NISTIR 5346

Indoor Air Quality Impacts of Residential HVAC Systems Phase I Report: Computer Simulation Plan

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Technology Administration
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February 1994
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U. S. Department of Commerce
Ronald H. Brown, *Secretary*
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati Prabhakar, *Director*

Prepared for:
U.S. Consumer Product Safety Commission
Directorate for Engineering Sciences
Division of Mechanical Engineering
Washington, DC 20207

ABSTRACT

NIST has completed the first phase of a project to study the impact of HVAC systems on residential indoor air quality and to assess the potential for using residential forced-air systems to control indoor pollutant levels. This project will use computer simulations to assess the ability of modifications to central forced-air heating and cooling systems to control the concentrations of selected pollutants in single-family residential buildings. The first phase consisted of three major efforts: conducting a literature review, developing a plan for computer analysis, and holding an expert workshop to discuss the plan. The second phase of the project will involve performing the computer simulations and analyzing the results. This report details the results of the Phase I efforts.

The objective of the literature review was to obtain information for planning computer simulations that will be performed in Phase II of the project. Specific subjects reviewed include indoor air quality simulation tools, previous studies of the impacts of residential HVAC systems on indoor air quality, residential pollutant sources, and indoor air quality control technologies associated with residential HVAC systems. The development of the plan for the computer simulations included the following items: selection of appropriate computer simulation techniques, definition of buildings to be analyzed in the simulations (including building and HVAC system designs and building locations), specification of pollutant source profiles, and selection of HVAC technologies for indoor air quality control. After the initial plan was developed, an expert workshop was held at NIST to discuss the proposed project plan and obtain feedback on its technical merit and relevance to residential indoor air quality issues. The overall reaction to the project objective and approach was positive and most of the workshop discussion focused on the details of the plan or on potential follow-up work. The workshop discussions were considered in developing the final plan as presented in this report.

KEY WORDS: airflow modeling, HVAC system, indoor air quality, computer simulation, residential buildings, ventilation, building technology

ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Consumer Product Safety Commission under Interagency Agreement No. CPSC-IAG-93-1124. The authors wish to acknowledge the efforts of Roy Deppa, Lori Saltzman, and Bill West of CPSC in support of this project. The participation of the expert workshop attendees (listed in Appendix A) was appreciated. The authors also express appreciation to Bill Freeborne of HUD for his effort in reviewing this report.

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INTRODUCTION

The National Institute of Standards and Technology (NIST) is conducting a study for the U.S. Consumer Product Safety Commission (CPSC) to assess the potential effectiveness of existing heating, ventilating, and air conditioning (HVAC) technology to reduce the levels of selected pollutants in single-family residential buildings. In this effort, NIST will perform whole building airflow and contaminant dispersal computer simulations to assess the ability of modifications of central forced-air heating and cooling systems to control pollutant sources relevant to the residential environment. This report summarizes the results of the first phase of this effort. Phase I consisted of three major efforts including: conducting a literature review, developing a detailed plan for the simulations, and hosting an expert workshop to discuss the project .

Background

Despite the increasing interest in residential indoor air quality (IAQ) problems, only limited research has been conducted which integrates the analysis of pollutant sources, residential HVAC system operation and building characteristics. These interactions between HVAC systems and building characteristics are important as they relate to both causes of residential indoor air quality problems and their solution. In particular, central forced-air heating and cooling systems may provide solutions to some problems based on the fact that large quantities of indoor air (on the order of 5 air changes per hour) circulate through these systems. Therefore, these systems offer the potential for treating the indoor air and then employing the associated system of ductwork to distribute this air throughout the building. In addition, this ductwork can be used to distribute outdoor air throughout the building, with outdoor air brought into the building by the forced-air system or an associated subsystem.

The impact of an indoor air quality control system on residential pollutant levels depends on the building characteristics, the design and performance of the IAQ control devices, the characteristics of the pollutants to be removed by the devices, the pollutant sources, the existence of any pollutant sinks within the building, and the ambient conditions of weather and outdoor pollutant concentration. A great deal of study, including computer simulation, laboratory testing and field testing, is required to determine which devices will be most beneficial and under what circumstances. Most of the research to date has employed simplified approaches to studying the the building and its systems. Experimental studies have often focussed on the performance of individual pieces of equipment without considering the interactions with the building, the HVAC system, and the ambient conditions. Computer simulation studies have often considered the building to be a single well-mixed zone, ignoring the multi-zone nature of the airflows involved. Both the computer simulation studies and the experimental work have not always considered the wide variety of pollutant sources that exist in the residential environment.

Technical Approach

In this project, NIST will use computer simulations to conduct a preliminary assessment of the potential for using forced-air heating and cooling systems to improve residential indoor air quality. Specifically, NIST will perform 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 will involve 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 will be located in selected zones and the air and pollutant mass balance equations will be solved to determine the pollutant concentrations in each zone. Simulations will be 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 will be compared to the baseline concentrations to evaluate the potential effectiveness of the control technologies.

The objective of the project is to conduct a preliminary assessment, using computer simulation, of the potential for using forced-air HVAC systems to improve residential IAQ. The preliminary nature of the project and the available resources limit the scope of the project in terms of the number of simulations and the detail of the simulations. The project is essentially a scoping study to determine the potential for forced-air systems and modifications of these systems to control indoor air quality. The project is not intended to conclusively determine the effectiveness of these controls under all circumstances.

Some key questions the study will answer include the following:

> Do the selected commercially-available modifications of forced-air systems have potential for reducing indoor pollutant levels from these specific sources?
>
> Which of these approaches merit more detailed study?
>
> How might these modifications impact other aspects of building performance such as thermal comfort, energy use, and indoor humidity levels?

Some questions the study will not answer include the following:

> Will these modifications control pollutants for all building and HVAC system configurations and indoor pollutant sources?
>
> Should these modifications be used today?
>
> How do these approaches using forced-air systems approaches compare to other residential ventilation systems?
>
> What are the specific thermal comfort, energy use, and humidity level impacts of these modifications?

These efforts are preliminary in that they will not determine definitively whether these modifications are reliable and cost effective. Rather, the analysis will provide insight as to whether the options investigated have the potential for mitigating residential indoor air quality problems and which pollutant sources they are most likely to impact. An important goal of the project is to identify key issues for further analysis and experimental work to meet the overall goal of cost-effective IAQ control in residential buildings.

Contents of Report

This report consists of four main sections titled: Literature Review, Considerations in Development of Simulation Plan, Expert Workshop, and Simulation Plan. 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 next section describes the factors considered in forming the detailed plan for the simulations to be performed in Phase II of this effort. This includes both the specific factors that could be included and varied in the simulations including, building and HVAC system characteristics, weather conditions, pollutant sources, and IAQ control technologies. This section also discusses other important related residential HVAC and IAQ issues that are not within the scope of the current efforts. The third section summarizes the discussions from the expert workshop held to discuss this project and the proposed simulation plan. The fourth section presents the final simulation plan which reflects consideration of the workshop feedback. A short discussion section presents and discusses several issues identified in Phase I for additional research.

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 to be performed in Phase II of the project. 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.

Pollutant Source Strengths

This section discusses available information on the pollutants of interest as defined in the project work statement (1) and pollutant sources relevant to HVAC system impacts on indoor air quality. These pollutants of interest were selected based on their having recently gained scientific concern. The pollutants of interest listed in the project work statement are 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 Ref. 2.

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. Ref. 3 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 in Refs. 4-10.

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 0.126 mg/hr to as high as 30 mg/hr. Ref. 3 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. Refs. 40 and 41 report the results of some flue gas spillage tests. However, available research results do not provide quantitative source strengths associated with spillage events.

In addition to 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, Ref. 11 reports on particle emissions from electrical resistance type heaters, and Ref. 12 quantifies particulate emissions from vacuum cleaners.

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 Ref. 2 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. In Ref. 42, Streifel reported a source strength of 5.5×10^5 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 Refs. 13-15) as opposed to the determination of source strengths.

Recently, Refs. 16-18 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 in Ref. 19) 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.

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, including the reviewed studies in Refs. 20-38 and 43-45.

Refs. 20-29 report the emission rates of VOCs from a wide range of consumer products. Refs. 25-35 and 43-45 include VOC emission rates from various building materials. Ref. 36 describes benzene emissions from parked vehicles in residential garages. Ref. 37 reports on VOCs present in tap water volatilizing in showers. Ref. 38 details the emissions of VOCs from dry cleaned fabrics. It is important to caution that all of 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. Ref. 39 describes a database on indoor air pollutants that will include this information. However, this database is not yet publicly available.

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 through the use of 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 in Ref. 46.

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 in Ref. 47.

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 of the multizone airflow models listed in Ref. 47 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 which has been used in a number of residential indoor air quality studies (48). 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 it is not capable of taking into consideration the flow characteristics of individual openings, weather effects and the pressures created by HVAC system operation.

CONTAM93 as described in Ref. 98 is a model which combines NIST's programs AIRNET and CONTAM87. AIRNET (49) performs the detailed multizone airflow calculations including the interaction of the building and its HVAC system with the ambient weather conditions. CONTAM87 (50) performs the multizone contaminant dispersal calculations. CONTAM93 evolved from CONTAM88 (51) and includes a graphical interface, updated airflow algorithms (CONTAM88 contained airflow algorithms from AIRMOV - a predecessor to AIRNET), and convenient profile factors for handling transient simulations. Due to its more complete airflow modeling capabilities (compared to IAQPC), CONTAM93 is more appropriate for achieving the project objectives.

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 in Refs. 52-54. Ref. 52 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%.

Ref. 53 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.

Ref. 54 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 Refs. 55-66. Ref. 55 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.

Refs. 56 and 57 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 human generated pollutants, but the performance advantage was generally reversed for other pollutant sources.

Ref. 58 used a simple single-zone infiltration model to perform yearlong simulations and predicted the pollutant concentrations as a function of source strength, weather conditions, 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.

Ref. 59 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.

Refs. 60-64 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. Refs. 60, 63, and 64 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.

Ref. 60 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. Refs. 61 and 62 used IAQPC to study impacts of air cleaning and various control strategies on indoor air pollution resulting from smoking in an office.

Ref. 63 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, .

Ref. 64 used INDOOR to study the predicted concentrations of particles from a kerosene heater and VOCs from moth crystals and drycleaned 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.

Ref. 65 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.

Ref. 66 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).

Several experimental and simulation studies relevant to the IAQ impacts of residential HVAC systems and components were reviewed. Although many of these studies did not consider pollutant dispersal, used single zone and other simplified airflow calculation methods, or examined very specific cases, some general conclusions can be drawn from their results. First, interactions between buildings, HVAC systems, pollutant sources, and ambient conditions are significant. Second, whole building analysis is essential for studying these interactions. Finally, multizone airflow and pollutant dispersal models are appropriate tools for the study being planned by NIST.

IAQ Control Technologies

This section presents 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 whole-house ventilation systems that would be used independently or instead of a forced-air system. The 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.

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 particulates and gaseous contaminants from air. Particulate removal is a fairly well developed technology with an ASHRAE test method (99) 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 (67), 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 (68-71), 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.

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 (72-73). In addition to 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 associated exhaust fan.

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 outgoing 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. However, the impact 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.

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 (66 and 74-77). 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.

Conclusions

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 both consumer products and building and furnishing materials. 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.

Multizone airflow and pollutant transport modeling enables the whole building approach to indoor air quality modeling needed to meet the project objective. CONTAM93 has the capability to model the HVAC system interactions with the building structure including the dependence on the ambient conditions.

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 very narrow aspects of the issue. No comprehensive analysis of the HVAC system and component impacts on residential IAQ have 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.

CONSIDERATIONS IN DEVELOPMENT OF SIMULATION PLAN

This section describes the factors considered in developing the simulation plan to be implemented in Phase II of this study. Each of the following issues is discussed in terms of how it will be dealt with in the simulation considering the project objectives and the findings of the literature review.

1. Selection of computer simulation techniques
2. Specification of buildings and HVAC system designs
3. Selection of ambient conditions
4. Specification of pollutant sources
5. Selection of IAQ control technologies
6. Duration of simulations
7. Other residential IAQ issues

Computer Simulation Techniques

There are two general types of computer simulation techniques for studying airflow and contaminant distribution in buildings, room airflow modeling and multizone modeling. As discussed in the literature review section, multizone airflow and contaminant dispersal simulation is appropriate for studying the impact of HVAC systems on residential indoor air quality. Room airflow modeling with application of computational fluid dynamics (CFD) programs is inappropriate for the project goals because it is not possible to model a whole house with available computing resources. Even if it were possible, such a modeling effort would be a research exercise and may not produce useful results. Multizone application of CFD is an issue that has not yet received significant attention within the airflow modeling research community.

The computer simulation model selected for the indoor air quality simulations is CONTAM93 (98). As discussed in the Literature Review, CONTAM93 combines the calculation of airflow rates from building leakage data, ambient weather conditions, and HVAC system flows with the calculation of contaminant concentrations from the airflow rates and pollutant source and sink data. It is the only readily available program which integrates a complete multizone airflow analysis with pollutant dispersal calculations.

In order to assess the appropriateness of the IAQ control technologies, their energy impacts must be evaluated. For the baseline cases, the energy use can be estimated by the procedures described in the ASHRAE Fundamentals Handbook (79). However, these procedures do 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. These thermal load calculation methods are therefore inadequate to assess the energy impacts of the IAQ control technologies to be studied in this project.

Adequately accounting for these energy impacts would require the use of a building thermal modelling program such as TRNSYS (80) or DOE-2 (81). Even these programs do not integrate complete multizone airflow analysis into their thermal load calculations. Kendrick (82) discusses the interactions between heat transport and air movement in buildings and some of the current efforts to combine multizone airflow modelling with building energy use calculations. Determining the energy impacts of the IAQ control technologies to be studied is an important issue which will be addressed in the project to the extent possible. However, given the limited resources of this project, calculating energy use with a building thermal simulation program is not included in the current simulation plan. It is an essential follow-up activity to determine whether the IAQ control technologies are cost effective.

Buildings and HVAC Systems

This study is restricted to the consideration of single family residential buildings. Three residential building designs are suggested for study in the project work statement (1). These building designs are described in some detail in NBSIR 77-1309 (92) and were originally used for energy conservation research. These buildings can be summarized as:

1. A compact ranch style house [109 m^2 (1170 ft^2)].
2. A townhouse [122 m^2 (1310 ft^2)].
3. A larger detached house [185 m^2 (1990 ft^2)].

These buildings were specified based on being typical of modern residential construction in 1977. The ranch house is a single storey with no basement or garage. The townhouse is two storeys with no basement or garage. The larger detached house is two storeys and has a basement but not an attached garage as described. Air and contaminant transport from attached garages due to HVAC system induced pressure differences is an area of potential importance to this project. Also, it is important to note that typical house designs vary by location and not all combinations of house design and location are realistic.

A townhouse presents additional modelling complexities because one or two surfaces of the townhouse will exchange air with another townhouse instead of with the outdoors. Therefore, airflow to and from the adjacent townhouses and the pollutant levels in the adjoining structures would need to be modelled.

The airtightness of the buildings employed in the simulations could have a significant impact on the effectiveness of the IAQ control technologies. Thus airtightness will be handled as a variable of interest in this study. CONTAM93 will be used to calculate the building air change rate based on envelope leakage data, including the magnitude and location of air leakage sites, and ambient conditions. Information on typical air leakage data is available in the ASHRAE Fundamentals Handbook (79).

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.

HVAC Systems

This study is restricted to consideration of central forced-air HVAC systems. The system design will employ heating and cooling equipment and components that are typically employed by HVAC contractors for residential installation. Equipment and duct locations will depend on the house designs and locations. The system designs will be specified by generally accepted engineering practices.

Ambient Conditions

The ambient conditions that are necessary to perform the simulations include outdoor temperature, wind conditions, and outdoor pollutant concentrations. These factors depend on the building location and will affect the air infiltration rates, building heating and cooling loads, and indoor pollutant concentrations. The project work statement suggests four house locations, including Miami, FL, Denver, CO, Phoenix, AZ, and Chicago, IL, representing a range of US climates. The selection of building location is also relevant to the building and HVAC system design as discussed above.

The inclusion of four building locations will increase the total number of simulations, and therefore limit the number of other factors that can be considered. Choosing fewer locations which still cover a range of climatic conditions could provide sufficient diversity of ambient conditions while allowing more project resources to be spent on other important considerations.

All simulations will include a typical outdoor pollutant concentration for each pollutant of interest. In addition, an extreme outdoor pollutant concentration may be included as a pollutant source as discussed below.

Pollutant Sources

Multizone contaminant dispersal modelling requires the specification of a pollutant source including strength, location, distribution, and temporal profile (i.e. constant, step input, exponential decay, etc.). The simulations will focus on sources of the pollutants of interest specified in Table 1 of the project work statement (1). These pollutants include nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, biological contaminants, and volatile organic compounds (VOCs). The literature review summarizes the various sources of these pollutants and cites previous studies that reported source strengths. Detailed information has been published on NO_2, CO, and particulates from combustion sources and VOCs from consumer products and common materials. However, no quantitative information was identified on source strengths for biological contaminants.

In the following sections, source strengths, spatial distribution (point vs. area), temporal profiles, and modeling issues are discussed for each of the pollutant sources that were considered for inclusion in this study. The temporal profile of the pollutant generation rate is an important factor for determining the total length and time step of the simulation. A range of the reported values of source strength is given for each source type.

VOCs: Decaying emission rate, area or point source

VOC emissions can be modeled as an area or point source for which the source strength decreases over time. An example of a decaying area source is the application of a wood finishing product to the floors of a house. The application of such a product to an individual table would be a point source. A decaying source strength can be described by $R=R_o*\exp(-kt)$ where R_o is the initial emission rate and k is a decay constant. R_o is reported to range from 2200 to 32000 mg/m^2-h, and k can range from 0.24 to 10.2 h^{-1} (23). This equation can also be applied to a point source in which case R_o would be given in units of mg/h.

Another possible area source would be the installation of new carpeting during which the carpet, padding, and adhesive can all contribute VOCs. The dominant VOC source can be the adhesive and typical decay curves have been reported showing decay periods lasting several weeks (33). A simulation duration of several weeks would be required to model the entire decay transient.

The concentration of VOCs in indoor air can be significantly affected by the presence of sinks, materials such as textile products which can remove pollutants from the air through adsorption (83). These pollutant sinks can be reversible, i.e. they can emit the adsorbed pollutants after the air concentration is reduced through a process called desorption. Sink effects, including reversible effects, can be modeled in CONTAM93 and will be included.

