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Multizone Modeling of Three Residential Indoor Air Quality Control Options

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Abstract

The National Institute of Standards and Technology (NIST) performed a preliminary study of the use of 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 multizone airflow and 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. 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.

This report summarizes the three phases of this effort, each of which consisted of three main tasks. The Phase I tasks included conducting a literature review, developing a plan for computer analysis, and holding a workshop to discuss the plan. The Phase II.A tasks included baseline simulations of contaminant levels without indoor air quality (IAQ) controls, design of the IAQ control retrofits, and preliminary simulations of contaminant levels with the IAQ control retrofits. The Phase II.B tasks included 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. This report is a consolidation of the three previous reports on the project: Emmerich and Persily 1994 on Phase I, Emmerich and Persily 1995a on Phase II.A, and Emmerich and Persily 1995b on Phase II.B.

The multizone airflow and pollutant transport program CONTAM93 was used to simulate the pollutant concentrations due to a variety of sources in eight buildings with typical HVAC systems under different weather conditions. Three indoor air quality control technologies were incorporated into the house models to determine their effectiveness in controlling the modeled pollutant sources. The technologies include the following: electrostatic particulate filtration, heat recovery ventilation, and an outdoor air intake damper on the forced-air system return.

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 was identified as a limitation of IAQ controls that operate in conjunction with forced-air systems.

Key Words: airflow, building technology, computer simulation, filtration, heat recovery ventilation, HVAC, indoor air quality, infiltration, modeling, residential, ventilation

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Executive Summary

Introduction

Central forced-air heating and cooling systems can have the potential for both positive and negative impacts on IAQ in residential building. Because they circulate large volumes of air, those systems can spread pollutants generated in one room to the rest of the house. They also can act as a source of indoor air pollution, for example, due to dirty ductwork. However, forced-air system modifications have the potential to improve IAQ through the addition of air cleaners or devices to introduce outdoor air into the house. Evaluating both the effectiveness and negative impacts of such modifications could require extensive field testing. Computer modeling can provide insight without the time and effort required to perform field tests. Such a modeling effort requires a whole building approach that accounts for the multizone nature of airflow and pollutant transport in residential buildings and considers all relevant factors - air leakage paths in the building envelope and interior walls, wind pressure coefficients, pollutant sources, HVAC system airflows, filter efficiencies, pollutant sinks, pollutant decay or deposition, and ambient weather and pollutant concentrations. Many residential IAQ modeling studies have employed simplified approaches to studying 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). 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 of this effort was to provide insight into the use of sophisticated 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. Another important objective was to identify key issues in the use of multizone airflow and pollutant transport models to study IAQ in residential buildings.

Modeling Method and Parameters

The program CONTAM93 (Walton 1994) was used to simulate the pollutant levels due to a variety of sources in four houses in two cities with typical HVAC systems. 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 containing pollutant sources and sinks and are modeled at a uniform temperature and pollutant concentration.

Simulations were performed for a hot, mild, and cold day in each city using Weather Year for Energy Calculation (WYEC) data (Crow 1983). Each simulation consisted of a one-day cycle repeated until peak concentrations converged to a specified tolerance. The 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, 96 simulations were performed to evaluate the impact of these controls on pollutants from the following sources: a constant-emission volatile organic compound (VOC) source, intermittent-emission (burst) VOC sources, combustion pollutant sources, and elevated outdoor pollution.

Buildings

The CONTAM93 description of buildings includes the building zones, characteristics of leakage paths connecting zones, and the wind pressure coefficients of leaks through the building envelope. The study included eight buildings - a ranch and a two-story house, located in two sites (Miami and Minneapolis), with typical and low levels of air leakage. The Minneapolis houses have basements. The air leakage of the house envelopes and interior partitions was modeled by including elements for leakage paths typically found in residential buildings. Most of the leakage values and wind pressure coefficients were based on data in the ASHRAE Fundamentals Handbook (1993).

HVAC Systems

The buildings were modeled with typical residential central forced-air heating and cooling systems with modest duct leakage and no outdoor air intake. System operation schedules were determined by calculating the fractional on-time required to meet the cooling or heating load. The baseline 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).

Pollutant Factors

The pollutants of interest for this study were nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, and volatile organic compounds (VOC). Based on a literature review of reports quantifying residential sources of these pollutants, the pollutant sources included eight VOC burst (short duration) sources, a constant VOC area source, and combustion sources of CO, NO_2, and fine particles.

Typical outdoor pollutant concentrations were used to account for pollution entering the dwelling from outside. The CO and NO_2 concentrations were selected to have a diurnal pattern with morning and afternoon peaks, and varied from 1 to 3 ppm for CO and 20 to 40 ppb for NO_2 based on a review of US EPA air quality documents (EPA 1991, EPA 1993a, EPA 1993b). A constant fine particle concentration of 13 $\mu g/m^3$ was based on Sinclair et al. 1990, and a constant TVOC concentration of 100 $\mu g/m^3$ was based on Shields and Fleischer 1993.

Elevated outdoor concentrations of CO, NO_2, and coarse particles were also simulated to evaluate the impact of the IAQ control technologies on pollutants brought into residences from outside. These elevated pollutant concentrations were also based on the EPA air quality documents. The elevated CO and NO_2 concentrations also had a diurnal pattern with morning and afternoon peaks, and varied from 4 to 12 ppm for CO, and 200 to 400 ppb for NO_2. The coarse particle concentration was constant at a level of 75 $\mu g/m^3$.

IAQ Control Technologies

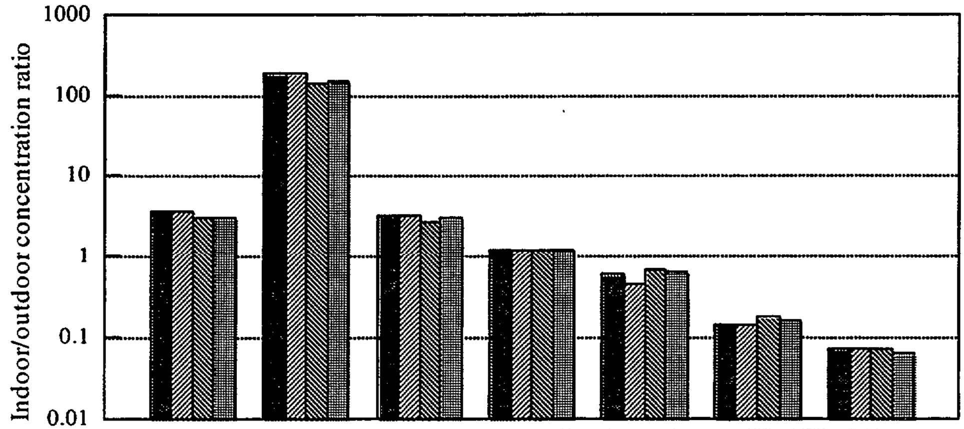
The IAQ control technologies considered for the study were limited to commercially available equipment that can be used with typical forced-air systems. Ventilation systems and IAQ controls that operate independently of a forced-air system were not considered. The three control technologies were electrostatic particulate filtration, heat recovery ventilation, and an outdoor air intake damper on the forced-air system return

The electrostatic particulate filter (EPF) 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 pollution). 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. The actual outdoor airflow rate during operation was selected to provide an air change rate of 0.35 h^{-1} through the HRV. The outdoor air intake damper (OAID) draws outdoor air into the return side of the forced-air system. The OAID was modeled similarly to the HRV by modifying the HVAC system to include a constant fraction of outdoor air to provide an air change rate of 0.35 ach through the system during operation. The primary difference between the OAID and the HRV is that the OAID does not include an exhaust duct. Thus, the OAID will tend to pressurize the house.

Results

Impact of IAQ Controls on Average Pollutant Concentrations

Figure *ES1* shows the ratio of the 24-hour, living-space average concentrations to the 24-hour average outdoor concentration for the baseline, EPF, HRV, and OAID cases in the tight, Miami ranch house on the cold day. The indoor/outdoor ratios are shown on a log scale as they range over five orders of magnitude depending on the source. The VOC burst source results shown use the average of the concentrations due to all eight burst sources to represent the average impact of the IAQ controls on localized sources in different rooms of the house. The variation in the indoor/outdoor ratio among the sources is due to the relative values of the source strength, indoor decay mechanisms and outdoor pollutant concentrations. The controls themselves have much less impact on these ratios, but the effects can still be seen.



Source	Burst-VOC	Floor-VOC	Oven-CO	Oven-NO2	Oven-fine	OA-NO2	OA-coarse
■ Baseline	3.7E+00	1.9E+02	3.2E+00	1.2E+00	6.2E-01	1.4E-01	6.9E-02
▨ EPF	3.7E+00	1.9E+02	3.2E+00	1.2E+00	4.4E-01	1.4E-01	6.8E-02
▧ HRV	3.0E+00	1.4E+02	2.7E+00	1.2E+00	6.8E-01	1.8E-01	7.1E-02
▦ OAID	3.0E+00	1.5E+02	3.0E+00	1.2E+00	6.5E-01	1.6E-01	6.1E-02

Figure *ES1* - Indoor/outdoor Ratios of Average Concentrations Due to Various Sources
(Tight Miami Ranch House on Cold Day)

The average impact of the IAQ controls for all pollutant sources are shown in Figure *ES*2 as percent reductions in baseline concentrations. In general, both the HRV and OAID reduced the concentrations due to indoor sources of the pollutants without non-ventilation removal processes (CO and VOC) and increased, or had little impact, on the concentrations of pollutants with decay/deposition and filtration removal processes (NO_2 and particles). The HRV and OAID had the greatest reduction for the constant, distributed source (Floor-VOC), which was also the source resulting in the largest indoor/outdoor concentration ratio. In general, the HRV and OAID increase NO_2 and particle concentrations the average indoor concentration is generally below the average outdoor concentration. Therefore, the additional outdoor air brought in by these controls increases the indoor concentration. However, whether an increase or decrease occurred for an individual case depended on several factors including the building air change rate, the indoor source strength, the outdoor pollutant concentration, decay/deposition rates, and the timing of the source, system operation, and outdoor peaks.

The impact of the OAID was nearly always similar to but slightly smaller than the impact of the HRV because it increases the average building air change rate by a smaller amount than the HRV. This smaller increase in building air change rates is due to the fact that the OAID pressurizes the building, while the HRV is balanced and has no effect on building pressure.

In general, the EPF had a small impact on the already low coarse particle concentrations with an average reduction of only 1.4%. This small impact is due to the small change in coarse particle filtration efficiency from 90% to 95%. Figure *ES2* shows that the EPF was more effective at reducing the fine particle concentrations with reductions of 30% and 31% for the oven and heater sources, respectively. It should be noted that, as indicated by the indoor/outdoor ratios, the conditions simulated provided only a modest challenge to the EPF.

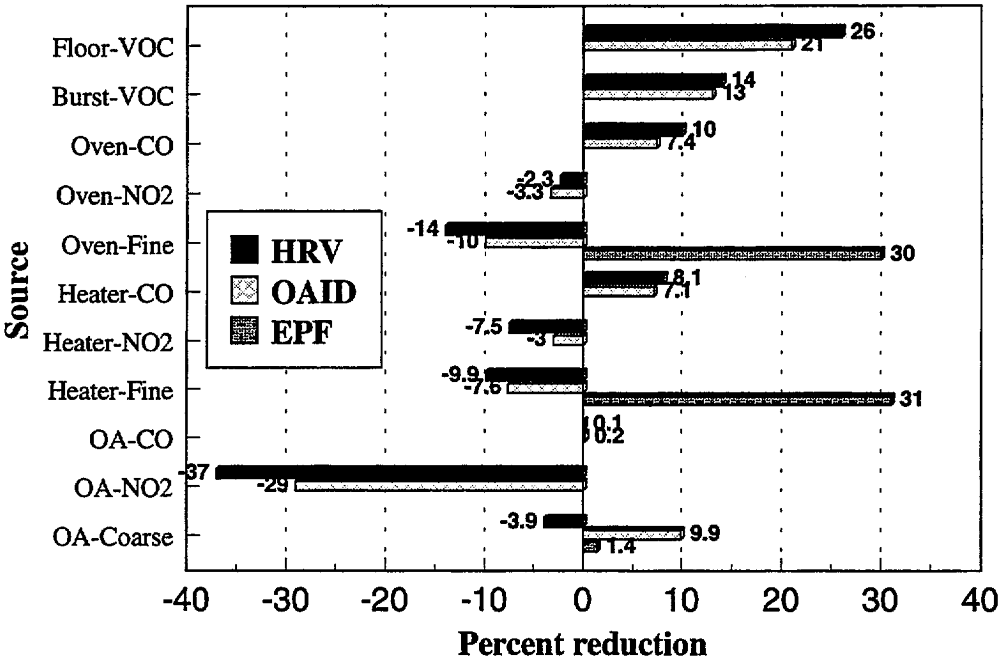


Figure *ES2* - Average Reductions in Living-space Average Concentrations

Factors Influencing Impact of IAQ Controls

Besides the pollutant and source dependent variations, the impact of the IAQ controls on the concentration due to a single source varied greatly. For example, the reduction for the floor source ranged from 3% to 69%. One reason for the variation was dependence on HVAC system run-time.

Figure ES3 shows both the average percent reduction in baseline Floor-VOC concentration due to the HRV and the average percent system run-time for the Miami cases. On the mild day, the system operated an average of 7% of the time to meet the low thermal load and reduced the baseline concentration by only 8%. On the hot day, the system operated 65% of the time to meet the high heating load and reduced the baseline concentration by 41%. Although this influence was observed for most sources,other factors, such as timing of system operation, also become important for short-duration sources.

Often, the conditions (small indoor-outdoor temperature difference) causing low system run-time also correspond to low infiltration and high pollutant concentrations. Therefore, days with high concentrations due to low infiltration could receive the least help from the HRV or OAID due to low system run-time. The effectiveness of the central forced-air modifications could also be limited if the cooling and heating equipment is oversized. Although it was not explored in this study, oversized equipment would further reduce the HVAC system run-time. The system run-time limitation could be overcome through other control options (e.g. constant operation, demand control, or scheduled operation) or through other approaches to residential ventilation.

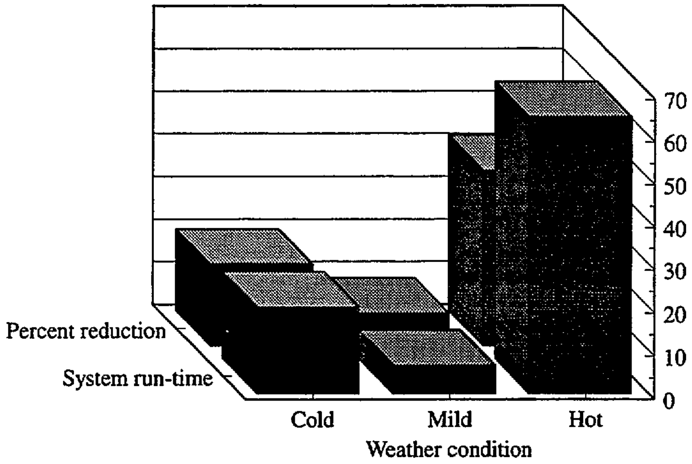


Figure *ES3* - Influence of System Run-time on IAQ Control Impact
(Floor-VOC for Miami HRV Cases)

Another factor showing a consistent influence on the IAQ control impacts was envelope airtightness. Figure *ES4* shows the average impact of the HRV on baseline CO and fine particle concentrations due to the oven. The HRV consistently had a larger impact, whether positive or negative, in the tight houses due to a greater relative change in the average building air change rates for the tight houses.

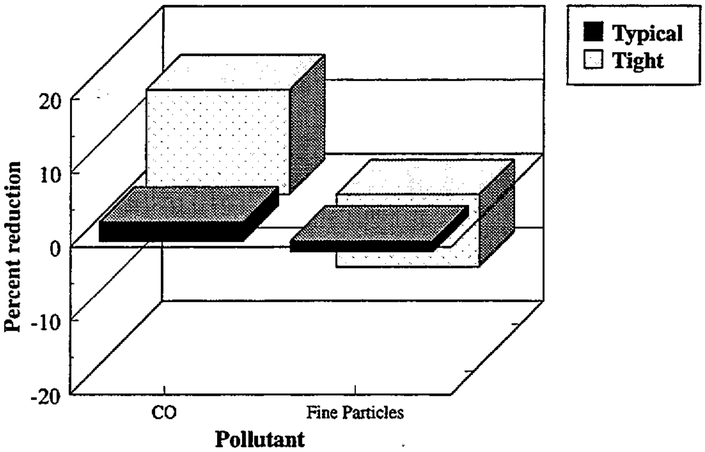


Figure *ES4* - Influence of envelope airtightness on IAQ control impact
(average percent reduction of oven pollutants due to HRV)

IAQ Modeling Issues and Follow-up Activities

An important goal of the project was to identify issues related to the reliability and usefulness of multizone IAQ models and to identify important areas for follow-up work. Several such issues were identified in planning the study, performing simulations, and analyzing the results. Follow-up activities to address these issues are discussed briefly below.

- Model validation - A systematic approach to multizone model validation that considers the types of models, building features, pollutants and sources is needed. Although absolute validation of a program such as CONTAM 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 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.

- Experimental evaluation - An issue related to model validation but specific to this project is the experimental evaluation of the IAQ controls that were modeled. Even a limited experimental effort would lend support to the model results or indicate deficiencies in the modeling method or details.

- Sensitivity analysis - The modeling results show that the outcome of a simulation varies dramatically for different input values due to the complexities of airflow and pollutant transport in multizone systems, and that the relationships between model inputs and outputs can be unexpected and difficult to understand based only on one's intuition. In this study, attempts were made to select reasonable values for all 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.

- Development of database for model parameters - In the process of setting up the houses in CONTAM93, difficulties were encountered in obtaining data for many model 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 limits the usefulness of airflow and IAQ models. Existing knowledge gaps need to be identified and analyzed, and a strategy should be developed to obtain the information needed to make modeling a more useful tool.

- Investigation of options to identify/eliminate input errors - Describing a building as a multizone system of airflow and pollutant transport elements is a complex process, depending on the configuration of the building and the factors being considered in the simulation. Use of any simulation program involves the risk of inputting erroneous numerical values or neglecting to input an individual element. Given that the results of a simulation may not be intuitive, it can 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 developed to identify input errors, but this issue merits attention as these programs are more widely used.

- Simulation of other buildings, pollutants, and IAQ control technologies - The factors included in the simulations were limited by project resources. The modeling approach could be used to investigate many other factors including other house characteristics, pollutants, sources, IAQ controls, and the side-effects of implementing the controls. 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 side-effects is important in evaluating 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.

- Development of representative building set - It will always be difficult to generalize the results of such simulations or to predict their impact on the residential building stock without considering the wide variety of house types and building features. Development of a set of houses to represent the building stock of a particular region or country based on a statistical analysis of important residential buildings features would make such generalizations possible.

- Development of additional simulation capabilities - Despite the limitations of IAQ modeling discussed here, these programs have the potential to provide valuable insight into a range of IAQ issues. However, the IAQ issues that can be studied by a program are determined by its simulation capabilities. In addition, these capabilities determine the ability of the model to consider the potential side-effects of an IAQ control method. All models are limited in their capabilities, and opportunities exist to expand these models to consider other issues, or to consider them more thoroughly. Some important additional capabilities include more complete treatment of chemical reaction and absorption 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.

Conclusions

The multizone program CONTAM93 was used to simulate the impact of several modifications to typical residential HVAC systems on pollutant concentrations due to a variety of sources in eight houses under different weather conditions. Although the system modifications reduced pollutant concentrations in the houses for some cases, the HRV and OAID increased pollutant concentrations in certain situations involving a combination of weak indoor sources, high outdoor concentrations, and indoor pollutant removal mechanisms. Limited system run-time during mild weather was identified as a limitation of IAQ controls that operate in conjunction with typical forced-air systems. However, this limitation could be overcome through other control options for these devices or through other approaches to residential ventilation. 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 important model inputs.

1 INTRODUCTION

1.1 Background

Central forced-air heating and cooling systems can have a significant impact on IAQ in residential buildings because they circulate large volumes of air, spreading pollutants generated in one room to the rest of the house. They also can act as a source of indoor air pollution, for example, due to dirty ductwork. However, forced-air system modifications have the potential to improve IAQ through the addition of air cleaners or devices to introduce outdoor air into the house. Evaluating the effectiveness of such modifications could require extensive field testing. Computer modeling can provide insight without the time and effort required to perform field tests. Such a modeling effort requires a whole building approach that accounts for the multizone nature of airflow and pollutant transport in residential buildings and considers all the relevant factors - air leakage paths in the building envelope and interior walls, wind pressure coefficients, pollutant sources, HVAC system airflows, filter efficiencies, pollutant sinks, pollutant decay or deposition, and ambient weather and pollutant concentrations. Many residential IAQ modeling studies have employed simplified approaches to studying 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). A few studies have employed a whole building modeling approach (Li 1993, Yuill et al. 1991).

1.2 Technical Approach

In this project, NIST used computer simulations to assess the potential for using forced-air heating and cooling systems to improve residential indoor air quality. Specifically, NIST performed whole building airflow and contaminant dispersal computer simulations of single-family residential buildings to assess the ability of modifications of forced-air heating and cooling systems, using commercially available technology, to control selected pollutant sources relevant to the residential environment. The whole building analyses involved modeling a building and its HVAC system as a network of zones connected by flow paths. Pollutant sources with specific spatial distributions and temporal profiles were located in selected zones and the air and pollutant mass balance equations were solved to determine the pollutant concentrations in each zone. Simulations were performed assuming standard, or baseline, HVAC systems and repeated with the IAQ control technologies installed in these systems. The concentrations calculated with the controls in place were compared to the baseline concentrations to evaluate the potential effectiveness of the control technologies.

The objective of the project was to conduct a preliminary assessment, using computer simulation, of the potential for using forced-air HVAC systems to control IAQ in residential buildings. The project was intended to provide insight into the use of sophisticated 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.

1.3 Contents of Report

This report consists of four main sections titled: Literature Review, Modeling Method, Results, and IAQ Modeling Issues and Follow-Up Activities. The first section summarizes the results of a literature review undertaken as the first task of this effort. The research literature and other available information were studied to determine the appropriateness of the project objective and the feasibility of the analysis approach, and to find specific information on residential pollutant sources and IAQ control technologies. The second 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. The third section of this report presents the results of the simulations, and includes transient pollutant concentration results for selected cases and a summary of peak and average concentrations for all cases. The fourth section discusses issues related to the use of multizone IAQ models and identifies several important follow-up activities.

The report also includes four appendices. The first appendix contains HVAC system information including equipment descriptions and air distribution system drawings. The second appendix describes modeling performed to characterize the airflow in the houses including the results of fan pressurization simulations and whole house infiltration simulations. The third appendix contains details on the indoor air quality control technologies that were evaluated in the computer simulations including revisions of the baseline house duct drawings, an estimate of the equipment and installation costs, and a discussion of the impacts of each of these technologies on "other contaminants". These other contaminants, as described in the original project work statement, include contaminants that have typically been of concern to designers of residential ventilation systems including cooking odors, tobacco smoke, moisture, outdoor pollen, outdoor odors and ozone. The fourth appendix includes summary tables of the baseline and preliminary simulation results.

2 LITERATURE REVIEW

This section summarizes a literature review of information on residential indoor air quality (IAQ) and HVAC systems conducted as the initial task of this effort. The objective of the literature review was to assess available information for use in developing a detailed plan for the computer simulations. The specific topics reviewed and discussed include the following:

1. Pollutant source strengths in single-family residential buildings
2. Computer simulation models
3. Other studies on the IAQ impacts of residential HVAC systems and components
4. Residential IAQ control technologies

In each case, the research literature and other available information were studied and assessed from the perspective of the overall project objective, i.e. to study the impact of forced-air distribution systems on indoor pollutant levels in single-family residential buildings.

2.1 Pollutant Source Strengths

This section discusses available information on the pollutants of interest as defined in the project work statement (CPSC 1993) and pollutant sources relevant to HVAC system impacts on indoor air quality. These pollutants of interest were selected by CPSC based on their having recently gained scientific concern, and include nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, biological contaminants, and volatile organic compounds (VOCs). The sources of these pollutants considered in this review are those that are expected to be impacted by the HVAC system, either positively or negatively. An extensive listing of the many potential sources of these and other common indoor air pollutants is found in Exhibit 2-7 of EPA 1991.

2.1.1 Nitrogen dioxide, carbon monoxide, and particulates

Combustion processes are the primary sources of both NO_2 and CO and a major source of particulates in residential buildings. The particles generated by combustion processes are almost entirely fine particles (less than 2.5 µm in diameter). Many studies have been done over the last decade to evaluate the indoor air quality impacts of indoor combustion processes. DOE 1990 summarizes many of the studies reporting source strengths of NO_2, CO, particulates and other combustion products, and provides source strengths from kerosene space heaters, gas space heaters, gas appliances, wood heaters, and cigarettes. Other studies of combustion process emissions are reported by Billick 1985, Lionel et al. 1986, Singh and Porter 1990, Tamura 1987, To and Hinchliffe 1983, Woodring et al. 1985, and Fortmann et al. 1984.

Although many studies have reported combustion source strengths, the data need to be interpreted carefully as a wide range of values have been reported and may be highly dependent on the specific equipment and test conditions. For example, reported gas range burner emissions of particulates range from as low as 0.13 mg/hr to as high as 30 mg/hr. DOE 1990 reports on the qualitative emission rate impacts of some gas range operating factors.

Under certain conditions, furnaces and other natural draft combustion appliances may experience flue gas spillage. Flue gas spillage occurs when house depressurization prevents the buoyancy forces developed between the flue gases and the outside air from removing the combustion products (including CO, NO_2, and particulates). House airtightness and exhaust ventilation equipment (e.g. bathroom fans and vented clothes dryers) can increase the potential for flue gas spillage. Wilson et al. 1986 and Shepherd 1992 report the results of some flue gas spillage tests. However, available research results do not provide quantitative source strengths associated with spillage events. Nagda et al. 1995 reports the results of a literature review on flue gas spillage and backdrafting.

Besides combustion processes, other sources of particulates in residences include occupants, pets, consumer products, building materials, and cleaning processes. Many of these indoor particle sources have not been studied quantitatively. However, Krafthefer and MacPhaul 1990 reports on particle emissions from electrical resistance type heaters, and Smith et al. 1990 quantifies particulate emissions from vacuum cleaners.

2.1.2 Biological Contaminants

Biological contaminants include pathogens (viruses, bacteria, and fungi) and allergens (fungi, pollen, insect and animal excreta, and animal dander). Common sources of bioaerosols in residential buildings include people, pets, rodents, insects, house dust, mites, wet carpeting, other wet furnishings and materials, plants, poorly maintained HVAC systems and components (including dirty filters, ducts, and in-duct insulation), humidifiers, and nebulizers. Section 4.4 of EPA 1991 provides a general discussion of bioaerosols.

Attention to biological contaminants as indoor air pollutants has increased in recent years and many contaminants, sources, and health effects have been studied. However, the literature review uncovered only one reported value of a bioaerosol source strength. Streifel et al. 1987 reported a source strength of $5.5x10^5$ CFU (colony forming units) per hour in a hospital from a rotting wood cabinet. However, this source strength was measured in situ and may not be relevant to a residential setting. Much of the published literature on residential biological pollution involves the measurement of concentrations in air in houses under different conditions (see for example Miller et al. 1989, Stetzenbach et al. 1990, and Pasenen et al. 1991), but not the determination of source strengths.

Recently, Strindehag et al. 1991, Lundqvist et al. 1990, and Foarde et al. 1992 have reported chamber studies on specific sources of biological contaminants in terms of either air concentrations or growth on materials but provide no information on airborne bioaerosol generation rates. The lack of quantitative source strength data may be due to a combination of the complicated testing methods for concentrations (as discussed Miller 1990) and the difficulty in designing laboratory tests that reasonably approximate the emission of bioaerosols in buildings. Additionally, there may be extreme variability of bioaerosol generation rates depending on factors such as temperature and relative humidity.

2.1.3 Volatile organic compounds (VOCs)

There are probably more potential sources of VOCs in residential buildings than any other class of indoor pollutant. These sources include building materials (pressed wood products, adhesives, insulating materials, tar paper, and plastic piping), interior furnishings (carpets, other floor coverings, upholstered furniture, wall coverings, and draperies), and consumer products (adhesives, caulking compounds, paints, cleaners, cosmetics, personal care products, deodorizers, wood finishers, waxes, fuels, pesticides, and plastic packaging), combustion processes, tap water, dry cleaned clothes, and vehicle exhaust. Emission rates of many of these sources have been reported in recent studies.

Colombo et al. 1990, Knoppel and Schauenburg 1989, Person et al. 1990, Tichenor and Guo 1991, van der Wal et al. 1990, Tichenor and Mason 1988, Tichenor 1989, Wallace et al. 1987, Sheldon et al. 1988, and Ozkaynak et al. 1987 report the emission rates of VOCs from a wide range of consumer products. Tichenor and Mason 1988, Tichenor 1989, Wallace et al. 1987, Sheldon et al. 1988, Ozkaynak et al. 1987, Colombo et al. 1990, Girman et al. 1984, Bayer and Papanicolopoulos 1990, Black et al. 1991, Nelms et al. 1986, Saarela and Sandell 1991, Nagda et al. 1993, Tirkonnen et al. 1993, and Christiansson et al. 1993 include VOC emission rates from various building materials. Furtaw et al. 1992 describes benzene emissions from parked vehicles in residential garages. Tancrede and Yanagisawa 1990 reports on VOCs present in tap water volatilizing in showers. Tichenor et al. 1990 details the emissions of VOCs from dry cleaned fabrics. It is important to caution that all the reported emission rates are specific for the material or product under the particular test conditions. Wide ranges of emissions have been reported for some sources and actual emission rates can depend on factors such as time, temperature, relative humidity, air speed, material composition, and airborne concentration.

Many of the reviewed studies were published in the last few years. None include a thorough collection of reported VOC emission rates. White et al. 1988 describes a database on indoor air pollutants that will include this information. However, this database is not yet publicly available.

2.2 Computer Simulation Models

There are two general types of computer simulation models for studying airflow and contaminant distribution in buildings - room airflow models and multizone models. Detailed or room airflow modeling takes a microscopic view of indoor air quality by examining the detailed flow fields and pollutant concentration distributions within a room (or rooms). Room airflow modeling applies the principles of conservation of momentum, mass, and energy by a computational fluid dynamics (CFD) technique. A recent review of the application of CFD programs to room airflow modeling by the International Energy Agency is reported by Moser 1992.

Multizone airflow and pollutant transport modeling takes a macroscopic view of indoor air quality by evaluating 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 constructing a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones which are modeled at a uniform pressure, temperature, and pollutant concentration. A survey of multizone airflow models is described by Feustel and Dieris 1992.

The whole building approach of multizone airflow and pollutant transport modeling is appropriate for studying the impacts of HVAC systems on residential indoor air quality. Accurately modeling an entire building with a CFD program would involve an unmanageable amount of detail and would require massive amounts of computing and data entry effort. A whole building CFD model has never been attempted and it is uncertain that such an effort would produce meaningful results. A more appropriate application of CFD modeling to residential IAQ would be comparing the impact of different combinations of air inlets and outlets on the airflow patterns and pollutant concentration distributions within a single room.

Not all the multizone airflow models listed by Feustel and Dieris 1992 are readily available nor do they all have the necessary pollutant transport calculation capabilities. Therefore, only two of the multizone models considered applicable to this project are described below.

IAQPC is a multizone pollutant transport model that has been used in a number of residential indoor air quality studies (Owen et al. 1989). IAQPC calculates airflows by balancing the user-specified total air exchange rate among the building zones based on the interzone connections. It does not implement network airflow analysis and, therefore, is not capable of considering the flow characteristics of individual openings, weather effects and the pressures created by HVAC system operation.

CONTAM93 as described by Walton 1994 is a model that combines NIST's programs AIRNET and CONTAM87. AIRNET (Walton 1989) performs the detailed multizone airflow calculations including the interaction of the building and its HVAC system with the weather. CONTAM87 (Axley 1988) performs the multizone contaminant dispersal calculations. CONTAM93 evolved from CONTAM88 (Grot 1991) and includes a graphical interface, updated airflow algorithms (CONTAM88 contained airflow algorithms from AIRMOV - a predecessor to AIRNET), and convenient ways to handle transient simulations. Due to its more complete airflow modeling capabilities (compared to IAQPC), CONTAM93 was determined to be more appropriate for achieving the project objectives.

2.3 Other Studies on IAQ Impacts of Residential HVAC Systems

The available literature was also reviewed for other studies on the indoor air quality impacts of residential HVAC systems and components. The review scope was limited to studies employing a whole building approach to residential indoor air quality as opposed to studies focussed on an individual aspect of the problem. The studies described below include both experimental and computer simulation work.

Experimental residential indoor air quality studies are reported by Matthews et al. 1990, Chang and Guo 1991, Leslie and Billick 1990. Matthews et al. 1990 studied the impacts of forced-air system operation and duct sealing on whole house air exchange rates and tracer gas transport from a crawlspace into a test house. This study found that forced-air system operation increased infiltration by up to a factor of 3.6; duct sealing reduced the impact of system operation on infiltration rates by one half; and duct sealing reduced tracer gas transport from the crawlspace by 30%.

Chang and Guo 1991 measured the effects of HVAC system operation, door and window opening, and local exhaust on the concentrations of a tracer gas (CO) used to simulate a source in the bathrooms of a single-story house. This study concluded that the central HVAC system acted as a pathway that transported pollutants from the source to the rest of the house. It also recommended installation of exhaust fans in all rooms where air pollutants are generated (bathrooms, kitchens, storage rooms and workshops) and operation of the exhaust fans with the central HVAC system off during periods of either intentional or accidental pollutant emission.

The study did not determine values of interzone airflow rates, but simply used CO as a qualitative tracer.

