Contract Report

Uncontrolled Air Flow in Non-Residential Buildings

Final Report

FSEC-CR-878-96
April 15, 1996

FEO CN 93-SE-20-06-15-05-069
FSEC-26-56-769

Prepared for:
Florida Energy Office
Department of Community Affairs
Tallahassee, Florida 32399

Prepared by:
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Philip Fairey
Bruce McKendry

Florida Solar Energy Center
1679 Clearlake Road
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1. EXECUTIVE SUMMARY

The objective of this study was to develop the capability to substantially reduce energy use, building degradation and indoor air pollution caused by uncontrolled air flow in non-residential buildings. For purposes of the study, "uncontrolled air flow" was defined as *air moving across the building envelope or between zones or components of a building, where the pathways of flow, the direction of flow, and the origin of the air are unknown, unspecified, or unintended.*

The study comes to three major conclusions as follows:

- Uncontrolled air flow is pervasive in buildings, often resulting in severe -- and sometimes even catastrophic -- consequences.
- Building practitioners lack the training, methods, and insight necessary to understand and avoid uncontrolled air flow in buildings.
- Given proper attention, problematic air flows in buildings can be virtually eliminated. Uncontrolled air flow can be avoided in new buildings and repaired in existing buildings.

A major goal of this study has been to characterize the nature and extent of uncontrolled air flow through testing, measurement and monitoring in 70 small commercial buildings. Results showed that the nature of uncontrolled air flows in these buildings varies widely, and is strongly dependent on a large variety of complex building system interactions. As to extent, the study found that uncontrolled air flow is ubiquitous. Out of the 70 buildings studied, only one was deemed to be a "good" building. Repairs were made on 20 of these buildings. Before and after monitoring showed average cooling energy savings of 15%.

Perhaps the most profound and compelling finding of the study is that, **given the present state of practice, whether a building will avoid serious, or even catastrophic problems due to uncontrolled air flow, is primarily a matter of <u>luck</u>.** Building practitioners do not have access to information about uncontrolled air flow and its potential consequences in buildings. Even the research community has only recently "discovered" uncontrolled air flow, as evidenced by the fact that this study is the first major research effort of its kind. This study has found uncontrolled air flow to be surprisingly complex, and the impacts and consequences to be quite well camouflaged. Under these circumstances, it is not surprising that a good building depends almost entirely on chance.

The salient characteristic of uncontrolled air flow that appears most elusive is the fact that our buildings are functioning as pressure vessels. Mechanical air distribution systems force air through not only "leaky" ducts, but also through the various zones of this complex pressure vessel. Because we cannot see the uncontrolled air flow that results, we normally are not aware of it. As a result, forced air systems are typically treated as discrete, separate systems that begin and end with the fans, blowers, and duct systems. In actuality, <u>the building is a complex series of pressure vessels that connect together the two ends of the air handler and duct systems</u>, and are thus an integral part of them.

It appears that this lack of information on building air flows has forced practitioners to accept things on faith. They are condemned to the *smart air syndrome* -- the belief that the air is "smart" enough to flow where it is supposed to flow, which is only within the designated ducts of the mechanical systems.

There is scant evidence from this study that the impacts of uncontrolled air flows in buildings are understood or appreciated. Buildings are designed and tested and balanced considering only the air flows at *designated* air inlets and outlets of the duct systems. Even though duct systems have been shown to be quite leaky, they are practically never tested for tightness. The field evidence points to two ill-fated assumptions: 1) the ducts will not leak, and 2) forced air flow begins and ends at the designated termination points of the air handler's duct systems. Numerous examples that show the widespread existence of the *smart air syndrome* are contained in the body of this report.

This study conclusively shows that duct systems normally leak, often extensively. Given this fact, and the fact that the building acts as a pressure vessel, it is clear that building pressure measurements are the only accurate means of determining air flow balance in buildings. The study concludes that building pressures must be measured under a variety of building and mechanical system operating conditions in order to accurately evaluate and understand the impacts of the forced air flow in buildings. Air flow measurements alone are simply insufficient.

The extensive test and measurement data from the 70 small commercial buildings studied here show that these buildings are considerably more "leaky" than residences. The data also show that uncontrolled air flow is more pervasive and more complex in these buildings than in residences. The data also disclose a labyrinth of complex building system interactions that make diagnostic generalizations virtually impossible. Almost any given diagnostic result (for instance, the degree of supply duct leakage) can have an enormous variety of impacts, depending quite literally on everything else in the building. Simple generalizations and rules-of-thumb inevitably have proven insufficient. Nonetheless, this study provides answers to many previous questions. It also provides much needed insight, and discloses an extensive array of additional gaps in our knowledge base. (See especially Sections 4, 7 and 8 of this report.)

It has become clear from the study that more research and extensive education and training are required before practitioners will be able to successfully evaluate the impacts of these complex building system interactions. One recommendation of this study is to transfer this "new" knowledge to the building industry -- its researchers, its practitioners, and its regulators. Section 7 of this report details the specific needs in this area and recommends implementation strategies for proceeding with this important task.

It has also become clear that, given the proper attention, most uncontrolled airflows and the problems they engender can be avoided. Section 6 of this report provides extensive discussion on the characteristics of a good building. It is now clear that a much improved set of "best practices" for building design, construction, and commissioning can be achieved. Extensive effort on the part of many individuals and organizations will be necessary to widely effect such a standard in our diverse building industry.

This study is important because uncontrolled air flows in buildings often have serious and sometimes catastrophic consequences. Increases in energy and demand costs may be the least critical of these. Often more critical and costly are the decreases in health and safety, building material durability, indoor air quality, indoor comfort, building moisture control, worker productivity, and business revenues that are experienced in problem buildings. Much too often, uncontrolled air flows cause massive building failures that result in dramatic remediation and litigation costs. In some cases, these costs have exceeded the original cost of constructing the building. Indoor air quality problems alone are estimated to result in tens of billions of dollars in unwanted costs annually in U.S. buildings.

The study presents strong evidence that many serious indoor air quality problems either arise directly from, or are exacerbated by, uncontrolled air flows in buildings. One of the important overall conclusions of this study can be concisely summarized as follows:

> **It is highly unlikely that indoor air quality can be ensured in any building unless the potential for uncontrolled air flow in that buildings is eliminated.**

In other words, if we cannot control the air flow, how can we expect to control the air quality?

In summary, virtually all uncontrolled air flows in buildings stem from one or more of the following three straightforward, building-system characteristics:

- Air flow pathways where there should be barriers.
- Air flow barriers where there should be pathways.
- Imbalances in the forced air flows between the inside and outside of the building.

The results of this study show that buildings do not have to be plagued by these unwanted air flow problems. Good buildings can be achieved.

2. PROJECT DESCRIPTION

2.1 Introduction

"The overall objective of this project is to develop the capability to substantially reduce energy use, building degradation, and indoor air pollution caused by uncontrolled air flow in non-residential buildings." (Workplan: Uncontrolled Air Flow in Non-Residential Buildings, February 4, 1993). The workplan goes on to say, "This involves gaining knowledge of air flow and pressure differentials in non-residential buildings, identifying tools and testing techniques for research and diagnostic work, and developing recommendations for dealing with uncontrolled air flow in non-residential buildings."

Before proceeding, a definition of uncontrolled air flow is helpful. Our working definition has been:

> "Uncontrolled air flow - air moving across a building envelope or between zones or components of a building, where the pathways of flow, the direction of flow, and the origin of the air is unknown, unspecified, or unintended."

Seventy small commercial buildings in central Florida were tested for various types of uncontrolled air flow, including duct leakage, return air imbalance problems, and exhaust air/intake air imbalance. These buildings ranged in size from 704 square feet to 22,461 square feet, and averaged 5030 square feet. Typical tests included building airtightness, duct system airtightness, infiltration rates, and pressure differentials; and air flow rates of supply, return, air handlers, exhaust fans, outdoor air, and make-up air. This study concludes that uncontrolled air flow is a serious and wide-spread problem that contributes to energy waste, elevated peak electrical demand, high relative humidity, building materials moisture degradation problems, mold and mildew growth, combustion safety concerns, and indoor air quality complaints.

Uncontrolled air flow is a function of the intensity of drivers (primarily mechanical air moving systems) and building complexity and tightness (see section 2.2 for discussion of uncontrolled air flow potential). Compared to residences, small commercial buildings have larger air flow drivers because they have larger HVAC systems which run a greater proportion of the time. Cooling systems are considerably larger, averaging 3.38 tons per 1000 square feet in these 70 buildings compared to 1.8 tons per 1000 square feet in typical residences, and in some small commercial buildings the air handlers run continuously. Exhaust fans are larger and operate longer periods of time in commercial buildings. Additionally, commercial buildings have outdoor air and make-up air which do not normally exist in Florida residences.

Duct leakage, as measured by duct depressurization test, is three times greater in commercial buildings than in Florida residences (area normalized). Even considering that the cooling systems of commercial buildings are nearly twice as large (in terms of tons of cooling capacity per 1000 square feet), this duct leakage is considerably in excess of duct leakage in Florida residences. According to SMACNA, these commercial duct systems are approximately 70 times more leaky than the SMACNA duct tightness standard. In Florida residences, duct leaks are almost always to and from unconditioned spaces (attics, garages, etc.). In small commercial buildings, however, duct leaks commonly exist in four different ambient environments. 1) In some cases, the duct leakage occurs inside both the building air barrier and thermal barrier (insulation). In these cases there is not much air exchange or heat exchange with outdoors. 2) In other cases, the duct leaks occur inside the building air barrier but outside the thermal barrier (such as when the ducts are in the space between the ceiling and the roof deck, but the insulation is on top of the ceiling tiles) and therefore have significant energy penalties. 3) In yet other instances, the duct leaks exist outside both air and thermal barriers (such as in vented ceiling spaces or vented attic spaces), and the energy penalties of duct leakage can be severe. 4) Ducts may also be located on the roof. In many cases, a small portion of the ductwork is located on top of the roof. In a small number of cases, the entire duct system is on top of the roof. The energy penalties of duct leakage are generally worst in case 3, but are also substantial in cases 2 and 4.

Small commercial buildings are more leaky and often have greater complexity than residences. Testing in 70 small commercial buildings found them to be 30% more leaky than residences, primarily because suspended t-bar ceilings are quite leaky. ACH50, the air exchange rate of the building when depressurized to -50 pascals by a blower door, averages 16.7 compared to 12.7 in Florida residences. The difference is even more pronounced in new construction. New commercial buildings are more than twice as leaky as new Florida residences.

Small commercial buildings are very leaky primarily because suspended t-bar ceilings are on the order of 10 times more leaky than gypsum board ceilings. Because the ceilings of most commercial buildings are so leaky, overall building leakiness depends primarily upon whether the ceiling space or attic space above the ceiling is well ventilated to outdoors. In those which have tight ceiling spaces, building airtightness may be 5 ACH50 or less. Several of the 70 buildings were considerably tighter than any Florida residence we have tested. In the majority of cases, where the ceiling space or attic space is vented, building airtightness is 15 ACH50 or greater. Also of note is that attached units, such as those in strip malls, are more than twice as leaky as stand-alone commercial buildings. Because much of the leakage of these attached units is to adjacent units, the energy impacts of this excessive building leakage may be relatively less severe.

Commercial buildings are often more complex than residences -- that is, they have a greater number of partitions and compartments. A building can be thought of as a matrix of barriers to air flow and pathways for air flow. Interior walls, closed interior doors, firewalls, and multiple stories create potential barriers to air flow which can interrupt the flow of air throughout the building. This disruption of air flow can create pressure imbalances which can cause elevated infiltration rates, accumulation of moisture in building cavities, and backdrafting of combustion equipment. Filters and coils, as they become dirty, become barriers to air flow and can create pressure imbalance in the air distribution system.

Repair of uncontrolled air flows was done on 20 of the 70 buildings. Repair candidates were selected based on the perceived potential for energy savings and whether the repair was financially feasible within the project budget. Repairs included sealing of duct leakage, provision of return air pathways, reducing outdoor air flow, airtightening the building envelope, and turning off attic exhaust fans. The majority of repairs were duct repair. Three major types of repairs that were not attempted were provision of make-up air, reducing exhaust air, and airtightening of leaky t-bar ceilings.

Cooling energy use was monitored for four to six summer months in each building. Repair of uncontrolled air flow was done in the middle of the summer. On average, cooling energy consumption decreased from 87.4 kWh/day to 75.1 kWh/day, or 12.4 kWh/day. On average, cooling energy use declined by 14.7% from repair of uncontrolled air flow. Based on the assumed $0.075/kWh electricity cost, projected annual cooling energy savings are $182. Given that the average projected retrofit cost is $454, simple payback is 2.5 years. This indicates that UAF repair can be a very cost-effective retrofit measure.

This report concludes that uncontrolled air flow is widespread in commercial buildings. Energy waste is one important consequence. However, other consequences of occupant discomfort, cooling/heating equipment being improperly sized, high humidity, moisture problems, indoor air quality complaints, and sick buildings are of equal or greater importance. Since uncontrolled air flow problems are widespread and often severe, there is a strong need to bring about changes to the way buildings are created and used.

A plan was developed to implement the findings of this project (chapter 7). The plan suggests three areas of further work. 1) More research needs to be done to understand the extent, consequences, and solutions to uncontrolled air flow in commercial buildings. 2) Based on findings from this research, various standards relating to building design, construction, commissioning, and maintenance need to be modified. 3) To bring about resolution of uncontrolled air flow problems, training programs need to be established to bring improved design, construction, commissioning, and maintenance skills to those responsible for buildings.

Uncontrolled air flow may be caused by duct leaks, return design problems, and exhaust/intake imbalance. Another and more inclusive way of stating this is that uncontrolled air flow occurs:

1) When there are pathways where there should be barriers (e.g., duct leaks)
2) When there are barriers where there should be pathways (e.g., closed interior doors when returns are centrally located, firewalls that restrict return air flow, and dirty coils and filters)
3) When there is building air flow imbalance (e.g., exhaust air not equal to outdoor air plus make-up air).

2.2 Building Categorization

Commercial buildings fall into a wide variety of building uses and types. By comparison, there is much less diversity in single family homes. Most homes have two, three, or four bedrooms, a living room, a dining room, a kitchen, one or two bathrooms, and a garage. There are, of course, regional variations regarding foundation style (slab on grade, crawlspace, or basement), number of stories, and attic configurations. In terms of air flow, homes often have air distribution systems, but no make-up air, no outdoor air, and small and infrequently used exhaust fans. Variations in homes is much smaller than in commercial buildings.

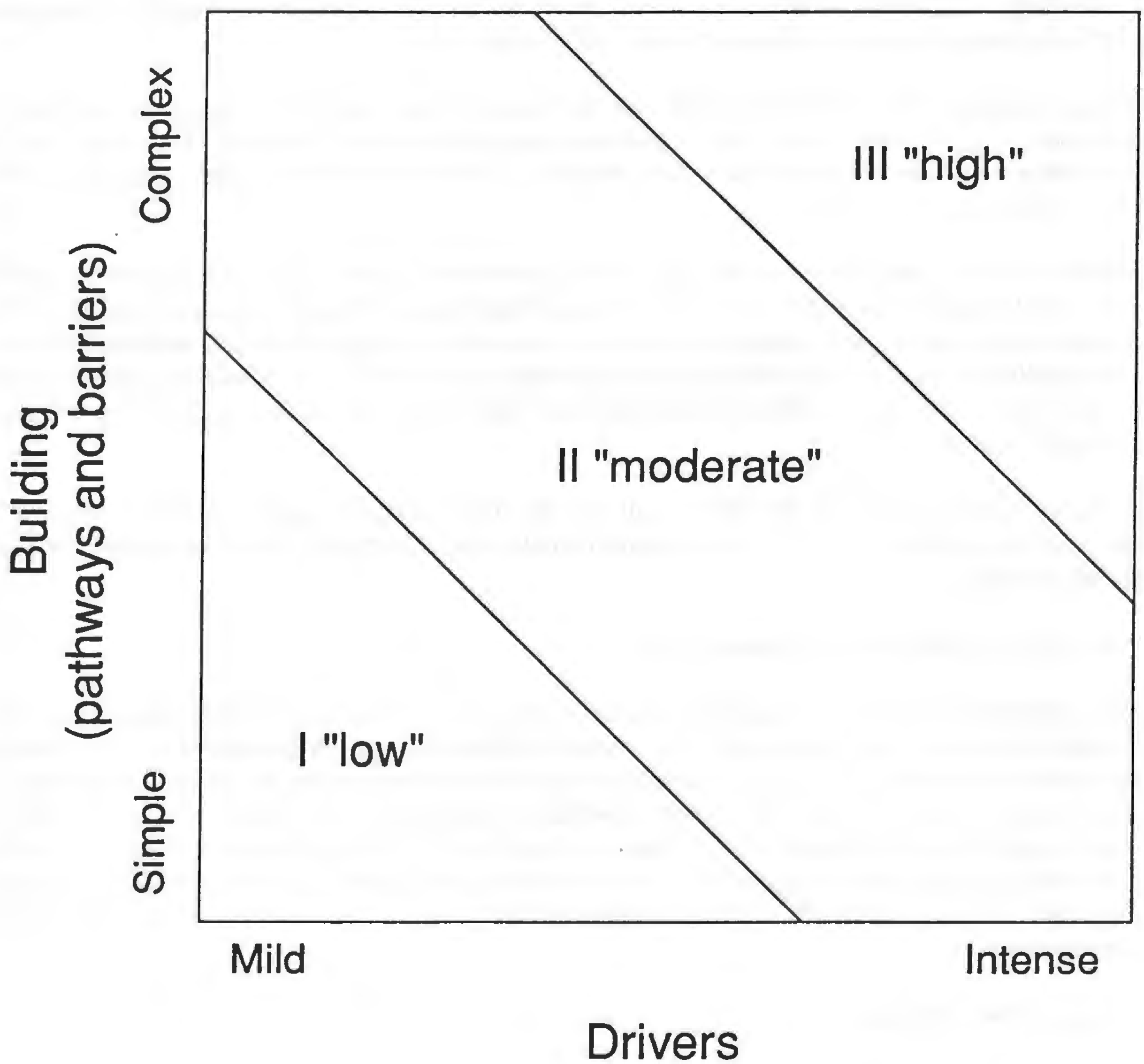
Commercial buildings have a much wider range of sizes, uses, construction styles, height, and mechanical systems. A conceptual framework was developed for thinking about the diversity of building types and configurations found in commercial buildings based on the potential for and consequences of uncontrolled air flow.

2.2.1 Uncontrolled air flow potential

A two-dimensional matrix has been developed that attempts to describe the potential for uncontrolled air flow in a building. The two axis are "drivers" and "building" (Figure 2.1).

Figure 2.1

Uncontrolled air flow potential



"Drivers" are the forces which move air within a building and across the building envelope. They include air handlers, exhaust fans, outdoor air, make-up air fans, and operation of combustion equipment (Figure 2.2). Drivers can also include wind driven air flow and pressure differentials, and stack effect pressures (especially in tall buildings in cold weather). Drivers range from mild to intense. The more intense or larger the drivers, the greater the potential for uncontrolled air flow to occur.

"Building" refers to building size and complexity, but complexity is most important. A building is an interwoven fabric of barriers and pathways. A wide-open retail space, for example, has few compartments, and is therefore "simple". A building which has many partitions and subdivided spaces is complex. Partitions provide the potential to restrict air flow and therefore have the potential to create substantial pressure imbalances and UAF (Figure 2.3).

Simple buildings with mild drivers fall into the "low potential" portion of the matrix and have less potential for UAF. Many small offices and retail spaces fall into this category. They may have open architecture and may have no exhaust fans (maybe a switch controlled fan in the bathrooms), outdoor air, or make-up air.

Simple buildings with intense drivers fall into the "moderate potential" portion of the matrix and have substantial potential for UAF and large pressure differentials. Examples include restaurants (large exhaust, make-up air, and outdoor air) and some recreation and light industrial/warehouse facilities. Complex buildings with mild drivers (only air handlers) also fall into the "moderate potential" portion of the matrix and have substantial potential for UAF because of closed doors when returns are centrally located.

Complex buildings with intense drivers fall into the "high potential" portion of the matrix and have the greatest potential for UAF; these would include hotels, hospitals, larger restaurants, and some sports facilities.

2.2.2 Uncontrolled air flow consequences

While uncontrolled air flow potential can be defined by a two-dimensional matrix consisting of drivers and building complexity, the potential for uncontrolled air flow can be thought of as the area defined by the two matrices (Figure 2.4). **Uncontrolled air flow consequences** can be conceived as a three-dimensional matrix defined by drivers, building complexity, and sources, and the extent of consequences can be thought of a volume defined by the three parameters of drivers, building complexity, and sources (Figure 2.5). Sources fall into three primary categories; 1) cold/heat, 2) moisture, and 3) pollutants. When transported by UAF, these sources often have negative consequences.

2.2.2.1 Cold and heat.

When drawn into the building by UAF, cold and heat can cause the following consequences:

1) Increased heating and cooling energy use
2) Increased electrical demand
3) Comfort problems
4) Oversizing of heating and cooling systems
5) Added run time and stress on HVAC equipment

Figure 2.2

Drivers

Direct

- HAC fans
- Exhaust fans
  - conditioned space
  - buffer zone
- Climate
  - wind
  - ΔT
- Elevators
- Combustion equipment

Indirect

- Shielding
- Height
- Use
  - occupancy load
  - heat sources
  - pollution sources
  - control strategy
    - timing
    - set point
    - economizer

Figure 2.3

Building
(pathways and barriers)

In ⟷ Out

- Shell construction details
- Airtightness
  — shell
  — ducts
- Air distribution barrier
- Inactive "vent ducts"
- Construction materials

Interzonal

- Air distribution barriers
- Building cavities/chases
  — horizontial
  — vertical
  — used as ducts
  — unconditioned fraction
- Duct airtightness

Figure 2.4

Uncontrolled air flow potential

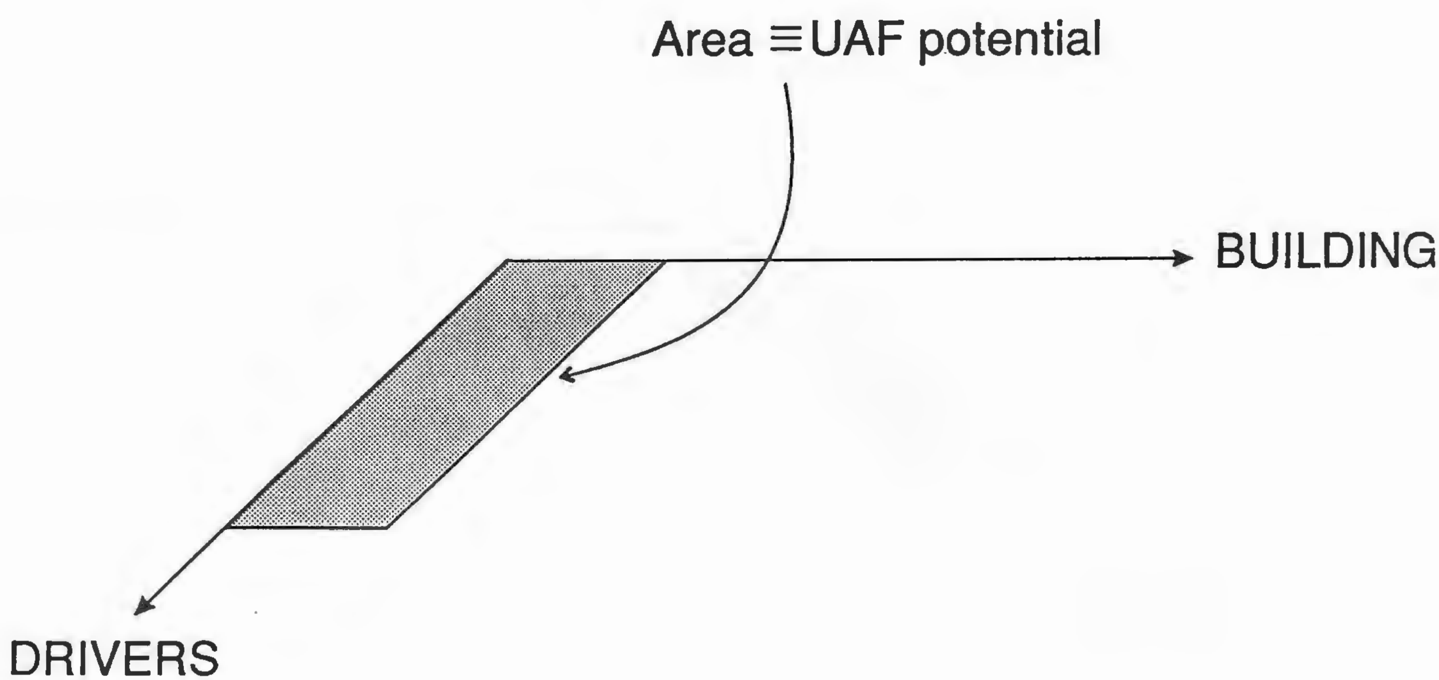
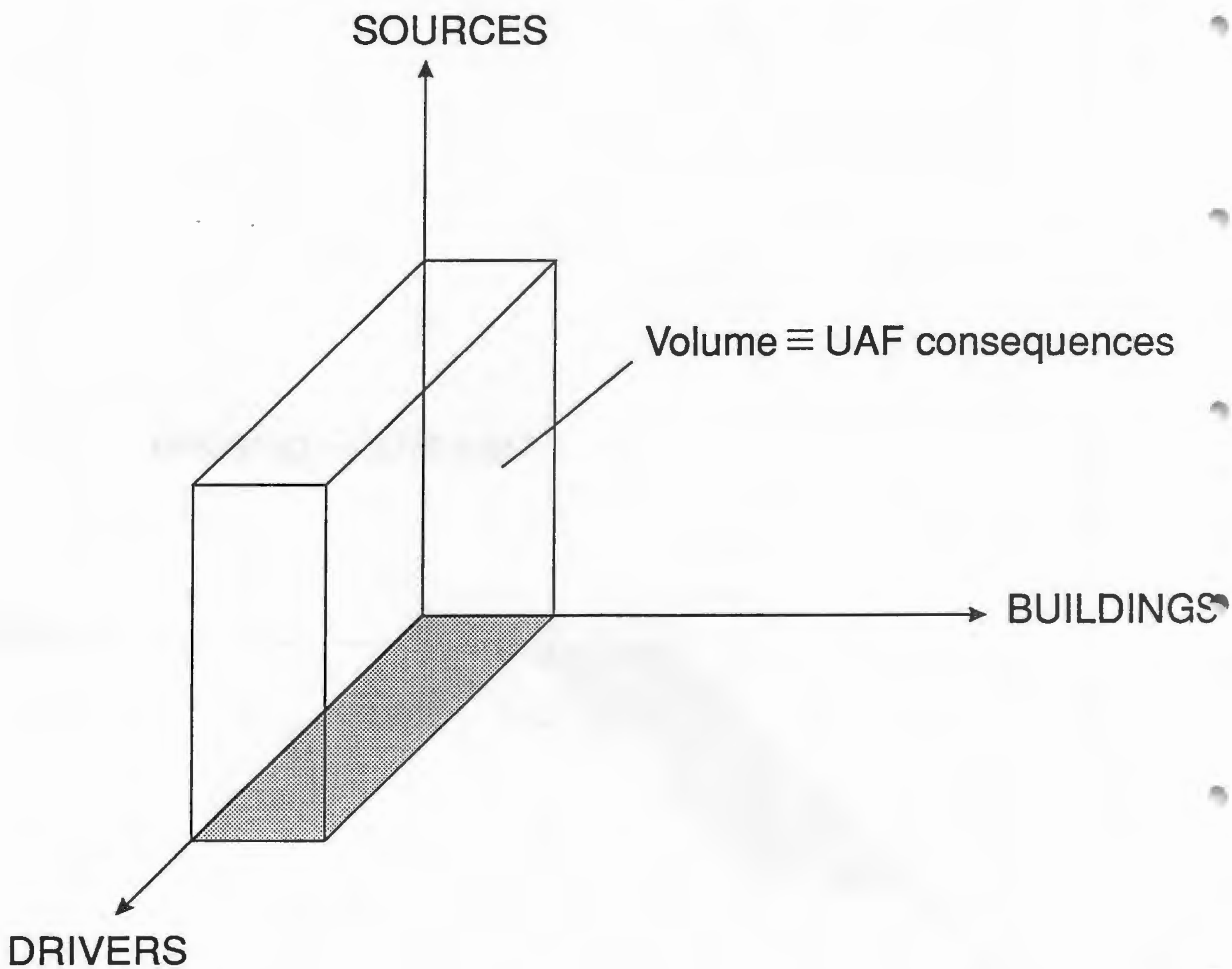


Figure 2.5

Uncontrolled air flow consequences



6) Stress on other equipment, such as copiers, printers, computers, etc., because of high or low temperatures and humidity.
7) Moisture condensation on building surfaces
8) Freezing of pipes
9) Low relative humidity
10) Static electricity problems.

