3.1.2 Floor - TVOC

Figure 8 shows the 24-hour, living-space average TVOC concentrations due to the floor source for all cases. The 24-hour, living-space average TVOC concentration due to the floor source ranges from 2150 to 29,100 µg/m^3 for the baseline cases with an average of 9150 µg/m^3. The baseline average TVOC concentration in the tight houses (13,790 µg/m^3) is over three times greater than the average in the typical houses (4500 µg/m^3). Since there are no decay effects and the pollutant source is constant and distributed throughout the houses, the differences in concentrations can be explained largely by the average building air change rates which are presented in Figures 35 and 36. The TVOC concentrations are also affected by the presence of reversible sinks which are expected to reduce concentration peaks and increase concentration minimums. However, the sink effects are not easily discernible in these results. More study is needed to identify these effects. The baseline average TVOC concentration was highest for the Miami hot weather cases (13,450 µg/m^3), followed by the Miami cold weather cases (11,650 µg/m^3), Miami mild weather cases (11,290 µg/m^3), Minneapolis mild weather cases (7,180 µg/m^3), Minneapolis hot weather cases (6,790 µg/m^3), and Minneapolis cold weather cases (4,510 µg/m^3). The rank and magnitude of these concentrations correspond to the average building air change rates which, in turn, are determined by a combination of weather-dependent infiltration rates and HVAC system operation. The 24-hour, living-space average concentration was highest for the tight Miami two-story houses in hot weather which, as seen in Figure 35, has the lowest average air change rate of any baseline case.

The HRV reduced the 24-hour, living-space average TVOC concentration due to the floor source by an average of 26% with the reductions ranging from 2.5% to 69%. The percent reduction for all tight house cases was larger than the reduction for the corresponding typical house cases with average reductions of 35% and 16%, respectively. The reduction is greater for the tight houses because the additional outdoor air brought in by the HRV, which on average is about the same absolute magnitude for both typical and tight houses, is a larger relative increase in the building air change rates for the tight houses compared to the typical houses. The impact of the HRV on building air change rates is presented in Figures 35 and 36. The average reduction was greatest for the Miami hot weather cases (41%) followed by the Minneapolis cold weather cases (40%), Minneapolis mild weather cases (25%), Minneapolis hot weather cases (22%), Miami cold weather cases (19%), and Miami mild weather cases (7.5%). A major factor contributing to the order of the percent reductions is the HVAC system run-time because the greater run-times result in larger increases in average outdoor air change rates. The Miami hot weather cases and Minneapolis cold weather cases, which have the highest average percent reductions, also have the highest HVAC system run-times, as shown earlier in Table 3. The Miami mild weather cases have the lowest system run-times and the smallest average percent reduction. The reduction in average pollutant concentration was largest for the tight Miami two-story house in hot weather (69%) because, as seen in Figure 35, the HRV increased the average air change rate by the greatest amount for this case (more than a factor of three).

The outdoor air intake duct (OAID) reduced the 24-hour, living-space average TVOC concentration due to the floor source by an average of 21% with the reductions ranging from 2.6% to 64%. The average OAID reduction is less than the average HRV reduction because the HRV increases the building air change rates by a greater amount as discussed later in this section. There are a few individual cases where the OAID reduction is larger. The percent reduction for most tight house cases (average of 29%) was larger than the reduction for the corresponding typical house cases (average of 13%) because, as explained above for the HRV, both typical and tight houses have about the same absolute increase in average air change rate but the increase in the tight houses is larger relative to the baseline air change rates. The average reduction was greatest for the Miami hot weather cases (30%) and the Minneapolis cold weather cases (30%) followed by the Minneapolis mild weather cases (21%), Minneapolis hot weather and Miami cold weather cases (19%), and Miami mild weather cases (4.8%). As discussed above for the HRV, the Miami hot weather cases and Minneapolis cold weather cases have both the highest HVAC system percent run-times and the greatest average percent reductions in TVOC concentrations, and the Miami mild weather cases have both the lowest system run-times and the smallest average percent reduction. The largest percent reduction occurs, once again, for the tight Miami two-story house in hot weather because, as seen in Figure 35, the OAID increases the average air change rate by nearly a factor of three.

Figure 9 shows the living-space peak TVOC concentrations due to the floor source for all cases. The peak TVOC concentration due to the floor source in any living-space zone ranges from 3140 to 34,490 $\mu g/m^3$. These concentrations are very high because the source strength was based on a material with high emissions. The HRV and OAID reduced the living-space peak TVOC concentrations by averages of 20% and 16%, respectively. As discussed for the reductions in average concentrations, the reductions in peak concentrations are dependent on system run-time.

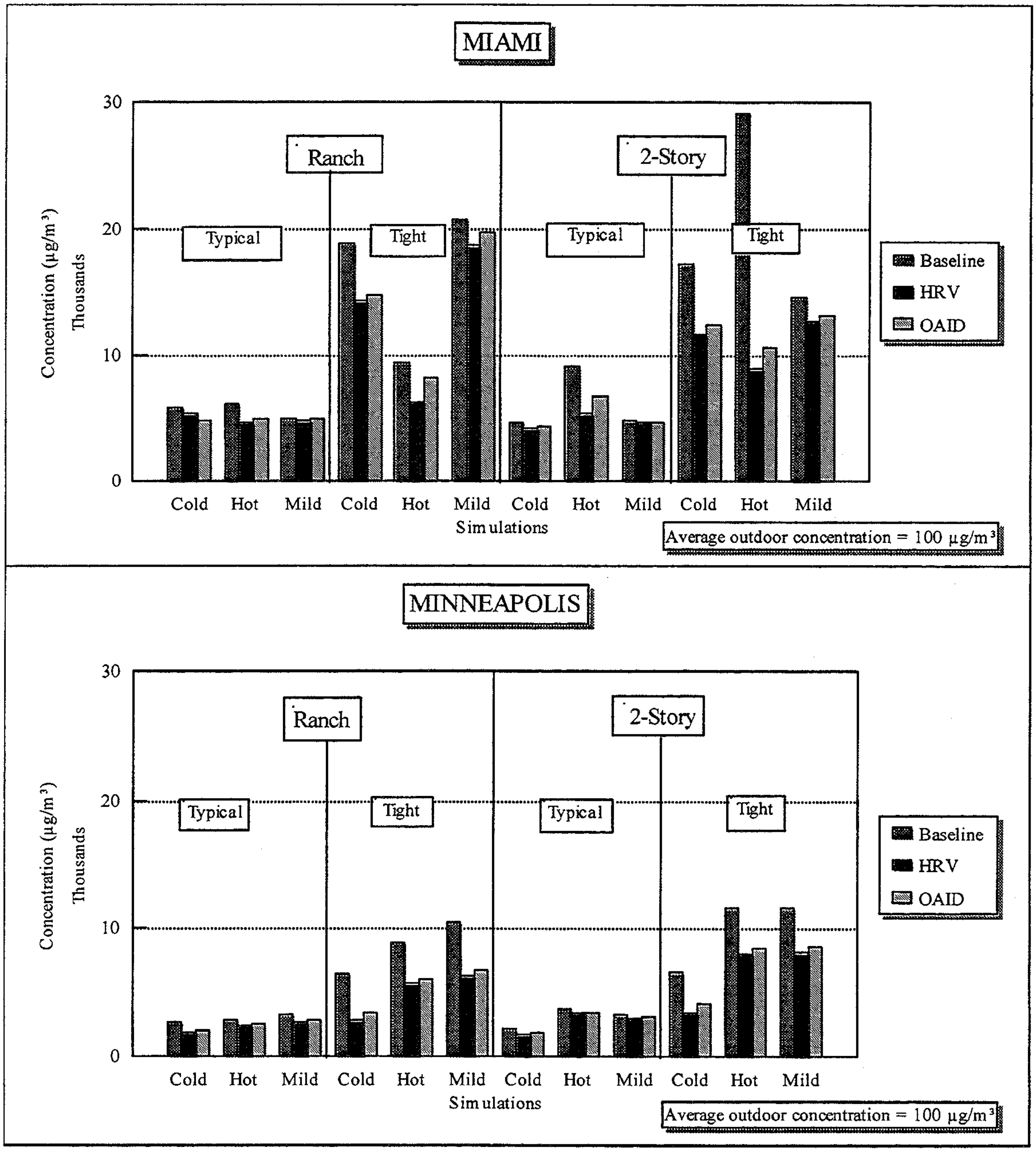


Figure 8 - 24-hour, Living-space Average TVOC Concentrations Due to Floor Source

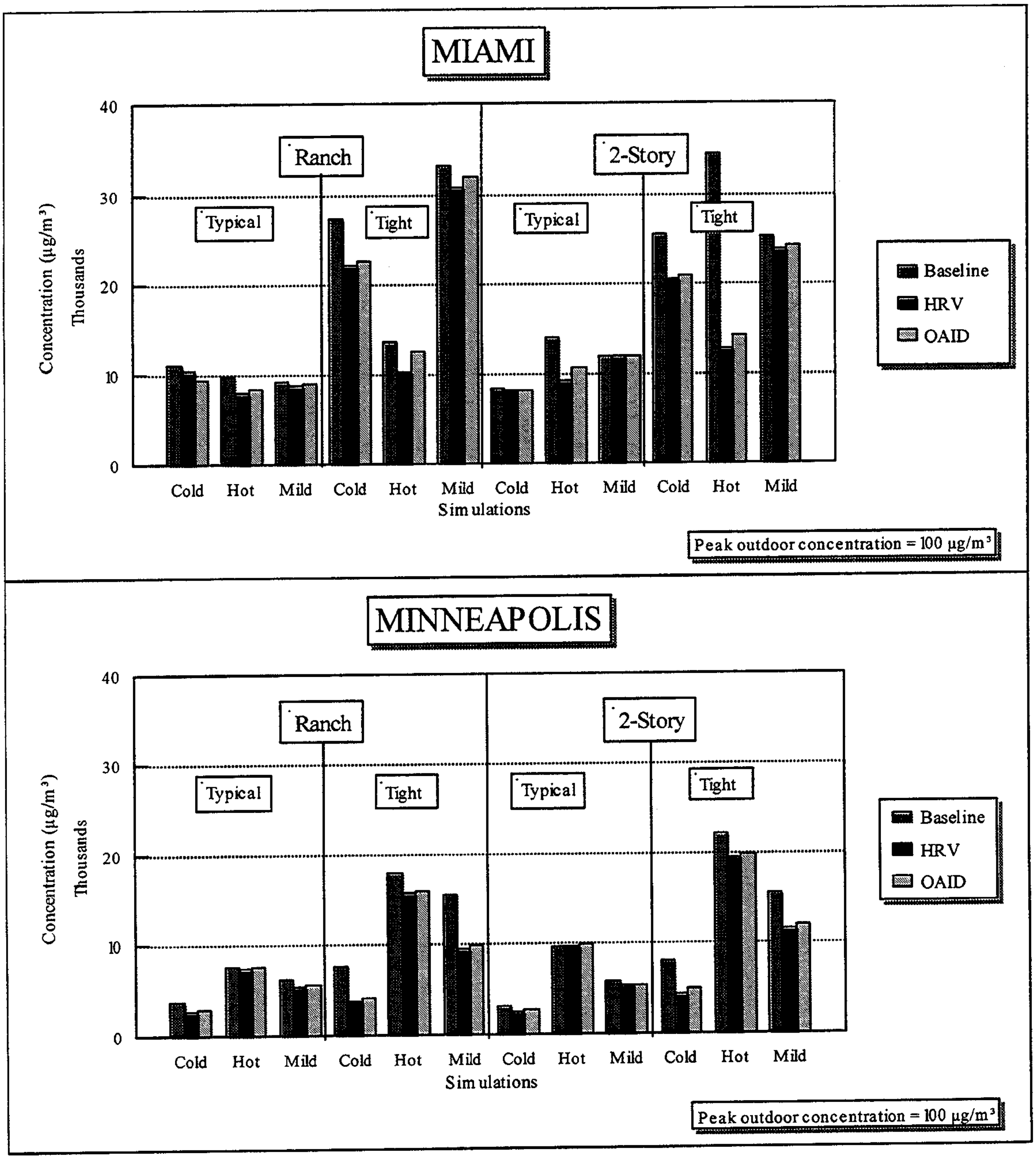


Figure 9 - Peak TVOC Concentrations Due to Floor Source

3.1.3 Burst - TVOC

Figure 10 summarizes the 24-hour, living-space average TVOC concentrations due to the VOC burst sources for the baseline, HRV, and OAID cases. This figure uses the average of the individually-tracked concentrations due to all eight VOC burst sources located in the various zones to characterize the average impact of the IAQ controls on these sources. While this summary of the data obscures the impact of the individual sources, it provides an overall indication of the impact of these local VOC sources. The 24-hour, living-space average TVOC concentration due to any individual zone burst source ranges from 100 to 1220 $\mu g/m^3$ for all baseline cases with an average of 230 $\mu g/m^3$. The average concentrations are substantially higher for the tight buildings (300 $\mu g/m^3$) than the typical buildings (160 $\mu g/m^3$) due to the lower air change rates in the tight buildings. The average TVOC concentration was highest for the Miami hot weather cases (250 $\mu g/m^3$), followed by the Minneapolis mild weather cases (240 $\mu g/m^3$), Miami cold weather cases (230 $\mu g/m^3$), Miami mild weather cases and Minneapolis hot weather cases (220 $\mu g/m^3$), and Minneapolis cold weather cases (210 $\mu g/m^3$). Unlike the floor source, the variation in these results can not be explained by only the building average air change rates. Since the burst sources are local and short term, the building average concentrations may also depend on the airflow pattern between building zones and on the relative timing of the HVAC system operation and the source emission.

The HRV reduced the 24-hour, living-space average TVOC concentrations due to individual zone burst sources by an average of 14% with the reductions ranging from -1.2% to 56%. The average, and nearly all individual, percent reductions in TVOC concentrations due to the burst sources were substantially less than the reductions in concentrations due to the floor source. One reason for this difference is the minimal impact of the HRV on the peak concentration due to a short-term emission (e.g., a 2.5% reduction for the case shown in Figure 6). Also, the HRV has a smaller relative impact on the zone containing the burst source. For the tight Miami ranch house in cold weather, the reduction was 9% in the LDA zone for the LDA burst source versus 21% for the other living space zones. Another reason for the lower reduction in peak concentrations for the burst sources may be the relative strength of the burst and floor sources. The burst sources result in average concentrations up to four times the ambient concentration, while the floor source results in average concentrations at least twenty-two times the ambient concentration.

As was the case for the floor source, the percent reduction in the average burst-source concentrations due to the HRV for all tight house cases was larger than or equal to the reduction for the corresponding typical house cases (average reductions of 22% and 6.8%, respectively) due to the greater relative increase in tight house air change rates. The average reduction was greatest for the Miami hot weather cases (26%) followed by the Minneapolis cold weather cases (18%), Minneapolis hot weather cases (15%), Minneapolis mild weather cases (13%), Miami cold weather cases (10%), and Miami mild weather cases (3.3%). As discussed earlier, the order of these reductions reflects the impact of system run-time on percent reductions in the average concentration. Once again, the average reduction in average pollutant concentration was largest for the tight Miami two-story house in hot weather (48%) because the HRV increased the average air change rate by the greatest amount for this case.

The OAID reduced the 24-hour, living-space average TVOC concentration due to the individual zone burst sources by an average of 13% with the reductions ranging from 0% to 75%. Once again, the percent reduction for most tight house cases was larger than or equal to the reduction for the corresponding typical house cases, with average reductions of 20% and 6.0%, respectively. The average reduction was greatest for the Miami hot weather cases (22%) followed by the Minneapolis cold weather cases (16%), Minneapolis hot weather cases (14%), Miami cold weather cases (12%), Minneapolis mild weather cases (11%), and Miami mild weather cases (2.6%). These results reflect the impact of system run-time on percent reductions in average concentration as discussed earlier.

The living-space peak TVOC concentrations for the MBR and KIT/KFA burst sources are displayed in Figures 11 and 12. The range of peak TVOC concentrations were 730 to 3330 $\mu g/m^3$ and 770 to 5590 $\mu g/m^3$ for the MBR and KIT/KFA sources, respectively. On average, the HRV reduced the living-space peak TVOC concentrations due to the MBR burst source and the KIT/KFA burst source by 1.3% and 1.6%, respectively. On average, the OAID reduced the living-space peak TVOC concentrations due to the MBR burst source and the KIT/KFA burst source by 0.9% and 0.4%, respectively.

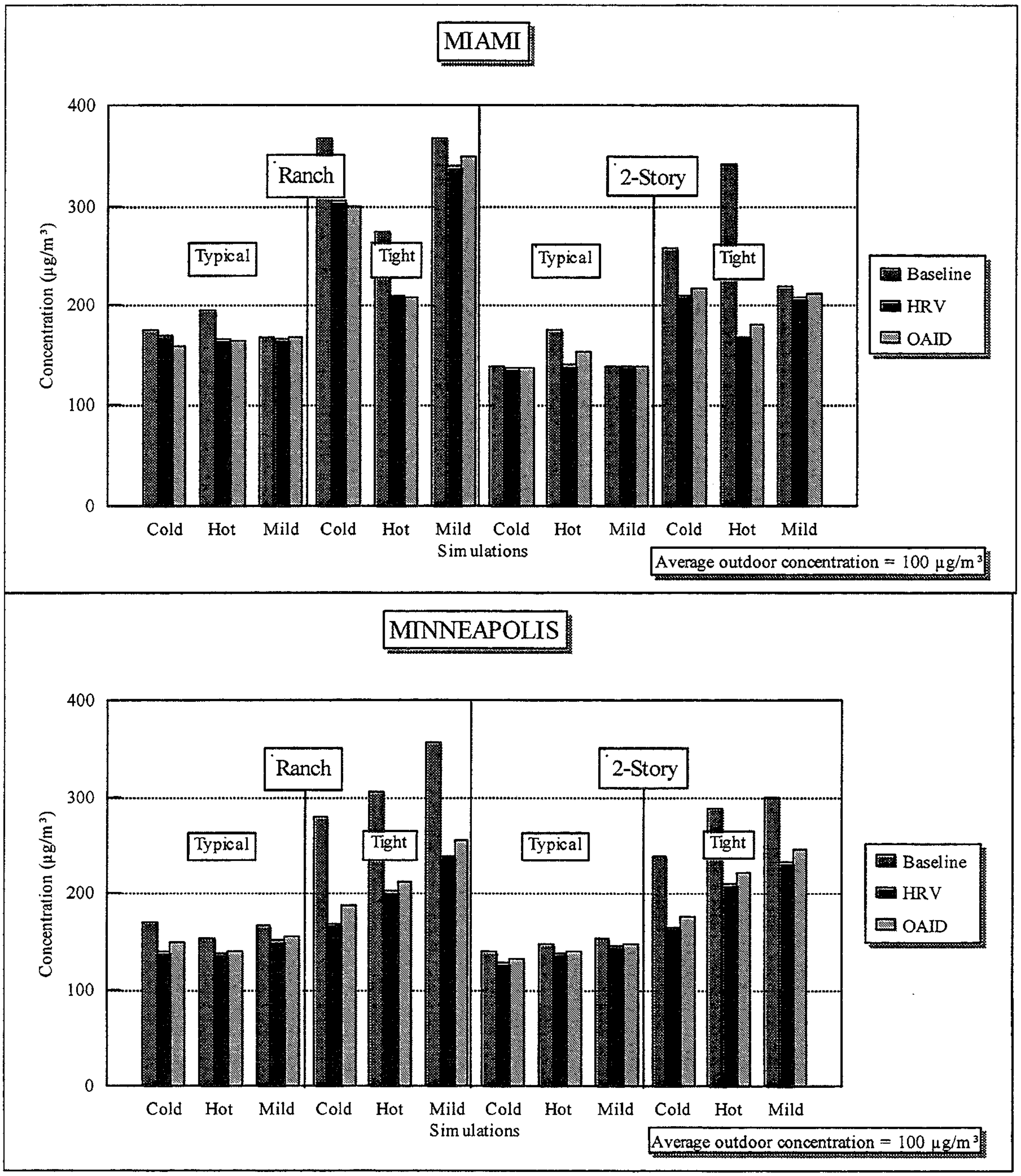


Figure 10 - Average of 24-hour, Living-space Average TVOC Concentrations Due to Burst Sources