VOCs: Constant emission rate, area or point source

VOC emissions can also be modeled as a constant source strength. A possible constant area source would be building materials (such as floor coverings, particle board, etc.) for which transients with relatively short time constants have already decayed. Reported source strengths range from 0.007 to 7.034 mg/m^{2}h (28,35). Such an area source will be modeled as a constant emission rate for the duration of the simulation. Long term changes in the emission rate and effects of temperature, relative humidity and air speed on the emission rate will be neglected.

Many household products are short term point sources (or burst sources) of VOCs. Reported source strengths range from 2 to 90000 mg/m^{2}h for waxes, caulks, deodorants, and cleansers (22, 25, 28, and 30). Many of these sources are actually decaying sources. Except for Ref. 30, however, decay information is not reported. These sources can be modeled as constant sources over a short period of time.

Combustion products: Constant emission rate, point source

The emission of combustion products (CO, NO_2, and particulates) can be modeled as a constant source emitted at a single point. One such source would be a kerosene or gas-fired space heater in an attached garage or other unheated space. Reported source strengths range from 2 to 1225 mg/h of NO, from 13 to 24882 mg/h of CO, and from 0.026 to 186 mg/h of particulates (3). The source strength depends on the size and type of heater and the operating conditions. This source could be modelled as constant throughout the day (or on a fixed schedule) and would only be included for the cold weather conditions.

Another possible source of this type would be a gas range or oven. Reported source strengths range from 36 to 669 mg/h of NO_2, from 180 to 3564 mg/h of CO, and from 0.118 to 30 mg/h of particulates (3). This source would be modelled as constant for a short time period. Additional sources of this type are cigarettes (modelling information is given in Ref. 3) and furnace backdrafting or flue gas spillage.

Nitrogen dioxide is removed by surface reaction in addition to dilution with outdoor air (84). This decay can have a significant impact on the indoor concentration of NO_2 and will be included in the simulation. Decay rates depend on the surface area within a zone and have been reported in Refs. 93-95. Similarly, particle deposition onto surfaces removes particles from the air and will be considered in the modeling.

Particulates: Constant emission rate, point source

Other sources of particulates can be modeled as a constant source source at a single point. One source of this type is vacuum cleaning and a source strength of approximately 5×10^8 particles/min has been reported (12). As mentioned above, the analysis must account for particle deposition on surfaces.

Particulates, carbon monoxide or nitrogen dioxide: Outdoor sources

Such sources would include an episodic release of pollen or dust or an increase in outdoor concentrations of combustion products during heavy rush hour traffic. The specific source itself would be modelled as a step increase in the concentration of pollutants in the outdoor air to a level based on the National Primary Ambient-Air Quality Standards (85) and measured data. Inclusion of an outdoor source of pollutants is important because options for introducing outdoor air to the HVAC system will be evaluated.

Biological pollutants

Examples of bioaerosol sources in residential buildings include a contaminated humidifier in a forced-air HVAC system or contaminated ductwork. Little information quantifying the strength or temporal and spatial profiles of biological pollutant generation rates has been found in the literature.

The appropriateness of studying such sources is questionable, since it is unlikely that these sources would be controlled by modifying the HVAC system. Rather, the appropriate course of action is to prevent the formation of such a source and to remove the source if it exists. In addition, the lack of measured emission rates prevents their inclusion in a modeling effort.

IAQ Control Technologies

The project work statement requires 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. A brief discussion of these and other retrofit technologies is presented below.

Filtration

Particulates:

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. These values will be obtained from manufacturer's literature and published research results (67, 100, 101). However, information on performance as a function of particle size is limited.

Gases:

Several different air cleaners for gaseous contaminants are also 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 (68-71), 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. At a minimum, the removal efficiency will be treated as a constant value based on the best available performance information. The treatment of filter capacity will depend on the duration of the simulations and may not be an issue for short term simulations.

Heat recovery ventilators

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. One available product has a heat recovery efficiency ranging from 56% to 84% and an airflow capacity of 30 to 130 L/s, depending on the specific model and operating conditions (86). Control options include continuous operation, scheduled operation, and control based on humidity or pollutant (e.g. carbon dioxide) levels.. Based on the capabilities of the CONTAM93 model, it may be necessary to select a simple control option for the study with a more sophisticated modelling of control being pursued as a follow-up activity.

Outdoor air intake devices

Several manufacturers offer outdoor air intake ducts and dampers which are connected to the return ductwork of a forced-air system. The outdoor air in such systems is distributed by the forced-air system blower. Since these blowers can consume 500 W, their use in such a system may result in a significant increase in energy consumption. The dampers may be controlled either manually or automatically. Automatic operation can be based on a schedule, relative humidity , or CO_2 concentration. Jackson (72-73) provides a detailed description of these systems. As mentioned above, it may be necessary to select a simple control option, while leaving more sophisticated modelling of control as a follow-up activity. Another option which could be investigated is the addition of an exhaust fan to balance the intake airflow.

Continuous blower operation

Operating the forced-air system blower continuously can be used to reduce contaminant concentrations in some circumstances by using the entire volume of air within the building to dilute a localized contaminant source. Such an approach will not be appropriate for all contaminant sources, particularly those for which it is more appropriate to exhaust the contaminant to the outdoors at its source. However, for other cases, continuous blower operation will reduce peak concentrations of the contaminant, and may be an effective control option.

Eliminating duct leakage

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 (52, 66, and 89-91). Duct leakage can greatly increase the total air change rate of a building resulting in increased energy consumption and can induce significant pressure differences in a building resulting in pollutant entry from adjoining spaces such as garages and the entry of soil gases. Sealing of air distribution ductwork could be an important residential IAQ control technique and merits further investigation.

HVAC system control

This is not really a stand alone IAQ control option but is used with the options described above. These other devices can be controlled based on CO_2, humidity, or other specific pollutants. Sophisticated modelling of such a control system could require the use of a coupled version of CONTAM93 with a transient simulation program such as TRNSYS. Such a coupled model would enable the investigation of more sophisticated HVAC system control options in a follow-up study.

Duration of Simulations

Since the total resources available to the project are limited, trade-offs must be considered between simulation length and the number of possible combinations of factors (i.e., different buildings, locations, pollutant sources, and IAQ control technologies) that can be investigated. Although it would be possible to perform yearlong simulations, it will be more productive to limit the length of individual simulations to the shortest reasonable period and to use the longest meaningful time steps for the simulations. Simulations on the order of one week with 15 minute time steps would be appropriate for most of the sources and control technologies discussed above. However, it is still important to examine the effects of different weather conditions. Weather effects could be evaluated by performing simulations for each combination of factors for typical cold, hot, and mild periods rather than performing yearlong calculations.

A longer term simulation would be necessary to model a pollutant source that decays over several weeks or even months. However, inclusion of such a source could come at the expense of including fewer combinations of the other simulation factors without providing significant additional information about the effectiveness of the technologies being evaluated.

Other Residential IAQ and HVAC Issues

In addition to the items considered in the development of the simulation plan discussed above, there are other issues related to the impact of residential HVAC systems on indoor air quality. These other issues include other configurations of houses and systems, ventilation approaches that do not involve forced-air systems, flue gas spillage, and soil gas entry. While these issues are beyond the scope of this project, it is important that they be recognized in planning this project. These issues are discussed briefly in this section, with additional discussion contained in the section "Discussion of Follow-Up Activities".

Other house and HVAC system configurations

Based on the resources available for this project, only forced-air heating and cooling systems are being studied and only in a small number of houses. There is a large variety of single-family residential building and system configurations with variability in features that may significantly affect indoor contaminant levels and the effectiveness of particular indoor air quality control technologies. Ultimately a larger number of house and system types will need to be studied to understand the indoor air quality impacts of HVAC systems. For example, there is an increasing number of manufactured houses, and this type of building will also need to be considered. Other building features of importance include foundation type, HVAC system location, and the existence, location, and operation of other appliances such as water heaters and dryers.

Non-forced air ventilation systems

While the indoor air quality control technologies considered in this project are restricted to those that can be incorporated into forced-air systems, there are other approaches to residential ventilation that do not involve forced-air systems. These include heat recovery ventilators that operate independent of the forced-air system and exhaust-based ventilation systems, with and without heat recovery. These other approaches have certain advantages and disadvantages, and their effectiveness need to be evaluated.

Flue Gas Spillage

Flue gas spillage or backdrafting refers to situations in which combustion products from furnaces and other natural draft combustion appliances enter the house instead of being removed via the flue by buoyancy forces. House airtightness, duct leakage, and exhaust ventilation equipment can contribute to the potential for flue gas spillage. Studies of flue gas spillage are discussed in Refs. 88-89. In order to study backdrafting with a whole-building approach, a flue model, such as FLUESIM (102), would need to be coupled with CONTAM93.

Soil gas entry

Soil gas, such as radon, will enter a house based on the source strength of the particular gas and the pressure difference across ground contact surfaces. The operation of forced-air systems and other house characteristics affect the rate of entry. These important sources are not within the current scope of the project, but the impact on soil gas entry of any ventilation-based indoor air quality control technology must be considered.

EXPERT WORKSHOP

On August 6, 1993, NIST hosted a workshop to discuss this project and the proposed simulation plan. The participants of the workshop included IAQ researchers and representatives of residential HVAC equipment manufacturers, industry associations, and federal agencies involved in residential IAQ. A list of workshop participants is contained in Appendix A. The objective of the workshop was to describe the study to the participants and to obtain feedback on the relevance and appropriateness of the proposed effort. The workshop agenda covered the project background, previous research, the issues considered in developing the project plan, the preliminary project plan itself and follow-up work. This section presents a summary of the preliminary project plan followed by a discussion of the main points of the workshop discussion.

Summary of Preliminary Project Plan

This section presents a summary of the preliminary project plan as presented at the workshop. The overheads from the workshop presentation are included in Appendix B. After the workshop, the simulation plan was revised by NIST. The revised plan is presented later in this report.

Project Objective and Technical Approach

The project objective is to assess the potential effectiveness of existing HVAC technology to reduce the levels of selected pollutants in single-family residential buildings. Several options exist for using forced-air systems to control indoor air quality (IAQ) including: high efficiency air filters and gaseous air cleaners; outdoor air intake ducts; and heat recovery ventilators. In addition, features of the system that may contribute to indoor air quality problems can be corrected, such as sealing leaky ducts. The impact of these modifications on residential IAQ depends on the building characteristics, the design and performance of the IAQ control device, the specific pollutants of concern, the characteristics of the pollutant sources, the existence of pollutant sinks, and the ambient conditions. A great deal of study, including computer simulation and laboratory and field testing, is required to determine which devices and modifications will be most beneficial and under what circumstances.

In this study, NIST will use computer simulations to conduct a preliminary assessment of the potential for forced-air HVAC systems to improve residential IAQ. The simulation plan has been developed to focus on the effects of the IAQ control technologies, including potentially significant interactions with other simulation factors (such as building airtightness and ambient weather conditions). The number of levels (e.g. typical vs. tight envelope) of each factor have been limited in order to include as many potentially significant factors as possible. The key elements of the simulation plan are described below.

Computer Simulation Model

The simulations will be performed with the multizone airflow and pollutant dispersal model CONTAM88 - a multizone model which combines the programs CONTAM87 and AIRMOV. (At the time of the workshop, CONTAM93 was not yet available.) AIRMOV performs detailed multizone airflow calculations including the interaction of the building structure and its HVAC system with the ambient weather conditions. Given building component leakage data and HVAC system flows, AIRMOV calculates infiltration and interzone airflow rates. Given the airflow rates calculated from AIRMOV, CONTAM87 calculates the pollutant concentrations in the zones based on pollutant source and sink information. CONTAM88 combines these calculations of airflow rates and contaminant concentrations. Although the energy impacts of the IAQ control technologies are critical to evaluating their cost effectiveness, coupling the detailed thermal analysis with these airflow calculations is beyond the scope of this study. The energy impacts of the control technologies will be estimated using simplified techniques.

Baseline Buildings and Locations

This study is restricted to the consideration of single family residential buildings. Two basic house designs will be modelled. The first house is a single storey ranch style house and the second is a larger two storey house with a basement. These houses will be based on building designs originally used for energy conservation research (92) and selected as being typical of modern residential construction (in 1977). Each house will have a central forced-air HVAC system designed by generally accepted engineering practices for each location.

The airtightness of the buildings employed in the simulations must be specified and could have a significant impact on the effectiveness of the IAQ control technologies. Each basic house design will be modelled for two levels of airtightness including typical and tight construction. Air leakage values for the exterior envelope and interior partitions will be based on measurements in the published literature, including the information in the ASHRAE Handbook of Fundamentals.

The ambient conditions that are necessary to perform the simulations include temperature, wind conditions, and outdoor pollutant concentrations. These factors will affect the air infiltration, building heating and cooling loads, and indoor pollutant concentrations.

The specific ambient conditions used depend on the building location. Each building will be modelled in two locations (Miami, FL and Chicago, IL) to include a range of climatic conditions.

Duration of Simulations

The individual simulations will be limited in duration to the shortest reasonable period (possibly a few days) with the longest meaningful time steps (approximately 15 minutes to one hour). The length of the simulations is driven primarily by the time constants of the pollutant sources and the ambient conditions. In order to examine the effects of different weather conditions, each combination of factors will be simulated for typical cold, hot and mild periods in each location. The simulations will take advantage of the ability of CONTAM88 to simultaneously model several different contaminants and contaminant sources.

Pollutant Sources

Contaminant dispersal modelling requires specifying a pollutant source including strength, location, distribution, and temporal profile (i.e. constant, step input, exponential decay, etc.). The simulations will focus on sources of the pollutants of interest specified by CPSC in the project work statement. These pollutants include nitrogen dioxide (NO_2), carbon monoxide (CO), particulates, biological contaminants, and volatile organic compounds (VOCs). A literature review performed as part of this project assessed the various sources of these pollutants and listed reported measurements of source strengths. Detailed information was found for sources of some of the pollutants including NO_2, CO, and particulates from combustion sources and VOCs from consumer products and common building materials. No useful information was found for sources of biological contaminants.

Based on the results of the literature review, consideration of pollutant sources relevant to the residential environment, and the capabilities of the CONTAM88 model, the following sources are being considered for analysis:

1. Short term decaying VOC point sources located on each story of each house with a time constant on the order of hours, e.g. application of a wood finishing product to a table.
2. A constant VOC area source located throughout the house, e.g. a floor covering for which the short-term transients have passed and is emitting at an approximately constant level.
3. A short term decaying VOC area source (or the initial transient of a long term decaying VOC area source) distributed throughout each house with a time constant on the order of days, e.g. the installation of new floor covering or the application of wood finishing product to the entire floor.
4. Short term constant combustion point sources (NO_2, CO, and particulates), e.g. a space heater in the garage or a gas oven in the kitchen.
5. A short term increase in the outdoor air concentration of particulates and CO on the order of hours, e.g. an episodic release of pollen due to wind or CO due to rush hour traffic.
6. A short term and constant bioaerosol point source, e.g. a contaminated humidifier or ductwork.

IAQ Control Technologies

Three IAQ control technologies will be added to the forced-air HVAC systems of the houses. The effectiveness of these technologies in reducing the indoor air pollutant levels will be assessed. The assessment will involve challenging the buildings with the above sources for the "baseline" force-air system under varying ambient conditions and two cases of house tightness. Each of the three control technologies will then be separately analyzed, and the predicted concentrations will be compared to the concentrations in the baseline cases.

The design and specifications of each of the IAQ control technologies will be based on commercially available equipment. Due to limitations in the current version of CONTAM88, only simple control options (continuous or scheduled operation) will be considered. Modifications of the program that are currently in progress will enable consideration of more sophisticated controls, such as those based on humidity or indoor pollutant concentration.

The indoor air quality control technologies that will be studied include the following:

1. A high efficiency particulate removal system and a gaseous contaminant air cleaner. Particulate removal efficiencies are available for a variety of particulate filters and other devices based on ASHRAE Standard 52. However, there is no test standard for gaseous contaminant air cleaners and performance data is limited. The issue of sorbent capacity will not be considered in these short-term simulations, but it is an important performance issue from the manufacturers of these devices.
2. A heat recovery ventilator designed for connection to a central forced-air HVAC system. Such devices are available that remove building air from the return side of the forced-air system, pass this airstream through a heat exchanger, and deliver the outdoor air supply from the heat exchanger back into the return side. Performance data on heat recovery and airflow rate are available for these devices.
3. An outdoor intake damper connected to the return ductwork of the forced-air system. Several manufacturers offer outdoor air intake ducts and dampers that are connected to the return ductwork of a forced-air system. The outdoor air from such devices is then distributed by the forced-air system whenever the blower operates. The blower can be controlled by the system thermostat or other control approaches such as a timer or humidistat. An interlocked building exhaust fan can be installed to improve the performance of these intake devices.

Workshop Discussion

General

The workshop participants displayed interest and enthusiasm, and agreed that the project objective and overall approach were sound. The use of a whole building approach in general and the simulation program CONTAM88 in particular were well received as appropriate to achieving the project objective. Some participants expressed a desire to further develop the modeling tools, but most considered the available tools to be sufficient for the preliminary nature of the project.

No objections were raised to the general thrust and objectives of the project, and the ensuing discussion focussed on the specifics of the project plan. Most of the comments can be classified into the following two categories:

1. Selecting the specific factors in the simulation matrix
2. Expanding the study

Selecting the Specific Factors in the Simulation Matrix

The program CONTAM88 requires the input of many factors to calculate the zone pollutant concentrations. Examples of these factors include detailed building design, building location, HVAC system design, pollutant sources, and IAQ control technologies. Additionally, decisions must be made regarding the appropriate duration of simulations. Collectively, these factors can be referred to as the *simulation matrix.* The simulation matrix includes all the possible options for the simulations that must eventually be pared down to the actual cases that will be included given the resource constraints of the project. It is important to develop as complete a simulation matrix as possible so that important issues are not neglected and to identify issues for future research. A large portion of the discussion at the workshop was devoted to specific factors to be included in the simulation matrix.

The first factor discussed was the proposed duration of the simulations. The two options considered were short term simulations as proposed in the simulation plan and yearlong simulations. The participants agreed that each option was appropriate for different pollutant sources and control technologies and both merit consideration. For example, long term simulation on the order of one year are appropriate for sources with long time constants and to analyze the long term performance of gaseous contaminant air cleaners.