Leslie and Billick 1990 studied the concentrations of NO_2 and CO emitted by a furnace, an unvented gas-fired space heater, and an oven in a single story research house. The effects of range exhaust hood operation on pollutant concentrations were also examined. Range, oven, and space heater operation increased NO_2 and CO levels in the house, but furnace operation did not.

Simulation studies reviewed include Hekmat et al. 1986, Yuill et al. 1991, Yuill and Jeanson 1990, Hamlin and Cooper 1992, Novosel et al. 1988, Owen et al. 1992, Owen et al. 1988, Owen et al. 1990, Sparks et al. 1988, Sparks et al. 1989, Li 1993, and Modera and Jansky 1992. Hekmat et al. 1986 used the transient simulation program TRNSYS with the LBL infiltration model to study the impacts of five ventilation strategies on energy use and whole-house air change rates. Pollutant transport was not modelled, and contaminant concentrations were not predicted. Based on calculated air change rates, the study concluded that exhaust ventilation with heat recovery provided better indoor air quality than balanced mechanical ventilation.

Yuill et al. 1991 and Yuill and Jeanson 1990 used the program CONAIR, a combination of the NIST programs CONTAM87 and AIRNET, to examine pollutant concentrations in a single story house with a basement. The study considered two ventilation systems (central HVAC with heat recovery and a distributed-supply system), two control strategies (constant ventilation and demand control ventilation), and several pollutants (radon, formaldehyde, CO_2, and several arbitrary pollutants generated by point sources). The study concluded that the demand control ventilation system performed significantly better than the constant ventilation system at controlling occupant-generated pollutants, but the performance advantage was generally reversed for other pollutant sources.

Hamlin and Cooper 1992 used a simple single-zone infiltration model to perform yearlong simulations and predicted the pollutant concentrations as a function of source strength, weather, mechanical ventilation equipment operation, and house airtightness. The study concluded that a balanced approach between controlling emissions and ventilation should be taken and that a ventilation strategy based on the indoor-outdoor temperature difference could reduce predicted pollutant concentrations and minimize the energy cost of ventilation for non-airtight houses.

Novosel et al. 1988 calculated the indoor concentrations of formaldehyde and VOCs under different combinations of ventilation and filtration using a desiccant air conditioner in humid climates. A simple single-zone method was used for pollutant concentration calculations. The study concluded that the desiccant system could reduce pollutant concentrations while providing enhanced comfort levels.

Owen et al. 1992, Owen et al. 1988, Owen et al. 1990, Sparks et al. 1988, and Sparks et al. 1989 are reports of studies performed by the U.S. Environmental Protection Agency and the Research Triangle Institute using the indoor air quality model IAQPC (or its predecessor INDOOR) described above. Owen et al. 1992, Sparks et al. 1988, and Sparks et al. 1989 include comparisons of predicted concentrations with measured values. The objective of many of these studies was to evaluate the capability of the model to predict pollutant concentrations based on laboratory data for pollutant source strengths.

Owen et al. 1992 used IAQPC to look at the influence of different air cleaners on the concentration of particles from smoking and vacuum cleaning in a house. This study concluded that improving the efficiency of the air cleaner can effectively improve the indoor air quality of a residence. Owen et al. 1988 and Owen et al. 1990 used IAQPC to study impacts of air cleaning and various control strategies on indoor air pollution resulting from smoking in an office.

Sparks et al. 1988 used INDOOR to compare the predicted and measured concentrations of p-dichlorobenzene from moth crystals located in the closet of a ranch-style house with varied source strength and airflow from the closet. This study showed that small chamber emission rate data could be used with a multizone pollutant transport model to predict pollutant concentrations in this test house. It concluded that reasonable predictions of pollutant concentrations can be made, given data for the important model parameters, .

Sparks et al. 1989 used INDOOR to study the predicted concentrations of particles from a kerosene heater and VOCs from moth crystals and dry-cleaned clothes in a house under several indoor air quality control options. The options were varying percent outdoor air, filtration, local ventilation, and source reduction. This study concluded that source control was important and increasing general ventilation rate was an ineffective pollution control option.

Li 1993 reported the use of the multizone model MIX to study three actual IAQ problems being investigated in single family residences. The three problems were odor transfer from a crawlspace, moisture content of kitchen air, and radon levels in houses with different heating systems. The study concluded that the choice of building airtightness and ventilation system should be coordinated.

Modera and Jansky 1992 used the building thermal simulation DOE-2 and the multizone airflow program COMIS coupled by a third program DUCTSIM to investigate the impacts of duct leakage, fan operation, and door closure on building thermal performance. Pollutant dispersal was not modelled. The study concluded that duct leakage increases the house air change rate, conductive losses, and energy consumption (even when the system is off).

2.4 IAQ Control Technologies

This section describes pollutant control technologies applicable to residential forced-air distribution systems for consideration in the modeling study. This discussion is based on the review of published literature and manufacturer's product descriptions, as well as discussions with several experts in the area of residential indoor air quality and ventilation. The technologies considered include equipment and components that can be used in conjunction with conventional forced-air systems as opposed to systems that would be used independently or instead of a forced-air system. Whole-house systems that are not included in the following assessment include whole-house exhaust systems, with and without heat recovery, that employ outdoor air inlets around windows and other locations. Similarly, other heat recovery ventilation systems that would operate independently of the forced-air heating and cooling system, with their own system of air distribution ductwork, are not included.

Four categories of control technologies are discussed: air filters and air cleaners; ducted outdoor air intakes; heat recovery ventilators that are connected to the forced-air system; and the sealing of air distribution ductwork. The performance information available in the research literature is limited for these systems, and in some cases information is only available from product literature.

2.4.1 Air Filters and Air Cleaners

A variety of devices are available that can be installed in the ductwork of a forced-air system to remove particulate and gaseous contaminants from air. Particulate removal is a fairly well developed technology with an ASHRAE test method (ASHRAE 1992) for determining the effectiveness of these devices. While a variety of devices are available to remove gaseous contaminants from air, obtaining reliable performance data is difficult because no standard test method exists, and only limited experimental work has been done.

Particulate air filters and cleaners fall into three major categories: panel filters, extended surface filters and electrostatic air cleaners. Panel filters include common furnace filters, which are low efficiency devices used primarily to protect the heating and cooling coils, and passive electrostatic filters, in which the filters have an electrostatic charge that increases particle removal efficiency. Extended surface filters, such as bag or HEPA filters, perform at a higher efficiency than panel filters. Electrostatic air cleaners are electronic devices that operate as two-stage electrostatic precipitators. In the first stage, the particles acquire an electrostatic charge which facilitates their collection in the second stage. Ducted particulate air filters and cleaners of all three types are available from many different suppliers and all have a performance rating based on ASHRAE Standard 52.1-1992. A comparison of their performance was conducted by Offermann et al. 1991, in which their ability to remove environmental tobacco smoke was evaluated in a test house.

While there are also many devices for the removal of gaseous contaminants, no standardized approach exists for assessing their performance. These devices consist of a sorbent, such as activated carbon or alumina, that may be impregnated with some substance to enhance performance. Several research studies have been conducted to assess their performance (Ensor et al. 1988, Liu 1992, Rodberg et al. 1991, and Weschler et al. 1992), but questions remain as to their effectiveness in the field, including issues of their capacity and their effectiveness for removing different contaminants from the air. Several different devices are commercially available, from panel filters impregnated with a sorbent to free-standing systems that attach to the return air ductwork.

2.4.2 Outdoor Air Intake Devices

The installation of an outdoor air intake damper on the return side of forced-air systems is another indoor air quality control approach. These intake devices generally consist of a barometric or motorized damper installed in a section of ductwork running from outdoors to the return side of the forced-air system (Jackson 1991 and Jackson 1993). Besides the damper and the intake duct, these systems may contain a control device to open the damper based on either indoor humidity levels, time of day or manual control by the occupant. Demand-controlled ventilation based on carbon dioxide concentrations or occupancy sensors is another option for controlling these dampers. In some cases an exhaust fan is installed in the house to balance the intake airflow. The exhaust fan may be interlocked with the damper control so that the fan operates whenever the damper is open.

These intake systems rely on the forced-air system fan to distribute the outdoor air throughout the house. These blowers are generally rated at 400 to 600 W. Depending on the means of outdoor air intake control, these fans may operate for many more hours a year than they would otherwise operate if they were not interlocked with the intake damper. The additional energy consumption associated with these fans is an important issue with outdoor air intake dampers. In addition, their performance is impacted by the tightness of the building envelope, the air distribution ductwork, and the existence and performance of an interlocked exhaust fan.

2.4.3 Heat Recovery Ventilators

Heat recovery ventilators of several different designs are available for use in single-family residential buildings. These systems include exhaust air heat pumps and balanced ventilation systems. In exhaust air heat pumps, a central exhaust fan draws air from various interior locations, often kitchen and bathrooms, and extracts heat from the exhaust air for space and/or water heating. In balanced systems, the heat recovery ventilator brings in outdoor air and exhausts indoor air in approximately equal amounts, and heat is transferred between the two airstreams. Exhaust air heat pumps are generally associated with a dedicated system of exhaust air ductwork, and outdoor air enters the building through vents distributed throughout the house. Some balanced systems have their own system of ductwork while others are connected to the forced-air distribution system. In the latter installations, the outdoor airstream from the heat recovery ventilator is connected to the return side of the forced-air system. The exhaust airstream, flowing from the house to the heat recovery device, flows from either upstream in the return ductwork or from elsewhere in the house. Performance data is available on the heat recovery efficiency and airflow performance of commercially available equipment. The impact of these systems on building ventilation rates is dependent on the tightness of the building envelope and distribution ductwork and other mechanical ventilation airflows such as exhaust fans.

2.4.4 Sealing of Air Distribution Ductwork

Leakage in air distribution ductwork that passes out of the conditioned space has been found to have significant impacts on building airflows, pollutant transport and energy consumption (Modera and Jansky 1992, Cummings 1989, Lambert and Robison 1989, Modera 1989, and Parker 1989). Depending on the magnitude of the leaks and their distribution on the return or supply sides of the system, such duct leakage can greatly increase the air change rate of a building and the associated energy use. Duct leakage can also induce significant pressure differences in a building, increasing the potential for the backdrafting of combustion appliances and the entry of pollutants from soil gas and adjoining spaces such as garages. Sealing of air distribution ductwork is a potentially important control technology for forced-air heating and cooling systems, with the impact of sealing these leaks dependent on the location of the leaks and ductwork.

2.5 Summary

In the last decade, many studies have been conducted to quantify the emission rates of indoor air pollutant sources. In particular, extensive data is available on the emission rates of CO, NO_2, and particulates from combustion processes and of VOCs from consumer products, building materials, and furnishings. However, wide ranges of values have been reported and information on emission rate dependence on factors such as time, ventilation rates, ambient conditions, and usage conditions is incomplete. In general, information on emission rates of biological contaminant sources is not available due to the difficulty in measuring concentrations, a lack of standardized measurement procedures, and the difficulty in modeling bioaerosol emission mechanisms in laboratory tests.

Over the past few years, several researchers have studied residential indoor air quality through simulations and experimental work. These studies have shown the feasibility of using multizone pollutant transport modeling to examine the effects of HVAC systems on residential indoor air quality. However, some studies have neglected the multizone nature of the airflow problem and others have focussed on narrow aspects of the issue. No comprehensive analysis of the HVAC system and component impacts on residential IAQ has been reported. Due to the complex interactions of the HVAC system with the building, the ambient conditions, and the pollutant sources, a multizone modelling approach that includes all of these factors is necessary.

Several options exist for using forced-air systems to control IAQ including: high efficiency particulate air filters and gaseous air cleaners; outdoor air intake ducts on the return air side of the system; heat recovery ventilators; and reducing duct leakage. Many of these technologies can be combined with HVAC system control options such as CO_2 or humidity control.

3 Modeling Method

The program CONTAM93 (Walton 1994) was used in this project to simulate pollutant levels, and this section describes the approach used to perform the simulations. Simulations were performed first 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, and the simulations were repeated. 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. In order to calculate airflow rates and contaminant concentrations, the following input was required: configuration and volume of the building zones, air leakage paths through the building envelope and interior walls, wind pressure profiles on the building envelope, pollutant source strengths as functions of space and time, HVAC system flows, filter efficiencies, pollutant sink characteristics, pollutant decay or deposition rates, and ambient weather and pollutant concentrations. This section describes CONTAM93, the simulations that were performed, and the input data.

3.1 CONTAM93

As discussed in the literature review section, there are two general types of computer simulation techniques for studying airflow and contaminant distribution in buildings, room airflow modeling and multizone modeling. Multizone airflow and contaminant dispersal modelling enables calculation of 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. The multizone model selected for the indoor air quality simulations is CONTAM93 (Walton 1994). CONTAM93 underwent further development at NIST as this study progressed and versions including modifications to the program as described by Walton 1994 were used.

3.2 Duration of Simulations

To maximize the number of possible combinations of factors (i.e., buildings, locations, pollutant sources, and IAQ control technologies) that could be investigated, the length of individual simulations was limited to the shortest reasonable period. However, it was considered important to examine the effects of different weather conditions. Therefore, simulations were performed under three sets of weather conditions (cold, mild, and hot) for each building (a total of 8 buildings as described in the next section). 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). There were, therefore, a total of 24 baseline simulation cases. Table 1 lists the baseline simulations by house type, location, airtightness and weather condition. The WYEC data is presented in Tables 2 and 3 for Miami and Minneapolis, respectively, and includes temperature, wind speed, and wind direction from north. 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

Table 2 - Miami weather data

	Cold			Mild			Hot		
Hour	T (°C)	V_{wind} (m/s)	Dir (°)	T (°C)	V_{wind} (m/s)	Dir (°)	T (°C)	V_{wind} (m/s)	Dir (°)
0	2.8	2.3	320	13.3	3.9	360	26.7	0	0
1	2.8	2.3	300	13.3	2.7	360	26.1	1.2	200
2	2.8	3.5	310	13.3	3.5	360	26.1	1.2	200
3	2.8	2.7	320	13.9	1.9	20	25.6	1.6	200
4	2.2	2.3	310	13.3	2.7	20	25.6	1.9	200
5	2.2	3.5	310	13.9	1.6	360	26.1	1.9	230
6	2.8	2.7	320	13.3	2.3	340	25.6	1.9	200
7	3.3	3.5	300	14.4	2.3	340	26.7	1.6	230
8	4.4	2.3	290	16.1	2.7	340	27.2	1.9	200
9	6.1	2.7	330	21.1	4.7	70	30.6	2.3	200
10	8.9	3.1	320	23.3	4.7	70	31.7	2.3	230
11	11.7	2.3	320	23.3	5.1	70	32.8	0	0
12	13.9	2.7	330	23.3	5.4	70	33.3	2.3	200
13	14.4	2.7	350	22.8	5.1	70	33.3	3.9	140
14	16.1	2.3	360	22.8	5.4	70	32.8	4.3	180
15	17.2	0.8	40	22.2	4.7	70	31.7	4.7	160
16	17.8	2.7	40	21.7	3.9	90	30.6	1.9	290
17	17.2	3.5	20	21.7	3.1	90	31.7	3.1	140
18	16.7	1.9	340	21.7	4.3	70	30.6	2.3	160
19	16.1	2.3	340	21.1	4.3	90	27.8	1.6	50
20	15	1.6	350	21.1	2.7	90	27.8	1.2	50
21	14.4	1.9	350	21.1	3.1	90	27.2	1.6	200
22	16.1	2.3	30	21.7	1.2	90	26.1	2.3	230
23	16.1	2.3	60	21.7	2.3	90	26.1	1.2	250
24	17.2	3.5	60	20.6	3.1	50	26.1	0	0

Table 3 - Minneapolis weather data

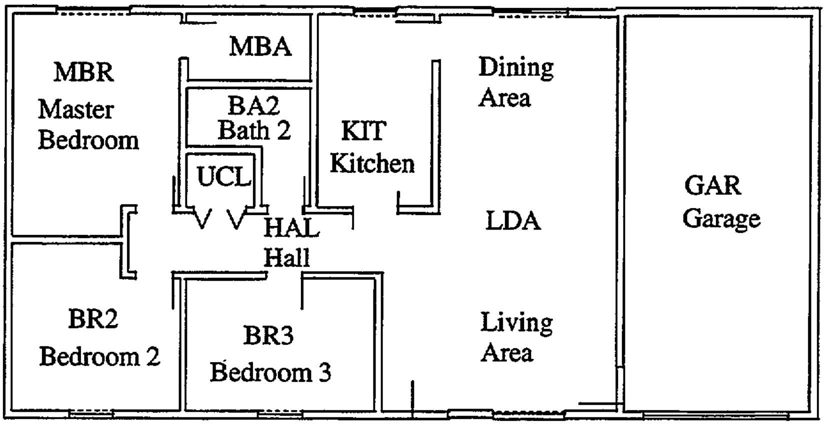
	Cold			Mild			Hot		
Hour	T (°C)	V_{wind} (m/s)	Dir (°)	T (°C)	V_{wind} (m/s)	Dir (°)	T (°C)	V_{wind} (m/s)	Dir (°)
0	-21.1	1.6	330	7.8	1.9	60	21.1	3.1	180
1	-21.1	1.6	330	7.8	1.9	40	20	2.7	180
2	-21.1	3.1	350	7.8	3.1	90	18.9	2.7	180
3	-21.1	3.1	350	7.2	1.9	100	17.8	1.9	180
4	-21.1	3.1	350	7.2	4.7	130	18.3	1.6	158
5	-21.1	3.1	350	7.2	3.9	130	17.2	2.7	135
6	-21.7	3.5	350	7.2	3.1	120	17.8	3.5	158
7	-21.7	2.7	340	7.2	3.9	140	20	1.9	158
8	-21.7	2.7	350	7.8	2.7	120	24.4	4.7	180
9	-21.1	3.9	340	8.9	3.1	130	26.1	5.8	180
10	-20.6	3.9	310	7.8	4.3	130	28.3	6.6	203
11	-20.6	4.7	310	8.3	4.7	130	30	6.2	203
12	-20.6	3.9	320	8.9	4.3	140	30.6	6.2	203
13	-20.6	4.3	320	8.9	4.7	140	31.1	7	203
14	-20	5.1	300	8.3	6.2	120	31.1	7.4	203
15	-20	4.7	290	8.9	6.2	110	31.1	6.6	203
16	-20.6	4.3	310	8.9	5.8	130	31.1	6.6	203
17	-21.1	3.5	290	9.4	5.1	130	28.9	4.7	203
18	-22.8	3.1	280	9.4	5.4	130	29.4	4.7	180
19	-23.3	2.7	280	11.1	5.4	160	27.8	4.7	180
20	-24.4	3.1	300	11.7	5.8	170	26.1	4.3	180
21	-25	3.1	280	11.1	6.2	180	24.4	3.9	180
22	-25.6	2.7	280	11.1	5.8	200	23.9	3.9	180
23	-27.2	2.3	240	10.6	6.2	220	23.3	4.7	158
24	-28.9	2.3	240	7.8	2.7	240	22.8	4.3	180

3.3 Building Factors

This study was restricted to the consideration of single family residential buildings, and included eight building models - a compact ranch style house [109 m^2 (1170 ft^2)] and a larger two-story house [185 m^2 (1990 ft^2)], 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. The buildings were based on houses used in energy conservation research that were typical of modern residential construction in 1977 (Hastings 1977). Attached garages were added to the original designs because the possibility of air and contaminant transport from attached garages due to HVAC system induced pressure differences was considered important. 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.

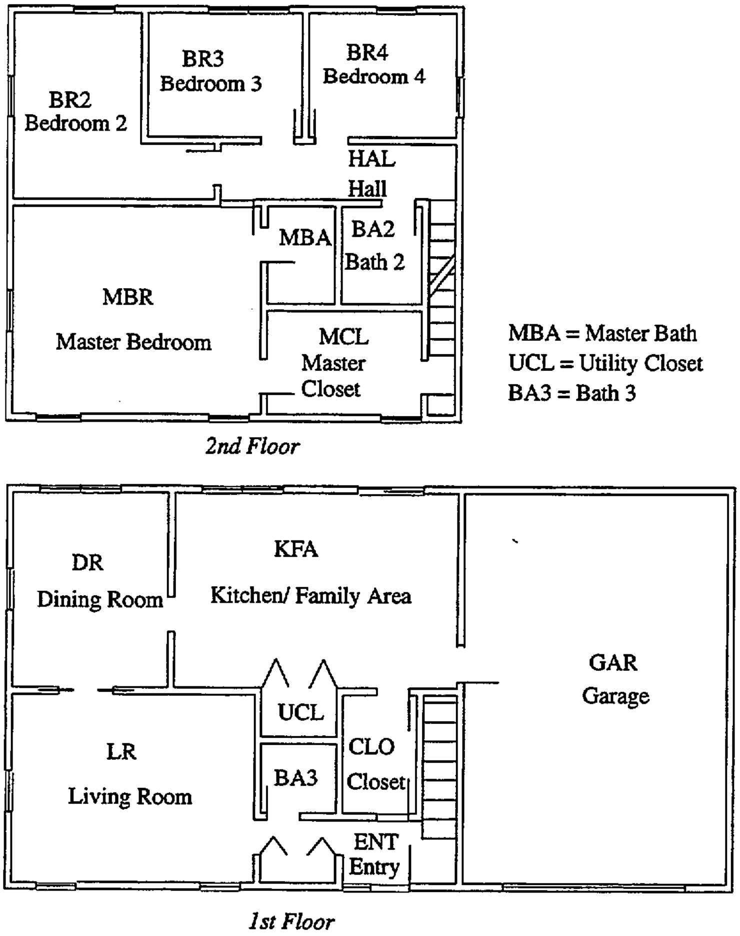
Several features of residential building designs typically vary by region. The most important of these features with respect to the computer simulations is the type of foundation. For example, basement foundations are common in the upper midwest and the northeast, while concrete slab foundations are predominant in Florida. The primary significance of the building foundation type is the influence on the location of HVAC equipment and ductwork. Therefore, basements were added to the Minneapolis houses. The basements (zone label BMT) and attics, which are in all the houses, are not shown in the figures.

The project work statement suggested four house locations, including Miami, FL, Denver, CO, Phoenix, AZ, and Chicago, IL, representing a range of US climates. The inclusion of four building locations would increase the total number of simulations, and therefore limit the number of other factors that can be considered. Fewer locations were chosen to provide sufficient diversity of ambient conditions while allowing more project resources to be spent on other considerations.



MBA = Master Bath
UCL = Utility Closet

Figure 1 - Ranch House Foorplan and Zones



MBA = Master Bath
UCL = Utility Closet
BA3 = Bath 3

Figure 2 - Two-story House Floorplan and Zones

The airtightness of the buildings was handled as a variable of interest in this study because it could have a significant impact on the effectiveness of the IAQ control technologies. Detailed information on building component leakage of the houses is not available as the houses modeled were not based on real buildings. However, since there is no attempt to compare predictions with experimental data, the building leakage modeled needs only to be reasonable in magnitude and distribution. Table 4 shows all the leakage paths between the zones of the Miami ranch house. Table 5 lists the values for those leakage paths for both the typical and tight cases. The Table 5 leakage areas are for a reference pressure difference of 4 Pa and a discharge coefficient of 1.0 and are based on values listed in Table 23-3 of ASHRAE (1993) unless otherwise noted. The typical values were generally based on "best estimate" and/or uncaulked entries in the ASHRAE table, while the tight values were based on minimum and/or caulked entries. All doors connecting zones other than closets were modeled as open. The same leakage values were used for the other houses, although the paths connecting the zones differed depending on the house configurations.

Table 4 - Air leakage paths for Miami ranch house

	MBR	BR2	BR3	MBA	BA2	UCL	KIT	LDA	HAL	GAR	ATC
BR2	INTW OUTL										
BR3		INTW OUTL									
MBA	INTD INTW										
BA2	INTW OUTL			INTW OUTL							
UCL	INTW				INTW						
KIT				INTW OUTL	INTW OUTL						
LDA			INTW OUTL				INTW INTD OUTL				
HAL	INTD INTW	INTD INTW	INTD INTW OUTL		INTD INTW	CLD INTW	INTD INTW OUTL	HAD			
GAR								EXTD EXW OUTL			
ATC	CEIL CPEN	CEIL CPEN	CEIL CPEN	CEIL CPEN PIP	CEIL CPEN PIP	CEIL CPEN	CEIL CPEN	CEIL CPEN CPEN	CEIL ATD		
AMB	WIN EXW OUTL	WIN EXW OUTL	WIN EXW OUTL	EXV EXW OUTL	EXV		WIN EXV EXW OUTL	SGD EXTD WIN EXW OUTL		GAD GARF EXW	VNT

Table 5 - Air leakage values

Name	Description	Typical	Tight
ATD	Attic door	30 cm^2/ea	18 cm^2/ea
CEIL	Ceiling [Based on general ceiling]	1.8 cm^2/m^2	0.79 cm^2/m^2
CLD	Closet door (closed) [Based on interior door]	0.9 cm^2/m	0.25 cm^2/m
	Closet door frame [Based on general door frame]	25 cm^2/ea	12 cm^2/ea
CPEN	HVAC ceiling penetration [Based on kitchen vent with damper closed]	5 cm^2/ea	1 cm^2/ea
EXTD	Exterior door [Single]	21 cm^2/ea	12 cm^2/ea
	Door frame [Wood]	1.7 cm^2/m^2	0.3 cm^2/m^2
EXV	Bathroom exhaust vent	20 cm^2/ea	10 cm^2/ea
	Kitchen exhaust vent	40 cm^2/ea	5 cm^2/ea
EXW	Ceiling-wall joint	1.5 m^2/m	0.5 m^2/m
	Floor-wall joint	4 cm^2/m	0.8 cm^2/m
	Wall-wall joint [Based on ceiling-wall joint]	1.5 m^2/m	0.5 m^2/m
GAD	Garage door [Based on general door (2 m x 4 m)]	0.45 cm^2/m	0.31 cm^2/m
	Garage door frame [Wood]	1.7 cm^2/m^2	0.3 cm^2/m^2
GARF	Garage roof [Based on general ceiling]	1.8 cm^2/m^2	0.79 cm^2/m^2
HAD	Hall doorway	2.4 m^2/ea	2.4 m^2/ea
INTD	Interior door (closed) [Based on Table 4.2 of Klote and Milke (6)]	140 cm^2/ea	75 cm^2/ea
	Interior door (open)	2.1 m^2/ea	2.1 m^2/ea
INTW	Interior wall [Based on gypsum board on stud wall (Shaw et al. 7)]	2.0 cm^2/m^2	2.0 cm^2/m^2
OUTL	Electric outlet	2.5 cm^2/ea	0.5 cm^2/ea
PIP	Piping penetrations	6 cm^2/ea	2 cm^2/ea
SGD	Sliding glass door	22 cm^2/ea	3 cm^2/ea
VNT	Attic vent [Based on Table 21-1 of 3]	1 cm^2 / 300 cm^2	1 cm^2 / 300 cm^2
WIN	Double hung window	2.5 cm^2/m	0.65 cm^2/m
	Window framing [Wood]	1.7 cm^2/m^2	0.3 cm^2/m^2

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, building shape, 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 (1993). The coefficient for the flat garage roof was based on Figure 14-6 of ASHRAE. These wind pressure coefficients do not include shielding effects and no modifier for shielding effects was used. However, recent studies have reported on the shielding effects of trees (Strathopolous 1994) and rows of houses (Walker and Wilson 1994).

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 6, 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 Appendix B.

Table 6 - 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

3.4 HVAC System Factors

This study was restricted to consideration of central forced-air HVAC systems with heating and cooling equipment and components typically employed by HVAC contractors for residential installation. 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). Table 7 summarizes HVAC system design information. More detailed descriptions of the systems including heating and cooling equipment types and descriptions, overall and individual supply and return airflow rate design values for both heating and cooling, and air distribution system drawings are included in Appendix A. 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 7 - 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		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		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. Cummings et al. (1991) tested duct leakage in 160 houses in Florida and found that return leaks were dominant in the majority of homes. They reported an average return leak fraction of 10.7% (based on ratio of leakage flow to total system flow). Based on that study, a duct leak equal to 10% of the total system flow was included for the houses with ducts in either the basement or attic. 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 8 summarizes the average percent system run-times.

Table 8 - 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

3.5 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.

Calculating pollutant concentrations requires the specification of pollutant sources including strength, location, distribution, and temporal profile (i.e. constant, step input, exponential decay, etc.). The pollutant sources used in the simulations were based on the literature review summarized in an earlier section. These sources included several VOC short-duration or burst sources (based on a medium strength source from a polish and high strength source from 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. As discussed in the literature review, there are many other sources of these pollutants and a wide range of source strengths have been reported. Although most of the source strengths selected were in the middle of reported ranges, 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 $mg/m^2 \bullet h$ recently reported in 5-day emission tests of finished particleboard (Hoag and Cade 1994). Table 9 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. The heater source was not applied during the hot day in either location or during the mild day in Miami.

Table 9 - 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 • m^2	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)

Besides the sources listed in Table 9, a newly-finished floor as a floor-area based decaying source of VOCs was considered. A test simulation with a medium strength source, modeled as a first order exponential decay source with initial emission rate of 17400 mg/m^{2}h and decay constant of 1.24 h^{-1} (based on a stain product (Tichenor and Guo 1991)) was performed for the Miami ranch house. This source resulted in extremely high concentrations of TVOCs with a peak concentration of over 2 g/m^3 and a concentration of 37 mg/m^3 at the end of the day. None of the IAQ control retrofits being evaluated were expected to have a significant impact on the extremely high concentrations from this source during the one-day simulation period. Therefore, this source was not included in the remaining baseline simulations. Decaying high-strength sources such as this one are of interest and may be studied in the future with simulations of longer duration.

Besides indoor sources, indoor pollutant concentrations depend on outdoor pollutant concentrations which vary by location and over time at any one location. The outdoor concentrations used in the simulations were selected as typical outdoor conditions and were specified per the schedules in Table 10. 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 (Leslie et al. 1988). Fine particles and TVOCs are not discussed in the EPA documents. 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 (Sinclair et al. 1990). The TVOC concentration chosen is in the middle of the reported range of 10 to 211 μg/m^3 measured at 68 sites in the US (Shields and Fleischer 1993).

Table 10 - 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/m^3)	13	13	13	13	13
TVOCs (µg/m^3)	100	100	100	100	100

Besides the ambient concentrations that served as the boundary conditions for the indoor sources, elevated levels of CO, NO_2 and coarse particles were also simulated to evaluate the effect of the IAQ control technologies on outdoor pollutants. 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 11.

Table 11 - 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 (µg/m^3)	75	75	75	75	75

The concentration of VOCs in indoor air can be significantly affected by the presence of sinks, i.e., materials such as textile products which can remove pollutants from the air through adsorption (Guo et al. 1990). These pollutant sinks may be reversible, i.e. they can re-emit the adsorbed pollutants after the air concentration is reduced. Reversible sink effects for the VOCs were modeled with elements based on a boundary layer diffusion controlled (BLDC) model with a linear adsorption isotherm. The BLDC adsorption model is 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, and these parameters would vary over time and by location within a house. However, since little data is available for these parameters (which depend on factors such as gas diffusion properties, airflow rates, and adsorbent material) and because the goal was to obtain a reasonable estimate of the reversible sink effects, constant values were used for all of the parameters and only the adsorbent mass was varied by zone. The film mass transfer coefficient used was 35 µm/s and was calculated from equation 3.17a of Axley with an assumed air velocity of 0.001 m/s, effective length of 4 m, Schmidt number of 1.0, and binary diffusion coefficient of 1.0 x 10^{-5} m^2/s. The partition coefficient used was 0.5 g-air/g-sorbent and was estimated from parameters reported for an empirical sink model for an experimental case of alkanes emitted by a wood stain in a test house (Chang and Guo 1993). The adsorbent mass used was based on a mass of 6 kg per m^2 of adsorbent surface area which was assumed to be equal to half of the zone interior surface area.

Besides dilution with outdoor air, nitrogen dioxide is removed from indoor air by surface reaction and particles are removed by deposition onto surfaces. 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 particle decay rate used for fine particles was 0.08 h^{-1} and was reported by Traynor et al. (1987) for combustion products from a wood-burning stove in a test house. Offerman et al. (1985) reported a similar mass-averaged value of 0.1 h^{-1} for tobacco smoke particles in a research house. The decay rate can be calculated as the product of an average deposition velocity and a room surface-to-volume ratio. Assuming a room surface-to-volume ratio of 2 m^{-1} (the actual value will depend on room geometry, furnishings, and surface finishes), a decay rate of 0.08 h^{-1} corresponds to a deposition velocity of approximately 0.001 cm/s. Sinclair et al. (1985, 1988) reported higher average deposition velocities of 0.005 cm/s for fine-mode sulfate in telephone equipment buildings. However, the nature of the indoor environment, and especially the airflow conditions, in a detached single-family home and a commercial building are very different. Nazaroff et al. (1993) discusses the use of deposition velocity and warns that "Deposition velocities determined for one indoor environment can only be applied to another to the extent that the air flow conditions are similar."

In the only report of coarse particle deposition rates in a test house found in the literature, Byrne et al. (1993) reported values of 1.51 and 2.10 h^{-1} for 4 μm particles in an unfurnished and furnished room, respectively. The reported mean deposition velocities of 0.027 to 0.038 cm/s fall within the range of approximately .01 to 0.1 cm/s calculated from a natural convection deposition model by Nazaroff and Cass (1989). The actual decay rate for the coarse outdoor air particles modeled in the simulations would depend on the size distribution of the particles. Since no specific distribution has been assumed, a decay rate of 1.5 h^{-1} was chosen for coarse particles based on the lower value reported by Byrne.

3.6 IAQ Control Technologies

The project work statement required that three different IAQ control technologies be added to the baseline forced-air HVAC systems of the houses, and that the effectiveness of these technologies in reducing the indoor air pollutant levels be assessed. Two of the retrofits are specified in the project work statement as air filters and heat recovery ventilators. The IAQ control technologies considered for the study were also limited to commercially available equipment that can be used with conventional forced-air systems. The third IAQ control technology included was 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 load impacts is in Appendix C.