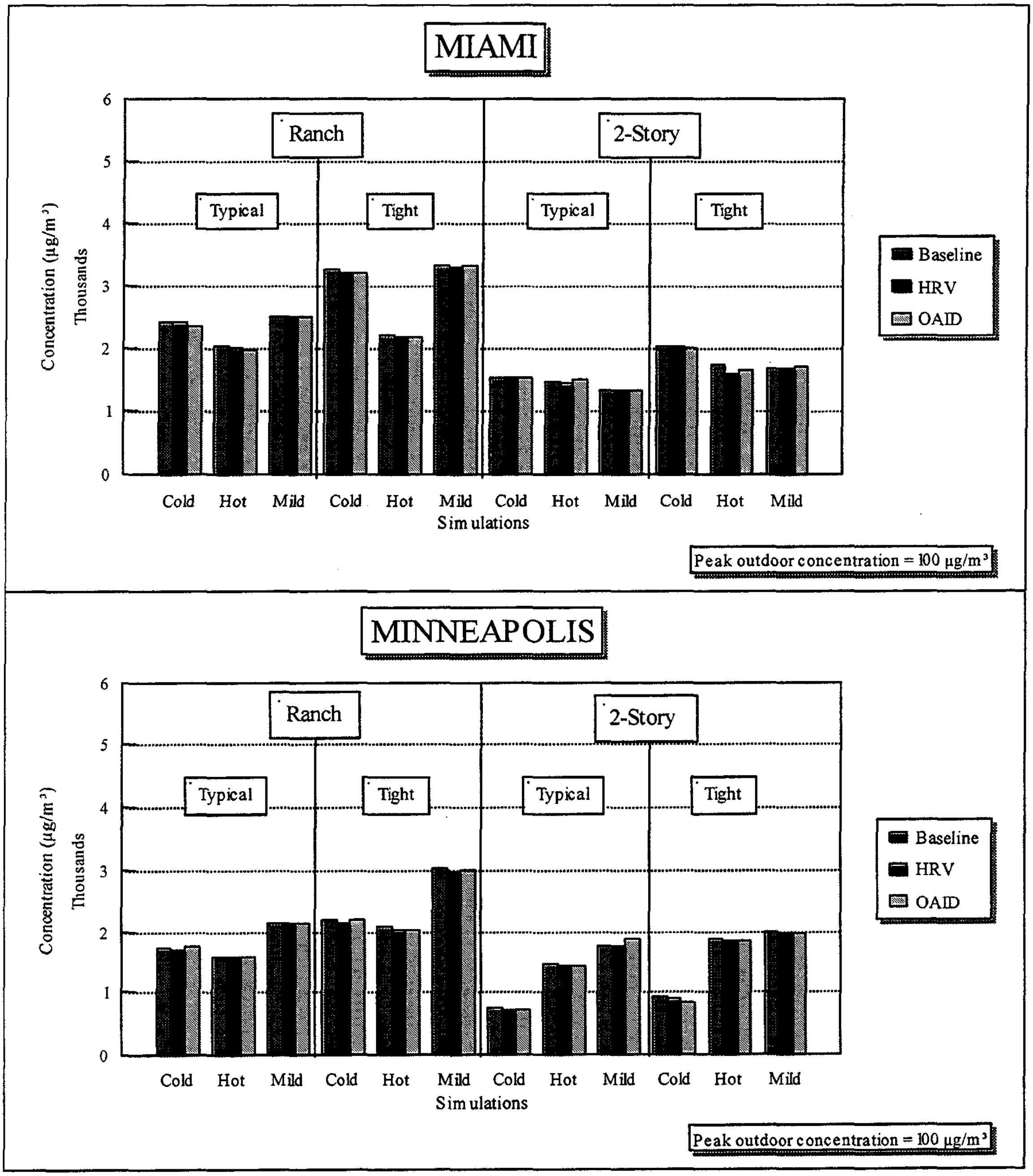


Figure 11 - Peak TVOC Concentrations Due to MBR Burst Source

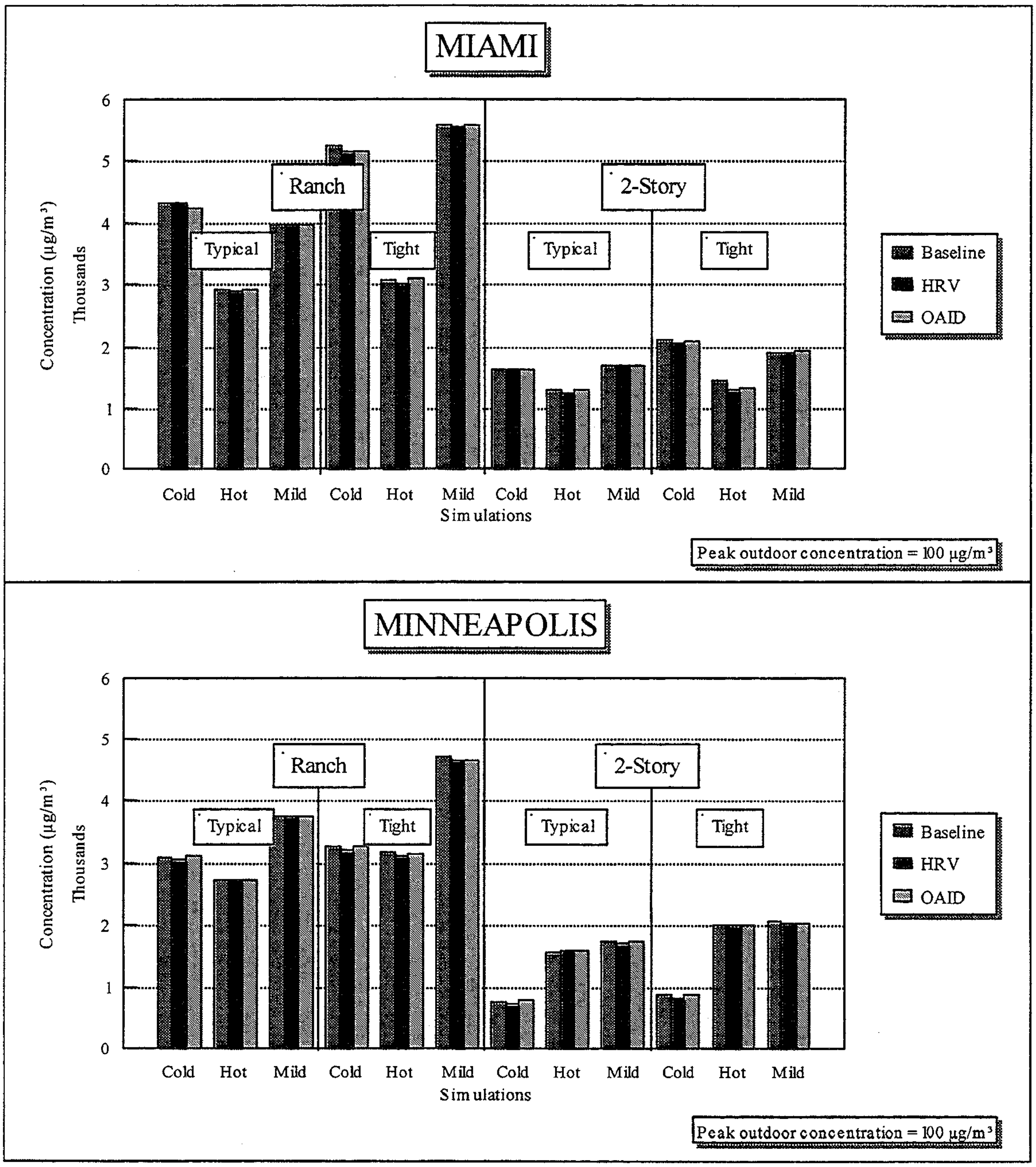


Figure 12 - Peak TVOC Concentrations Due to KIT/KFA Burst Source

3.2 Combustion Sources

This subsection presents the simulation results for the oven and unvented gas space heater sources of CO, NO_2, and fine particles. The oven was located in the KIT/KFA zones and operated for 30 minutes starting at 7 a.m. and 1 hour at 6 p.m. The heater was located in the garage and basement zones and operated for 3 hours starting at 7 a.m. in the garage and 2 hours at 7 p.m. in the basement. Selected transient results for the oven are presented first, and are followed by detailed summaries of average and peak concentrations for the oven, transient results for the heater, and average and peak results for the heater.

3.2.1 Oven - Transient

Examples of the transient living-space average concentrations of CO, NO_2, and fine particles due to the oven are shown in Figures 13, 14, and 15. These results are for the tight Miami ranch house in cold weather. Peak CO concentrations corresponding to the oven operation schedule are evident in Figure 13. The living-space average CO concentrations remain below both the initial/maximum burden (200 ppm) and reduced level reference points (25 ppm for 8-hour average and 15 ppm for 1-hour average) of the Interagency Agreement (CPSC 1993). The HRV and OAID resulted in small reductions in CO concentrations, with the modest increase in the building air change rate having little impact on the peaks caused by this short-term source.

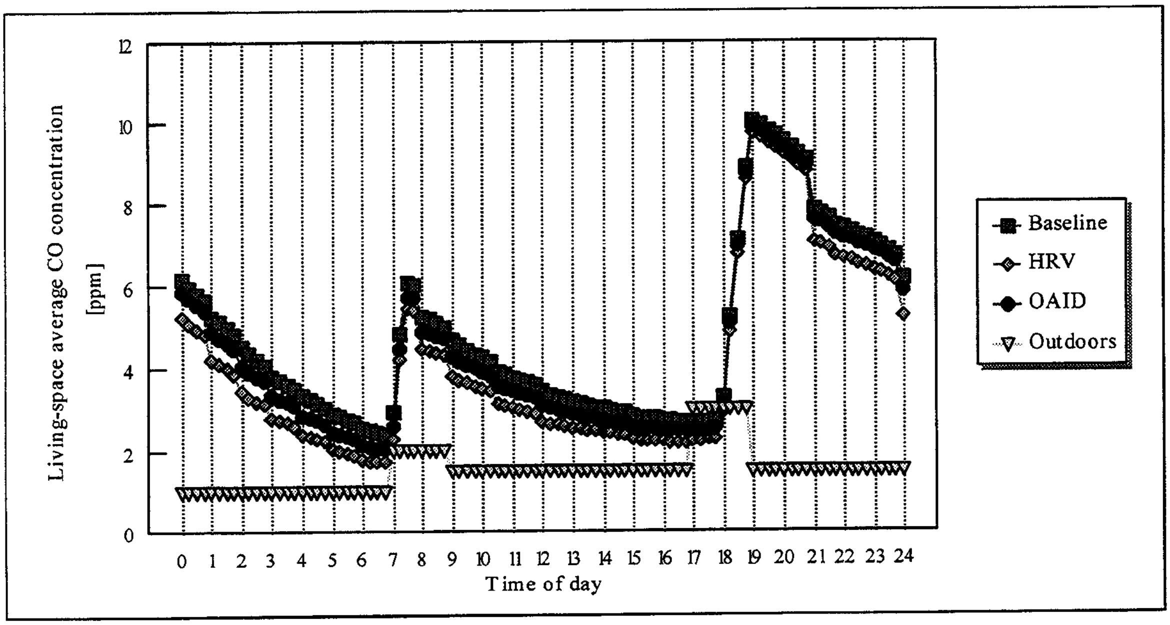


Figure 13 - Transient Living-space Average CO Concentration Due to Oven Source (Tight Miami Ranch House on Cold Day)

Figure 14 clearly shows the NO_2 concentration peaks corresponding to the oven operation schedule. The living-space average NO_2 concentrations remain below both the initial/maximum burden (1000 ppb) and the short-term reduced level (300 ppb) throughout the day. The 24-hour average concentration is below the long-term reduced level (52 ppb). Figure 14 shows that the impact of the IAQ controls on the NO_2 concentrations for this case were negligible as the short-term source and pollutant decay combine to cause steep and short-lived concentration peaks. Because the HVAC system only operates 16% of the time on this day, and because the source is localized and of a short duration, the HRV and OAID have little effect on the NO_2 concentration.

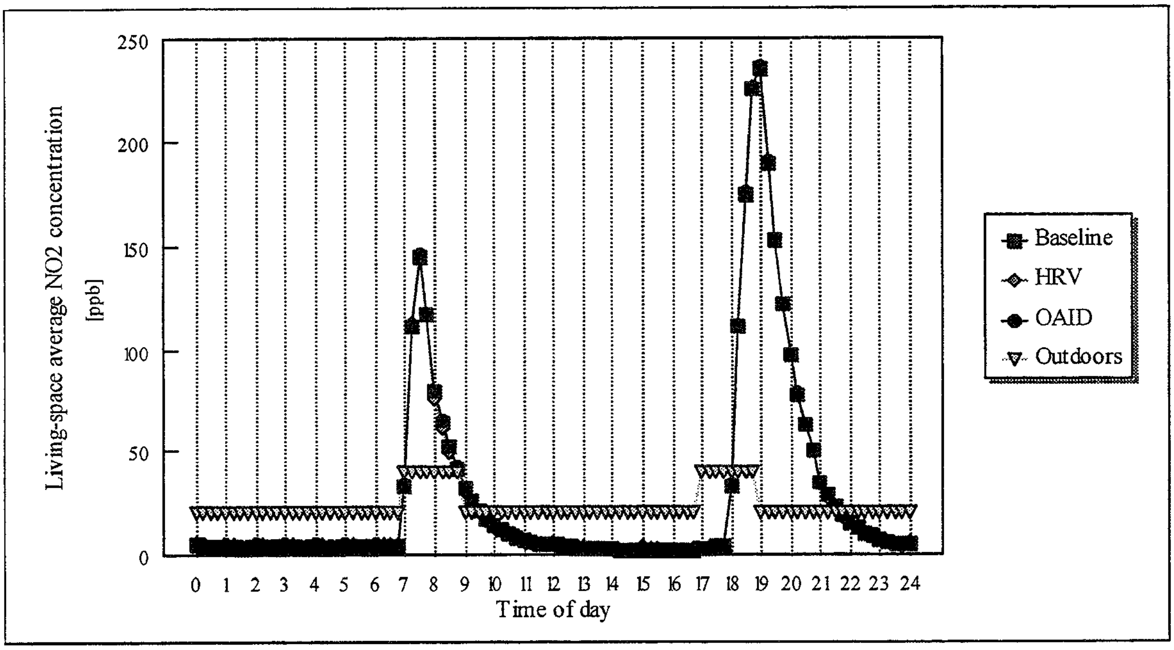


Figure 14 - Transient Living-space Average NO_2 Concentration Due to Oven Source (Tight Miami Ranch House on Cold Day)

As shown in Figure 15, the baseline living-space average fine particle concentration is below the outdoor concentration of 13 μg/m^3 due to a combination of a weak source and pollutant removal inside the building due to deposition and filtration. The peaks due to the oven operation are still apparent but are relatively small compared to the CO and NO_2 peaks shown previously. The fine particle concentrations shown in Figure 15 are below both the initial/maximum burden and reduced level reference points (500 and 100 μg/m^3, respectively) at all times. The EPF reduced the fine particle concentration substantially (an average of 29%) due to an increase in fine particle efficiency from 5% to 30% while the HRV and OAID actually resulted in 5 to 10% increases in fine particle concentrations. These increases in the fine particle concentrations are due to these devices increasing the flow of outdoor air with higher particle concentrations than those inside. The operation of the HVAC system is apparent in the EPF results, in which the system operation causes a sharp decrease in the particle concentration. The particle concentration then increases after the system turns off as particles from outside enter the building due to infiltration.

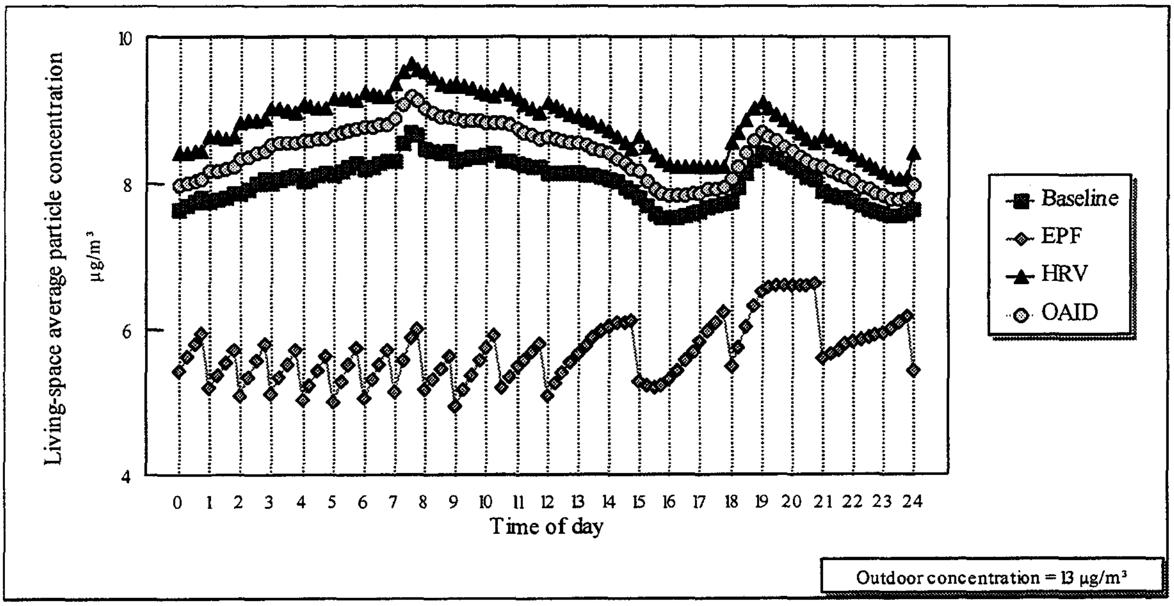


Figure 15 - Transient Living-space Average Fine Particle Concentration Due to Oven Source (Tight Miami Ranch House on Cold Day)

3.2.2 Oven - CO

Figure 16 summarizes the baseline, HRV, and OAID results for CO from the oven. The 24-hour, living-space average CO concentrations range from 1.9 to 4.8 ppm for the baseline cases with an average of 2.7 ppm. Once again, the average concentrations in the tight buildings (3.3 ppm) are higher than in the typical buildings (2.2 ppm) due to the lower air change rate.

The HRV reduced the 24-hour, living-space average CO concentrations due to the oven source by an average of 10% with the reductions ranging from 0.4% to 44%. The percent reduction in CO concentration for all tight house cases was larger than the reduction for the corresponding typical house cases with average reductions of 16% and 4.5%, respectively. The average reduction in CO was greatest for the Miami hot weather cases (22%) followed by the Minneapolis cold weather cases (14%), Miami cold weather cases (9.1%), Minneapolis hot weather cases (7.6%), Minneapolis mild weather cases (7.2%), and Miami mild weather cases (2.6%). The HRV results show the same impacts of envelope airtightness and HVAC system run-time on building air change rates as discussed for the TVOC sources.

The OAID reduced the 24-hour, living-space average CO concentration due to the oven source by an average of 7.4% with the reductions ranging from -0.4% to 37%. As discussed earlier for the floor TVOC source, the average OAID reduction is less than the average HRV reduction because the HRV increases the building air change rates by a greater amount. The impacts of the HRV and OAID on building air change rates is discussed later in this section. The percent reduction in CO concentration for most tight house cases was larger than the reduction for the corresponding typical house cases with average reductions of 12% and 3.1%, respectively. The average reduction in CO was greatest for the Miami hot weather cases (15%) followed by the Minneapolis cold weather cases (11%), Miami cold weather cases and Minneapolis hot weather cases (6.0%), Minneapolis mild weather cases (5.6%), and Miami mild weather cases (0.8%). The OAID results also show the impacts of envelope airtightness and HVAC system run-time.

Maximum 1-hour average CO concentrations for the living-space zones were calculated and are shown in Figure 17. The 1-hour average was calculated for the oven from 6 p.m. to 7 p.m. and is the largest value of the hourly average among the living-space zones. It ranges from 7.7 to 39.3 ppm. On average, the HRV reduced the living-space maximum 1-hour average CO concentration by 0.9%. On average, the OAID *increased* the living-space maximum 1-hour average CO concentration due to the oven source by 0.9%. As seen previously in Figure 13, the modest increase in building air change rates caused by the HRV and OAID has a small impact on the relatively large concentration peaks due to the short-term nature of the oven source. The average impacts of the HRV and OAID are in opposite directions because of nonlinear interactions between the different air change rate increases of the devices, emission rate and timing, outdoor concentration levels and timing, and system operation schedule. If the outdoor concentration were constant, instead of increasing before the source emission, both devices would be expected to reduce the 1-hour concentration slightly with the OAID having a smaller effect.

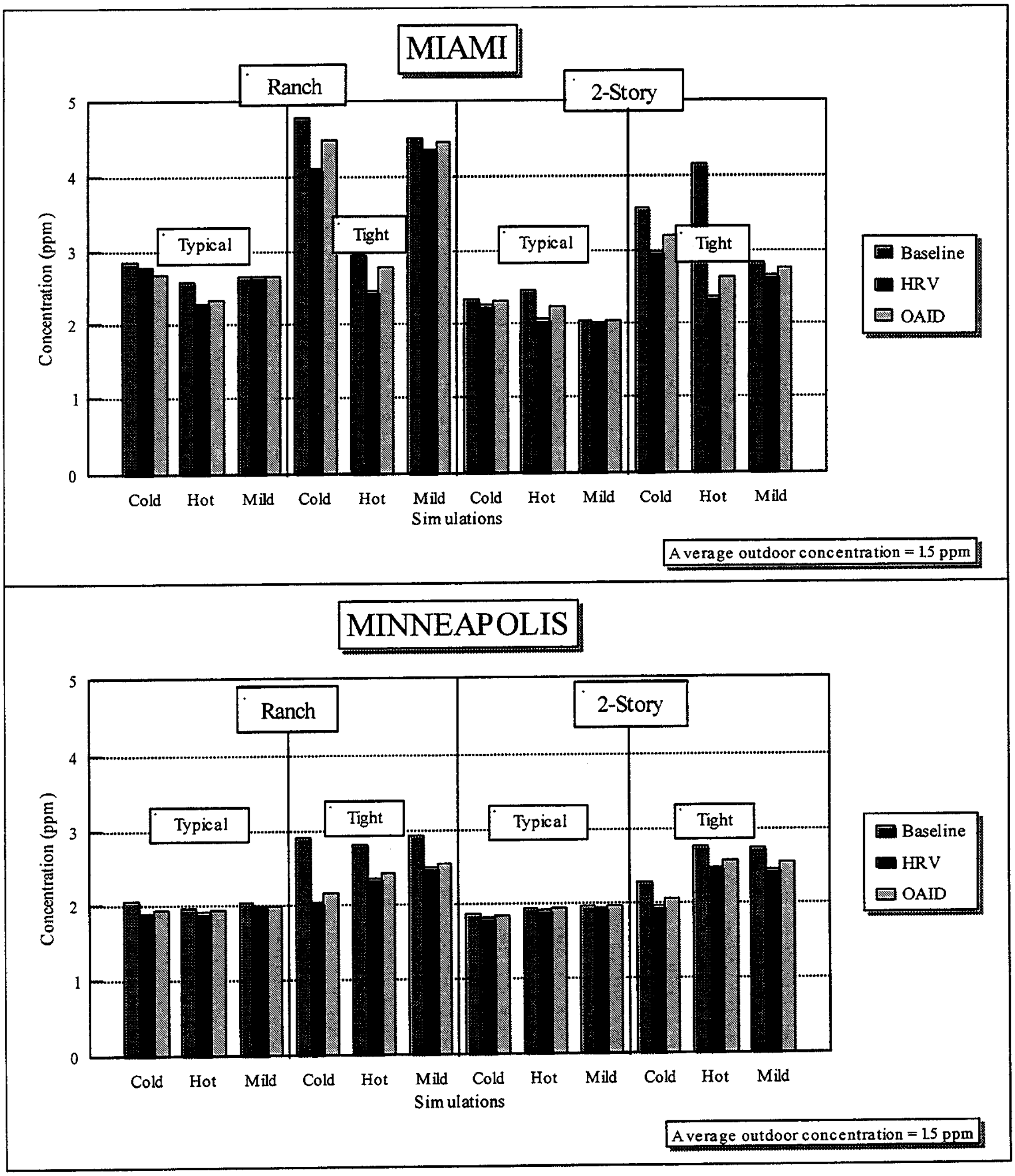


Figure 16 - 24-hour, Living-space Average CO Concentrations Due to Oven Source

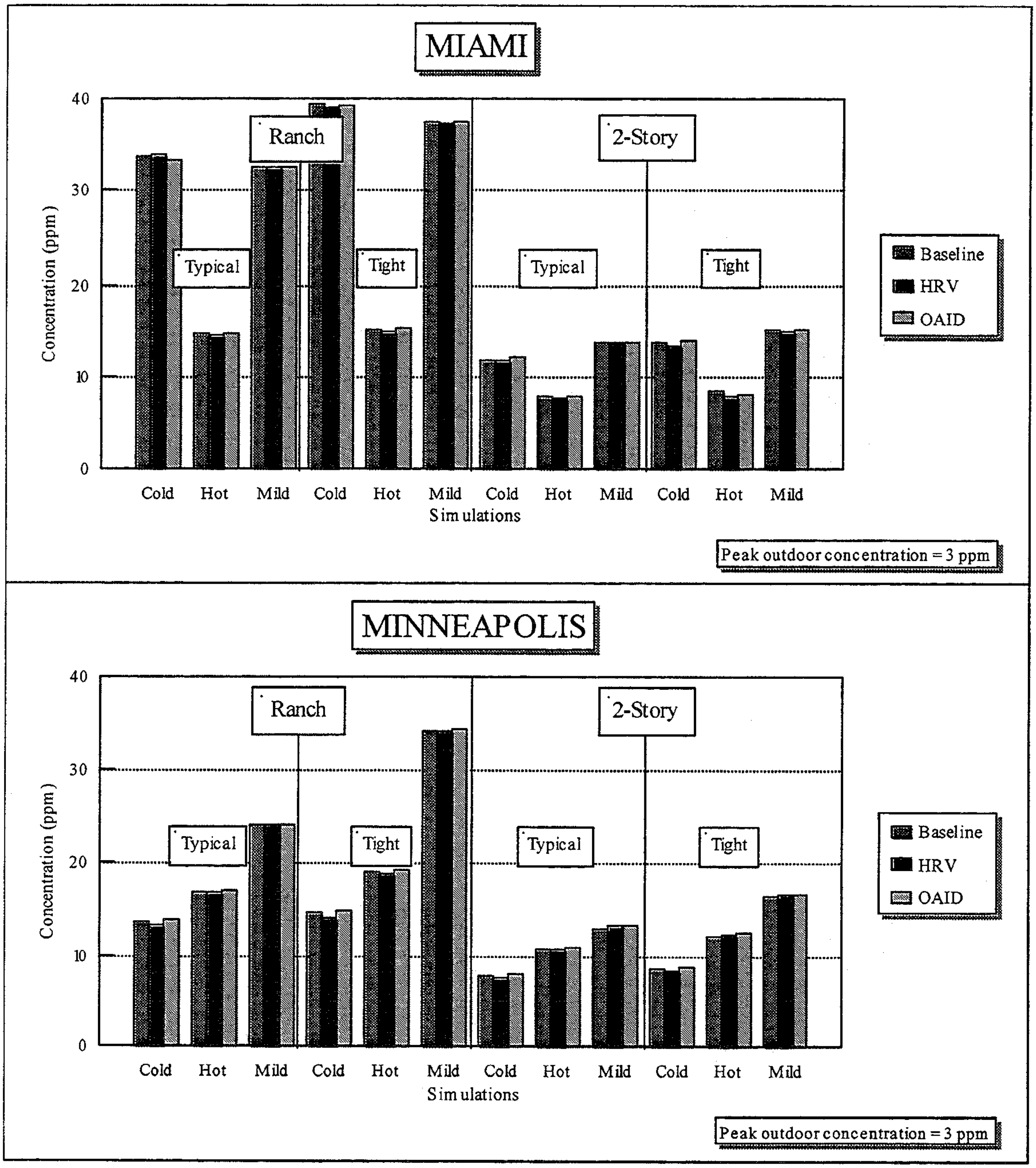


Figure 17 - Maximum One-hour Average CO Concentrations Due to Oven Source

3.2.3 Oven - NO_2

Figure 18 summarizes the baseline, HRV, and OAID results for NO_2 from the oven. The 24-hour, living-space average NO_2 concentrations range from 16 to 28 ppb for the baseline cases with an average 21 ppb. Contrary to the TVOC and CO sources, the average NO_2 concentration is greater for the typical houses (22 ppb) than the tight houses (20 ppb). As shown previously in Figure 14, the NO_2 concentrations are below the outdoor level much of the day because of pollutant decay inside the buildings. Therefore, the increased air change rate of the typical house tends to increase the average indoor concentration. However, this effect is small because the average indoor concentration is only slightly below the average outdoor concentration of 23 ppb.