2.2.2.2 Moisture or dryness.

When drawn into the building by UAF, moisture or dryness (air with low moisture content) can cause the following consequences:

1) Increased cooling energy use
2) High relative humidity
3) Condensation on surfaces
4) Mold/mildew/microbial growth
5) Building materials decay
6) Comfort problems
7) Damage to paper products
8) Stress on equipment, such as copiers, printers, computers, etc., because of high or low temperatures and humidity.
9) Increased emission rates of VOC (volatile organic compounds) and formaldehyde
10) Low relative humidity
11) Static electricity problems
12) Dry skin and eye irritations

2.2.2.3 Pollutants.

Pollutants can be drawn into buildings or not properly diluted (diminished ventilation) as a result of uncontrolled air flow. UAF can cause indoor air quality problems by four mechanisms; 1) mining of pollutants, 2) transporting of pollutants, 3) generation of pollutants, especially microbial growth, and 4) diminishing of ventilation.

Mining of pollutants occurs when depressurization caused by UAF draws pollutants from the soil (radon, methane), sewer pipes (methane, sulfur dioxide), or combustion equipment (carbon monoxide, moisture, particulates, and nitrous oxides). Space depressurization draws pollutants through cracks or penetrations in the slab (soil gases such as radon or methane), from sewer lines when plumbing fixtures are not seated properly or when traps are dry, and from combustion appliances when backdrafting or spillage is induced.

Transport of pollutants occurs when UAF carries pollutants from zones that have air contaminants. Following are examples. Return leaks in ducts or air handlers located in crawl spaces, garages, attics, etc. may transport radon, volatile organic compounds (oil and gasoline in garage), and insulation particles from these zones to the occupied space. In at least two reported incidents in Duval and Brevard counties in Florida, a total of seven persons died in their homes from carbon monoxide poisoning when cars were left running in closed garages. Leaks in the air handlers and ducts in the garage transport carbon monoxide-laden air into the house, resulting in lethal carbon monoxide poisoning. Return leaks in a roof-top package air conditioner may be drawing air from contaminated sources such as cooling towers, plumbing stacks, or exhaust fan discharges.

Generation of pollutants occurs when UAF actually creates or increases the pollution source. Four examples are presented.

1) **Mold/mildew.** The most important example occurs when humid air is transported into building cavities (walls, ceiling spaces, etc.). When the humid air meets cool interior building surfaces, moisture accumulates in those materials. Moist building materials can support mold and mildew growth, which in turn can contaminate indoor air and cause indoor air quality and health problems. There are great numbers of buildings throughout Florida which suffer from mold and mildew growth, a significant portion of which is caused by uncontrolled air flows.

2) **Fouling of ducts and air handler.** A second example of UAF generated pollution occurs as a result of return leaks when the filter is located at the return grill. In this situation, the air entering the return leaks is not filtered (it missed the filter since the filter is at the grill) and may be quite dirty because it comes from outdoors, the attic, the garage, or the crawl space. The dirt may quickly foul the cooling coil, the blower wheel, the drain pan, and duct surfaces, and with the presence of moisture and high humidity around the coil and downstream in the supply ducts it often generates various types of microbial growth. This growth, in turn, can generate odor and indoor air quality problems.

3) **Wet ducts as a result of failed condensate traps.** A third example of UAF-generated pollution occurs as a result of dysfunctional (or missing) condensate traps. The purpose of the trap is to prevent air from being sucked into the air handler (draw through air handlers) through the drain line. In a properly functioning trap, a plug of water is held in a low spot in the drain line, thus preventing air flow. If this plug of water disappears because of leakage, evaporation, or improper design (e.g., insufficient elevation from low to high point of trap), then air will rush through the drain pipe and into the air handler.

   The velocity of the air depends upon the extent of air handler depressurization and air flow resistance in the drain pipe. This high velocity air can prevent condensate from flowing out of the drain pan so the condensate collects into a "pond". As the water level rises, and it will rise to a height approximately equal to the static pressure in the air handler (e.g., -250 pascals depressurization equals 1.0 inches WC, so water will pond to about 1 inch depth), air entering from the drain pipe will be discharging into this body of water and causing bubbling and splattering. Water droplets will begin to splatter wetting interior surfaces of the air handler. The splattered water may also be drawn into the blower where they can be "atomized" and blown downstream into the supply plenum and ductwork. The moist environment created in the air handler and supply ductwork is ideal for mold and other microbial growth. The odors and spores from this growth can create air quality and sick building problems (Trent and Trent, 1994).

   In this study, we found that a large number of traps were dysfunctional. Some no longer had traps or in some cases even drain lines. In other cases, the trap clean-out cap had been left off so that air was coming into the drain line and by-passing the trap. Commonly, little or no condensate was coming from the line when the unit was on, and then when it shut off a rush of condensate would flow out. In one building, the accumulation of condensate in the drain pan was confirmed and observed by replacing one panel of the air handler with a sheet of plexiglas. As the water level rose, it overflowed the pan and covered the 35 square foot area of the bottom of the air handler with about 1 inch deep water.

The rise in water level and splattering of water inside the air handler was observed through and on the plexiglas panel. (Note that water was not easily draining out of leaks in the bottom of the air handler because pressure between the coil and blower was -330 pascals, so streams of air bubbles were flowing up through the water and little water was draining out.) There was no indication, however, that water particles were being drawn into the blower or discharged into the supply ductwork by the blower. The fact that water particles apparently were not being drawn into the blower may have been the result of the very thick coil assembly (heat pipe, coil, and heat pipe) and a several foot distance from the coil to the blower. Other researchers have found wet supply plenums and ducts as a result of dysfunctional traps (Trent and Trent, 1994).

4) **Elevated carbon monoxide generation.** A fourth example of UAF generated pollution occurs in some cases with atmospherically vented combustion water heaters. By "atmospheric" it is meant that the water heater and the vent pipe are separated by the draft diverter. One purpose of the diverter is to permit entry of room air into the vent pipe to dilute the combustion gases and thereby reduce the dewpoint of the gases in the vent pipe, diminishing condensation on the vent pipe walls. The diverter also allows combustion gases in the flue (inside the appliance) to vent even if the vent is blocked or backdrafting. In cases of severe backdrafting, however, the velocity of the air coming down the vent pipe can push into the flue (the flue is inside the appliance), reducing the flow rate of gases up the flue, thus reducing the entry of combustion air into the combustion chamber, and sometimes causing substantial increases in the generation rate of carbon monoxide. In these cases, an appliance that otherwise may be producing little carbon monoxide may now be producing large amounts. And since these combustion gases are no longer leaving the building through the vent pipe, serious health hazards may result.

Diminished ventilation may occur if outdoor air, exhaust air, or make-up air ducts have leaks. Consider some examples. Outdoor air ductwork is located in a ceiling space. If the ductwork leaks, then building air is drawn into the outdoor air ducts and thus reduces building ventilation air. If exhaust fan ductwork leaks (blower at or near the grill), so that air is discharging from the ducts into the building, then polluted air may be re-entrained into the building and the overall ventilation rate may be diminished.

2.2.3 Types of air quality consequences

Uncontrolled air flow often generates substantial energy consequences. However, these consequences are often dwarfed by the indoor air quality and materials damage consequences. Air quality problems produced by the four UAF mechanisms listed in the preceding section can result in various types of consequences.

1) Odor problems
2) Health consequences
   a) chronic
   b) acute
3) Reduced worker productivity
4) Sick buildings
   a) headaches
   b) respiratory stress
   c) increased illness

d) anxiety developed among workers
5) Evacuation of buildings, temporarily or long-term
6) Law suits

UAF may lead to increased sick leave and reduced worker productivity. Add to this the possibilities of having to evacuate the building, renovation costs, and law suits, the air quality nationwide consequences of UAF may run into the billions of dollars each year.

2.2.4 Consequences are somewhat random

Just because there are intense drivers, a complex building, or both, does not ensure that uncontrolled air flow will result. These factors simply increase the potential for uncontrolled air flows.

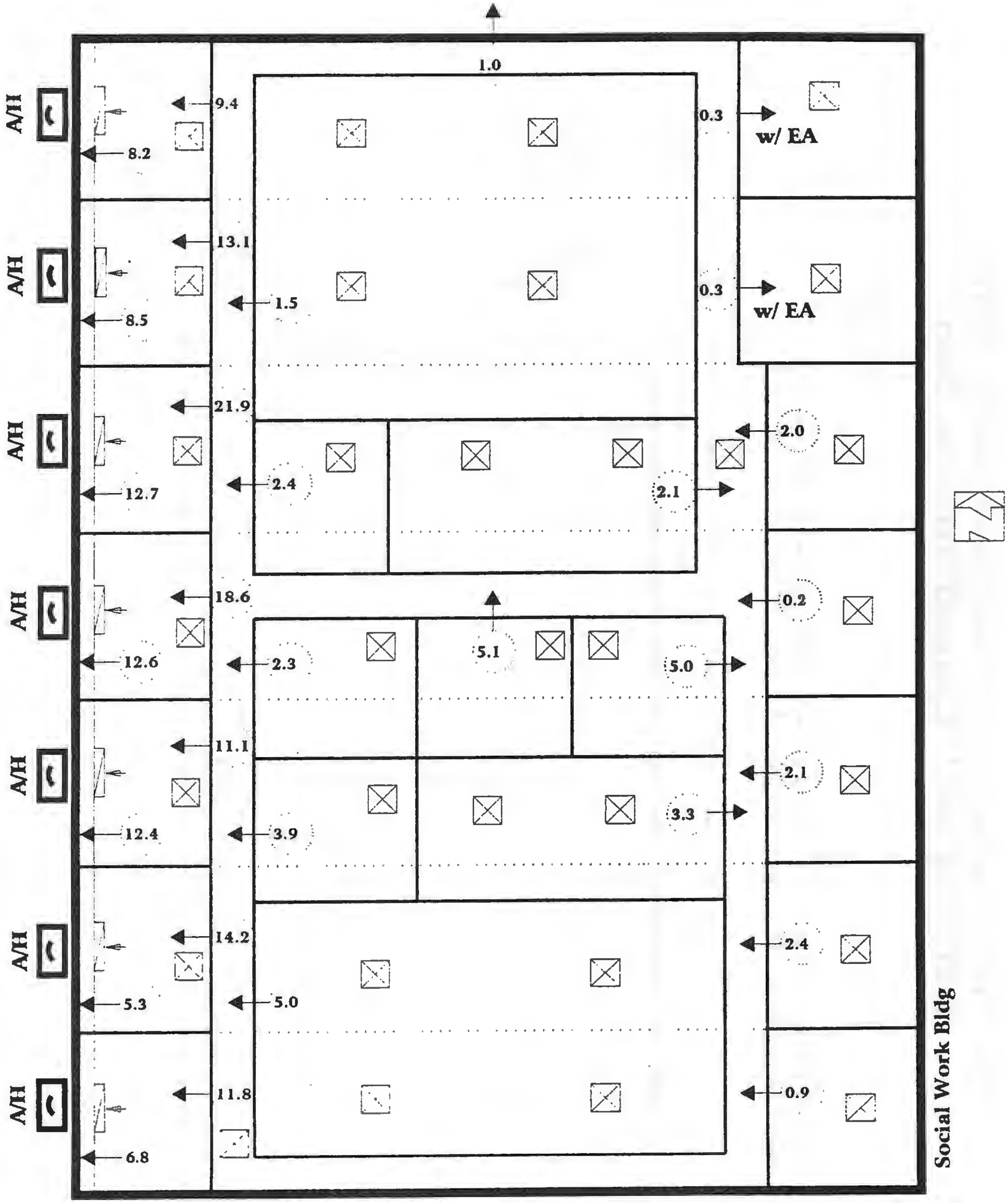
Just because there are uncontrolled air flows does not mean there will be consequences. The presence of uncontrolled air flow simply increases the potential for significant consequences. Whether there are consequences or not depends in large part upon luck (often the randomness of how buildings are put together) and of course whether there are sources.

Just a matter of luck. Whether uncontrolled air flow leads to serious consequences is often just a matter of luck. Consider the case of one manufactured office building (#16 on Master Table in Appendix B) tested in this project. Seven package air handlers are mounted on the exterior wall of the building, through-the-wall returns pull air from office, return transfer grills in the office doors were greatly undersized (allowing only about 5% of the needed air flow), and office doors are closed most of the time (Figure 2.6 -- note the numbers are pressure differentials and the arrows indicate the direction of pressure gradient and air flow). The closed doors then acted as barriers to air flow, creating strong depressurization in the closed offices, and thus pulling a majority of the return air from the space above the ceiling, a space which had 34 passive roof vents to outdoors (Figure 2.7).

Two fortunate circumstances prevented this major form of uncontrolled air flow from being a serious problem. First, the roof vents had dampers and these dampers were quite tight. Second, the ceiling insulation (batts) was attached to the bottom of the roof deck. Therefore, this ceiling space, which was acting like a return plenum, was located inside both the air barrier and thermal barrier of the building. If the insulation had been located on top of the ceiling tiles or the roof vents actually ventilated the ceiling space, then there could have been substantial energy and humidity consequences.

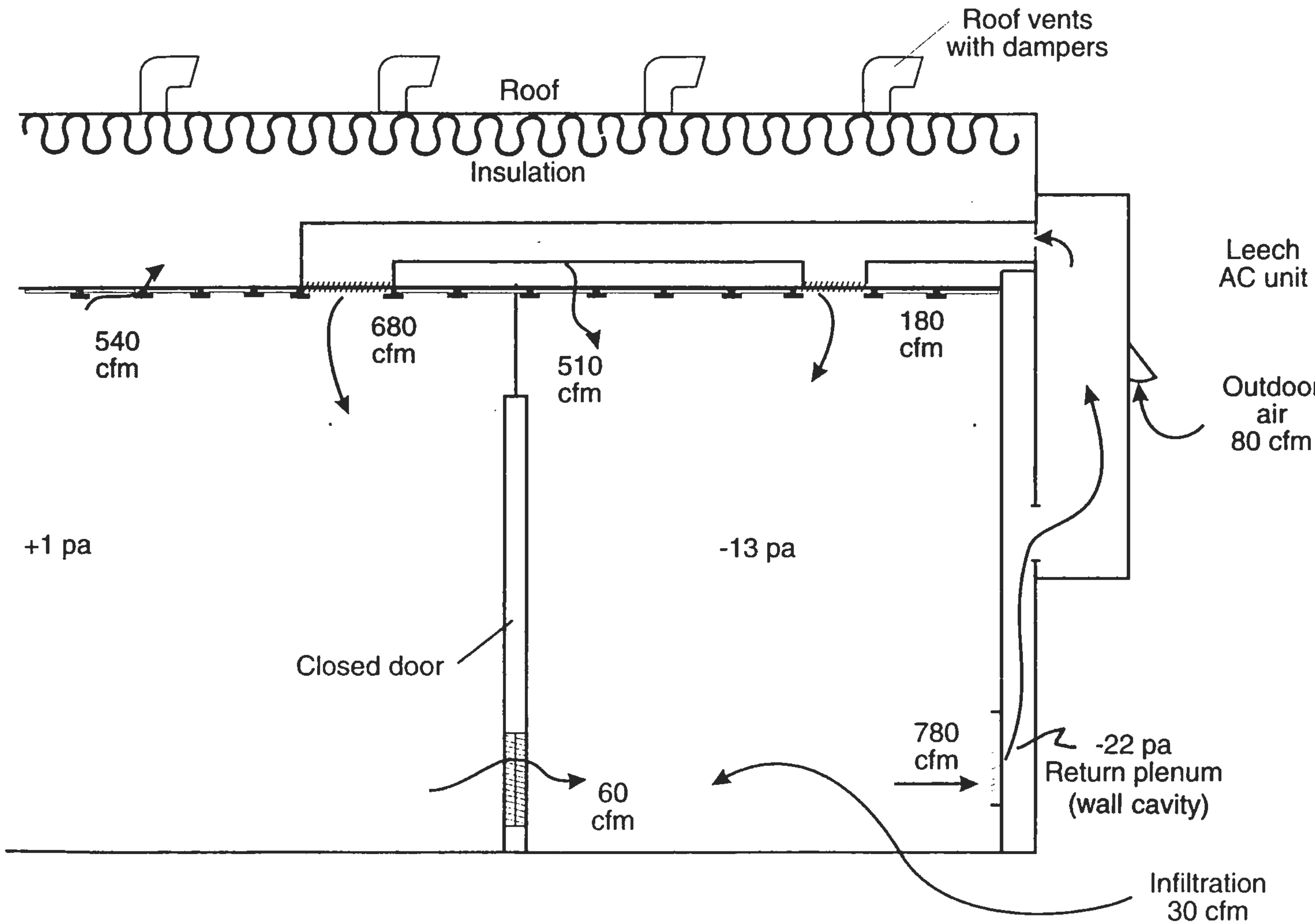
Importance of sources. The importance of sources can be illustrated by considering the following example. If we have a building with considerable UAF, and it is drawing considerable air from outdoors, but the air being drawn into the building is virtually identical to the desired indoor conditions (75F and 50% RH) and has no pollutants, then there may be no energy, comfort, humidity, building material damage, or indoor air quality consequences from UAF. This could occur, for example, in a city like San Diego, California when cool and clean breezes blow from the ocean much of the time. In real life, however, the air brought into buildings by UAF is generally too cold, too hot, too humid, too dry, or polluted. Even in San Diego on a perfect day, air can be drawn from an attic space (which may be hot) or a loading dock area (which may be polluted), and there may be negative consequences.

Figure 2.6



Pressure Map w/ AH on Doors Closed

Figure 2.7 **Air Flow Balance on Manufactured Office Building with Closed Interior Door**



2.3 How buildings were selected

The conceptual framework of drivers and building complexity provides a way to understand the potential for uncontrolled air flow to occur, but it did not prove useful in subdividing commercial buildings into groups or selection of candidates for testing. We set as a goal to obtain a sample that was reasonably representative of small commercial buildings which exist in east central Florida. The following criteria and targets for selection of buildings were used.

Size. Selections were made based on our desire for a diversity of building types and business types. Selections were also made on size criteria. The focus of this study was small commercial, therefore we did not seek out large buildings and included only a modest number of medium-sized buildings. Our target size was 5000 square feet of occupied floor space. Those selected ranged in size from 704 square feet to 22461 square feet, and the average size of the 70 tested buildings was 5030 square feet (Figure 2.8).

Use. In order to achieve representation from a range of building types, general numerical targets were set for office, education, restaurants, assembly/recreation, and light industrial/warehouse. Figure 2.9 shows a breakdown of the building types tested in each category. Small office is 10,000 square feet or less.

Medical offices are presented separately from the small and medium office categories. Education buildings included high school buildings, day care, martial arts school, business training school, university classrooms, safety school, and special education facility.

Commercial lodging could include hospitals, nursing care facilities, hotels, and motels. In this project, the only two commercial lodgings tested were motel buildings. Light industrial/warehouses included two printing facilities, plastic fabrication, sail manufacturing, and two conditioned warehouses.

Age. The buildings tested in this study ranged from 1 to 65 years old, and the average age was 21 years old. Figure 2.10 shows age distribution.

Location. Sixty-two of the 70 buildings were located in Brevard County on the east coast of Florida. Seven were located in Orange County (Orlando) and one in Polk County, Florida.

Selection procedure. Buildings were found using two basic procedures -- 1) we approached them without knowledge of any problems (59 buildings) or 2) they approached us because there was some indicated problem (11 buildings).

We believe most candidates said yes because they perceived potential benefit from our testing. Toward the end of the project, we were more selective since we wanted to meet the targets we had set for various building types. Virtually all candidates that would permit us to test for two or three days in their building were included in the study.