Ducted particulate air filters and cleaners, with performance ratings based on ASHRAE Standard 52.1-1992, are available from many suppliers. The particle removal efficiency depends on the type of filter or cleaner and the size range of the particles. To model the performance of these devices, a value of the particle removal efficiency is required for the particle size range of interest. However, information on performance as a function of particle size is limited. The electrostatic particulate filter (EPF) selected for the study was assumed to have 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.

Several different air cleaners for gaseous contaminants are commercially available, however, there is no standardized approach to rating their performance. These devices include panel filters impregnated with a sorbent and free-standing systems that attach to the return ductwork. Several studies have been conducted to assess their performance (Ensor et al. 1988, Liu 1992, Rodberg et al. 1991, and Weschler et al. 1992), but questions remain concerning their effectiveness and capacity. Their removal efficiency is a function of the contaminant, the contaminant concentration, temperature, humidity, and the previous history of exposure of the sorbent material to contaminants. However, these issues are not yet understood well enough to incorporate into a model. Therefore, gasesous contaminant filters were not included in the studied.

Heat recovery ventilators (HRVs) that connect to central forced-air HVAC systems are commercially available. These devices supply outdoor air to the return side of the forced-air system and exhaust air from either upstream in the return ductwork or from elsewhere in the house. Performance data is available from the manufacturers on their heat recovery efficiency and their airflow performance. Figure 3 shows a schematic of a HRV. In the simulations, the outdoor airflow rate provided by these systems 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 is 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.

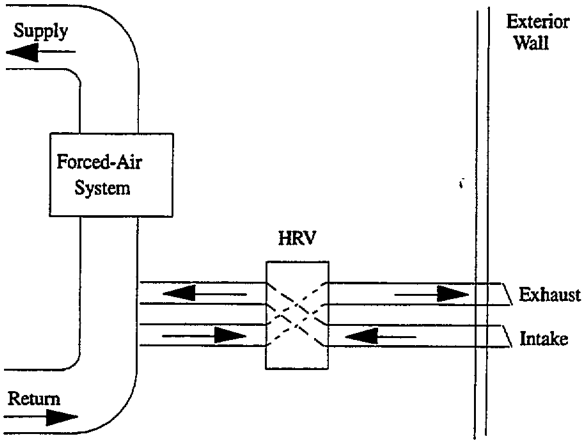


Figure 3 - Schematic of Heat Recovery Ventilator

Several manufacturers offer outdoor air intake ducts and dampers (OAID) which draw outdoor air into the return ductwork of a 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.

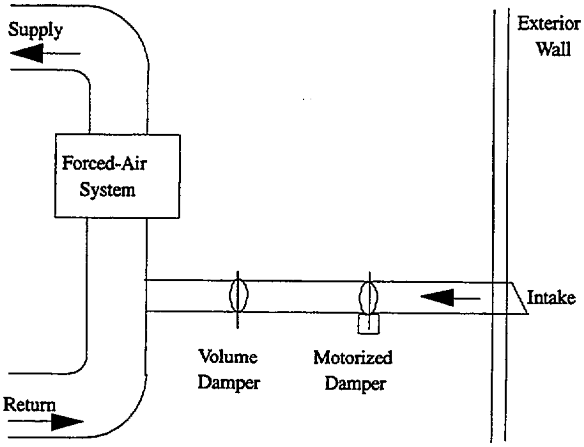


Figure 4 - Schematic of Outdoor Air Intake Damper

4 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 D contains tables summarizing the baseline average and peak concentrations and percent reductions due to each IAQ control for all individual cases.

4.1 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.

4.1.1 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.

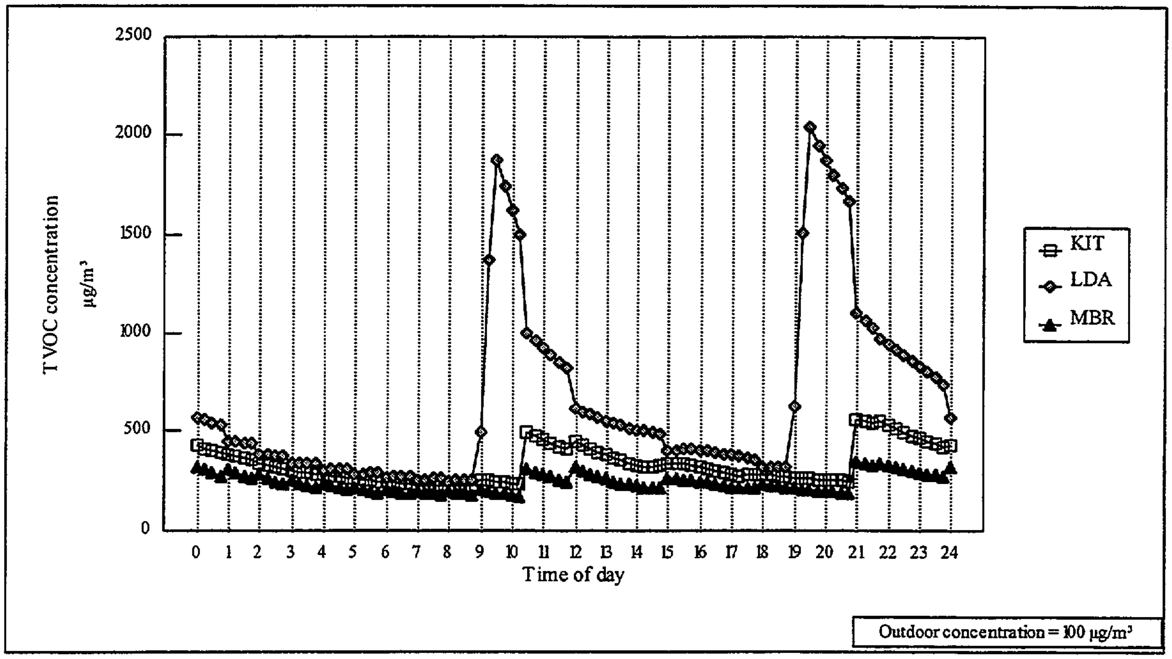


Figure 5 - Transient TVOC Concentration Due to LDA Burst Source
(Tight Miami Ranch House on Cold Day)

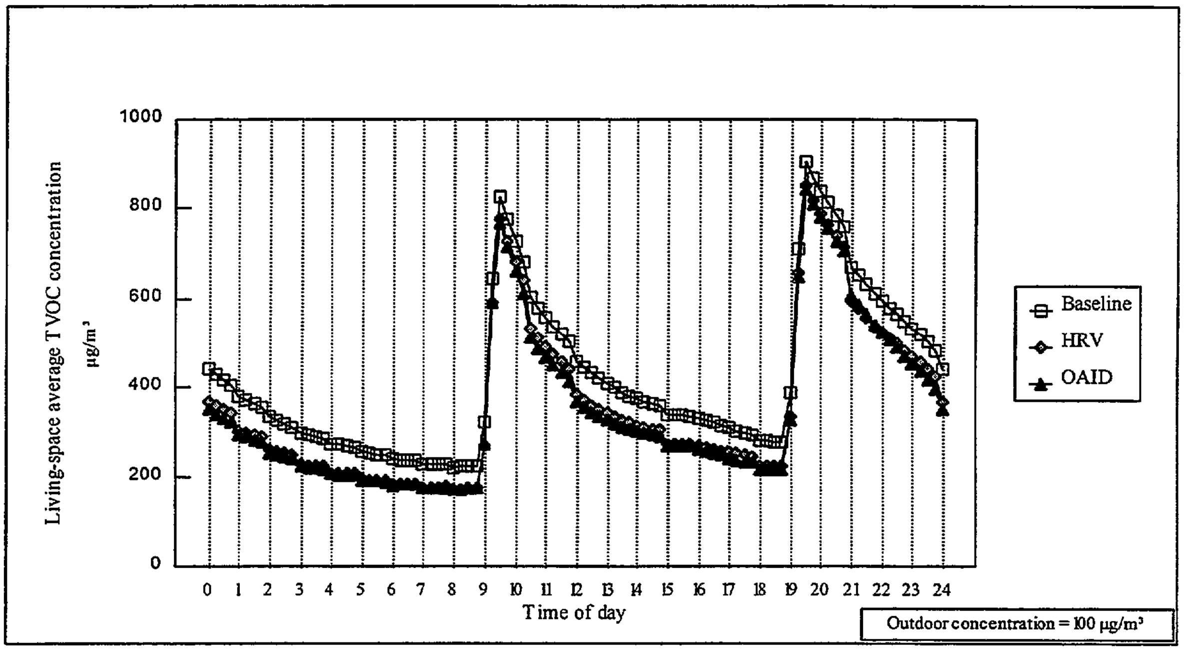


Figure 6 - Transient Living-space Average TVOC Concentration Due to LDA Burst Source
(Tight Miami Ranch House on Cold Day)

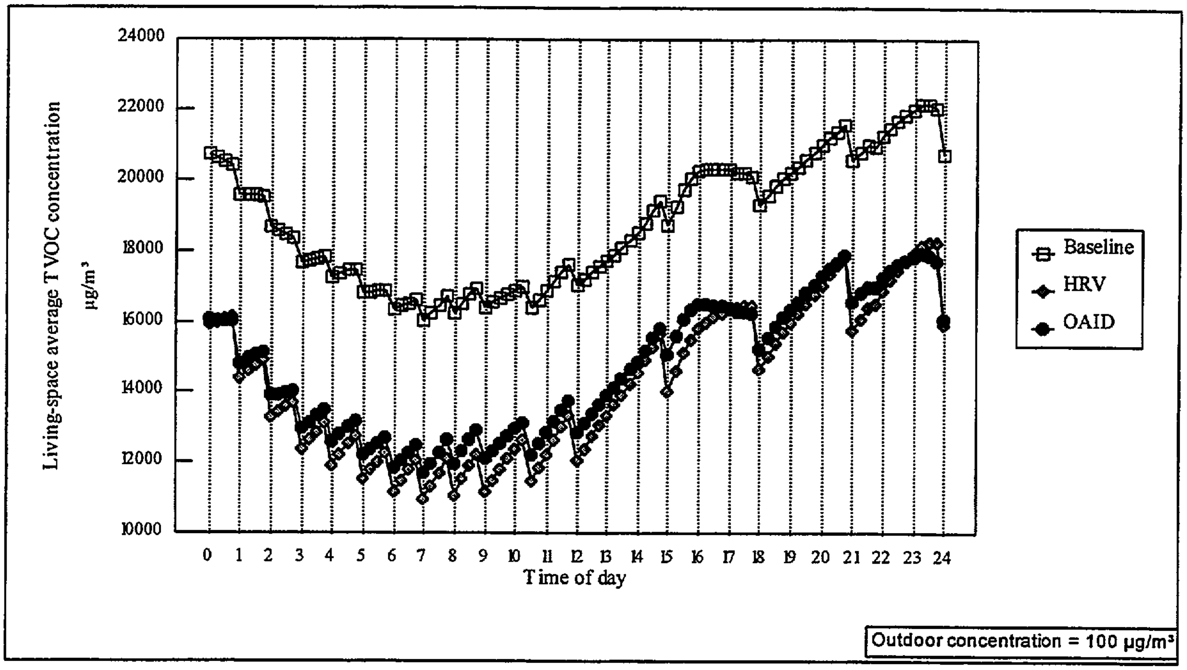


Figure 7 - Transient Living-space TVOC Concentration Due to Floor Source (Tight Miami Ranch House on Cold Day)

4.1.2 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 that 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 that, 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.

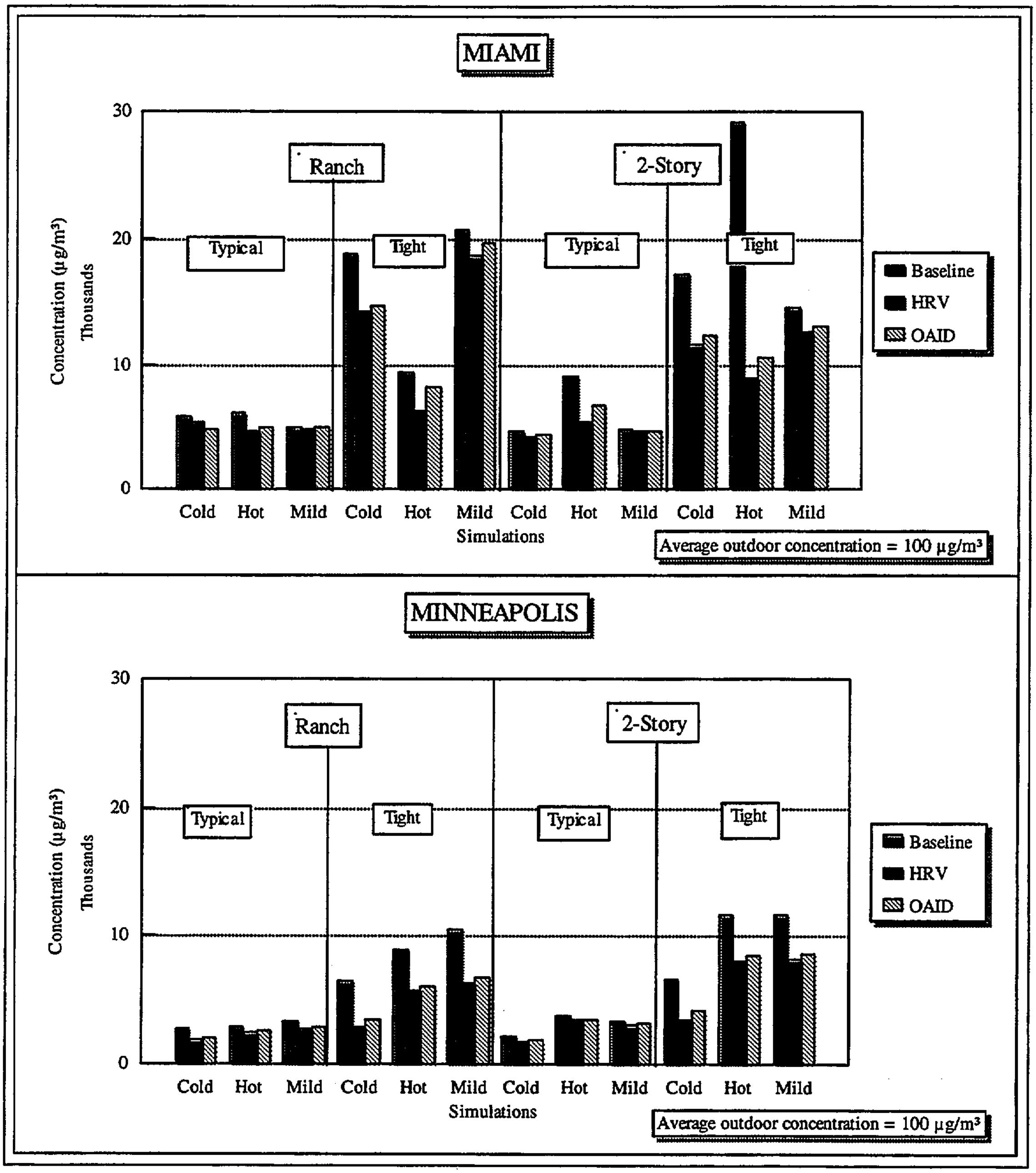


Figure 8 - 24-hour, Living-space Average TVOC Concentrations Due to Floor Source

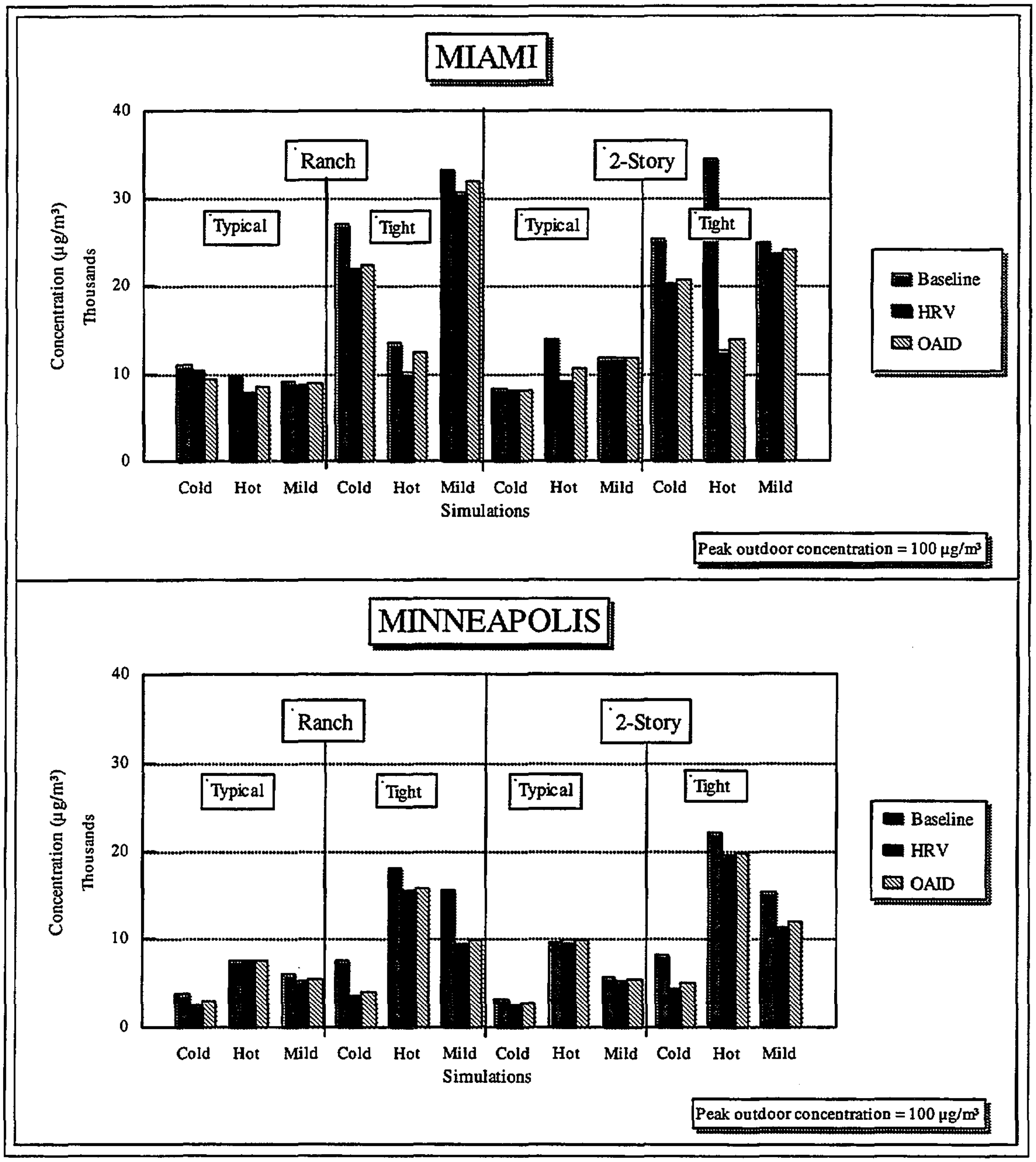


Figure 9 - Peak TVOC Concentrations Due to Floor Source

4.1.3 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 μg/m^3 for all baseline cases with an average of 230 μg/m^3. The average concentrations are substantially higher for the tight buildings (300 μg/m^3) than the typical buildings (160 μg/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 μg/m^3), followed by the Minneapolis mild weather cases (240 μg/m^3), Miami cold weather cases (230 μg/m^3), Miami mild weather cases and Minneapolis hot weather cases (220 μg/m^3), and Minneapolis cold weather cases (210 μg/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%. 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.

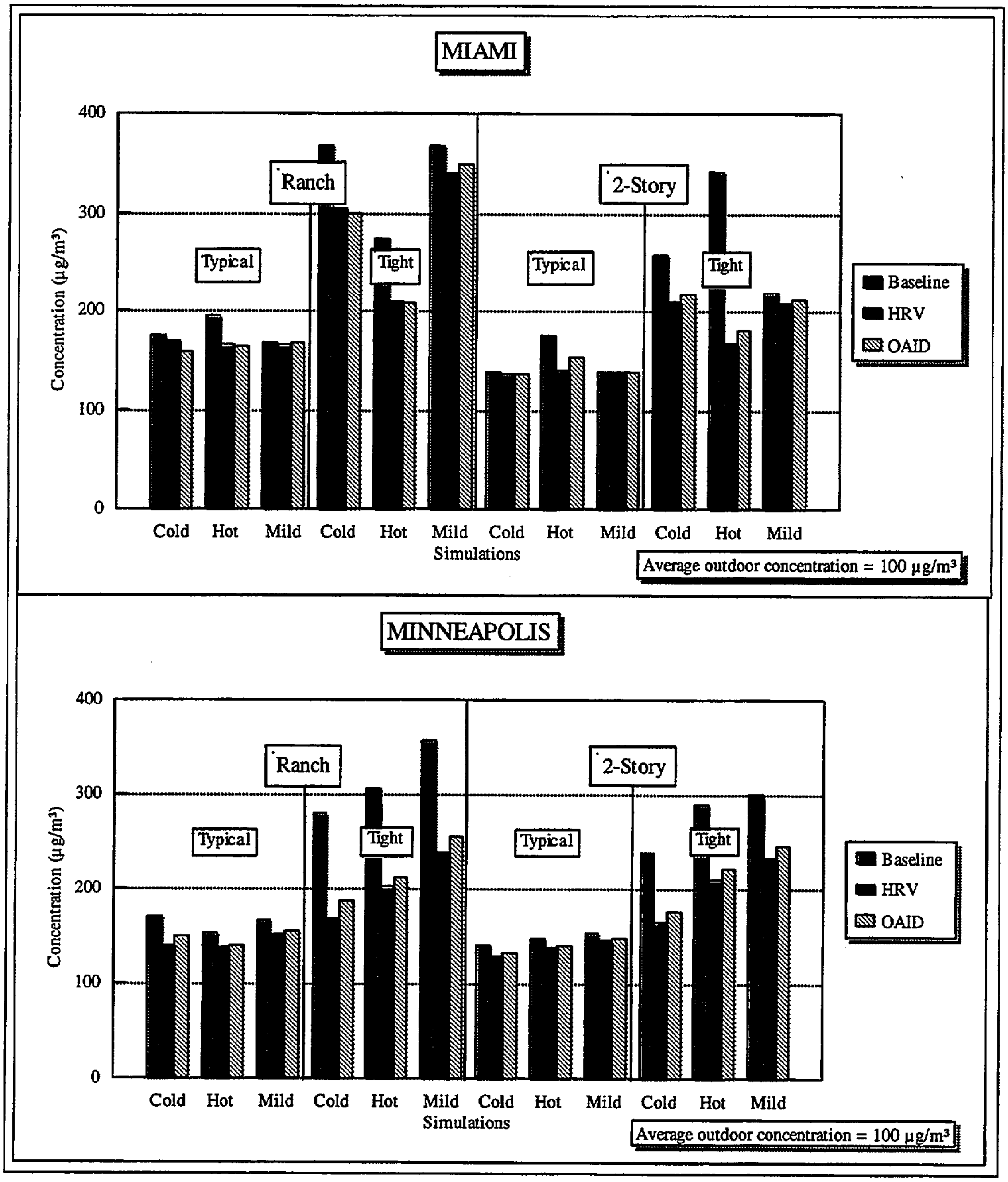


Figure 10 - Average of 24-hour, Living-space Average TVOC Concentrations Due to Burst Sources

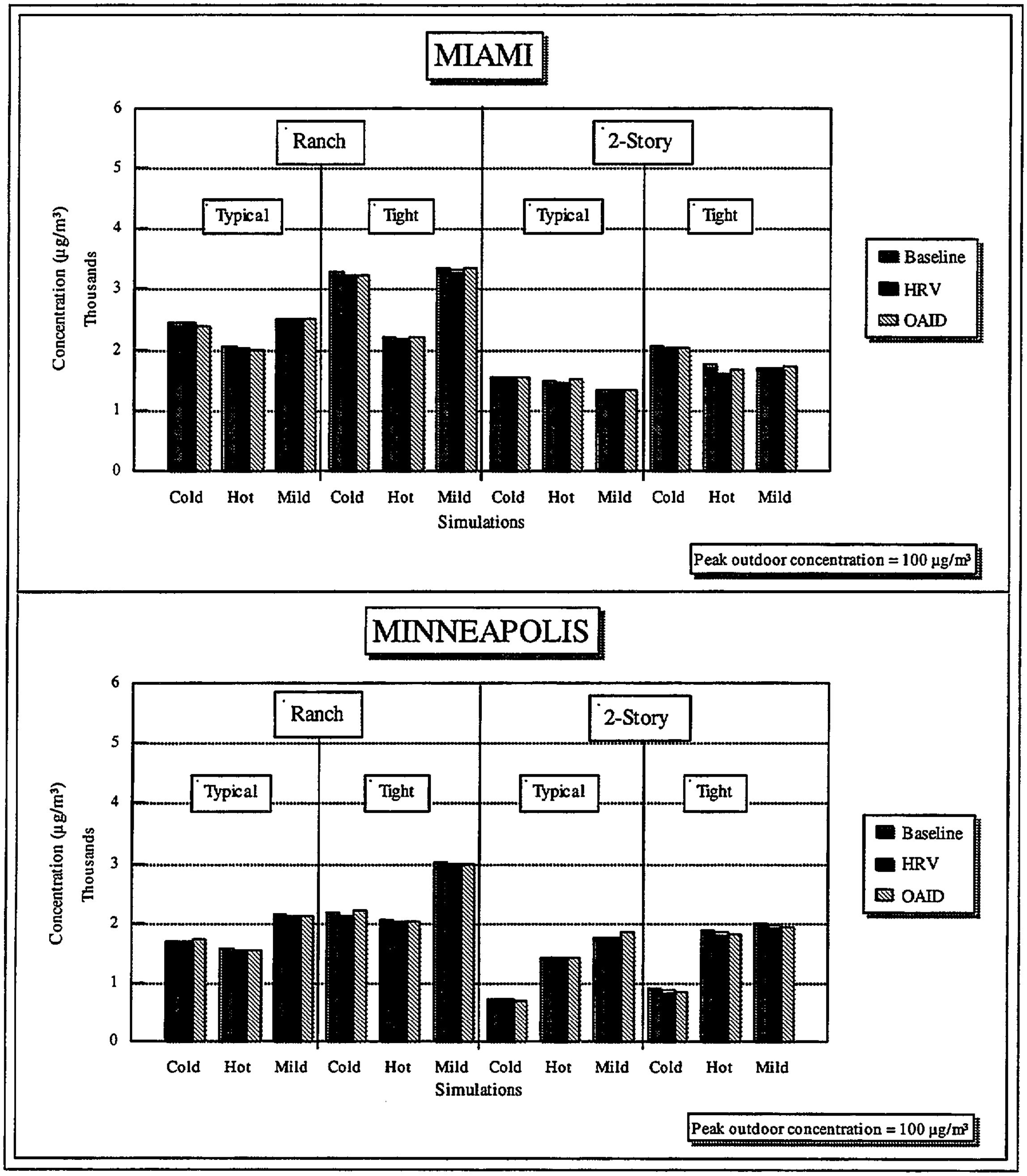


Figure 11 - Peak TVOC Concentrations Due to MBR Burst Source

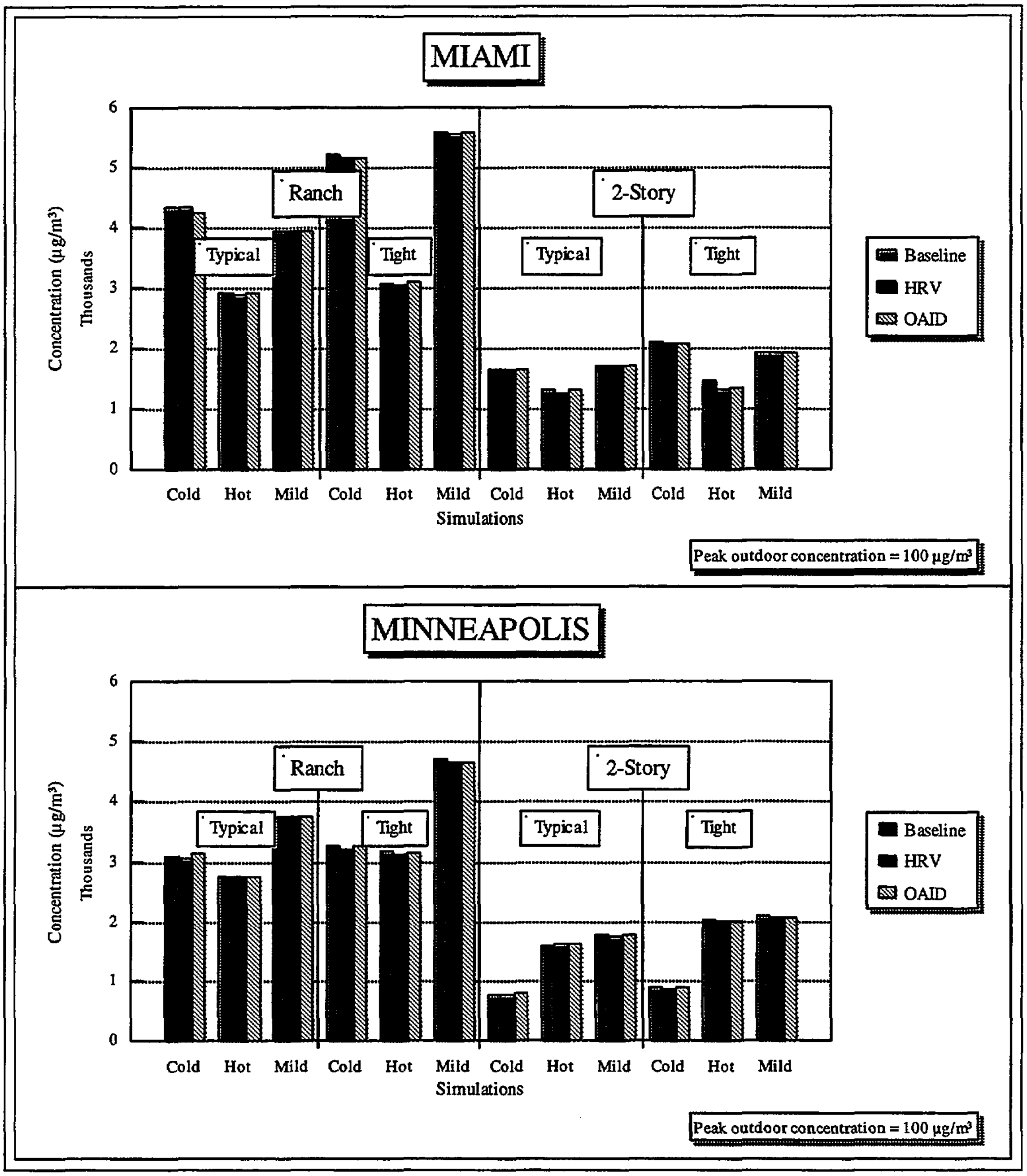


Figure 12 - Peak TVOC Concentrations Due to KIT/KFA Burst Source

4.2 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.

4.2.1 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.

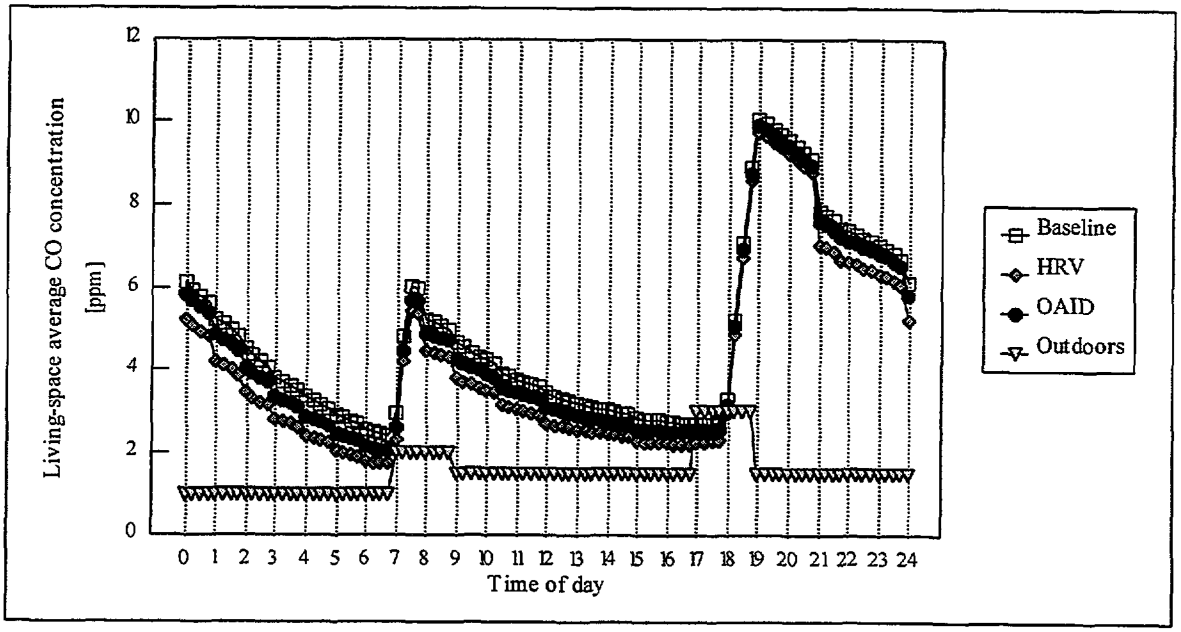


Figure 13 - Transient Living-space Average CO Concentration Due to Oven Source (Tight Miami Ranch House on Cold Day)

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.