Some participants strongly suggested tailoring the house designs to the selected locations . The building foundation, i.e. slab-on-grade, crawl space and basement, was considered the most important building feature to be location specific as this influences the location of the HVAC equipment and ducts. One suggestion was to base the building types on HUD (96) and DOE (97) databases, and then to consider the prevalent house design features in each location.

The proposed project plan did not include a townhouse building as was suggested in the project work statement. The workshop participants did not reach a consensus on the importance of including townhouses. Arguments in favor of inclusion were the large number of townhouses and an interest in characterizing pollutant transport between units. Reasons presented against include modeling complexities, lack of needed leakage data, and an inconsistency with the preliminary nature of the project.

The proposed plan added the building airtightness as a factor to be varied in the simulation matrix. The participants agreed that this is a significant factor and should be included.

The proposed plan reduced the number of locations to be included from the original four cities suggested in the project work statement to only two cities. No consensus was reached on the most appropriate number of locations, but a suggestion was made to change the cold climate location from Chicago to Minneapolis.

A ranking of the specified pollutants of interest in terms of modeling capability was suggested by the participants as CO, VOCs, NO_2, particulates, and biological contaminants. Additional pollutants suggested for inclusion were CO_2, humidity, NO, and ozone. CO_2 could be used as a comfort (odor) indicator, and humidity could be used as an indicator of the potential for growth of biological contaminants. It was recognized that the modeling humidity would require year long simulations and would greatly add to the complexity of the project. NO and ozone need to be included in order to model the chemistry of indoor NO_2. One participant suggested modeling sources over a range of strengths to determine the effective range of the IAQ control options.

It was strongly suggested that particulates be separated by particle size into at least two classes, less than and greater than 2.5 μm. This distinction is important because of the dependency of source generation rates, deposition characteristics, and filtration efficiencies particle size.

The participants expressed a general consensus that the lack of specific modeling information for bioaerosol sources was a substantial barrier to including biological contaminants in the project. The possibility of using indoor relative humidity levels as an indicator of the potential for growth of biological contaminants was suggested as a substitute for direct modeling of bioaerosols and was viewed as a potentially important contribution to the field.

No objections were raised to the three system modifications proposed (air cleaning, heat recovery ventilators, and outdoor air dampers), although concern was expressed that heat recovery ventilation might not be used to its best advantage when constrained to operate with a central forced-air system. It was also stated that it would be difficult to model gas air cleaners with much confidence in relation to reality because of a lack of performance information on them. In addition, the limitation to forced-air systems eliminated consideration of other promising approaches to residential ventilation, such as whole building exhaust systems combined with outdoor air inlets. Duct sealing and sophisticated system control were considered in developing the proposed plan, but were not included in the plan discussed at the workshop. These options were considered to have merit for study but not possible given the project resources. Several participants suggested examining 'typical' system operation vs. 'as-intended' system operation.

Expanding the Study

Much of the discussion at the workshop concerned issues outside of the proposed simulation plan and the limited project objectives. Their inclusion would result in significantly modifying or expanding the study beyond the current proposal, but the discussion is important for identifying the limitation of the current project and opportunities for future work.

Several participants strongly suggested including an experimental component to the study. This issue raised the possibility of modeling an available test house rather than the proposed theoretical buildings. A general consensus was reached that there is great value to including experimental study, but it was not seen as necessary at this time.

Interest was expressed in expanding the study to include HVAC systems other than central forced-air systems. During the initial project planning, it was felt that the limited focus on central systems was necessary to maintain the project to a manageable size. It is important to remember the focus only on central systems does not imply that they are inherently better than other residential HVAC systems. Also, the consideration of only forced-air systems limits the IAQ control technologies that can be considered. Both of these issues will limit the scope of the study's conclusions and need to be pointed out when reporting the results.

Some participants expressed interest in including consideration of flue gas spillage or backdrafting. Options for modeling flue gas spillage ranged from a detailed model of the physical phenomena to imposing a contaminant source profile that would be associated with a spillage episode. Another approach that was discussed by the group was to report the pressure differential between the room containing the furnace and the outdoors as an indicator of the potential for backdrafting. The presentation and analysis of these pressures were seen as an important contribution to the flue gas spillage issue.

The possibility of including computational fluid dynamics (CFD) modelling in the project was also suggested. While not appropriate for the specific objective of the project, CFD modelling could be used to evaluate side issues such as pollutant distribution in a room due to stratification. The participants agreed that such work should not be included at this time, but could be pursued as future work for any promising option.

One participant suggested adding moisture transport modeling to the plan. A consensus existed on the importance of this issue, particularly for humid regions of the country where it could be a deciding factor for actual application of any HVAC system modification. As mentioned earlier, the idea was also proposed that modelling humidity could be used as an indicator of the potential for the growth of biological contaminants. Questions were raised about the adequacy of CONTAM88 for modelling moisture transport, but in fact the program could model moisture. The main obstacle is associated with obtaining reliable values for the many inputs required to conduct such modeling. Including the modeling of moisture in these simulations would be a matter of complexity, and would reduce the number of other issues that could be addressed.

One participant suggested that the measure of the effectiveness of the modifications should be the impact on human exposure to the contaminants. Several participants agreed that integrated exposure is the bottom line in IAQ, but an argument against it was made based on a lack of time and analytical tools to do an adequate treatment.

Other suggestions regarding analysis of the effectiveness of the modifications included determining whether ASHRAE Standard 62 was met and modeling CO_2 concentration as a general comfort indicator.

Conclusion

A preliminary version of the project plan was presented to participants at an expert workshop held at NIST to discuss the plan and obtain feedback on its technical merit and relevance to residential indoor air quality issues. The general objective and analytical approach of the project were well-received and considered feasible and important. Response to the proposed simulation plan was positive and generated much discussion regarding which details should be included.

SIMULATION PLAN

This section presents the simulation plan for Phase II of the project based on the literature review, the preliminary project plan and the discussion at the workshop. As mentioned earlier, the preliminary nature of the project has impacted significantly on the development of the simulation plan. Therefore, the number of levels of each factor were limited in order to be able include as many potentially significant factors as possible.

All simulations will be performed with the NIST multizone airflow and pollutant dispersal model CONTAM93. CONTAM93, developed since the workshop, has an improved user interface and improved airflow modeling capabilities compared to CONTAM88. Although the impacts of the IAQ control technologies on energy use, indoor humidity levels, and other contaminants are important and will be considered in the study, the detailed analysis of these impacts is beyond the scope of this project.

Baseline buildings, HVAC system designs, and locations

Two basic house designs will be modeled. The first house is a single-story ranch style house and the second is a larger two-story house with a basement, both based on the houses described in Ref. 92. Garages have been added to the basic design of each house to enable consideration of a contaminant source in the garage. Building floorplan drawings are included in Appendix C. Each basic house design will be modeled with two levels of airtightness corresponding to typical and tight construction.

Each building will be modeled in two locations (Miami, FL and Minneapolis, MN) to include a wide range of climate conditions. Both basic house designs will include a basement in Minneapolis and a concrete slab foundation in Miami. ASHRAE WYEC (Weather Year for Energy Calculation) data will be used for the ambient weather conditions in the simulations. A summary of long-term average monthly weather data for these cities is included in Appendix D (104).

Each house will have a central forced-air HVAC system designed. Cooling and heating load calculations have been performed for each building to size the HVAC equipment. The calculation method used is described in the ASHRAE Handbook of Fundamentals (79) and in the Sheet Metal and Air Conditioning Contractors National Association (SMACNA) Installation Standards (105). This method is considered standard engineering practice for residential applications. Details of the calculations are included in Appendix E.

Features of the HVAC system design for the Miami houses include: equipment located in a first floor utility closet, supply ducts located in the attic and a central return for the ranch house; and supply ducts interior and a return on each floor for the two-story house. Features of the HVAC system design for the Minneapolis houses include: equipment located in the basement, interior supply ducts, and return in each room for both houses. Guidelines published by the National Association of Home Builders (103) were used to assist in designing the HVAC system.

A more detailed description of the HVAC system and HVAC system layout drawings are included in Appendix F.

Duration of simulations

The simulations will employ the 24 hour cyclic modeling approach implemented in CONTAM93. A cyclic simulation repeats a 24 hour cycle until steady-periodic conditions are achieved. Longer simulations are not required since the selected sources do not include any long term variation and changes in performance of the controls over time are not being considered. To examine the effects of different weather conditions, each combination of factors will be simulated for typical cold, hot and mild days in each location. The simulations will be performed with 15 minute time steps.

Pollutant sources

The pollutant sources included in this plan are listed below in a tabular format. In this list, *pollutant* indicates the pollutant generated by the source. *Spatial distribution* indicates how the source is distributed within the building, e.g., whether the source strength is a function of the floor area of the zone in which it is located or whether it is a point source. *Temporal profile* indicates the dependence of the generation rate on time: decay - first order exponential decay modeled as $R=Ro*\exp(-kt)$; burst - constant emission rate lasting over one or two time steps; constant - no dependence on time; and constant per schedule - constant for short periods of time and zero at all other times. *Location* indicates the specific building zones in which the contaminant source will be located. The entries under *low, medium, and high strengths* provide a range of strengths at which the source may occur. Most of the sources will be modeled at their medium strengths, although some of the sources may be modeled at more than one strength level. *Remarks* includes any other relevant information for the particular source.

1. Newly finished floor
   Pollutant(s): Total VOCs
   Spatial distribution: Floor area
   Temporal Profile: First order exponential decay (modeled as: $R=Ro*\exp(-kt)$)
   Location: All rooms except basement, kitchen, bathroom
   Strength low: Ro=1680 mg/m^{2}h [k=0.25 h^{-1}] - polyurethane
   Strength medium: Ro=17400 mg/m^{2}h [k=1.24 h^{-1}] - stain
   Strength high: Ro=38000 mg/m^{2}h [k=6.3 h^{-1}] - wax
   Remarks: Sink effects will be included.
   Reference: Tichenor and Guo 1991 (23)

2. <u>Consumer product</u>

Pollutant(s): Total VOCs
Spatial distribution: Point
Temporal Profile: Burst
Location: All rooms (including basement and garage) per schedule
Strength low: 20 mg/h - liquid floor detergent on 1 m^2
Strength medium: 300 mg/h - polish on 1 m^2
Strength high: 1100 mg/h - spray carpet cleanser on 1 m^2
Remarks: Sink effects will be included.
Reference: Colombo et al 1990 (30)

3. <u>Unvented space heater</u>

Pollutant(s): NO2, CO, Particulates
Spatial distribution: Point
Temporal Profile: Constant per schedule
Location: Basement and garage
NO_2
- Strength low: 30 mg/h
- Strength medium:250 mg/h
- Strength high: 740 mg/h

CO
- Strength low: 20 mg/h
- Strength medium: 1000 mg/h
- Strength high: 25000 mg/h

Particulates (<2.5 μm)
- Strength low: 0.1 mg/h
- Strength medium: 2 mg/h
- Strength high: 190 mg/h

Remarks: Particle deposition and NO_2 decay will be included.
Reference: DOE 1990 (3)

4. <u>Elevated outdoor air pollution</u>

Pollutant(s): NO_2, CO, Particulates
Temporal Profile: Constant per schedule
Location: Outdoor
NO_2
 Concentration low: 0.0053 ppm (0.1*medium)
 Concentration medium: 0.053 ppm (annual average National Ambient Air Quality Standard)
 Concentration high: 0.15 ppm (3*medium)
CO
 Concentration low: 0.9 ppm (0.1*medium)
 Concentration medium: 9 ppm (8 hr avg NAAQS)
 Concentration high: 35 ppm (1 hr avg NAAQS)
Particulates (≤10 µm)
 Concentration low: 5 µg/m3 (0.1*medium)
 Concentration medium: 50 µg/m3 (annual avg NAAQS)
 Concentration high: 150 µg/m3 (24 hr avg NAAQS)
Remarks: Low concentrations will be used for baseline cases.
 High concentrations will be used on "rush-hour" schedule for outdoor source.
 Particle deposition will be considered.
Reference: EPA 1987 (85)

5. <u>Flooring material, constant emission</u>

Pollutant(s): Total VOCs
Spatial distribution: Floor area
Temporal Profile: Constant
Location: All rooms except basement
Strength low: 0.007 mg/m^2h - cork
Strength medium: 0.216 mg/m^2h - untreated pinewood
Strength high: 7.034 mg/m^2h - PVC
Remarks: Sink effects will be included.
Reference: Saarela and Sandell 1991 (35)

6. Gas oven

Pollutant(s): NO_2, CO, Particulates

Spatial distribution: Point

Temporal Profile: Constant per schedule

Location: Kitchen

NO_2

Strength low: 60 mg/h

Strength medium: 160 mg/h

Strength high: 270 mg/h

CO

Strength low: 100 mg/h

Strength medium: 1900 mg/h

Strength high: 3600 mg/h

Particulates (<2.5 μm)

Strength low: 0.1 mg/h

Strength medium: 0.2 mg/hr

Strength high: 0.4 mg/hr

Remarks: NO_2 decay, particle deposition, and capture efficiency of hood will be included.

Reference: DOE 1990 (3)

IAQ control technologies

After completing analysis of the baseline cases, each HVAC system will be modified by the following three retrofits. The design of each of the retrofit items will be based on commercially available equipment.

1. A passive, electrostatic air filter for removing particulates. The device will be modeled with a constant removal efficiency for fine (diameter < 2.5 μm) and coarse (diameter > 2.5 μm) particles.
2. A heat recovery ventilator designed for connecting to a central forced-air HVAC system. Only simple control options will be considered: specifically scheduled and continuous operation, and operation whenever the furnace is on.
3. An outdoor intake damper connected to the return ductwork of the forced-air system. Only simple control options will be considered: specifically scheduled and continuous operation, and operation whenever the furnace is on.

Output analysis

To determine the effectiveness of the IAQ control technologies at reducing the levels of indoor air pollutants in the houses, the pollutant concentrations calculated during simulations with the retrofits will be compared to those calculated for the baseline systems. These comparisons will include peak concentrations in individual zones and hourly average concentrations for individual zones and the entire building. These comparisons will be made for typical hot, cold, and mild days.

Impacts of IAQ control technologies

As discussed in the project work statement, these IAQ control technologies may have unintended impacts on such factors as the concentration of other contaminants, heating and cooling energy use, thermal comfort, and humidity. Because detailed analysis of these impacts is beyond the scope of this project, these system modification impacts will be assessed using simplified approaches as appropriate. Additionally, furnace room pressures will be examined to evaluate the potential for flue gas spillage caused by the modifications.

DISCUSSION OF FOLLOW-UP ACTIVITIES

In order to fully address the overall goal of understanding the indoor air quality impacts of HVAC systems in residential buildings, significantly more work is required than that planned for this project. As mentioned earlier, this project is preliminary in nature and limited in scope, and this section discusses some follow-up activities that would be needed to meet the overall goal cited above. Many of these follow-up activities were mentioned earlier in this report, and this section simply itemizes them. The follow-up activities fall into two categories, additional factors that could be considered within the current simulation plan and major activities that would involve a significantly expanded effort.

The factors included in the proposed simulation plan were limited to those appropriate to a preliminary assessment of the effectiveness of the selected IAQ control technologies. Some of the additional factors which could be pursued within the current project framework using the planned analysis approach include the following:

Other house types and configurations: attached houses, manufactured housing, houses with crawl spaces
Other system types: non-forced air heating and cooling systems, residential ventilation systems separate from forced-air systems
Advanced ventilation system controls: demand controlled ventilation based on pollutant levels or occupancy sensors
Other indoor air quality control technologies: duct sealing
Other pollutants: soil gas, carbon dioxide

Additional activities that would involve a major expansion of the project include the following:

Modeling of flue gas spillage
Humidity analysis based on material properties of building materials
Building thermal analysis to determine energy impacts
Modeling of bioaerosol sources when emission rates are available
Experimental work to validate results and assess field performance of control technologies

SUMMARY

The National Institute of Standards and Technology (NIST) is conducting a study for the U.S. Consumer Product Safety Commission (CPSC) to assess the potential effectiveness of existing HVAC technology to reduce the levels of selected pollutants in single-family residential buildings. In this effort, NIST will perform whole building airflow and contaminant dispersal computer simulations to assess the ability of modifications of forced-air heating and cooling systems to control pollutant sources relevant to the residential environment. During Phase I of this project, three major efforts were completed: a literature review, simulation plan development, and an expert workshop.

The research literature and other available information was reviewed for developing the simulation plan. Common sources of indoor air pollution in residential buildings have received much research attention in the last decade, and many studies have been conducted to quantify their emission rates. In particular, extensive data is available on the emission rates of CO, NO_2, and particulates from combustion processes and of VOCs from both consumer products and building and furnishing materials. However, wide ranges of values have been reported, and information on the dependence of emission rates on factors such as time, ventilation rates, ambient conditions, and usage conditions is incomplete. Information on emission rates of biological contaminant sources is not available.

Over the past few years, several researchers have studied residential indoor air quality through simulations and/or 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. Due to the complex interactions of the HVAC system with the building, the ambient weather conditions, and the pollutant sources, a multizone airflow and pollutant dispersal modelling approach that includes all of these factors is necessary to understand and evaluate these impacts. The program CONTAM93 has the capability to model the HVAC system interactions with the building zones including dependence on the ambient conditions.

A detailed plan was developed for the computer simulations to be performed in Phase II of this effort. The plan includes the computer simulation techniques and the specification of building and HVAC system designs, building locations, pollutant sources and IAQ control technologies to be modeled. A preliminary version of the plan was presented to participants at an expert workshop held at NIST to discuss the plan and obtain feedback on its technical merit and relevance to residential indoor air quality issues. The overall reaction to the project objective and approach was positive. The general objective and analytical approach of the project were well-received and considered feasible and important by the participants. The workshop discussion was considered in preparing the final project plan.

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Appendix A List of Workshop Attendees

The following people attended the expert workshop at NIST on 6 August 1993:

Jim Axley
Massachusetts Institute of Technology

Terry Brennan
Camroden Associates

Cherie Bulala
NIST

Roy Deppa
CPSC

Tim Dyess
U.S. EPA
Office of Research and Development

Steve Emmerich
NIST

Bob Franklin
CPSC

Bill Freeborne
HUD

Dave Godwin
Air-Conditioning and Refrigeration Institute

David Grimsrud
University Of Minnesota

Mike Koontz
GEOMET Technologies

Brian Krafthefer
Honeywell Inc

Bryan Ligman
U.S. EPA
Office of Air and Radiation

Andy Persily
NIST

Dale Rammien
Home Ventilating Institute

Lori Saltzman
CPSC

Joe Spurgeon
U.S. EPA
Office of Air and Radiation

John Talbott
DOE
Office of Building Technologies

Kevin Teichman
U.S. EPA
Office of Research and Development

Bill West
CPSC

Stan Wrezski
Broan Manufacturing Co. Inc.