The HRV *increased* the 24-hour, living-space average NO_2 concentrations due to the oven source by an average of 2.3% with the impacts ranging from a decrease of 2.7% to an increase of 9.4%. The percent increase in NO_2 concentration for all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 3.2% and 1.4%, respectively. The HRV tends to increase the average NO_2 concentration slightly because, as explained above, the indoor concentration is generally lower than the outdoor concentration. This effect may be partially offset by a slight decrease in the peak concentration when the indoor concentration is well above the outdoor concentration.

On average, the OAID *increased* the 24-hour, living-space average NO_2 concentration due to the oven source by 3.3% with the impact ranging from a decrease of 3.6% to an increase of 11%. The percent increase in NO_2 concentration for nearly all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 4.6% and 2.1%, respectively. In general, the OAID results for NO_2 are similar to the HRV results discussed above.

Peak NO_2 concentrations in the living-space zones were examined and are shown in Figure 19. The living-space peak NO_2 concentration due to the oven ranges from 280 to 1686 ppb. Both the HRV and OAID changed the living-space peak NO_2 concentrations due to the oven source by averages of less than 1% with the HRV averaging a small decrease and the OAID averaging a small increase. As seen previously in Figure 14, the modest increases in building air change rate have little effect on the concentrations peaks. As explained for CO due to the oven, the average impact of the HRV and OAID is in opposite directions because of nonlinear interactions between the different air change rate increases of the devices, emission rate and timing, outdoor concentration levels and timing, and system operation schedule.

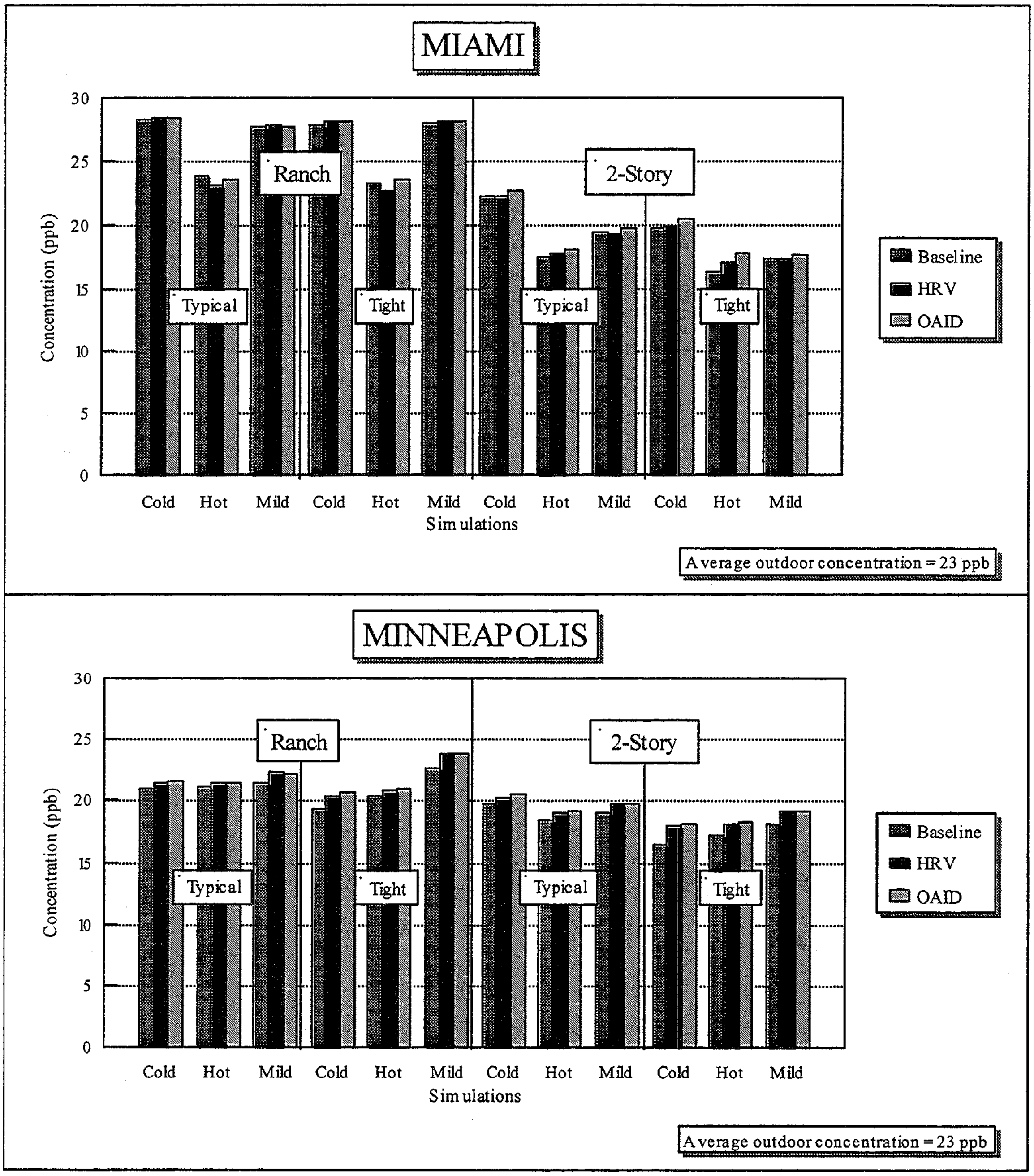


Figure 18 - 24-hour, Living-space Average NO_2 Concentrations Due to Oven Source

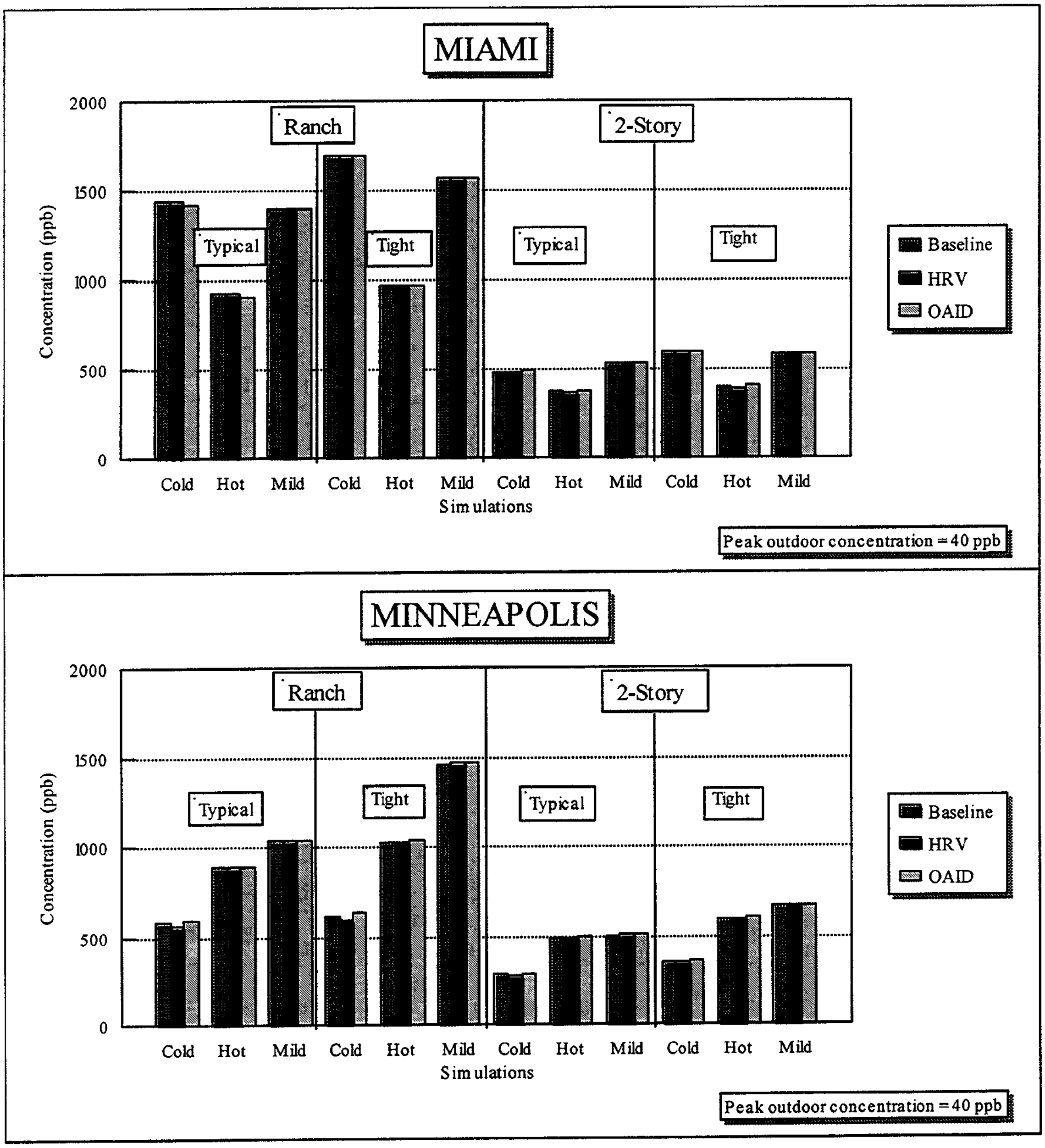


Figure 19 - Peak NO_2 Concentrations Due to Oven Source

3.2.4 Oven - Fine Particles

Figure 20 summarizes the baseline, HRV, OAID, and EPF results for fine particles from the oven source. The 24-hour, living-space average fine particle concentrations range from 5 to 12 $\mu g/m^3$ for the baseline cases with an average of 9 $\mu g/m^3$. The average particle concentration in the typical houses (11 $\mu g/m^3$) was higher than in the tight houses (8 $\mu g/m^3$) because, as explained previously for NO_2, the outdoor air entering the houses is at a higher particle concentration than the indoor concentration because of pollutant removal inside the buildings (deposition and filtration). The difference is somewhat larger for the particles than for NO_2 because the particle source strength is small relative to the NO_2 source strength.

The HRV *increased* the 24-hour, living-space average fine particle concentration due to the oven source by an average of 14% with the increases ranging from 0.3% to 78%. The percent increase in fine particle concentration for all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 22% and 4.5%, respectively. The tight houses have larger relative increases because they start at lower baseline concentrations and experience larger absolute increases. The absolute increases are larger in the tight house cases because a larger difference exists between the outdoor and the indoor concentrations for these cases. The average increase in fine particle concentration was greatest for the Miami hot weather cases (30%) followed by the Minneapolis cold weather cases (21%), Minneapolis hot weather cases (11%), Minneapolis mild weather cases (10%), Miami cold weather cases (6.4%), and Miami mild weather cases (1.8%). The increases depend on system run-time with the greatest increases occurring for the cases with largest system run-time. The dependence on run-time exists because, as shown for one case in Figure 15, outdoor air brought in by the HRV is at a higher concentration than the baseline indoor concentration.

The OAID *increased* the 24-hour, living-space average fine particle concentration due to the oven source by an average of 10% with the increases ranging from 0.3% to 65%. The percent increase in fine particle concentration for all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 18% and 3.1%, respectively. The average increase in fine particle was greatest for the Miami hot weather cases (22%) followed by the Minneapolis cold weather cases (16%), Minneapolis hot weather cases (10%), Minneapolis mild weather cases (8.4%), Miami cold weather cases (4.9%), and Miami mild weather cases (1.1%). The impact of the OAID is similar to that of the HRV explained above, but the OAID impact was somewhat smaller than the HRV impact. This may be a result of the OAID pressurizing the house, which would reduce the flow of unfiltered air through the building envelope and partially offset the increased particle concentration increase due to the increased building air change rate. However, the offset due to the filtration of air entering through the OAID was small because the filtration efficiency of the standard furnace filter in the outdoor air path was only 5% for fine particles.

The electrostatic particulate filter (EPF) reduced the 24-hour, living-space average fine particle concentration due to the oven source by an average of 30% for the oven with the reductions ranging from 4.5% to 63%. The average percent reduction was larger for all tight house cases (37%) than for the corresponding typical house cases (23%). The typical and tight house reductions varied only slightly in absolute magnitude, but the tight house percent reductions were larger than the typical house reductions because they were based on lower baseline concentrations. For the oven source, the average reduction was greatest for the Miami hot weather cases (54%) followed by the Minneapolis cold weather cases (45%), Minneapolis hot weather cases (28%), Minneapolis mild weather cases (26%), Miami cold weather cases (21%), and Miami mild weather cases (7.4%). Once again, the reductions depend on system run-time with the largest reductions occurring for the cases with the greatest system run-time.

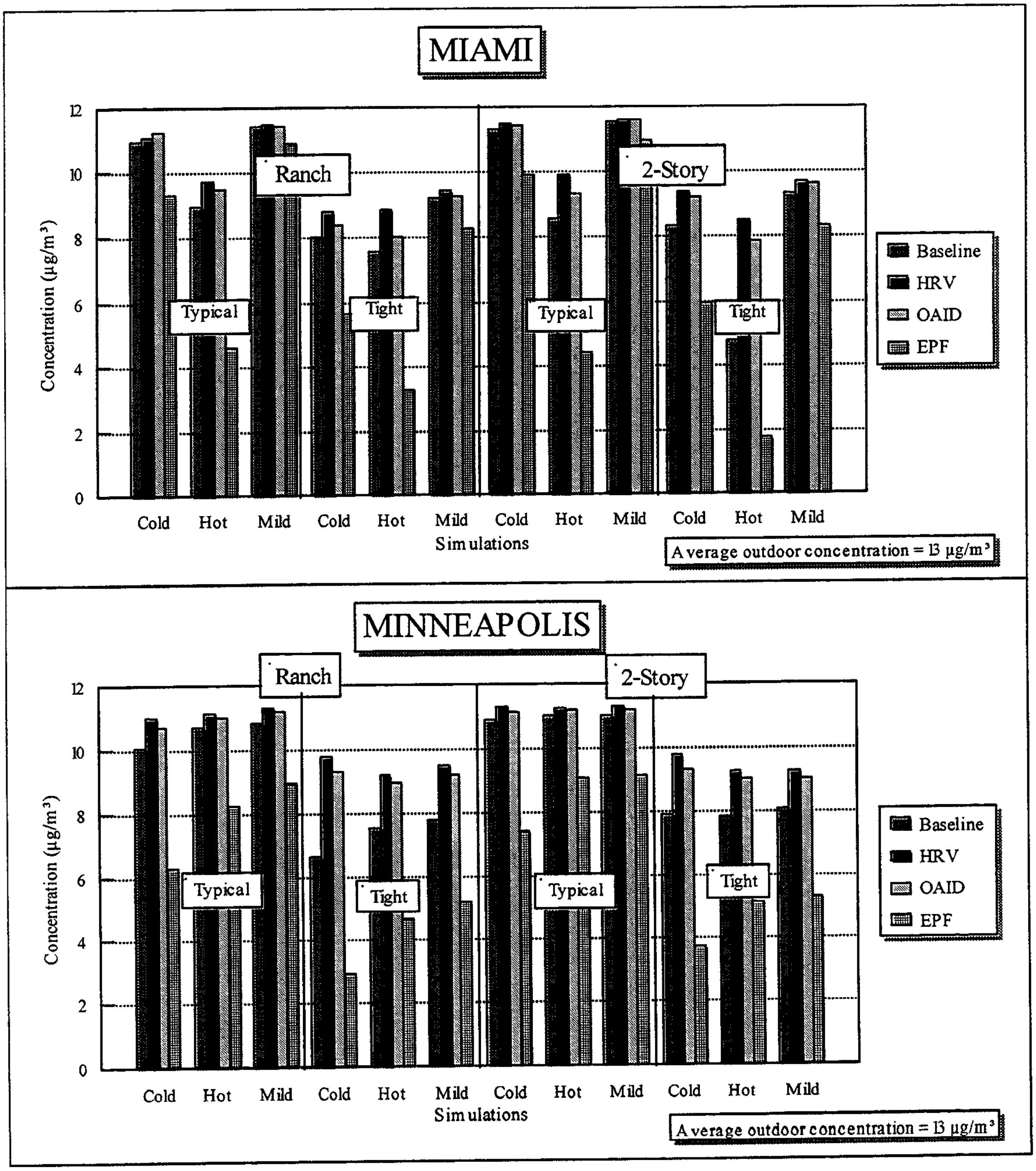


Figure 20 - 24-hour, Living-space Average Fine Particle Concentrations Due to Oven Source

3.2.5 Heater - Transient

Examples of the transient living-space average concentrations of CO, NO_2, and fine particles due to the heater are shown in Figures 21, 22, and 23. These results are for the tight Miami ranch house in cold weather. All three figures show very low living-space pollutant concentrations with levels below those outdoors throughout the day for NO_2 and fine particles, and part of the time for CO. As a result, the HRV and OAID increase indoor pollutant concentrations for this case, although the increases are modest. As seen in Figure 23, the EPF reduced the fine particle concentrations by an average of about 29%.

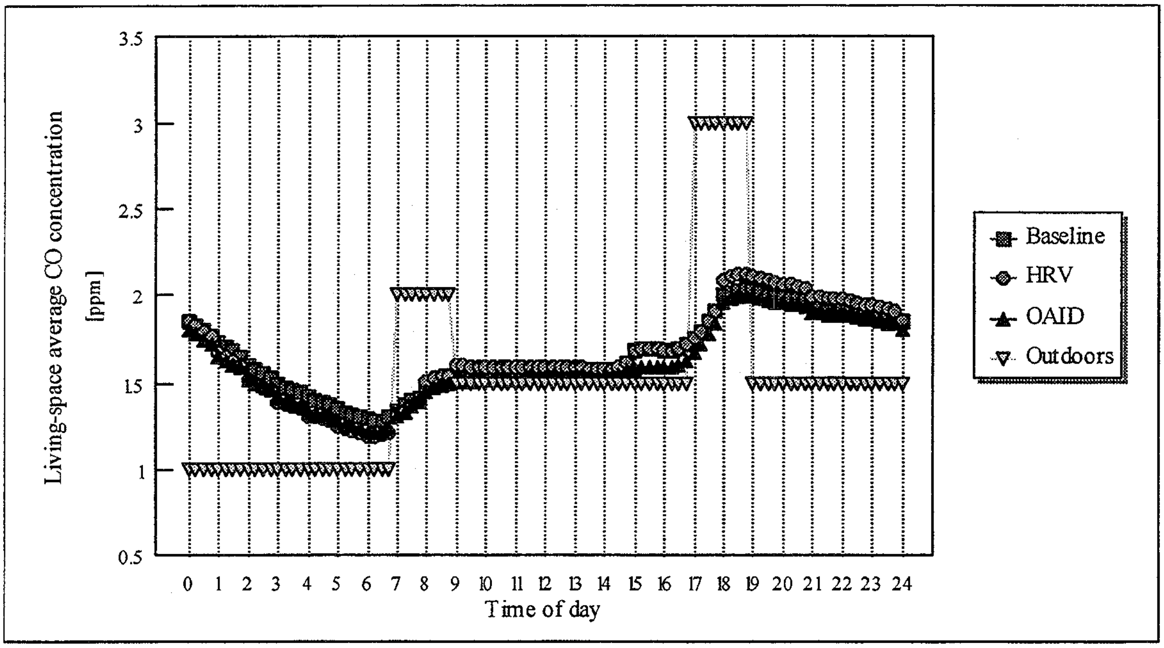


Figure 21 - Transient Living-space Average CO Concentration Due to Heater Source (Tight Miami Ranch House on Cold Day)

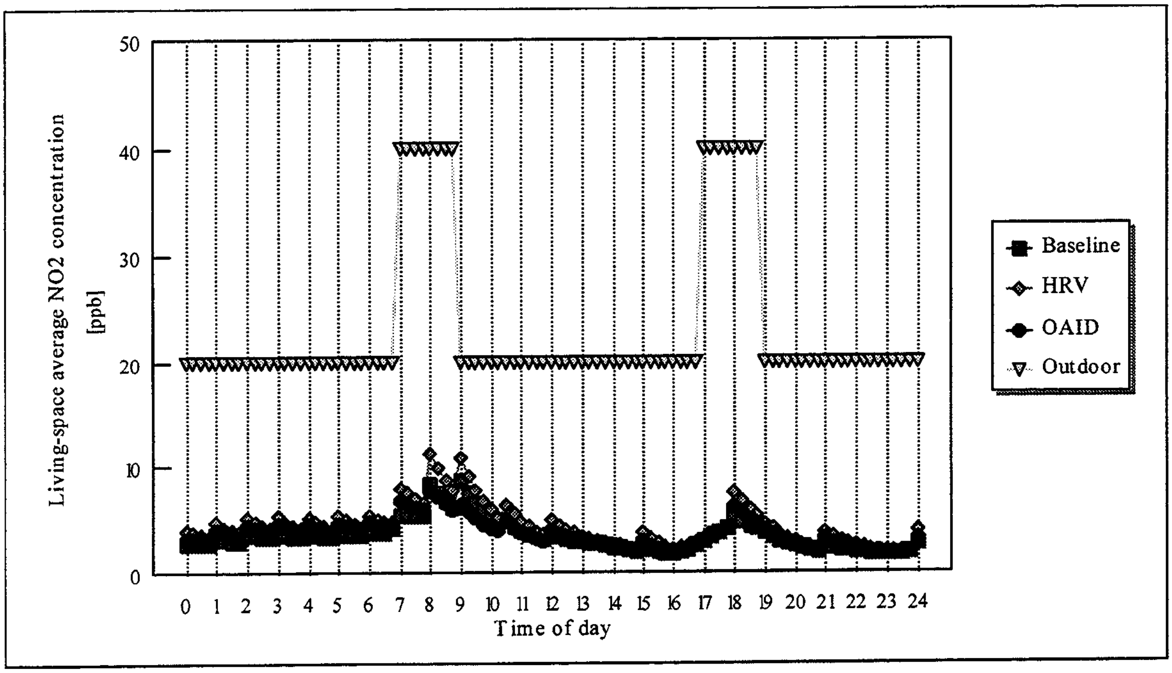


Figure 22 - Transient Living-space Average NO_2 Concentration Due to Heater Source (Tight Miami ranch House on Cold Day)

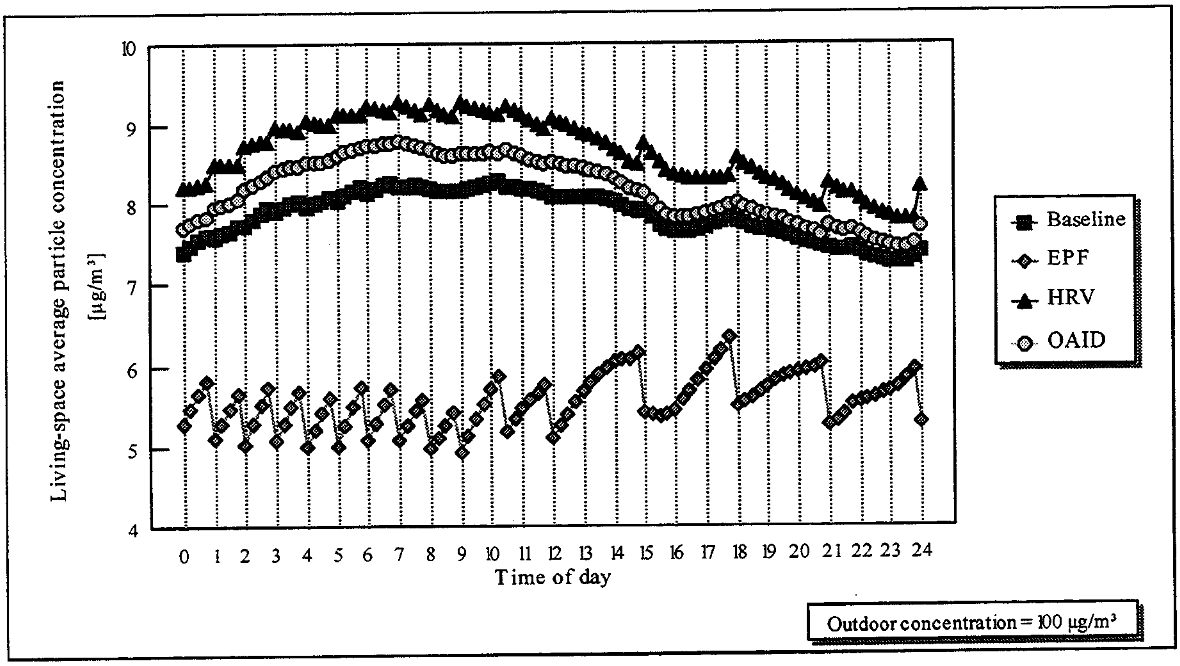


Figure 23 - Transient Living-space Average Fine Particle Concentration Due to Heater Source (Tight Miami Ranch House on Cold Day)

3.2.6 Heater - CO

Figure 24 summarizes the baseline, HRV, and OAID results for CO from the heater. The 24-hour, living-space average CO concentrations due to the heater source range from 1.6 to 2.8 ppm for the baseline cases with an average of 2.0 ppm. The average concentration in tight houses (2.2 ppm) is higher than in typical houses (1.8 ppm) due to the lower building air change rates in the tight houses. The average concentration was highest in the Minneapolis mild weather cases (2.3 ppm) followed by the Minneapolis cold weather cases (2 ppm) and the Miami cold weather cases (1.6 ppm). Concentrations were higher in the Minneapolis cases, in part, due to an additional heater located in the basement zone which did not exist in the Miami house (all cases had a heater in the garage zone). Little CO is transported from the heater in the garage to the living space as evidenced by the lack of variation in pollutant concentrations between the Miami cases, which all have average concentrations close to the average outdoor concentration. The "NA" designation in the figure indicates that the heater was not used for the Minneapolis hot, Miami mild, and Miami hot cases.