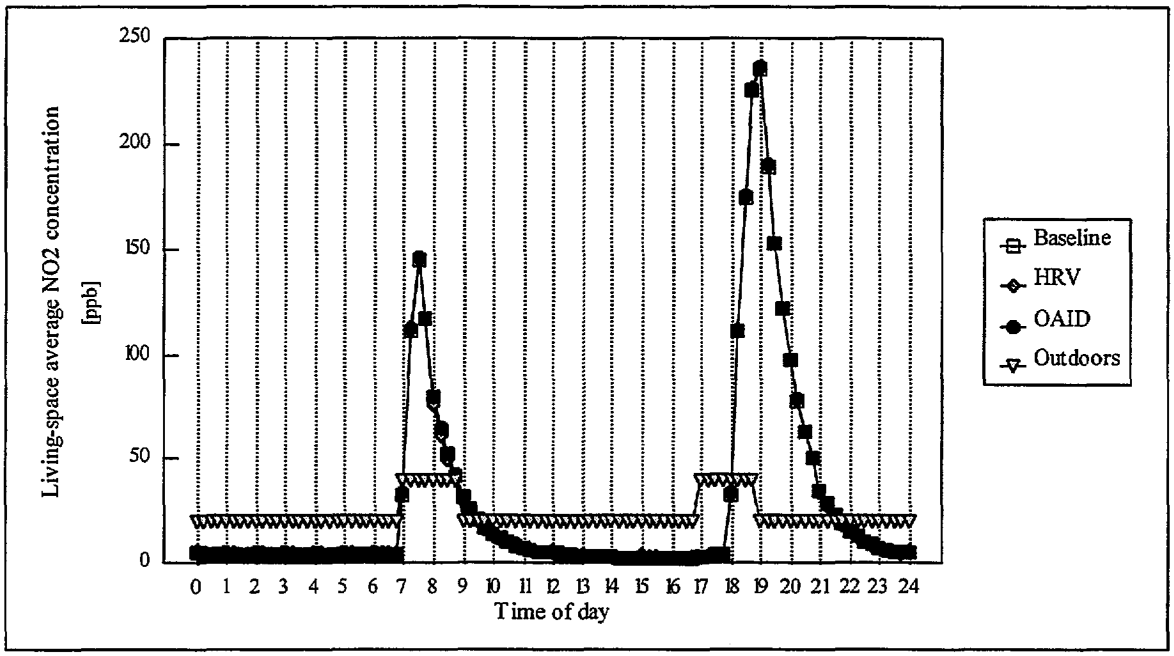


Figure 14 - Transient Living-space Average NO_2 Concentration Due to Oven Source (Tight Miami Ranch House on Cold Day)

As shown in Figure 15, the baseline living-space average fine particle concentration is below the outdoor concentration of 13 μg/m³ 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/m³, 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.

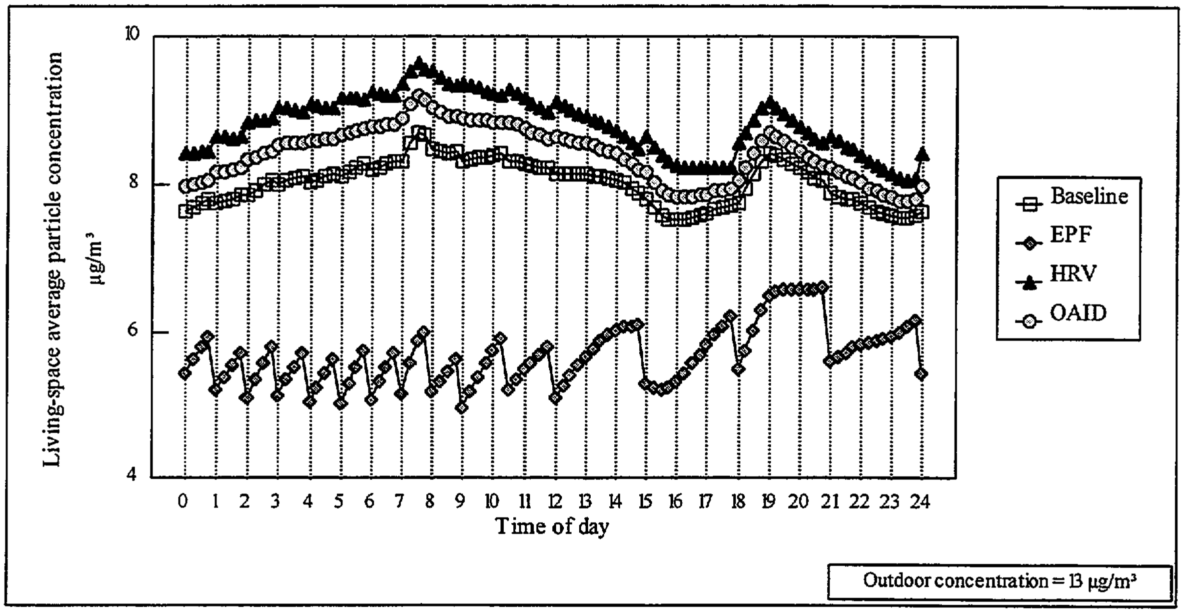


Figure 15 - Transient Living-space Average Fine Particle Concentration Due to Oven Source (Tight Miami Ranch House on Cold Day)

4.2.2 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. 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.

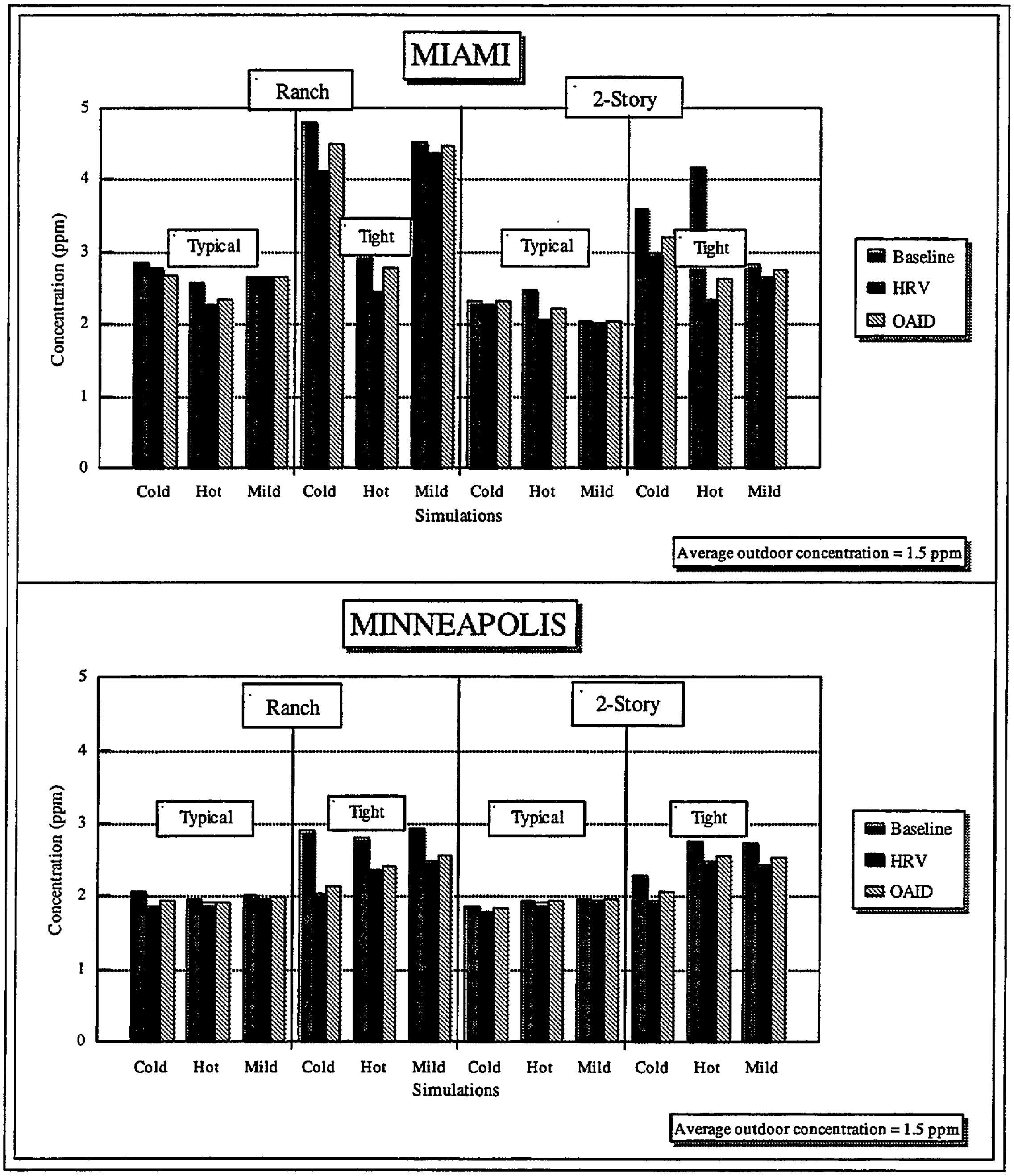


Figure 16 - 24-hour, Living-space Average CO Concentrations Due to Oven Source

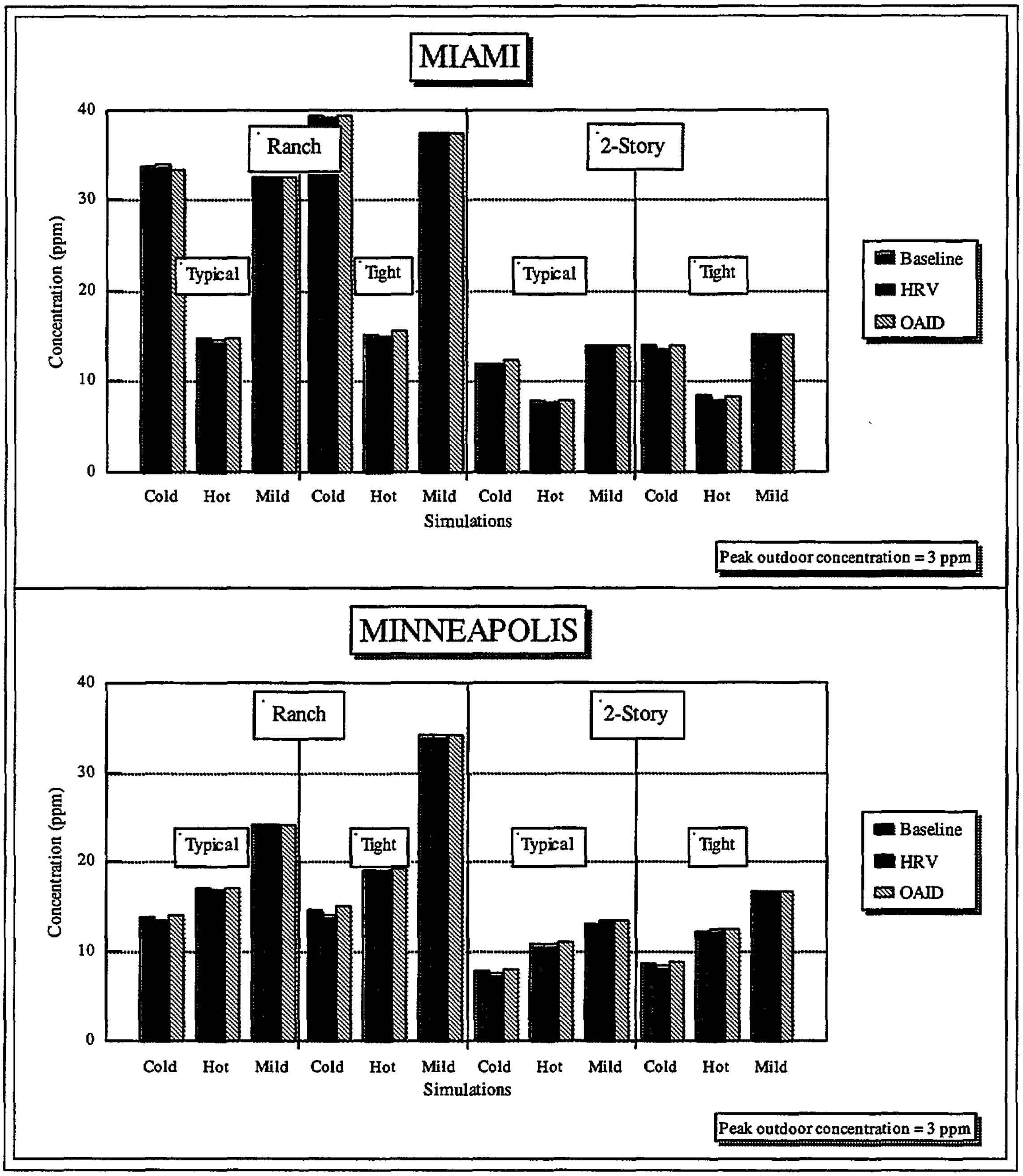


Figure 17 - Maximum One-hour Average CO Concentrations Due to Oven Source

4.2.3 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.

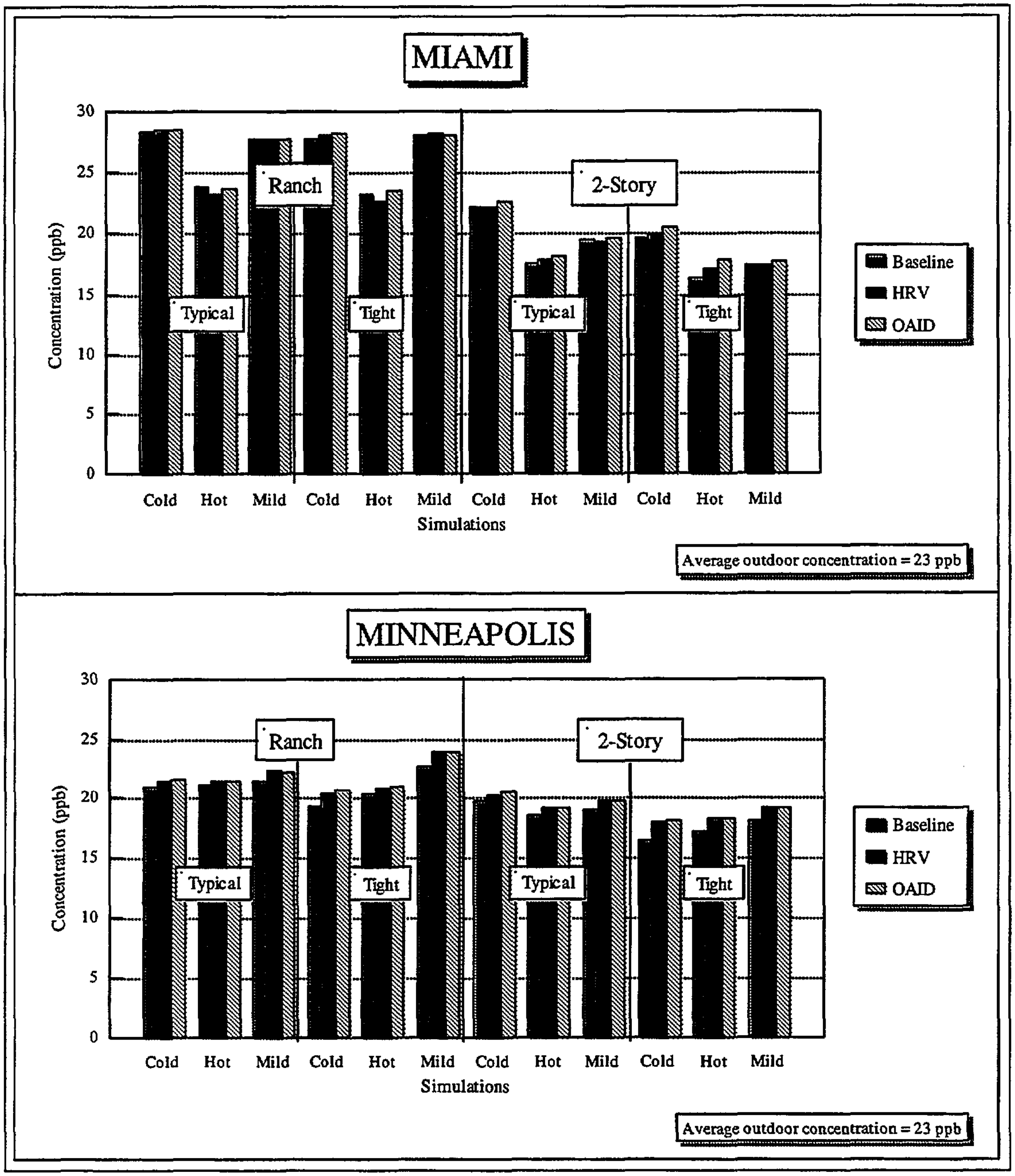


Figure 18 - 24-hour, Living-space Average NO_2 Concentrations Due to Oven Source

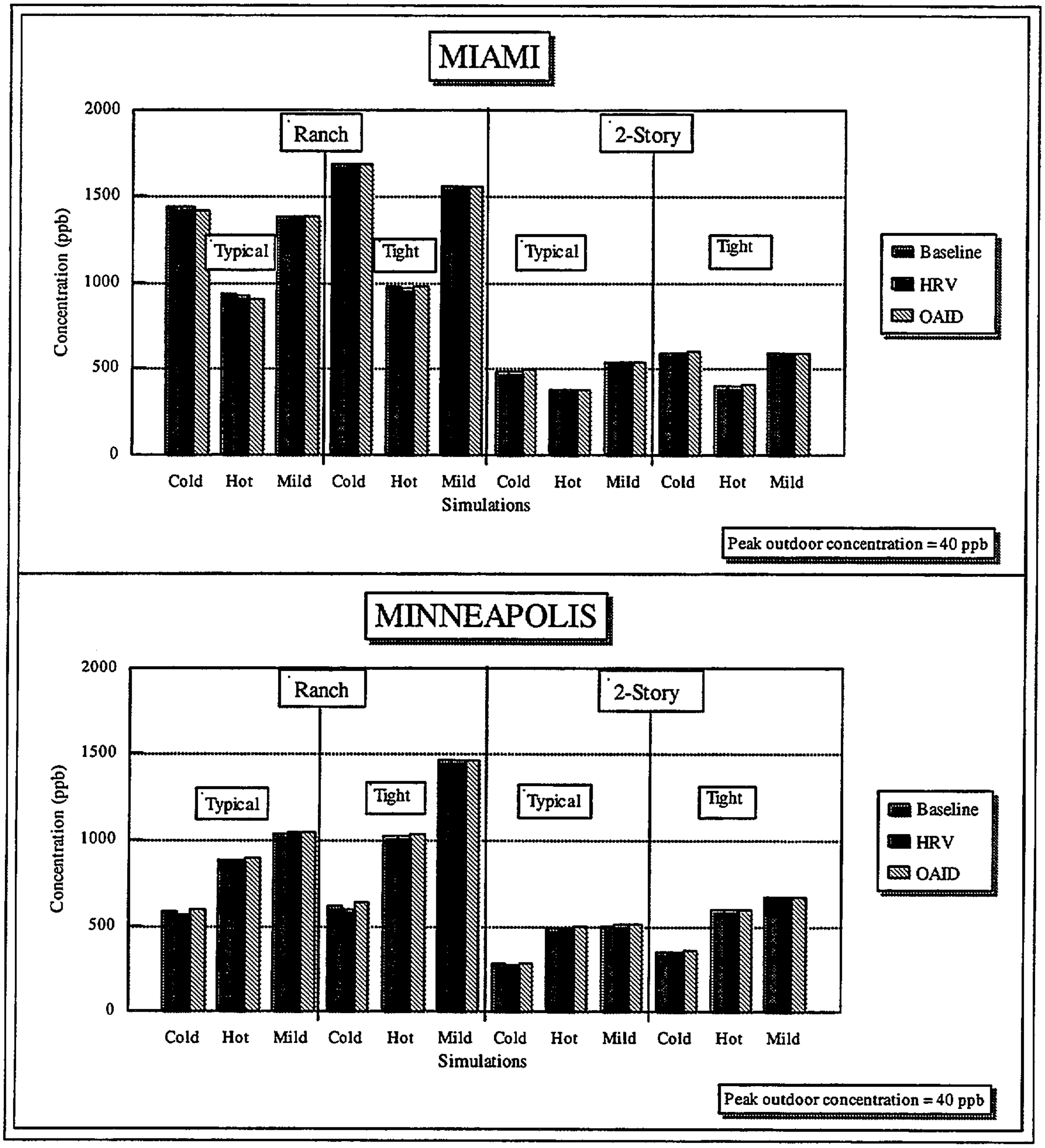


Figure 19 - Peak NO_2 Concentrations Due to Oven Source

4.2.4 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%). Again, the reductions depend on system run-time with the largest reductions occurring for the cases with the greatest system run-time.

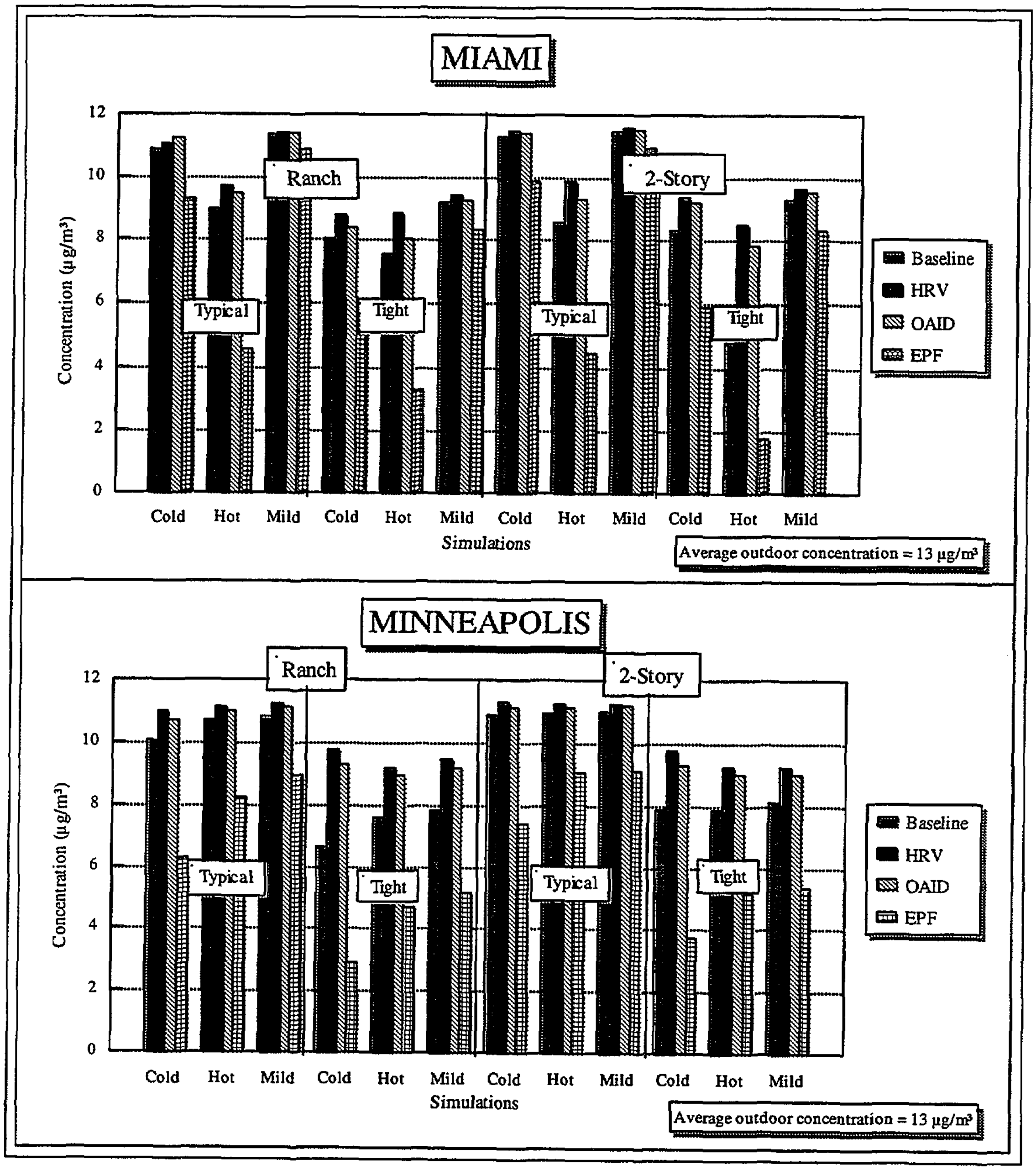


Figure 20 - 24-hour, Living-space Average Fine Particle Concentrations Due to Oven Source

4.2.5 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%.

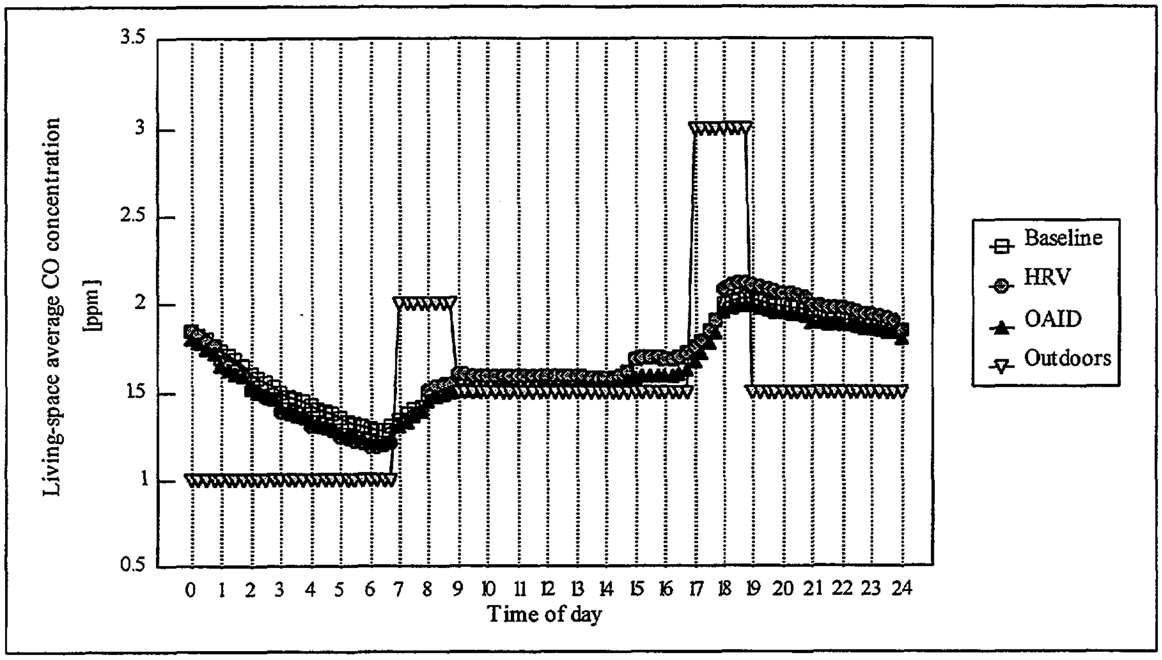


Figure 21 - Transient Living-space Average CO Concentration Due to Heater Source (Tight Miami Ranch House on Cold Day)

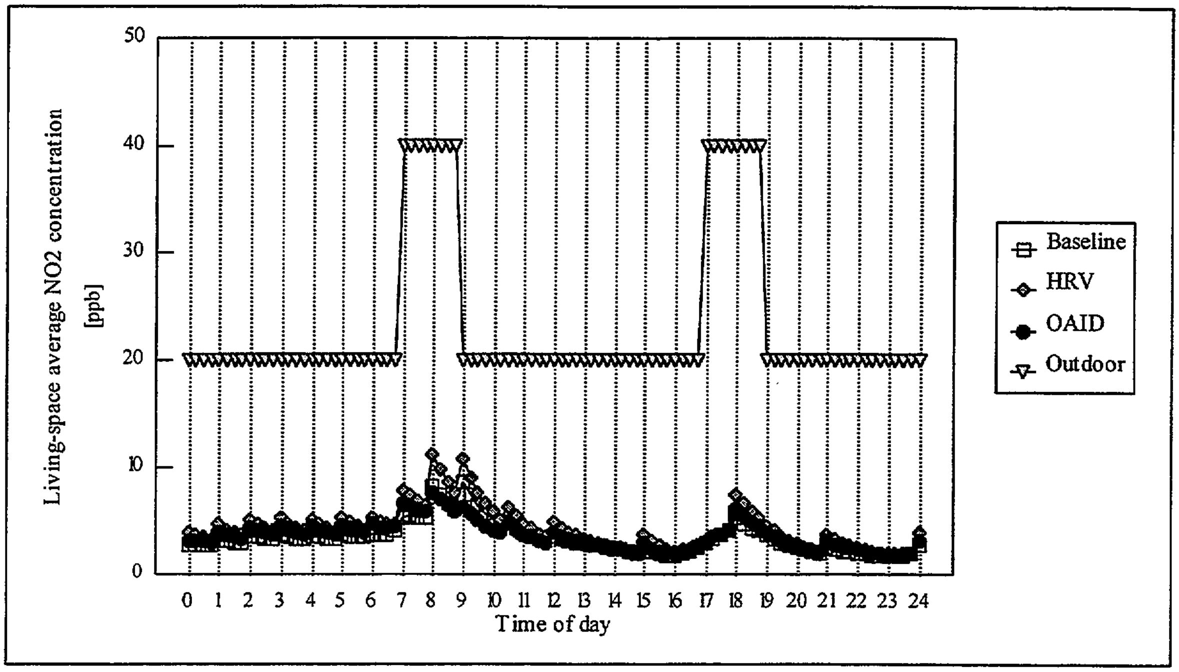


Figure 22 - Transient Living-space Average NO_2 Concentration Due to Heater Source (Tight Miami ranch House on Cold Day)

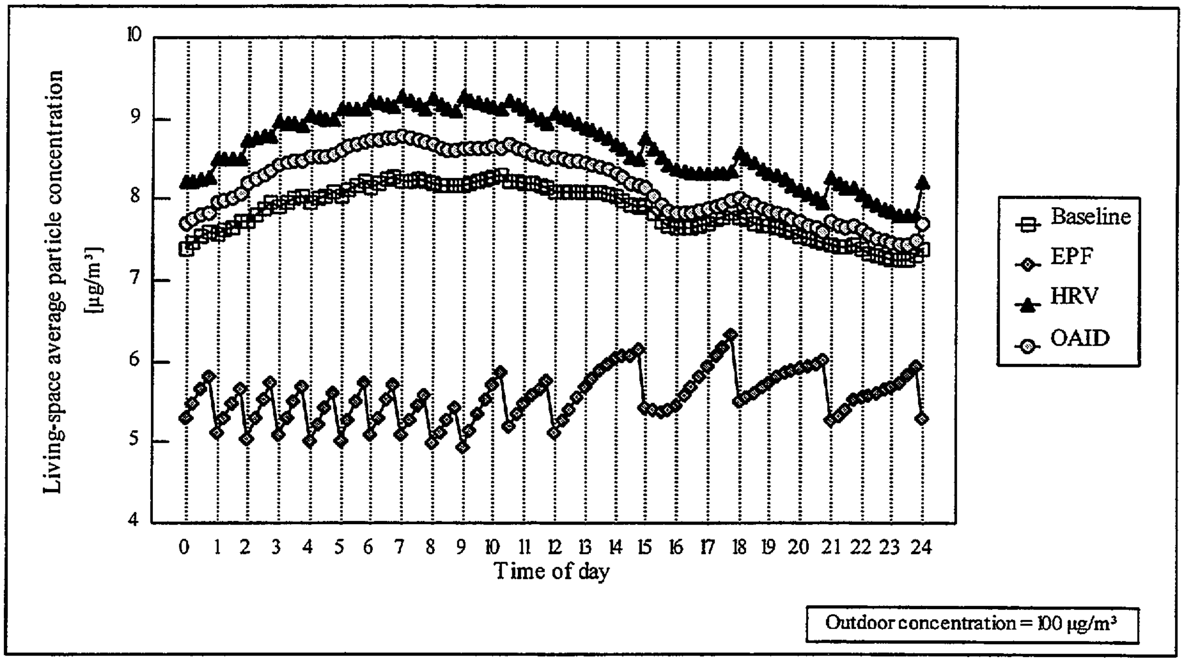


Figure 23 - Transient Living-space Average Fine Particle Concentration Due to Heater Source (Tight Miami Ranch House on Cold Day)

4.2.6 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 that 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.