Figure 2.8

FLOOR AREA OF 70 COMMERCIAL BUILDINGS

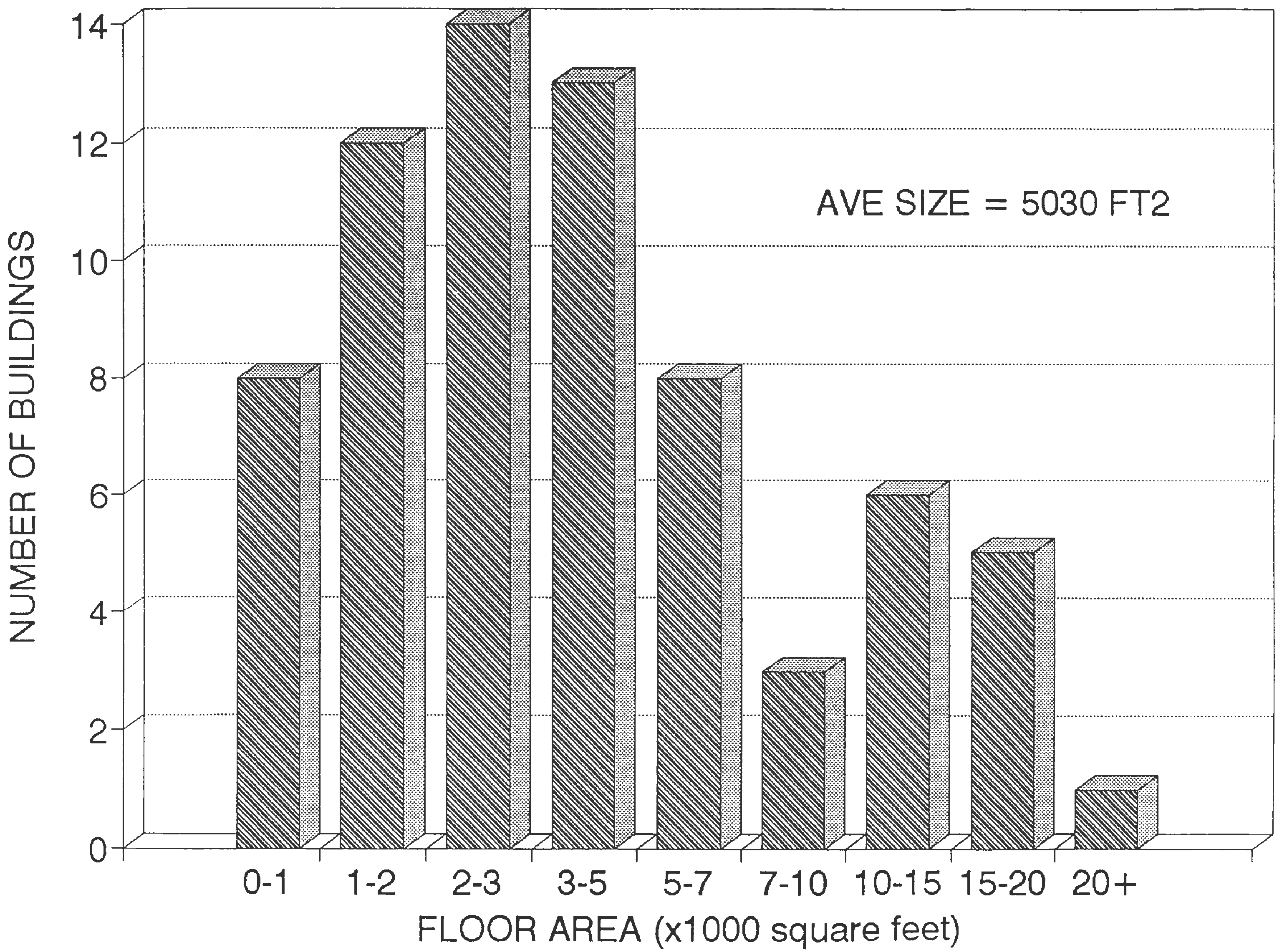


Figure 2.9

TYPES OF BUILDINGS TESTED IN UNCONTROLLED AIR FLOW PROJECT

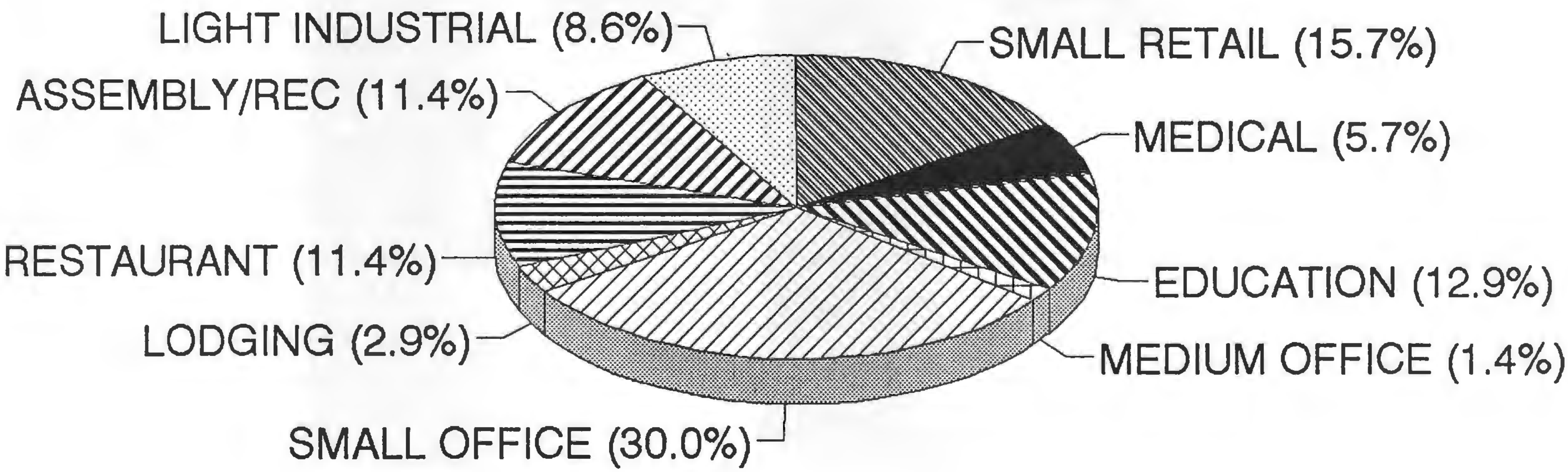
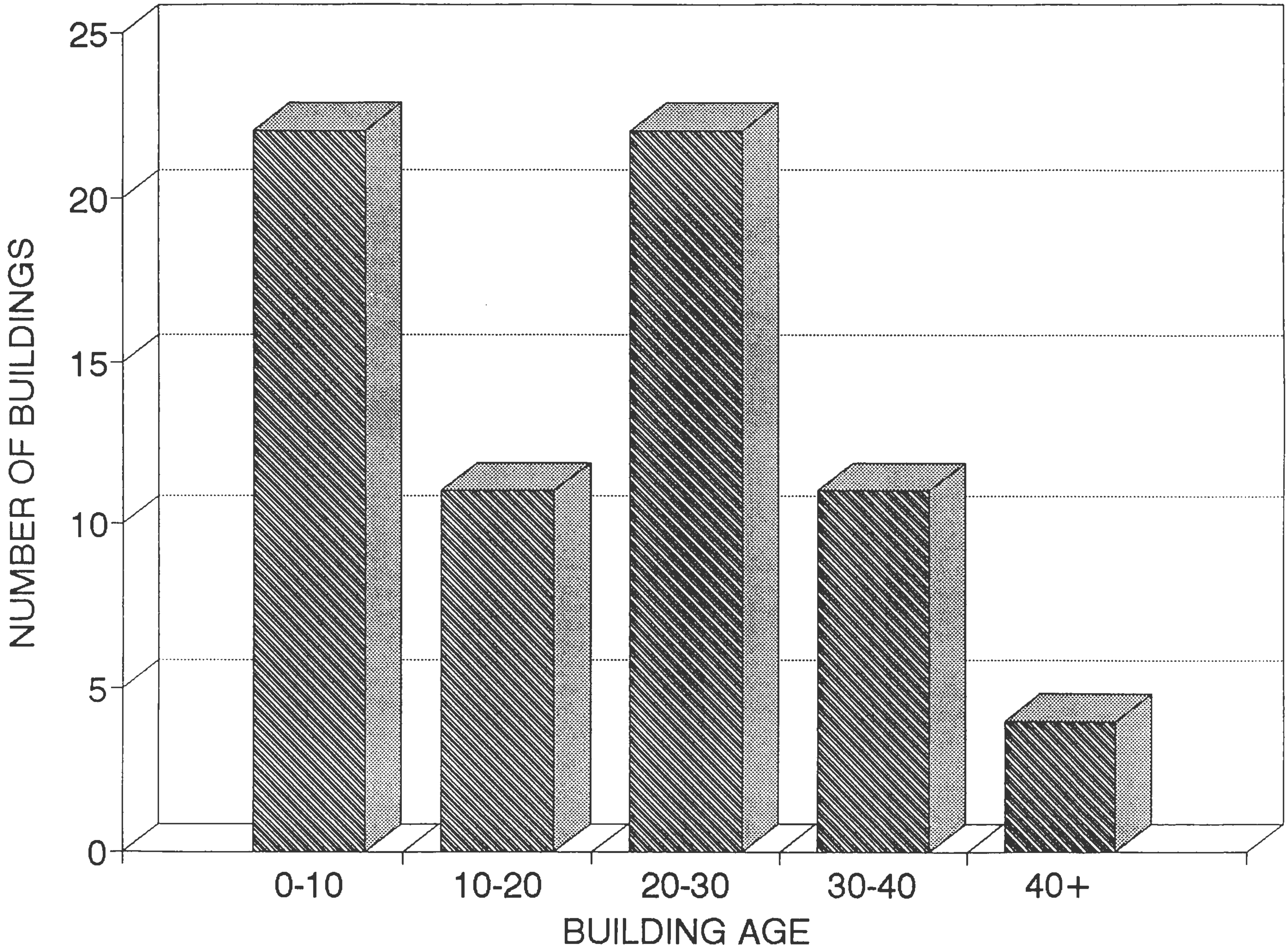


Figure 2.10

AGE OF 70 COMMERCIAL BUILDINGS



3. DIAGNOSTIC AND TESTING PROTOCOLS

One of the primary objectives of this project was to develop diagnostic and testing methodologies which can be used to diagnose UAF problems in buildings. Since this project is research, the testing actually done on these buildings was more comprehensive than we expect will be used in typical "real world" diagnosis. Nevertheless, many of the research procedures and testing methodologies developed in this project will be incorporated into real world diagnostics. A number of new measurement techniques were developed and refined in this project, and they allow measurement of air flows and pressure differentials in buildings more accurately and quickly than is commonly available in the industry.

3.1 Not All Tests Were Done In All 70 Buildings

Not all tests were done in all 70 buildings. In terms of building airtightness, one business owner would not allow us to do a blower door test because he felt it would disrupt his business activities. Building airtightness tests exist for the other 69 buildings.

In 24 of the 70 buildings, duct system airtightness was not measured. Three factors determined whether the duct airtightness test was done.

1) This is the most time-consuming of the tests. In a 15,000 square foot building with six air conditioning systems, duct system airtightness testing could take two or more person-days.

2) This test is the most intrusive to the operations of the business because it requires turning off the air conditioning systems for a several-hour period and (in some cases) simultaneously running blower doors (when determining leakage to outdoors). Depending upon outdoor weather and building thermal efficiency, some building occupants would not allow us to turn off the systems for any length of time.

3) In a significant number of buildings (17 buildings), ducts were located within both the air and thermal barriers of the building, or even inside the ceiling return plenum. In these cases, the importance of duct leakage in understanding UAF and the consequences of UAF is greatly reduced, so the test results are of less value. In other cases, the ductwork was located within the building primary air barrier but not within the primary thermal barrier (see definitions). In these cases the roof deck is the primary air barrier while the insulation is typically located on top of the ceiling tiles. Commonly, however, the roof deck (especially flat roofs) may have some thermal resistance (or thermal mass) because of a layer of concrete, layers of built-up roofing materials, semi-reflective roof surfaces, or loose gravel (the latter poorly conducts heat downward into the building but readily dissipates its heat into the air). Depending upon the thermal resistance of the roof construction, consequences of duct air leakage in these circumstances is also diminished because significant recovery of lost energy is likely to occur.

In 13 of the 70 buildings, the building infiltration rate with the air handlers (and normally operating exhaust fans) turned off was not measured. This occurred almost exclusively in cases where the occupants were very reluctant to allow us to turn off the air conditioning systems for a one-hour-plus period. Business owners are generally very sensitive to things that affect worker productivity or customer comfort. In many buildings, turning off the cooling system on summer days results in rapidly rising temperature and humidity. In restaurants, it is virtually impossible to turn off the exhaust fans because the cooking appliances require continuous exhaust.

In one small real estate office building, for example, the air handler-off infiltration test was done over the lunch hour when most of the employees were out to lunch. During the 70-minute test, the temperature in the space rose by about 5F. Because the air conditioner was undersized (this was a thermally inefficient building because of a very leaky building shell and poorly located insulation), the temperature in the space never recovered and the occupants were hot (and not particularly happy with us) throughout the remainder of the work day.

Typical protocol. A typical protocol includes visual inspection, building and duct airtightness testing, pressure differential measurement, infiltration/ventilation tests, air flow measurement, and visual inspection of building mechanical components which may contribute to uncontrolled air flow and pressure differentials. The objective of the testing is to characterize air flows and pressure differentials within the building, characterize the air flow balance across the building envelope, identify the cause of air flow and pressure imbalances, and understand the interacting relationships between building airtightness, air flows, pressure differentials, the operation of building equipment, indoor air quality, ventilation, and energy consumption.

3.2 Visual Inspection

Following is a discussion of the various diagnostic and testing protocols used to characterize airtightness, pressure differentials, and air flow rates in this project.

The first step in the diagnostic process is visual inspection and obtaining information from persons familiar with the building. Following are steps typically taken.

1) Inspection includes reviewing building architectural and mechanical plans, if available.

2) Inspect mechanical rooms, mechanical equipment, duct systems, ceiling spaces, attics, and control devices (thermostats, etc.). Learn how to control the HVAC systems. Look for signs of problems, such as moisture damage on walls, ceilings, ducts, and air handler support platforms. Learn typical use patterns for air conditioners, thermostats, and exhaust equipment.

3) Inspect combustion equipment for any irregularities related to vent pipes, leaking fuel, signs of incomplete combustion (excess carbon), or signs of flame roll-out (burned areas on or adjacent to the combustion equipment, or melted wire or pipe insulation).

4) Inspect for sources of air contamination, such as cleaners, fuel, pesticides, volatile organic compounds, etc, that may contribute to air quality problems. Note any smells that may give clues to problems or sources that should be identified. In one restaurant, for example, there was a strong sewer odor in one of the bathrooms that led us eventually to identify that strong negative pressure in the building was drawing gases out of the sewer lines. In another building, foul odors were coming from the men's bathroom during the blower door test. The floor drain trap was dry, so sewer gases were coming rapidly from the sewer pipe during the test and would be coming out more slowly during normal building operation. If these gases come into the bathroom rapidly when depressurized to -50 pascals, they may be entering the bathroom slowly during normal operation with the bathroom depressurized to about -1

pascals. Basically we are looking for any and all clues that indicate any types of problems that may be related to equipment efficiency, energy waste, building damage, comfort problems, or indoor air quality problems.

5) Speak with the business or building owner, facilities manager, or other persons familiar with the building to get their perspective on any problems that may exist. One can learn a considerable amount by listening to their comments, about comfort, air quality, utility bill, or other symptoms.

3.3 Important Definitions

Following are definitions that will be important to understanding some of the following discussions.

Attic space is a space above the ceiling that has trusses or joists which can be walked on and often has sloped roof, wood decking, intentional ventilation, and insulation at the attic floor level.

Backdrafting is reversal of flow of gases down the chimney or vent of a combustion appliance.

Ceiling space is the space above a ceiling that has no structural members that could support a person's weight, may have insulation at the ceiling or roof deck level, and generally is not intentionally vented.

Pressure pan is a pan that can be placed over supply and return registers to measure pressure difference. It is made of a cake pan (or other type of pan). Gasketing is put on the pan rim to facilitate an airtight fit and a tap penetrates the pan to allow measurement of pressure in the ductwork.

Primary air barrier is that portion of the building envelope which provides the greatest resistance to air flow and the greatest pressure drop when the building is exposed to a significant pressure differential compared to outdoors. In the ceiling/roof plane, the roof deck may be the primary air barrier or the ceiling may be the primary air barrier. Note that this means only that the primary air barrier is only relatively tight; that is, it is tight only by comparison to any other air barriers in series with the primary air barrier. A suspended t-bar ceiling may be the primary air barrier, but it nevertheless may be very leaky.

Primary thermal barrier is that portion of the building envelope which provides the greatest resistance to heat flow. In the ceiling/roof plane of the building, insulation may be located at the ceiling, at in the roof deck, or suspended in between. Often the primary insulation barrier is located on top of the ceiling tiles, but the (flat) roof assembly may also have some significant R-value, so the ceiling space is actually sandwiched between two thermal barriers.

Spillage occurs when only a portion of the combustion gases leave the building through the vent pipe. The remainder spill into the space. Spillage often occurs during start-up of a combustion appliance when the chimney or vent is cold. Ad the flue gases warm, draft strength increases and complete drafting of combustion gases results. Continuation of spillage beyond one minute indicates a draft problem.

3.4 Building Airtightness Testing

Typically, the second step in the diagnostic process is building airtightness testing. The building is prepared by turning off vented combustion equipment and air moving equipment including air handlers, exhaust fans, make-up air fans, and clothes dryers. Outdoor air, exhaust fans, and make-up air openings are sealed off, since these holes in the building do not respond passively to building air flow and pressure dynamics.

A multi-point airtightness test is performed (we follow the ASTM E 779-87, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization", except we only depressurize the building), using from one to six calibrated fans (blower doors), depending upon the building airtightness and size, and generally obtaining air flow at five to eight building pressures in the range from -10 pascals to -60 pascals depressurization. **(Note: all pressures expressed in this paper are "with respect to outdoors" unless otherwise indicated).** Knowledge of building airtightness assists in interpretation of other field testing, especially pressure differential measurements, and in developing recommendations for air flow and pressure balancing.

3.5 Identification of Building Air Barriers

With the building depressurized to -50 pascals by the calibrated fan(s), pressures in various zones of the building are measured in order to identify the primary building air barrier; in other words to determine which portions of the building are "indoors" and which are "outdoors". Pressure may be measured in the ceiling space, attic space, wall cavities, chases, soffits, mechanical rooms, ducts, space between floors, etc. Consider an example; if the ceiling space of an office buildings is at -5 pascals when the occupied space is at -50 pascals, this indicates that the ceiling is the primary air barrier. It may also indicate that the ceiling space is reasonably well ventilated to outdoors and that ducts located in the ceiling space are in a zone that is effectively "outdoors". If the ducts are "outdoors", then it will be more important to test for duct leakage.

If, on the other hand, the ceiling space is at -49 pascals when the occupied space is at -50 pascals, then the ceiling space and the ducts are located "indoors". (Note that being inside the building air barrier does not ensure, however, that the ceiling space and the ducts are inside the thermal barrier; for example, the insulation may be on top of the ceiling tiles while the roof deck is the air barrier.)

Consider another example; a mechanical room containing a gas water heater is at zero pressure when the occupied zones are at -50 pascals. This indicates that the mechanical room is well connected to outdoors and poorly connected to indoors, and that the combustion equipment located in that room will not be significantly affected by any pressures which may be created in the occupied zones. On the other hand, if the mechanical room is well ventilated to the occupied space and is at -48 pascals when the occupied space is at -50 pascals, then the combustion equipment located in that room could be significantly affected by any pressures which may be created in the occupied zones. This could lead to spillage or backdrafting of combustion equipment.

3.6 Duct System Airtightness Testing

Airtightness of the duct system can be measured by means of a depressurization test. Airtightness of the duct system can also be indicated by means of a pressure pan test.

3.6.1 Duct system depressurization test

Duct system airtightness may be measured using calibrated fans (duct test rigs or duct testers). All registers except one supply and one return (in proximity to the air handler) are masked off. Outdoor air inlets, if any, are masked off. Calibrated fans are attached to the open registers. An air flow barrier is placed in the air handler (at the filter, coil, or blower) to divide the system into supply and return. Air is drawn from the duct system by the calibrated fans and a multi-point (multiple pressures) airtightness test is done, with each side of the system at the same pressure (duct pressure is measured near the air handler and referenced to the zone in which the ducts are located). CFM25 (air flow through leaks in the duct system when the ducts are at -25 pascals) is determined for both the supply and the return side of the system. The combined CFM25 (add supply and return sides together) represents the combined leakage to outdoors, unconditioned building space, and conditioned building space, and can be expressed as $CFM25_{TOTAL}$.

The duct system airtightness test can be repeated to determine what portion of the duct leakage is to outdoors (or to buffer zones which are well ventilated to outdoors). Using a calibrated fan, the building is depressurized to the same pressure as the duct system, usually at just one pressure of -25 pascals, and the duct system airtightness test is repeated. Since the occupied zone and the ducts are at the same pressure, the duct test rig is measuring only duct leaks to outdoors. The resulting CFM25 can be expressed as $CFM25_{OUT}$.

If the ducts, plenums, and air handler are within the air barrier of the building, then the second test (with the building depressurized) is not needed. Note that in some cases, the ducts may be inside the building air barrier but there are leak pathways between the "designated" duct system and interstitial cavities that lead to outdoors.

In other cases, the ducts are located within the air barrier of the building, but outside the thermal barrier, such as when the roof deck is the building air barrier, the ducts are located in a ceiling space, and the insulation is on top of a t-bar ceiling. (T-bar ceilings are used in the vast majority of all commercial buildings. They are composed of t-shaped metal framework suspended from above with ceiling tiles supported within the metal framework). Duct leakage to and from these ducts causes considerable heat gain from the ceiling space during the cooling season and heat loss during the heating season. Even though this leakage occurs within the air barrier of the building, it occurs outside the thermal barrier of the building and consequently causes significant energy penalties (the extent of the energy penalties largely depends upon the thermal resistance inherent in the roof construction, the color of the roof surface, whether the roof surface is covered by gravel, and the extent of roof shading).

3.6.2 Pressure pan test

Duct system airtightness can be indicated (though not measured) by means of a pressure pan test. In this test, the building is depressurized to -50 pascals by the blower door. The air handler is turned off. A pan, similar to a cake pan, is attached to a pole and placed over each supply and return register, one register at a time. A micromanometer is attached to a pressure port on the pan so that the pressure in the ductwork (with respect to the room) can be measured. If the duct pressure is the same as the room pressure, then there is no duct leakage (to outside the building envelope). If the duct pressure is considerably different from room pressure, this indicates substantial duct leakage near that register. The following table provides a means of interpreting the pressure pan results.

TABLE 3.1.
Interpretation of pressure pan results when house is depressurized to -50 pascals. (Cummings, Tooley, and Moyer, 1993).

pressure difference (pa)	condition of duct system
0.0	completely airtight
0.5	very small duct leakage
1.0	small duct leakage
3.0	moderate duct leakage
8.0	large duct leakage
15.0	very large duct leakage
30+	open to the world!

The interpretation of pressure pan test results shown in Table 3.1 assumes that the duct system is located in a zone which is well ventilated to outside, so that when the occupied space is at -50 pascals, the duct zone is near neutral with respect to outdoors. In single family residences, this assumption is most often correct. In commercial buildings, however, the zone containing the ductwork is frequently located inside the primary air barrier and may experience pressure much closer to indoors than outdoors.

Consider the following example. In Realty 2 (building #37), the attic space is at -43 pascals with respect to outdoors when the occupied space was at -50 pascals with respect to outdoors (the attic is at +7 pascals with respect to the occupied space). Pressure pan tests were done on the 10 supplies and 1 return of the duct system. The indicated pressures ranged from 0.7 pascals to 5.0 pascals and the average was 2.0. Since the maximum pressure that could occur was 7 pascals (50 pascals - 43 pascals), these pressures indicate large duct leakage. In order to convert these number to values which can be interpreted on Table 3.1, multiply the pressure pan pressures by 50 (the assumed pressure difference between the occupied zone and the duct zone) and divide by the actual pressure difference between the occupied zone and the duct zone. In this example, multiply by 50 and divide by 7. The converted pressure pan pressures would range from 5 to 35.7 pascals. In many commercial buildings, pressure in the duct zone is the same or virtually the same as in the occupied space (blower door operating); consequently the pressure pan test will not work in these buildings. In conclusion, while the pressure pan test is widely useful in residences, it is often not an effective diagnostic tool in commercial buildings.

3.7 Building Pressure Differentials

Pressure differentials were measured in the building with the building and HVAC systems in various modes of operation. Pressure in the building is measured with respect to (wrt) outdoors once with the air handlers turned to continuous "on" and the exhaust fans operated in normal operation. Pressure in the building is measured a second time with all mechanical systems turned off. Pressure in various rooms and zones of the building are measured with doors open and closed and various HVAC equipment turned on and off in order to characterize pressure differentials between various zones of the building and between those zones and outdoors. A primary objective is to characterize the effect of the air moving equipment on building and zone pressures, especially negative pressure.

Pressure differential measurements are made with 2-channel and 8-channel digital micromanometers with resolution to 0.1 pascals. The hand held units have time-averaging capabilities which allow discriminating small pressure differentials even when significant fluctuations exist because of wind. The 8-channel micromanometer with interface to computer display and memory was used to sample at up to eight locations simultaneously throughout the building and mechanical systems, plot continuously on a computer screen, and store data for later analysis.

3.8 Infiltration/Ventilation Rates

Using tracer gas decay methodology (ASTM E 741, "Standard Test Method for Determining Air Leakage Rate by Tracer Dilution"), the building infiltration/ventilation rate was measured, once with the HVAC equipment operating and then again with the HVAC equipment turned off (if possible or practical). In 13 of the 70 commercial buildings, the "equipment off" test was not done because it was difficult to find a period when the occupants would allow turning off the mechanical systems.

Foxboro Miran 101 Specific Gas Analyzers and a Bruel and Kjaer 1302 multi-gas analyzer were used in various types of infiltration testing. Sulfur hexafluoride and nitrous oxide were the two gases that were commonly used as tracers. The typical test method using the Miran 101 was as follows:

1) Turn on the gas analyzer and allow it to warm up for an hour before testing begins.
2) Inject tracer gas into the building, typically into the return air, with the AHs operating.
3) Zero the gas analyzer using air from outdoors.
4) Take tracer gas concentration measurements at a number of locations throughout the building at approximately 10 minute intervals over a 60 to 90 minute period.
5) Check zero of the gas analyzer every 20 minutes and rezero if needed.

3.9 Air Flow Rates

In virtually all buildings, HVAC system air flow rates were measured. A number of different measurement techniques were used.

Various methods were used because 1) some methods work better than others because of intake or discharge configuration, 2) some methods take more time, and 3) some methods take duct leakage into account and others do not. Air flow hoods are useful for getting a "quick and dirty" picture of overall flows of the HVAC systems. They are not the best choice, in many cases, for measuring exhaust air flows, make-up air flows, or outdoor air flows. They also may overestimate air flows, especially at discharge grills/registers (more discussion in 3.9.1).

Tracer gas injection in conjunction with a gas analyzer can measure total air flow through ducts, air handlers, exhaust fans, and make-up air fans. Calibrated blowers can be used to measure air flows through air handlers, exhaust fans, make-up air fans, and even outdoor air. Both methods can deal with most intake or discharge configurations and accurately take duct leakage into account, but they are both more time consuming compared to using a flow hood.