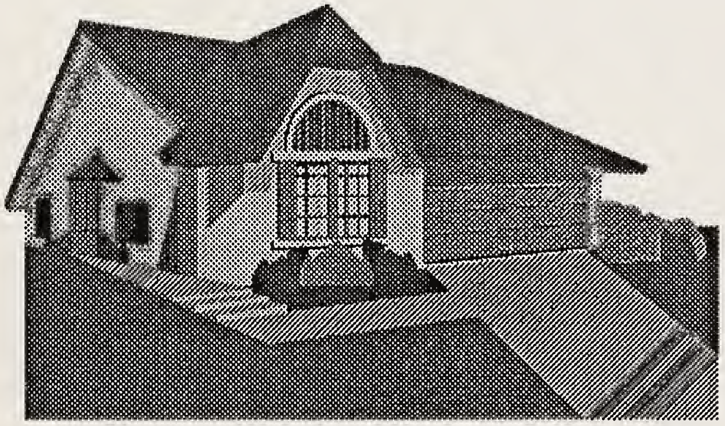
Appendix B Overheads from Workshop Presentation

This appendix contains the overheads presented during the expert workshop held at NIST to discuss the project.

IAQ and Residential HVAC Systems

Expert Workshop
NIST Gaithersburg, MD

6 August 1993



AGENDA

- Project Background: NIST and CPSC
- Discussion of previous research
- Discussion of critical issues in developing project plan
- Outline of project plan
- *Lunch at NIST Cafeteria*
- Discussion of project plan
- Discussion of follow-up work and related issues

PROJECT BACKGROUND

Objectives

- **Overall: Understand the IAQ impacts of residential HVAC systems and assess the potential for using these systems to reduce the indoor levels of selected pollutants**
- **Project: Conduct a preliminary assessment, using computer simulation, of the potential for forced-air HVAC systems to improve residential IAQ.**

Why HVAC Systems?

- They move a lot of air.
  - Cleaning
  - Distribution
- They impact building airflow.
  - Building air change rates
  - Interzone airflow patterns
  - Pressure differences

HVAC System Impacts on IAQ

- Problems
  - Leaks in exterior return ducts drawing in pollutants from garages, crawl spaces, ...
  - Leaks in basement return ducts depressurizing basement, increasing soil gas entry and increasing potential for backdrafting
  - Leaks in exterior supply ducts depressurizing building, drawing in pollutants from garages, soil, ...
  - Dirty ductwork and system components as a source of bioaerosols, particulates, ...
- Solutions
  - Particle filters and gaseous air cleaners
  - Incorporate outdoor air intake into forced-air system
  - Heat recovery ventilators
  - Humidifiers under heating conditions
  - Dehumidifiers under cooling conditions

Key Questions

- Questions the study will answer
  - Do *these* commercially-available modifications of forced-air systems have potential for reducing indoor pollutant levels from *these* sources?
  - Which approaches merit more detailed study?
  - How might these modifications impact other aspects of building performance such as thermal comfort, energy-use and indoor humidity levels?
- Questions the study won't answer
  - Will these modifications control pollutants for the wide variety of building and system configurations and indoor pollutant sources?
  - Should these modifications be used today?
  - How do these forced-air system approaches compare to other residential ventilation systems?
  - What are the energy loads associated with these modifications? (Based on building load simulation)

Discussion of Project Plan

- General
  - Is this a reasonable thing to do?
  - Is the approach appropriate?
- Specific
  - Are the components of the plan correct?
  - Are there omissions?

PREVIOUS RESEARCH RELATED TO IAQ IMPACTS OF RESIDENTIAL HVAC SYSTEMS

- Whole building approach
  - Considers interactions between building, HVAC system, pollutant sources and ambient conditions

- Examples
  - Impact of HVAC system operation on building airflows
  - Impact of HVAC system type and control on pollutant cencentrations
  - Impacts of ventilation strategies on airflow and energy use

Impact of HAC system operation and leakage

- Evaluated impact of:
  - Forced-air system operation
  - Duct sealing
- Measured whole house air exchange and tracer gas transport from crawlspace
- Concluded:
  - HAC operation increased infiltration by up to 3.6 times
  - Sealing reduced impact of HAC operation by one half
  - Sealing reduced gas transport from crawlspace by 30%

Matthews et. al. "Impact of Heating and Air Conditioning System Operation and Leakage on Ventilation and Intercompartment Transport: Studies in Unoccupied and Occupied Tennessee Valley Homes" JAWMA Vol 40.

Study of 3 IAQ problems in single family residences

- Used multizone model MIX to investigate:
  - Smell transfer from crawlspace
  - Moisture content of kitchen air
  - Radon in houses with different heating systems
- Concluded:
  - Operation of boiler with chimney is effective means of lowering radon levels
  - Choice of building airtightness and ventilation system should be coordinated

Li. "Prediction of IAQ in Multi-room Buildings" Indoor Air 93.

Study of different ventilation systems and control strategies

- Used CONAIR (combination of CONTAM87 and AIRNET) to evaluate:
  - Central vs. distributed ventilation
  - Continuous operation vs. CO_2 based demand control
- Concluded:
  - DCV better at controlling human generated pollutants but not other sources

Yuill and Jeanson. "An Analysis of Several Ventilation Strategies for 4 Ventilation Systems" Indoor Air 90.

Yuill et. al. "Simulated Performance of Demand-controlled Ventilation Systems using Carbon Dioxide as an Occupancy Indicator" ASHRAE Transactions 1991.

Impacts of different ventilation strategies

- Used TRNSYS program with LBL infiltration model to predict whole-house air change rate and energy use for:
  - Natural ventilation
  - Balanced mechanical ventilation
  - Exhaust ventilation
- No pollutant dispersal modelled
- Concluded:
  - Exhaust ventilation with heat recovery provided better IAQ than balanced mechanical ventilation

Hekmat et. al. "Impacts of Ventilation Strategies on Energy Consumption and IAQ in Single-Family Residences" E&B Vol. 9.

Investigation of duct leakage, fan operation and door closure

- Used DOE-2, COMIS, and DUCTSIM for coupled multizone thermal and airflow modelling
- No pollutant dispersal modelled
- Emphasis on thermal performance
- Concluded:
  - Duct leakage increases the house air exchange rate, conductive losses and energy consumption (even when system is off)

Modera and Jansky. "Residential Air-Distribution Systems: Interactions with the Building Envelope" TPOEEB V.

Parametric study on Canadian housing

- Used AQ1 (single zone model)
- Varied:
  - Source strengths
  - Weather conditions
  - Ventilation system operation
  - House airtightness
- Concluded:
  - Ventilation strategy based on outdoor to indoor temperature difference could reduce pollutant concentrations and minimize energy cost for non-airtight houses

Hamlin and Cooper. "CMHC Residential Indoor Air Quality - Parametric Study" 13th AIVC Conference.

US EPA and Research Triangle Institute Studies

- Used multizone model IAQPC and conducted experiments
- Model does not include stack effect or weather dependence
- Several pollutant sources and IAQ control options studied
- Concluded:
  - Model pollutant concentration predictions are reasonable
  - Improving efficiency of air cleaners can be effective
  - Source control is important
  - Increasing general ventilation may be ineffective

Owen et. al. "Relating Air Cleaner Efficiency to IAQ" IAQ 92.

Sparks et. al. "Verification and Uses of the EPA IAQ Model" IAQ89. (and others)

Conclusions

- Interactions between building, HVAC system, pollutant sources, and ambient conditions are significant.
- Whole building analysis is essential for studying these interactions.
- Multizone airflow and contaminant dispersal models are appropriate tools for this analysis.

KEY ELEMENTS

- Computer simulation techniques
- Duration of simulations
- Building and HVAC system designs
- Ambient conditions
- Pollutant sources
- IAQ control technologies

Computer Simulation Techniques

- 2 general types of models
  - Room airflow modeling (CFD)
    - Microscopic view
    - Appropriate for studying details within a single zone
  - Multizone modeling
    - Macroscopic view
    - Appropriate for studying whole building including interactions between rooms, HVAC system, pollutant sources, and ambient conditions
    - Examples: CONTAM88, MIX and IAQPC

CONTAM88

- Combination of AIRMOV and CONTAM87
- AIRMOV (predecessor to AIRNET)
  - Input: Building zone and leakage data, HVAC system flows, and ambient conditions
  - Output: Building infiltration and interzone flows
- CONTAM87
  - Input: Infiltration and interzone flows (from AIRMOV) and pollutant source and sink information
  - Output: Zone pollutant concentrations

Duration of simulations

- Project work statement suggested yearlong simulations
- Trade-off between duration of simulations and number of factors to be investigated
- Limit simulations to shortest reasonable period with longest meaningful time steps
- Simulate each combination for typical cold, hot, and mild periods to examine effects of different weather conditions

Building and HVAC system designs

- Only single family residential buildings with central, forced-air HVAC systems
- Project work statement suggests 3 building designs
  - 1. A compact ranch house (1176 ft^2)
  - 2. A townhouse (1315 ft^2)
  - 3. A larger 2 story detached house (1994 ft^2)
- Issues
  - Complexity of modeling townhouse
  - Building airtightness
  - System and duct location

Ambient conditions

- Temperature, wind, and outdoor pollutant concentrations needed
- Dependent on building location
- Project work statement suggests 4 house locations
  - 1. Miami, FL
  - 2. Denver, CO
  - 3. Phoenix, AZ
  - 4. Chicago, IL

Pollutant sources

- Project work statement specifies pollutants of interest
    - NO_2
    - CO
    - Particulates
    - Total VOCs
    - Biologicals
- Source information required includes source strength, location, distribution, and temporal profile
- Literature reviewed for source strength values relevant to residential sources

Decaying area or point source of VOCs

- Modeled by

$$R=R_o*\exp(-kt)$$

- Area example: New floor covering throughout house
- Point example: Newly finished wood table
- R_o: 2200 to 32000 mg/m^2h
- k: 0.24 to 10 h^{-1}
- Issue
    - Sink effects (CONTAM88 includes only non-reversible sink model)

Constant area or point source of VOCs

- Area example: Floor covering for which transients have already decayed
  - Reported source strengths from 0.007 to 7 mg/m^{2}h
- Point example: Household cleaning product
  - Reported source strengths from 2 to 9000 mg/m^{2}h

Constant point source of CO, NO_2, and particulates

- Model as constant source over specific time interval
- Example: Kerosene or gas-fired space heater in attached garage or unheated space
  - Reported source strengths range from 2 to 1225 mg/h of NO_2, from 13 to 25000 mg/h of CO, and from 0.026 to 186 mg/h of particulates
- Example: gas stove or oven
  - Reported source strengths range from 36 to 700 mg/h of NO_2, from 180 to 3600 mg/h of CO, and from 0.1 to 30 mg/h of particulates
- Issues
  - NO2 decay and particle deposition (CONTAM88 includes simple deposition and kinetic reaction models)

Constant short term (or intermittent) point source of particulates

- Model as constant source over specific time interval
- Example: vacuum cleaning
  - Reported source strength of 5×10^8 particles/min

Outdoor source of particulates, CO or NO_2

- Model as constant change in outdoor pollutant concentration over specific time interval
- Examples: episodic release of pollen or dust and large emission of pollutants from traffic

Source of biological pollutants

- Examples: contaminated humidifier or ductwork and moldy wood
- Little quantitative information in literature
  - Reported souce strength of 5.5×10^5 CFU/h from a rotting wood cabinet in hospital
- Issue
  - Appropriateness of controlling by modifying HVAC system
  - Least specific modeling information

IAQ Control Technologies

- Filtration
  - Particulates
    - Many available with performance ratings per ASHRAE Standard 52-76
  - Gases
    - Available types include panel filters impregnated with a sorbent and free-standing systems that attach to return ductwork
    - No standardized performance rating
    - Limited performance data
  - Issue
    - Capacity of gaseous sorbents

IAQ Control Technologies

- Heat recovery ventilators
  - Outdoor air supplied to return ductwork
  - Exhaust air removed from upstream in return ductwork or elsewhere in house
  - Control options: continuous operation, schedule, humidity
  - Performance data available
- Outdoor air intake devices
  - Connect to return ductwork
  - Air distributed by system blower
  - Control options : manual, schedule, humidity, CO_2
  - Exhaust fan to balance intake airflow is optional

IAQ Control Technologies

- Eliminating duct leakage
  - Impact can be significant
- HVAC system control
  - Would be in combination with other options (E.g. CO_2 control of outdoor intake damper)
  - Requires use of coupled version of CONTAM88 with a transient simulation program such as TRNSYS

OUTLINE OF PROJECT PLAN

Outline

- Use CONTAM88
- Limit each simulation to short duration (~ 1 week). Perform for typical cold, hot and mild periods

- 2 basic house designs
  - Single story ranch house
  - Two story house with basement
- 2 levels of airtightness
  - Typical
  - Tight
- 2 locations
  - Miami, FL
  - Chicago, IL

Outline

- Pollutant sources
  - 1. Decaying VOC point sources located on each story of each house
  - 2. Constant VOC area source located throughout each house (excluding the basement)
  - 3. Short term constant combustion point sources: space heater in garage and gas oven in kitchen of each house
  - 4. Short term increase in the outdoor concentration of particulates and CO
  - 5. Short term bioaerosol point source on each story of each house

Outline

- Include three IAQ control technologies
  - 1. Improved particulate air filter and gaseous contaminant air cleaner
  - 2. Heat recovery ventilator designed for connecting to a central forced-air HVAC system
  - 3. Outdoor intake damper connected to the return ductwork of the forced-air system

FOLLOW-UP WORK AND RELATED ISSUES

- Other pollutants and sources
- Other residential ventilation systems
- Energy impacts
- Duct leakage
- Backdrafting
- Moisture effects

Other Pollutants and Sources

- Soil gas
- Formaldehyde
- Carbon dioxide
- Ozone

Other Residential Ventilation Systems

- Air-to-air heat exchanger independent of forced-air system
- Exhaust air heat pump
  - Fresh air inlets
  - Whole house or spot exhaust
- Exhaust ventilation without heat recovery
  - Fresh air inlets
  - Whole house or spot exhaust
- Controls
  - Humidity
  - Manual
  - Schedule
  - Carbon dioxide
  - Occupancy sensor
  - VOCs or other pollutants

Energy Impacts

- Requires coupled thermal and airflow analysis
  - DOE-2 or TRNSYS with multizone airflow analysis, e.g. AIRNET
  - Fully integrated analysis, e.g. dTAM

Duct Leakage

- Requires coupled thermal and airflow analysis
- Impacts pressure driven sources
  - Soil gas
  - Airflow from adjoining spaces, e.g. garages
- Impacts building air change rates
- Requires more detailed ventilation system model in airflow analysis

Backdrafting

- Requires coupled thermal and airflow analysis
- Requires flue model, e.g. FLUESIM

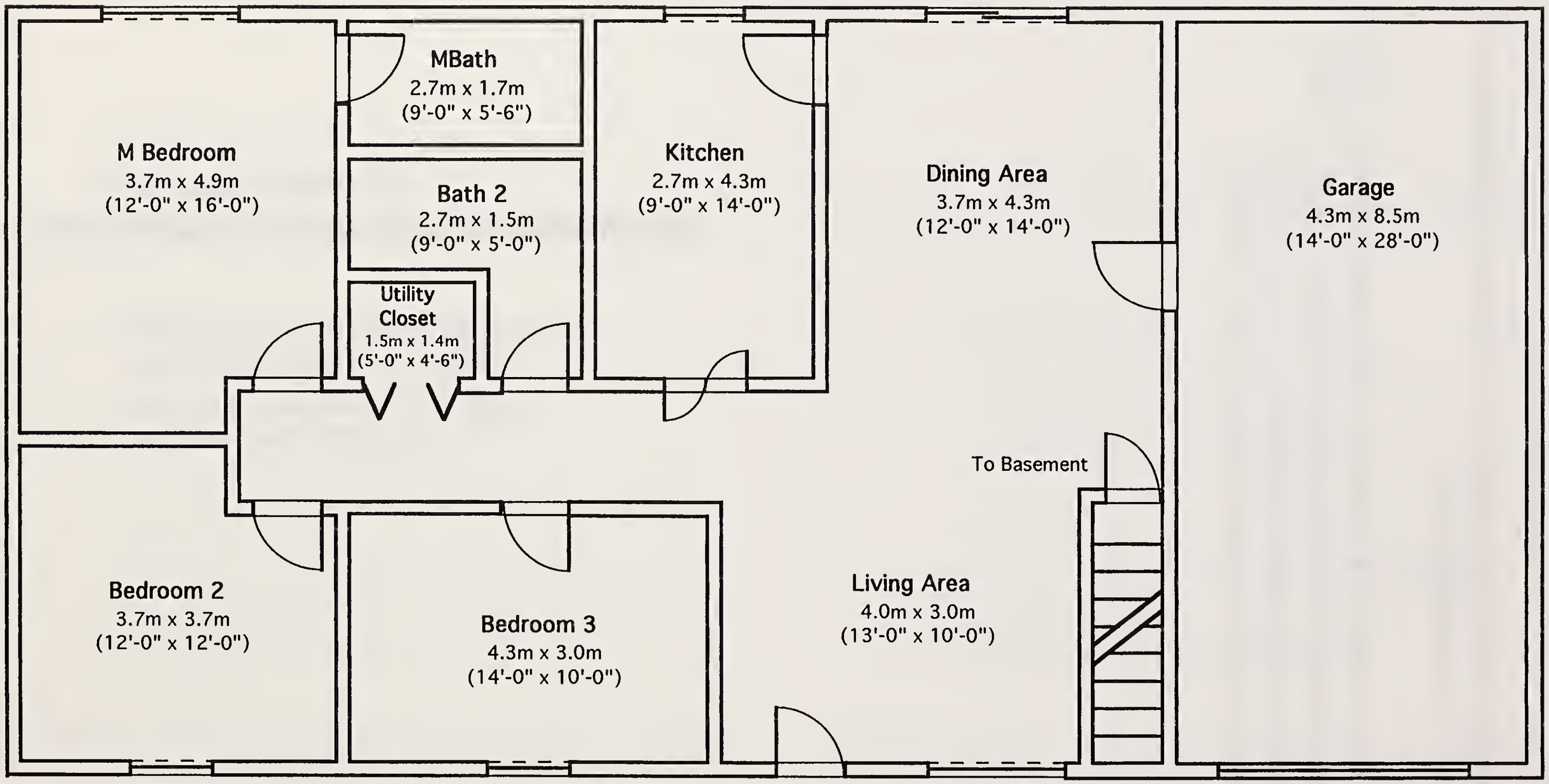
Moisture effects

- Requires modeling of moisture absorption and desorption
- Requires moisture transport properties of materials