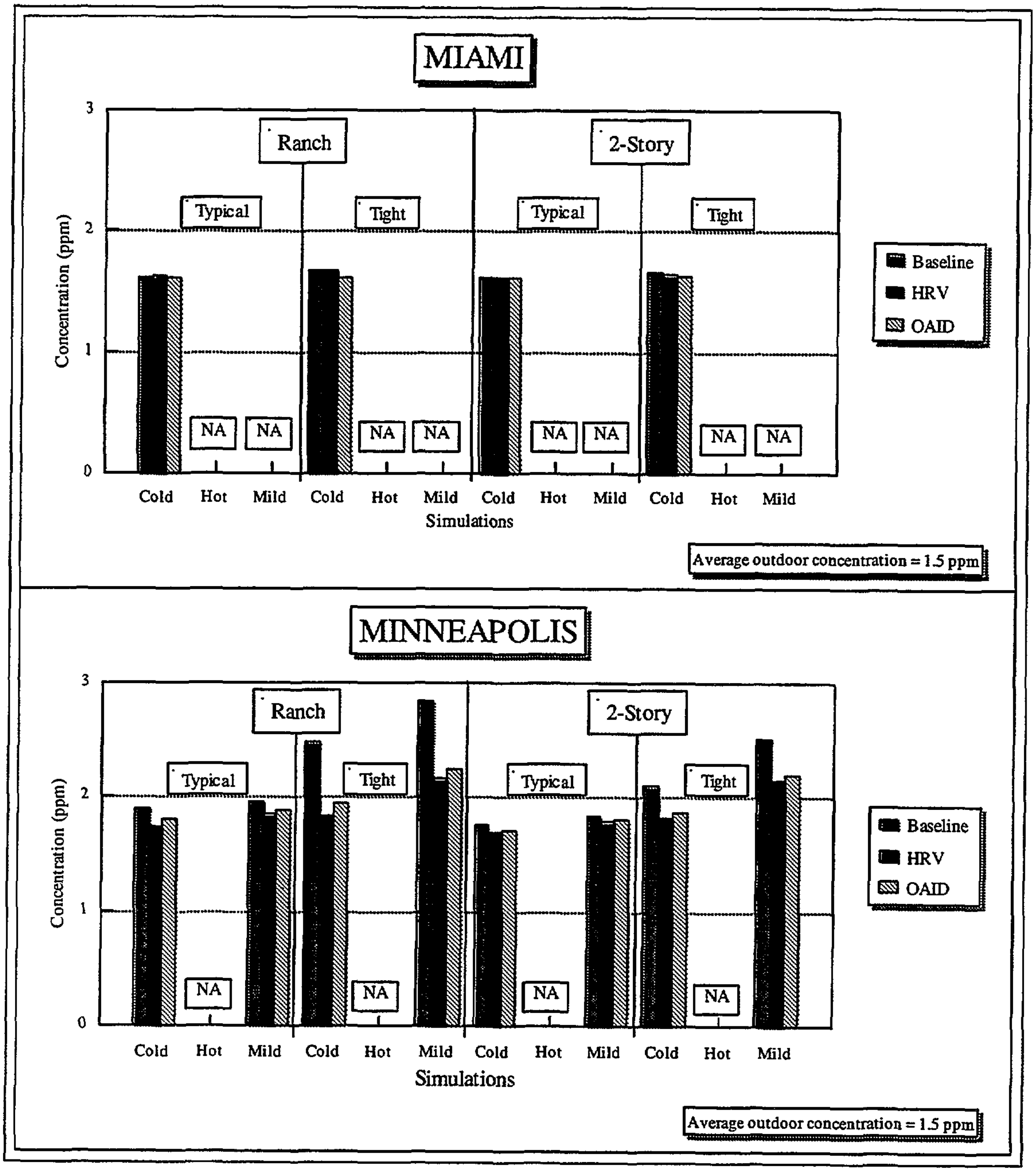


Figure 24 - 24-hour, Living-space Average CO Concentrations Due to Heater Source

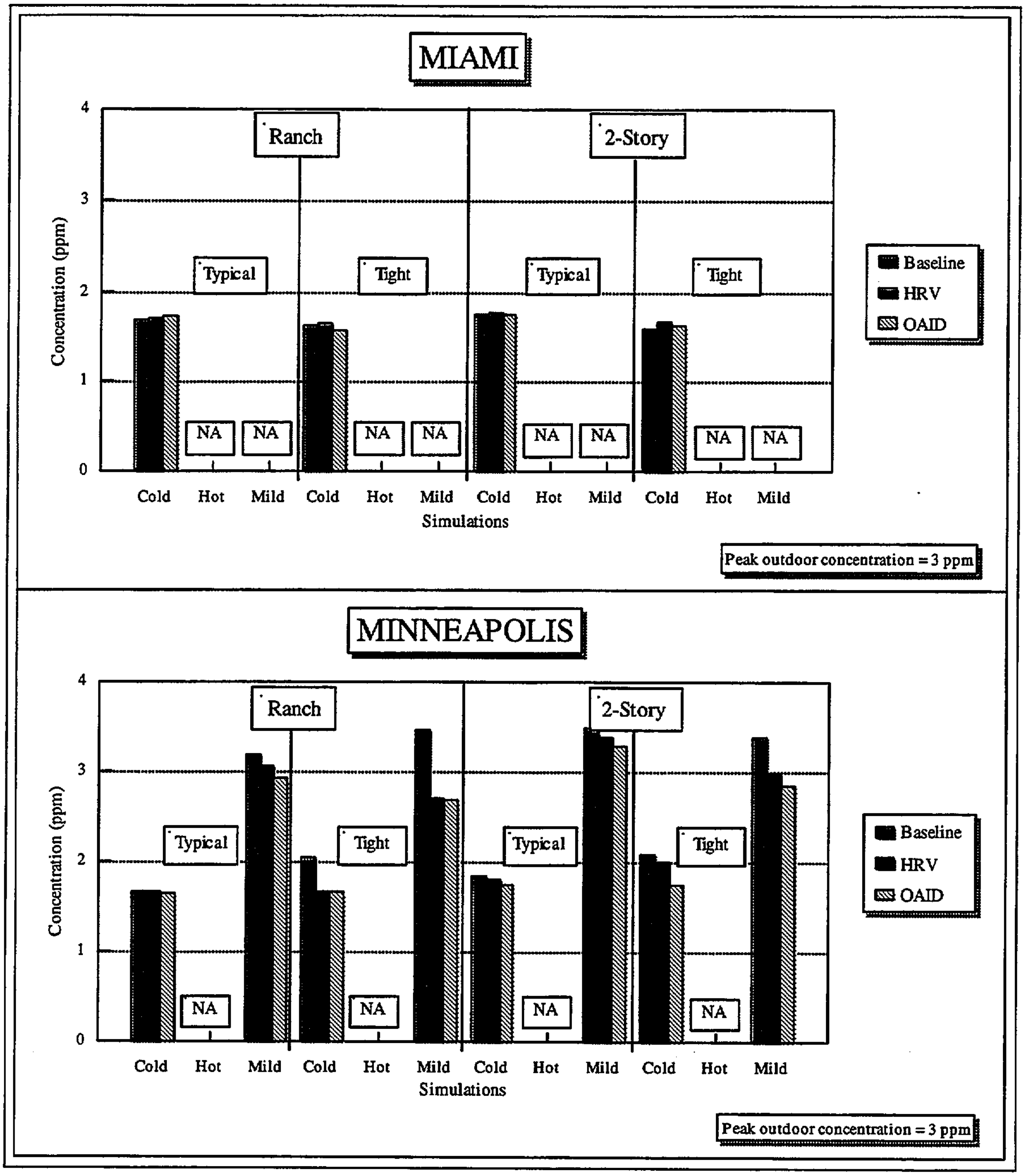


Figure 25 - Maximum One-hour Average CO Concentrations Due to Heater Source

4.2.7 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.

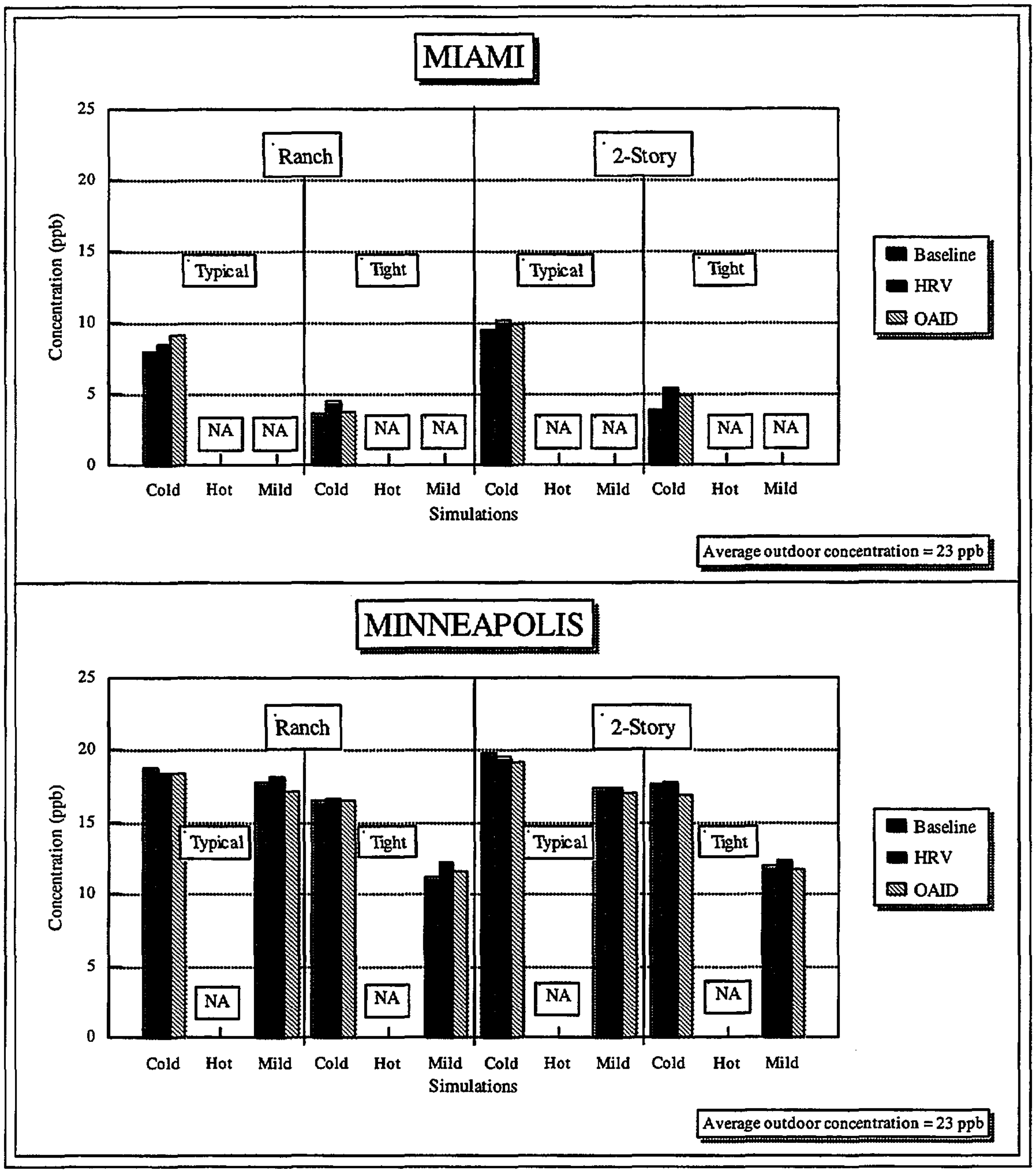


Figure 26 - 24-hour, Living-space Average NO_2 Concentrations Due to Heater Source

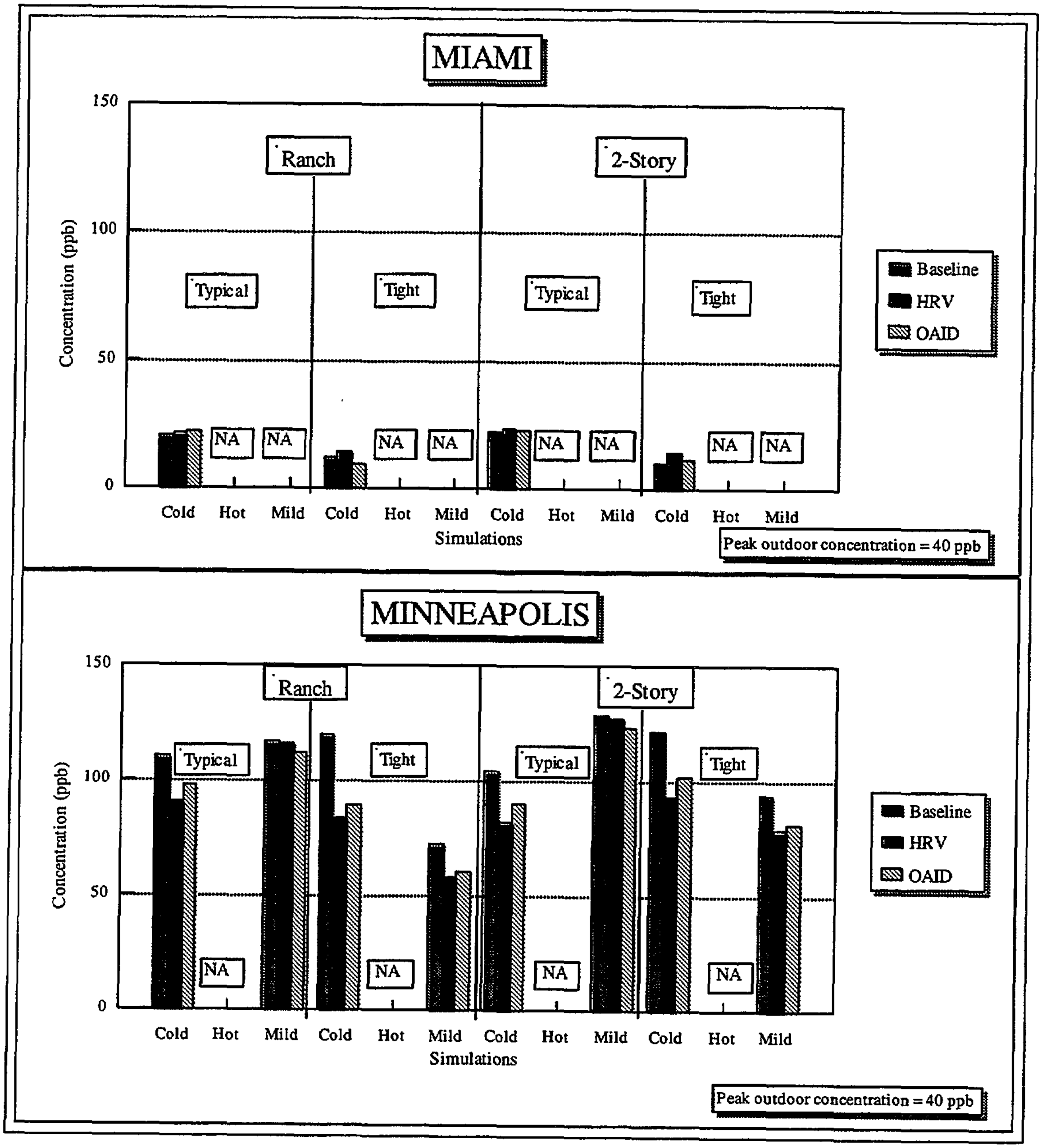


Figure 27 - Peak NO_2 Concentrations Due to Heater Source

4.2.8 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%). 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.

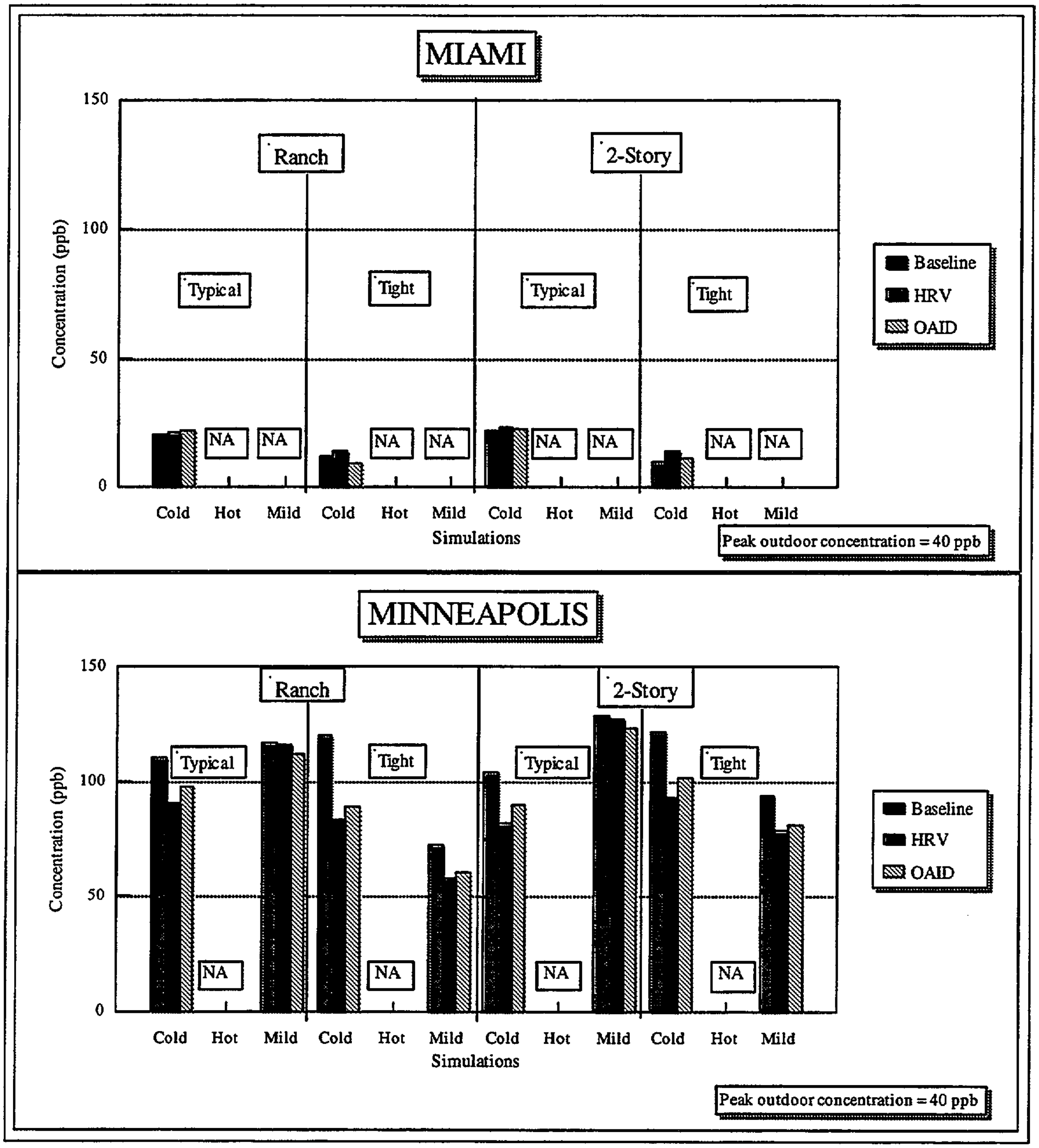


Figure 28 - 24-hour, Living-space Average Fine Particle Concentrations Due to Heater Source

4.3 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.

4.3.1 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.

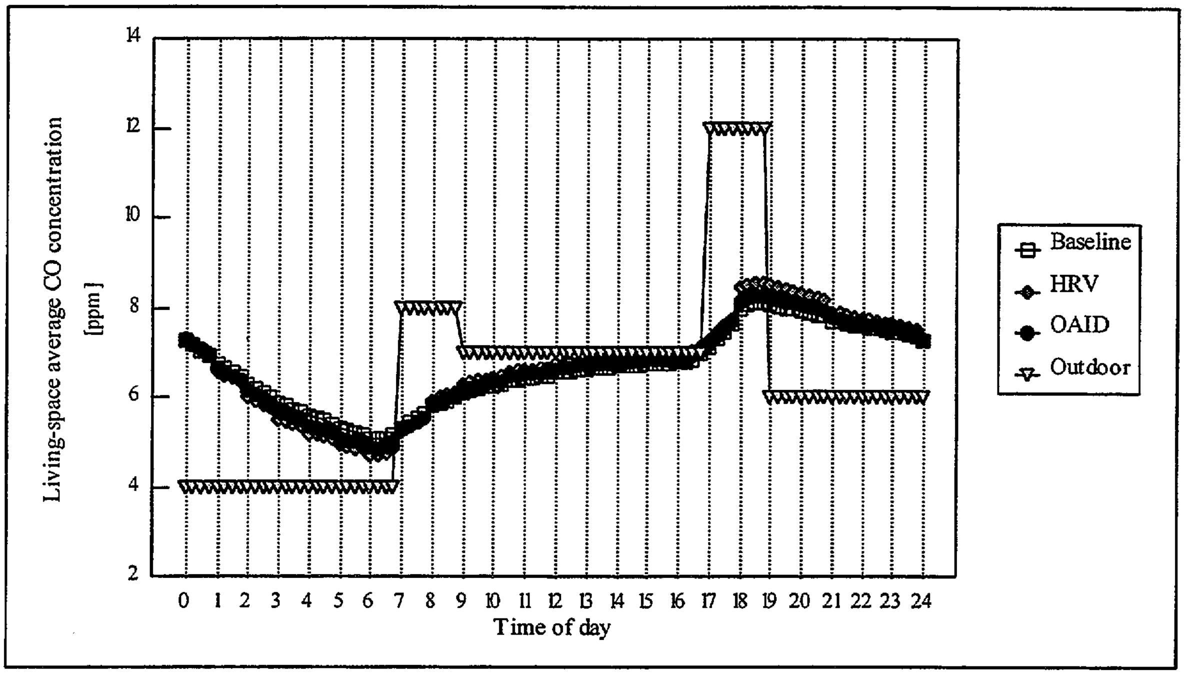


Figure 29 - Transient Living-space Average CO Concentration Due to Elevated Outdoor Pollution (Tight Miami Ranch House on cold Day)

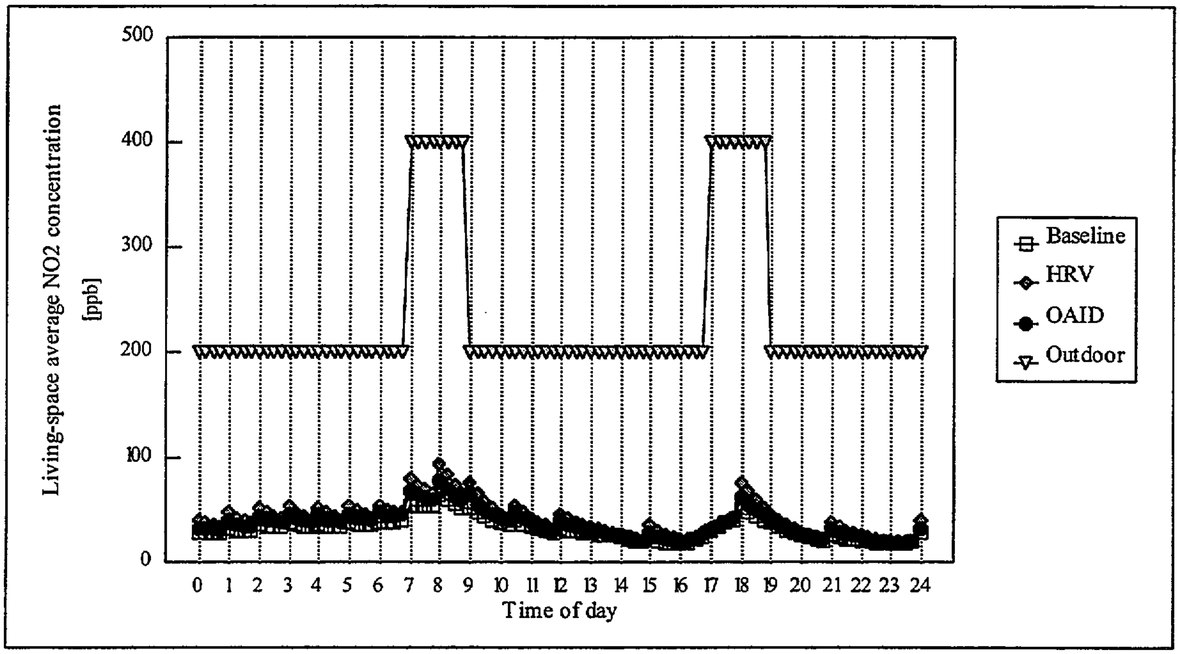


Figure 30 - Transient Living-space Average NO_2 Concentration Due to Elevated Outdoor Pollution (Tight Miami Ranch House on Cold Day)

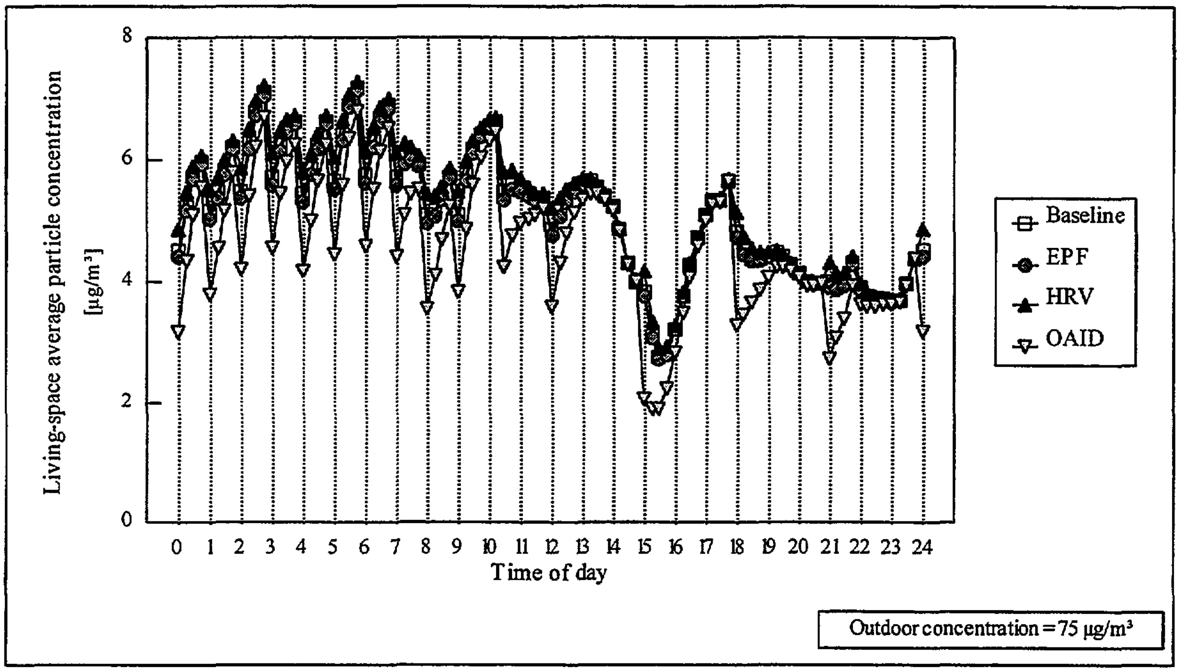


Figure 31 - Transient Living-space Average Coarse Particle Concentration Due to Elevated Outdoor Pollution (Tight Miami Ranch House on Cold Day)

4.3.2 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%.

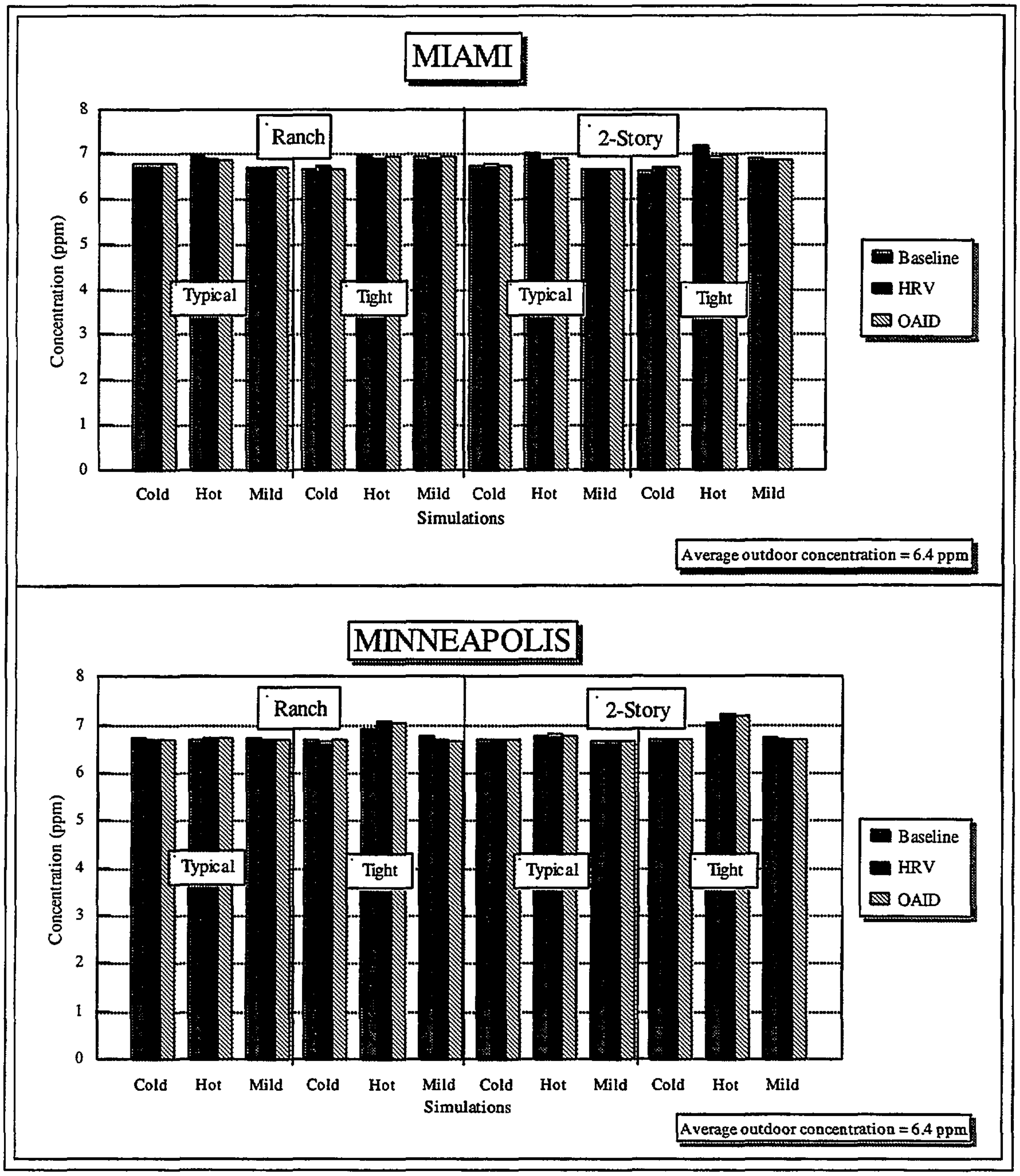


Figure 32 - 24-hour, Living Space Average CO Concentrations Due to Elevated Outdoor Levels

4.3.3 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.

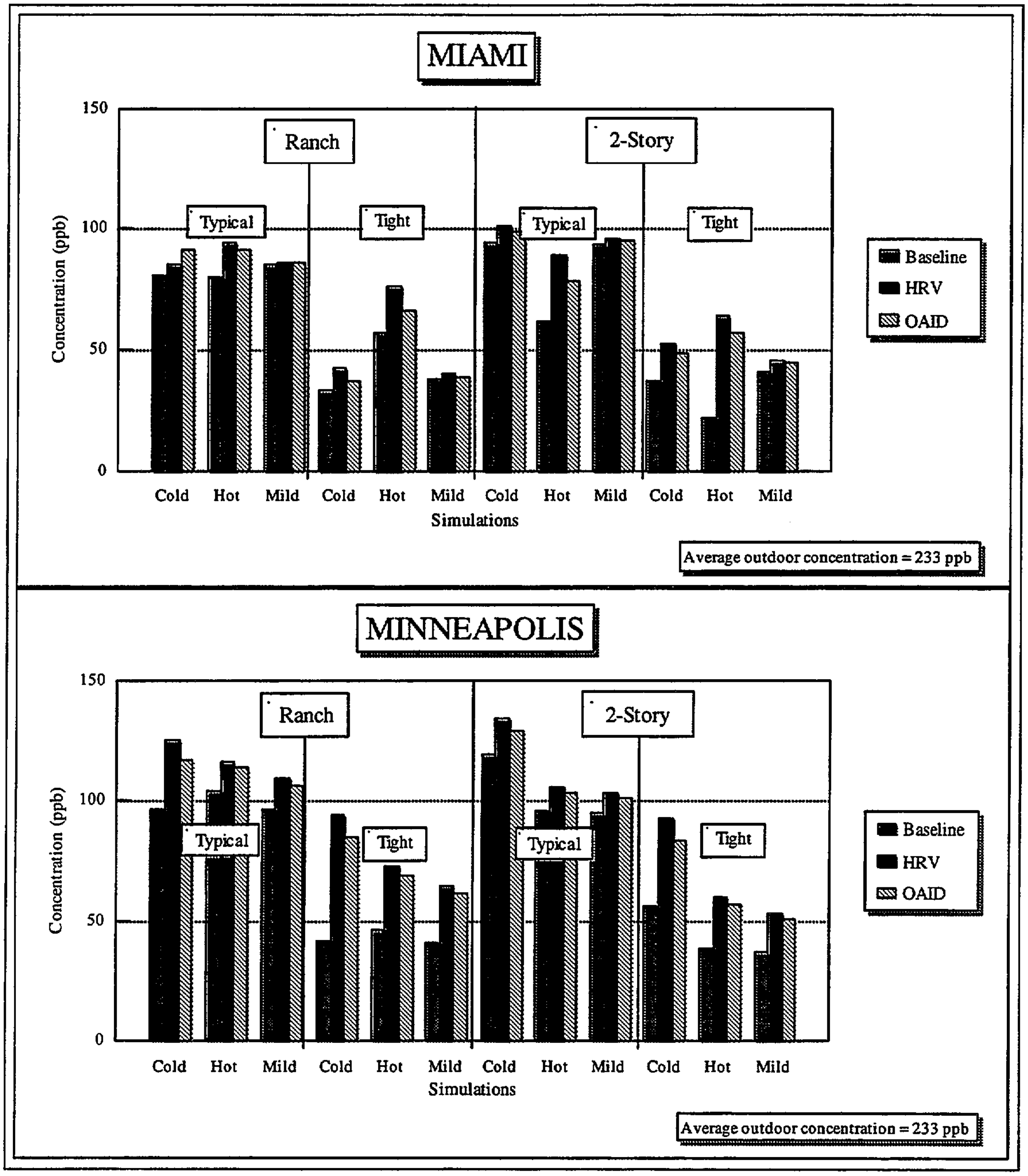


Figure 33 - 24-hour, Living Space Average NO_2 Concentrations Due to Elevated Outdoor Levels

4.3.4 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 μg/m^3 with an average 11 μg/m^3. The average concentration was substantially higher in the typical houses (16 μg/m^3) than in the tight houses (6 μg/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.