Since an important aspect of diagnosing uncontrolled air flow is accurately measuring net air flows across the building envelope, the more time consuming methods are often called for. Following are detailed descriptions of the various air flow measurement methods.

3.9.1 Flow hood

Air flow at supply registers and return grills is measured by air flow hood. Outdoor air is typically measured with a flow hood, by placing the air flow hood over the outdoor air intake opening. Both Shortridge and Alnor hoods were used in this project.

These air flow hoods provide the fastest means for determining flow from registers and grills. They are generally quite accurate measuring flow into return grills and exhaust grills. They are not so accurate measuring air coming from some supply registers, especially those that discharge mostly to one side or have "jetting" of air into the hood (these occur in small commercial and are most common in residential systems). With some register configurations and air discharge configurations, we have found measurement of air flow from supply registers often are 20% too high and can be as much as 50% to 80% too high. The larger 24"x24" grills with diffuse holes or discharging equally to all four sides can often be measured with very little error.

3.9.2 Tracer gas

While tracer gas is most commonly used to determine the building infiltration or ventilation rate, it can also be used to determine return leak or outdoor air flow rates. Tracer gas is distributed into the building (as in the tracer gas decay infiltration test) and well mixed (about 15 minutes with the air handlers operating). Tracer gas concentration is then sampled at three locations for each air handler; A) in the room near the return grill, B) at the discharge of a supply grill, and C) at the return leak or outdoor intake location (since some tracer gas may be re-entrained into the outdoor air intake). To obtain return leak fraction (RLF), run the test once with the outdoor air intakes masked off. Then run the test a second time with the outdoor air grills open.

RLF_T, the proportion of return air flow that enters the return air distribution system through all leaks, whether from inside the building shell or not, is calculated by the following equation (Cummings and Tooley, 1989).

$$RLF_T = (A - B)/(A - C)$$

where

A is the tracer gas concentration of air entering the return grill(s)
B is the tracer gas concentration of air coming from a supply grill
C is the tracer gas concentration of air at the return leak site.

Note that as the concentration of tracer gas at C approaches the value of that at A, the accuracy of the test diminishes rapidly.

RLF_O, the proportion of return air flow that enters the return air distribution system through leaks from outside the building, is calculated by the following equation:

$$RLF_O = (A - B)/A$$

Note that this test is done with outdoor air intake sealed off.

To obtain outdoor air fraction, repeat the return leak fraction test but this time with the outdoor air intake open. OAF_T, the proportion of return air entering through both the outdoor air opening and return leaks from outdoors, is calculated by:

$$OAF_T = (A - B)/(A - C)$$

where

C is the concentration of tracer gas entering the outdoor air opening.

Outdoor air fraction (OAF; air entering only through the outdoor air vent) is calculated as follows:

$$OAF = OAF_T - RLF_O$$

Total return leak flow is calculated by:

$$RLflow_T = RLF_T * \text{air handler flow rate}$$

Return leak flow from outdoors is calculated by:

$$RLflow_O = RLF_O * \text{air handler flow rate}$$

Outdoor air flow rate (OAflow) is calculated by multiplying OAF times total air handler flow rate.

$$OAflow = OAF * \text{air handler flow rate}$$

3.9.3 Measuring air flow rates using tracer gas injection

Flow rate of exhaust fans and make-up air fans (and air flow through most duct systems) can be measured by means of tracer gas injection and sampling with a gas analyzer downstream. Tracer gas is continuously injected into the air stream such that the gas is well distributed (tubing with holes is often used), and the gas is sampled downstream in a distributed manner (a loop of tubing with holes attached to a sampling pump). The injection rate of the tracer gas must be accurately measured. Tracer gas concentrations before the injection point (C_s) and downstream (C_b) must be accurately measured. Flow rate is calculated by means of the following formula (Grieve, 1991):

$$q = dose/(C_s - C_b)$$

where

q	is the air flow rate in cfm
dose	is tracer injection rate in cfm
C_s	is the tracer concentration at the sample point
C_b	is the tracer concentration upstream of the injection location

Gas flow meters. Two sizes of flow meters were purchased to allow a wide range of gas flow rates. Computer software was purchased which allows accurate determination of flow rates through these two meters for a wide range of gases.

A water-displacement procedure was developed to calibrate the flow meters. An airtight, five-gallon container of water was placed on an accurate weight measurement scale. Tracer gas then flowed into the container and displaced the water. The change in water volume was determined by means of change in weight. In order to avoid compression of the tracer gas within the five gallon container, pressure (wrt the room) in the container was measured. The flow rate of water out of the tank was modulated so that pressure inside the container remained within about ± 10 pascals of the room environment. The calibration results indicate that the computer software/flow meter was accurate to within 3%, and the data was extremely linear ($r^2 = 0.9915$ fit to straight line indicates little scatter in the experimental data).

Using the calibrated flow meter and a tracer gas analyzer (either our Bruel and Kjaer 1302 or Miran 101), the air flow rate through a duct, air handler, or exhaust system could be measured quickly. On a test building, for example, we were able to measure the flow rate through six roof-top package units in less than one hour. By comparison, measuring that same rate using a duct blaster or blower door would have required considerably more time. Depending up the air handler configuration and outdoor air flow rate, an air flow hood could provide a fast and relatively accurate means of measurement. Using a capture tent with a calibrated blower might have been almost as fast, depending upon how much time is involved in assembling and moving the tent (see section 3.8.4 for further discussion of the capture tent method).

3.9.4 Calibrated fans

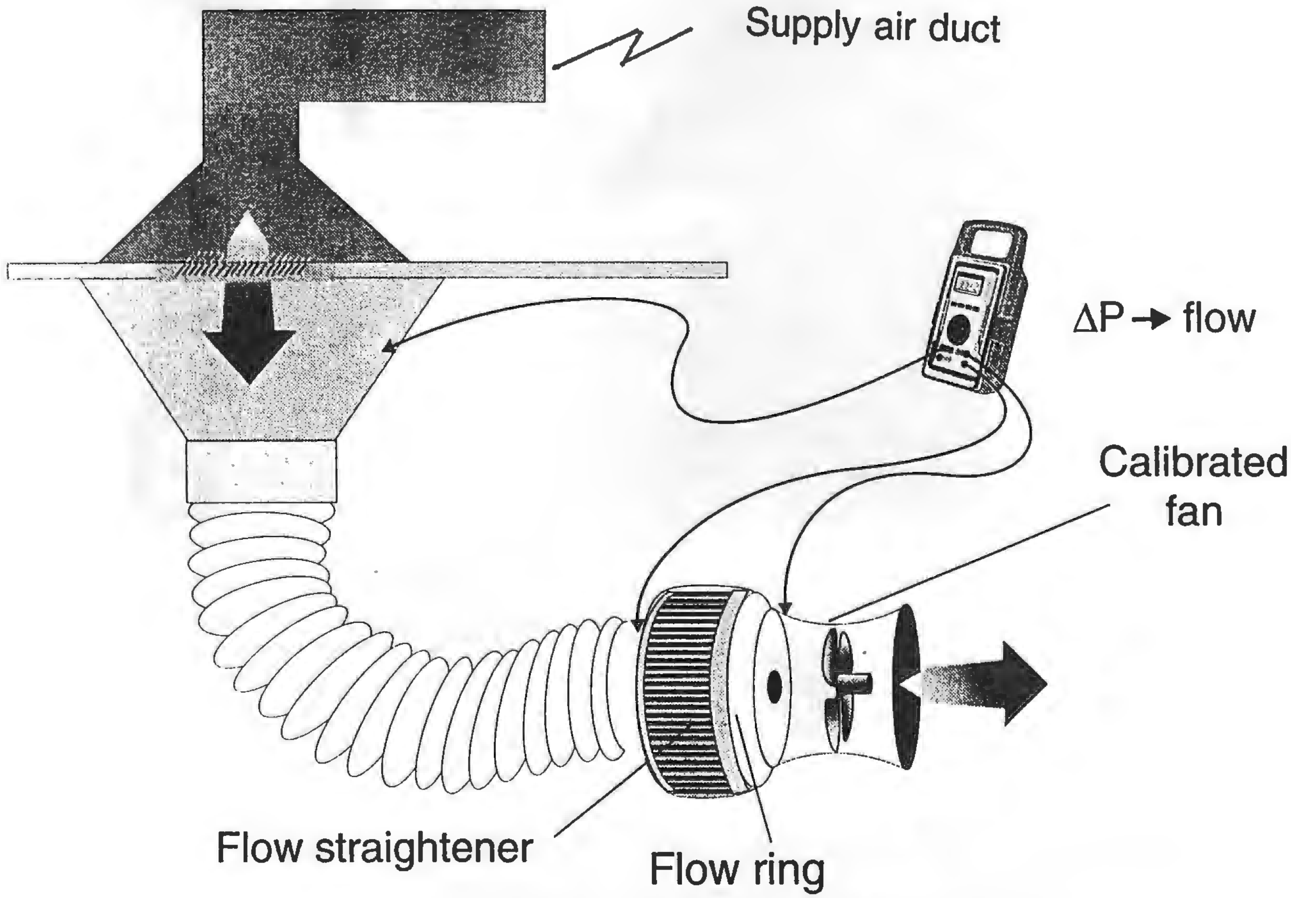
Calibrated fans, such as those used with blower doors and duct test rigs, can be used to measure air flows. They can be installed in capture tents, attached directly to the HVAC system, or used with the building as a capture tent.

Capture tent. Air flows, especially the discharge of exhaust fans or the intake of make-up air fans, can also be measured by means of calibrated fans and a capture tent (polyethylene sheeting on a PVC frame will do). A tent is placed over the discharge of the exhaust fan, for example, and a calibrated fan is mounted into the side of the tent (a flow conditioner may be needed to reduce turbulence at the intake side pressure sensor). A micromanometer measures the pressure in the tent wrt outdoors. The calibrated fan is turned on to draw air out of the tent and reduce the pressure in the tent (recall that the exhaust fan is blowing air into the tent) until the pressure in the tent is neutral wrt outdoors. Air flow through the calibrated fan is then equal to the flow through the exhaust system. Make-up air may be measured in an analogous manner, with the calibrated fan blowing air into the tent. Figure 3.1 illustrates use of a capture tent and calibrated fan at a supply register.

Calibrated fans mounted directly to the HVAC system. The calibrated fan may be mounted directly to a portion of the HVAC system. For example, if one wishes to measure the air flow of an air handler, the following steps may be taken. First, measure static pressure in the supply plenum as the system normally operates. Then remove a panel from the air handler, attach the calibrated blower to the opening in the air handler, seal off any remaining openings around the calibrated fan, place a barrier at the bottom of the air handler to isolate the return side of the system, turn on the air handler, then turn on the calibrated fan and increase its speed till static pressure in the supply plenum is equal to that measured previously. The air flow through the calibrated fan is then equal to the air handler flow rate (Figure 3.2).

Figure 3.1

Measuring Discharge Air Flow with a Capture Tent and a Calibrated Blower

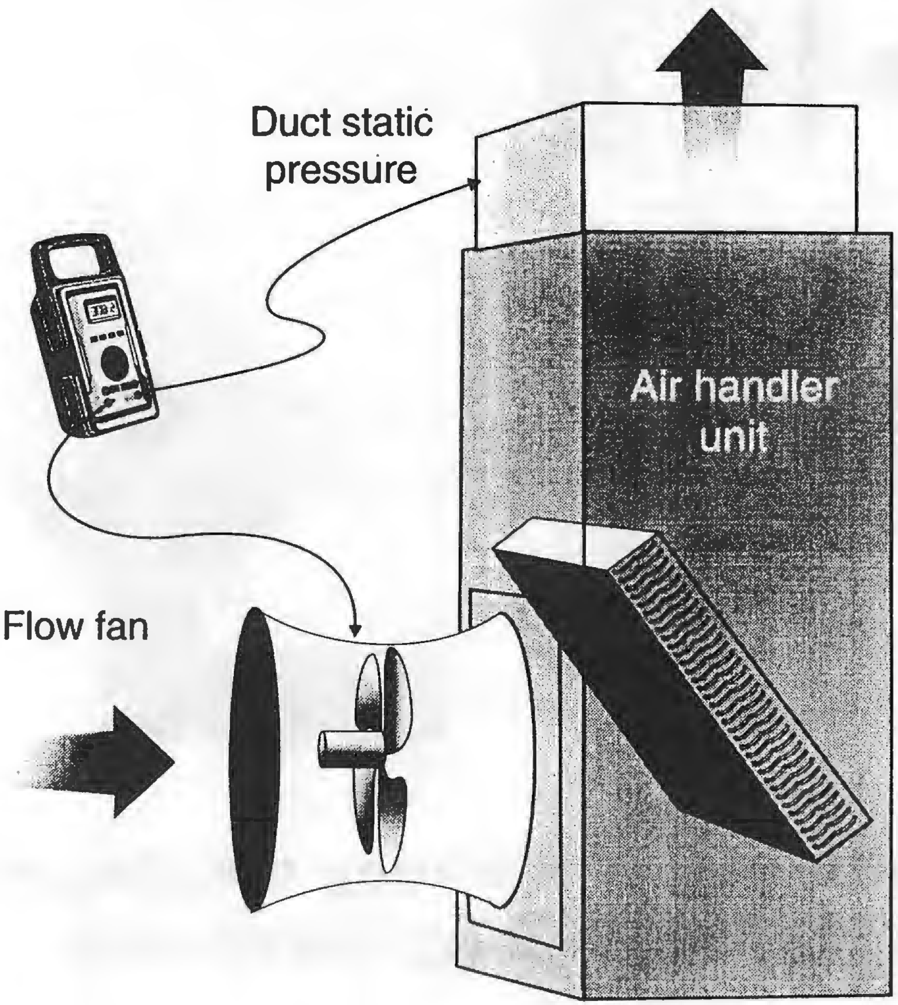


74-4 95s

Figure 3.2

Measuring Air Handler Flow with a Calibrated Blower

(Match supply plenum pressure with blower to obtain flow)



Building as a capture tent. The building can also be used as a capture tent. Look at an example of measuring exhaust fan flow in a restaurant. With the exhaust fan(s) turned on (all other air moving equipment turned off), the pressure in the building is measured (this could be -60 pascals or greater in many restaurants). The calibrated fan is turned on to blow air into the building until the pressure in the building is neutral wrt outdoors. The air flow through the calibrated fan is then equal to the exhaust fan flow rate. (Note this method works well if the building is tight or the exhaust fans are large. Restaurants may be tight and often have large exhaust fans.)

Note, however, that this is the flow rate that occurs when the building is at neutral pressure. If the normal operating pressure (NOP) of the building is much different from neutral, -10 pascals for example, then the measurement of exhaust or make-up air may be different than that which actually occurs, because building depressurization will reduce exhaust fan flow and increase make-up air flow. To correct for this, the calibrated fan is turned on to move air into the building until the NOP is reached (-10 pascals); record the flow rate through the calibrated fan (say 3600 cfm). Now calculate the air flow rate into the building due to the -10 pascals depressurization using the airtightness curve developed from the building airtightness test. (Example: say $C = 300$, $n = .65$, then q would be equal to 1340 cfm at -10 pascals). Exhaust fan flow is equal to flow through the calibrated fan plus the building leakage; 3600 cfm plus 1340 cfm = 4940 cfm.

The flow of make-up air can be measured in an analogous manner. Turn on only the make-up air fan and use a calibrated fan to pull air out of the building until reaching NOP. Make-up air flow is then equal to the air flow through the calibrated fan minus the air flow through the building envelope (this assumes the NOP is negative). Alternatively, the make-up air flow can be measured with the make-up air and the exhaust fans operating simultaneously (note that the make-up air flow is usually less than the exhaust air flow). If the building is at its NOP, then make-up air is equal to exhaust fan flow minus building leakage at NOP. If the building is depressurized beyond its NOP, then turn on the calibrated fan to blow air into the building until it reaches its NOP. The make-up air flow is equal to the exhaust fan flow minus building leakage minus calibrated fan flow. Note also that in this situation, the calibrated fan flow is equal to $OAflow_T$ (the sum of outdoor air flow and return leaks that draw air from outdoors).

3.10 Example Diagnostic Forms

As part of the diagnostic development, computerized forms were developed. Separate forms are provided for various tests, including blower door tests, duct airtightness tests, infiltration tests, return leak and outdoor air fraction tests, tracer injection air flow rate.

The forms are generated on a spread-sheet program. Data can be input in the field during the testing so that immediate results and quality assurance is obtained. An example set of forms is included in Appendix A.

3.11 Equipment Calibration

A considerable number of pieces of equipment and instrumentation was used in this project for both field testing and monitoring of energy savings. A list follows:

Field testing: (number of units in parentheses)

(4) blower door
(3) duct test rig
(2) digital micromanometer (resolution 0.01 pascals)
(9) 2-channel digital micromanometer (resolution 0.1 pascals)
(1) 8-channel micromanometer
(3) carbon monoxide detector
(1) multi-gas analyzer (CO, nitrous oxide, CO_2, volatile organic compounds, sulfur hexafluoride, methane, formaldehyde, and dewpoint temperature)
(1) single gas analyzer (sulfur hexafluoride)
(1) single gas analyzer (nitrous oxide)
(2) calibrated flow meter (low flow, multi-fluid)
(2) air flow hood
(2) pitot tube
(1) hot wire anemometer
(6) vane anemometer
(1) hand held anemometer
(1) fuel leak detector
(5) temperature probes
(1) portable relative humidity/temperature probes
(1) portable weather station; temperature and wind speed

Field monitoring:

(5) carbon dioxide detectors
(10) relative humidity probes (thin film polymer capacitor)
(6) cup anemometers
(6) micromanometers with analog output
(15) energy meters
(10) dataloggers

3.11.1 Calibration standards

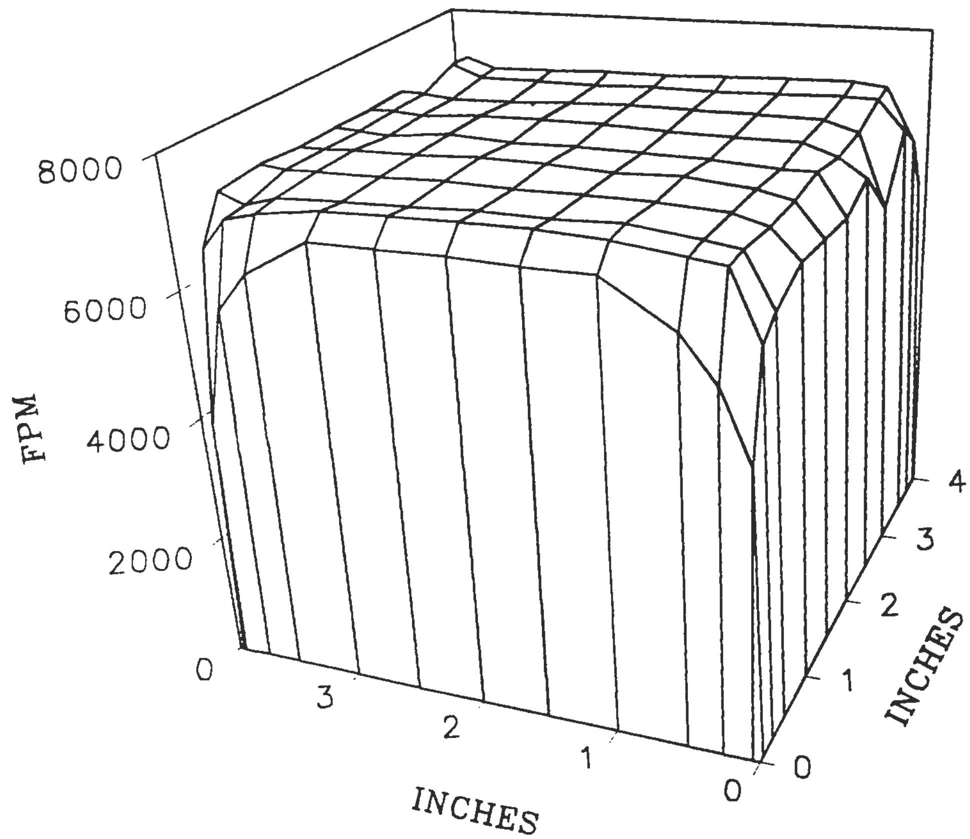
Calibration requires standards against which to evaluate equipment performance. Following are standards used for calibration:

TSI Benchtop Wind Tunnel
certified gas mixtures
inclined manometer
ice water bath
General Eastern Hygro-M1 Chilled Mirror Hygrometer

A careful calibration check of our TSI bench top wind tunnel was done using a small dimension Dwyer pitot tube and our Shortridge ADM-860 micromanometer. Air velocity was measured at 108 locations within the 4 inch by 4 inch cross-section of the tunnel in order to verify its accuracy. At 1/2 inch or more from each wall, the wind tunnel air velocity varied from 1.0% to 2.6% greater than the velocity measured by the pitot tube, averaging 1.6%, indicating very good agreement and stability across the flow regime. The resulting air flows are presented in Figure 3.3. Based on this analysis, we were able to develop a multiplier to convert from mid-stream velocity (fpm) to total air flow rate (cfm) through the wind tunnel.

Figure 3.3

VELOCITY PROFILE IN TSI WIND TUNNEL



Gas mixtures for carbon monoxide, carbon dioxide, nitrous oxide, and sulfur hexafluoride were purchased. The accuracy of the mixtures were certified by the manufacturer.

Digital, electronic micromanometers were compared against an inclined manometer. Since all the micromanometers agreed with each other, basically within about 3% in all cases, and with the inclined manometer, we had great confidence in the accuracy of our pressure measurements.

Relative humidity probes were calibrated against the Hygro-M1 Chilled Mirror Hygrometer, which has accuracy of $\pm$0.2F dewpoint temperature. The reliability of this standard was checked from time to time by comparing to another Hygro-M1.

3.11.2 Calibration methods

It is important that the readings obtained from measurement equipment and instrumentation is accurate. Therefore, periodic calibration was done.

The following equipment was calibrated at the factory: Shortridge ADM-860 micromanometer, Bruel and Kjaer 1302 multi-gas analyzer, Miran 101 (set up for nitrous oxide), and Energy Conservatory Blower Door with flow conditioner.

The following equipment was calibrated in our laboratory: four Duct Blasters, one blower door, six micromanometers, humidity probes (Solomat, Bruel and Kjaer 1302, Omega RH), and several gas analyzers. The gas analyzers include Bruel and Kjaer 1302 (carbon monoxide, carbon dioxide, sulfur hexafluoride, and nitrous oxide), Miran 101 (sulfur dioxide), Miran 101 (nitrous oxide), Miran 203 (sulfur hexafluoride and carbon dioxide), Gaztech carbon dioxide monitors, and Bacharach Monoxers (carbon monoxide). The gas analyzers are calibrated against certified gas mixtures provided by various specialty gas suppliers.

Verification of calibrated gas mixtures. In 1994, it was found that calibration gases provided by our gas supplier (under state contract for gas supply) were nearly 100% higher than stated and certified values, and that the Foxboro Miran 101 instrument which we originally suspected was inaccurate, was in fact quite accurate.

After our Bruel and Kjaer 1302 multi-gas analyzer was calibrated at the factory, calibration checks were made for carbon dioxide, carbon monoxide, and sulfur hexafluoride versus our calibrated gas mixtures. We found that the calibrations for the first two gases showed significant cross-sensitivity to moisture content of the air (means that they can be considerably inaccurate under certain humidity conditions). The instrument was returned to the factory for re-calibration.

When the Bruel and Kjaer 1302 was received back from the factory, calibration checks were done to confirm the accuracy of the factory calibrations. Cross sensitivity had decreased, but the accuracy of the dewpoint measurement had gotten worse. When we originally received the instrument, dewpoint temperature was +0.4F with respect to our chilled mirror reference. After several trips to the factory, dewpoint temperature was further off, reading +2.5F compared to the reference.

Calibration checks were done on four blower doors, three duct blasters, and seven micromanometers. The blower doors and duct blasters were set up in series with the bench-top wind tunnel. For flow rates over 1000 cfm (the maximum wind tunnel flow rate), we used tracer gas injection/gas analyzer sampling for a standard. We found that the various blowers generally agreed with the standard within ±5%. Calibration checks were done on the two Miran 101 gas analyzers several times during the project. They were compared against two gas mixtures of sulfur hexafluoride (30 parts per million [ppm] and 50 ppm) and two gas mixtures of nitrous oxide (30 ppm and 50 ppm).

Monitoring equipment. Twenty buildings were monitored for energy savings. Measurements were also taken of temperature, humidity, carbon dioxide, and pressure differential.

Temperatures were measured using t-type thermocouples. Occasional spot checks of accuracy were done. Based on years of experience, we have found that thermocouples provide very accurate measurements, generally within ±0.1F. Relative humidity probes were compared to the chilled mirror standard and found to be accurate generally within ±4 percentage points. Carbon monoxide probes were calibrated using certified gas mixtures. Pressure measurement probes were calibrated, as described previously.

4. PROJECT FINDINGS

Air flow across a building envelope is a function of hole size and pressure differential across that hole. Without a hole there is no air flow. With no pressure differential, there is (almost) no air flow. It is the combination of holes and driving forces which create most uncontrolled air flows in buildings.

Mechanically induced pressure differentials are a function of the net air flow into a space and the airtightness of that space. This applies to occupied and unoccupied building spaces, building spaces used as ducts, and ducts themselves.