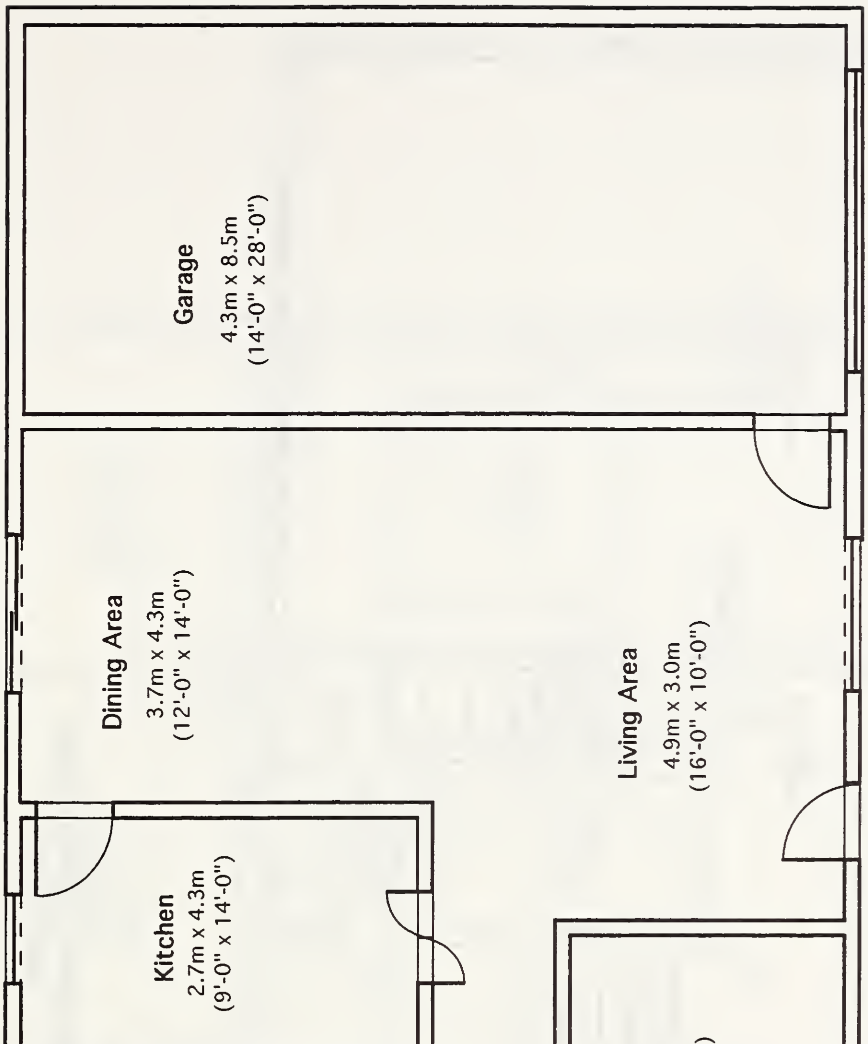
Appendix C Building Floorplans

This appendix contains floorplan drawings for each of the building/city combinations to be modeled in the simulations. The four buildings are:

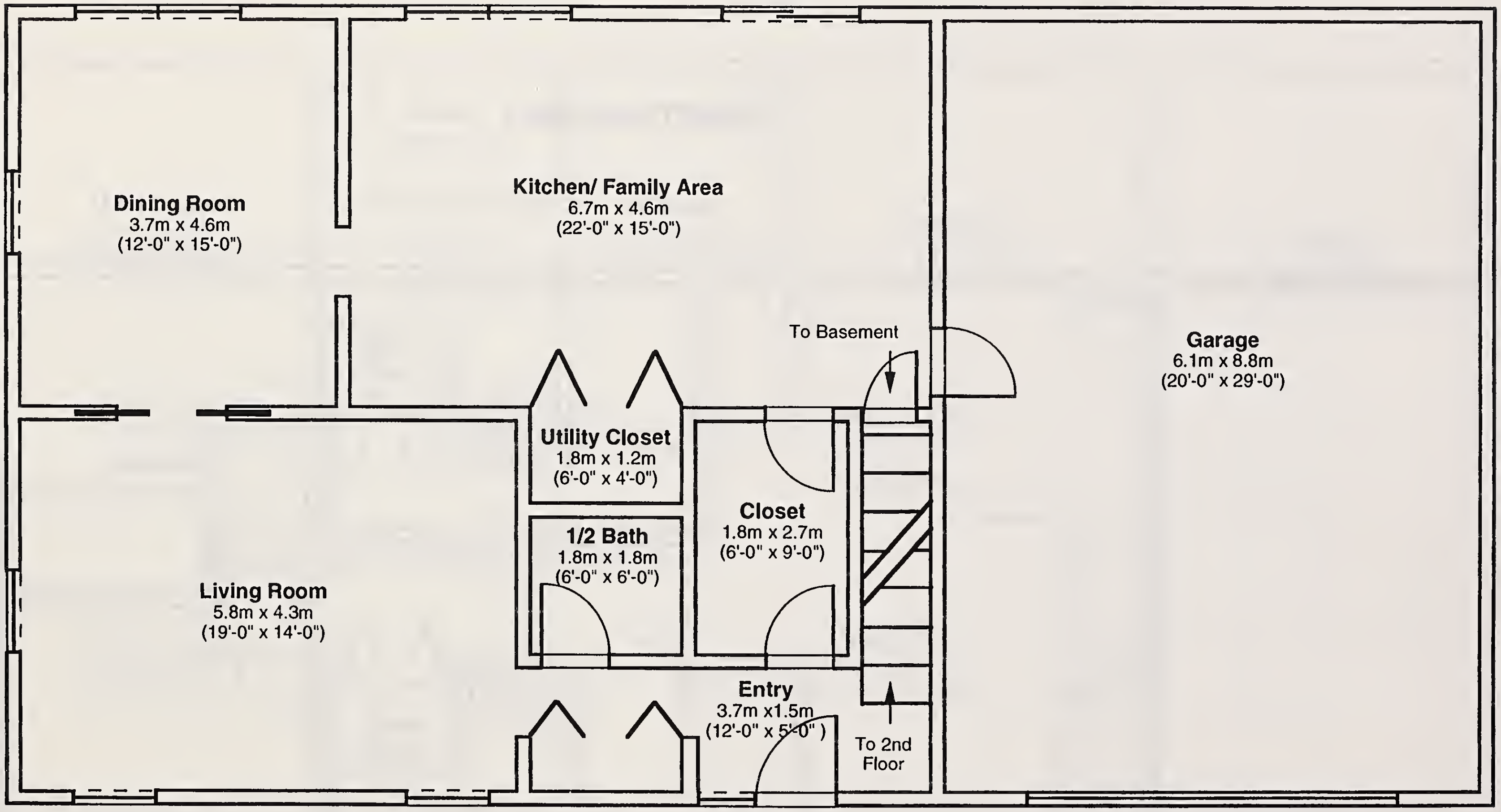
1. A compact ranch style house with a basement in Minneapolis, 109 m^2 (1170 ft^2).
2. A compact ranch style house with a slab-on-grade in Miami, 109 m^2 (1170 ft^2) .
3. A two story house with a basement in Minneapolis, 185 m^2 (1990 ft^2).
4. A two story house with a slab-on-grade in Miami, 185 m^2 (1990 ft^2).