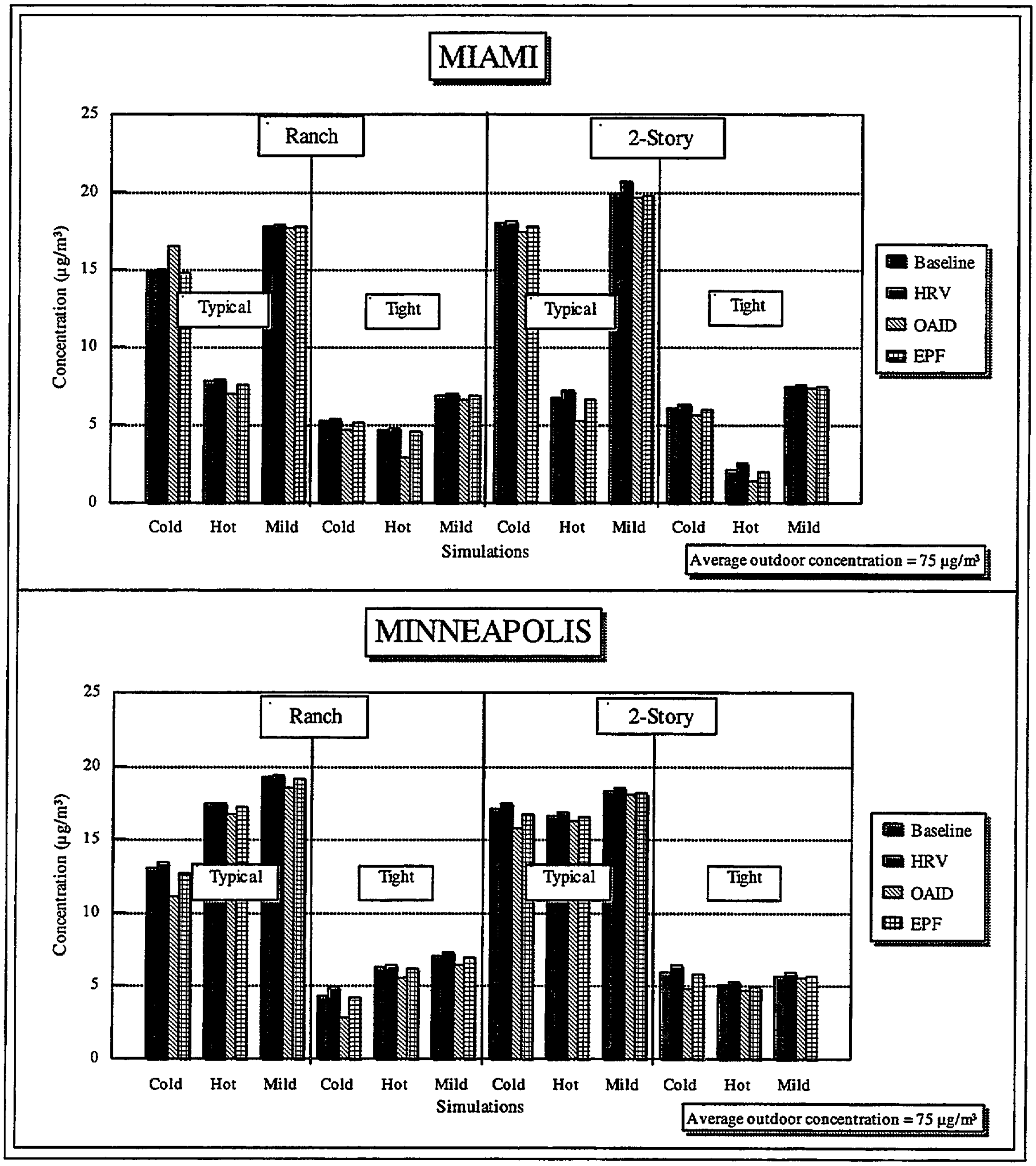


Figure 34 - 24-hour, Living Space Average Coarse Particle Concentrations Due to Elevated Outdoor Pollution

4.4 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. 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.

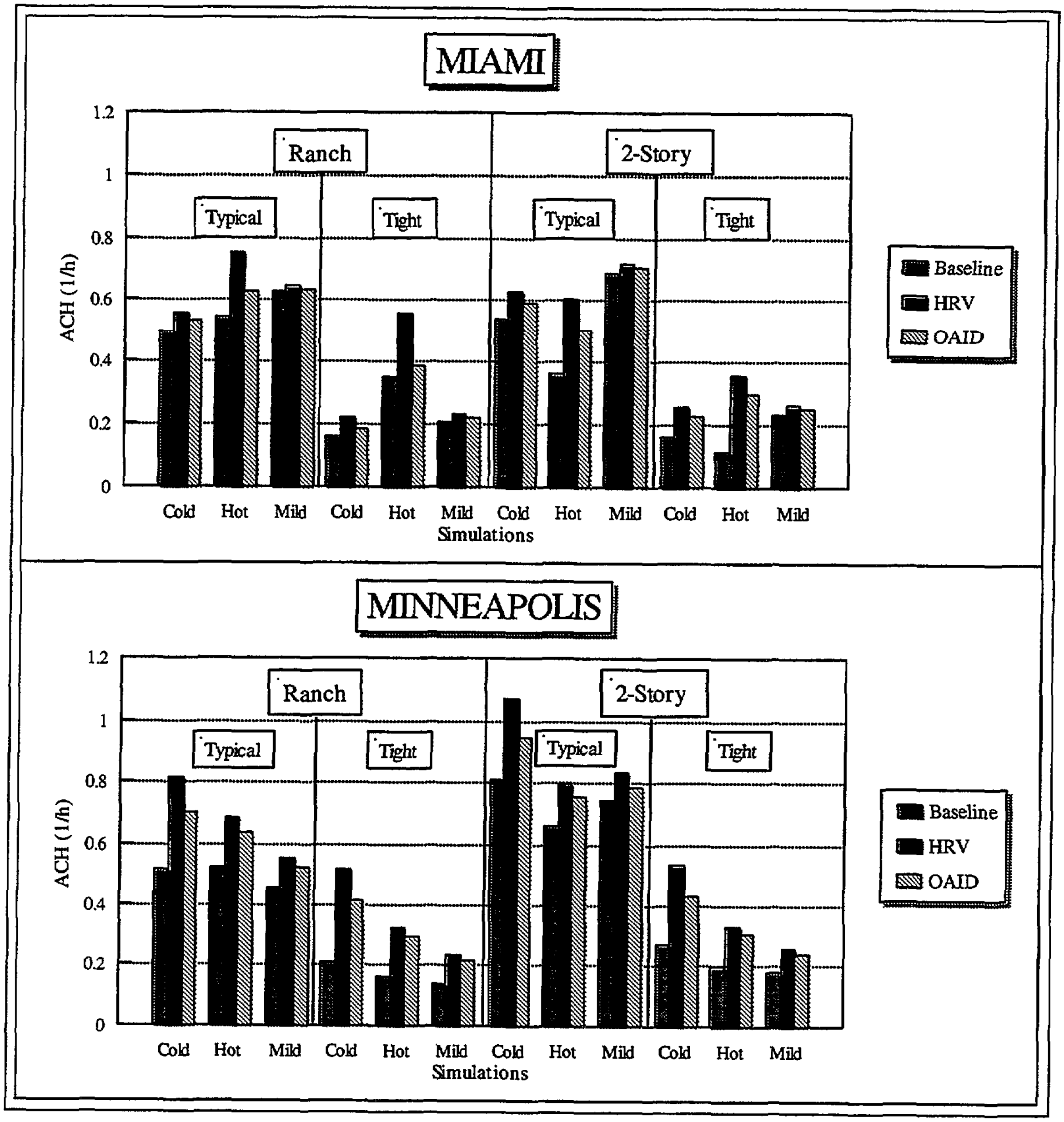


Figure 35 - 24-hour Average Building Air Change Rates in h^{-1}

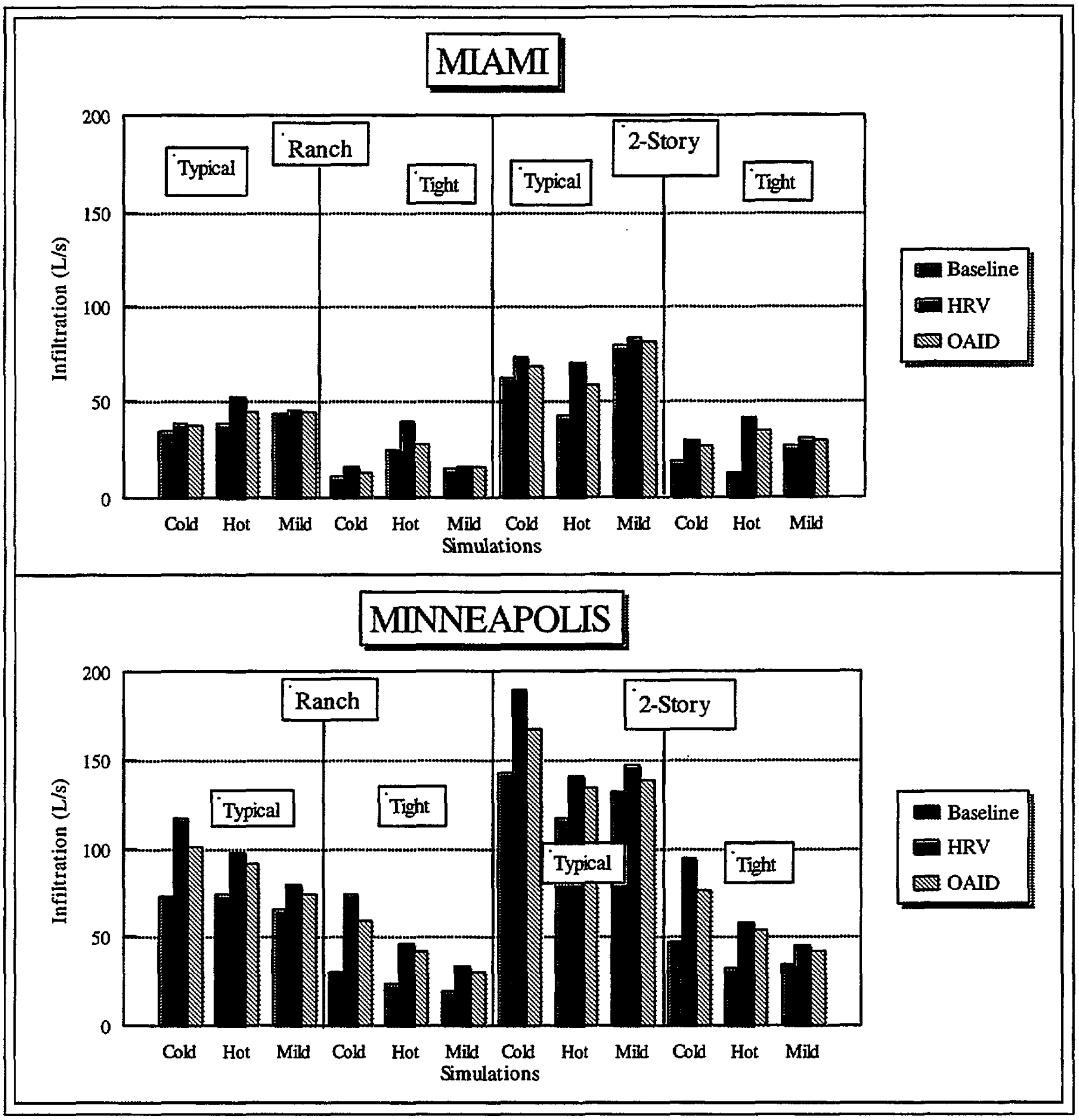


Figure 36 - 24-hour Average Building Air Change Rates in L/s

4.5 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, the generality of these results is limited because they are affected by the manner in which the houses, systems, pollutants, and sources were modeled. 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).

4.5.1 Summary Tables

Table 12 summarizes the 24-hour, living-space average concentrations due to indoor sources for the baseline cases. Tables 13, 14, and 15 summarize the percent reductions in these concentrations for the EPF, HRV, and the OAID, respectively. Table 16 summarizes the 24-hour, living-space average concentrations due to the elevated outdoor pollution for the baseline cases. Table 17 summarizes the percent reductions in these concentrations for all three IAQ controls. Note that in Tables 13, 14, 15, and 17, positive values represent reductions and negative values represent increases.

Table 12 - Summary of Average Pollutant Concentrations
Due to Indoor Sources for Baseline Cases

Source	Floor - TVOCs ($\mu g/m^3$)	Burst - TVOCs ($\mu g/m^3$)	Oven - CO (ppm)	Oven - NO_2 (ppb)	Oven - Particles ($\mu g/m^3$)	Heater - CO (ppm)	Heater - NO_2 (ppb)	Heater - Particles ($\mu g/m^3$)
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 13 - 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 14 - 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 15 - 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 16 - Summary of Average Concentrations Due to Elevated Outdoor Levels for Baseline Cases

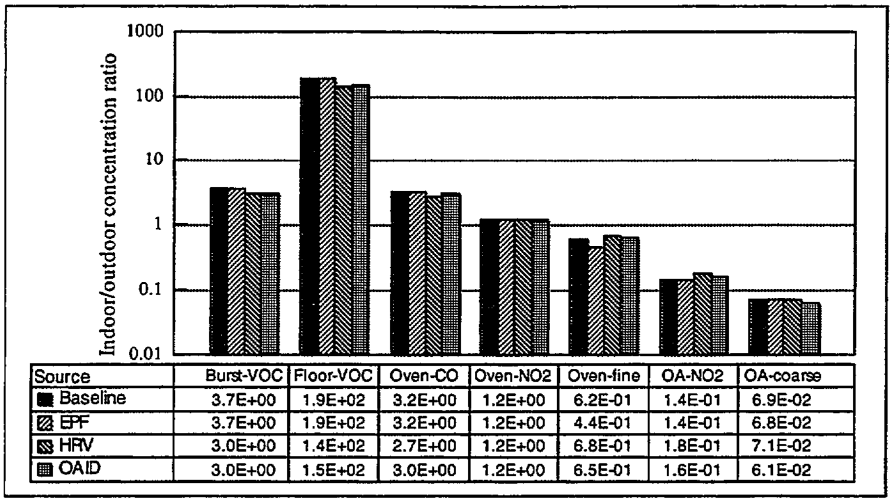
Pollutant	CO (ppm)	NO_2 (ppb)	Coarse particles ($\mu g/m^3$)
Overall average	6.8	66	11
Range	6.6 to 7.2	21 to 119	2 to 20
Typical houses	6.8	94	16
Tight houses	6.8	40	6
Miami cold weather	6.7	61	11
Miami hot weather	7	54	5
Miami mild weather	6.8	64	13
Minneapolis cold weather	6.7	78	10
Minneapolis hot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

Table 17 - 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

4.5.2 Impact of IAQ Controls on Average Pollutant Concentrations

Figure 37 shows the ratio of the 24-hour, living-space average concentrations to the 24-hour average outdoor concentration for the baseline, EPF, HRV, and OAID cases in the tight, Miami ranch house on the cold day. The indoor/outdoor ratios are shown on a log scale as they range over five orders of magnitude depending on the source. The VOC burst source results shown use the average of the concentrations due to all eight burst sources to represent the average impact of the IAQ controls on localized sources in different rooms of the house. The variation in the indoor/outdoor ratio among the sources is due to the relative values of the source strength, indoor decay mechanisms and outdoor pollutant concentrations. The controls themselves have much less impact on these ratios, but the effects can still be seen.



Source	Burst-VOC	Floor-VOC	Oven-CO	Oven-NO2	Oven-fine	OA-NO2	OA-coarse
■ Baseline	3.7E+00	1.9E+02	3.2E+00	1.2E+00	6.2E-01	1.4E-01	6.9E-02
▨ EPF	3.7E+00	1.9E+02	3.2E+00	1.2E+00	4.4E-01	1.4E-01	6.8E-02
▧ HRV	3.0E+00	1.4E+02	2.7E+00	1.2E+00	6.8E-01	1.8E-01	7.1E-02
▦ OAID	3.0E+00	1.5E+02	3.0E+00	1.2E+00	6.5E-01	1.6E-01	6.1E-02

Figure37 - Indoor/outdoor Ratios of Average Concentrations Due to Various Sources (Tight Miami Ranch House on Cold Day)

The average impact of the IAQ controls for all pollutant sources are shown in Figure 38 as percent reductions in baseline concentrations. In general, both the HRV and OAID reduced the concentrations due to indoor sources of the pollutants without non-ventilation removal processes (CO and VOC) and increased, or had little impact, on the concentrations of pollutants with decay/deposition and filtration removal processes (NO_2 and particles). The HRV and OAID had the greatest reduction for the constant, distributed source (Floor-VOC), which was also the source resulting in the largest indoor/outdoor concentration ratio. In general, the HRV and OAID increase NO_2 and particle concentrations because, as shown in Figure 37, the baseline average indoor concentration is generally below the average outdoor concentration. Therefore, the additional outdoor air brought in by these controls increases the indoor concentration. Figure 38 shows that this trend was true on average. However, whether an increase or decrease occurred for an individual case depended on several factors including the building air change rate, the indoor source strength, the outdoor pollutant concentration, decay/deposition rates, and the relative timing of the source, system operation, and outdoor peaks.

The impact of the OAID was nearly always similar to but slightly smaller than the impact of the HRV because, as shown in Figure 35, it increases the average building air change rate by a smaller amount than the HRV. As discussed previously, this smaller increase in building air change rates is due to the pressurization effect of the OAID. However, the HRV and OAID did not always have similar impacts, as seen in the case of coarse particle concentrations due to elevated outdoor air pollution. For this pollutant, the OAID reduced the baseline concentration by an average of 9.9% while the HRV increased the baseline concentration by an average of 3.9%. This impact is believed to be due to the pressurization effect of the OAID. Both devices include a standard furnace filter with filtration efficiency of 90% for coarse particles in the intake path. However, no penetration factor was included for infiltration air and, therefore, the filtered air entering through the OAID and HRV has a lower particle concentration than the unfiltered air entering through the envelope. Since the operation of the OAID results in less infiltration than the baseline and HRV cases, it reduces the indoor coarse particle concentration.

In general, the EPF had a small impact on the already low coarse particle concentrations with an average reduction of only 1.4%. This small impact is due to the small change in coarse particle filtration efficiency from 90% to 95%. Figure 38 shows that the EPF was more effective at reducing the fine particle concentrations with reductions of 30% and 31% for the oven and heater sources, respectively. It should be noted that, as indicated by the indoor/outdoor ratios, the conditions simulated provided only a modest challenge to the EPF.

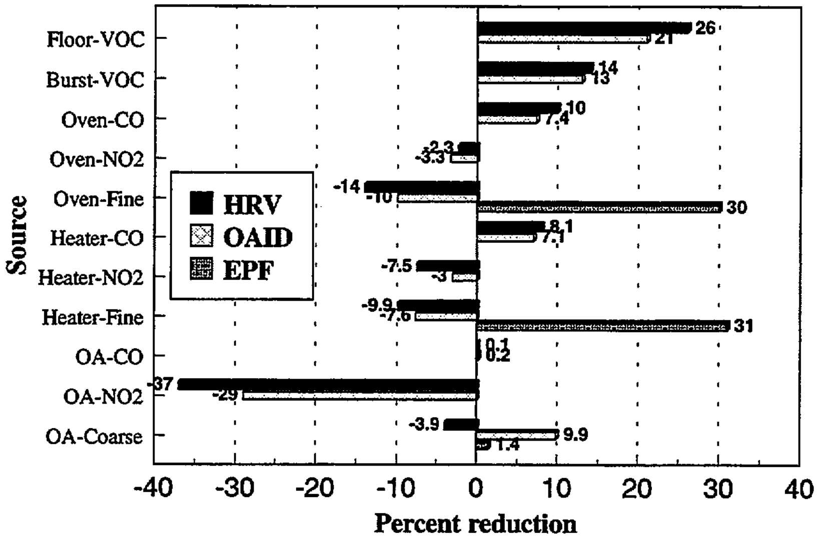


Figure 38 - Average Reductions in Living-space Average Concentrations

4.5.3 Factors Influencing Impact of IAQ Controls

In addition to the pollutant and source dependent variations, the impact of the IAQ controls on the concentration due to a single source varied greatly. For example, the reduction for the floor source ranged from 3% to 69%. One reason for the variation was dependence on HVAC system run-time.

Figure 39 shows both the average percent reduction in baseline Floor-VOC concentration due to the HRV and the average percent system run-time for the Miami cases. As shown by the building air change results, the system run-time is an important factor for these IAQ controls that were specified to operate only in conjunction with the system. On the mild day, the system operated an average of 7% of the time to meet the low thermal load and reduced the baseline concentration by only 8%. On the hot day, the system operated 65% of the time to meet the high heating load and reduced the baseline concentration by 41%. Although this influence was observed for most sources and cases, other factors, such as timing of system operation, also become important for short-duration sources.

Often, the conditions (small indoor-outdoor temperature difference) causing low system run-time also correspond to low infiltration and high pollutant concentrations. Therefore, days with high concentrations due to low infiltration could receive the least help from the HRV or OAID due to low system run-time. For example, the tight Miami ranch house in mild weather has the second highest baseline 24-hour average TVOC concentration (20,700 μg/m^3) but, after modest reductions due to the HRV and OAID, it ends up having the highest TVOC concentrations for the modified cases with concentrations of 18,600 μg/m^3 and 19,600 μg/m^3, respectively. The effectiveness of the central forced-air modifications could also be limited if the cooling and heating equipment is oversized. Although it was not explored in this study, oversized equipment would further reduce the HVAC system run-time. The system run-time limitation could be overcome through other control options (e.g. constant operation, demand control, or scheduled operation) or through other approaches to residential ventilation. Also, a tendency of occupants to open windows during mild weather could offset the impacts of low system run-time.

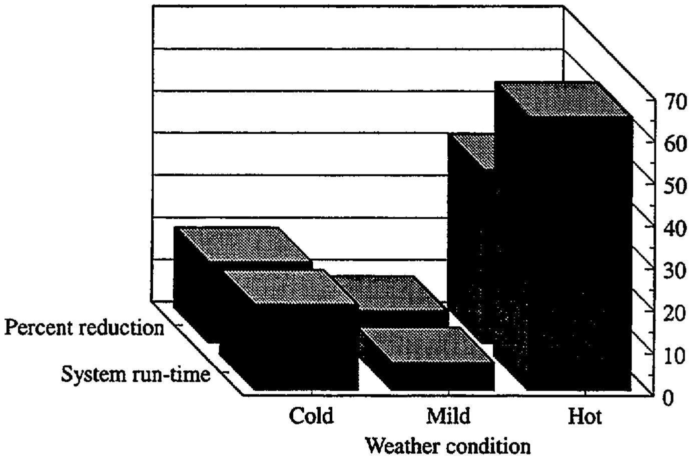


Figure 39 - Influence of System Run-time on IAQ Control Impact (Floor-VOC for Miami HRV Cases)

Another factor showing a consistent influence on the IAQ control impacts was envelope airtightness. Figure 40 shows the average impact of the HRV on baseline CO and fine particle concentrations due to the oven. The HRV consistently had a larger impact, whether positive or negative, in the tight houses due to a greater relative change in the average building air change rates for the tight houses.

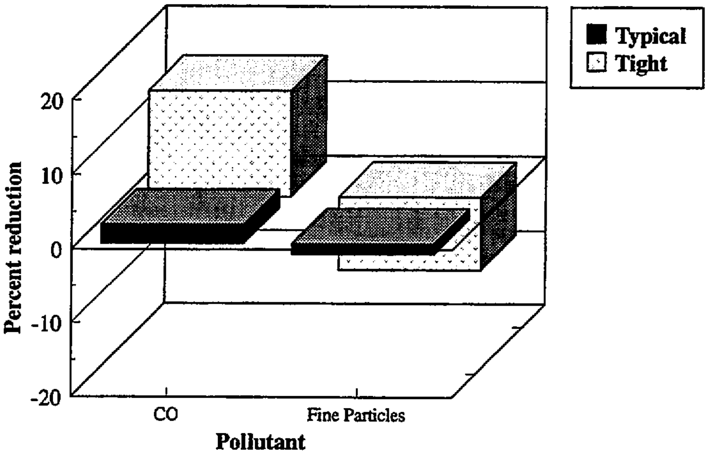


Figure 40 - Influence of envelope airtightness on IAQ control impact
(average percent reduction of oven pollutants due to HRV)

4.5.4 Impact of Enhanced Filtration

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 13). As expected, use of the EPF never resulted in an increase in particle concentrations. However, the dependence on system run-time discussed in the previous section was a limitation to the effectiveness of the EPF. For example, 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 Miami mild weather cases. 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 17. This minimal reduction may also be influenced by the particle deposition rate used in the simulations; larger reductions would occur for lower deposition rates.

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.

4.5.5 Impact of Ventilation Options

As mentioned earlier, the heat recovery ventilator (HRV) and outdoor air intake damper (OAID) resulted in substantial reductions in indoor pollutant concentrations for some cases, but in other cases 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 8). 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 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 levels). 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 has a smaller impact on short-duration source emissions. For the tight Miami ranch house in cold weather, the HRV reduced the average TVOC concentration due to the kitchen 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.

As mentioned earlier, 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 observed, 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 results in an overall neutral effect on building pressure.

5 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 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 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 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 limits 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 is a 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. While 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 that the results of a simulation may not be intuitive, it can 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. 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, sources, IAQ controls, and the 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 studied 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 is 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. Bioaerosol pollutants, of interest to CPSC, can be studied when sufficient information is available to model generation and removal processes.

The project was restricted to IAQ controls in the form of modifications to forced-air systems that are commercially available, 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 in evaluating IAQ controls. Some of these issues could be addressed with the current version of CONTAM93, while others 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. However, 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, exposure analysis, detailed humidity analysis, and modeling of flue-gas spillage.

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 HVAC System Design Details

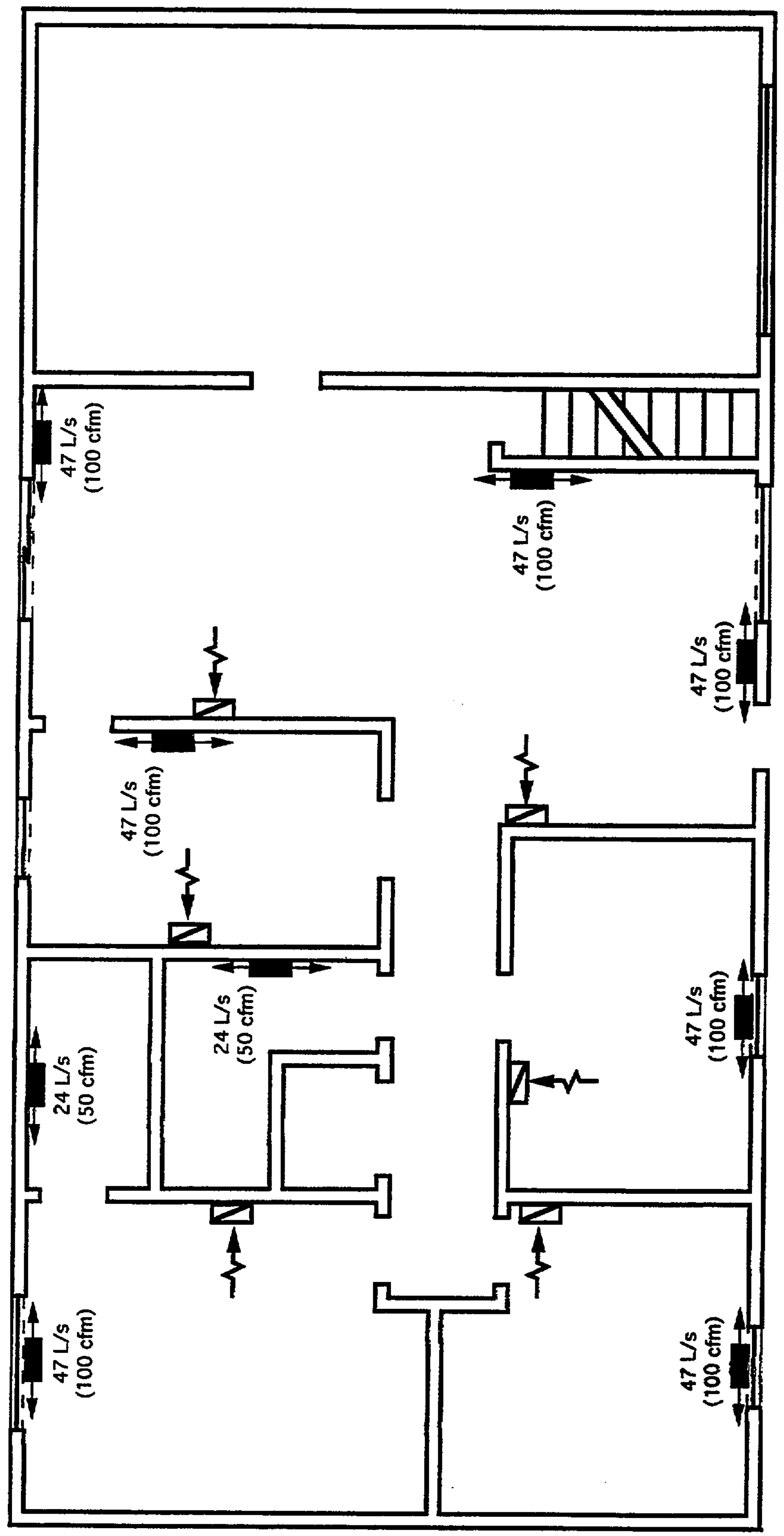
This appendix contains detailed HVAC system design information including system equipment descriptions, and air distribution system drawings. Commercially available HVAC equipment was chosen based on the heating and cooling load calculations presented in Appendix E of Emmerich and Persily (1994). Guidelines published by the National Association of Home Builders (Yingling et al. 1981) were used to assist in designing the HVAC system layouts.

Equipment selected for the Minneapolis ranch house includes a condensing sealed-combustion gas furnace, a cased heating/cooling coil, and a split-system air conditioner. The furnace has a heating capacity of 10.9 kW (37,200 Btu/hr) with an Annual Fuel Utilization Efficiency (AFUE) of 92%. The air conditioner has a capacity at design conditions of 4.90 kW (16,700 Btu/hr) and an SEER of 10.0. The system blower has three speeds and is set to nominal flows of 271 L/s (575 cfm) for heating and 425 L/s (900 cfm) for cooling at a nominal external static pressure drop of 125 Pa (0.5 in wc). Features of the HVAC system design for the Minneapolis ranch house include: equipment located in the basement, interior supply ducts, and a return in each room.

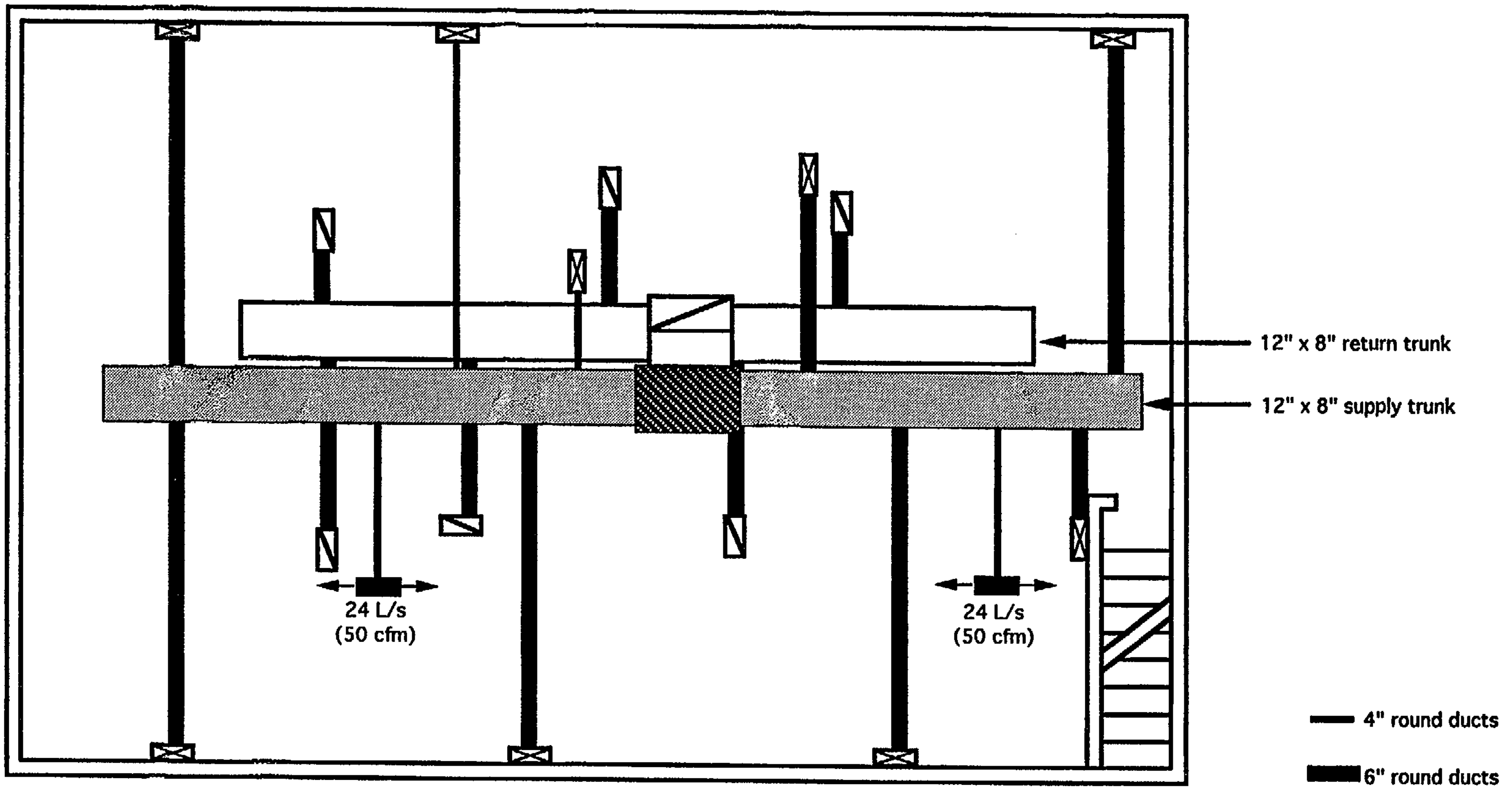
Equipment selected for the Miami ranch house is a split-system air conditioner and a direct expansion fan coil with an electric heater. The heater has a capacity of 10 kW (34,100 Btu/hr). The air conditioner has a capacity at design conditions of 6.35 kW (21,700 Btu/hr) and an SEER of 10.0. The system blower has three speeds and is set to nominal flows of 222 L/s (470 cfm) for heating and 356 L/s (755 cfm) for cooling at a nominal external static pressure drop of 125 Pa (0.5 in wc). Features of the HVAC system design for the Miami ranch house include: equipment located in a first floor utility closet, supply ducts located in the attic and a central return.