The HRV reduced the 24-hour, living-space average CO concentration by an average of 8.1% with the impacts ranging from an increase of 0.3% to a reduction of 26%. The percent reduction in CO concentration for all tight house cases was larger than the reduction for the corresponding typical house cases with average reductions of 13% and 3.1%, respectively. The average reduction in CO was greatest for the Minneapolis cold and mild weather cases (12%) followed by the Miami cold weather cases (0.2%). The HRV had little or no effect on the CO concentrations in the Miami houses because, as discussed above, the garage source contributed little CO to the living-space zones. The higher CO concentrations in the Minneapolis houses were reduced by the HRV through the introduction of outdoor air through the HVAC system.

The OAID reduced the 24-hour, living-space average CO concentration due to the heater source by an average of 7.1% with the reductions ranging from 0% to 22%. The percent reduction in CO concentration for all tight house cases was larger than the reduction for the corresponding typical house cases with average reductions of 12% and 2.2%, respectively. The average reduction in CO was greatest for the Minneapolis cold and mild weather cases (10%) followed by the Miami cold weather cases (1.4%). In general, the OAID results were similar to the HRV results for the heater source of CO.

Maximum 1-hour average CO concentrations for the living-space zones due to the heater source are shown in Figure 25. The maximum 1-hour average CO concentration for the heater was calculated from 9 a.m. to 10 a.m. and is the largest value of the hourly average concentrations among the living-space zones. It ranges from 1.6 to 3.5 ppm for the baseline cases. On average, the HRV reduced the living-space maximum 1-hour average CO concentration by 4.8% and the OAID reduced the living-space maximum 1-hour average CO concentration by 7.9%. The OAID may have reduced the 1-hour average concentration by a greater amount than the HRV by pressurizing the living-space zones relative to the basement and garage which would reduce airflow and pollutant transport from these zones into the living-space.

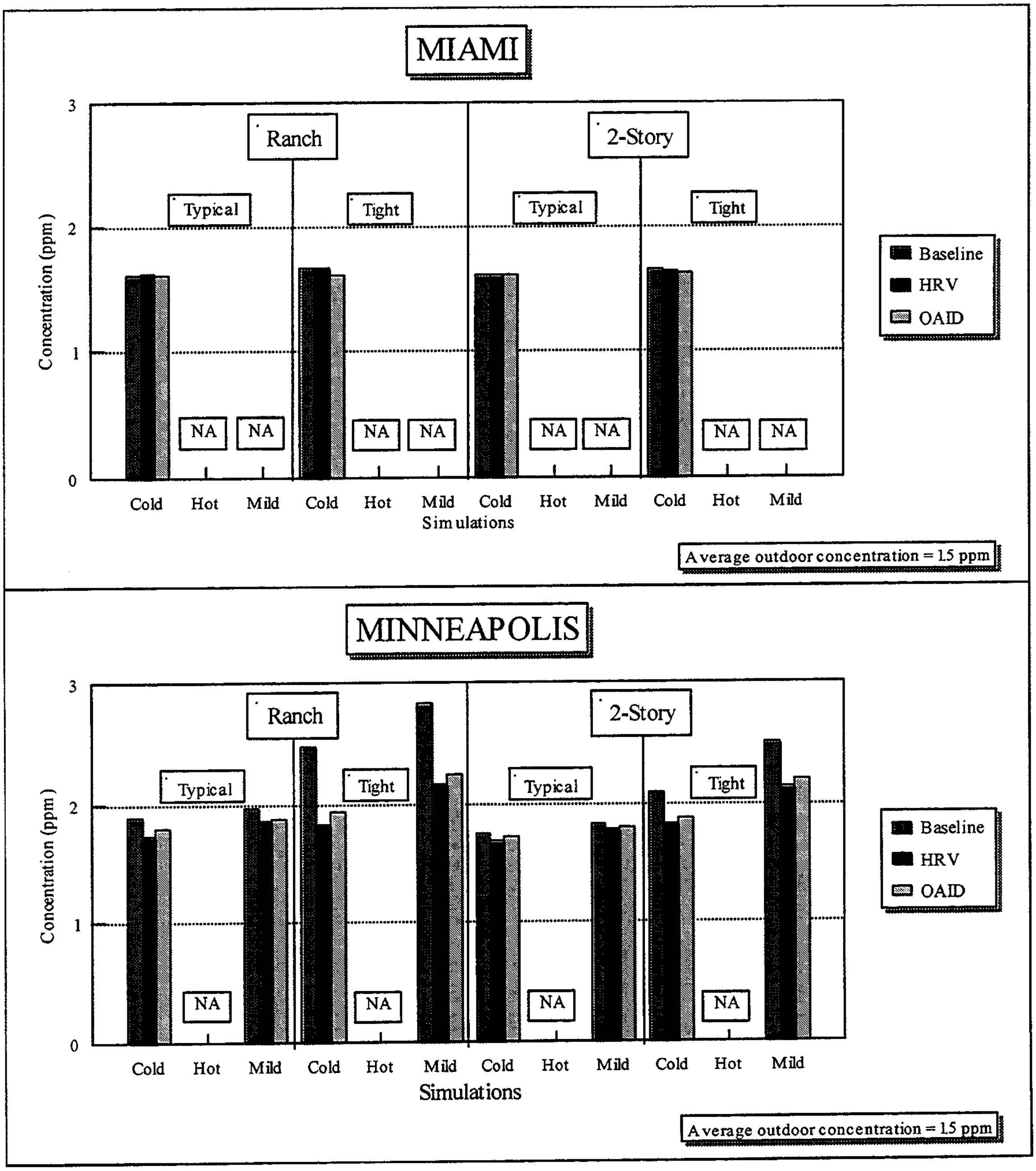


Figure 24 - 24-hour, Living-space Average CO Concentrations Due to Heater Source

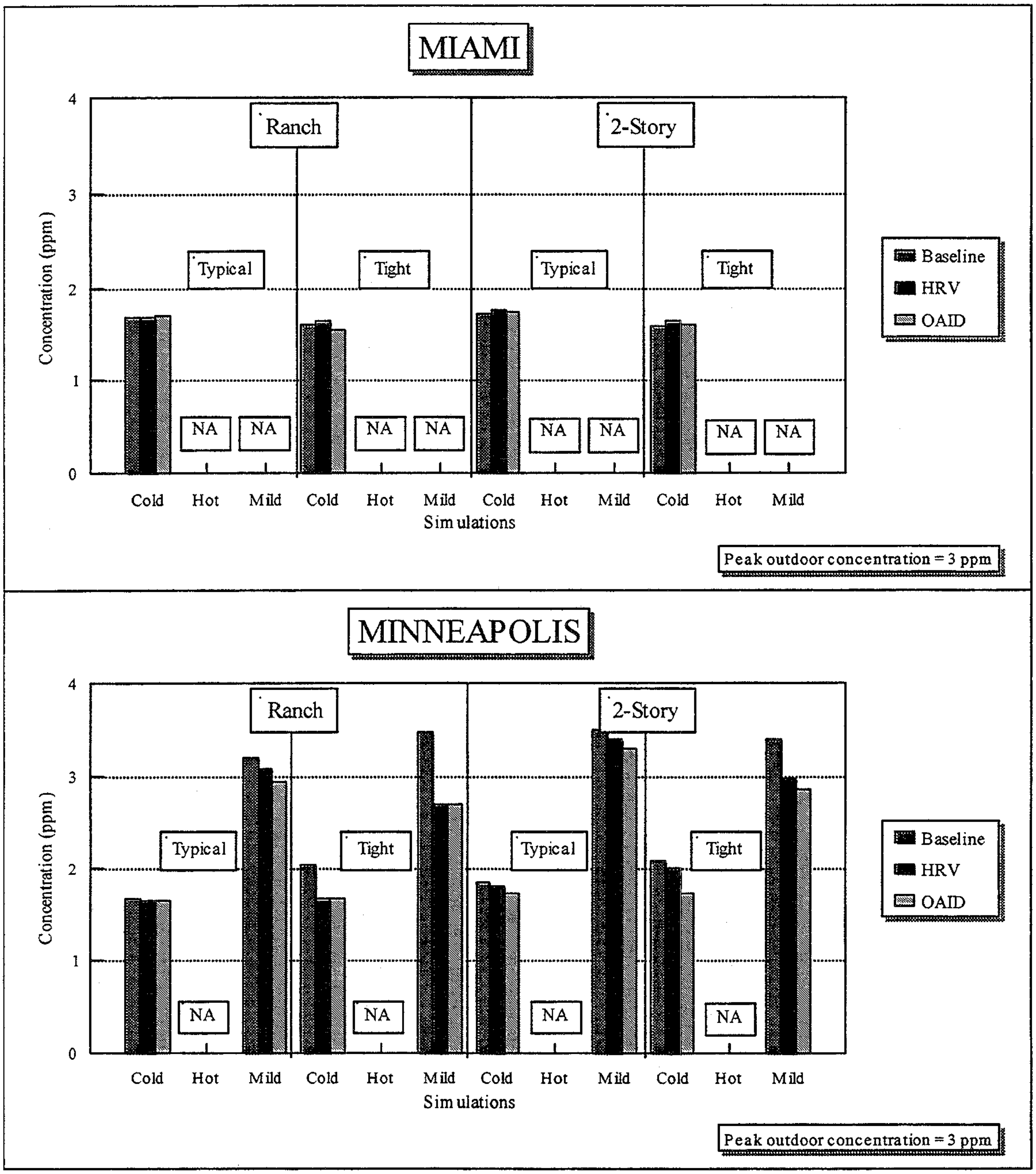


Figure 25 - Maximum One-hour Average CO Concentrations Due to Heater Source

3.2.7 Heater - NO_2

Figure 26 summarizes the baseline, HRV, and OAID results for NO_2 from the heater. The 24-hour, living-space average NO_2 concentrations range from 4 to 20 ppb for the baseline cases with an average of 13 ppb. The tight houses had lower average NO_2 concentrations than the typical houses (11 ppb versus 15 ppb) because the indoor NO_2 concentration is below the outdoor concentration through most or all of the day, as shown in Figure 22 for the tight Miami ranch house in cold weather. The living-space concentration is below the outdoor concentration because of a combination of pollutant decay inside the buildings and a relatively weak indoor source. The concentrations are highest for the Minneapolis cold weather cases (18 ppb) followed by the Minneapolis mild weather cases (15 ppb) and the Miami cold weather cases (6 ppb). As discussed for CO from the heater, the concentrations are lower in the Miami houses because they contain only a heater in the garage while the Minneapolis houses have an additional heater in the basement. The large difference between the two cities for NO_2 relative to CO could exist because of NO_2 decaying inside the buildings.

The HRV *increased* the 24-hour, living-space average NO_2 concentration due to the heater source by an average of 7.5% with the impacts ranging from a decrease of 1.7% to an increase of 37%. The concentration increased because more NO_2 entered the buildings from the outdoors than was generated from the indoor source, with the significance of this difference increased by the existence of NO_2 decay. The percent increase in NO_2 concentration for all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 13% and 2.1%, respectively. The concentration increased more in the tight houses because the HRV had a larger relative impact on the air change rate. The average increase in NO_2 was greatest for the Miami cold weather cases (19%) followed by the Minneapolis mild weather cases (3.7%). On average, the HRV reduced the NO_2 concentration for the Minneapolis cold weather cases (0.3%). The impacts for the individual cases depended on the interaction and timing of the system run-time, source emission, outdoor concentration, and pollutant removal. For example, the HRV reduced the average NO_2 concentration in the typical Minneapolis cold weather cases because the increases in concentration when the heater was off were relatively small and were outweighed by large reductions when the heater was on.

On average, the OAID *increased* the 24-hour, living-space average NO_2 concentration due to the heater source by 3.0% with the impact ranging from a decrease of 4.5% to an increase of 27%. The percent increase in NO_2 concentration for most tight house cases was larger than the increase for the corresponding typical house cases with average increases of 4.9% and 1.2%, respectively. The OAID increased the NO_2 concentration for the Miami cold weather cases by 13%. The OAID reduced the NO_2 concentration for the Minneapolis mild (1.1%) and Minneapolis cold weather cases (2.3%).

The peak living-space NO_2 concentrations were examined and are shown in Figure 27. The peak living-space NO_2 concentration due to the heater source for any baseline case ranges from 10 to 129 ppb. The NO_2 peaks were lower in the Miami houses because they lacked the basement source. The HRV and OAID reduced the living-space peak NO_2 concentrations by averages of 5.9% and 8.8%, respectively.

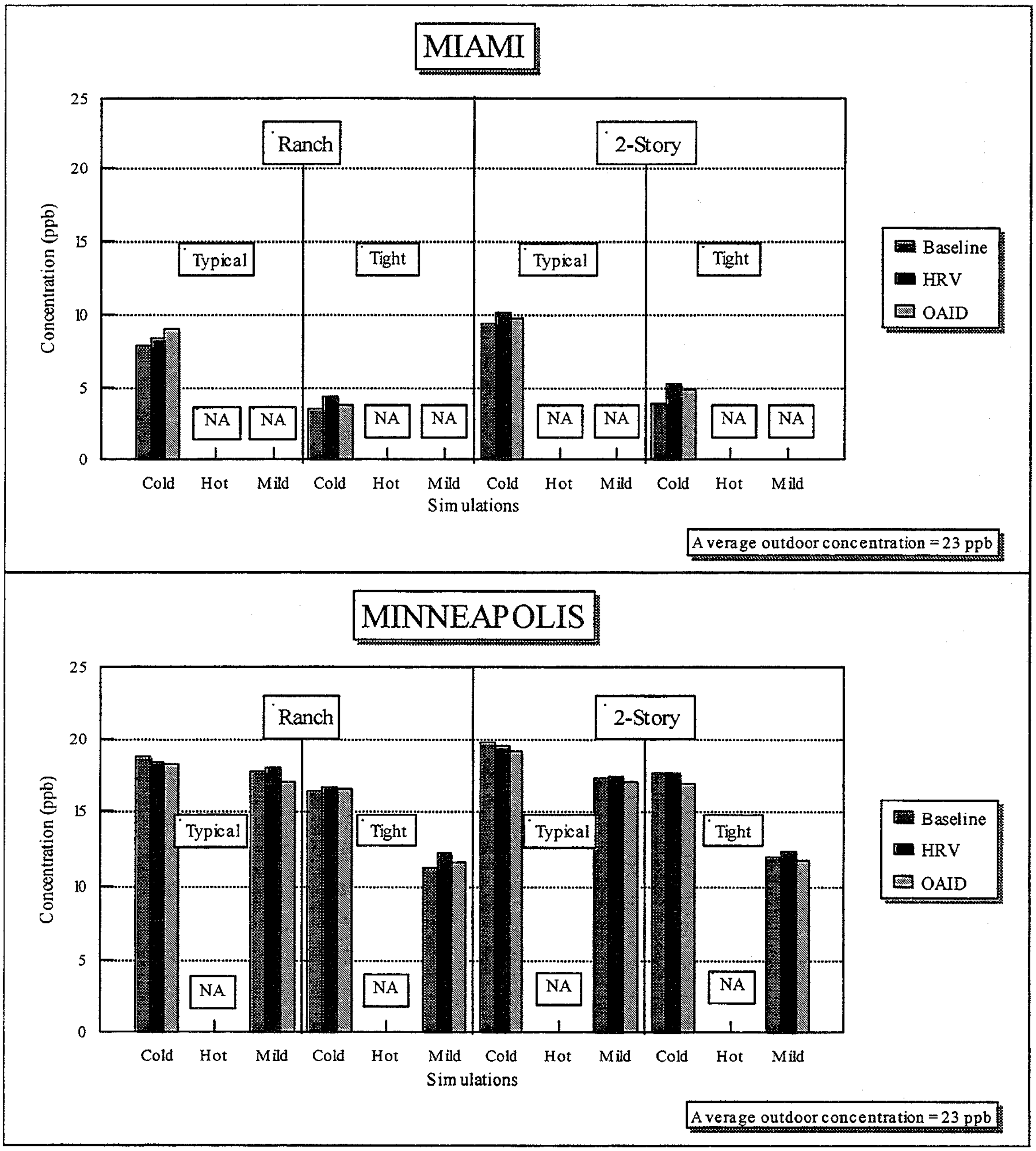


Figure 26 - 24-hour, Living-space Average NO_2 Concentrations Due to Heater Source

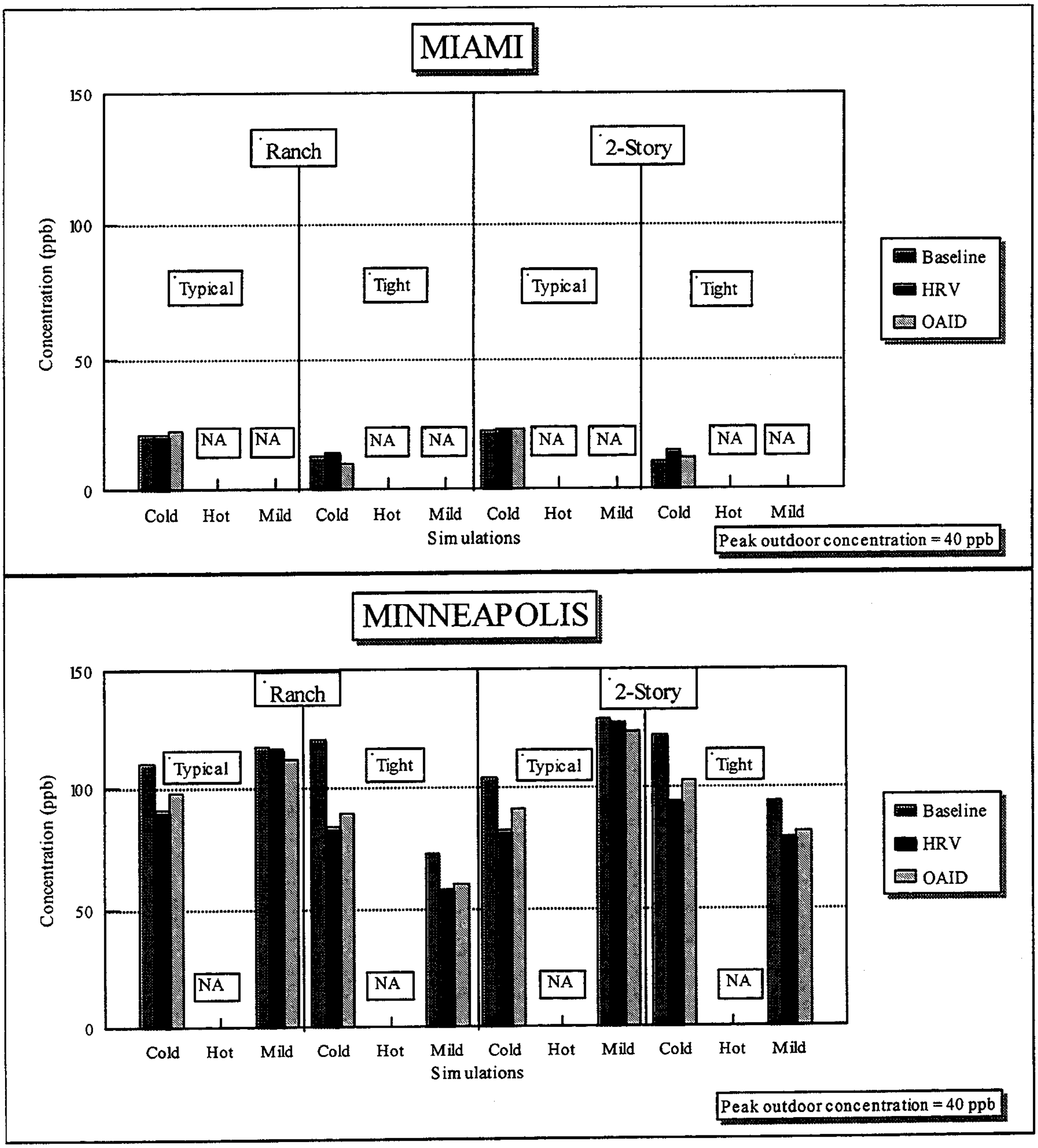


Figure 27 - Peak NO_2 Concentrations Due to Heater Source

3.2.8 Heater - Fine Particles

Figure 28 summarizes the baseline, HRV, OAID, and EPF results for fine particles from the heater. The 24-hour, living-space average fine particle concentrations range from 7 to 11 $\mu g/m^3$ for the baseline cases with an average 10 $\mu g/m^3$. The baseline heater fine particle concentration results are nearly identical to the baseline oven fine particle concentration results shown in Figure 20 because, for both cases, the sources are weak enough that the living-space concentrations depend almost entirely on the entry of particles from outside. Since the outdoor conditions and airflows are the same for both sources, the living-space concentrations are the same.

The HRV *increased* the 24-hour, living-space average fine particle concentration due to the heater source by an average of 9.9% with the increases ranging from 1.4% to 35%. As explained for the oven source, the particle concentration increases are caused by increased building air change rates with outdoor air containing higher particle concentrations than the indoor air. The percent increase in fine particle concentration for all tight house cases (17%) was larger than the increase for the corresponding typical house cases (3.0%) because, as explained for the oven, the tight houses start at lower baseline concentrations and experience larger absolute increases. The absolute increases are larger in the tight house cases because a larger difference exists between the outdoor and the indoor concentrations for these cases. The average increase in fine particle concentration was greatest for the Minneapolis cold weather cases (16%) followed by the Minneapolis mild weather cases (7.0%) and the Miami cold weather cases (6.6%). As discussed above for the baseline concentrations, the percent changes due to the HRV are nearly the same as those shown in Figure 20 for the oven source of fine particles.

The OAID *increased* the 24-hour, living-space average fine particle concentration due to the heater source by an average of 7.6% with the increases ranging from 1.0% to 30%. The percent increase in fine particle concentration for all tight house cases (13%) was larger than the increase for the corresponding typical house cases (2.3%). The average increase in fine particle was greatest for the Minneapolis cold weather cases (13%) followed by the Minneapolis mild weather cases (5.3%), and the Miami cold weather cases (4.8%). The OAID results for the HRV impact on heater fine particle concentrations were nearly identical to those shown in Figure 20 for the oven source. As described for the oven source, the OAID impact was somewhat smaller than the HRV impact - possibly because the OAID pressurizes the house and reduces the flow of unfiltered air through the building envelope. This pressurization effect partially offsets the particle concentration increase caused by the increased building air change rate.

The electrostatic particulate filter (EPF) reduced the 24-hour, living-space average fine particle concentration by an average of 31% for the heater source with the reductions ranging from 13% to 58%. The average percent reduction was larger for all tight house cases (28%) than for the corresponding typical house cases (15%). The average reduction was greatest for the Minneapolis cold weather cases (46%) followed by the Minneapolis mild weather cases (27%), and the Miami cold weather cases (21%). Once again, the EPF results for the heater are nearly the same as those for the oven. As explained previously, the reductions depend on the HVAC system run-time with the largest reductions occurring for the cases with the greatest system run-time.