In commercial buildings, we expected mechanically induced pressure differentials to be the big story. And certainly they are. However, a big concern, and a surprise to most of us, emerged -- that many small commercial buildings have big holes, especially in the ceiling plane, and that these big holes may be the source of substantial energy problems. A significant number of commercial buildings are tighter than most Florida homes (12 of 70 buildings have ACH50 less than 5). On the other hand, a large number of commercial buildings are much leakier than almost all Florida homes built in the last 20 years (26 of 70 buildings have ACH50 greater than 20). On the whole, central Florida commercial buildings are considerably more leaky than central Florida homes.

Also of considerable concern is the magnitude of problems associated with ceiling insulation systems. Many ceiling insulation systems are functioning poorly, because the insulation is missing, has been moved around, or is being by-passed by uncontrolled air flow. Following is a discussion of the major findings of this project.

4.1 General Building Information

A large portion of the project findings are contained in a single table contained in Appendix B. The following general summary can be presented for our sample of 70 central Florida small commercial buildings. Average floor area was 5030 square feet. Five buildings were manufactured (non-metal), either an office trailer or a modular office space. Four buildings were metal. Twenty buildings were frame or predominantly frame. The remaining 41 buildings were masonry or predominantly masonry (Figure 4.1).

Six buildings are on crawl spaces. The remaining 64 are slab-on-grade construction.

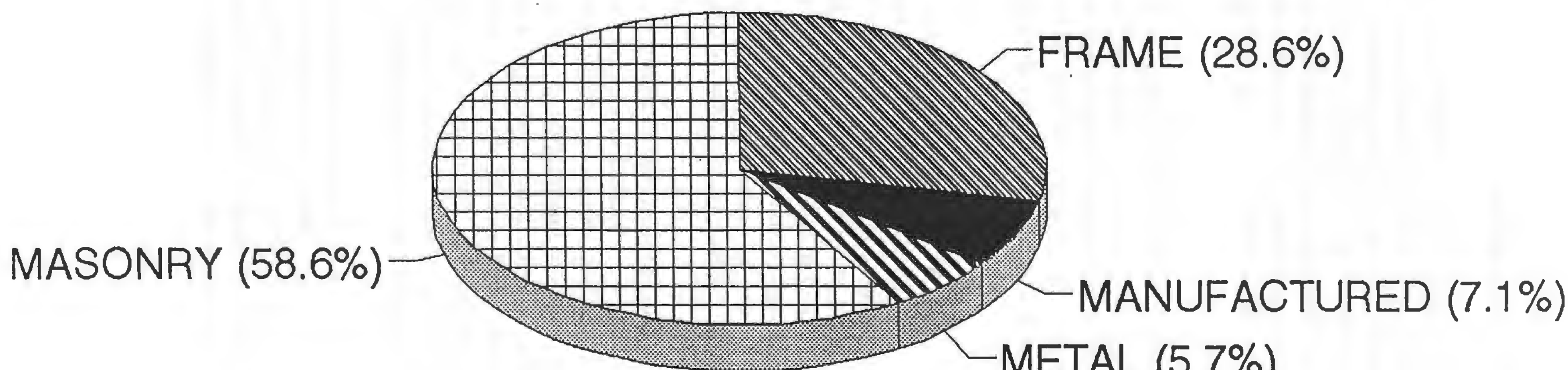
Five are two story. The remaining 65 are one story buildings.

Nine buildings have no attic or ceiling space. The bottom of the roof deck, in most of these cases, is the ceiling of the occupied space. In two cases, the space above the ceiling is a warehouse. In other words, this is an office space in an unconditioned warehouse. Fifteen buildings have attics. The remaining 44 buildings have a ceiling space above the ceiling.

There seems to be confusion among contractors about whether ceiling spaces should be vented and about construction details at the eaves. It is common, for example, to install perforated soffit facia while attempting to block off the soffit space from the ceiling space by insulation batts. The insulation batts, of course, do not stop air flow so the ceiling space is unintentionally vented. In general, it appears that small commercial buildings in Florida contain a hybrid of residential and commercial construction materials and methods which often do not make sense from the perspective of heat flow and air flow control.

Figure 4.1

CONSTRUCTION TYPE
70 SMALL COMMERCIAL BUILDINGS



4.2 General HVAC Information

Cooling capacity. Cooling capacity in commercial buildings is greater than in residential buildings. Total cooling capacity per building ranged from 2 tons to 129 tons, with an average of 16.9 tons. Number of air conditioning systems ranged from one to eight per building, with an average of 3.1 units per building. While Florida residences typically have 1.5 to 2.0 tons of air conditioning capacity per 1000 square feet floor area, the commercial buildings in our sample averaged 3.38 tons per 1000 square feet. They ranged from 1.54 tons per 1000 square feet to 11.1 tons per 1000 square feet. Figure 4.2 presents a breakdown of cooling capacity for the 66 buildings for which cooling capacity is known.

The three buildings with the highest capacity per floor area are fast-food restaurants. Cooling capacity in these three averages 9.8 tons per 1000 square feet. Cooling capacity in all eight buildings which are restaurants or contain restaurants (and for which we know cooling capacity) is 6.1 tons per 1000 square feet, or twice the capacity of the non-restaurant commercial buildings in this study. Interestingly, the fourth largest capacity per floor area is in a 1512 square foot dentist office with a 9 ton air conditioner.

Air handler location. Air handlers are located in mechanical rooms in 13 buildings and in mechanical closets in 16 buildings. We define a mechanical room as a space containing mechanical equipment (air handlers, etc.) in which persons can move around. A mechanical closet is smaller, too small to allow persons to move around or in some cases even enter. Air handlers are in attics in four buildings, in ceiling spaces in two cases, and in the occupied space in six instances. Air handlers are outdoors in five cases and on the roof in 19 cases. Air handlers were in unconditioned warehouses in three buildings (Figure 4.3). (In eight buildings air handlers are located in two locations. The numbers reported in this paragraph consider only the dominant location for each building.)

Ductwork location. Duct systems are generally located in the ceiling space or attic space. Some are located outdoors and some are located in a warehouse space. The attic space and outdoors are always unconditioned. Some ceiling spaces are conditioned and some are unconditioned. Some warehouses are conditioned and some are unconditioned. In two buildings, the ducts are primarily outdoors. In 48 buildings, ducts were located in unconditioned building space, either in an unconditioned ceiling, an attic, or an unconditioned warehouse. In 17 buildings, ducts were located in conditioned space. Conditioned space is defined as either the occupied space or another building space that is inside both the air barrier and thermal barrier of the building. When ducts are lcoated in the conditioned space, penalties from duct leakage are greatly minimized.

Types of ducts. Three types of duct materials dominate air distribution system construction. Nine systems were entirely metal. Twenty-one systems were entirely ductboard. None were entirely flex duct. Hybrid systems were the norm. (In the following, the dominant duct type is listed first.) Nine systems were metal with ductboard. Three were metal with flex duct. Twenty-three systems were ductboard with flex. One system was flex with ductboard. Two buildings had no ductwork (Figure 4.4).

Figure 4.2 COOLING CAPACITY IN 70 COMMERCIAL BLDGS

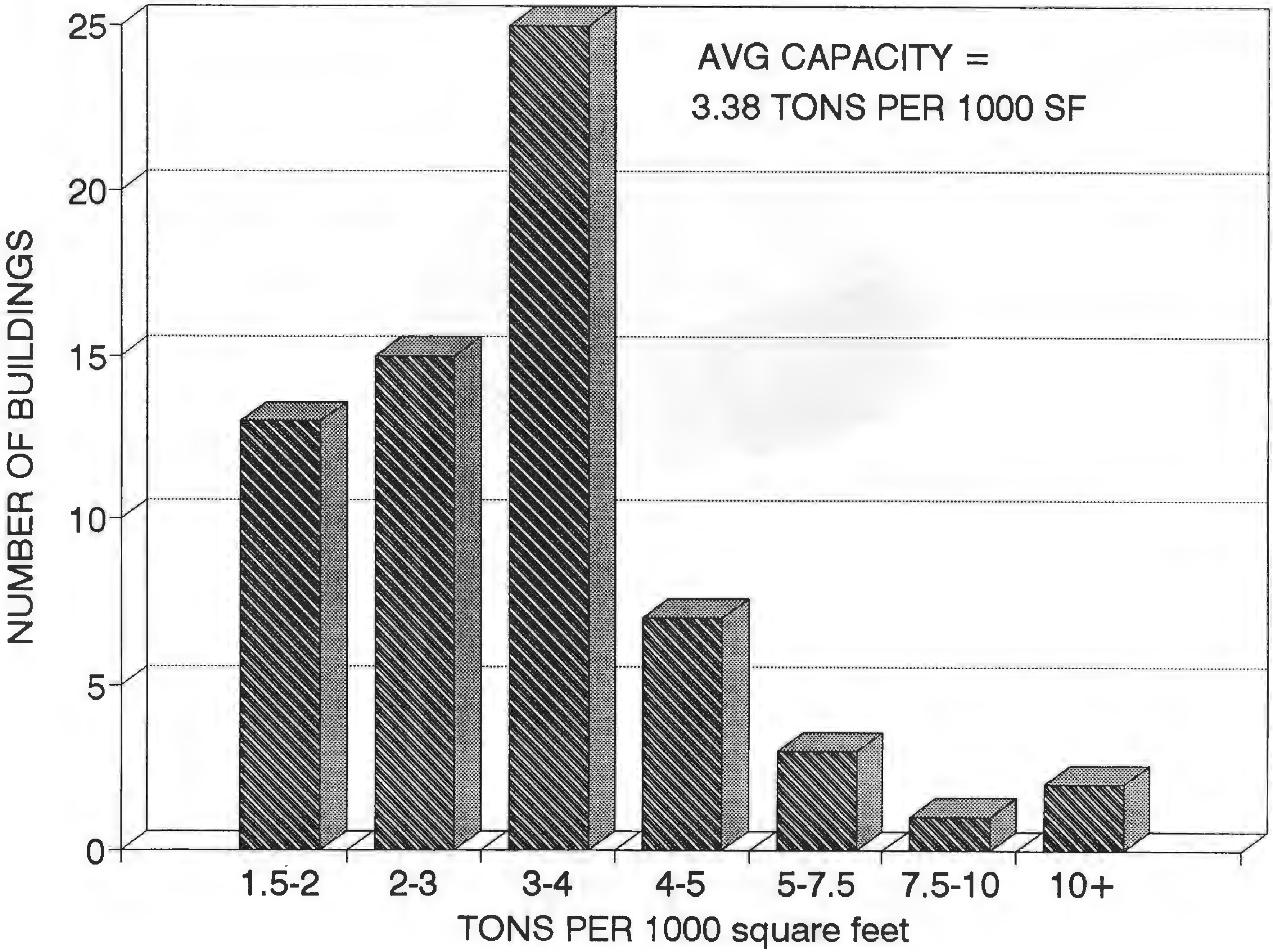


Figure 4.3

AIR HANDLER LOCATION IN 70 SMALL COMMERCIAL BUILDINGS

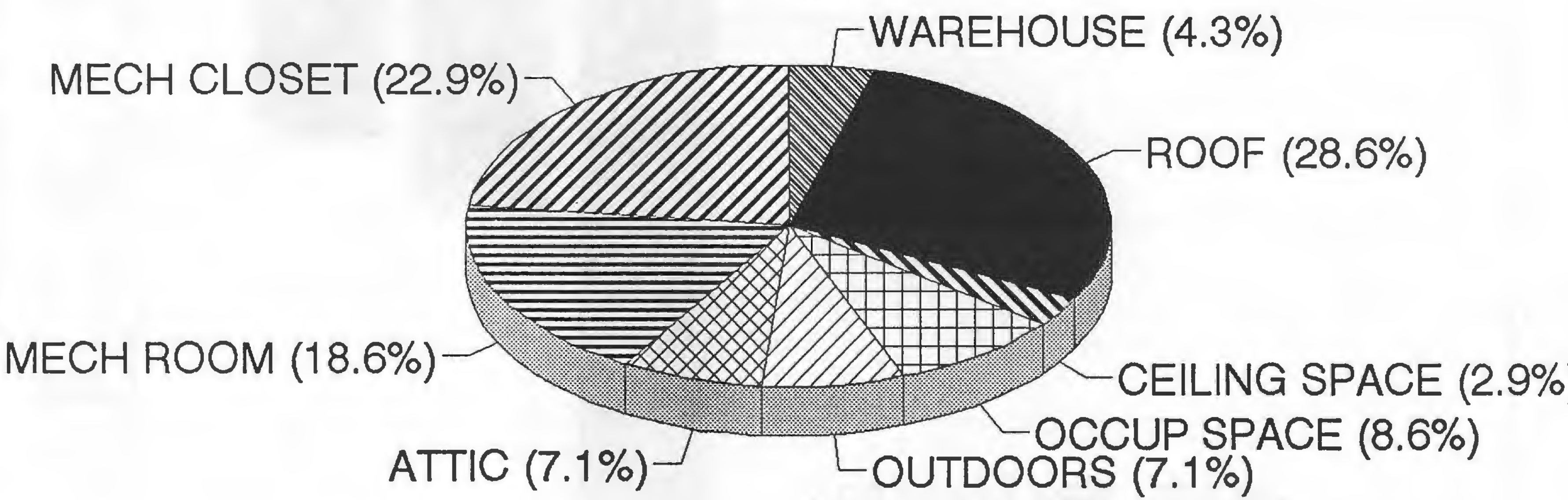
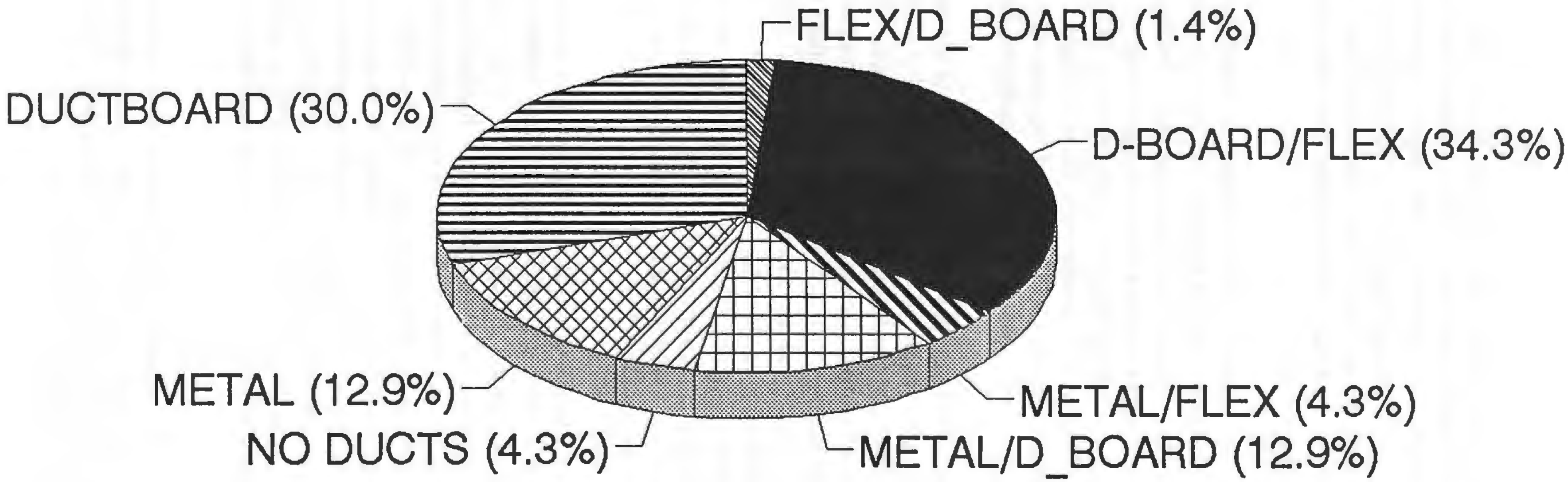


Figure 4.4

DUCT CONSTRUCTION IN 70 SMALL COMMERCIAL BUILDINGS



Building cavities as ducts. Building cavities are also used as portions of air distribution systems. In Florida single family residences, it is common for air handler support platforms to be used as part or all of the return air ductwork. Wall cavities, panned floor joists, mechanical closets, dropped ceiling cavities, and spaces below staircases are also used as ducts in homes. Since these building cavities are almost always very leaky, they represent a large portion of all duct leaks in existing Florida residences. In total, it is estimated that 60% of all duct leak air flow in Florida residences occurs in building cavities used as ducts.

It is also common to use building cavities as ducts in small commercial buildings. In 34 of 70 buildings, one or more types of building cavities are used as ducts (Figure 4.5). In eight buildings, the mechanical room is used as a return plenum. In six buildings, a mechanical closet is used as a return plenum. In most of these 14 cases, the ceiling of the room or closet is t-bar, and in many of those cases the space above the mechanical room is unconditioned attic or ceiling space. Since t-bar ceilings are very leaky, it is common for these mechanical rooms or mechanical closets to experience 20% to 40% return leakage (20% to 40% of the systems return air is originating from leakage through the ceiling or other leak pathways from unconditioned space).

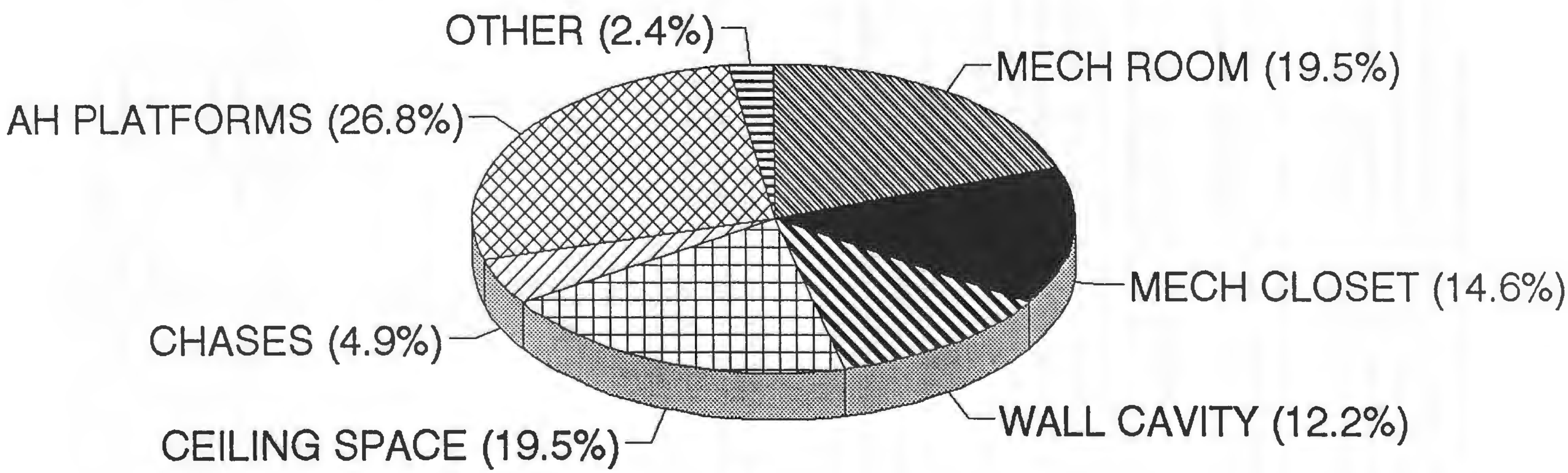
In five buildings, wall cavities are used as ducts or plenums. In eight buildings, the ceiling space is used as a return plenum. In 11 buildings, air handler support platforms are enclosed to form a return plenum, similar to what is found in many residences. In two buildings, chases are used as return ducts. In another building, the space between two dropped ceilings (one above the other) was enclosed to form a return plenum. In this case, one of the ceiling tiles in the upper ceiling had been removed and as a result there was an enormous return leak drawing from an unconditioned ceiling space (CFM25 for that leak site alone was about 4000). Even if all the tiles had been in place, there would still be considerable leakage from the unconditioned ceiling space because t-bar panel construction of the top portion of this plenum was very leaky. (Note that while 34 buildings use building cavities as ducts, the total of the various building cavity types comes to 41 because more than one building cavity type exists in 7 buildings.)

In general, use of building cavities as ductwork is poor practice. Building cavities virtually always leak, and in many cases the leakage can be very severe. Ceiling spaces used as return plenums can be a significant exception to this general rule. If the negative pressure in the ceiling space is fairly small (which is what we observed in most builings) and the ceiling space is reasonably tight to unconditioned spaces (which we found in some cases), then leakage associated with use of the ceiling space as a plenum can be relatively small. It is possible to design the ceiling return plenum to operate at neutral pressure with respect to outdoors. If outdoor air pressurizes the building to +2 pascals, for example, and the plenum runs at -2 pascals with respect to the occupied space, then the plenum will be at neutral pressure with respect to outdoors. Consequently, the plenum can experience next to no duct leakage. (Note that we have observed ceiling return plenums in several buildings operating at positive pressure with respect to outdoors, so in effect these return plenums are experiencing "supply leaks".)

On the other hand, if ceiling space return plenums are rather leaky to outdoors and are significantly depressurized wrt outdoors, then use of the ceiling space as a return plenum will produce substantial air distribution system leakage. Use of the ceiling space as a return plenum can also be poor practice if the roof has little insulation R-value.

Figure 4.5

BUILDING CAVITIES USED AS DUCTS IN 34 OF 70 BUILDINGS



Outdoor air. Twenty-seven buildings have outdoor air. "Outdoor air" is air intentionally drawn into (or pushed into, if there is a dedicated outdoor air fan) the return side of the air distribution system and is generally designed to provide ventilation for occupants in the space. The other 43 buildings do not have outdoor air. They rely on naturally occuring infiltration, leakage in the distribution system, or operation of exhaust fans to bring in ventilation air.

Outdoor air only occurs when the air handler is on. Therefore, when the air handler is off, either because the system has been turned off, or the air handler has cycled off with the compressor, outdoor air ceases, building pressure will decrease, and the building ventilation rate may decrease.

Make-up air. Five buildings have make-up air. "Make-up" air is mechanically induced air blown into the building simultaneously with the operation of the exhaust fans. It is filtered, but in most cases (and in all five cases found in this study) it is unconditioned. Typically the same control switch activates both the make-up air and the exhaust air. Make-up air is designed to reduce the air flow imbalance on the building and thereby reduce space depressurization and space conditioning energy use. Typically make-up air is designed to be 75% to 80% of the flow rate of the exhaust fans (Gaylord Industries, Inc. Smoke Pollution Control Ventilator Model CG-AB-SPC technical bulletin).

As can be seen in Table 4.1, make-up air is substantially undersized in the five restaurants that have make-up air, averaging only 50% of exhaust air flow. Outdoor air is insufficient to make up the balance, averaging only 12% of exhaust air flow. Combined, make-up air and outdoor air represent only 62% of total exhaust air. As a consequence, these buildings operate at negative pressure.

TABLE 4.1.

Building air flow and pressure imbalance in five commercial buildings which have make-up air and which contain restaurants. Note that while make-up air operates when the exhaust fans operate, outdoor air may or may not occur when the exhaust fans operate. Therefore, the net air flow balance may actually be worse than indicated.

ID#	building	EA	MA	OA	NET	dP
32	golf club house	-3038	1107	0	-1931	-6.1
67	hotel	-12907	5140	815	-6952	-3
22	sub restaurant	-5603	3220	1450	-933	-25
35	chicken rest. 2	-9222	5110	1250	-2862	-8
33	chicken rest. 1	-10616	6157	2253	-2206	-43
	average	-8277	4147	1154	-2977	-17.0

In four other buildings containing restaurants, there is no mechanically induced make-up air. In one case, the kitchen exhaust fans are not operated at all (building #19). In another, an exterior kitchen door is left open throughout the day thereby reducing building depressurization from -26 pascals to -4.6 pascals (building #62). In the third, the building is depressurized to -1.8 pascals and passive make-up air comes primarily through the leaky t-bar ceiling from a residential-type attic (building #69). In the fourth, the exhaust fan operates 8 to 10 hours a day. After the duct leaks were repaired, the exhaust fan caused depressurization of -1.8 pascals and most of the passive make-up air comes through a leaky interior knee-wall facade above the bar (building #31). (See section 5.5.9 for additional discussion of building #31.)

Exhaust fans. Forty-three buildings have exhaust fans that discharge air from the occupied space to outdoors. There are a few additional buildings that have exhaust fans that discharge air into ceiling spaces that are within the air barrier of the building. Operation of these latter fans does little to affect building ventilation rates or pressure differentials. The size of exhaust fans (building total) in these 43 structures varies from as little as 44 cfm to as much as 10,606 cfm and averages 1767 cfm. In some buildings the exhaust fans operate virtually whenever the building is occupied, including restaurants, sports facilities, and some other buildings. In others, the exhaust fans are manually operated, either wired into the light switch or on a separate switch, and their operation time is then a function of user interaction.

4.3 Ducts Are Leaky

Testing of duct system airtightness was done in 46 of the 70 buildings. In a majority of these buildings, ducts were found to be very leaky. On average, CFM25 (air flow through leaks when the ducts are depressurized to -25 pascals) was 1209, or 341 CFM25 per 1000 square feet of floor area. By comparison, leakage in 100 central Florida residences (old and new together) was only 116 CFM25 per 1000 square feet, or about one-third as much (Cummings, Tooley, and Moyer, 1991). Note that the ducts measured for airtightness excluded ceiling return plenums in all but one case (building 17).