Equipment selected for the Minneapolis two-story house includes a condensing sealed-combustion gas furnace, a cased heating/cooling coil, and a split-system air conditioner. The furnace has a heating capacity of 16.4 kW (55,800 Btu/hr) with an AFUE of 92%. The air conditioner has a capacity at design conditions of 6.30 kW (21,500 Btu/hr) and an SEER of 10.0. The system blower has four speeds and is set to nominal flows of 495 L/s (1050 cfm) for heating and 432 L/s (915 cfm) for cooling at a nominal external static pressure drop of 125 Pa (0.5 in wc). Features of the HVAC system design for the Minneapolis two-story house include: equipment located in the basement, interior supply ducts, and a return in each room.

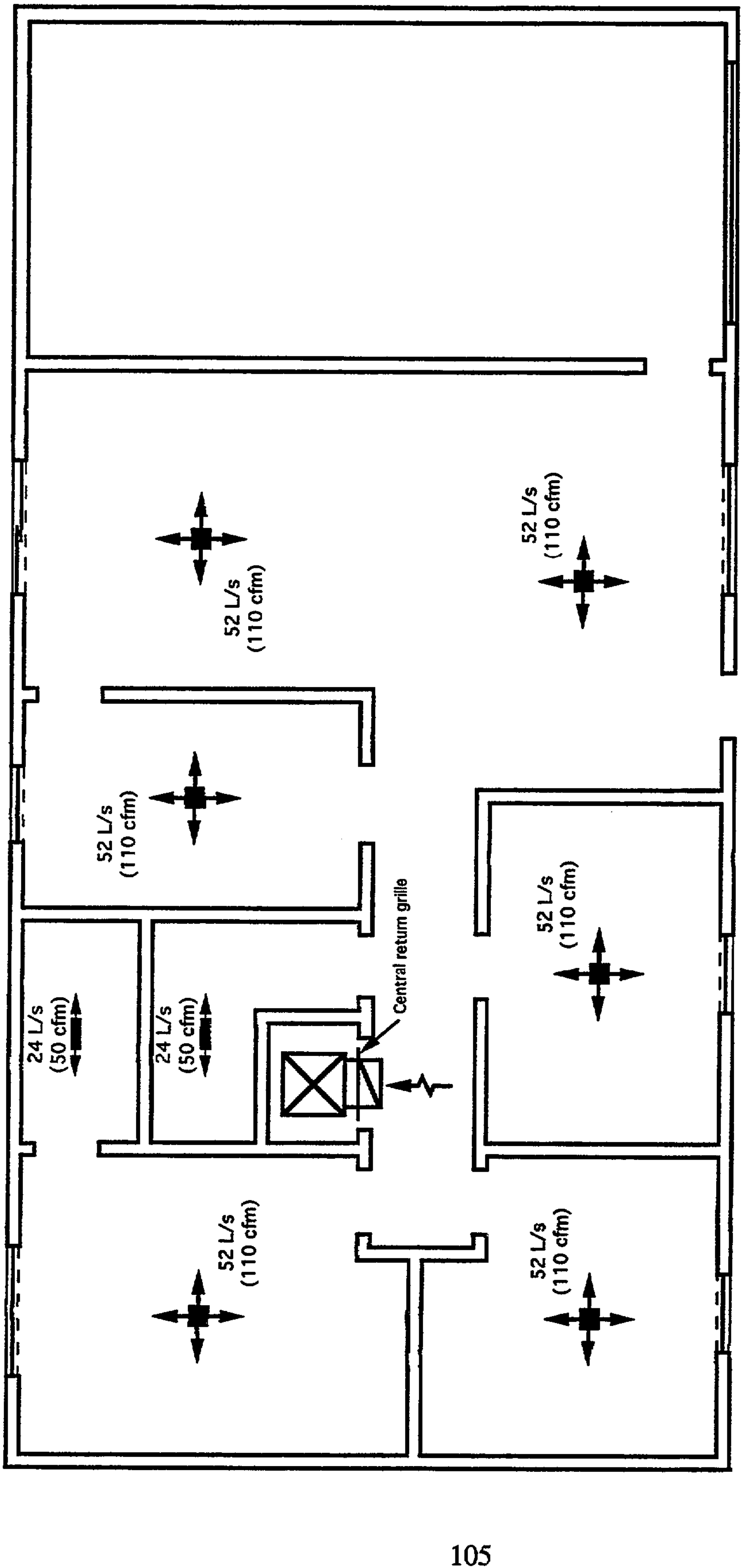
Equipment selected for the Miami two-story house is a split-system air conditioner and a direct expansion fan coil with an electric heater. The heater has a capacity of 10 kW (34.100 Btu/hr). The air conditioner has a capacity at design conditions of 6.35 kW (21,700 Btu/hr) and an SEER of 10.0. The system blower has three speeds and is set to nominal flows of 222 L/s (470 cfm) for heating and 356 L/s (755 cfm) for cooling at a nominal external static pressure drop of 125 Pa (0.5 in wc). Features of the HVAC system design for the Miami two-story house include: equipment located in a first floor utility closet, supply ducts in a plenum between the first and second floors, and a central return on each floor.



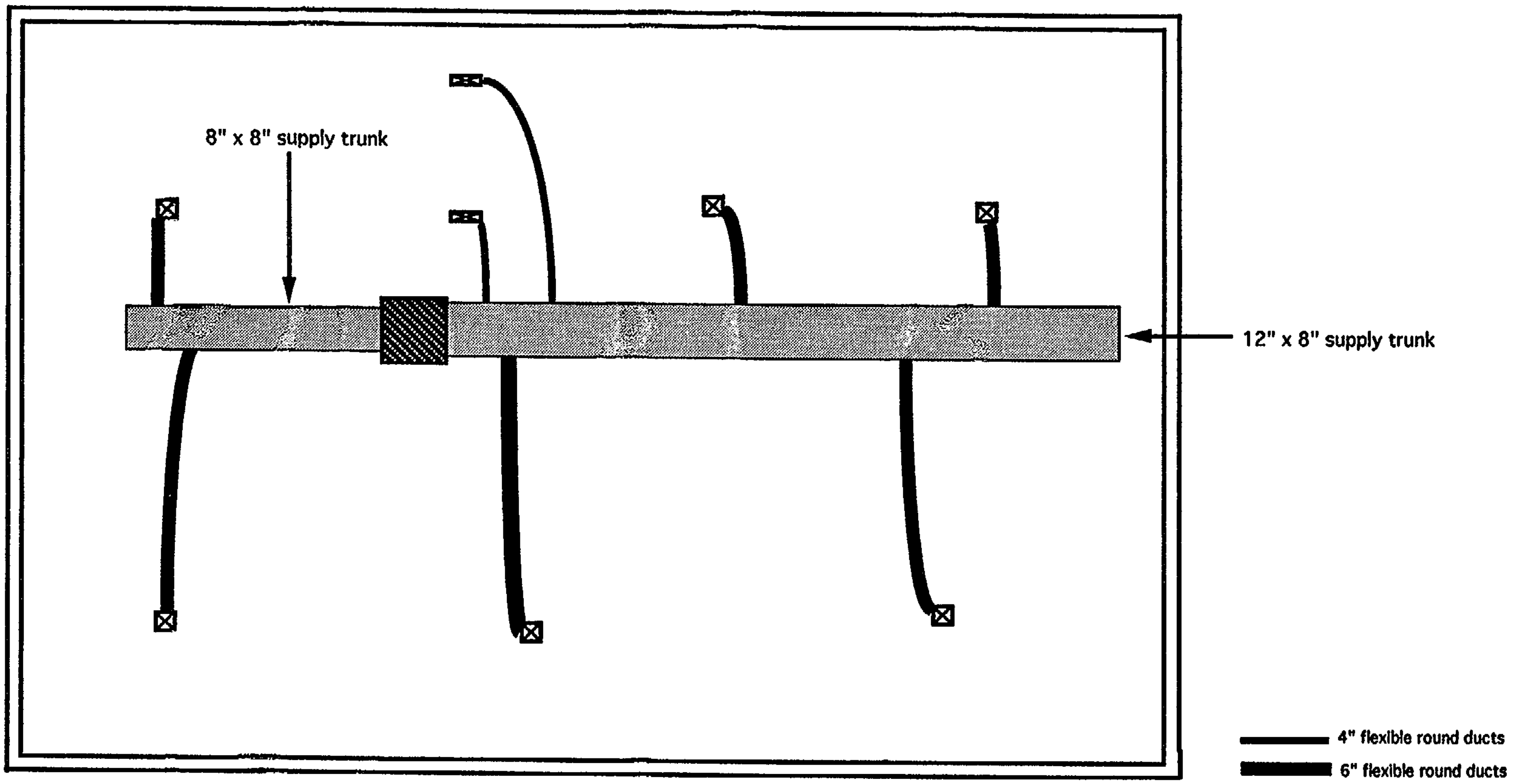
Minneapolis Ranch House



Minneapolis Ranch House
Basement



Miami Ranch House



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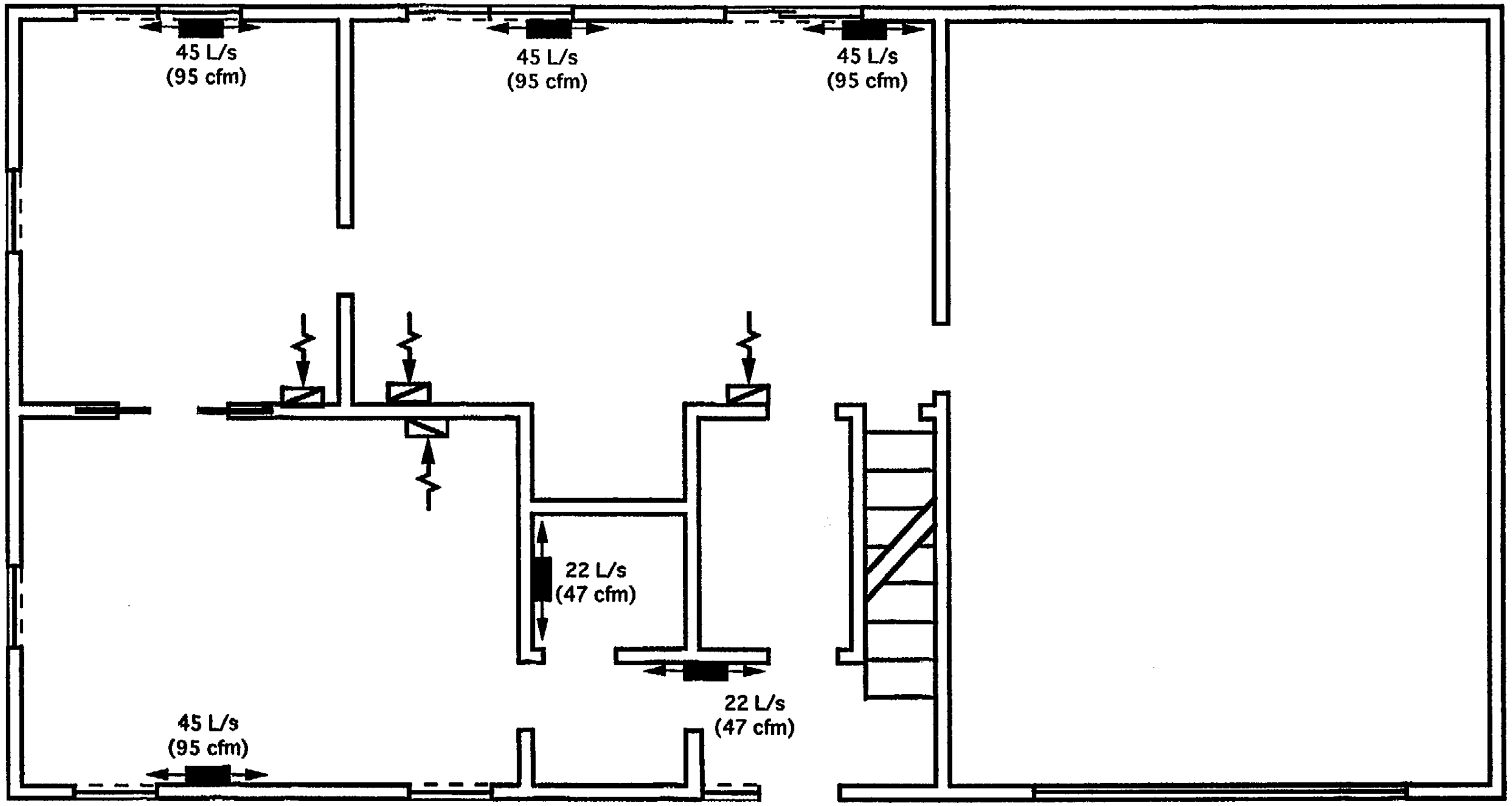
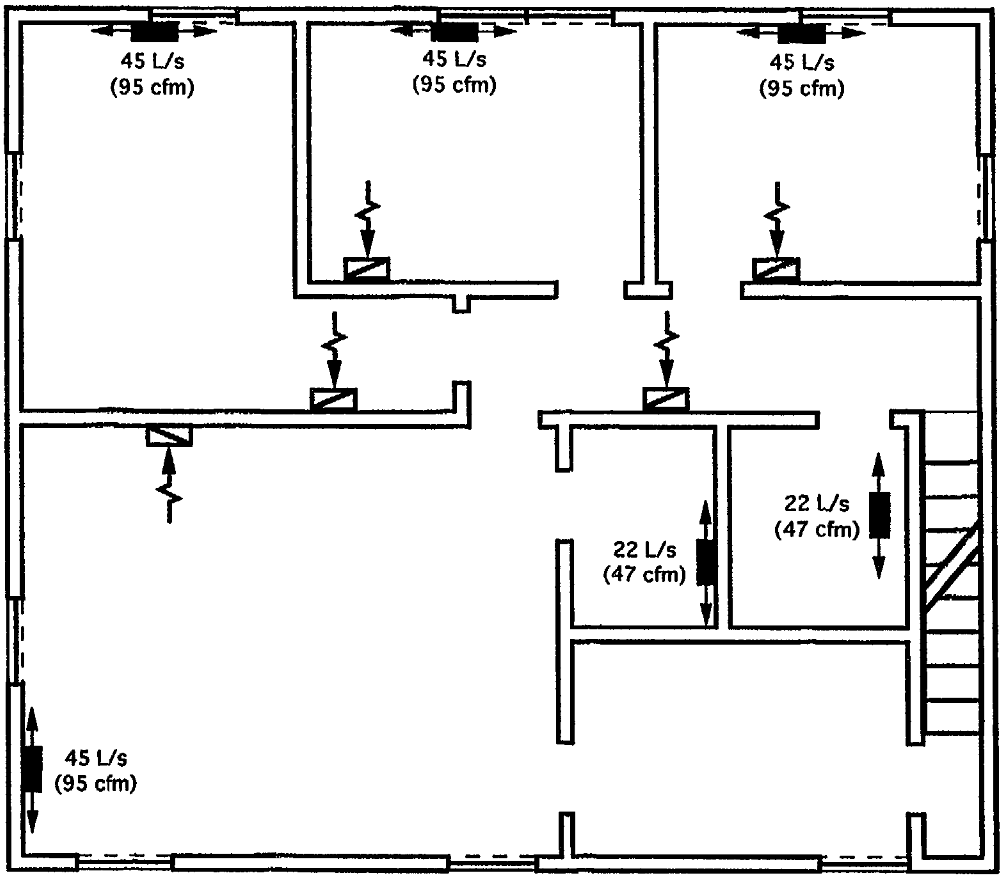
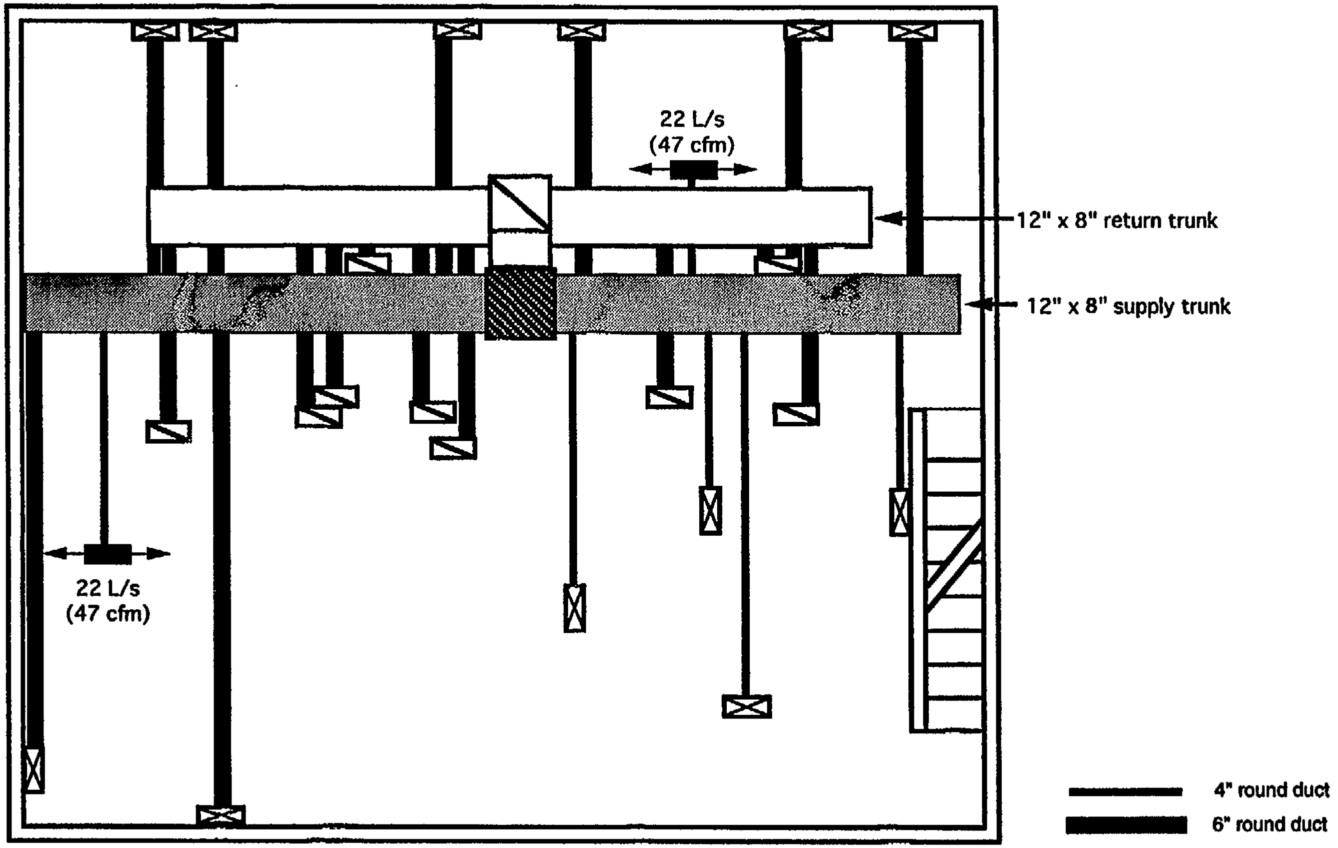


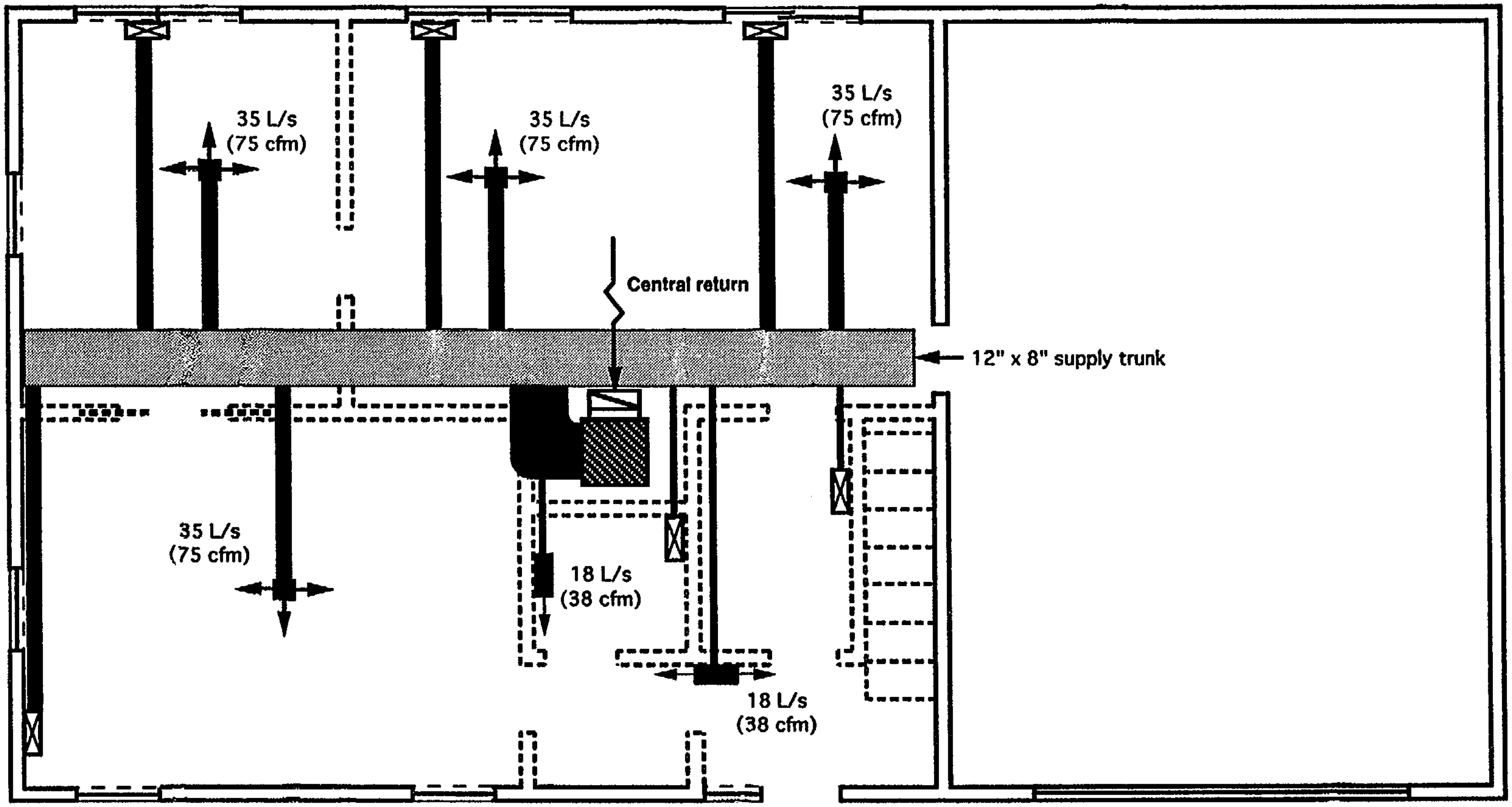
Minneapolis 2-Story House
Lower Floor



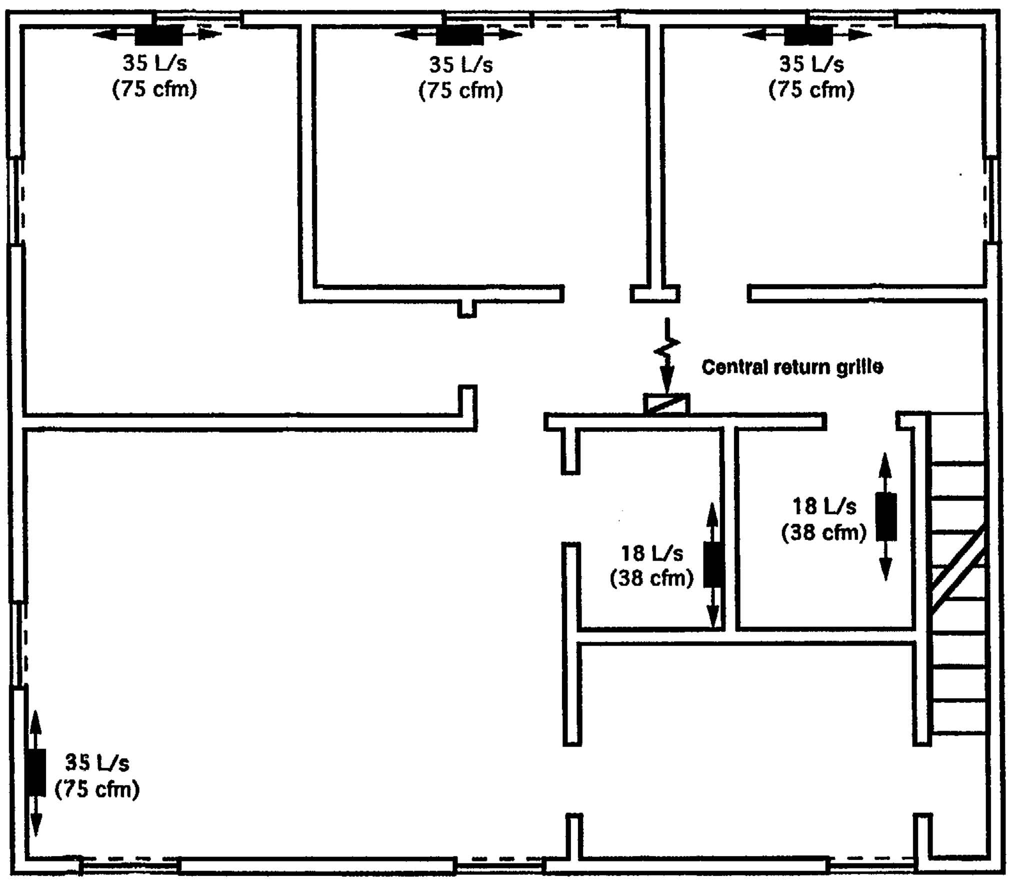
Minneapolis
2- Story House
Upper Floor Plan



Minneapolis 2-Story House
Basement



Miami
2-Story House
Plenum Between Floors



Miami
2- Story House
Upper Floor Plan

Appendix B Airflow Modeling Results

CONTAM93 was used to analyze airflow in the houses using two approaches: simulated fan pressurization tests and directly calculated whole building air change rates under a range of wind speed and indoor - outdoor temperature differences. This appendix describes the simulations performed and summarizes the airflow modeling results.

Fan Pressurization Tests

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 a pressure differences of 4 and 50 Pa was 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 using Equation 27 in Chapter 23 of ASHRAE 1993. The results of the fan pressurization simulations are shown in Table 1. The difference between the Miami and Minneapolis houses is due primarily to the existence of the basement in the Minneapolis houses. The tight houses are about 66% tighter than the houses of typical leakage.

Table 1 - Fan pressurization simulation results

House	ach_{50} (hr^{-1})	Leakage area (cm^2)
Typical Miami ranch	13.2	680
Tight Miami ranch	4.1	220
Typical Minneapolis ranch	6.6	720
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	1,170
Tight Minneapolis 2 story	3.1	410

Whole building air change rates

CONTAM93 was used to calculate whole building air change rates for wind speeds from 0 to 10 m/s and indoor-outdoor temperature differences from -10 to 30 °C. The wind direction was held constant throughout the simulations. These simulations were performed with the HVAC systems both on and off. Whole building air change rates were calculated by adding the airflow entering the conditioned space of the house through all leakage paths. The results of these airflow simulations are shown in Tables 2 through 9 for the system off.

Several general trends are shown by these tables. Using 'tight' values for the airflow elements vs. 'typical' or best estimate values reduced the whole building air change rate by up to a factor of four as compared to a factor of three for the fan pressurization results. Also, over the range considered here, the wind speed had a much greater impact on the whole building air change rate than the temperature difference. However, the tight airflow elements reduced the impact of the wind speed more than the impact of the temperature difference.

Table 2 - Whole house air change rate for typical Miami ranch house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.33	0.21	0.00	0.22	0.35	0.46	0.57	0.67	0.76
2	0.40	0.32	0.33	0.38	0.47	0.54	0.65	0.74	0.84
4	0.75	0.78	0.82	0.85	0.89	0.94	1.00	1.08	1.15
6	1.31	1.34	1.38	1.42	1.46	1.50	1.54	1.61	1.67
8	1.92	1.96	2.01	2.06	2.11	2.16	2.21	2.27	2.33
10	2.57	2.63	2.69	2.75	2.81	2.87	2.94	3.01	3.08

Table 3 - Whole house air change rate for tight Miami ranch house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.10	0.07	0.00	0.07	0.11	0.14	0.17	0.20	0.23
2	0.11	0.09	0.08	0.10	0.14	0.17	0.20	0.23	0.26
4	0.18	0.18	0.19	0.21	0.22	0.24	0.26	0.28	0.31
6	0.30	0.31	0.32	0.33	0.34	0.36	0.38	0.39	0.42
8	0.44	0.46	0.47	0.48	0.49	0.51	0.53	0.54	0.57
10	0.60	0.61	0.63	0.64	0.65	0.67	0.69	0.71	0.73

Table 4 - Whole house air change rate for typical Minneapolis ranch house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.25	0.16	0.00	0.16	0.26	0.34	0.42	0.49	0.56
2	0.29	0.23	0.18	0.23	0.31	0.39	0.46	0.53	0.59
4	0.45	0.41	0.44	0.47	0.50	0.54	0.59	0.64	0.69
6	0.69	0.72	0.75	0.78	0.81	0.83	0.87	0.91	0.95
8	1.03	1.06	1.09	1.12	1.16	1.19	1.22	1.26	1.29
10	1.39	1.43	1.46	1.50	1.54	1.57	1.62	1.66	1.70

Table 5 - Whole house air change rate for tight Minneapolis ranch house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.09	0.06	0.00	0.06	0.10	0.13	0.16	0.19	0.21
2	0.09	0.07	0.04	0.07	0.11	0.14	0.17	0.20	0.22
4	0.13	0.10	0.11	0.12	0.14	0.16	0.19	0.21	0.24
6	0.17	0.18	0.19	0.19	0.21	0.22	0.23	0.25	0.27
8	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.33	0.34
10	0.34	0.35	0.36	0.37	0.38	0.39	0.41	0.42	0.44

Table 6 - Whole house air change rate for typical Miami 2 story house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.38	0.24	0.00	0.25	0.40	0.53	0.64	0.76	0.87
2	0.44	0.34	0.36	0.42	0.51	0.62	0.72	0.81	0.91
4	0.82	0.86	0.89	0.93	0.96	1.02	1.08	1.15	1.21
6	1.43	1.47	1.51	1.55	1.60	1.64	1.68	1.74	1.80
8	2.10	2.15	2.20	2.25	2.30	2.36	2.41	2.47	2.53
10	2.82	2.88	2.94	3.01	3.07	3.14	3.21	3.28	3.35

Table 7 - Whole house air change rate for tight Miami 2 story house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.13	0.08	0.00	0.09	0.14	0.18	0.22	0.26	0.30
2	0.14	0.10	0.09	0.12	0.16	0.21	0.25	0.28	0.32
4	0.20	0.22	0.23	0.24	0.26	0.28	0.30	0.34	0.38
6	0.36	0.37	0.38	0.40	0.41	0.43	0.44	0.47	0.49
8	0.53	0.54	0.56	0.57	0.59	0.60	0.62	0.64	0.66
10	0.71	0.73	0.75	0.76	0.78	0.80	0.82	0.84	0.86

Table 8 - Whole house air change rate for typical Minneapolis 2 story house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.25	0.15	0.00	0.17	0.27	0.35	0.43	0.50	0.58
2	0.30	0.24	0.25	0.28	0.34	0.42	0.48	0.54	0.61
4	0.57	0.60	0.62	0.64	0.66	0.70	0.74	0.78	0.83
6	0.99	1.02	1.05	1.08	1.10	1.13	1.16	1.20	1.24
8	1.46	1.49	1.52	1.56	1.60	1.63	1.67	1.71	1.75
10	1.95	2.00	2.04	2.08	2.12	2.17	2.22	2.27	2.32

Table 9 - Whole house air change rate for tight Minneapolis 2 story house (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.09	0.06	0.00	0.06	0.09	0.12	0.15	0.18	0.20
2	0.10	0.07	0.06	0.08	0.11	0.14	0.17	0.19	0.21
4	0.14	0.15	0.16	0.17	0.18	0.19	0.21	0.23	0.26
6	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.33	0.34
8	0.37	0.38	0.39	0.40	0.41	0.42	0.44	0.45	0.47
10	0.50	0.51	0.53	0.54	0.55	0.56	0.58	0.59	0.61

Tables 10 through 17 present the results of the simulations with the HVAC system on. Operation of the HVAC system increased the building air change rate as much as 0.31 ach at zero wind speed and temperature difference due to supply duct leakage in the attic. The effect of the system fan was less than 0.07 ach at high wind speeds (> 4 m/s) and temperature differences (> 10°C).