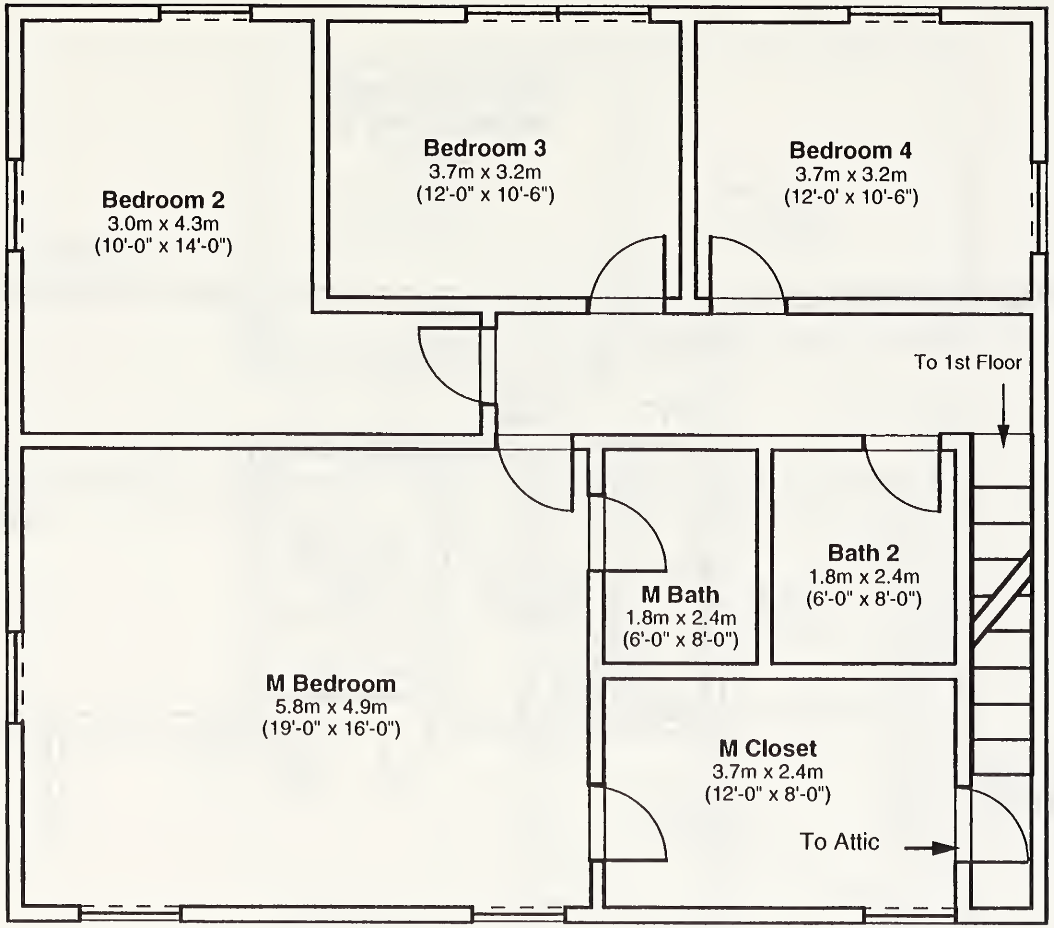
Minneapolis Ranch House



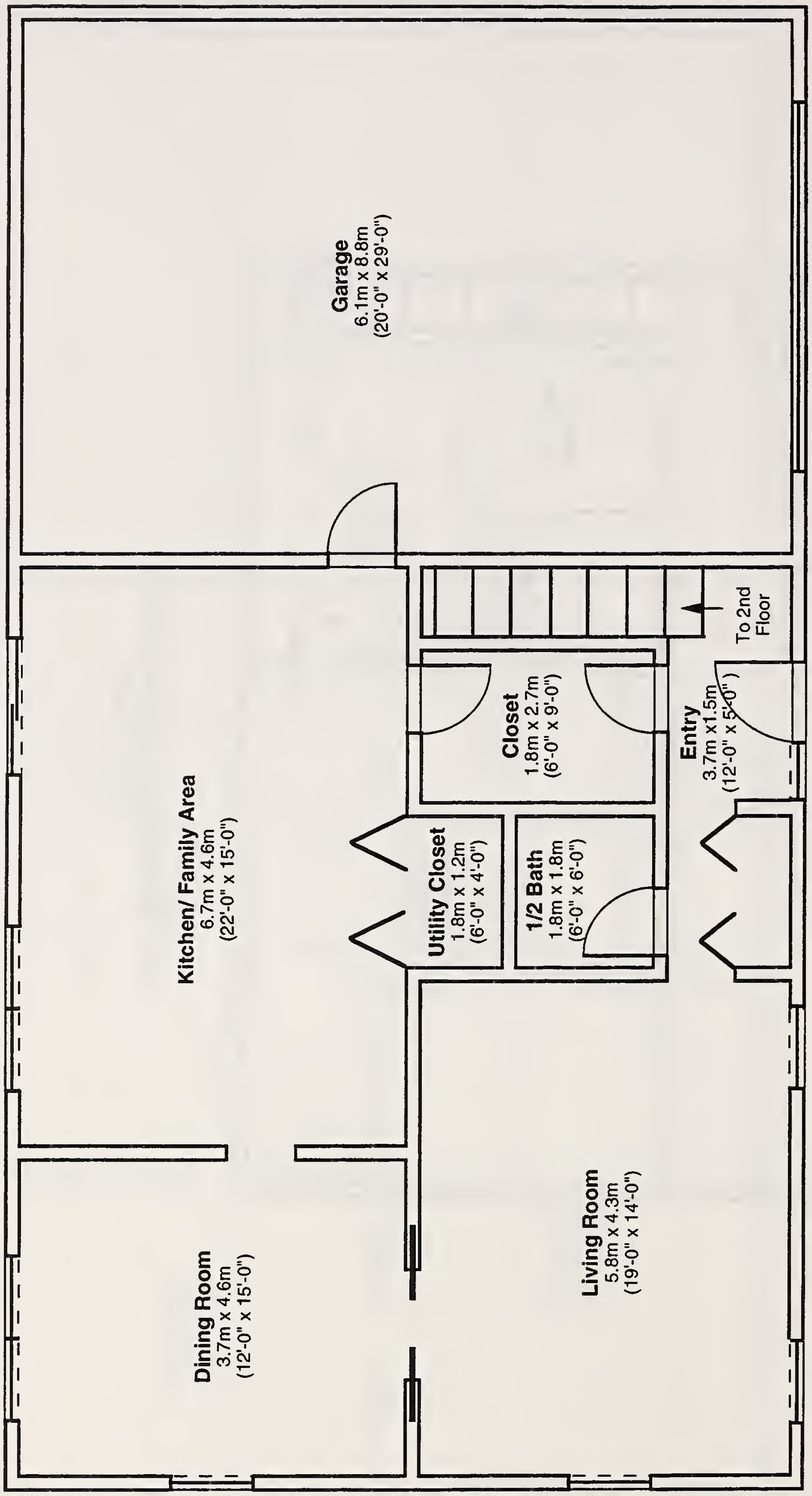
Miami Ranch House



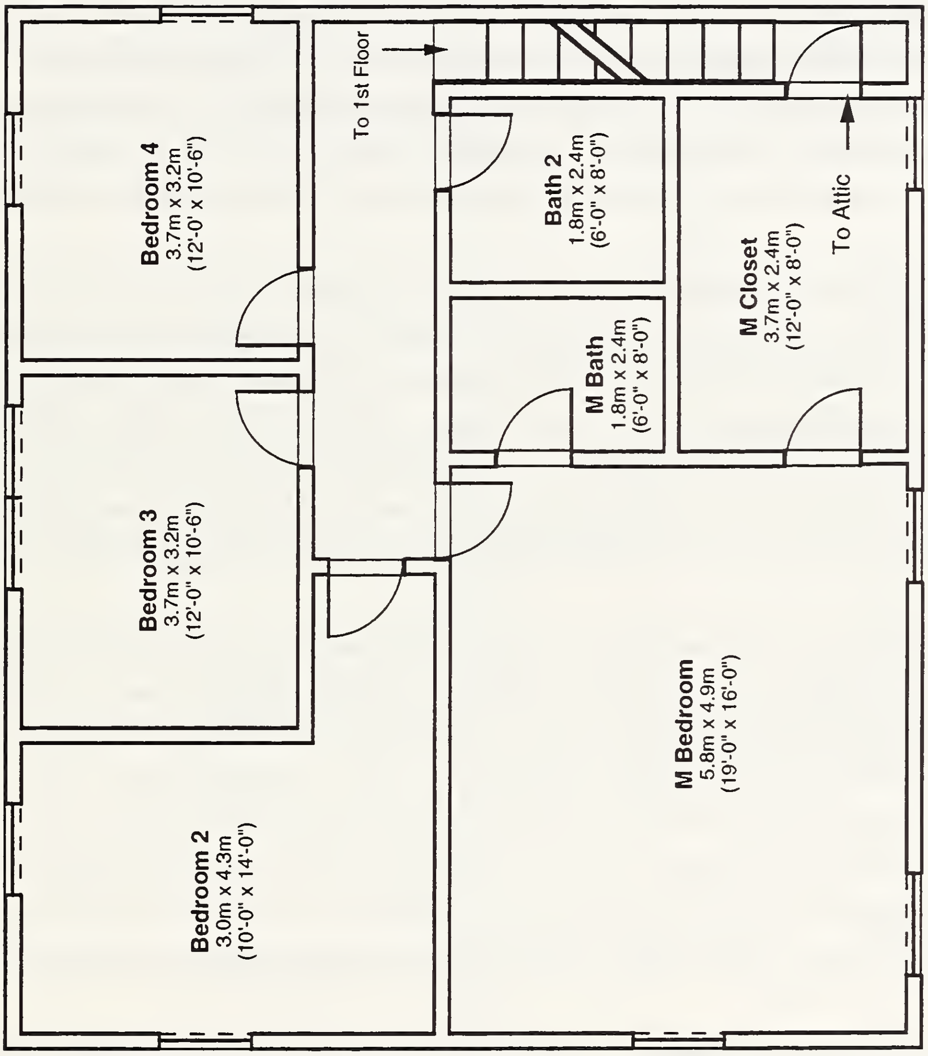
Minneapolis 2-Story House
Lower Floor



Minneapolis 2- Story House
Upper Floor



Miami
2-Story House
Lower Floor Plan



Miami 2- Story House
Upper Floor

Appendix D HVAC System Descriptions

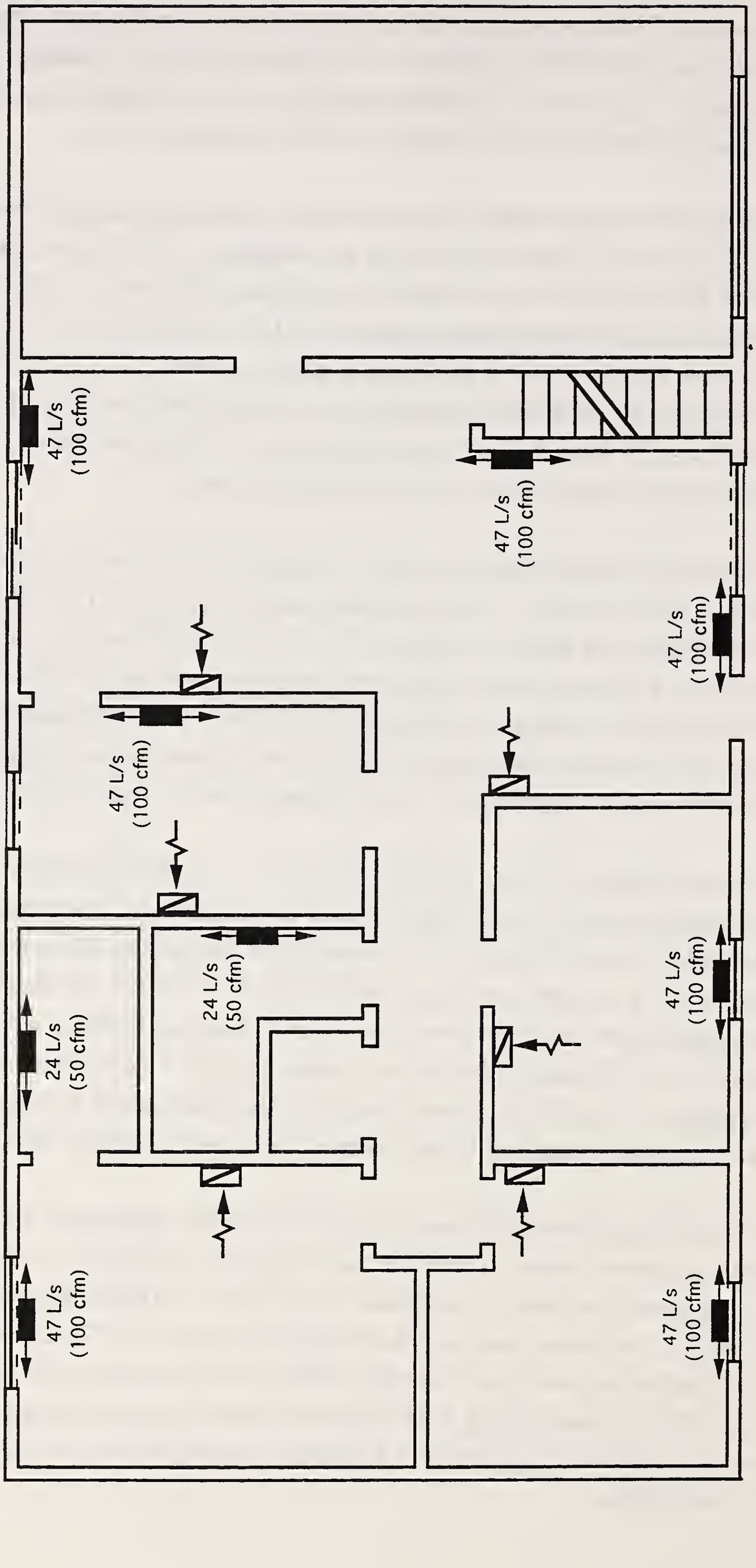
This appendix describes the HVAC systems for each of the four houses and contains duct layout drawings. Commercially available HVAC equipment was chosen based on the heating and cooling load calculations presented in Appendix E. Guidelines published by the National Association of Home Builders (103) 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.

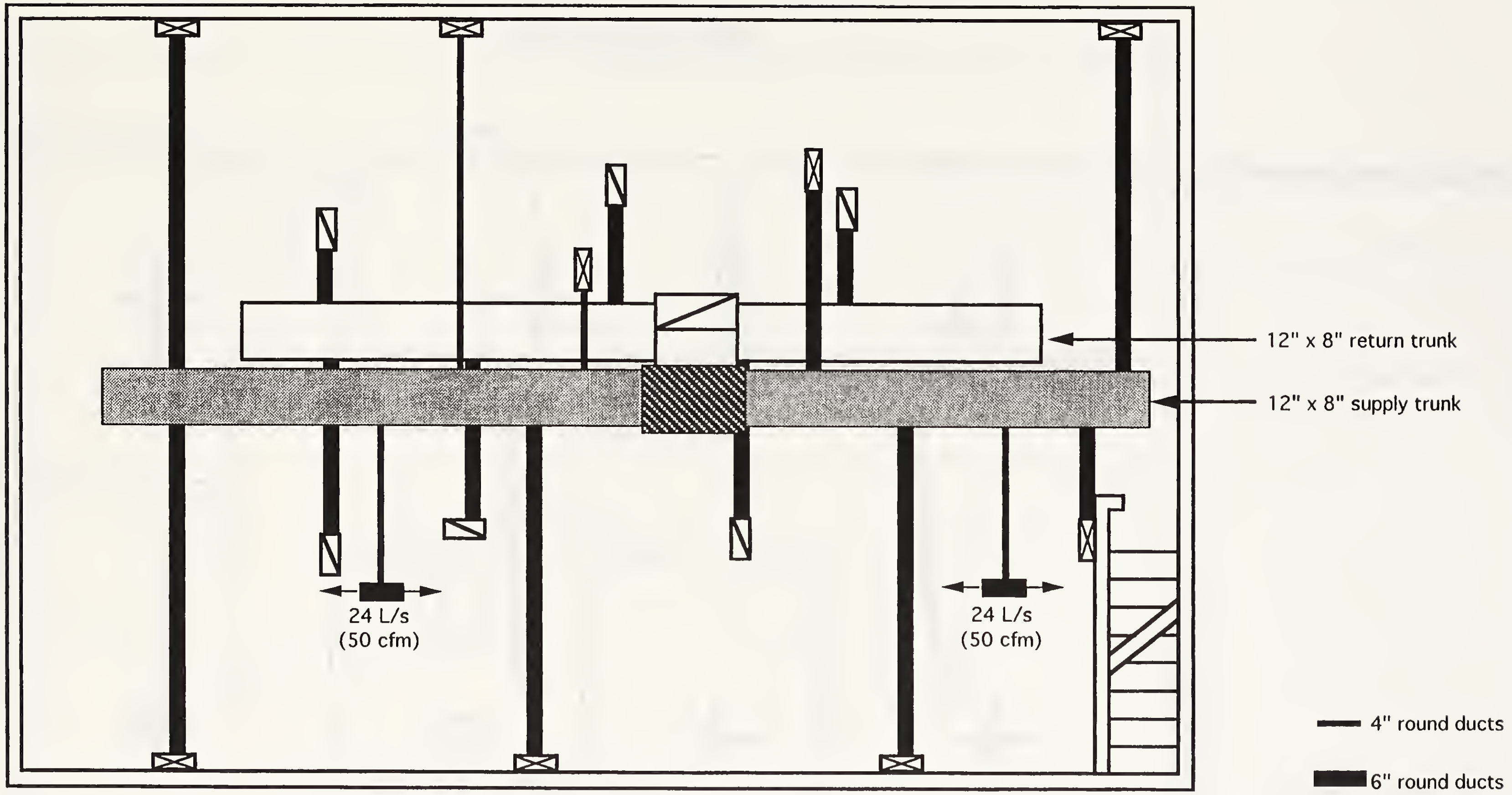
Equipment selected for the Miami ranch house is a split-system air conditioner and a direct expansion fan coil with an electric heater. The heater has a capacity of 10 kW (34,100 Btu/hr). The air conditioner has a capacity at design conditions of 6.35 kW (21,700 Btu/hr) and an SEER of 10.0. The system 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 Annual Fuel Utilization Efficiency (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.

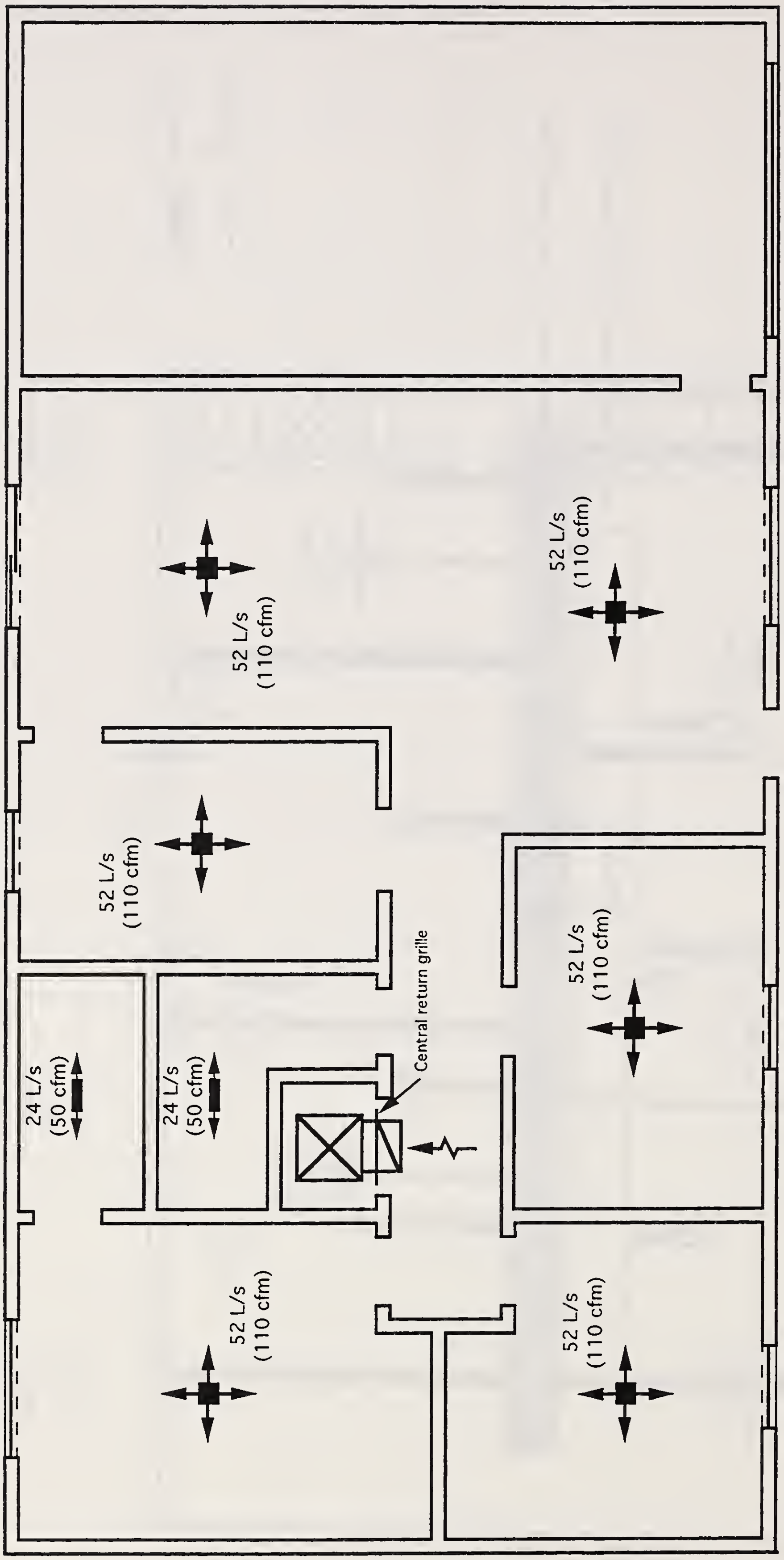
Equipment selected for the Miami two-story house is a split-system air conditioner and a direct expansion fan coil with an electric heater. The heater has a capacity of 10 kW (34.100 Btu/hr). The air conditioner has a capacity at design conditions of 6.35 kW (21,700 Btu/hr) and an SEER of 10.0. The system 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.