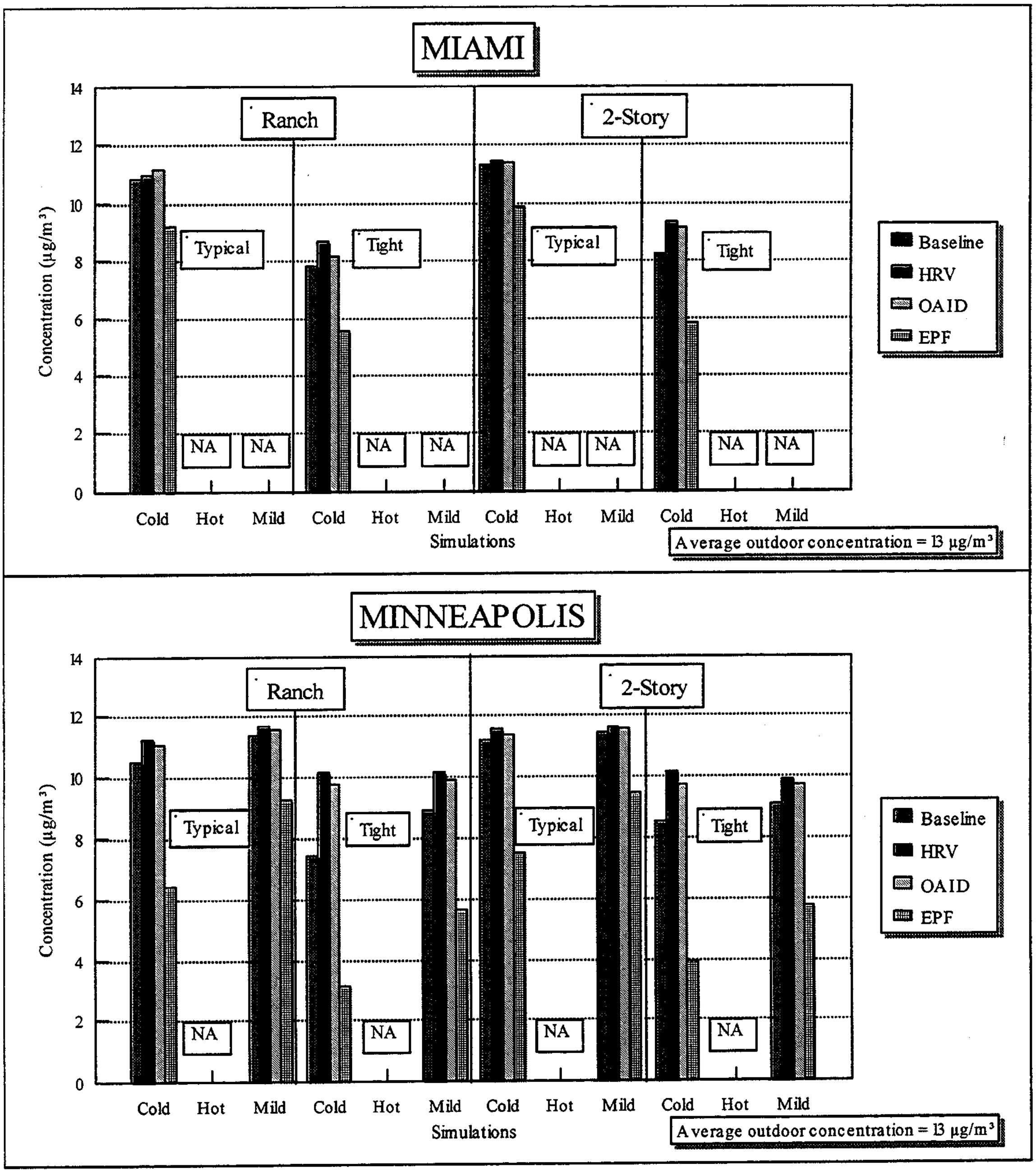


Figure 28 - 24-hour, Living-space Average Fine Particle Concentrations Due to Heater Source

3.3 Elevated Outdoor Air Pollutants

This subsection presents the simulation results for the elevated outdoor levels of CO, NO_2, and coarse particles. For the elevated outdoor pollution cases, no indoor sources were included. Selected transient results for all pollutants are presented first and are followed by detailed summaries of average concentrations for each pollutant. It is important to note that, due to the cyclic calculation approach used in the simulations, the cases presented correspond to a situation where the ambient concentrations are high for several days in a row rather than a single day of elevated concentrations that follows a number of more typical days.

3.3.1 Outdoor Air - Transient

Examples of the transient living-space concentrations of CO, NO_2, and coarse particles due to elevated outdoor pollution are shown in Figures 29, 30, and 31, respectively, for the tight Miami ranch house in cold weather. The indoor CO concentrations for all cases in Figure 29 are nearly identical; the concentration gradually increases when the outdoor concentration is higher than indoors and gradually decreases when the outdoor concentration is lower. This simple pattern occurs because CO is a non-reactive pollutant with no filtration and, for these cases, no indoor source exists. The HRV and OAID increase the indoor CO concentration slightly during the portion of the day that the indoor concentration is below the outdoor concentration, and decrease the indoor CO concentration when it is above the outdoor concentration.

Since NO_2 decays inside the houses and there is no indoor source, the living-space NO_2 concentration is always below the outdoor concentration in Figure 30. The indoor NO_2 concentration increases when the HVAC system is on, due to an increase in the building air change rate, and when the outdoor concentration increases. The HRV and OAID increase the indoor concentration above the baseline cases because they bring in additional NO_2 from outside. However, their impact is relatively small due in part to the limited system run-time.

Similarly to NO_2, the coarse particle concentrations are always well below the outdoor concentration in Figure 31 because of pollutant removal inside the building. The difference between indoor and outdoor particulate levels is much larger than for NO_2 because particles are removed from the air by both filtration and deposition. For this case, the OAID has the greatest impact on the particle concentration with a small reduction in concentrations throughout the day; the EPF reduces the particle concentration by an even smaller amount; and the HRV increases the particle concentration slightly. The OAID results may be due to the pressurization effect, discussed previously for the heater and oven sources, which reduces the infiltration of unfiltered air through the building envelope and replaces it with filtered air entering through the OAID. The reductions due to the EPF are small due to the small increase in filtration efficiency from 90% to 95% for coarse particles. The HRV increases the particle concentrations because, as discussed previously, the additional air brought into the building has a higher particle concentration than the indoor air.

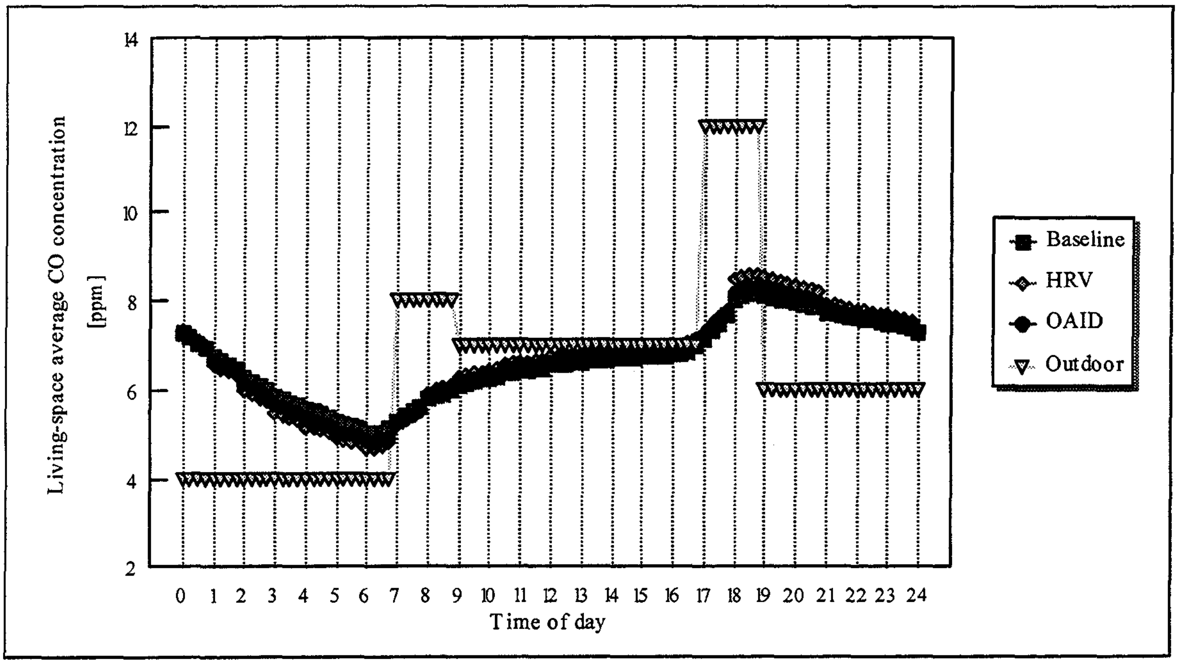


Figure 29 - Transient Living-space Average CO Concentration Due to Elevated Outdoor Pollution (Tight Miami Ranch House on cold Day)

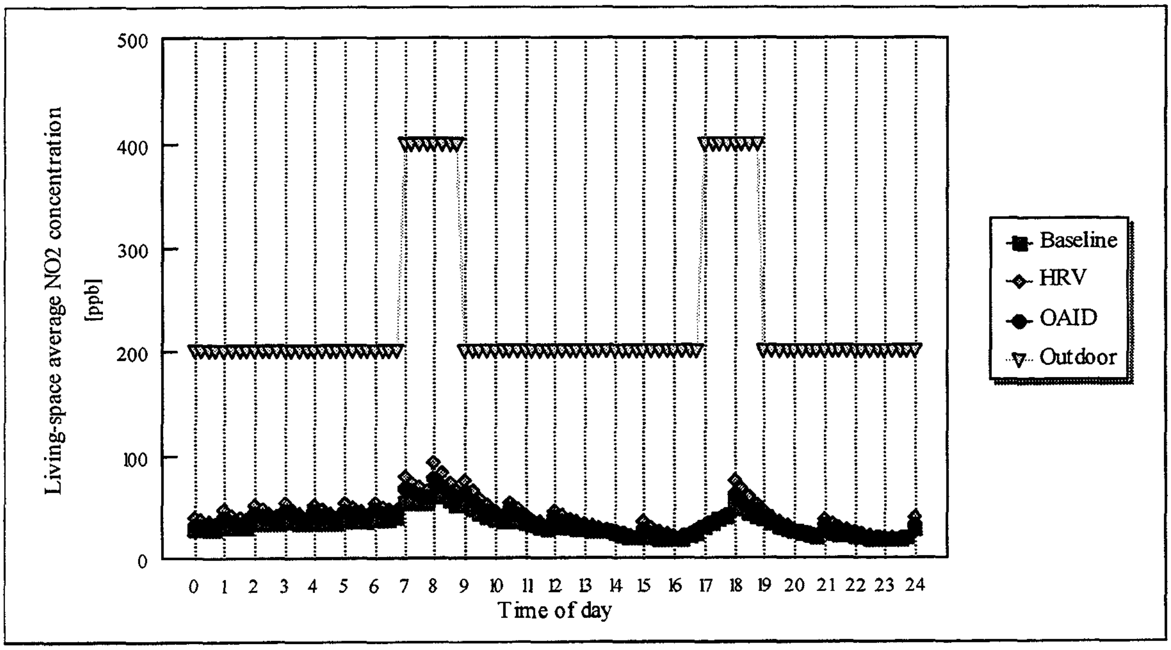


Figure 30 - Transient Living-space Average NO_2 Concentration Due to Elevated Outdoor Pollution (Tight Miami Ranch House on Cold Day)

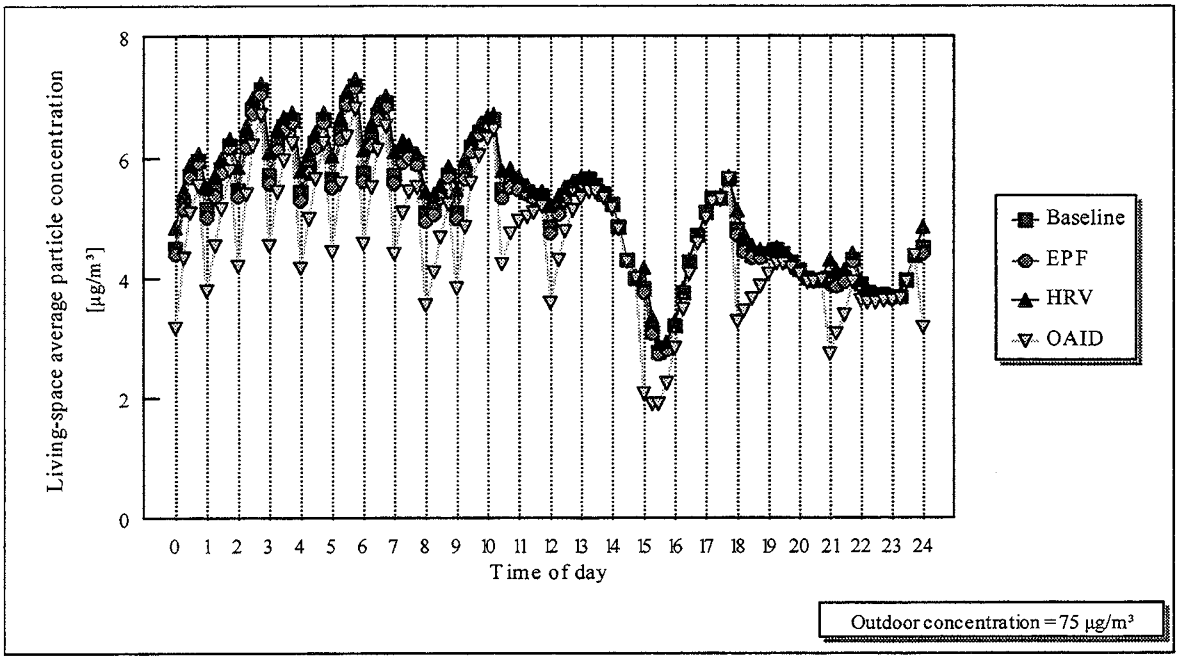


Figure 31 - Transient Living-space Average Coarse Particle Concentration Due to Elevated Outdoor Pollution (Tight Miami Ranch House on Cold Day)

3.3.2 Outdoor Air - CO

The 24-hour, living-space average concentrations due to elevated outdoor CO are shown in Figure 32. The baseline concentrations range from 6.6 to 7.2 ppm with an average of 6.8 ppm. The variations from case to case are minimal because the cyclic calculation approach used in the simulations results in the indoor concentration building up to approximately the same 'equilibrium' concentration for each case regardless of the building air change rate. The HRV and OAID both had very small impacts on the 24-hour, living-space CO concentration. The impacts ranged from a decrease of 3.2% to an increase of 2.7% with the average change being a decrease of 0.1% for the HRV and 0.2% for the OAID. The small impacts of the IAQ controls were also due to the cyclic calculation approach. The direction of the small impacts depended on the timing of the HRV and OAID operation with respect to the CO peaks (more operation during the peaks tends to increase the indoor concentration while more operation during the valleys tends to decrease it). A single test case (tight Minneapolis 2-story house on cold day) of a single day calculation with initial concentration of zero was examined. For this test case, operation of the HRV increased the average indoor concentration in a single zone by about 10%.

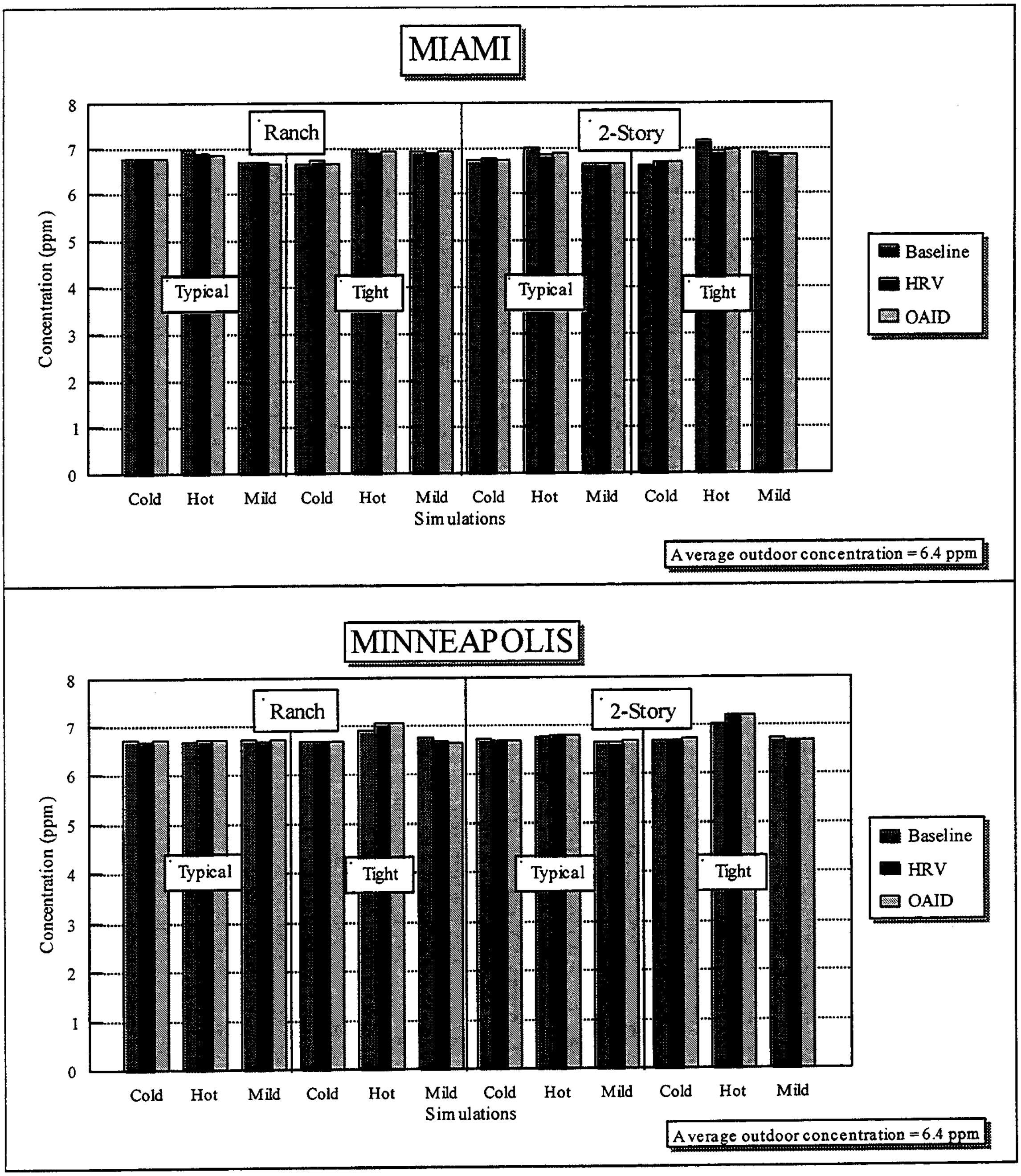


Figure 32 - 24-hour, Living Space Average CO Concentrations Due to Elevated Outdoor Levels

3.3.3 Outdoor Air - NO_2

The 24-hour, living-space average concentrations due to elevated outdoor NO_2 are shown in Figure 33. The baseline concentrations range from 21 to 119 ppb with an average 66 ppb. The average concentration was substantially higher in the typical houses (94 ppb) than in the tight houses (40 ppb) because, as seen in Figure 30 for the tight Miami ranch house in cold weather, the pollutant decay causes lower concentrations inside the buildings than outside.

The HRV *increased* the 24-hour, living-space average NO_2 concentration due to the elevated outdoor levels by an average of 37% with the increases ranging from 1.4% to 196%. The percent increase in NO_2 concentration for all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 60% and 14%, respectively. This difference in the relative increase is due to the larger relative increase in building air change rates and the lower baseline NO_2 concentrations. The average increase in NO_2 was greatest for the Miami hot weather cases (74%) followed by the Minneapolis cold weather cases (58%), Minneapolis hot weather cases (34%), Minneapolis mild weather cases (31%), Miami cold weather cases (20%), and the Miami mild weather cases (5.7%). As discussed previously, these increases depend on the HVAC system run-time which was greatest in the Miami hot weather and Minneapolis cold weather cases and lowest in the Miami mild weather cases.

The OAID *increased* the 24-hour, living-space average NO_2 concentration due to the elevated outdoor levels by an average of 29% with the increases ranging from 0.7% to 164%. The percent increase in NO_2 concentration for nearly all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 48% and 10%, respectively. The average increase in NO_2 was greatest for the Miami hot weather cases (56%) followed by the Minneapolis cold weather cases (45%), Minneapolis hot weather cases (28%), Minneapolis mild weather cases (25%), Miami cold weather cases (16%), and the Miami mild weather cases (3.5%). In general, the OAID impacts were similar but somewhat smaller than the HRV impacts because the OAID increases the building air change rates by a slightly smaller amount.

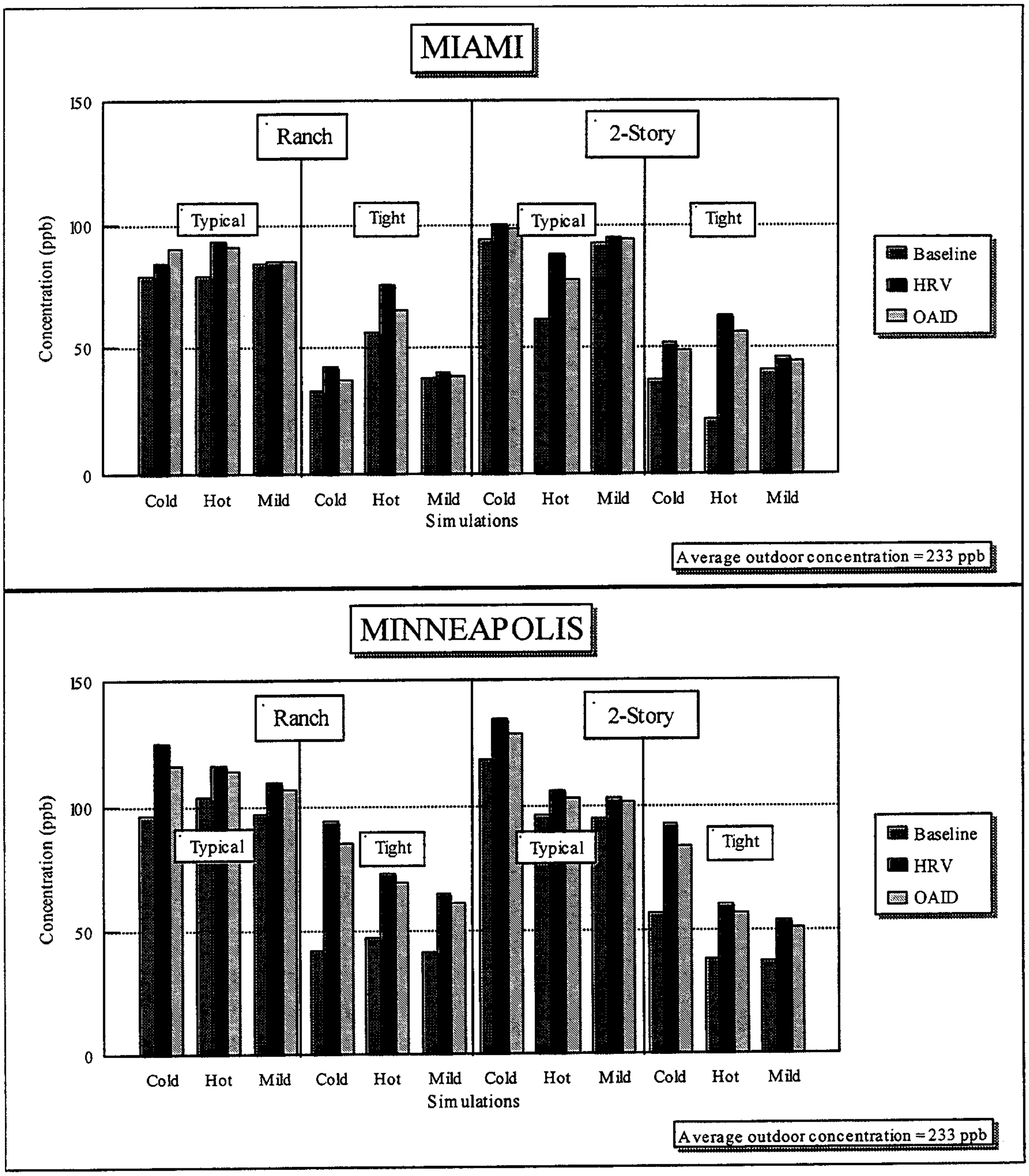


Figure 33 - 24-hour, Living Space Average NO_2 Concentrations Due to Elevated Outdoor Levels

3.3.4 Outdoor Air - Coarse Particles

The 24-hour, living-space average concentrations due to elevated outdoor coarse particle concentrations are shown in Figure 34. The baseline concentrations range from 2 to 20 $\mu g/m^3$ with an average 11 $\mu g/m^3$. The average concentration was substantially higher in the typical houses (16 $\mu g/m^3$) than in the tight houses (6 $\mu g/m^3$) because, as discussed previously, the pollutant deposition and filtration causes lower concentrations inside the buildings than outside and the additional airflow into the typical buildings is at a higher concentration.