One factor that affects the amount of duct leakage is that commercial buildings have about twice the installed cooling capacity per 1000 square feet, so ducts in commercial buildings should have about 45% greater surface area. Nevertheless, even considering that difference, duct leakage in these small commercial building is disproportionately much greater than in residences. Note that SMACNA (Sheet Metal and Air Conditioning Contractors National Association) has set a leakage standard for ductwork that is much tighter than what is found in residences or commercial buildings. For Class 6 ductwork (ductboard, flex duct, and other sealed ducts), the standard expects 1.2 CFM25 per 100 square feet of duct surface area (Figure 6.1). For a typical residence, this might be 3 CFM25 per 1000 square feet of floor area. In commercial buildings, this might be 5 CFM25 per 1000 square feet of floor area. Therefore, duct systems in small commercial buildings are about 70 times more leaky than the SMACNA standard.

While the excessive leakiness of commercial duct systems is evident, the impact of duct leakage on energy consumption is not as clear. In some buildings, we expect that duct leaks have little impact on energy consumption when the ducts are fully inside the building. When they are outside the building or in an attic, the energy penalties should be quite large. However, when the ducts are partly inside the building, that is, they are inside either the primary air barrier or the primary thermal barrier, the energy impacts are less certain. We anticipate that a significant amount of energy lost from the duct leaks will be recovered in this scenario.

Energy savings from repair of UAF was examined by repairing UAF in 20 of the 70 buildings. Energy consumption in these 20 buildings decreased by an average 15%. There are still many questions to be answered about the savings that are likely to result from repair when the ducts are in various environments. The candidates selected for energy monitoring generally had ducts that were outside the conditioned space and therefore would be likely to experience significant energy savings.

A number of factors dictate what the energy costs of duct leakage will be. Not all duct leaks are created equal, even those that are the same size. The impact of duct leakage depends upon whether the ducts are completely "inside" the building, partially "inside" the building, outdoors, or -- in the worst case -- in a ceiling or attic space that is outside the air and thermal barrier of the building. By "inside the building" we mean inside the primary air barrier, inside the primary thermal barrier, or inside both the air barrier and the thermal barrier. If the duct leaks occur in a space that is outside the building air and thermal barriers, then only a small portion of the energy lost by duct leaks may be recovered. If the ceiling space is inside the air and thermal barrier, then we expect that the majority of lost energy is covered to the occupied space.

Note that being located in an attic is even worse than being located outdoors. Attics are generally hotter than outdoors, especially during the portions of the day when air conditioning system operate the most. Therefore, any air drawn into duct leaks will be hotter (and generally have a higher dewpoint temperature) than outdoors.

Another factor to consider is the direction of mechanically driven air flow. Consider this example. Building 35, a fast food restaurant serving chicken, had a completely disconnected supply duct discharging approximately 500 cfm of air into the ceiling space. Insulation batts were located on top of the ceiling tiles. Kitchen exhaust fans were drawing about 9200 cfm of air from the restaurant while, on average, make-up air fans and outdoor air were discharging about 5800 cfm into the restaurant. The net air flow imbalance caused the entire restaurant to be depressurized to -43 pascals. This negative pressure was sucking air into the building from all directions, including from the ceiling space. Therefore, the approximately 500 cfm of supply air that was being dumped into the ceiling space would be almost immediately drawn into the occupied space. What portion of the lost energy was being recovered? 25%? 50%? 75%? 100%? We do not know. What would be the energy savings that would result from repairing that large duct leak? Again we do not know. Before retrofit programs can effectively determine which duct systems should be repaired, more investigation needs to be done to understand the energy losses associated with duct leakage in various types of ceilings spaces.

Consider another example, building 69. This is a convenience store with a small kitchen. A kitchen exhaust fan draws 1546 cfm from the building and depressurizes the space to -1.8 pascals. Since nearly all of the building leakage is in the ceiling, nearly all of the air drawn into the building comes from the vented, residential style attic. Since this air may be 110F or hotter in the summer, the energy impacts will be great. Consider, however, if make-up and outdoor air were added to the building so that it ran at a slight positive pressure, say +0.5 pascal. Air would then be passing from the occupied space into the attic. Under this new condition, cooling energy use would be much reduced. Savings are greatest from make-up air, because this air does not need to be conditioned before being injected into the building and when properly designed, a large proportion of the make-up air is drawn directly into the exhaust air stream and is not distributed more generally into the occupied zones. Savings are also significant with outdoor air (compared to drawing air from the attic). Both outdoor air and air drawn in from the attic must be conditioned, but the air from outdoors is cooler and generally drier than air from the attic.

4.4 Ceilings Are Leaky

Commercial buildings, on average, are leaky, and the primary location for building leakage is the ceiling. ACH50, the air exchange rate of the building when depressurized to -50 pascals by a blower door, averages 16.7, about 30% greater than Florida residences, and about 150% leakier than new Florida residences. Not only are these commercial buildings more leaky than residences, the range of leakiness is much greater. As can be seen in Figure 4.6, there is a bi-polar distribution of building airtightness, with peaks at the 5 to 10 ACH50 bin and at the 20 to 25 ACH50 bin.

This twin peak occurs, we believe, because of t-bar suspended ceilings which are used in the greatest majority of commercial buildings. (In our sample, 54 of 70 buildings have suspended, t-bar ceilings. Six of the remaining 16 have no ceiling other than the bottom of the roof deck. Six have gypsum board. Four have some other form of ceiling tiles but are not suspended on t-bar framework.) These suspended ceilings are very leaky, because of cracks, joints, penetrations, openings, vented light fixtures, and duct leaks.

Since the ceilings are almost always leaky, it is what is happening above the ceiling level that determines in most buildings whether the building is very tight or very leaky. In almost all cases, a very leaky building is leaky because the space above the ceiling has large leak pathways to outdoors, sometimes intentionally and sometimes unintentionally. If the building is very airtight, it is because this space above the ceiling is quite tight to outdoors.

There appears to be some confusion on the part of builders and architects about whether ceiling spaces should be vented or not. It is common, for example, for small commercial buildings to have vented soffits under the eaves (with a flat or sloped roof), openings from the eaves into the ceiling space, and insulation batts filling those openings. Since the batts do not create a tight air barrier, air can flow through and around the batts. It is not clear whether the builder intends for ambient air to flow through the ceiling space or not. <u>Based on our understanding of energy and moisture control issues, we suggest that the air and thermal barriers of the building be located at the roof deck and that the ceiling space be made airtight with respect to outdoors.</u>

Single family homes in Florida have become increasingly more airtight over time, as can be seen in Figure 4.7 (Cummings, Tooley, Moyer, 1991). By contrast, commercial buildings in Florida do not show a significant trend toward airtightness (Figure 4.8). Those built in the past 10 years are only slightly more airtight than the entire sample; 14.5 ACH50 in the past 10 years versus 17.7 ACH50 for buildings more than 10 years old. Commercial buildings built in the past 10 years are twice as leaky as home built in the past 10 years. Homes built since 1985 have an average ACH50 of about 7 while commercial buildings have an average ACH50 of 14.5.

Some attempts were made to measure ceiling airtightness. In one facility, an office space is located inside a warehouse. Three exterior walls face outdoors, one wall faces into the warehouse, and the ceiling is exposed to the warehouse. Blower door tests were done, once with the office at -50 pascals and the warehouse at neutral (both with repect to outdoors) and a second time with the warehouse also depressurized to -50 pascals. By sealing obvious leak sites in the one wall facing the warehouse and assuming that remaining leakage in that wall was negligible, we calculate that ceiling leakage is 5.49 $CFM50/ft^2$. For the entire 360 square feet of ceiling area, CFM50 equals 1976, or 86% of total CFM50. Measurements found that the ceiling surface area breaks down to 76.7% suspended ceiling (t-bar and tiles), 17.8% fluorescent light fixtures, 4.4% supply grills, and 1.1% return grill. Ceiling airtightness was measured with the duct registers and grill sealed off, so duct leakage is not included in this number. Results from testing in several other buildings indicate similar ceiling leakage.

Figure 4.6

AIRTIGHTNESS OF 69 CENTRAL FLORIDA SMALL COMMERCIAL BUILDINGS

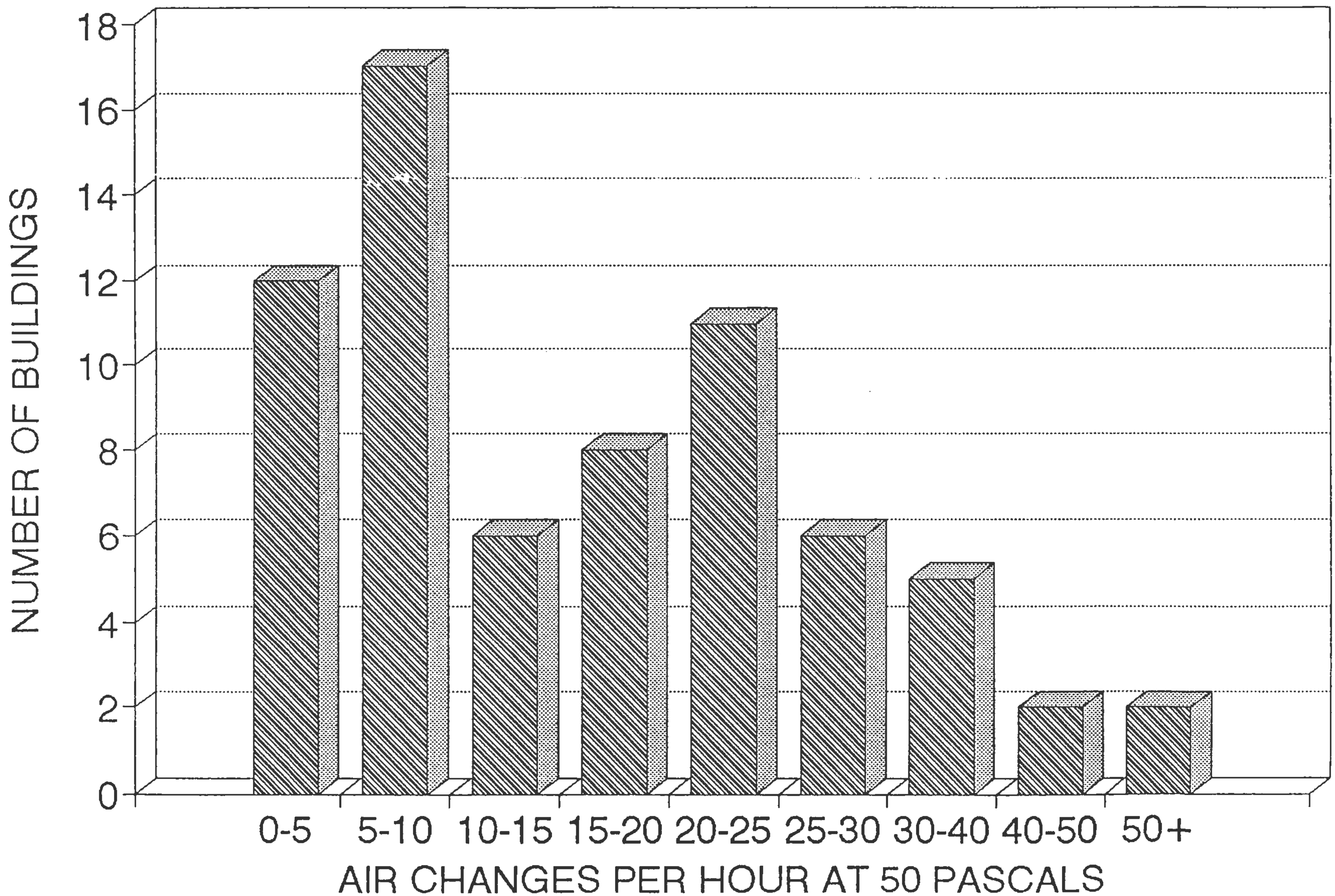


Figure 4.7

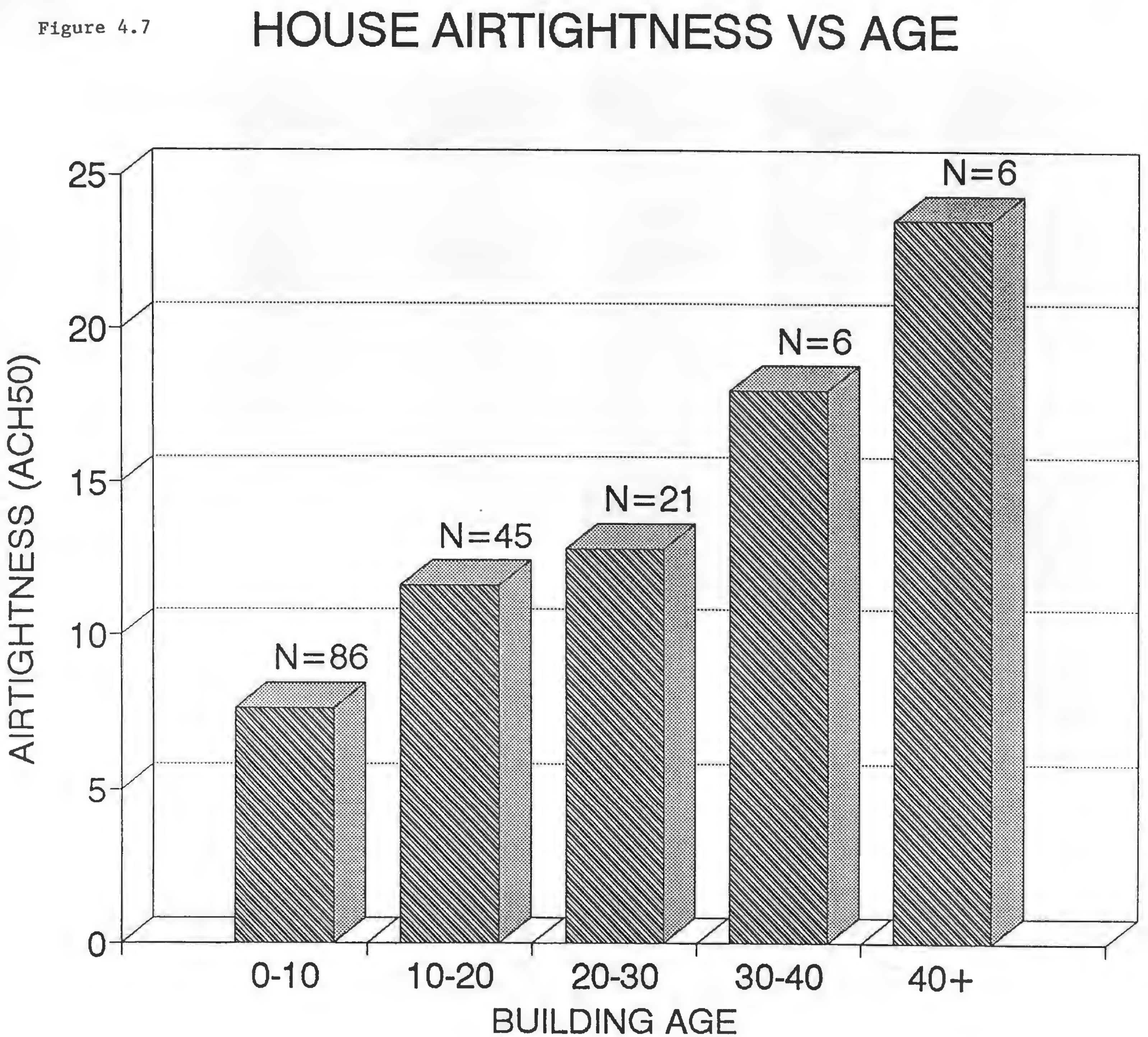
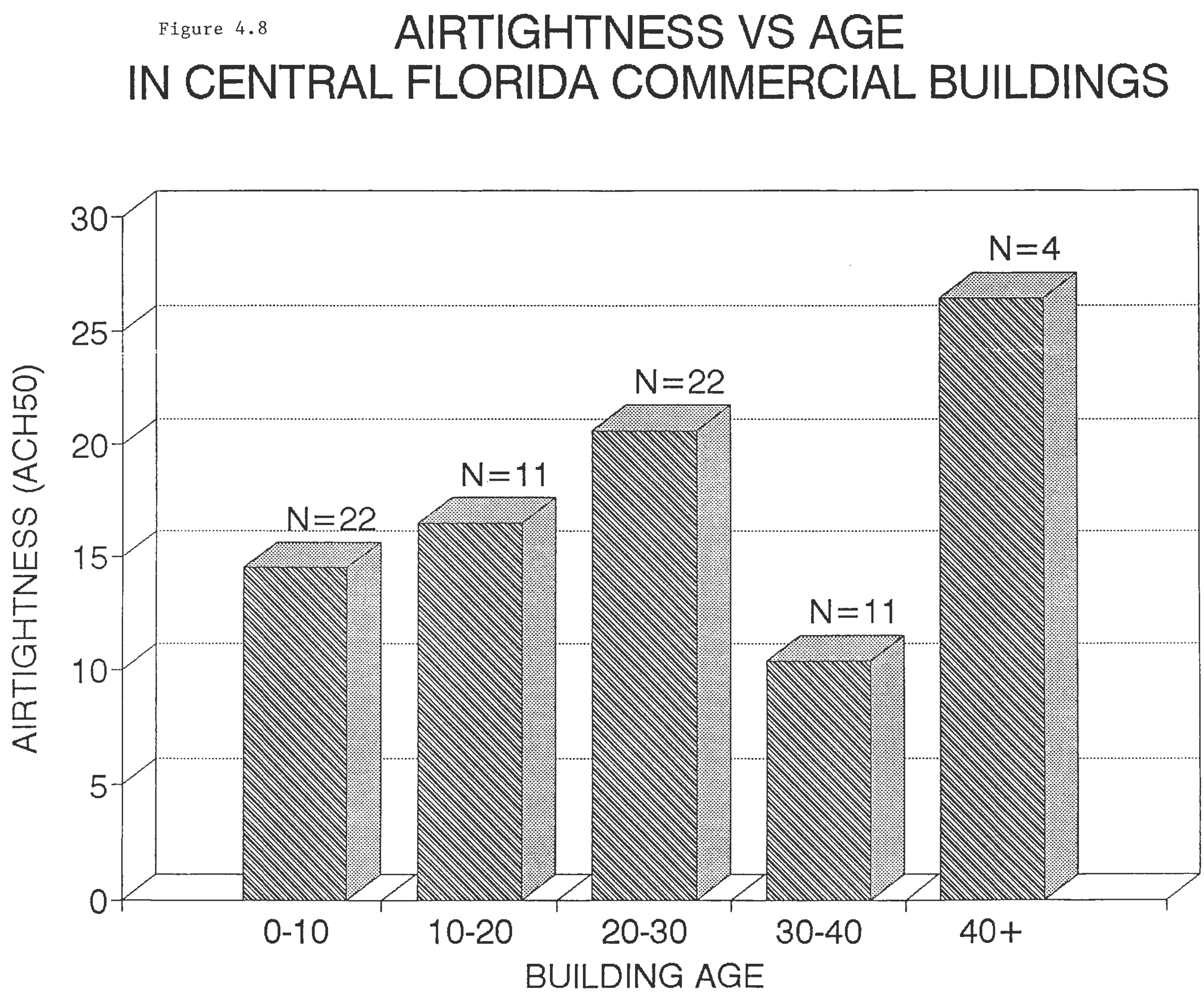

HOUSE AIRTIGHTNESS VS AGE
AIRTIGHTNESS (ACH50)
25
20
15
10
5
0
N=86
N=45
N=21
N=6
N=6
0-10
10-20
20-30
30-40
40+
BUILDING AGE

Figure 4.8


AIRTIGHTNESS VS AGE
IN CENTRAL FLORIDA COMMERCIAL BUILDINGS
AIRTIGHTNESS (ACH50)
30
25
20
15
10
5
0
N=22
N=11
N=22
N=11
N=4
0-10
10-20
20-30
30-40
40+
BUILDING AGE

4.5 Ventilation and Infiltration Rates

In most residences, ventilation is not provided intentionally. It results from natural infiltration (wind and stack driven infiltration), duct leakage, operation of exhaust fans and exhaust equipment, and to a small extent the operation of combustion equipment. Tests in 160 central Florida homes found natural infiltration (air handler and exhaust systems turned off) of 0.28 ach (air changes per hour). When the air handlers were turned on, infiltration increased to 0.91 ach (Cummings, Tooley, and Moyer, 1991), indicating that homes have substantial duct leakage and that mechanically driven infiltration dominates.

As indicated in the previous section, commercial buildings are quite leaky. This shows in passive infiltration rates. In the 55 buildings in which an "air handler off" test was done, passive ventilation averaged 0.43 ach. For these same 55 buildings, ACH50 averaged 17.66. The ratio of ACH50 to natural ach is 41. In a sample of 99 central Florida homes, the ACH50 to passive ach ratio was 39 (Cummings, Tooley, and Moyer, 1991). In a sample of 70 new Florida homes, this ratio was 35. **The general rule for central Florida buildings, then, is that passive infiltration can be predicted (on average for a large sample) by dividing ACH50 by 40, for both residences and small commercial buildings.** (Note: it must be recalled that passive infiltration varies considerably depending upon wind and temperature conditions at the time of the test.)

In commercial buildings, ventilation is often provided intentionally. Twenty-seven buildings have outdoor air, which intentionally ventilates the space when the air handlers operate. Forty-three buildings have exhaust fans that discharge air to outdoors. In some buildings the exhaust fans operate virtually all the time that the building is occupied, including restaurants, sports facilities, and some other buildings. In others, the exhaust fans are manually operated, either wired into the light switch or on a separate switch, and there operation time is then a function of user interaction.

When the air handlers are operating and exhaust fans are in their normal operating mode, the ventilation rate averaged 1.24 ach in 68 buildings (unavailable in two buildings). Note, however, that air handlers do not operate continuously in a majority of these buildings, so the actual "as operated" ventilation rates will be somewhat smaller.

Note that "AH on" ventilation rates are much lower in the 55 buildings for which a passive infiltration test was done. The 13 buildings for which a passive infiltration test was not done are, to a large extent, restaurants and other buildings with large exhaust fans, outdoor air, and make-up air. It is more difficult to obtain the "AH off" test in these buildings because the business owners want the equipment on all the time, especially the kitchen exhaust fans. AHon ventilation in the 55 buildings was 0.85 ach.

Passive and mechanically induced ventilation varies substantially from one building to another. Figure 4.9 graphically displays the distribution of ventilation for the sample of 55 buildings for which AH off infiltration tests were done.

Figure 4.10 graphically displays the distribution of ventilation for the sample of 68 buildings for which AH on ventilation tests were done.