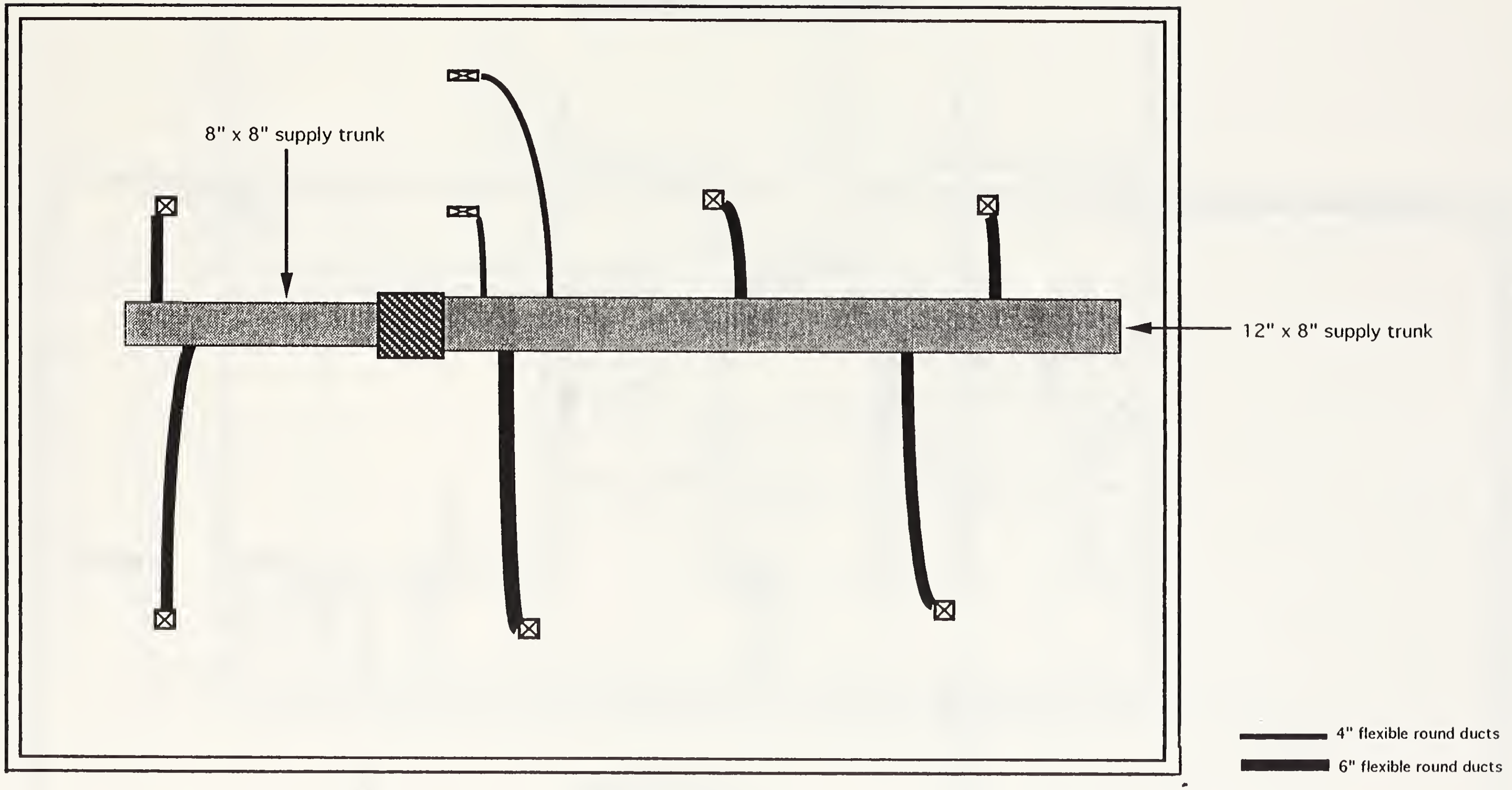
Minneapolis Ranch House



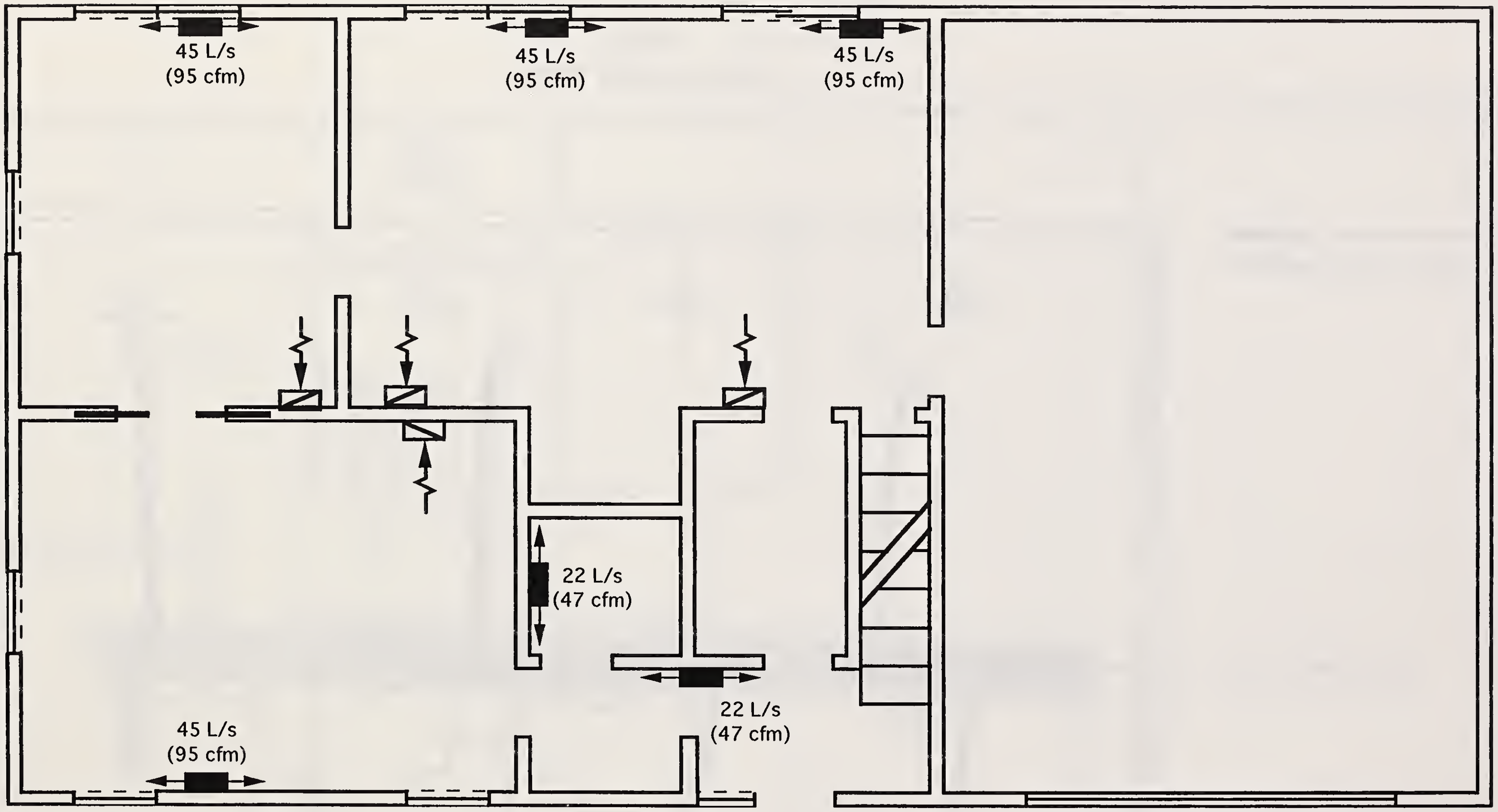
Minneapolis Ranch House
Basement



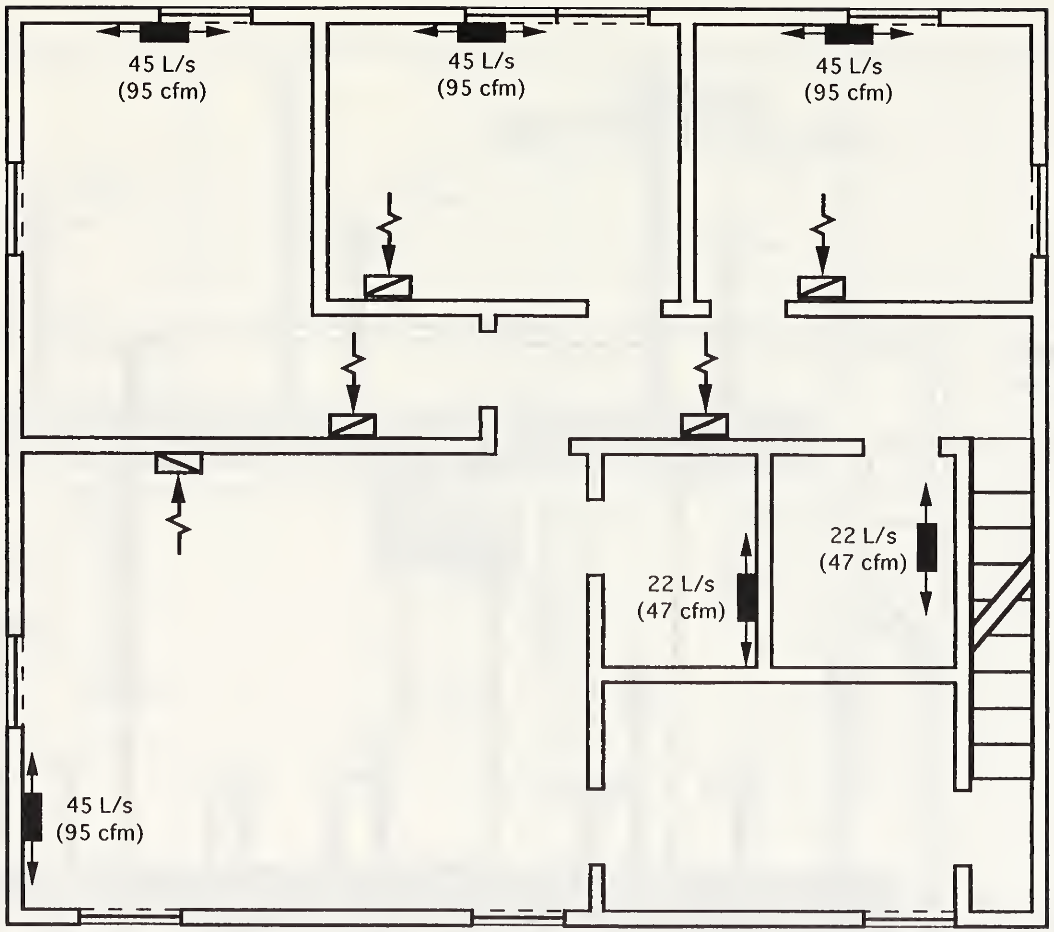
Miami Ranch House



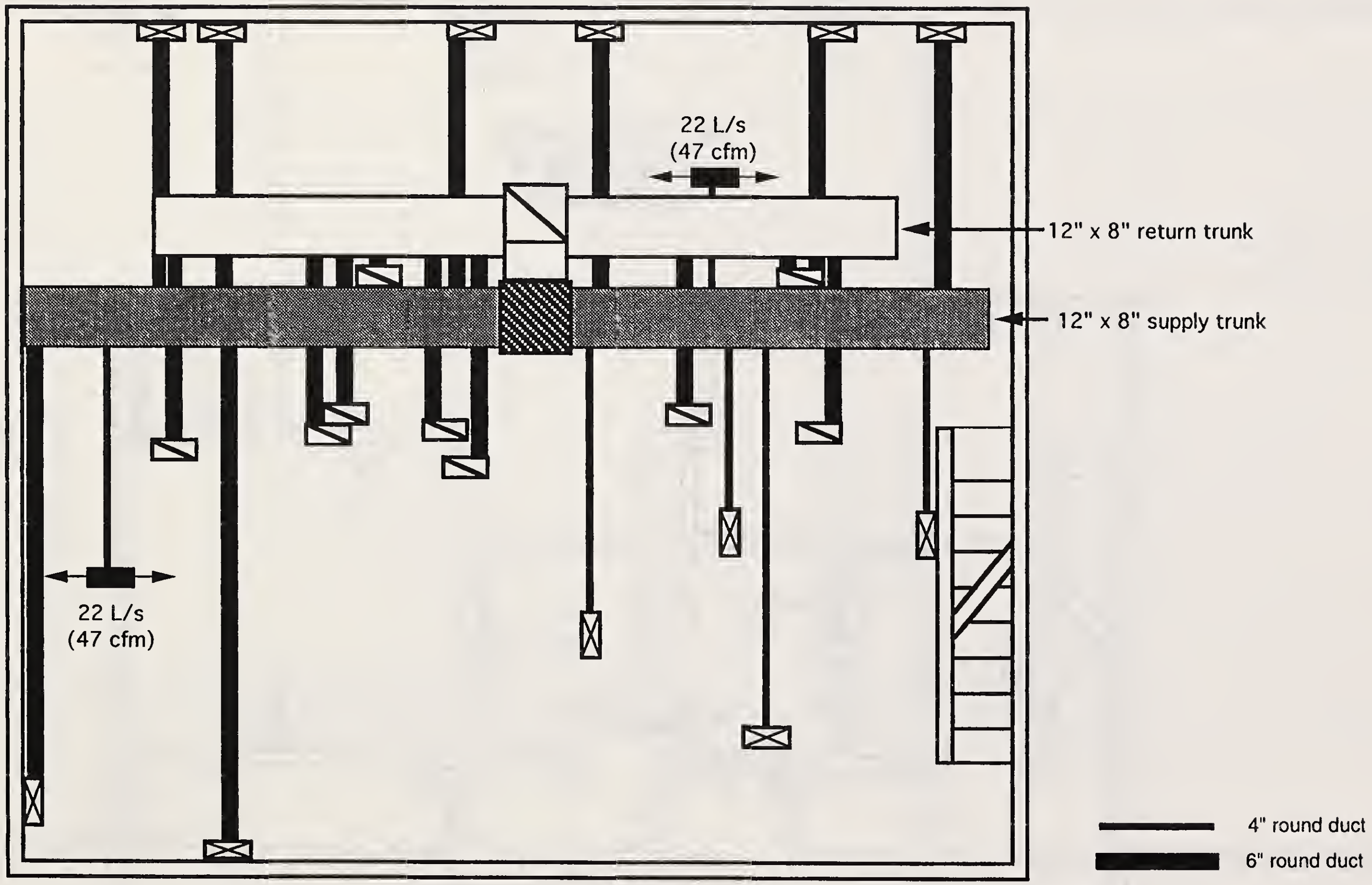
Miami Ranch House
Attic



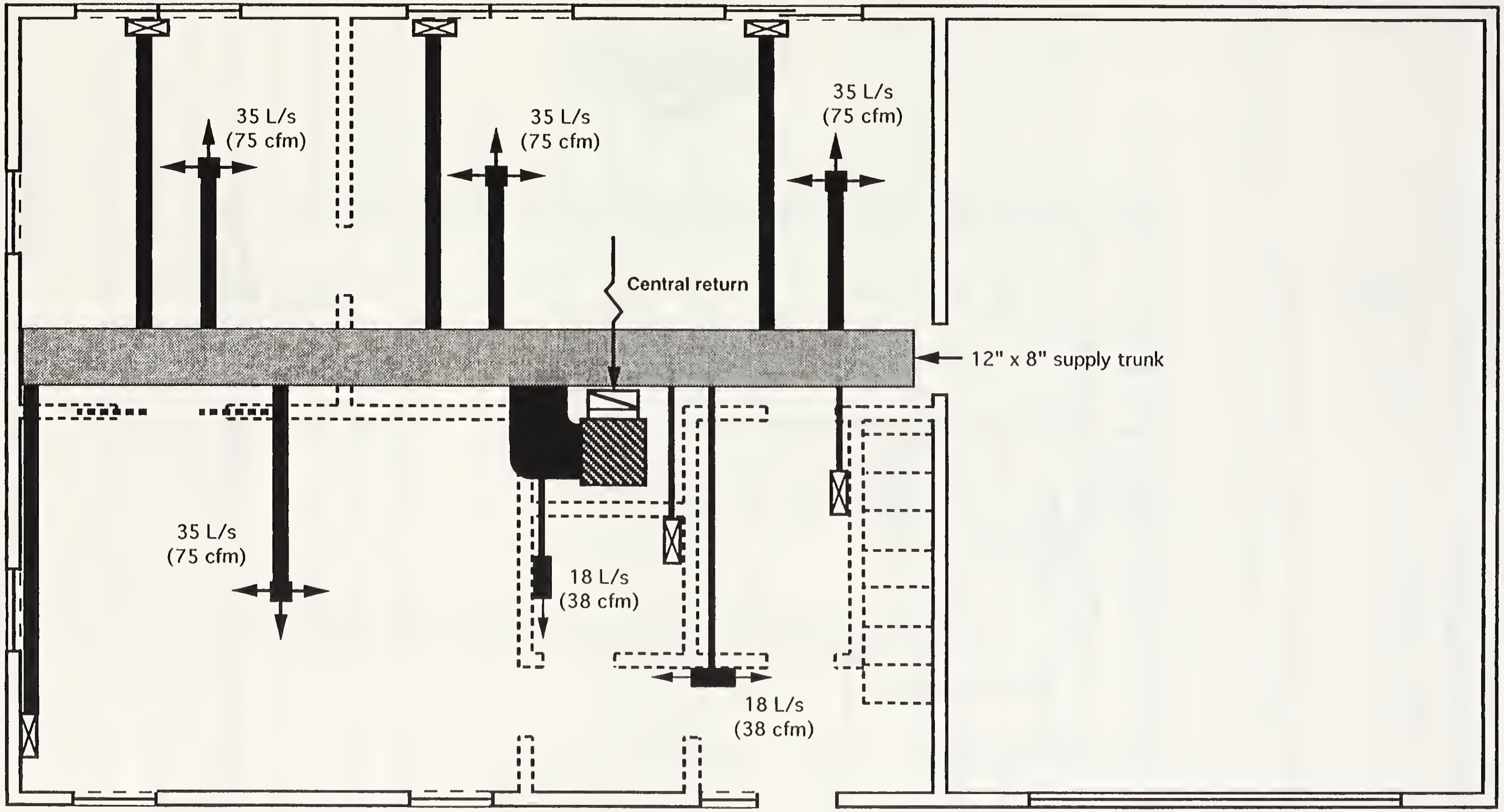
Minneapolis 2-Story House
Lower Floor



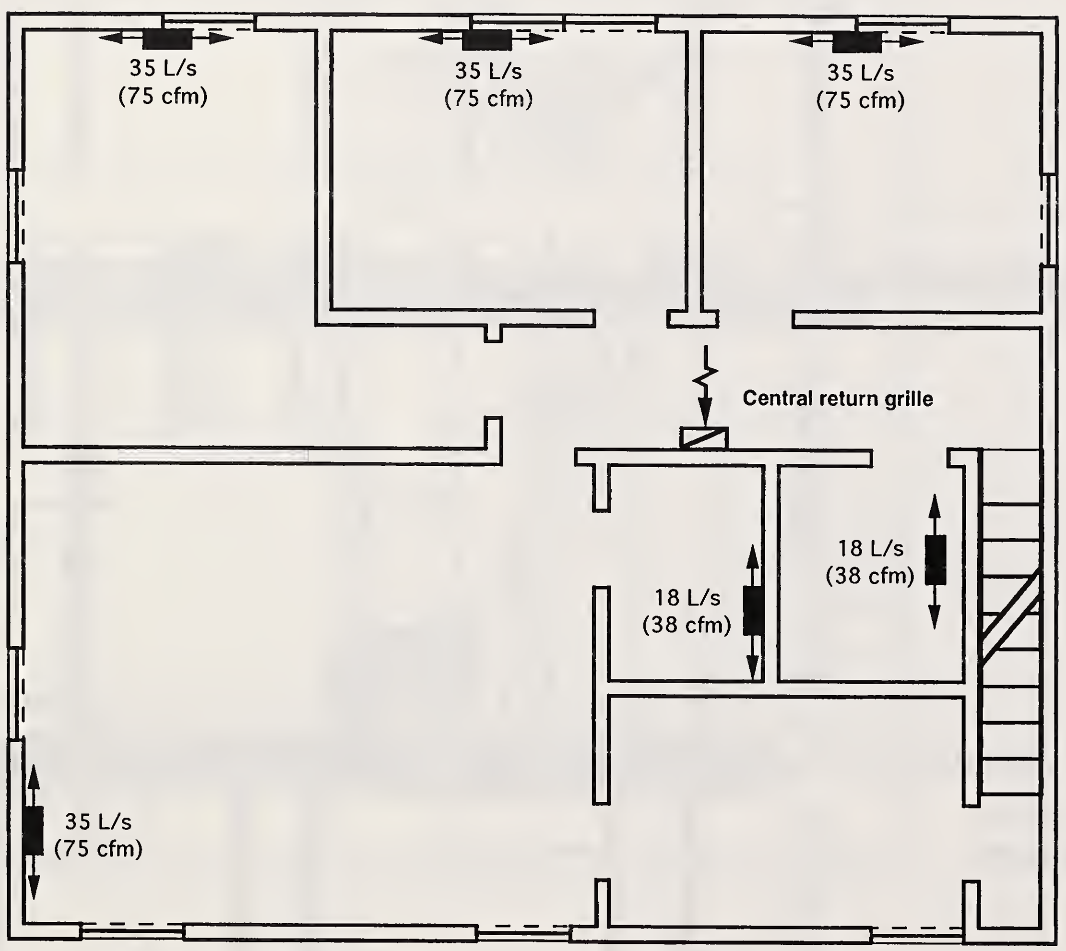
Minneapolis
2- Story House
Upper Floor Plan



Minneapolis 2-Story House
Basement



Miami
2-Story House
Plenum Between Floors



Miami
2- Story House
Upper Floor Plan

Appendix E Design Heating and Cooling Load Calculations

This appendix contains design heating and cooling load calculations for each of the four building/location combinations. The calculation method used is from the ASHRAE Handbook of Fundamentals (79) and the Sheet Metal and Air Conditioning Contractors National Association (SMACNA) Installation Standards (105).

The design heating load calculation method consists of calculating conduction losses through the walls, windows, ceiling, and foundation and the infiltration losses through the building envelope.

$$q = UA\Delta T \qquad [1]$$

Conduction losses through walls, windows, and ceilings are calculated by equation 1 (79). The values used for U are from the project work statement (1). The areas are from the NBSIR describing the houses (92). Temperature differences across each surface based on an indoor design temperature of 21 C (79), the 97.5% winter design outdoor temperature (79), a garage temperature at the average of the indoor and outdoor temperature (105), and an attic temperature of 6 C above the outdoor design temperature (105).

$$q = F_2 P\Delta T \qquad [2]$$

Conduction losses through a slab on grade foundation (Miami houses) are calculated by equation 2 (79). The heat loss coefficient per meter of perimeter, F_2, is from Table 25-16 of ASHRAE (79). The perimeter is from the NBSIR (92). The temperature difference used in this equation is the indoor - outdoor design temperature (79).

$$q = UP\Delta T \qquad [3]$$

Conduction losses through the walls of a basement foundation are calculated by equation 3 (79). The overall heat loss factor, U, is determined as a sum of heat loss factors for each 300 mm increment below grade according to Table 25-14 of ASHRAE (79). An 8" block wall with 2" of insulation for the first 1.2 m was assumed. The temperature difference used was the indoor - ground design temperature. The ground design temperature was determined by subtracting the mean ground surface fluctuation from the mean winter air temperature for each location (79). Conduction losses through the basement floor were calculated by equation [1] with the temperature difference based on the indoor - ground design temperature (79).

$$q = 1.2Q\Delta T \qquad [4]$$

The infiltration loss is calculated with equation 4 (79). The infiltration flow, Q, is based on 0.75 air changes per hour (ach) from the project work statement (1). The temperature difference is the indoor - outdoor temperature difference.

The design cooling load calculation method consists calculating sensible cooling loads for each room for doors, walls, glass, ceilings, and partitions to unconditioned spaces, infiltration loads through the building envelope, and internal loads due to people, appliances, and lights. Duct losses are added to the sensible cooling load and a latent load factor is then used to determine the total cooling load.

$$q = (GLF)A \qquad [5]$$

Equation [5] was used for the cooling load due to glass. The glass load factor , GLF, includes effects of both transmission and solar radiation and is determined from ASHRAE Tables 25-3 (79) according to window orientation, type of glass, interior shading, and outdoor design temperature. 2.5% summer design temperatures were used (79). According to the project work statement , the wall with the maximum glazing was assumed to face west (1). Windows were assumed to be regular double glass with medium interior shading. The first floor windows under the overhang were treated as north facing windows (79). The window areas were from the NBSIR (92).

$$q = UA(CLTD) \qquad [6]$$

Equation 6 was used for the transmission cooling load due to the walls, ceilings, doors, and partitions. As above, values from the NBSIR (92) and the project work statement (1) were used for A and U, respectively. The cooling load temperature differences, CLTD, used were from ASHRAE Table 25-1 (79) according to orientation, design temperature, and the design daily temperature range. The design daily temperature range accounts for the outdoor temperature swing on a design day and is found in ASHRAE Table 24-1 (79).