Table 10 - Whole house air change rate for typical Miami ranch house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.45	0.38	0.31	0.39	0.52	0.63	0.73	0.83	0.93
2	0.59	0.52	0.41	0.50	0.63	0.74	0.84	0.93	1.03
4	0.86	0.81	0.85	0.89	0.95	1.02	1.10	1.17	1.24
6	1.34	1.37	1.41	1.45	1.49	1.55	1.61	1.67	1.73
8	1.95	1.99	2.04	2.09	2.14	2.19	2.25	2.30	2.38
10	2.60	2.66	2.72	2.78	2.84	2.91	2.97	3.04	3.11

Table 11 - Whole house air change rate for tight Miami ranch house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.29	0.29	0.30	0.30	0.30	0.31	0.31	0.33	0.37
2	0.30	0.30	0.30	0.30	0.30	0.31	0.32	0.36	0.39
4	0.37	0.36	0.34	0.33	0.31	0.32	0.36	0.41	0.44
6	0.46	0.45	0.44	0.43	0.41	0.40	0.42	0.46	0.49
8	0.56	0.55	0.53	0.52	0.53	0.55	0.57	0.58	0.61
10	0.65	0.64	0.64	0.66	0.69	0.71	0.73	0.75	0.77

Table 12 - Whole house air change rate for typical Minneapolis ranch house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.24	0.16	0.00	0.15	0.25	0.33	0.41	0.48	0.55
2	0.28	0.22	0.18	0.22	0.30	0.38	0.45	0.52	0.58
4	0.44	0.41	0.44	0.47	0.50	0.53	0.59	0.64	0.68
6	0.69	0.72	0.75	0.78	0.80	0.83	0.87	0.91	0.94
8	1.03	1.06	1.09	1.12	1.16	1.19	1.22	1.26	1.29
10	1.39	1.42	1.46	1.50	1.53	1.57	1.61	1.65	1.70

Table 13 - Whole house air change rate for tight Minneapolis ranch house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.09	0.05	0.00	0.05	0.09	0.12	0.15	0.18	0.21
2	0.08	0.06	0.04	0.06	0.10	0.13	0.16	0.19	0.21
4	0.12	0.10	0.11	0.12	0.13	0.15	0.18	0.21	0.23
6	0.17	0.18	0.18	0.19	0.20	0.22	0.23	0.25	0.26
8	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.34
10	0.34	0.35	0.36	0.37	0.38	0.39	0.40	0.42	0.43

Table 14 - Whole house air change rate for typical Miami 2 story house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.38	0.24	0.00	0.25	0.40	0.53	0.64	0.76	0.87
2	0.44	0.34	0.36	0.42	0.51	0.62	0.72	0.81	0.91
4	0.82	0.86	0.89	0.93	0.96	1.02	1.08	1.15	1.21
6	1.43	1.47	1.52	1.56	1.60	1.64	1.68	1.74	1.80
8	2.10	2.15	2.20	2.25	2.31	2.36	2.41	2.47	2.53
10	2.82	2.88	2.94	3.00	3.07	3.14	3.21	3.28	3.35

Table 15 - Whole house air change rate for tight Miami 2 story house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.13	0.08	0.00	0.09	0.14	0.18	0.22	0.26	0.30
2	0.14	0.10	0.09	0.12	0.16	0.21	0.25	0.28	0.32
4	0.20	0.22	0.23	0.24	0.26	0.27	0.30	0.34	0.38
6	0.36	0.37	0.38	0.39	0.41	0.43	0.44	0.47	0.49
8	0.53	0.54	0.56	0.57	0.59	0.60	0.62	0.64	0.66
10	0.71	0.73	0.75	0.76	0.78	0.80	0.82	0.84	0.87

Table 16 - Whole house air change rate for typical Minneapolis 2 story house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.25	0.16	0.01	0.17	0.27	0.35	0.43	0.51	0.58
2	0.31	0.24	0.25	0.29	0.35	0.42	0.48	0.55	0.61
4	0.57	0.60	0.62	0.64	0.66	0.70	0.74	0.79	0.83
6	0.99	1.02	1.05	1.08	1.11	1.13	1.16	1.20	1.24
8	1.46	1.49	1.53	1.56	1.60	1.63	1.67	1.71	1.75
10	1.95	2.00	2.04	2.08	2.13	2.17	2.22	2.27	2.32

Table 17 - Whole house air change rate for tight Minneapolis 2 story house with system on (ach)

Tin - Tout (K)	-10	-5	0	5	10	15	20	25	30
Wind speed (m/s)									
0	0.09	0.06	0.00	0.06	0.09	0.12	0.15	0.18	0.20
2	0.10	0.07	0.06	0.08	0.11	0.14	0.17	0.19	0.21
4	0.15	0.15	0.16	0.17	0.18	0.19	0.21	0.23	0.26
6	0.26	0.26	0.27	0.28	0.29	0.30	0.31	0.33	0.34
8	0.38	0.38	0.39	0.40	0.41	0.42	0.44	0.45	0.47
10	0.50	0.51	0.53	0.54	0.55	0.56	0.58	0.59	0.61

Appendix C Indoor Air Quality Controls

This appendix describes the indoor air quality control technologies that were evaluated in the study. These technologies were incorporated into the baseline house models to determine their effectiveness in controlling the selected pollutant sources. The three technologies described in this section include the following:

Electrostatic particulate filtration

Heat recovery ventilation

Outdoor air intake damper on the forced-air system return

This appendix describes each of these technologies and includes revisions of the baseline house duct drawings. In addition, this appendix contains an estimate of the equipment and installation costs and a revision of the thermal load calculations based on the modifications. However, the procedure used does not adequately account for the temporal variations in ventilation rates, the multizone characteristics of the airflows, and the interactions between mechanical ventilation and infiltration that are predicted by CONTAM93. Therefore, these thermal load calculation methods only give an indication of the energy impacts of the IAQ control technologies. Adequately accounting for these energy impacts would require the use of a building thermal modelling program such as TRNSYS (Klein 1992) or DOE-2 (Curtis et al. 1984).

Finally, the impacts of each of these technologies on "other contaminants" are discussed. These other contaminants, as described in the original project work statement, include contaminants that have typically been of concern to designers of residential ventilation systems including cooking odors, tobacco smoke, moisture, outdoor pollen, outdoor odors, and ozone.

Electrostatic Particulate Filtration

The first IAQ control technology is increased particulate filtration through the installation of passive, electrostatic particulate filters. These filters were chosen based on the availability of performance data. In addition, the low pressure drop through these filters enables their installation without modification of the existing forced-air distribution system. The baseline houses are assumed to have standard furnace filters with an ASHRAE dust spot efficiency of less than 20% and an arrestance of 90%. These values are based on tests conducted in accordance with ASHRAE Standard 52.1 (ASHRAE 1992). The increased filtration is based on the use of electrostatic filters with an ASHRAE dust spot efficiency of 30% and an arrestance of 95%.

Although the efficiencies of particulate filters change over time as they become loaded, the computer simulations in this project will employ a constant filter efficiency. The efficiencies of the baseline and improved filters used in the simulations will be as follows:

	Baseline	Control #1
Particles <2.5 µm in diameter	5%	30%
Particles between 2.5 and 10 µm in diameter	90%	95%

The improved filters are installed in place of the regular furnace filters. Their location is indicated in the revised duct drawings (at the end of this appendix) showing all of the IAQ control technologies.
The installation of the improved filters are assumed not to affect the thermal loads of the houses. Due to a higher pressure drop through the filters, they may cause a slight reduction in the airflow rate through the system, which could affect the pressures across the building envelope and the resultant building infiltration rates. However, this effect is expected to be small, and the thermal load calculations were not modified for this control technology.

The cost of this first control technology includes the cost of the filters themselves and their installation. For comparison, the furnace filters in the baseline houses are assumed to cost $2 each and to be changed every month. Therefore, the annual cost of the baseline filters is $24. The improved filters are assumed to cost $15 each and to be changed every 2 months. Therefore, the annual cost of the improved filters is $90.

The installation of improved filters will reduce the concentrations of the so-called "other contaminants" in the houses to the degree that the filtration of each contaminant is increased. The concentrations of particulate contaminants with outdoor sources (pollen) will be reduced due to the increased particulate filtration. The concentrations of VOCs associated with outdoor odors will not be decreased. The increased filtration will not affect indoor ozone levels due to outdoor sources, since ozone removal rates will be unaffected by the new filters. In addition, these electrostatic filters are not sources of ozone themselves. The concentrations of other contaminants with indoor sources will also be affected to the degree that the filtration of each contaminant is increased. The levels of cooking odors and tobacco smoke will be decreased based on the increased filter efficiency for both fine and coarse particulates. Indoor moisture levels will be unaffected by the new filters because the outdoor air change rates will not be affected and because the improved filters have no humidification or dehumidification impacts.

Electronic air cleaners are also of interest and may be investigated in follow-up work. The existence of reliable performance data is being investigated.

Heat Recovery Ventilator

The second IAQ control technology is the installation of a heat recovery ventilator (HRV) in conjunction with the forced-air distribution system. As seen in the drawing, the device brings outdoor air into the building where it exchanges heat with an airstream leaving the return side of the forced air system. Under heating conditions, the outdoor air is warmed by the outgoing airstream, and under cooling the outdoor air is cooled. The outgoing airstream is exhausted to the outdoors after leaving the heat recovery ventilator. The airstream from outdoors flows into the return side of the forced-air system after leaving the HRV.

The HRV specifications are based on a commercially-available model designed for residential use and installation in conjunction with forced-air systems. The airflow rate capacity of the device was selected to obtain an air change rate of at least 0.5 air changes per hour (ach) at full flow. The actual outdoor airflow rate during operation was selected to provide 0.35 ach through the HRV. The actual whole building air change rate will also include envelope infiltration, which in turn depends on the airtightness of the house, weather conditions and ventilation equipment operation. The HRV specifications for the four houses are as follows:

Miami, 2-story
Airflow capacity: 30 to 60 L/s (65 to 127 cfm), roughly 0.25 to 0.5 ach
Airflow rate during operation: 44 L/s (93 cfm)
Efficiency: 69% at 0 °C (32 °F), 60% at -25 °C (-13 °F)
Maximum power consumption: 115 W
No defrost

Miami, Ranch
Airflow capacity: 30 to 60 L/s (65 to 127 cfm), roughly 0.4 to 0.8 ach
Airflow rate during operation: 26 L/s (55 cfm)
Efficiency: 69% at 0 °C (32 °F), 60% at -25 °C (-13 °F)
Maximum power consumption: 115 W
No defrost

Minneapolis, 2-story
Airflow capacity: 55 to 95 L/s (115 to 200 cfm), roughly 0.3 to 0.5 ach
Airflow rate during operation: 66 L/s (140 cfm)
Efficiency: 68% at 0 °C (32 °F), 61% at -25 °C (-13 °F)
Maximum power consumption: 216 W
Defrost cycle

Minneapolis, Ranch
Airflow capacity: 30 to 70 L/s (65 to 150 cfm), roughly 0.2 to 0.5 ach
Airflow rate during operation: 52 L/s (110 cfm)
Efficiency: 76% at 0 °C (32 °F), 56% at -25 °C (-13 °F)
Maximum power consumption: 105 W
Defrost cycle

The defrost cycle involves closing the outdoor air dampers for 5 minutes when the outdoor temperature is below -5 °C (23 °F). For outdoor temperatures between -5 and -30 °C (23 and -22 °F), each 5-minute defrost cycle is followed by a 35 minute period of air exchange before the next defrost cycle. For outdoor temperatures below -30 °C (-22 °F), each 5-minute defrost cycle is followed by 20 minutes of air exchange.

The HRV can be operated in several different control modes. The operation of the device and the fan speed (high or low) can be controlled by a timer, manually by the occupant or by a humidistat.

The installation of the HRV in each of the four houses is indicated in the revised duct drawings at the end of this appendix.

The thermal loads of the houses are affected by the installation and operation of the HRV due to the increased outdoor air change rate of the house when the devices are in operation. The air change rate due to the HRV operation is assumed to be additive to the baseline infiltration rate of 0.75 ach assumed for the design thermal load calculations. The thermal loads are increased by only a fraction of the increased outdoor air change rate based on the heat exchange efficiencies of the devices. For an additional air change rate of 0.35 ach and the rated heat exchange efficiencies of the HRVs, the revised design thermal loads for the four houses are given below.

Miami, 2-story	Baseline	With HRV
Heating	2.87 kW	3.14 kW
Cooling	6.43 kW	6.60 kW

Miami, Ranch	Baseline	With HRV
Heating	1.83 kW	1.99 kW
Cooling	5.76 kW	5.88 kW

Minneapolis, 2-story	Baseline	With HRV
Heating	12.64 kW	13.59 kW
Cooling	6.21 kW	6.36 kW

Minneapolis, Ranch	Baseline	With HRV
Heating	9.25 kW	9.86 kW
Cooling	4.89 kW	4.97 kW

The cost of the HRVs includes the cost of the equipment and installation, the operating costs for the fans in the devices and the increased energy consumption due to the additional outdoor air change of the building. The cost of the equipment is $500 for both of the Miami houses, $600 for the Minneapolis ranch house and $700 for the Minneapolis two-story house. These are list prices from the manufacturer of the HRV on which the specifications are based. The installation costs are more variable, based on the layout of the house and local labor rates, and they can range from $200 to $500. The cost of the energy consumed by the device and by the additional outdoor air change rate requires detailed thermal modeling of the building and system. Such modeling is beyond the scope of this project.

The installation of the HRV will impact the so-called “other contaminants” in the houses due to the increased outdoor air change rate. Due to the additional outdoor airflow into the houses, the concentrations of contaminants with outdoor sources (pollen, outdoor odors and ozone) will increase. For a simple, nonreactive and unfiltered contaminant, there will be an increased contaminant load equal to the outdoor concentration multiplied by the outdoor airflow rate. The impact of particulates will be reduced based on the efficiency of the filters in the HRV and of the furnace filter. The impact of outdoor ozone will be reduced somewhat by losses on the interior surfaces of the HRV ductwork. The concentrations of other contaminants with indoor sources (cooking odors and tobacco smoke) will be reduced based on the increased air change rate of the building. The impact of the additional ventilation on moisture will depend on the building location, indoor moisture sources, and season. Indoor humidity levels will be reduced when there are large indoor sources and low relative humidity outdoors, but will be increased when the outdoor humidity is higher than the indoor level. Detailed modeling of moisture transport is required to assess these impacts and is beyond the scope of the current project.

Outdoor Intake Duct

The third IAQ control technology is the installation of an outdoor air intake duct on the return side of the forced air distribution system. As seen in the drawing, the system consists of an intake, a duct, a motorized damper, and a volume damper for adjusting the airflow rate, and is connected to the return side of the return duct. The maximum airflow rate capacity of the intake is 78 L/s (165 cfm), which corresponds to the following air change rates for the four houses:

Miami, 2-story: 0.62 ach
Miami, Ranch: 1.05 ach
Minneapolis, 2-story: 0.41 ach
Minneapolis, Ranch: 0.53 ach

The actual airflow rate through the intake depends on the position of the volume damper, the overall airflow resistance of the intake system, and the pressure developed by the forced-air fan. In the computer simulations, it is assumed that the volume damper is adjusted such that the intake system provides 0.35 ach to the building when the furnace fan is in operation. This air change rate corresponds to the following outdoor air intake rates for the four buildings:

Miami, 2-story: 44 L/s (93 cfm)
Miami, Ranch: 26 L/s (55 cfm)
Minneapolis, 2-story: 66 L/s (140 cfm)
Minneapolis, Ranch: 52 L/s (110 cfm)

The motorized damper can be controlled in several different ways. It is generally interlocked with the forced-air system fan so that it opens only when the forced-air fan is operating. The motorized damper can also be controlled to open based on a timer, humidistat or pollutant (e.g. carbon monoxide or carbon dioxide) sensor.

The installation of the outdoor air intake duct in each of the four houses is indicated in the revised duct drawings at the end of the appendix.

The thermal loads of the houses are affected by the installation and operation of the outdoor air intake duct due to the increased outdoor air change rate of the house when the devices are in operation. The air change rate due to the HRV operation is assumed to be additive to the baseline infiltration rate of 0.75 ach assumed for the design thermal load calculations. Based on an additional air change rate of 0.35 ach and no heat exchange, the design thermal loads for the four houses are given below.

Miami, 2-story	Baseline	With OAID
Heating	2.87 kW	3.54 kW
Cooling	6.43 kW	6.96 kW
Miami, Ranch	Baseline	With OAID
Heating	1.83 kW	2.23 kW
Cooling	5.76 kW	6.09 kW
Minneapolis, 2-story	Baseline	With OAID
Heating	12.64 kW	15.00 kW
Cooling	6.21 kW	6.71 kW
Minneapolis, Ranch	Baseline	With OAID
Heating	9.25 kW	10.73 kW
Cooling	4.89 kW	5.18 kW

The cost of the outdoor air intake duct includes the cost of the equipment and installation and the increased energy consumption due to the additional outdoor air change of the building. The cost of the equipment, including the controls and the motorized dampers, is $750 based on list prices from the manufacturer of the outdoor air intake duct on which the specifications are based. The installation costs are more variable, based on the layout of the house and local labor rates, and they can range from $100 to $300. The cost of the energy consumed by the device and by the additional outdoor air change rate requires detailed thermal modeling of the building and system. Such modeling is beyond the scope of this project.

The installation of the outdoor air intake duct will impact the so-called "other contaminants" in the houses. Due to the additional outdoor airflow into the houses, the concentrations of contaminants with outdoor sources (pollen, outdoor odors and ozone) will increase. For a simple, nonreactive and unfiltered contaminant, the impact will be an increased contaminant load equal to the outdoor concentration multiplied by the outdoor airflow rate. The impact of particulates will be lessened based on the removal efficiency of the furnace filter. The impact of ozone will be lessened by losses on the interior surfaces of the ductwork. The concentrations of other contaminants with indoor sources (cooking odors and tobacco smoke) will be reduced based on the increased air change rate of the building. As in the case of the HRV, the impact of the additional ventilation on moisture will depend on the building location, indoor moisture sources, and season.

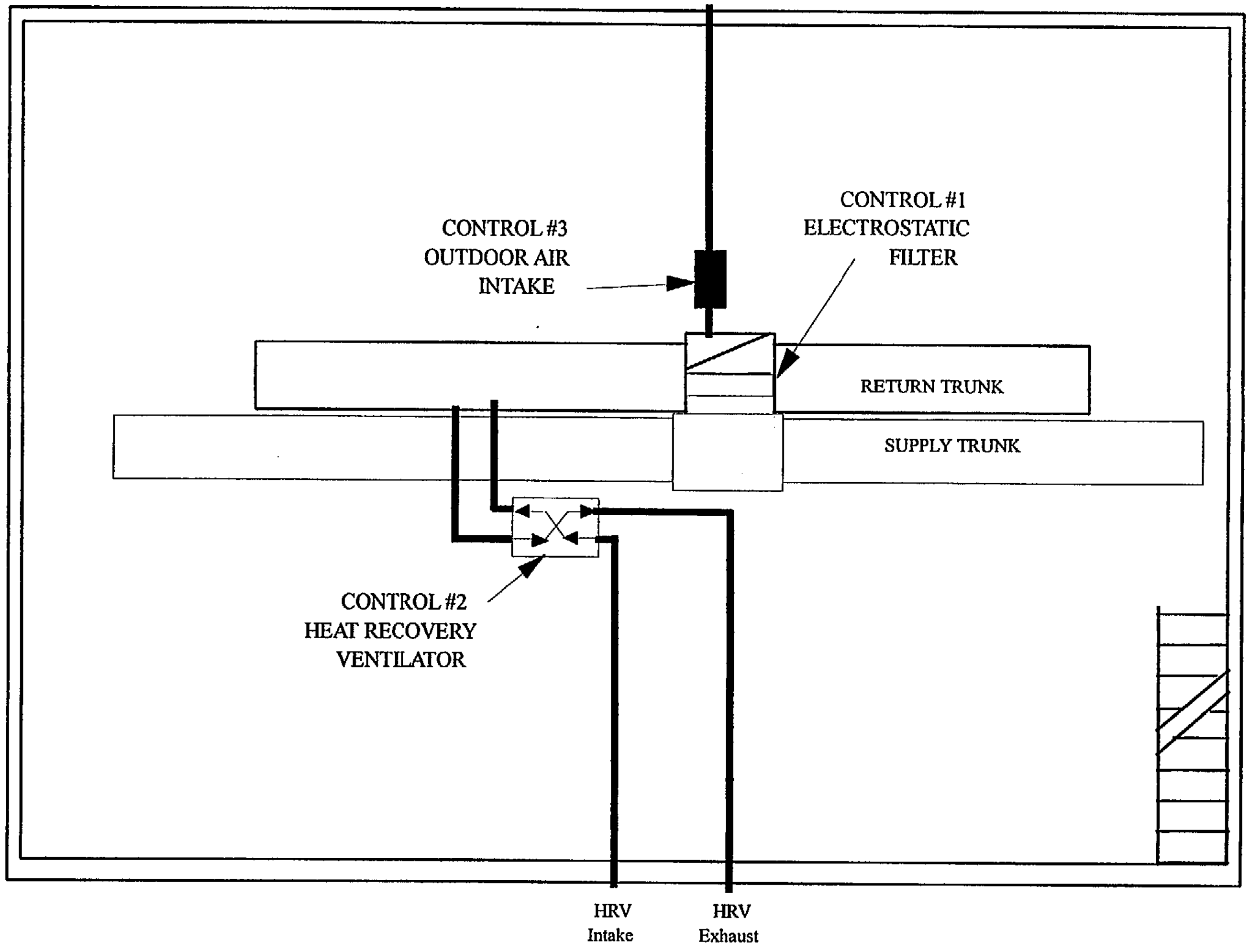


Figure 13 - IAQ Controls for Minneapolis Ranch House

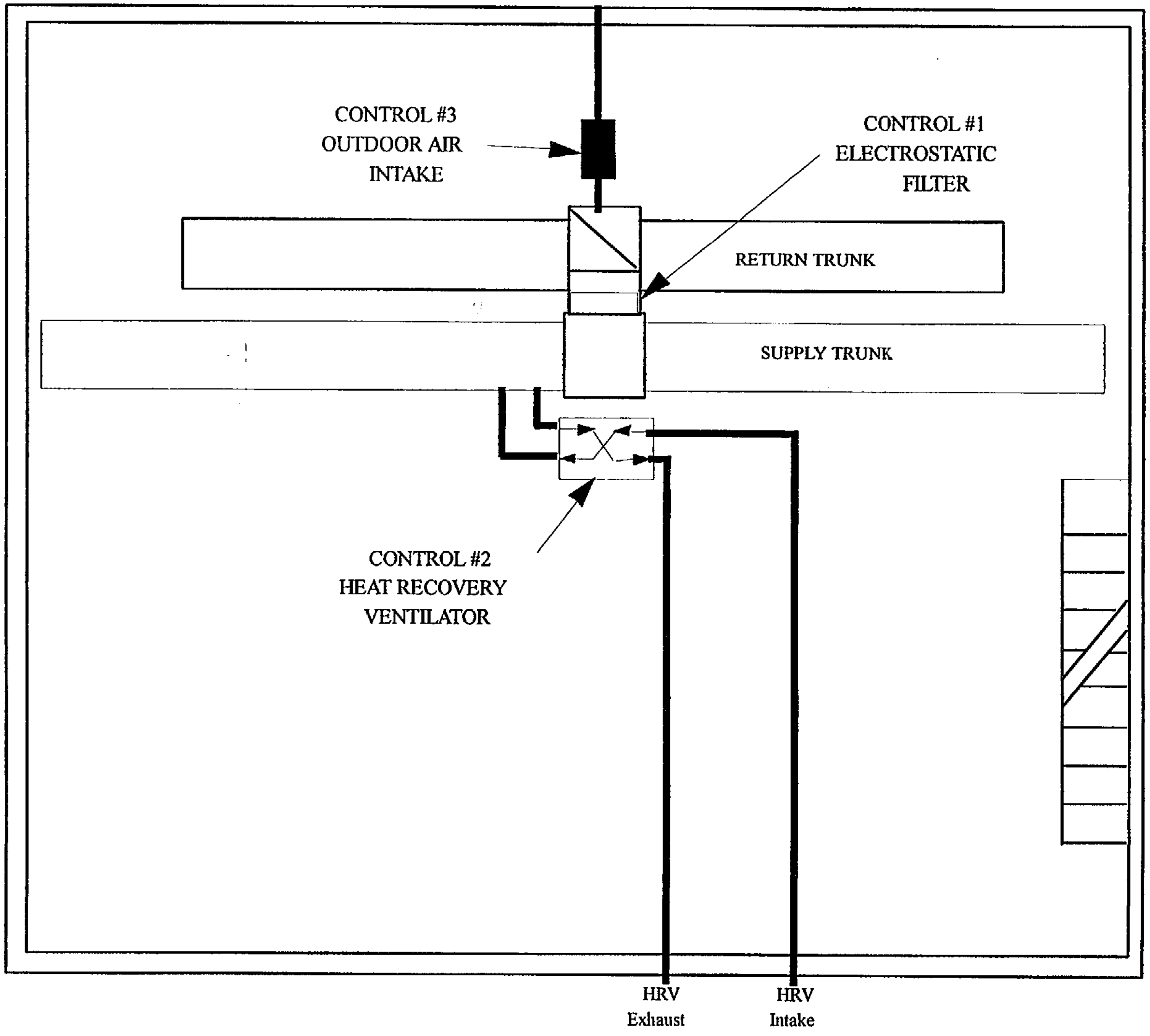


Figure 14 - IAQ Controls for Minneapolis 2-Story House

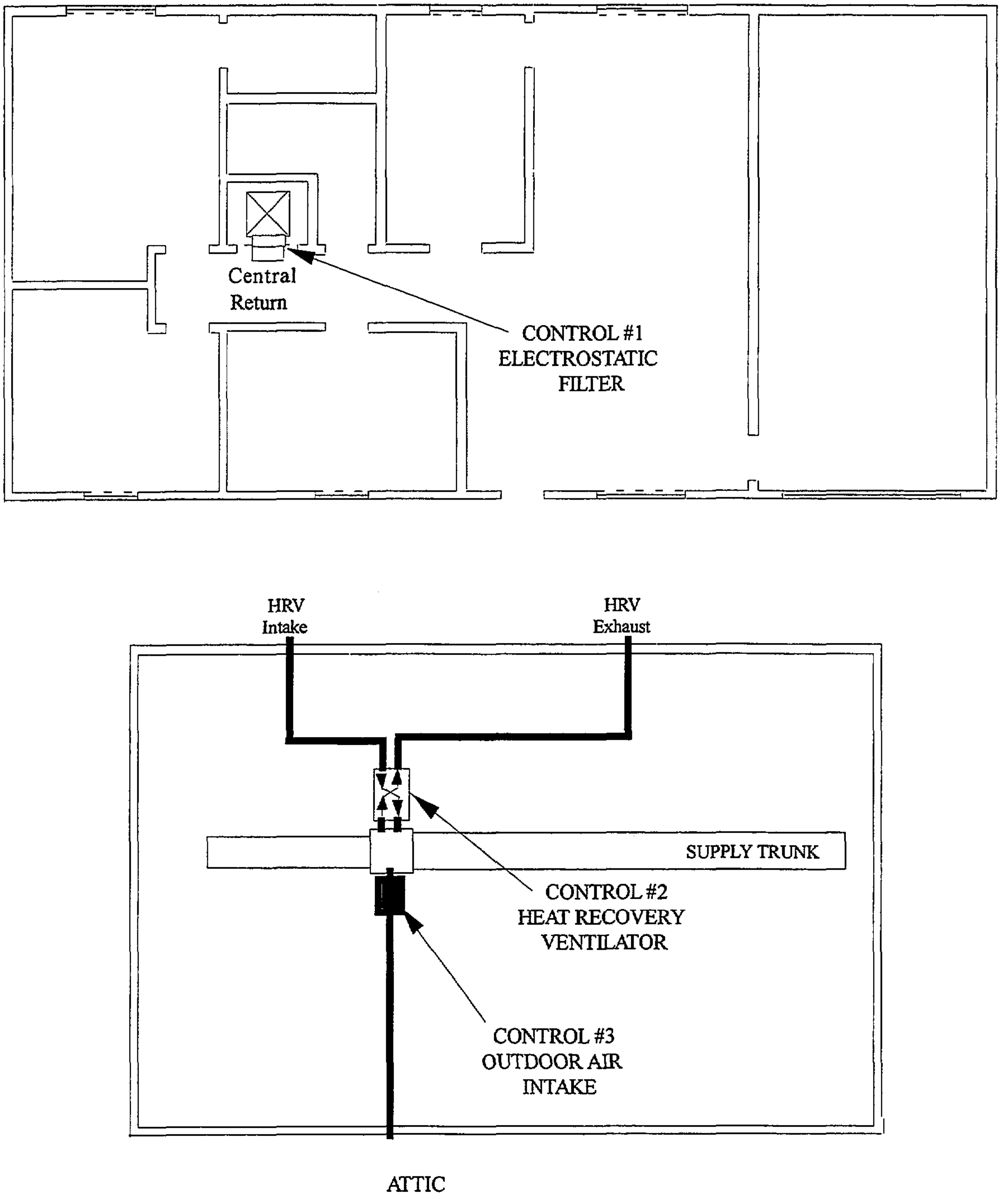


Figure 15 - IAQ Controls for Miami Ranch House

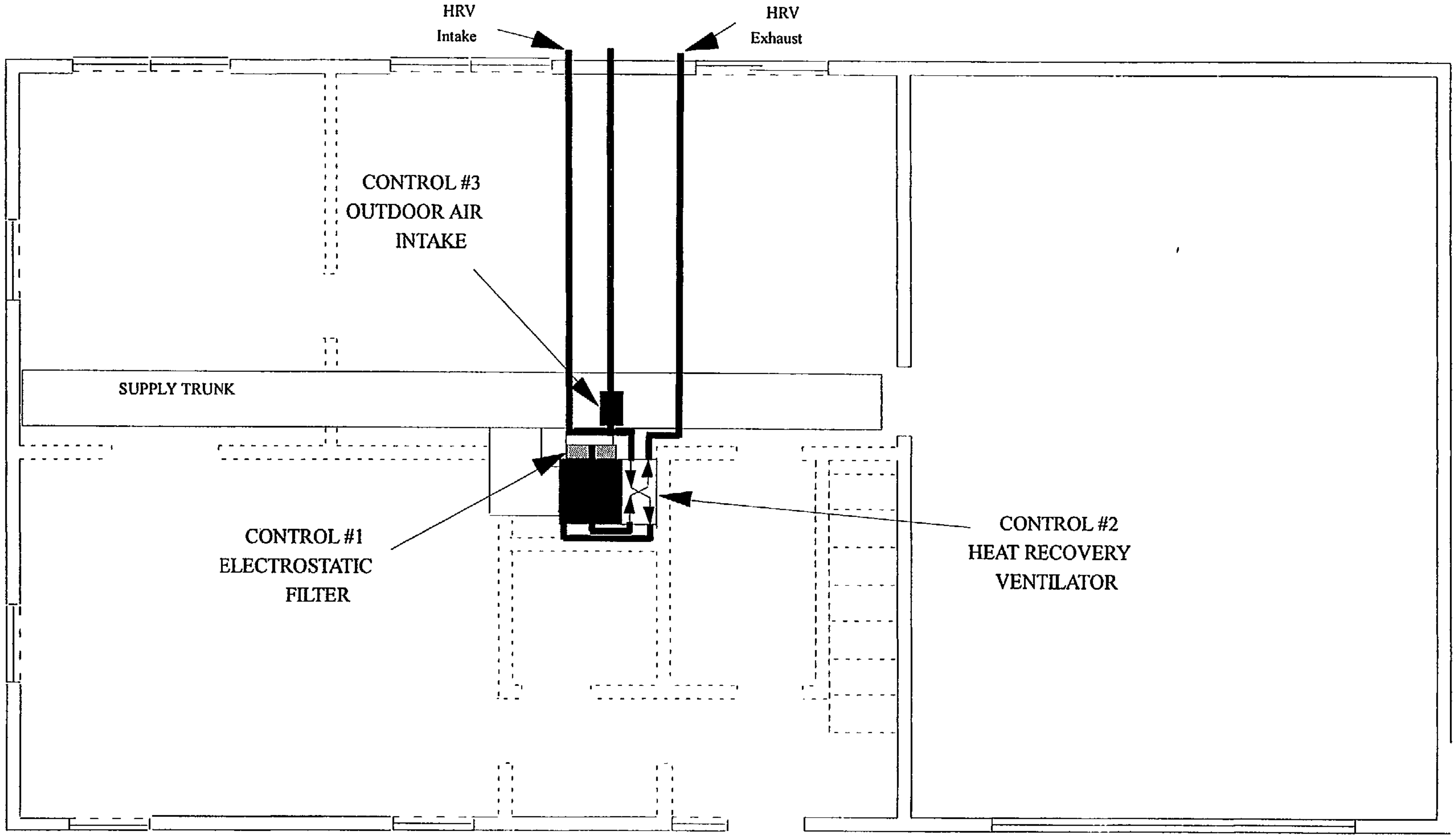


Figure 16 - IAQ controls for Miami 2-Story House

Appendix D Simulation Results

This appendix summarizes the results of the simulations. Tables 1a through 24e of Appendix D summarize the results of all 24 baseline simulations. Tables 25a through 27e summarize the results of the 3 preliminary simulations of the IAQ control retrofits. Tables 1a through 27a show the overall peak concentrations (excluding the basement, attic, garage and closet zones), the location of that overall peak, and the whole house 24-hour average concentrations (excluding the basement, garage, and attic zones). Tables 1b through 27b show the individual zone peak concentrations for the main living space zones. Tables 1c through 27c show the individual zone 24-hour average concentrations. Tables 1d through 27d show the individual zone 4-hour average concentrations. The 4-hour average was calculated for the VOC burst sources from 7 p.m. to 11 p.m., for the oven from 6 p.m. to 10 p.m., and for the heater from 7 am to 11 am. No 4-hour average was calculated for either the floor VOC source or the outdoor air pollutants. Tables 1e through 27e show the individual zone 1-hour average CO concentrations. The 1-hour average was calculated for the oven from 7 p.m. to 8 p.m. and for the heater from 9 am to 10 am.

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

SIMULATION	VOC1 µg/m^3	VOC2 µg/m^3	VOC3 µg/m^3	VOC4 µg/m^3	VOC5 µg/m^3	VOC6 µg/m^3	VOC7 µg/m^3	VOC8 µg/m^3	VOC9 µg/m^3
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 $\mu g/m^3$	Heater - CO ppm	Heater - NO_2 ppb	Heater - Particles $\mu g/m^3$	Outdoor - CO ppm	Outdoor - NO_2 ppb	Outdoor - Particles $\mu g/m^3$
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.