The HRV *increased* the 24-hour, living-space average coarse particle concentration due to the elevated outdoor levels by an average of 3.9% with the increases ranging from 0.2% to 24%. The percent increase in coarse particle concentration for nearly all tight house cases was larger than the increase for the corresponding typical house cases with average increases of 5.9% and 1.8%, respectively, due to the larger relative increase in building air change rates and the lower baseline concentrations in the tight houses. The average increase in coarse particle concentration was greatest for the Miami hot weather cases (7.8%) followed by the Minneapolis cold weather cases (6.6%), Minneapolis mild weather cases (2.8%), Minneapolis hot weather cases (2.4%), Miami cold weather cases (2.0%), and Miami mild weather cases (1.6%). As discussed previously, these increases depend on the HVAC system run-time which was greatest in the Miami hot weather and Minneapolis cold weather cases and lowest in the Miami mild weather cases.

The OAID reduced the 24-hour, living-space average coarse particle concentration due to the elevated outdoor levels by an average of 9.9% with the impacts ranging from an increase of 11% to a decrease of 38%. As discussed previously for the heater and oven source of fine particles, the OAID tends to reduce coarse particle concentrations because it pressurizes the indoor space which reduces the unfiltered air entering through envelope leaks. This does not happen with the HRV because it has an exhaust air stream which causes an overall neutral effect on building pressure. The percent reduction in coarse particle concentration for most tight house cases was larger than the decrease for the corresponding typical house cases with average reductions of 15% and 3.9%, respectively. On average, the OAID reduced the coarse particle concentration the most for the Miami hot weather cases (25%) followed by the Minneapolis cold weather cases (19%), Minneapolis hot weather cases (6.4%), Minneapolis mild weather cases (4.0%), Miami cold weather cases (2.9%), and Miami mild weather cases (2.0%).

The EPF reduced the 24-hour, living-space average coarse particle concentrations due to elevated outdoor levels by an average of 1.4% with the reductions ranging from 0.2% to 3.2%. The reductions were relatively small because the coarse particle filtration efficiency was only increased from 90% to 95%. The average percent reduction was slightly larger for the tight house cases (1.5%) than for the typical house cases (1.3%). The percent reduction was greatest for the Miami hot weather cases (2.8%) followed by the Minneapolis cold weather cases (2.6%), Miami cold weather cases (1.1%), Minneapolis hot weather cases (1.0%), Minneapolis mild weather cases (0.7%), and the Miami mild weather cases (0.4%). As discussed previously, the amount of the reduction depended on the HVAC system run-time.

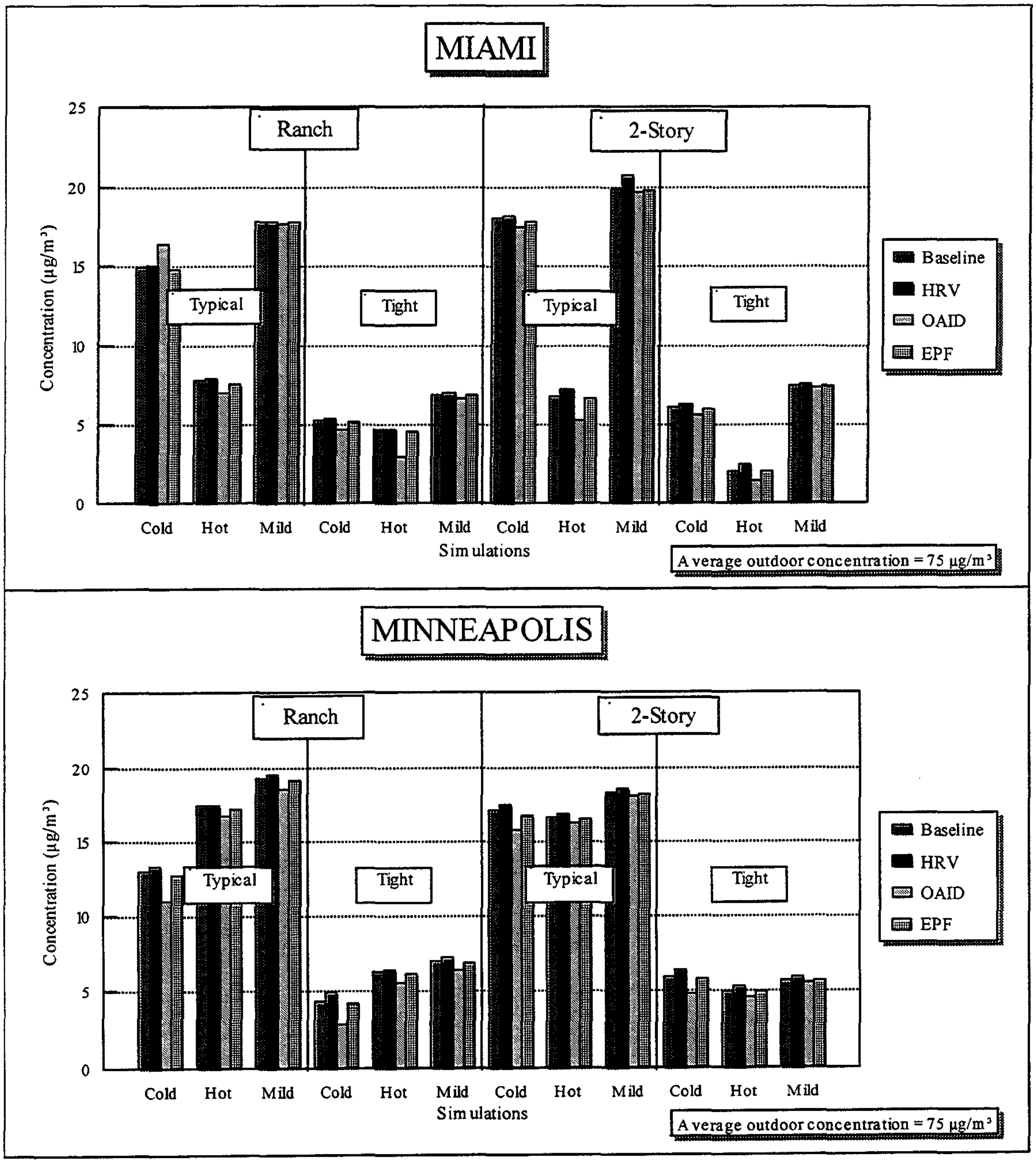


Figure 34 - 24-hour, Living Space Average Coarse Particle Concentrations Due to Elevated Outdoor Pollution

3.4 Outdoor Air Change Rates

The impact of the HRV and the OAID may also be evaluated by comparing the resulting air change rates in the buildings with those required by ASHRAE Standard 62 (ASHRAE 1989). Standard 62 requires a minimum outdoor air change rate of 0.35 air changes per hour (h^{-1}) or, if greater, 7.5 L/s (15 cfm) per person with an assumption of 2 people for the first bedroom and 1 person for each additional bedroom. Based on this, the minimum outdoor air change rates are 0.41 h^{-1} for the Miami ranch house, and 0.35 h^{-1} for all other houses.

Figure 35 shows the 24-hour average air change rates for the houses under all baseline, HRV, and OAID cases in h^{-1}. The air change rates in h^{-1} may be misleading as the Minneapolis air change rates were calculated including the volume of the basement. The results are also shown in Figure 36 in L/s. The baseline average air change rate is below the ASHRAE minimum air change rate for all tight houses under all weather conditions. While the HRV and OAID do increase the building air change rates for all cases, the benefit is limited by the HVAC system run-time (shown in Table 3). With the additional outdoor air brought in by the HRV, the tight Miami houses meet the ASHRAE minimum air change rate for the hot case but still fall short for the cold and mild cases. The tight Minneapolis houses meet the requirement for the cold case but still fall short for the mild and hot cases.

In all cases, the OAID increases the building average air change rate by a smaller amount than the HRV. Because the OAID does not have an exhaust path, the air entering the house through the OAID pressurizes the building and reduces the airflow entering the building through envelope leaks. This reduction of envelope infiltration partially offsets the increase in building air change rate due to the ventilation air entering through the OAID resulting in a smaller overall increase than the HRV. With the OAID, the tight Minneapolis houses meet the ASHRAE minimum air change rate for the cold case but all other tight house cases fall short.

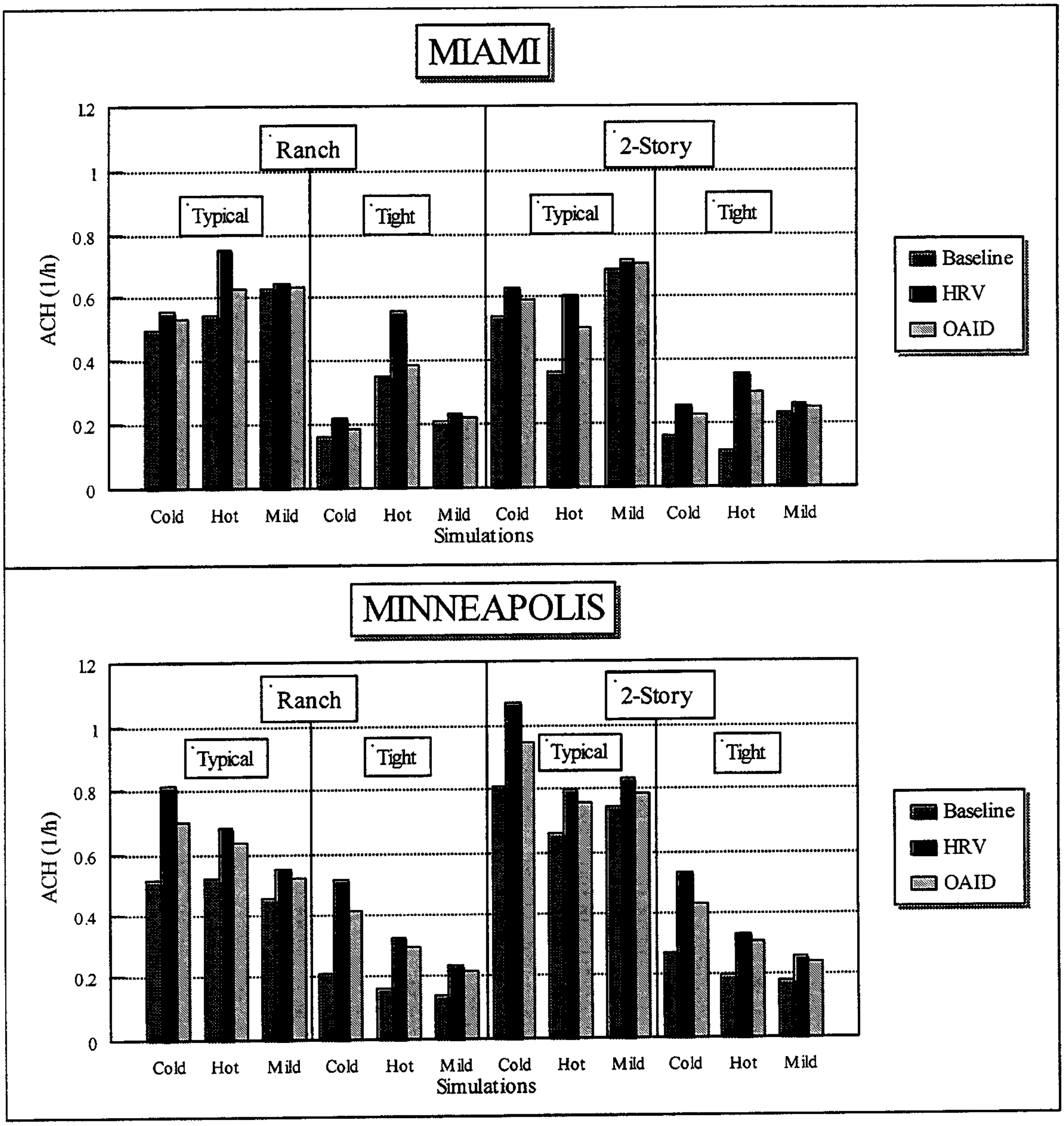


Figure 35 - 24-hour Average Building Air Change Rates in h^{-1}

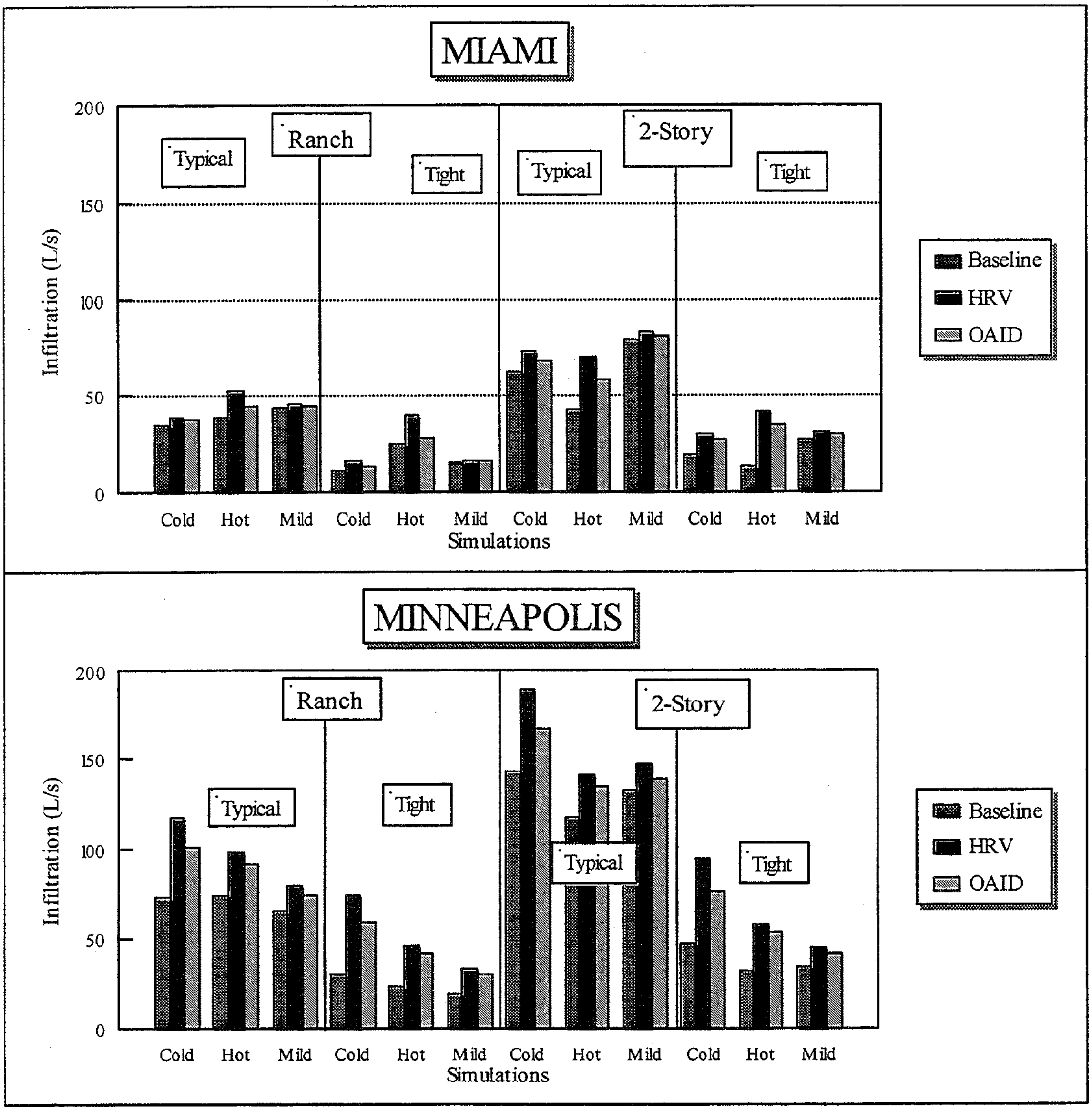


Figure 36 - 24-hour Average Building Air Change Rates in L/s

3.5 Summary and Discussion

The results detailed above indicate that all three of the IAQ controls modeled have the potential to reduce the indoor pollutant concentrations resulting from some typical sources. Also, some situations were identified in which there were significant limitations on the effectiveness of the controls modeled. However, these results are affected by the manner in which the houses, systems, pollutants, and sources were modeled, and therefore, the generality of the results is limited. This section summarizes and discusses the results presented in the previous sections. Summary tables of the percent reductions in 24-hour, living-space average concentrations are presented first. The discussion of the results is then broken down into two parts as the IAQ controls impact the indoor pollutant concentration by either enhanced filtration (EPF) or ventilation (HRV and OAID).

3.5.1 Summary Tables

Table 8 summarizes the 24-hour, living-space average concentrations due to indoor sources for the baseline cases. Tables 9, 10, and 11 summarize the percent reductions in these concentrations for the EPF, HRV, and the OAID, respectively. Table 12 summarizes the 24-hour, living-space average concentrations due to the elevated outdoor pollution for the baseline cases. Table 13 summarizes the percent reductions in these concentrations for all three IAQ controls. Note that in Tables 9, 10, 11, and 13, positive values represent reductions and negative values represent increases.

Table 8 - Summary of Average Pollutant Concentrations
Due to Indoor Sources for Baseline Cases

Source	Floor - TVOCs (μg/m³)	Burst - TVOCs (μg/m³)	Oven - CO (ppm)	Oven - NO_2 (ppb)	Oven - Particles (μg/m³)	Heater - CO (ppm)	Heater - NO_2 (ppb)	Heater - Particles (μg/m³)
Overall average	9,150	230	2.7	21	9	2	13	10
Range	2150 to 29,100	100 to 1220	1.9 to 4.8	16 to 28	5 to 12	1.6 to 2.8	4 to 20	7 to 11
Typical houses	4,500	160	2.2	22	11	1.8	15	11
Tight houses	13,790	300	3.3	20	8	2.2	11	8
Miami cold weather	11,650	230	3.4	25	10	1.6	6	10
Miami hot weather	13,450	250	3	20	8			
Miami mild weather	11,290	220	3	23	10			
Minneapolis cold weather	4,510	210	2.3	19	9	2	18	9
Minneapolis hot weather	6,790	220	2.4	19	9			
Minneapolis mild weather	7,180	240	2.4	20	9	2.3	15	10

Table 9 - Percent Reductions in Average Concentrations for Electrostatic Particulate Filter

Source	Oven - Fine Particles	Heater - Fine Particles
Overall average	30	31
Range	4.5 to 63	13 to 58
Typical houses	23	22
Tight houses	37	40
Miami cold weather	21	21
Miami hot weather	54	
Miami mild weather	7.4	
Minneapolis cold weather	45	46
Minneapolis hot weather	28	
Minneapolis mild weather	26	27

Table 10 - Percent Reductions in Average Concentrations for Heat Recovery Ventilator

Source	Floor - TVOCs	Burst - TVOCs	Oven - CO	Oven - NO_2	Oven - Particles	Heater - CO	Heater - NO_2	Heater - Particles
Overall average	26	14	10	-2.3	-14	8.1	-7.5	-9.9
Range	2.5 to 69	-0.1 to 59	0.4 to 44	-9.4 to 2.7	-78 to -0.3	-0.3 to 26	-37 to 1.7	-35 to -1.4
Typical houses	16	6.8	4.5	-1.4	-4.5	3.1	-2.1	-3
Tight houses	35	22	16	-3.2	-22	13	-13	-17
Miami cold weather	19	10	9.1	-0.7	-6.4	0.2	-19	-6.6
Miami hot weather	41	26	22	-0.2	-30			
Miami mild weather	7.5	3.3	2.6	0.1	-1.8			
Minneapolis cold weather	40	18	14	-4.8	-21	12	0.3	-16
Minneapolis hot weather	22	15	7.6	-3.2	-11			
Minneapolis mild weather	25	13	7.2	-4.8	-10	12	-3.7	-7

Table 11 - Percent Reductions in Average Concentrations for Outdoor Air Intake Damper

Source	Floor - TVOCs	Burst - TVOCs	Oven - CO	Oven - NO_2	Oven - Particles	Heater - CO	Heater - NO_2	Heater - Particles
Overall average	21	13	7.4	-3.3	-10	7.1	-3	-7.6
Range	2.6 to 64	0 to 75	-0.4 to 37	-11 to 3.6	-65 to -0.3	0.0 to 22	-27 to 4.5	-30 to -1.0
Typical houses	13	6	3.1	-2.1	-3.1	2.2	-1.2	-2.3
Tight houses	29	20	12	-4.6	-18	12	-4.9	-13
Miami cold weather	19	12	6	-1.8	-4.9	1.4	-13	-4.8
Miami hot weather	30	22	15	-3.3	-22			
Miami mild weather	4.8	2.6	0.8	-0.8	-1.1			
Minneapolis cold weather	30	16	11	-6	-16	10	2.3	-13
Minneapolis hot weather	19	14	6	-3.7	-10			
Minneapolis mild weather	21	11	5.6	-4.5	-8.4	10	1.1	-5.3

Table 12 - Summary of Average Concentrations Due to Elevated Outdoor Levels for Baseline Cases

Pollutant	CO (ppm)	NO_2 (ppb)	Coarse particles ($\mu g/m^3$)
Overall average	6.8	66	11
Range	6.6 to 7.2	21 to 119	2 to 20
Typical houses	6.8	94	16
Tight houses	6.8	40	6
Miami cold weather	6.7	61	11
Miami hot weather	7	54	5
Miami mild weather	6.8	64	13
Minneapolis cold weather	6.7	78	10
Minneapolis hot weather	6.8	71	11
Minneapolis mild weather	6.7	67	12

Table 13 - Percent Reductions in Average Concentrations Due to Elevated Outdoor Pollution for All IAQ Controls

IAQ control	EPF	HRV			OAID		
Pollutant	Coarse particles	CO	NO_2	Coarse particles	CO	NO_2	Coarse particles
Overall average	1.4	0.1	-37	-3.9	0.2	-29	9.9
Range	0.2 to 3.2	-2.7 to 3.2	-196 to -1.4	-24 to -0.2	-2.4 to 2.8	-164 to -0.7	-11 to 38
Typical houses	1.3	0.2	-14	-1.8	0.2	-10	5.2
Tight houses	1.5	0.1	-60	-5.9	0.1	-48	15
Miami cold weather	1.1	-0.7	-20	-2	-0.4	-16	2.9
Miami hot weather	2.8	2	-74	-7.8	1.6	-56	25
Miami mild weather	0.4	0.3	-5.7	-1.6	0.4	-3.5	2
Minneapolis cold weather	2.6	0.2	-58	-6.6	1	-45	19
Minneapolis hot weather	1	-1.5	-34	-2.4	-1.3	-28	6.4
Minneapolis mild weather	0.7	0.6	-31	-2.8	0.6	-25	4

3.5.2 Enhanced Filtration (EPF)

The electrostatic particulate filter (EPF) substantially reduced indoor particle concentrations for certain situations. Reductions in average fine particle concentrations due to indoor sources averaged around 30% and were as large as 63% (see Table 9). As expected, use of the EPF never resulted in an increase in particle concentrations. However, some limitations to the effectiveness of the EPF at reducing concentrations were demonstrated in these simulations.

These limitations include a dependence on forced-air system operation and a relatively small increase in the coarse particle filtration efficiency. The dependence on forced-air system operation is best demonstrated by the oven source for the Miami mild weather cases. As shown earlier in Table 3, the system operates only 5% of the time for the ranch house and 8% of the time for the 2-story house to meet the small space conditioning load imposed by the mild weather. This minimal system operation results in an average reduction for these cases of only 7.4% compared to the overall average of 30%. For the EPF, the coarse particle filtration efficiency was increased from 90% to 95%. This small increase resulted in reductions in coarse particle concentrations due to elevated outdoor levels that averaged only 1.4% and were always less than 3.2% as seen in Table 13. This minimal reduction may also be influenced by the particle deposition rate used in the simulations; larger reductions could occur for lower deposition rates.