As above, the infiltration load is calculated by equation 4 and is based on 0.75 ach.

Internal gains included 67 W per person (assuming two people for the first bedroom and one person for each other bedroom) divided evenly among rooms not used as bedrooms and 470 W for the appliance load for both kitchen and laundry rooms divided among the adjacent rooms (79).

Duct losses were assumed to be 10% for ducts located in the attic (79), 5% for ducts located in the basement, and 0% for ducts located within the conditioned space (105).

The total cooling load was estimated by multiplying the total sensible load (from the loads above) by a latent factor. The latent factor used was from ASHRAE Figure 25-1 (79) for a 50% design indoor relative humidity, medium construction, and 2.5% design outdoor humidity ratio based on the mean coincident design wet bulb temperature from ASHRAE Table 24-2 (79).

HOUSE: Ranch
LOCATION: Minneapolis
LOAD TYPE: Heating
INDOOR T (C): 21
OUTDOOR T (C): -24
ATTIC T (C): -19
GARAGE T (C): -2

CONDUCTION LOSSES						
			U (W/sq m K)	A (sq m)	dT (K)	q (W)
WINDOWS			2.84	11.8	46	1526
WALLS	To ambient		0.28	69.6	46	900
	To garage		0.28	19.0	23	123
DOORS	To ambient		1.89	1.9	46	160
	To garage		1.89	1.9	23	80
CEILING	To attic		0.19	109.3	40	827
BASEMENT						
Walls above grade	To ambient		0.68	21.1	46	655
Walls below grade	Depth	U (W/mK)				
	0 - 0.3 m	0.16				
	0.3 - 0.6 m	0.14				
	0.6 - 0.9 m	0.12				
	0.9 - 1.2 m	0.10				
	1.2 - 1.5 m	0.17				
	1.5 - 1.8 m	0.14				
	1.8 - 2.1 m	0.12				
	Total	0.94				
			U (W/mK)	P (m)	dT (K)	q (W)
	To ground		0.94	42.7	35	1420
Floor			U (W/sq m K)	A (sq m)	dT (K)	q (W)
	To ground		0.13	109.3	35	505
INFILTRATION LOSSES						
		ACH	(kJ/cu. m K)	Vol. (cu. m)	dT (K)	q (W)
		0.75	1.21	266.4	46	3056
TOTAL HEAT LOSS						q (W)
						9252

HOUSE: Ranch
LOCATION: Minneapolis
LOAD TYPE: Cooling
INDOOR T (C): 24
OUTDOOR T (C): 32
WET BULB (C): 23

Room Transmission Cooling Loads

MBedroom					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.9		0.28	10	0.02
West glass	2.0	129			0.26
Roof	18.1		0.19	23	0.08
South Wall	11.8		0.28	6	0.02
Total					0.38

Bedroom 3					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East Wall	9.0		0.28	10	0.03
East Glass	1.3	129			0.17
Roof	13.7		0.19	23	0.06
Total					0.25

Kitchen					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	5.5		0.28	10	0.02
West glass	1.0	129			0.13
Roof	11.6		0.19	23	0.05
Total					0.20

Bathroom 2					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
Roof	4.1		0.19	23	0.02
Total					0.02

Bedroom 2					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	7.6		0.28	10	0.02
East glass	1.3	129			0.17
Roof	13.7		0.19	23	0.06
South Wall	8.9		0.28	6	0.01
Total					0.26

Living/Dining Area

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	7.3		0.28	10	0.02
East glass	2.6	129			0.34
East door	1.9		1.89	10	0.04
Roof	30.6		0.19	23	0.13
Partition (garage)	20.4		0.28	4	0.02
West wall	5.2		0.28	10	0.01
West glass	3.7	129			0.48
Total					1.04

M Bathroom

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.5		0.28	10	0.02
Roof	4.6		0.19	23	0.02
Total					0.04

Other space

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
Roof	26.0		0.19	23	0.11
Total					0.11

Summary of Sensible Cooling Load Estimate

Room	Walls, doors, etc kW	Internal gains kW	Infiltration kW	Total kW
M bedroom	0.38	0.12	0.09	0.59
Bedroom 2	0.26		0.07	0.33
Bedroom 3	0.25		0.06	0.31
Kitchen	0.20	0.24	0.06	0.50
Living/dining area	1.04	0.51	0.15	1.70
M bathroom	0.04		0.02	0.06
Bathroom 2	0.02	0.12	0.02	0.16
Other space	0.11	0.24	0.05	0.40
Total	2.30	1.23	0.52	4.05

Duct loss (5%)		0.20
Total sensible		4.25
Total sensible & latent cooling load	Latent Factor 1.15	**4.89**

HOUSE:	Ranch
LOCATION:	Miami
LOAD TYPE:	Heating
INDOOR T (C):	21
OUTDOOR T (C):	8
ATTIC T (C):	14
GARAGE T (C):	14

CONDUCTION LOSSES					
		U (W/sq m K)	A (sq m)	dT (K)	q (W)
WINDOWS		2.84	11.8	13	428
WALLS	To ambient	0.28	69.6	13	252
	To garage	0.28	19.0	7	36
DOORS	To ambient	1.89	1.9	13	45
	To garage	1.89	1.9	7	23
CEILING	To attic	0.19	109.3	7	149
SLAB		F2 (W/m K)	P (m)	dT (K)	q (W)
	To ground	0.07	42.7	13	41

INFILTRATION LOSSES					
	ACH	(kJ/cu. m K)	Vol. (cu. m)	dT (K)	q (W)
	0.75	1.21	266.4	13	857

TOTAL HEAT LOSS	q (W)
	1832

HOUSE: Ranch
LOCATION: Miami
LOAD TYPE: Cooling
INDOOR T (C): 24
OUTDOOR T (C): 32
WET BULB (C): 25

Room Transmission Cooling Loads

MBedroom					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.9		0.28	13	0.03
West glass	2.0	129			0.26
Roof	18.1		0.19	26	0.09
South Wall	11.8		0.28	9	0.03
Total					0.40

Bedroom 3					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East Wall	9.0		0.28	13	0.03
East Glass	1.3	129			0.17
Roof	13.7		0.19	26	0.07
Total					0.27

Kitchen					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	5.5		0.28	13	0.02
West glass	1.0	129			0.13
Roof	11.6		0.19	26	0.06
Total					0.21

Bathroom 2					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
Roof	4.1		0.19	26	0.02
Total					0.02

Bedroom 2					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	7.6		0.28	13	0.03
East glass	1.3	129			0.17
Roof	13.7		0.19	26	0.07
South Wall	8.9		0.28	9	0.02
Total					0.29

Living/Dining Area					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	7.3		0.28	13	0.03
East glass	2.6	129			0.34
East door	1.9		1.89	13	0.05
Roof	30.6		0.19	26	0.15
Partition (garage)	20.4		0.28	7	0.04
West wall	5.2		0.28	13	0.02
West glass	3.7	129			0.48
Total					1.10

M Bathroom					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.5		0.28	13	0.02
Roof	4.6		0.19	26	0.02
Total					0.05

Other space					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
Roof	26.0		0.19	26	0.13
Total					0.13

Summary of Sensible Cooling Load Estimate

Room	Walls, doors, etc kW	Internal gains kW	Infiltration kW	Total kW
M bedroom	0.40	0.12	0.09	0.61
Bedroom 2	0.27		0.07	0.33
Bedroom 3	0.27		0.06	0.33
Kitchen	0.21	0.24	0.06	0.50
Living/dining area	1.10	0.51	0.15	1.76
M bathroom	0.05		0.02	0.07
Bathroom 2	0.02	0.12	0.02	0.16
Other space	0.13	0.24	0.05	0.42
Total	2.43	1.23	0.52	4.19

Duct loss (10%)		0.42
Total sensible		4.60
Total sensible & latent cooling load	Latent Factor 1.25	**5.76**

HOUSE:	Two story
LOCATION:	Minneapolis
LOAD TYPE:	Heating
INDOOR T (C):	21
OUTDOOR T (C):	-24
ATTIC T (C):	-19
GARAGE T (C):	-2

CONDUCTION LOSSES						
			U (W/sq m K)	A (sq m)	dT (K)	q (W)
WINDOWS			2.84	20.5	46	2655
WALLS	To ambient		0.28	118.8	46	1537
	To garage		0.28	21.7	23	141
DOORS	To ambient		1.89	1.9	46	160
	To garage		1.89	1.9	23	80
CEILING	To attic		0.19	94.8	40	717
BASEMENT						
Walls above grade	To ambient		0.68	18.9	46	587
Walls below grade	Depth	U (W/mK)				
	0 - 0.3 m	0.16				
	0.3 - 0.6 m	0.14				
	0.6 - 0.9 m	0.12				
	0.9 - 1.2 m	0.10				
	1.2 - 1.5 m	0.17				
	1.5 - 1.8 m	0.14				
	1.8 - 2.1 m	0.12				
	Total	0.94				
			U (W/mK)	P (m)	dT (K)	q (W)
	To ground		0.94	38.2	35	1270
Floor			U (W/sq m K)	A (sq m)	dT (K)	q (W)
	To ground		0.13	90.6	35	419
INFILTRATION LOSSES		ACH	(kJ/cu. m K)	Vol. (cu. m)	dT (K)	q (W)
		0.75	1.21	442.2	46	5072
TOTAL HEAT LOSS						q (W)
						12638

HOUSE: Two story
LOCATION: Minneapolis
LOAD TYPE: Cooling
INDOOR T (C): 24
OUTDOOR T (C): 32
WET BULB (C): 23

Room Transmission Cooling Loads

MBedroom

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	11.9		0.28	10	0.03
East glass	2.0	129			0.26
South glass	1.0	93			0.09
South Wall	10.8		0.28	6	0.02
Roof	28.4		0.19	23	0.12
Total					0.40

Bedroom 2

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.2		0.28	10	0.02
West glass	1.0	129			0.13
South glass	1.0	93			0.09
Roof	12.9		0.19	23	0.06
South Wall	9.3		0.28	6	0.02
Total					0.31

Bedroom 3

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.9		0.28	10	0.02
West glass	2.0	129			0.26
Roof	11.8		0.19	23	0.05
Total					0.33

Bedroom 4

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	10.8		0.28	10	0.03
West glass	1.0	129			0.13
North glass	1.0	50			0.05
Roof	11.8		0.19	23	0.05
North wall	6.7		0.28	4	0.01
Total					0.27

M Bath/closet

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	7.9		0.28	10	0.02
East glass	1.0	129			0.13
Roof	13.2		0.19	23	0.06
Total					0.06

Bathroom 2

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
Roof	4.3		0.19	23	0.02
Total					0.02

Other space - upper

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
North wall	14.2		0.28	4	0.02
Roof	12.1		0.19	23	0.05
Total					0.05

Kitchen/family area

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	11.0		0.28	10	0.03
West glass	5.1	129			0.66
Partition (garage)	11.0		0.28	5	0.02
Total					0.70

Dining room

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.9		0.28	10	0.02
West glass	2.2	129			0.28
South glass	1.1	93			0.10
South Wall	9.9		0.28	6	0.02
Total					0.42

Living room

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	11.7		0.28	10	0.03
East glass (shaded)	2.2	50			0.11
South glass	1.1	93			0.10
South Wall	9.2		0.28	6	0.02
Total					0.26

Other space - lower					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	8.3		0.28	10	0.02
East door	1.9		1.89	10	0.04
East glass (shaded)	0.8	50			0.04
Partition (garage)	13.9		0.28	5	0.02
Total					0.12

Summary of Sensible Cooling Load Estimate

Room	Walls, doors, etc kW	Internal gains kW	Infiltration kW	Total kW
M bedroom	0.40		0.14	0.54
Bedroom 2	0.31		0.06	0.37
Bedroom 3	0.33		0.06	0.39
Bedroom 4	0.27		0.06	0.33
M Bath/closet	0.06		0.06	0.12
Bathroom 2	0.02		0.02	0.04
Other space - upper	0.05		0.06	0.11
Kitchen/family area	0.70	0.76	0.15	1.62
Dining room	0.42		0.08	0.51
Living room	0.26	0.29	0.12	0.67
Other space - lower	0.12	0.24	0.09	0.44
Total	2.95	1.29	0.91	5.14

Duct loss (5%)		0.26
Total sensible		5.40
Total sensible & latent cooling load	Latent Factor 1.15	**6.21**

HOUSE: Two story
LOCATION: Miami
LOAD TYPE: Heating
INDOOR T (C): 21
OUTDOOR T (C): 8
ATTIC T (C): 14
GARAGE T (C): 14

CONDUCTION LOSSES					
		U (W/sq m K)	A (sq m)	dT (K)	q (W)
WINDOWS		2.84	20.5	13	745
WALLS	To ambient	0.28	118.8	13	431
	To garage	0.28	21.7	7	41
DOORS	To ambient	1.89	1.9	13	45
	To garage	1.89	1.9	7	23
CEILING	To attic	0.19	94.8	7	130
SLAB		F2 (W/m K)	P (m)	dT (K)	q (W)
	To ground	0.07	38.2	13	36
INFILTRATION LOSSES					
	ACH	(kJ/cu. m K)	Vol. (cu. m)	dT (K)	q (W)
	0.75	1.21	442.2	13	1423
TOTAL HEAT LOSS					q (W)
					2874

HOUSE: Two story
LOCATION: Miami
LOAD TYPE: Cooling
INDOOR T (C): 24
OUTDOOR T (C): 32
WET BULB (C): 25

Room Transmission Cooling Loads

MBedroom					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	11.9		0.28	13	0.04
East glass	2.0	129			0.26
South glass	1.0	55			0.06
South Wall	10.8		0.28	9	0.03
Roof	28.4		0.19	26	0.14
Total					0.38

Bedroom 2					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.2		0.28	13	0.02
West glass	1.0	129			0.13
South glass	1.0	55			0.06
Roof	12.9		0.19	26	0.06
South Wall	9.3		0.28	9	0.02
Total					0.29

Bedroom 3					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.9		0.28	13	0.03
West glass	2.0	129			0.26
Roof	11.8		0.19	26	0.06
Total					0.34

Bedroom 4					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	10.8		0.28	13	0.04
West glass	1.0	129			0.13
North glass	1.0	50			0.05
Roof	11.8		0.19	26	0.06
North wall	6.7		0.28	7	0.01
Total					0.29

M Bath/closet

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	7.9		0.28	13	0.03
East glass	1.0	129			0.13
Roof	13.2		0.19	26	0.07
Total					0.07

Bathroom 2

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
Roof	4.3		0.19	26	0.02
Total					0.02

Other space - upper

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
North wall	14.2		0.28	7	0.03
Roof	12.1		0.19	26	0.06
Total					0.06

Kitchen/family area

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	11.0		0.28	13	0.04
West glass	5.1	129			0.66
Partition (garage)	11.0		0.28	7	0.02
Total					0.72

Dining room

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
West wall	6.9		0.28	13	0.03
West glass	2.2	129			0.28
South glass	1.1	55			0.06
South Wall	9.9		0.28	9	0.03
Total					0.39

Living room

Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	11.7		0.28	13	0.04
East glass (shaded)	2.2	50			0.11
South glass	1.1	55			0.06
South Wall	9.2		0.28	9	0.02
Total					0.24

Other space - lower					
Item	Area sq m	GLF W/sq m	U value W/(sq m K)	CLTD K	Cooling Load kW
East wall	8.3		0.28	13	0.03
East door	1.9		1.89	13	0.05
East glass (shaded)	0.8	50			0.04
Partition (garage)	13.9		0.28	7	0.03
Total					0.14

Summary of Sensible Cooling Load Estimate

Room	Walls, doors, etc kW	Internal gains kW	Infiltration kW	Total kW
M bedroom	0.38		0.14	0.52
Bedroom 2	0.29		0.06	0.36
Bedroom 3	0.34		0.06	0.40
Bedroom 4	0.29		0.06	0.35
M Bath/closet	0.07		0.06	0.13
Bathroom 2	0.02		0.02	0.04
Other space - upper	0.06		0.06	0.12
Kitchen/family area	0.72	0.76	0.15	1.63
Dining room	0.39		0.08	0.48
Living room	0.24	0.29	0.12	0.65
Other space - lower	0.14	0.24	0.09	0.47
Total	2.95	1.29	0.91	5.15

Internal ducts		0.00
Total sensible		5.15
Total sensible & latent cooling load	Latent Factor 1.25	**6.43**

Appendix F Summary of Weather Data

This appendix contains long-term monthly average weather data for the two locations chosen for the simulations (104). (Note: Actual weather data used in the simulations will be hourly data from ASHRAE Weather Year for Energy Calculation (WYEC) data.)

Miami, Florida

Month	Average Outdoor Temperature (°C) [°F]		Heating Degree Days Base 18.3 °C [Base °F]		Cooling Degree Days Base 18.3 °C [Base °F]	
January	19.55	[67.2]	29	[52]	67	[121]
February	19.88	67.8	37	67	80	144
March	21.83	71.3	9	16	117	211
April	23.88	75.0	0	0	166	299
May	25.55	78.0	0	0	223	401
June	27.22	81.0	0	0	266	479
July	27.94	82.3	0	0	297	535
August	28.27	82.9	0	0	308	554
September	27.61	81.7	0	0	278	500
October	25.44	77.8	0	0	220	396
November	22.33	72.2	7	13	127	229
December	20.16	68.3	31	56	88	158
Annual	24.16	75.5	114	205	2243	4037

Minneapolis, Minnesota

Month	Average Outdoor Temperature (°C) [°F]		Heating Degree Days Base 18.3 °C [Base °F]		Cooling Degree Days Base 18.3 °C [Base °F]	
January	-10.99	[12.2]	909	[1636]	0	[0]
February	-8.61	16.5	754	1357	0	0
March	-2.05	28.3	632	1138	0	0
April	7.27	45.1	331	596	0	0
May	13.94	57.1	150	270	14	25
June	19.38	66.9	36	65	67	121
July	22.16	71.9	6	11	125	225
August	21.22	70.2	11	20	101	182
September	15.55	60.0	96	173	12	22
October	10.00	50.0	262	472	3	5
November	0.22	32.4	543	977	0	0
December	-7.44	18.6	798	1436	0	0
Annual	6.72	44.1	4532	8158	325	585