Figure 4.9

INFILTRATION RATE IN 70 COMMERCIAL BUILDINGS WITH HVAC OFF

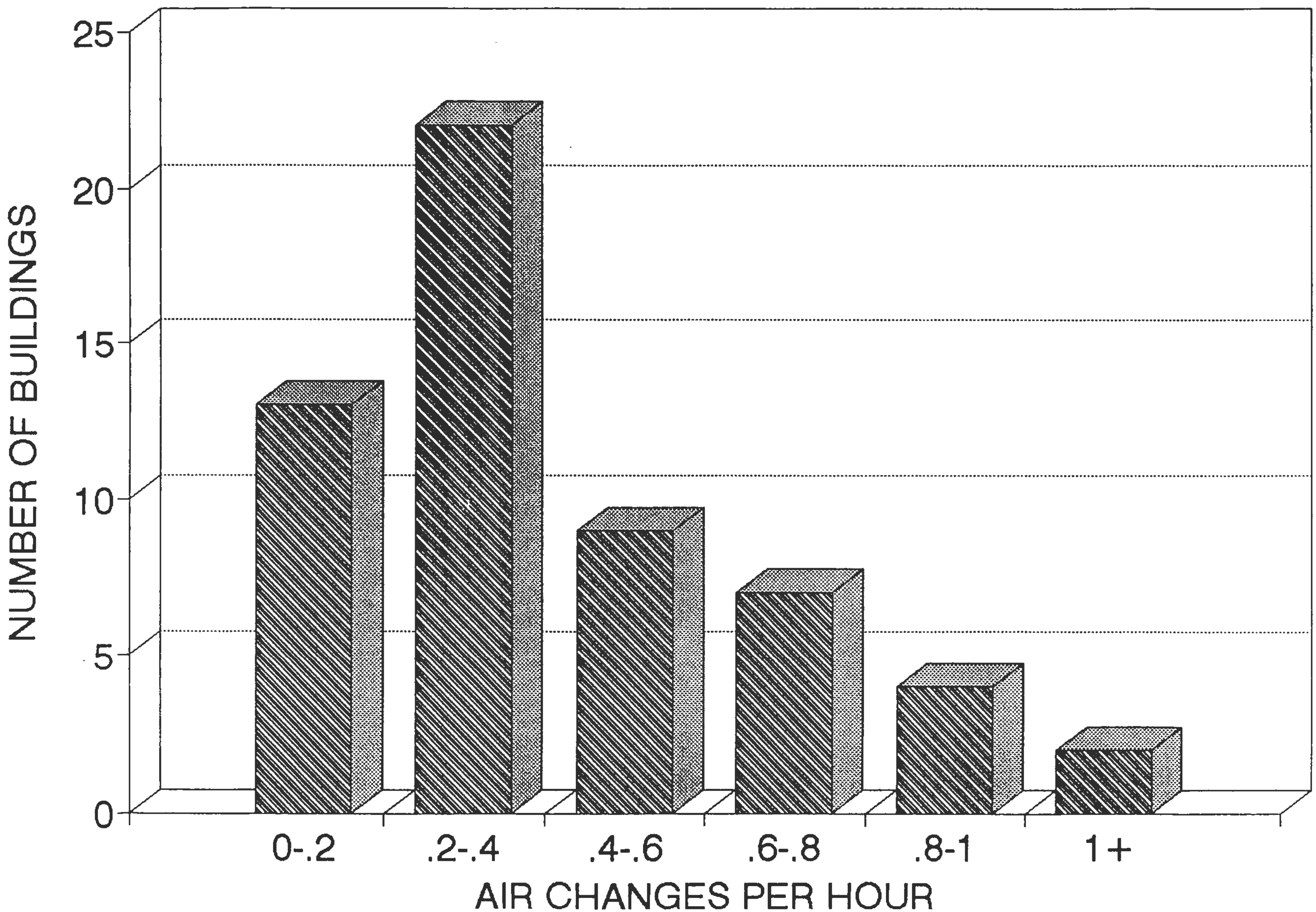


Figure 4.10 INFILTRATION RATE IN 70 COMMERCIAL BUILDINGS WITH NORMAL HVAC OPERATION

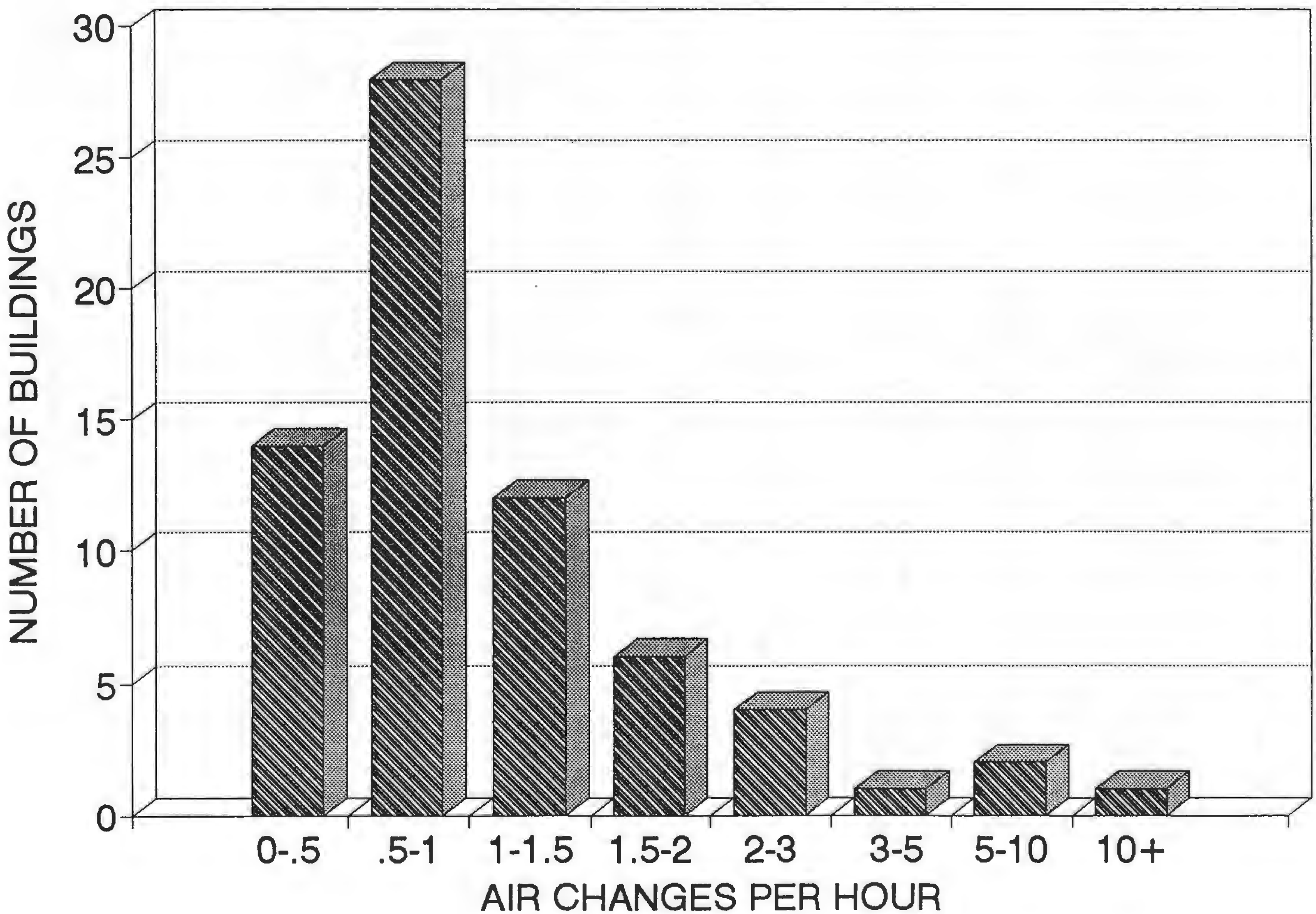


Figure 4.11 illustrates passive infiltration rates versus building airtightness and shows that in general tighter buildings have lower passive infiltration rates.

4.6 Air and Thermal Barriers Are Often Separate

In small commercial buildings, the primary air barrier and primary thermal barrier in the ceiling/roof plane are often separated. The primary air barrier may be located at the roof deck (38 of 68 cases) or at the ceiling plane (30 of 68 cases). The primary thermal barrier may be located at the roof deck, on top of the ceiling tiles, or suspended from the trusses. (By "primary" -- referring to air or thermal barriers -- we mean that this air or thermal barrier provides greater resistance to air or heat flow compared to any other barriers that may be in series.)

By contrast, the ceiling air and thermal barriers in residences are almost always in the same plane. The ceiling gypsum is the air barrier and the thermal barrier (insulation) lies on top of the gypsum.

In small commercial buildings we have identified seven different ceiling/attic space configurations. These configurations are defined by the location of the air and thermal barriers. These configurations also define the type of conditions that likely exist in the space above the ceiling. These configurations are illustrated in Figure 4.12.

1) The roof deck is the primary air and thermal barrier of the building. The roof deck is also the ceiling of the occupied space. **There is no enclosed ceiling space.**

2) The roof deck is the primary air and thermal barrier of the building. Suspended t-bar panels form the ceiling of the occupied space. **The ceiling space is cool and dry.** (Note that ceiling space descriptors refer to summer conditions during hot/humid weather).

3) The roof deck is the primary air barrier of the building. In some cases the ceiling space is very airtight to outdoors. In other cases the ceiling space may be considerably ventilated to outdoors. However, the leakiness of the ceiling space to outdoors is less than the leakiness of the ceiling. The primary thermal barrier of the building is insulation positioned on top of the ceiling panels. The roof deck may have R-value, but its thermal resistance is less than that located at the ceiling. Suspended t-bar panels form the ceiling of the occupied space. **The ceiling space is hot and dry.** The degree of heat in the ceiling space depends upon the R-value inherent in the roof construction and the color of the roof surface.

4) The ceiling of the occupied space is the primary air and thermal barrier of the building. The ceiling or attic space is ventilated, intentionally or unintentionally, such that the leakiness of the ceiling or attic space to outdoors is greater than the leakiness of the suspended ceiling. Suspended t-bar panels form the ceiling of the occupied space. **The ceiling space is hot and humid.**

5) This is the reverse of #3. The suspended ceiling is the primary air barrier while the thermal insulation is located at the roof deck. **The ceiling space is warm and humid.**

   This is an unusual case. For the suspended ceiling to be the primary air barrier requires that the ceiling space be well ventilated to outdoors (because t-bar suspended ceilings are so leaky). What makes this case unusual and surprising is that it makes little sense to place insulation at the roof deck when air can flow freely through the ceiling space from outdoors.

Figure 4.11

PASSIVE INFILTRATION RATE VERSUS BLDG AIRTIGHTNESS IN 69 BUILDINGS

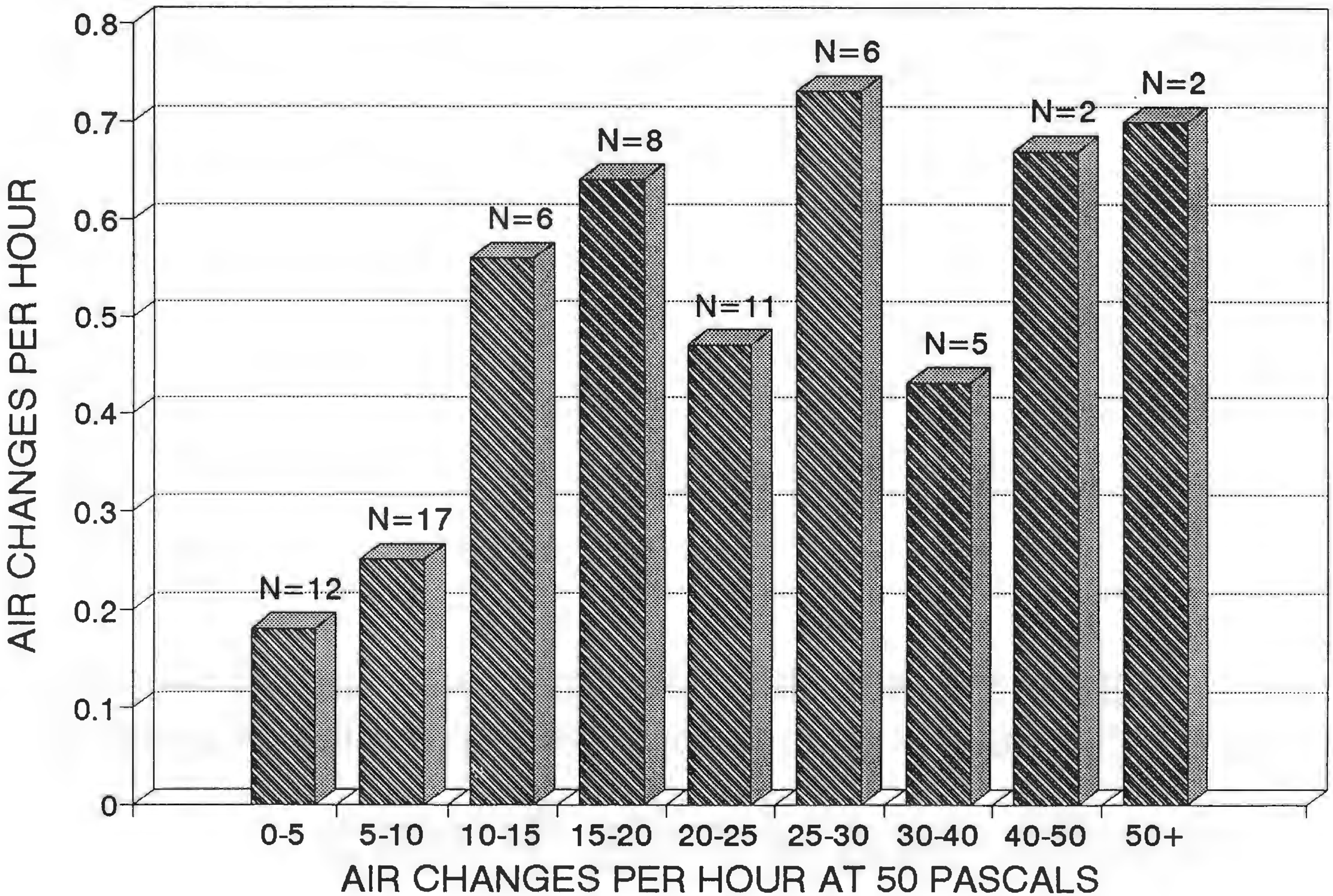
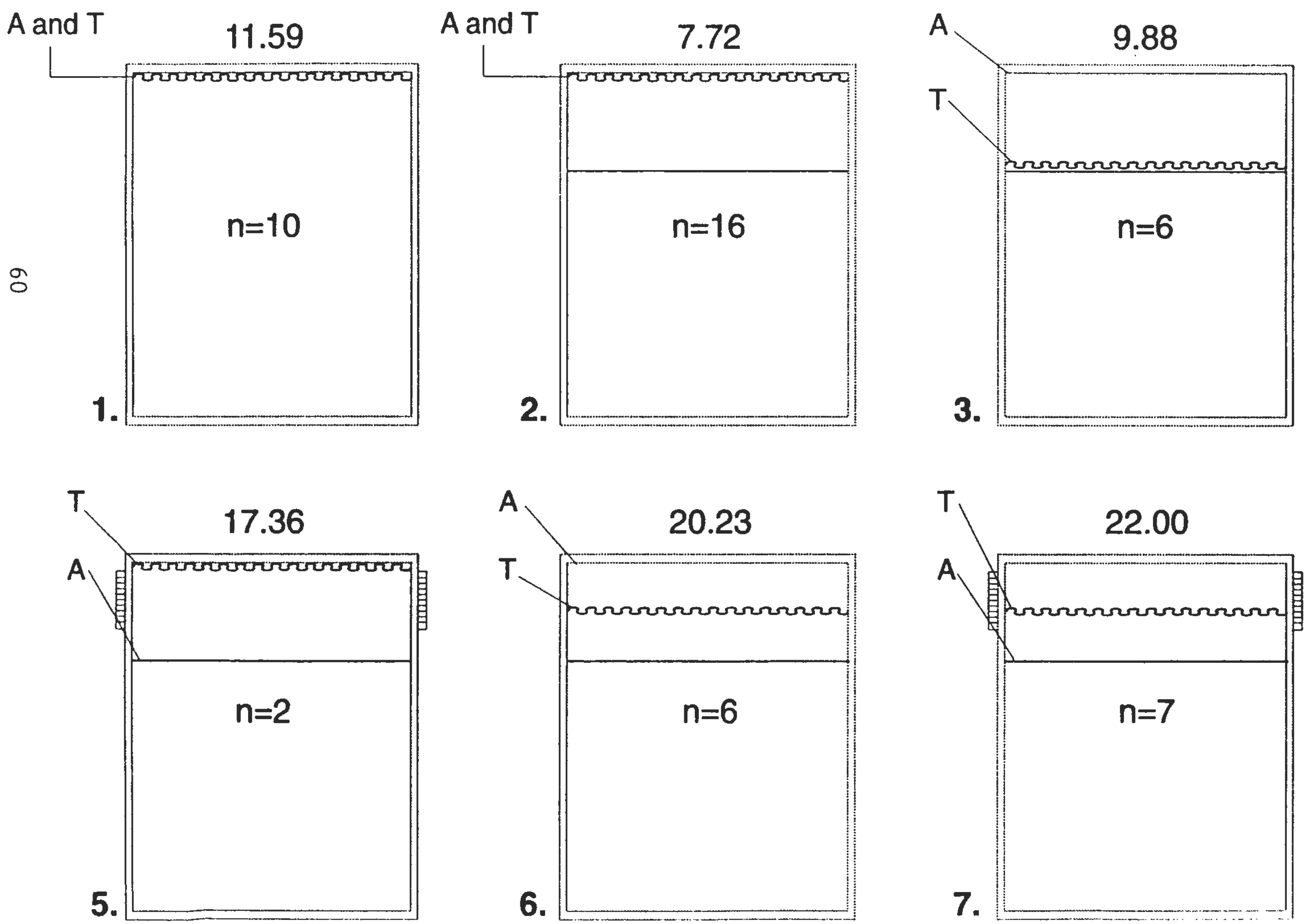


Figure 4.12

Ceiling Space Descriptor:

In commercial buildings the location of ceiling air and thermal barriers greatly affects building airtghtness (ACH50).



A = Primary air barrier
T = Primary thermal barrier

Number above each building is average ACH50.

Only two of the buildings tested in this project qualify as category 5. Uncontrolled air flow in one of these buildings was repaired by sealing the ventilation that existed in the ceiling space. In other words, we moved the building air barrier from the fairly leaky suspended ceiling to the roof deck. Total building ACH50 decreased dramatically from 24.9 to 6.4.

6) The roof deck is the primary air barrier but the thermal barrier is "floating". This occurs when the insulation batts are neither at the roof deck or on top of the ceiling but rather are attached to the bottom of the truss system. Often the insulation batts are located only 8" to 12" above the ceiling tiles. In other cases, they may be suspended three feet or more in the air. In a significant number of the test buildings, insulation batts were falling partially or completely from the bottom of the trusses onto the ceiling space below. **The space above the insulation is hot and dry.** Depending upon the amount and direction of air flow through the suspended insulation, the space between the ceiling and the insulation may be hot and dry, warm and dry, or cool and dry.

   Four of the six buildings that fall into category 6 have attics. In spite of the fact that the attic spaces are intentionally vented, the roof deck is the primary air barrier. This is remarkable, and means that the ceiling plane is very leaky. It also means that in many of these buildings there is almost no air barrier in the ceiling/roof plane of the building. Though we may call the ceiling or roof deck a primary air barrier, this only means that it is tighter than the other. Both may be very leaky.

7) The suspended ceiling of the occupied space is the primary air barrier and the thermal barrier is floating. The fact that the suspended ceiling is the primary air barrier means that the space above the ceiling (almost always an attic) is well vented to outdoors. As with category 6 buildings, parts of the insulation in category 7 buildings may have also fallen.

Table 4.2 contains the same information as Figure 4.12 and illustrates that buildings with leaky or ventilated ceiling spaces are generally considerably more leaky than those with no ceiling space or those where the roof deck is the primary air barrier.

TABLE 4.2
Types of ceiling spaces as defined by the location of the air and thermal barriers in 68 buildings.

	Ceiling Barrier Configuration	#buildings	ACH50
1.	no ceiling space	10	11.59
2.	inside A&T barriers	16	7.72
3.	inside A, outside T	6	9.88
4.	outside A&T	21	26.78
5.	inside T, outdside A	2	17.36
6.	inside A, part inside T	6	20.23
7.	outside A, part inside T	7	22.00

In ceiling barrier configurations 1, 2, 3, and 6 (total of 38 buildings), **the roof deck is the primary air barrier**. That does not mean the roof deck and exterior walls above the ceiling level are completely airtight or even very airtight. It just means that they are tighter than the suspended ceiling. Those buildings where the roof deck is the primary air barrier have an average airtightness of 11.0 ACH50.

In ceiling barrier configurations 4, 5, and 7 (total of 30 buildings), **the suspended ceiling (or in a few cases the gypsum board ceiling) is the primary air barrier.** Those buildings where the ceiling is the primary air barrier have an average airtightness of 25.9 ACH50. As indicated earlier, this greater leakiness is caused by the leakiness of the ceiling space (or attic space) to outdoors.

4.7 Problems That Result From Separate Air and Thermal Barriers

Ideally, the thermal and air barriers should be located in the same plane, and those barriers should be sufficiently effective to stop most heat and air flow into the building. The heat flow resistance of the primary thermal barrier and the air flow resistance of the primary air barrier should be great enough to minimize space conditioning energy loads. A substantial proportion, however, of the small commercial buildings examined in this study have inadequate thermal and air flow resistance in the ceiling/roof plane of the building. Following is a discussion of the pros and cons of the various categories related to the location of the ceiling air and thermal barriers. (Note: categories in the following discussions are as shown in Figure 4.12.)

Categories 1 and 2. The 10 buildings that fall into category 1 and the 16 buildings that fall into category 2 have air and thermal barriers at the roof deck. In almost all of these cases, the air barrier is effective. Average airtightness for these buildings is 9.2 ACH50. The thermal barrier is also likely to be effective, because it is located at the primary air barrier, so air transported heat does not have an opportunity to pass through the insulation. In this study, we have almost no information about the insulation levels that exist in the roof construction; all we could see was the bottom of the roof deck and the top of the roof membrane. Nevertheless, we feel that in most of these cases the building envelope (in terms of both air and thermal barriers) is working quite well, especially in comparison to the following categories.

Categories 3 and 6. The six buildings that fall into category 3 and the six buildings that fall into category 6 may have significant problems. The roof deck is the primary air barrier. This means, however, only that leakage from the ceiling or attic space to outdoors is smaller than the leakage across the ceiling. Note that four of the six category 6 buildings have vented attics! Even though the attic spaces are vented to outdoors, the attic is still more airtight (to outdoors) than the suspended ceiling. In other cases, the ceiling space may be very tight to outdoors. Two examples are a video productions office building (building #6) and a fast food restuarant (building #22) which have ACH50s of 3.7 and 3.9, respectively.

Since the primary thermal barrier is located on top of the ceiling tiles, the space above the insulation may become quite hot on summer days. The extent of the heat penetration into the ceiling space (or attic space) depends upon the thermal resistance of the roof construction. (While the roof may not have insulation materials, nevertheless flat roofs often have significant thermal and mass characteristics related to materials used in its construction.) Heat in this ceiling space can be easily transported into the occupied space by means of duct leakage or air flow through the permeable t-bar ceiling by several types of driving forces, including wind, return duct leaks, supply duct leaks, closed interior doors, and exhaust fans.

Category 4. Like categories 1 and 2, category 4 buildings have the air and thermal barriers located in the same plane, but both barriers are at the ceiling. This is important because in nearly all cases (19 of the 21 cases), the primary air barrier is a suspended t-bar ceiling, and t-bar ceilings are very leaky. Therefore, even though the ceiling is the primary air barrier (i.e., it is tighter than the ceiling space to outdoors interface), it is nevertheless quite leaky. Therefore, air can easily be transported from the hot ceiling space above the insulation into the occupied space by various driving forces such as wind, duct leakage, closed interior doors, and exhaust equipment. By contrast, if the air and thermal barriers are located at the roof deck, then the ceiling space will stay cool and mechanically driven air flow across the suspended ceiling will have very little impact on building energy use.

Category 5. In this category, which is rather rare, the ceiling space or attic space is fairly well ventilated (such that the t-bar ceiling is the primary air barrier), but the insulation is at the roof deck. The insulation may stop most of the heat flow through the roof into the ceiling space, but air from outdoors is free to flow through this space. The ceiling space is likely to be warm and humid. This may result in elevated cooling energy use and possible moisture problems as humid air comes into contact with cool building surfaces, especially the ceiling tiles.

Category 7. This is very similar to category 4, except the insulation is "floating" above the ceiling tiles (attached to the bottom of the trusses). This configuration has all the problems of category 4, but is even worse because in many cases some of the insulation batts have fallen (partly or completely) from the bottom of the trusses onto the ceiling tiles below. This leaves large gaps in the insulation barrier and thus allows air to flow freely through the insulation barrier.

4.8 Insulation Problems

The location of insulation in the ceiling/roof plane of the building has important implications. In 29 buildings, insulation was located at the roof deck, either integral to the roof construction or attached to the bottom of the decking. In 28 buildings, insulation was located on top of the ceiling. In 13 cases, insulation was attached to the bottom of attic trusses and therefore was "floating" between the ceiling and roof.

In general, locating insulation at the roof deck is the best choice. In all but one building, this means the air and thermal barriers are at the same location. As a consequence air flow and heat flow (in the plane of the ceiling) is well controlled. Additionally, this keeps the ceiling space cool and dry which in turn minimizes the energy impacts of other types of uncontrolled air flow which may exist in the building.

Insulation located on top of the ceiling tiles can be a problem, for two reasons.

1) In many cases, insulation batts have been moved around as persons lift ceiling tiles to gain access to the ceiling space. Over time, the number of insulation batts shifted from their place increases as more persons access the ceiling space to run wires and work on mechanical systems. This leads to substantial insulation voids which significantly reduce the overall insulation system thermal resistance.

   Insulation voids also exist at light fixtures. In many ceilings, light fixtures represent 10% to 15% of the total ceiling area. In other cases, portions of the ceiling have simply not been insulated. It is not unusual to find voids due to light fixtures, moved batts, and installation oversight reaching 20% to 30%, and in some cases 50% or more.

2) Air can pass through the leaky ceiling and through the insulation. The amount of heat that enters the occupied space depends upon the amount of ambient heat that enters the ceiling or attic space and the extent of driving forces that move air across the ceiling. Exhaust fans can depressurize the occupied space causing hot air to be readily drawn into the building. Closing interior doors (when the return is located in the central zone) pressurizes the closed rooms and depressurizes the central zones, thus transporting significant amounts of hot air across the ceiling. Return leaks, if the return leakage occurs in the ceiling or attic space, can transport hot air into the occupied space. Supply leaks can depressurize the occupied space and cause considerable amounts of ceiling space air to be drawn into the occupied zone. Mechanical rooms used as return plenums are depressurized and thus can draw considerable amounts of air from the ceiling space/attic space into the occupied zone.

Insulation attached to the bottom of attic trusses generally has problems. Often insulation batts partially or completely detach from the trusses and fall to the ceiling below (often 6 inches to 36 inches), leaving significant gaps in the insulation system. Even if the batts remain attached to the trusses, air can flow through this thermal barrier. With a ventilated attic above and a leaky t-bar ceiling below, there is great potential for hot attic air to move into the occupied zone and conditioned air to flow out of the building.

Insulation may be located at the roof deck, but the ceiling space is intentionally or unintentionally vented. The insulation may be effective in rejecting the solar load coming through the roof deck, but air transported heat from outdoors bypasses the insulation, so its overall effectiveness is greatly reduced.

4.9 Exhaust Air/Make-up Air Imbalance

Forty-five of the 70 buildings have exhaust fans that discharge air from the building. There are a few additional buildings that have exhaust fans that discharge air into ceiling spaces that are within the air barrier of the building. The exhaust systems flow rates range from a low of 44 cfm to 12,907 cfm per building. Normalized to floor area, flow rates range from 5 cfm per 1000 square feet to 3355 cfm per 1000 square feet. On average, exhaust fans in these 45 buildings move 362 cfm per 1000 square feet out of the building.