The EPF reduced the average fine and coarse particle concentrations by greater relative amounts for nearly all tight house cases than for the corresponding typical house cases. The typical and tight house reductions varied only slightly in absolute magnitude, but the tight house percent reductions were larger than the typical house reductions because they were based on lower baseline concentrations.

It should be noted that the conditions simulated provided only a modest challenge to the EPF. None of the cases resulted in average particle concentrations as high as the initial maximum burden of 500 $\mu g/m^3$ specified in the Interagency Agreement (CPSC 1993) or even as high as the target reduced 24-hour average level of 100 $\mu g/m^3$. The indoor concentrations were well below the outdoor concentrations for all cases due to a combination of low indoor sources and significant rates of particle deposition and filtration. These results should not be interpreted to mean that higher indoor particle concentrations are not possible. In addition, if either stronger indoor sources or lower deposition rates were used, the indoor concentrations would be less dependent on outdoor concentrations and the effect of lower percent reductions for the tight houses may be reversed.

3.5.3 Ventilation (HRV and OAID)

The heat recovery ventilator and outdoor air intake damper also resulted in substantial reductions in indoor pollutant concentrations for some cases. However, for other cases, the HRV and OAID, as modeled in this study, were not particularly effective or even resulted in increased pollutant concentrations.

In general, both the HRV and OAID reduced the average indoor pollutant concentrations for the pollutants without decay or deposition effects (CO and TVOCs). Both controls reduced the average CO concentrations due to both the oven and the heater by an average of 8.2% with reductions as large as 44%. They reduced the average TVOC concentrations due to the burst sources by an average of 14% with reductions as large as 75%. They reduced the TVOCs due to the floor source by an average of 23% with reductions as large as 69%. The reduction was greater for the floor source because the source strength was larger relative to the outdoor concentration, the source was distributed uniformly throughout the house, and the source was constant. For the burst VOC sources and the CO sources, the reductions in individual cases also depended on the source location and the relative timing of the pollutant generation and the system operation.

As discussed above for the EPF, the effectiveness of the HRV and OAID was limited by their dependence on the forced-air system operation. The Miami mild weather cases once again had the smallest reductions in average pollutant concentrations with the average reductions ranging from 0.8% (the OAID for the oven CO source) to 7.5% (the HRV for the floor TVOC source). The largest reductions always occurred for the Miami hot weather cases followed by the Minneapolis cold weather cases, which had the largest system percent run-times (see Table 3). The reductions were larger for the Miami hot weather cases than the Minneapolis cold weather cases despite a somewhat smaller system percent run-time.

The conditions (low indoor - outdoor temperature differences) causing low system run-time generally also correspond to lower infiltration rates and, therefore, higher baseline pollutant concentrations for cases with significant indoor sources. Thus, mild days with high concentrations could receive the least help from the HRV or OAID due to low system run-times.

For example, the baseline case of the tight Miami ranch house in mild weather has the second highest average TVOC concentration (20,700 $\mu g/m^3$). After modest reductions due to the HRV and OAID, this case has the highest TVOC concentrations for the modified cases of 18,600 $\mu g/m^3$ and 19,600 $\mu g/m^3$, respectively. The effectiveness of the forced-air modifications could also be limited if the cooling and heating equipment is oversized, which would further reduce the HVAC system run-time. However, a tendency of occupants to open windows during mild weather could offset the impacts of low system run-time.

The HVAC system run-time effect is strongly dependent on the control approach employed. In these simulations, the HRV and OAID operated only when the HVAC system was heating or cooling the houses. Other control options for the HRV and OAID include continuous operation, scheduled operation, and pollutant concentration feedback control (based on, for example, humidity or carbon dioxide). These control options may entail additional equipment, installation, and energy costs, but may also result in more effective pollutant control.

Another limitation of both the HRV and OAID is their minimal impact on peak concentrations for short-duration sources. The average reductions in peak concentrations due to the VOC burst sources examined were less than 2%. The average impacts on maximum 1-hour average CO concentrations were less than 1% for the oven and less than 8% for the heater. The HRV and OAID have a smaller impact on the peak concentrations compared to the average concentrations for two reasons. The peak concentrations are much larger than the average and the increase in building air change rate is less significant for the short-duration source emissions. For the tight Miami ranch house in cold weather, the HRV reduced the average TVOC concentration due to the KIT burst source by 80 $\mu g/m^3$, which is 18% of the baseline average concentration of 480 $\mu g/m^3$, but the peak reduction of 70 $\mu g/m^3$ is only 1.3% of the peak baseline concentration of 5240 $\mu g/m^3$. The reduction in peak concentrations was larger for the floor VOC source with a reduction of 24%. This larger reduction occurs because the source is constant and results in relatively uniform (compared to the burst source) concentrations throughout the day.

One potential drawback of the HRV and OAID indicated by the simulations is increased pollutant concentrations for some situations. As expected, the introduction of outdoor air increased the indoor concentrations of pollutants during periods of elevated outdoor pollutant levels. For example, the HRV and OAID increased the average NO_2 concentrations by averages of 37% and 29%, respectively. The HRV also increased the average coarse particle concentrations.

Unexpectedly, the HRV and OAID also increased the NO_2 and fine particle concentrations for both the oven and the heater cases even when the outdoor concentrations were at non-elevated levels. For the oven case, the average increase due to the HRV ranged from 2.3% for the NO_2 concentrations to 14% for the fine particle concentrations. As explained previously, these increases occurred at the non-elevated outdoor concentrations because of the relatively weak indoor source strength and the pollutant removal processes inside the buildings. These factors combined to result in very low indoor concentrations through much of the day. Therefore, the additional outdoor air brought in by the HRV and OAID was often at a higher concentration than inside the buildings.

Like many of the effects discussed here, there were exceptions to the trend of increased indoor pollutant concentrations due to the HRV and OAID during elevated outdoor levels. On average, the CO concentrations due to elevated outdoor pollutant levels were reduced by both devices and the coarse particle concentrations were reduced by the OAID. For CO, the impact in all cases was very small because of the cyclic calculation method employed. However, for the OAID, the average reduction in coarse particles was 9.9% and the reduction was as high as 38%. This result may be due to the OAID pressurizing the indoor space which reduces the unfiltered air entering through envelope leaks. This does not happen with the HRV because it has an exhaust air stream which causes an overall neutral effect on building pressure.

For nearly all conditions simulated, the percent changes due to the HRV and OAID were greater for tight houses than typical houses. This trend applied to both concentration reductions and increases. For example, the HRV reduced the average TVOC concentrations due to the floor source by an average of 35% in the tight houses compared to 16% in the typical houses, and the OAID increased the average fine particle concentrations for the oven source by an average of 18% in the tight houses compared to 3.1% in the typical houses.

4 IAQ Modeling Issues and Follow-up Activities

While one objective of this research effort was to investigate the impact of selected IAQ control technologies on residential contaminant levels, another important goal was to identify issues related to the reliability and usefulness of multizone IAQ models and to identify important areas for follow-up work. This section discusses several such issues that were identified in planning this effort and in the process of performing and analyzing the results of the simulations. The IAQ modeling issues that were identified include model validation, sensitivity analysis, input data adequacy, and input errors. These issues are discussed in this section, and follow-up activities are suggested to address them. In addition, other follow-up activities are discussed, including additional cases for simulations and the development of additional simulation capabilities.

Although absolute validation of a complex program such as CONTAM93 is impossible, empirical evaluation of a model's predictions is important to establish its range of applicability, to reduce the potential for large errors, and to verify that it correctly predicts trends of interest. While model validation is often discussed as an issue related to an entire computer program, validation is in fact a situation-specific issue. In this context, the term situation refers to the specific combination of factors related to the details of a simulation including the pollutant and source, the pollutant transport mechanisms impacting that pollutant, and the building and HVAC system configuration. While a number of multizone airflow and pollutant transport model validation efforts have been conducted, the efforts to date have not been sufficient to identify the situations in which such models will perform reliably and the situations where they are expected to be less reliable. A systematic approach to multizone model validation that considers the types of models, different approaches to model validation, and the range of applicability of these models to different buildings and sources types is needed. An issue that is specific to this project is the experimental evaluation of the IAQ controls that were evaluated, as such an effort may help resolve some of the questions that the simulations raised regarding their performance.

The results discussed in this report show that the outcome of a simulation may vary dramatically for different input values due to the complexities of airflow and pollutant transport in multizone systems. The results also show that the relationships between model inputs and outputs can be unexpected and difficult to understand based only on one's physical intuition. In this study, attempts were made to select reasonable values for all of the inputs, but the range of reasonable values is quite large for many inputs and some uncertainty in the input values will always exist. Therefore, it is critical to understand which model inputs are most important to the results of a given simulation. Sensitivity analysis can be used to determine the relative importance of different input parameters. There are many different approaches to sensitivity analysis (Lomas and Eppel 1992). As with model validation, a systematic approach to sensitivity analysis must be employed that considers different building factors, pollutant sources and IAQ issues.

In the process of setting up the houses in CONTAM93, difficulties were encountered in obtaining data for many model input parameters. Specific inputs that were particularly problematic include, but are not limited to, leakage areas of building components, wind pressure coefficients, particle and NO_2 decay rates, VOC source strengths, and VOC sink characteristics. The lack of a reliable database for model inputs is not a new problem, but it can limit the usefulness of airflow and IAQ models. Existing knowledge gaps need to be identified and analyzed. A strategy should be developed to obtain the information needed to make modeling a more useful tool. The sensitivity analysis and model validation efforts discussed previously could be used to help set priorities for improving model input data.

Another important issue that arose during this project relates to errors in model inputs. Describing a building as a multi-zone system of airflow and pollutant transport elements can be a very complex process, depending on the configuration of the building and the factors being considered in the simulation. When entering the data into CONTAM93, or any simulation program, there is always the possibility of entering erroneous numerical values or neglecting to enter an individual element. CONTAM93 performs some checks on the internal consistency of the inputs, but no program can identify every conceivable input error. In the course of running the simulations in this project, input errors were identified that required some simulations to be corrected and performed again. Some of these errors were fairly obscure and hard to identify. Given the fact that the results of a simulation may not be intuitive, it may be far from obvious that an input error has occurred. This problem is particularly serious for the less experienced modeler who is more likely to make an error and less likely to recognize its existence. It is not clear what features could be added to these programs to identify input errors, but this issue merits attention as these programs are more widely used.

The factors included in the simulations were limited by project resources and by the fact that it was a preliminary assessment of the potential for using forced-air HVAC systems to improve residential IAQ. The modeling approach used in this study could be employed to investigate many other factors that were not part of this effort. These other factors include house characteristics, pollutants and sources, IAQ controls, and side-effects of implementing the controls. The current study involved only two types of detached houses with slab or basement foundations, attics, and attached garages. Many other residential building types exist in a wide range of configurations. These include attached houses, manufactured housing, and houses with crawl spaces. Other climate-related or regional building features could also be considered to broaden the scope and applicability of the analysis. It will always be difficult to generalize the results of such simulations or to assess their relevance to the residential building stock without considering the wide variety of house types and building features. The development of a set of houses to represent the U.S. residential building stock based on a statistical analysis of climate, type, size and other important features should be considered. Such an analysis has been done for U.S. office buildings for use in energy analysis, resulting in a set of twenty-five buildings that represents the office building stock (Briggs et al. 1987, Crawley and Schliesing 1992).

The pollutants investigated in this study were based on the interests of CPSC, and the sources were selected based in part on their relevance to HVAC-based control options. There are many other pollutants and sources that could be selected for study based on residential IAQ concerns and the availability of input data. Some pollutants that are candidates for study using computer simulation include formaldehyde, soil gases such as radon, and CO_2, which can be used as an indicator of human bioeffluents. The sources included in this study were indeed limited, and there are many other sources of the pollutants investigated that vary in magnitude, temporal pattern and spatial distribution. The thorough study of any pollutant requires consideration of its different potential sources.

The project was restricted to IAQ controls in the form of modifications to forced-air systems that are commercially available now, but many other types of controls could be studied through multizone IAQ modeling. These include other ventilation system control strategies, ventilation systems that are not modifications of forced-air systems, IAQ controls that are not ventilation related, and controls and ventilation systems that are only at the conceptual phase. In this study, the evaluation of the control options was limited to the pollutants of interest and to a small number of outdoor pollutants. These control options could and ultimately need to be evaluated in several other respects including equipment and installation costs, energy impact, and the potential impacts on the concentrations of other pollutants such as indoor humidity. The consideration of these side-effects is important to evaluating the appropriateness of IAQ controls. Some of these issues could be addressed with the current version of CONTAM93, while others may require the development of additional simulation capabilities as discussed below.

Despite the limitations discussed here, IAQ modeling has the potential to provide valuable insight into a range of IAQ issues. The IAQ issues that can be studied by a program are determined by its simulation capabilities, such as the ability to model specific pollutant transport mechanisms. In addition, these capabilities determine the ability of the model to consider the potential side-effects of an IAQ control method. All models, including CONTAM93, are limited in their capabilities, and opportunities exist to expand these models to consider other issues. Other issues that could be incorporated into these programs include more complete and theoretically-rigorous treatment of chemical reaction and adsorption phenomena, more detailed HVAC system models to enable realistic consideration of system interactions, thermal analysis to enable the determination of energy impacts, and exposure analysis.

This section recommended several follow-up activities that are summarized below:

- A systematic approach to multizone model validation that considers the important types of models, building features, pollutants and sources.
- Experimental evaluation of the IAQ controls that were evaluated in this project.
- Sensitivity analysis of IAQ models based on consideration of building factors, pollutant sources and IAQ issues.
- Identification and analysis of knowledge gaps related to model inputs, and development of a strategy to obtain the information needed.
- Investigation of options for adding input-error identification features to IAQ models.
- Investigation of other factors including house characteristics, pollutants and sources, IAQ controls, and side-effects of implementing the controls.
- Development of additional simulation capabilities including theoretically-rigorous treatments of chemical reaction and absorption phenomena, more detailed system models, thermal analysis, and exposure analysis.

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Appendix A Simulation Results

Tables 1 and 2 of Appendix A summarize the results of the 24 baseline simulations. Table 1 lists the 24-hour, living-space average concentrations resulting from each source. The living-space average includes the kitchen, living and dining area, and bedroom zones in the ranch houses, and the kitchen and family area, living room, dining room, and bedroom zones in the two-story houses. Table 2 lists the maximum living-space zone peak concentrations due to the floor source, the MBR zone burst source, the KIT/KFA zone burst source, the oven NO_2 source, and the heater NO_2 source and the maximum living-space zone 1-hour average CO concentrations due to the oven and heater sources. The 1-hour average was calculated from 6 p.m. to 7 p.m. for the oven and from 9 a.m. to 10 a.m. for the heater.

Tables 3 through 7 summarize the results of the simulations of the IAQ control retrofits. Tables 3 through 5 list the percent reductions in the 24-hour, living-space average concentrations for the electrostatic particulate filter, heat recovery ventilator, and outdoor air intake duct, respectively. Table 6 lists the percent reductions in the living space peak and maximum 1-hour average concentrations for the heat recovery ventilator. Table 7 lists the percent reductions in the living space peak and maximum 1-hour average concentrations for the outdoor air intake damper.

Table 1a - Baseline 24-hour, living-space average concentrations (VOC sources)

SIMULATION	VOC1 µg/m³	VOC2 µg/m³	VOC3 µg/m³	VOC4 µg/m³	VOC5 µg/m³	VOC6 µg/m³	VOC7 µg/m³	VOC8 µg/m³	VOC9 µg/m³
SIM1FLC	108	5,931	212	193	119	236	177	143	217
SIM1FLH	190	6,175	197	202	194	198	193	189	201
SIM1FLM	166	5,017	174	162	99	222	151	169	197
SIM1FTC	200	18,787	453	423	185	477	390	343	469
SIM1FTH	234	9,357	242	247	518	240	241	229	243
SIM1FTM	138	20,710	475	442	139	562	355	269	551
SIM1MLC	98	2,757	147	143	109	151	136	425	148
SIM1MLH	98	2,868	132	137	134	137	120	326	140
SIM1MLM	101	3,266	132	148	171	148	110	357	154
SIM1MTC	98	6,487	213	214	158	216	199	921	216
SIM1MTH	98	8,848	225	230	210	230	211	1,000	235
SIM1MTM	110	10,510	239	266	272	262	197	1,222	279
SIM2FLC	103	4,720	126	163	142	182	113	121	160
SIM2FLH	171	9,163	194	186	187	188	185	103	192
SIM2FLM	124	4,863	141	148	144	157	133	99	165
SIM2FTC	115	17,157	211	348	321	336	223	201	308
SIM2FTH	293	29,100	393	382	385	382	382	125	390
SIM2FTM	181	14,581	225	248	255	234	205	107	302
SIM2MLC	254	2,153	114	125	122	128	110	133	121
SIM2MLH	279	3,748	125	129	137	132	115	134	126
SIM2MLM	270	3,354	133	131	117	143	120	166	131
SIM2MTC	615	6,658	155	179	176	180	152	271	171
SIM2MTH	825	11,702	189	215	225	221	184	244	206
SIM2MTM	892	11,593	188	214	227	229	182	265	205

Note: VOC1 and VOC3 through VOC9 are the burst sources which were located in various zones throughout the buildings. They may be located in different zones in different buildings. VOC2 is the floor source.

Table 1b - Baseline 24-hour, living-space concentrations (non-VOC sources)

SIMULATION	Oven - CO ppm	Oven - NO_2 ppb	Oven - Particles µg/m³	Heater - CO ppm	Heater - NO_2 ppb	Heater - Particles µg/m³	Outdoor - CO ppm	Outdoor - NO_2 ppb	Outdoor - Particles µg/m³
SIM1FLC	2.9	28.2	10.91	1.6	8	10.79	6.8	79.7	14.88
SIM1FLH	2.6	23.8	8.95	NA	NA	NA	7	78.9	7.77
SIM1FLM	2.6	27.7	11.39	NA	NA	NA	6.7	84.3	17.82
SIM1FTC	4.8	27.8	8.02	1.7	3.5	7.85	6.7	32.7	5.16
SIM1FTH	2.9	23.2	7.55	NA	NA	NA	7	56.1	4.66
SIM1FTM	4.5	28	9.19	NA	NA	NA	6.9	37.3	6.85
SIM1MLC	2	21	10.07	1.9	18.8	10.48	6.7	96.4	12.96
SIM1MLH	2	21.1	10.7	NA	NA	NA	6.7	103.7	17.42
SIM1MLM	2	21.5	10.84	2	17.8	11.33	6.7	96.5	19.28
SIM1MTC	2.9	19.4	6.65	2.5	16.4	7.47	6.7	41.5	4.33
SIM1MTH	2.8	20.4	7.55	NA	NA	NA	6.9	46.6	6.24
SIM1MTM	2.9	22.6	7.79	2.8	11.2	8.85	6.8	41.2	6.96
SIM2FLC	2.3	22.2	11.31	1.6	9.5	11.24	6.7	93.9	18.06
SIM2FLH	2.5	17.4	8.54	NA	NA	NA	7	61.3	6.77
SIM2FLM	2	19.4	11.5	NA	NA	NA	6.6	92.6	19.88
SIM2FTC	3.6	19.7	8.31	1.7	3.9	8.23	6.6	37	6.02
SIM2FTH	4.2	16.3	4.77	NA	NA	NA	7.2	21.3	1.99
SIM2FTM	2.8	17.4	9.3	NA	NA	NA	6.9	40.5	7.46
SIM2MLC	1.9	19.7	10.87	1.7	19.8	11.11	6.7	118.7	17.08
SIM2MLH	1.9	18.5	10.96	NA	NA	NA	6.8	95.8	16.62
SIM2MLM	2	19	11.02	1.8	17.3	11.39	6.6	94.8	18.26
SIM2MTC	2.3	16.4	7.88	2.1	17.7	8.48	6.7	56.4	5.89
SIM2MTH	2.8	17.2	7.85	NA	NA	NA	7	38.3	4.98
SIM2MTM	2.7	18.1	8.08	2.5	11.9	9.02	6.7	37.1	5.62

Table 2 - Baseline peak and maximum 1-hour average living-space zone concentrations

SIMULATION	Floor - VOC $\mu g/m^3$	MBR - VOC $\mu g/m^3$	KIT/KFA - VOC $\mu g/m^3$	Oven - NO_2 ppb	Heater - NO_2 ppb	Oven - CO ppm	Heater - CO ppm
SIM1FLC	10,907	2,430	4,332	1,434	21	33.72	1.68
SIM1FLH	9,722	2,037	2,923	932	NA	14.73	NA
SIM1FLM	9,145	2,508	3,953	1,386	NA	32.42	NA
SIM1FTC	27,100	3,273	5,238	1,686	12	39.33	1.61
SIM1FTH	13,565	2,211	3,067	974	NA	15.11	NA
SIM1FTM	33,256	3,333	5,588	1,558	NA	37.36	NA
SIM1MLC	3,752	1,707	3,089	577	110	13.71	1.67
SIM1MLH	7,629	1,562	2,736	886	NA	16.97	NA
SIM1MLM	6,190	2,137	3,743	1,038	117	23.97	3.19
SIM1MTC	7,634	2,189	3,264	615	120	14.62	2.05
SIM1MTH	17,976	2,067	3,162	1,026	NA	19.07	NA
SIM1MTM	15,432	3,025	4,701	1,458	73	34.23	3.46
SIM2FLC	8,299	1,529	1,627	486	23	11.9	1.73
SIM2FLH	13,914	1,472	1,289	377	NA	7.74	NA
SIM2FLM	11,894	1,323	1,685	539	NA	13.76	NA
SIM2FTC	25,423	2,050	2,096	595	10	13.79	1.58
SIM2FTH	34,488	1,739	1,464	399	NA	8.39	NA
SIM2FTM	25,048	1,698	1,911	591	NA	15.11	NA
SIM2MLC	3,136	726	768	280	104	7.71	1.85
SIM2MLH	9,722	1,437	1,576	481	NA	10.62	NA
SIM2MLM	5,785	1,742	1,743	499	129	12.97	3.48
SIM2MTC	8,131	907	873	350	122	8.44	2.08
SIM2MTH	22,074	1,862	2,024	591	NA	12.18	NA
SIM2MTM	15,364	1,983	2,077	663	94	16.54	3.39

Note: The VOC and NO_2 concentrations are peak values; the CO concentrations are maximum 1-hour average values. All concentrations are for individual living-space zones.

Table 3 - Percent reductions in 24-hour average baseline concentrations due to electrostatic particulate filter

SIMULATION	Oven - Particles	Heater - Particles	Outdoor - Particles
SIM1FLCF	14.54	14.6	0.72
SIM1FLHF	48.86	NA	2.69
SIM1FLMF	4.5	NA	0.23
SIM1FTCF	29.24	29.36	0.96
SIM1FTHF	56.52	NA	3.17
SIM1FTMF	9.91	NA	0.33
SIM1MLCF	37.44	38.18	2.3
SIM1MLHF	23.33	NA	1.17
SIM1MLMF	17.67	18.27	0.78
SIM1MTCF	56.67	58.06	2.67
SIM1MTHF	38.41	NA	1.35
SIM1MTMF	33.62	35.75	0.99
SIM2FLCF	12.63	12.66	1.26
SIM2FLHF	47.9	NA	2.65
SIM2FLMF	4.86	NA	0.42
SIM2FTCF	28.79	28.86	1.59
SIM2FTHF	62.98	NA	2.5
SIM2FTMF	10.49	NA	0.51
SIM2MLCF	31.96	32.33	2.42
SIM2MLHF	17.57	NA	0.91
SIM2MLMF	17.12	17.46	0.54
SIM2MTCF	52.91	53.7	2.84
SIM2MTHF	34.38	NA	0.69
SIM2MTMF	34.46	35.86	0.5

Note: Only particle sources are listed because the filters have no effect on other pollutants.

Table 4a - Percent reductions in 24-hour average baseline concentrations due to heat recovery ventilator (VOC sources)

SIMULATION	VOC1	VOC2	VOC3	VOC4	VOC5	VOC6	VOC7	VOC8	VOC9
SIM1FLCH	1.2	8.4	4.2	2.3	1	4	4.4	6.2	3.1
SIM1FLHH	14.7	23.4	14.8	14.4	13.9	15.4	14.7	16.5	15
SIM1FLMH	0.6	2.5	0.3	0.2	0	0.5	0.5	0.8	0.4
SIM1FTCH	15.9	24	17.9	14.3	10	17.5	19.1	23.9	16.2
SIM1FTHH	21.8	31.7	22	21.4	28.9	22.3	22	23.4	21.9
SIM1FTMH	4.3	10.3	7.6	5	2.2	7.2	9.2	14.2	6.5
SIM1MLCH	0	33.5	11.5	11	3.6	11.9	10.1	37	11
SIM1MLHH	0	13.1	6	7	5.1	6.6	4.5	22	7
SIM1MLMH	0.5	17.3	3	4.6	5.6	4.2	2	23.3	4.6
SIM1MTCH	-0.1	56.1	30.6	31.4	21.5	31	29.4	59.1	30.4
SIM1MTHH	0	35.5	27.4	28.5	17.9	28	26.3	47.8	28.2
SIM1MTMH	4.6	40.3	20.7	24.1	24.1	22.6	19.7	48.9	23.2
SIM2FLCH	1.1	9.8	0.1	2.2	1.3	3.9	3.4	1.6	3
SIM2FLHH	17.1	40.2	21.4	21.6	19.6	23	23.8	2	21.8
SIM2FLMH	0.7	3.9	0.4	0.3	0.2	0.1	0.9	0.1	0.7
SIM2FTCH	5.7	32.1	10.8	19.5	17.3	22.8	25.3	17.6	19.7
SIM2FTHH	46.1	69.1	53	53.5	51.7	54.5	55.5	16	53.6
SIM2FTMH	4.7	13.2	4.3	5.6	5	5.6	9.1	1.8	5.8
SIM2MLCH	20.6	21.1	3	5.2	4.9	5.4	2.6	6	4.8
SIM2MLHH	17.2	9.6	3.5	3.7	4.7	3.2	3.5	3.3	4
SIM2MLMH	13.8	11.4	2.4	2.6	2.3	2.7	2.4	3.7	2.7
SIM2MTCH	47.2	47.3	17.3	22.2	22.4	22.2	18.4	30.8	21.5
SIM2MTHH	42.8	30.7	18.7	20.5	22.3	20.3	20.9	14.2	21.2
SIM2MTMH	35.4	29.8	12.8	14.8	16.6	15.4	15.5	18	15.4

Note: VOC1 and VOC3 through VOC9 are the burst sources which were located in various zones throughout the buildings. They may be located in different zones in different buildings. VOC2 is the floor source.

Table 4b - Percent reductions in 24-hour average baseline concentrations due to heat recovery ventilator (non-VOC sources)

SIMULATION	Oven - CO	Oven - NO_2	Oven - Particles	Heater - CO	Heater - NO_2	Heater - Particles	Outdoor - CO	Outdoor - NO_2	Outdoor - Particles
SIM1FLCH	2.6	-0.6	-1.4	-0.3	-6.4	-1.5	-0.3	-6.4	-0.7
SIM1FLHH	11.5	2.7	-8.9	NA	NA	NA	1.3	-18.8	-1.1
SIM1FLMH	0.4	-0.3	-0.3	NA	NA	NA	0	-1.4	-0.2
SIM1FTCH	14.2	-0.9	-9.8	0.3	-25.5	-10.3	-0.9	-27.8	-2.9
SIM1FTHH	16.8	2.5	-16.8	NA	NA	NA	1.3	-35	-0.3
SIM1FTMH	3.4	-0.4	-2.2	NA	NA	NA	0.5	-6.4	-0.7
SIM1MLCH	8.9	-1.9	-9.3	8.2	1.7	-7.2	0.4	-29.4	-3
SIM1MLHH	2.7	-1.3	-3.8	NA	NA	NA	-0.7	-12	-0.3
SIM1MLMH	2.4	-4	-3.9	5.7	-1.9	-2.7	0.4	-13.2	-0.9
SIM1MTCH	29.9	-5.4	-47	25.9	-1.5	-35.3	0.2	-125.9	-12.4
SIM1MTHH	16	-2.5	-21.8	NA	NA	NA	-2.2	-56	-1.6
SIM1MTMH	15	-5.7	-21.6	23.8	-8.9	-14.1	1.4	-57.2	-3.8
SIM2FLCH	2.5	0	-1.4	-0.1	-6.8	-1.4	-0.3	-7	-0.5
SIM2FLHH	16.5	-1.9	-16	NA	NA	NA	2.1	-44.2	-5.7
SIM2FLMH	1.1	0.7	-0.8	NA	NA	NA	-0.1	-2.6	-4.2
SIM2FTCH	17.1	-1.2	-12.8	0.9	-37.3	-13.2	-1.3	-39.8	-3.8
SIM2FTHH	43.6	-4.3	-77.7	NA	NA	NA	3.2	-196.1	-24
SIM2FTMH	5.6	0.3	-3.8	NA	NA	NA	0.8	-12.2	-1.1
SIM2MLCH	3.3	-2.7	-4.1	2.9	1.2	-3.3	0.1	-13.3	-2
SIM2MLHH	1.1	-3.2	-2.4	NA	NA	NA	-0.5	-10.2	-1.4
SIM2MLMH	1	-3.9	-2.3	2.4	-0.5	-1.7	-0.1	-8.7	-1.3
SIM2MTCH	14.3	-9.4	-23.9	13.1	-0.3	-19.2	0	-64.2	-9
SIM2MTHH	10.6	-5.8	-17.5	NA	NA	NA	-2.7	-57.2	-6.4
SIM2MTMH	10.4	-5.8	-13.9	14.5	-3.3	-9.4	0.8	-43.7	-5.3

Table 5a - Percent reductions in 24-hour average baseline concentrations due to outdoor air intake damper (VOC sources)

SIMULATION	VOC1	VOC2	VOC3	VOC4	VOC5	VOC6	VOC7	VOC8	VOC9
SIM1FLCO	4.5	18.7	8.7	7.8	0.3	10.2	14.7	15.6	11.3
SIM1FLHO	11	18.4	11.2	13	45.6	10.6	11.8	11.2	11.5
SIM1FLMO	0.3	1.2	0.2	0.2	0.1	0.1	0.3	0.3	0.2
SIM1FTCO	31.4	21.7	12.4	16.6	21.2	14.6	21.7	26	16.4
SIM1FTHO	7.9	11.7	8.2	8.9	75.4	7.7	8.8	8	7.9
SIM1FTMO	13.9	5.3	3.2	3.6	12.2	2.8	4.7	7.1	2.8
SIM1MLCO	0	25.4	8	9.1	7.9	8	8.4	23.4	8.3
SIM1MLHO	0	10.6	5.4	5.1	14.2	5.1	5.7	15.4	5.4
SIM1MLMO	1.2	13.2	2.8	3.1	9.2	3.3	3.6	14.5	3.1
SIM1MTCO	0	47	24.7	27.3	33.2	25	25.8	45.4	25.7
SIM1MTHO	0	32.2	25.2	25.3	28.2	24.6	26.6	40.6	24.7
SIM1MTMO	8.1	36	18.5	20.5	29.2	19	21.8	38.8	19.5
SIM2FLCO	1.3	7.2	1.1	2.1	2.6	1.2	2.4	1.6	1.9
SIM2FLHO	17.2	26.2	11.9	12.8	12.2	12.8	13	3.5	12.5
SIM2FLMO	0.8	2.6	0.3	-0.1	0.1	-0.6	0.6	0.2	0.5
SIM2FTCO	8.6	27.9	17.2	13.8	16.9	14.5	20.1	21.3	15.6
SIM2FTHO	57.6	63.8	49.9	46.4	45.1	46.9	48.6	21.1	47.1
SIM2FTMO	6.4	10.1	3.6	2.8	3.1	2.4	6.2	2.7	3.9
SIM2MLCO	9.3	12.8	2.5	2.6	3	2.3	2.4	12.6	2.8
SIM2MLHO	10.4	7.4	4.1	2.9	2.3	1.6	3.7	6.9	3.1
SIM2MLMO	5.8	8	2.4	2.1	0.2	1.6	1.2	5.3	2.4
SIM2MTCO	32.6	36.6	16.1	15.4	16.4	15.8	16.5	50.1	16.3
SIM2MTHO	33.4	27	21.1	16.1	15.9	15.9	21.5	23.5	18
SIM2MTMO	24.9	25.4	14.9	10.7	10.8	11.1	16	23.5	12.2

Note: VOC1 and VOC3 through VOC9 are the burst sources which were located in various zones throughout the buildings. They may be located in different zones in different buildings. VOC2 is the floor source.

Table 5b - Percent reductions in 24-hour average baseline concentrations due to outdoor air intake damper (non-VOC sources)

SIMULATION	Oven - CO	Oven - NO_2	Oven - Particles	Heater - CO	Heater - NO_2	Heater - Particles	Outdoor - CO	Outdoor - NO_2	Outdoor - Particles
SIM1FLCO	6.5	-0.5	-3.1	0	-13.5	-3.3	-0.2	-13.6	-10.6
SIM1FLHO	9	0.8	-6.2	NA	NA	NA	1.5	-15.2	10.2
SIM1FLMO	0.1	-0.2	-0.2	NA	NA	NA	0	-0.7	0.7
SIM1FTCO	6.1	-1.2	-4.8	3.6	-5.7	-4.3	-0.1	-13.6	11.2
SIM1FTHO	6.1	-1.1	-6.1	NA	NA	NA	0.8	-16.2	38.1
SIM1FTMO	0.9	-0.3	-0.8	NA	NA	NA	0.2	-2.5	3.3
SIM1MLCO	6.2	-2.7	-6.3	5	2.1	-5	0.3	-20.8	15.2
SIM1MLHO	2	-1.5	-2.8	NA	NA	NA	-0.5	-9.6	4.2
SIM1MLMO	1.8	-3.1	-2.8	4.7	3.6	-1.7	0.3	-10.1	3.8
SIM1MTCO	26	-6.9	-39.4	21.7	-0.5	-30	0	-103.9	33.9
SIM1MTHO	13.9	-3.2	-18.6	NA	NA	NA	-2.1	-48.2	11.3
SIM1MTMO	13	-5.4	-18.1	21.2	-2.8	-11.5	1.7	-48.5	8.3
SIM2FLCO	0.5	-1.8	-1	0	-4.2	-1	-0.2	-4.6	3.3
SIM2FLHO	9.5	-3.7	-9.2	NA	NA	NA	1.4	-27	22.8
SIM2FLMO	-0.4	-1.1	-0.3	NA	NA	NA	-0.1	-1.6	1.1
SIM2FTCO	10.9	-3.8	-10.8	2.1	-27	-10.7	-1	-31	7.7
SIM2FTHO	37.2	-9.1	-65.1	NA	NA	NA	2.8	-164.1	30.4
SIM2FTMO	2.6	-1.6	-2.9	NA	NA	NA	0.9	-9	2.9
SIM2MLCO	1.3	-3.8	-2.3	1.9	3.2	-1.8	0	-8.4	7.7
SIM2MLHO	0.4	-3.5	-1.7	NA	NA	NA	-0.3	-7.6	2.6
SIM2MLMO	0.3	-3.6	-1.6	1.8	1.7	-1.1	-0.1	-6.6	1.4
SIM2MTCO	9.5	-10.5	-17.5	11	4.5	-13.7	-0.1	-48.4	19
SIM2MTHO	7.8	-6.5	-14.7	NA	NA	NA	-2.4	-47.7	7.4
SIM2MTMO	7.3	-6	-11.1	12.4	2.1	-7.1	0.7	-36.6	2.6

Table 6 - Percent reductions in living-space peak and maximum 1-hour average concentrations due to heat recovery ventilator

SIMULATION	Floor - VOC	MBR - VOC	KIT/KFA - VOC	Oven - NO_2	Heater - NO_2	Oven - CO	Heater - CO
SIM1FLCH	4.74	0.07	0.08	-0.03	-1.51	-0.1	-0.99
SIM1FLHH	18.9	1.18	1.04	0.71	NA	1.59	NA
SIM1FLMH	4.31	0	0.01	0	NA	0	NA
SIM1FTCH	18.62	1.52	1.28	-0.04	-15.83	0.79	-1.37
SIM1FTHH	25.53	1.74	1.46	0.68	NA	1.22	NA
SIM1FTMH	7.73	0.64	0.66	0	NA	0.18	NA
SIM1MLCH	30.93	1.27	1.18	3.28	17.99	3.1	0.4
SIM1MLHH	1.75	0.32	0.23	0.59	NA	0.78	NA
SIM1MLMH	13.77	0.24	0.2	-0.07	0.48	-0.32	3.69
SIM1MTCH	52.54	2.76	2.37	3.33	30.79	3.87	18.5
SIM1MTHH	13.35	2.35	1.59	0.5	NA	0.91	NA
SIM1MTMH	38.55	1.61	1.23	-0.16	20.4	0.04	22.01
SIM2FLCH	3.79	-0.24	-0.96	-0.3	-3.57	0.07	-1.62
SIM2FLHH	34.1	1.42	3.54	1.44	NA	1.69	NA
SIM2FLMH	1.21	0.02	0.22	0	NA	0.01	NA
SIM2FTCH	20.4	1.05	2.23	0.12	-38.62	2.3	-3.89
SIM2FTHH	63.39	7.52	11.8	1.3	NA	7.69	NA
SIM2FTMH	5.46	0.68	0.29	-0.19	NA	0.43	NA
SIM2MLCH	20.52	1.17	2.22	2.16	20.89	2.28	2.39
SIM2MLHH	-0.45	1.24	-1.7	-1.86	NA	-1.4	NA
SIM2MLMH	9.15	-0.59	1.8	-2.42	1.21	-2.48	2.47
SIM2MTCH	46.55	2.83	4.53	1.88	23.42	0.67	3.69
SIM2MTHH	11.94	1.45	1.22	-0.68	NA	-1.04	NA
SIM2MTMH	25.57	1.12	1.79	-0.49	15.62	-0.5	12.08

Note: The VOC and NO_2 results are for peak concentrations; the CO results are for maximum 1-hour average values. All reductions are for individual living-space zones.

Table 7 - Percent reductions in living-space peak and maximum 1-hour average concentrations due to outdoor air intake damper

SIMULATION	Floor - VOC	MBR - VOC	KIT/KFA - VOC	Oven - NO_2	Heater - NO_2	Oven - CO	Heater - CO
SIM1FLCO	13.94	2.38	1.94	1.45	-7.62	1.4	-1.8
SIM1FLHO	13.82	3.03	0.51	2.8	NA	0.2	NA
SIM1FLMO	2.77	0	-0.01	0	NA	0	NA
SIM1FTCO	17.56	1.6	1.48	-0.15	22.11	0.1	3.7
SIM1FTHO	8.57	0.85	-0.53	0.16	NA	-2	NA
SIM1FTMO	3.93	0.17	-0.09	0	NA	0	NA
SIM1MLCO	23.6	-1.83	-1.06	-2.15	11.21	-1.7	1.2
SIM1MLHO	1.44	0.34	-0.01	-0.37	NA	-0.6	NA
SIM1MLMO	11.14	0.22	0.1	-0.04	4.3	-0.2	8.1
SIM1MTCO	47.25	-0.43	0.19	-3.2	25.68	-2	18.5
SIM1MTHO	12.16	2.19	1.2	-0.79	NA	-0.8	NA
SIM1MTMO	35.92	1.39	0.91	-0.2	16.83	-0.1	22.4
SIM2FLCO	3	-0.2	-1.05	-2.16	-1.91	-2.9	-0.5
SIM2FLHO	24.62	-2.66	0.16	-1.03	NA	-1.7	NA
SIM2FLMO	0.92	-0.28	-0.32	-0.38	NA	-0.4	NA
SIM2FTCO	18.14	1.68	1.26	-1.36	-12.22	-1	-1.4
SIM2FTHO	59.22	4	8.2	-1.65	NA	3.4	NA
SIM2FTMO	3.83	-0.26	-0.15	-0.19	NA	0.1	NA
SIM2MLCO	14.92	2.84	-2.99	-1.66	13.2	-2.1	6.5
SIM2MLHO	-0.82	1.47	-1.92	-2.41	NA	-2.9	NA
SIM2MLMO	6.07	-6.42	0.28	-2.44	4.32	-2.5	5.6
SIM2MTCO	38.18	7.06	0.09	-1.6	16.37	-3	16.4
SIM2MTHO	10.33	1.99	0.89	-1.04	NA	-2	NA
SIM2MTMO	22.18	1.62	1.37	-0.49	13.48	-0.6	15.9

Note: The VOC and NO_2 results are for peak concentrations; the CO results are for maximum 1-hour average values. All reductions are for individual living-space zones.

Appendix B Residential Ventilation and IAQ Modeling Workshop

Introduction

On May 4, 1995, NIST hosted a workshop on Residential Ventilation and IAQ Modeling in accordance with the Interagency Agreement with CPSC to discuss the computer simulation study performed by NIST. The participants of the workshop included IAQ researchers and representatives of residential HVAC equipment manufacturers, industry associations, and federal agencies involved in residential IAQ. A list of workshop attendees is included in this appendix. The objective of the workshop was to describe the project and results to the participants, to discuss IAQ modeling issues identified during the project, and to discuss ideas for follow-up work. The feedback received from the participants will be considered in developing future research plans in the area of residential IAQ modeling. The purpose of this appendix is to summarize the workshop discussion.

General

The workshop was organized into the following main sections: Description of the Project, Discussion of Project Results, IAQ Modeling Issues, and Additional Issues for Simulations. The Description of the Project section explained the objectives and motivation behind the project and presented many of the modeling details concerning the buildings, HVAC systems, pollutants and sources, and IAQ controls included in the study. Also, the latest available version of the program, CONTAM94, was demonstrated to provide a better sense of the modeling process. The Discussion of Project Results section presented selected simulation results including average building air change rates, transient pollutant concentrations, average pollutant concentrations, and percent changes in concentrations due to the IAQ controls. The IAQ Modeling Issues section described the issues identified during the project including model inputs, model validation, sensitivity analysis, input errors, simulation capabilities, and analysis of model outputs. Finally, the Additional Issues for Simulations section discussed other factors which could be studied using the analysis approach of the project including building factors, pollutants and sources, IAQ controls, side effects of the IAQ controls, and key residential IAQ issues.

Each of the workshop sections generated discussion which ranged beyond the specific information being presented, and many subjects were brought up at several points during the workshop. As such, the comments are classified into four categories which are discussed below:

1. Analysis Approach Employed in Project
2. Ideas for Other Simulations and Follow-Up Work
3. Development of CONTAM
4. Model Validation

Analysis Approach Employed in Project

Although the description of the project and discussion of the project results generated much discussion, many of the participants' comments were more general in nature and, therefore, are discussed in other sections of this appendix. The comments specifically regarding the analysis approach employed in the project may be further classified as concerning either the modeling method or the simulation results. Some of the issues raised were discussed previously at the project Phase I workshop held at NIST in August 1993 (Emmerich and Persily 1994).

One basic issue raised by a participant was the reason for choosing a multizone model rather than a single zone model. The single-zone modeling mentioned was not computational fluid dynamics (CFD) modeling discussed in the Phase I report but instead is a single node implementation of the uniform temperature and concentration assumptions employed in multizone models. Single-zone modeling of this type could yield much of the same information as the multizone modeling with less input, simulation, and output analysis effort. However, this type of modeling would lack some of the information provided by the multizone model such as effects of local sources and interzonal transport of pollutants. It was mentioned that the difference would become apparent if an exposure analysis were performed.

A few other comments were made regarding more specific aspects of the modeling. One participant wondered why occupants were not include as sources. This issue was discussed at the Phase I workshop and it was explained that the pollutants were limited to the list of pollutants of interest in the interagency agreement which defined the scope of the project. The observation was made by one participant that the reference to a heat recovery ventilator (HRV) could be misleading because thermal effects were not modeled. It was suggested that this could be clarified by referring to the HRV as a balanced ventilation system. Other participants observed that the modeling of NO_2 and particles could be considered incomplete as chemical reactions between NO and ozone and pollutant penetration factors were not considered. A related comment concerned the importance of outdoor pollutant concentrations as a function of time, particularly if chemical reactions are modeled. Another potentially important feature not considered is depressurization of the buildings by a furnace flue.

One significant comment regarding analysis of the simulation output was a suggestion that, rather than reporting concentrations and percent changes in concentrations, it may be informative to examine indoor/outdoor ratios of concentrations. Examining the results in this way may put the relative impacts of the IAQ controls on the various pollutants in a better perspective. Other comments regarding the simulation output included the observation that the NO_2 results indicate the potential need for an outdoor air cleaner to control NO_2, the suggestion that the simulation results should be compared to any experimental results that might be available, and the proposition that a pollutant index approach be employed through nondimensionalizing the pollutant transport.

Ideas for Other Simulations and Follow-up Work

Although many additional issues for simulations were presented by NIST, the participants generated several more ideas regarding both the form and substance of future simulations. One participant suggested considering days with low infiltration driving forces as a "worst case" scenario rather than using more typical weather data. Other participants proposed performing yearlong simulations as a means of evaluating exposure and accounting for "bad" days throughout the year. It was also suggested that a simple estimate of the energy loads due to the ventilation air could be made. Several participants commented that occupant behavior (including impact on pollutant sources) should be considered. It was suggested that other ventilation approaches such as non-forced air system HRV, continuous operation of systems, exhaust ventilation, and enthalpy recovery units be studied. Other participants proposed more detailed investigation of the pressurization of the building and the effects of duct leakage.

One participant expressed a need in the industry for a "level playing field" for comparing IAQ control options. He suggested that, after various validation efforts are undertaken, the program could be used with standard cases to provide a rating system. It was mentioned that such a rating program was in line with the original goal of CPSC in supporting this project.

Development of CONTAM

Throughout the workshop, comments were made on features which could be added to CONTAM to enhance its capabilities. These comments ranged from fundamental changes in the model assumptions to additional modeling capabilities and features enhancing the usefulness to the less-knowledgeable user. Many of the suggestions are ideas which have already been considered and are already being pursued, but others are new ideas or old ideas that have been given a new perspective and will be considered.

One fundamental issue discussed was converting the model from a trace element basis to a non-trace analysis. The non-trace analysis would improve the ability of the program to model moisture and smoke transport in buildings. Additional modeling capabilities suggested by participants included detailed duct system modeling, system controls, thermal analysis modeling, exposure analysis, a Darcy flow subsoil model, pollutant re-entrainment modeling, and deposition velocity modeling for pollutant decay. At the same time, comments were made warning against overextending the program.

Interest was expressed in three features that would make the program more usable and reliable including libraries of data, generic buildings, and automated tests of building models. Libraries of data on pollutants, sources, leakage data, weather, exposure scenarios and other inputs would simplify the data entry process and would provide the less-knowledgeable user with the best available data. Several comments were made regarding the usefulness of generic buildings including residential, commercial, hospital, and vehicles (such as airplanes). Such generic building files would provide the user with a standard building to model with minimal effort and would ensure that the building model has been "debugged" to eliminate errors. Automated tests such as fan pressurization, tracer gas decay, and pure free convection simulations could help verify that a building has been idealized in a reasonable manner and that data was entered correctly. It was also suggested that input data could be checked and flagged if it falls outside of reasonable limits and that a chapter in the program manual be devoted to assisting the user in verifying that their model is reasonable.

Model Validation

Although model validation could have been listed with other follow-up activities, enough discussion occurred to warrant separate consideration. Opinions expressed on model validation ranged from participants who felt that detailed model validation against experimental results was an absolute necessity to those who believe that the model is based on well-established theory and, therefore, validation only determines the accuracy of the inputs. A participant characterized model validation as having three aspects: benchmarking in which one compares the output of two different programs, verification in which the results are compared to theory, and validation in which predictions are compared to experimental results. Another participant commented that errors in the idealization of the building may be more important than any errors in the program or input data. Although no consensus was reached on either the importance or direction of a validation effort, it is an issue of great interest.

List of Workshop Attendees

The following people attended the Residential Ventilation and IAQ Modeling Workshop.

Jim Axley
Yale University

Terry Brennan
Camroden Associates

Roy Deppa
CPSC

Kevin Dunshee
Carrier Corporation

Tim Dyess
U.S. EPA

Steve Emmerich
NIST

Conrad Flessner
U.S. EPA

Bill Freeborne
HUD

Dave Godwin
ARI

David Grimsrud
University of Minnesota

Roger Hedrick
Electrocom GARD

Mark Jackson
Bonneville Power Adminstration

Pat Kennedy
U.S. EPA

John Kesselring
EPRI

Mike Koontz
GEOMET Technologies

Bryan Ligman
U.S. EPA

David Mudarri
U.S. EPA

Niren Nagda
Energen Consulting

Tim Obee
UTRC

Andy Persily
NIST

Lori Saltzman
CPSC

Dilip Vyavaharkar
Carrier Corporation

George Walton
NIST

Charlie Weschler
Bellcore

Charlie Wilkes
GEOMET Technologies

GrenYuill
Pennsylvania State University