Restaurants generally are at the high end of the exhaust fan air flow rate spectrum. In fact, in this sample of 70 buildings, the eight highest exhaust "cfm per 1000 square feet" are restaurants or buildings that contain restaurants (hotels, golf club house, convenience store). These eight range from 411 to 3355 cfm per 1000 square feet, with an average of 1521 cfm per 1000 square feet of floor area. One other restaurant, actually a stop-and-go gas station/convenience store with a kitchen area, has exhaust flow of 375 cfm per 1000 square feet. The remaining 35 building having exhaust fans have an average exhaust air flow of 100 cfm per 1000 square feet.

Exhaust fans tend to depressurize buildings. The greater the exhaust flow rate and the tighter the building, the greater the depressurization. In some buildings the exhaust fans operate only intermittently and are typically occupant controlled. In other buildings the exhaust fans operate continuously or almost continuously.

Space depressurization may be off-set by outdoor air or make-up air. **Outdoor air** is generally an intentional return leak drawing air from outdoors when the air handler is operating, and is generally intended to meet ventilation requirements. In some cases outdoor air is induced by its own blower but still operates only when the air handler operates. **Make-up air**, by contrast, operates only when the exhaust fans are operating and is intended to make-up for air drawn out of the building by the exhaust fans. It pushes (generally unconditioned) air into the building in proximity to the exhaust fan intakes so that less conditioned building air is exhausted from the building. Its purpose is to reduce space depressurization, allow downsizing of space conditioning equipment, improve indoor humidity and thermal comfort, and reduce space conditioning energy use.

Twenty-five of the 45 buildings with exhaust fans have outdoor air. In most small commercial buildings, outdoor air is intermittent because the air handlers cycle according to load. In other cases, the air handlers may run continuously but have variable speed, and as a consequence outdoor air varies with load as well. In buildings where exhaust fans operate continuously for extended periods, outdoor air is therefore not a reliable means to avoid excessive space depressurization.

Make-up air can be quite useful in avoiding excessive space depressurization. Since it operates whenever the exhaust fans are operating, the building air flow balance can be controlled and predictable. Two problems exist, however. 1) Most buildings do not have make-up air. Of the 45 buildings that have exhaust fans that discharge to outdoors, only five have make-up air. These five are all restaurants. Four other restaurants do not have mechanically induced make-up air. 2) Make-up air flow is substantially less than exhaust air flow. By design, make-up air is set at only 60% to 80% of the flow rate of the exhaust fans, so that the kitchen area will be depressurized with respect to the dining area. This will cause heat, humidity, and odors from cooking operations to move from the dining area toward the kitchen, and not vice versa.

For example, if the kitchen exhaust fans move 10,000 cfm, the make-up air fan may move only 7000 cfm. Thus there is a 3000 cfm net deficit, so the building will be depressurized. In some cases, outdoor air can make-up some or all of the remaining imbalance. As indicated, since the air handlers may cycle with load, outdoor air may therefore operate only a portion of the time and net air flow and building pressure may fluctuate up and down.

In the case of the chicken restaurant 1 (building #33), air flow and pressure imbalance exists because the four air handlers cycle on and off according to load. As a consequence, building pressure fluctuates up and down in a stair-step fashion throughout the day as air handlers cycle on and off, ranging from -3 pascals when all are on to -18 pascals when all are off (Figures 13 - 15). During the afternoon hours of hot summer days, most of the outdoor air is operational, and building pressure is in the range of -3 pascals to -8 pascals. During cool morning hours in the spring and fall, three or even all four of the air handlers may be off and the pressure in the building will be in the range of -13 pascals to -18 pascals. Late at night when the thermostats are set to higher levels in order to save energy overnight, all four air handlers (and the outdoor air) shut off and building pressure goes to a consistent -18 pascals. This space depressurization has lead to considerable mold and mildew growth on the interior walls, backdrafting of the water heater, and flame roll-out from the water heater on two occasions.

4.10 Variable Air Volume Systems

Variable air volume (VAV) systems impact internal air flows, ventilation rates, and building pressure differentials. Instead of cycling on and off to meet load, these systems vary air flow through individual air terminal boxes and through the main air handler in response to changes in cooling or heating load. In VAV systems, total air flow through the air handlers varies, either because of variable speed drive or inlet vane damper control. In many systems, as a consequence, outdoor air flow rates

Figure 4.13

Restaurant Air Flow Balance

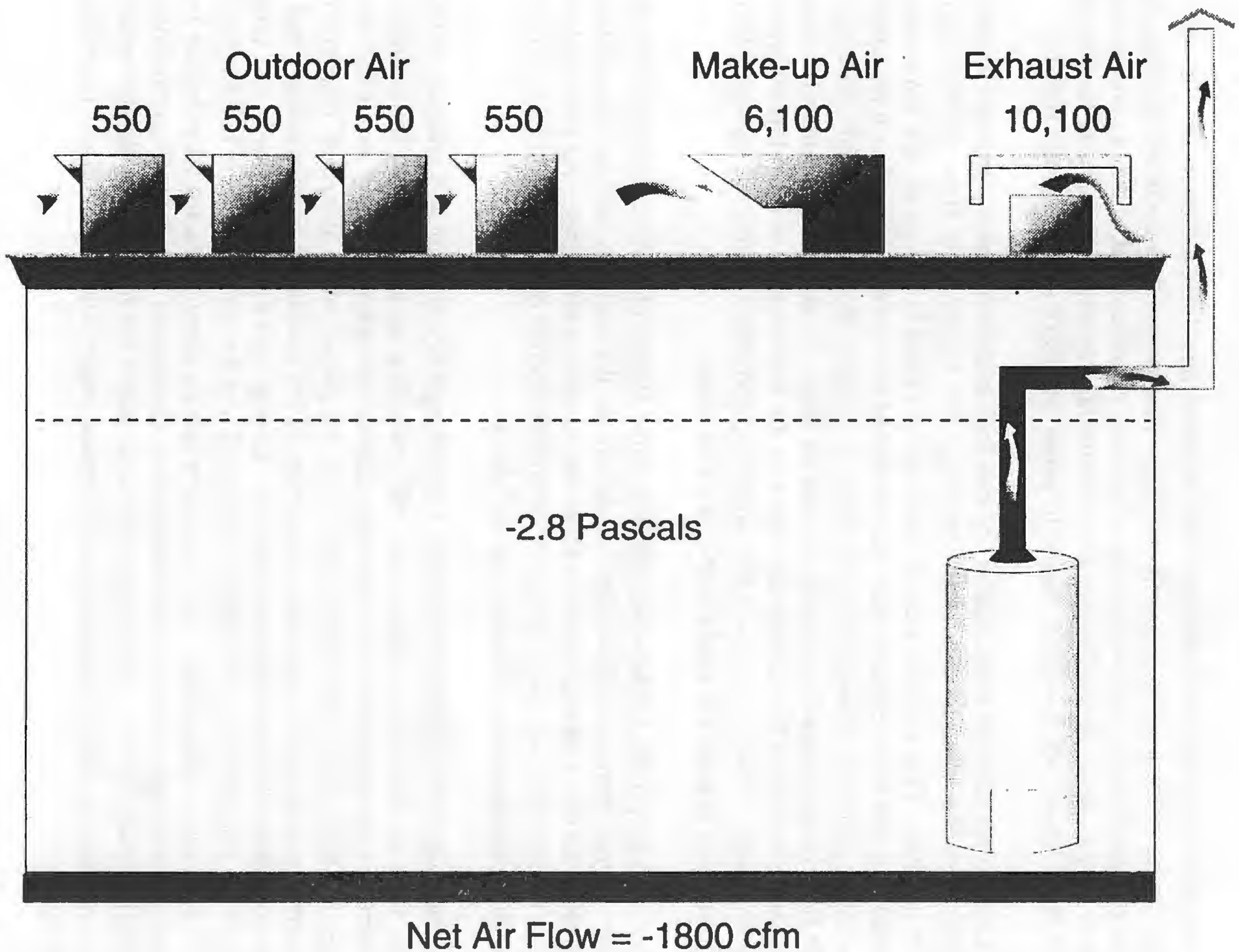
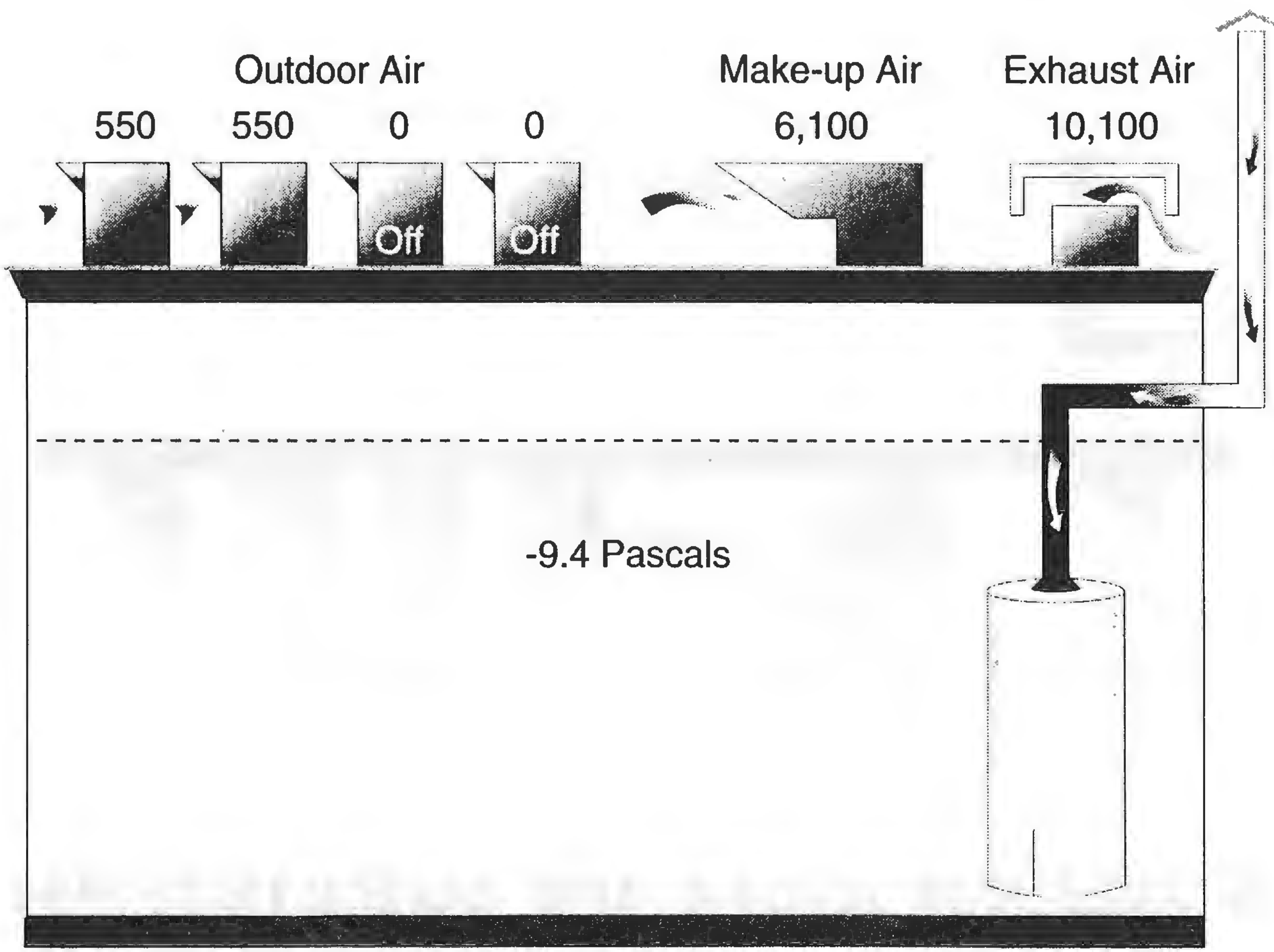


Figure 4.14

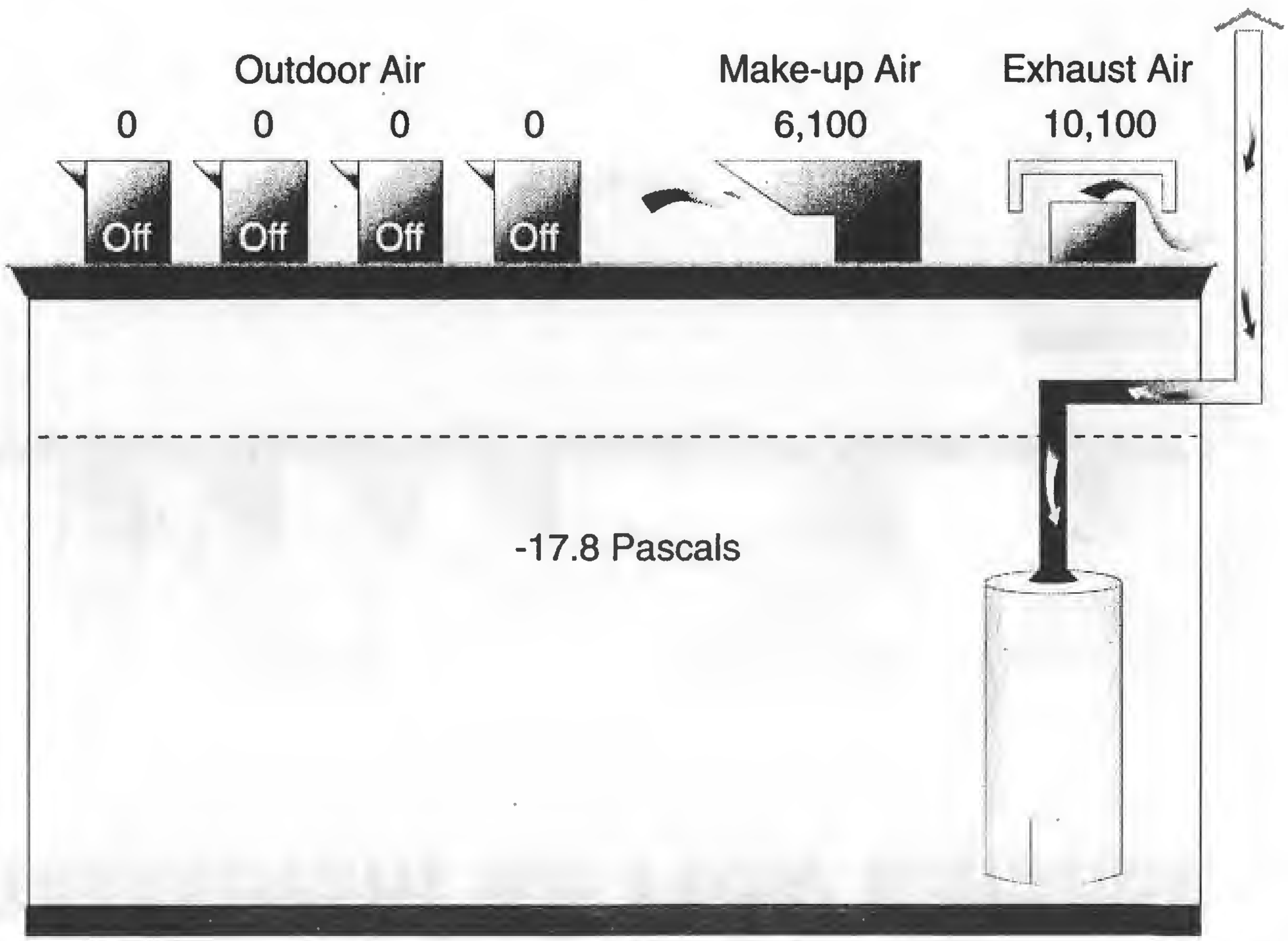
Restaurant Air Flow Balance



Net Air Flow = -2900 cfm

Figure 4.15

Restaurant Air Flow Balance



Net Air Flow = -3950 cfm

also vary because depressurization on the return side of the system varies as a function of the air handler flow rate. In other cases, outdoor air may be fairly constant because it has its own blower to induce flow.

When outdoor air fluctuates, primarily as a function of load, the building ventilation rate can change and the net air flow into the building can change. In many buildings, exhaust fans operate continuously and at a constant rate. Therefore, it is possible that building pressure can flip-flop back and forth between positive and negative pressure as a function of VAV operation. Our observations are based on testing in three buildings which have VAV systems, including one which was a large 145,000 square foot central Florida office building not tested as part of this project. Additional research into VAV systems and the impacts of their operation upon building air flow balance and pressure differential is needed.

4.11 Failure of Design

In many small commercial buildings, it appears that HVAC systems are not designed in any detail. Rather, they are simply installed by the HVAC contractors. In many cases, layout of ductwork, sizing of exhaust fans, settings of outdoor dampers, and even whether outdoor air is provided is left up to the contractor and/or the installing technicians. As commercial buildings get progressively larger, the proportion with detailed HVAC design and specifications increases.

In other cases, HVAC designs are flawed. Provision of return air, for example, is often left to chance. Returns are often located in central zones of buildings with little or no provision for return air to get from closed rooms to those returns. Significant pressure imbalances may result. In many commercial buildings, the ceiling space is used as a return plenum. If the ceiling space is significantly depressurized with respect to outdoors, substantial return leakage may result if the ceiling space is leaky. In other cases, firewalls may separate various sections of the building and restrict the return air from moving from one zone to another and back to the air handler. In some cases, no return pathways are provided through the firewalls. In other cases, return transfer windows are provided (with fire dampers) but the windows are undersized. In other cases, the dampers (which are supposed to be closed only in case of fire) are closed and thus restrict return air flow. Consequently, significant pressure imbalances may result.

In one building a single air handler served two zones, and the ceiling space was the return plenum. Because the return transfer windows were only about 1/3 the required size, pressure in the remote zone went to as high as +17 pascals while pressure in the zone housing the air handler went to as low as -8 pascals.

In other buildings, no provision was made for make-up air. Consequently, exhaust fans cause serious depressurization of the building which can result in humidity control problems, microbial growth problems, moisture damage to building materials, and backdrafting of combustion appliances. In one restaurant (building #62), no mechanical make-up air was provided and the building was depressurized to -26 pascals. Since this created excessive infiltration and made it difficult to maintain acceptable room temperature and humidity, the business owner responded by keeping the exterior door to the kitchen open throughout the entire day. Even with the door open, the building was depressurized to -4.6 pascals. In another restaurant (building #19), a passive make-up vent was located in the ceiling above the pizza assembly counter. Because the make-up air would blast down onto the workers (and a considerable portion of this air was coming from the attic space above), the kitchen exhaust fan was never operated in spite of the fact that it was always very hot because of the large pizza oven.

In some buildings, little or no mechanical ventilation was installed in spite of considerable sources of indoor air contamination. One print shop (building #55) had neither outdoor air or exhaust air, and measurement of total volatile organic compounds (TVOCs) was measured at 700 ppm (measured by Bruel and Kjaer 1302 multi-gas monitor). By contrast, TVOCs in most other buildings we have measured were less than 4 ppm. In another print shop (building # 36), there was no outdoor air and only 23 cfm/1000 square feet of exhaust. TVOC levels were also very high, at over 150 ppm. Also in a plastics fabrication facility (building #56), no mechanical ventilation of any kind was provided. Since these three buildings have considerable air contamination sources, it is important that adequate ventilation (either spot ventilation or distributed ventilation) be provided in order to ensure acceptable indoor air quality.

In other cases, HVAC components may be specified but important information is left out. The size of the cooling system may be specified, but the amount of outdoor air or whether there should be any outdoor air is omitted. In some cases, return transfer windows may be indicated but the size of the windows may not be specified. Exhaust fans may be indicated, but not how they are to be controlled. Cooling system capacity may be specified, but whether it will be two-stage or whether the air handler blower cycles with the compressor is left to the discression of the contractor. Therefore, these operation and control decisions then go by default to the HVAC contractor and/or his technician.

4.12 Test and Balance Issues

In this study, a number of building failure modes have been detected that relate to test and balance (TAB). The first point is that in a majority of small commercial buildings, it appears that no test and balance is done. The system is installed by the HVAC contractor, who may adjust flows to within reasonable specifications, but no independent TAB is done. Consequently, air distribution air flows and exhaust/intake air flows may be considerably out of balance.

The second point is that outdoor air settings seem to be somewhat random, though it is not clear from our research that the blame rests with the TAB firms. In some buildings, the outdoor air may be sealed off or in other cases it may be wide open and providing excessive amounts of outdoor air. In one dentist office (building #9), for example, we found that the cooling system was greatly oversized (a 10-ton unit serving a 1512 square foot building and outdoor air was wide open and providing 911 cfm, or 32% of the total air handler air flow). Since average building occupancy was 9 persons, this means there was over 100 cfm of ventilation per person. As a consequence, cooling energy use and indoor relative humidity were high.

Several months later we came back to this dentist office in order to monitor the building for energy savings that would result from reducing outdoor air. To our surprise, we found that the large roof-top package unit had been moved about 15 feet from its earlier position, the old sheet metal duct system (located on the roof) had been replaced by a completely new duct system (ductboard ducts completely exposed on the roof with only a mastic coating), and the outdoor air was completely sealed off. This clearly shows that after-the-fact modifications can result in significant system changes that are, of course, beyond the control of both designer and TAB personnel.

The third point is that TAB firms may, in some cases, fail to balance building air flows or may even create unbalanced air flows because there may be little room or inadequate provisions made for proper air flow measurements. The TAB firm may achieve the wrong building pressure because they often rely too greatly on measurement of air flows to determine if the building is at positive or negative pressure. Relying upon air flow measurements to determine building net air flow (whether it is positive or negative) can lead to significant error because of measurement inaccuracies, duct leakage (duct leak air flows are not accounted for), or air flow imbalances caused by restricted return air.

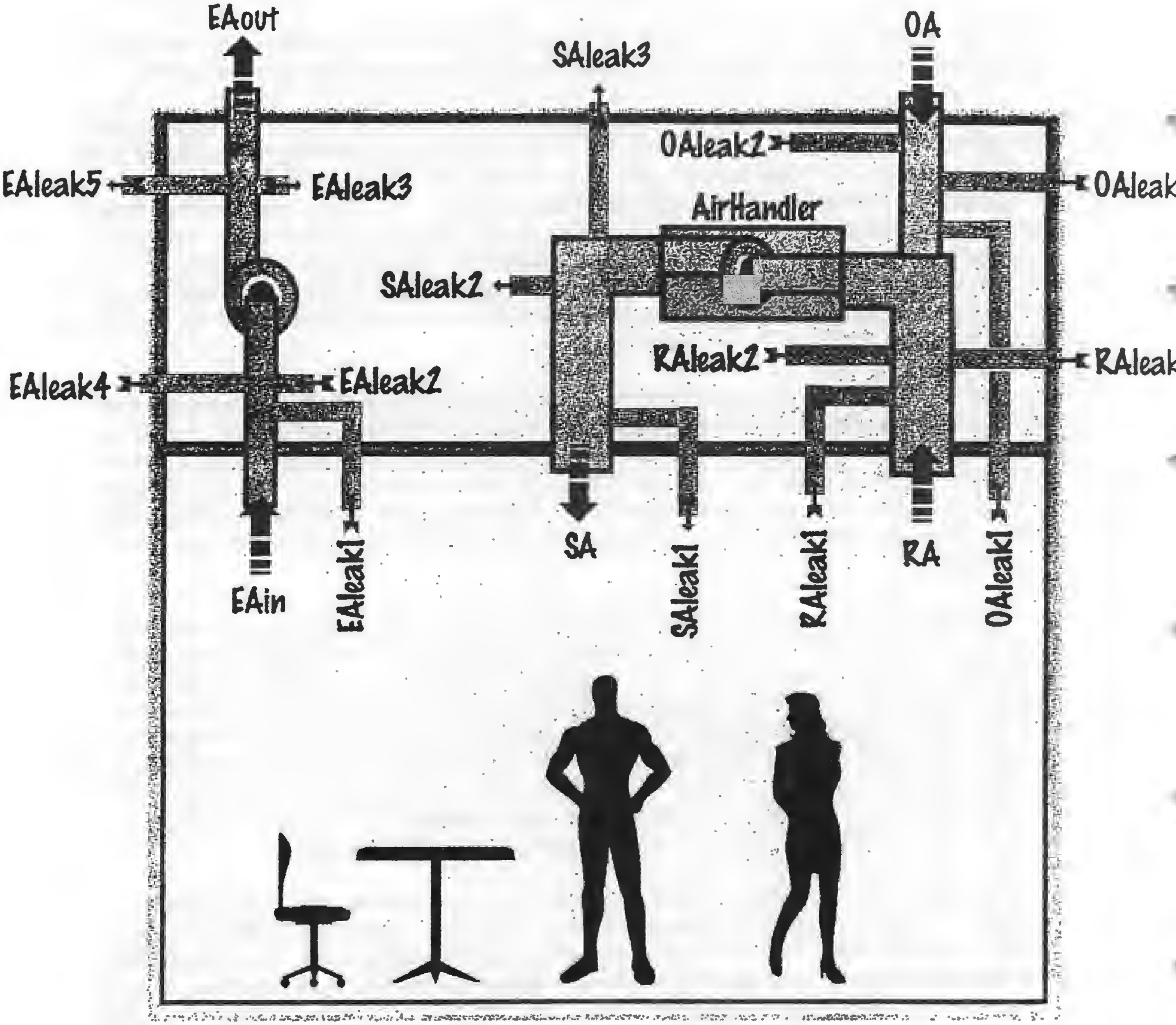
Air flow hoods, the primary tool of the TAB industry, often overestimate air flows being discharged into the room from supply registers (see Section 3.9.1). Since they sometimes overestimate air flow entering the conditioned space and generally accurately measure air leaving the conditioned space, relying upon the balance between the supply and return measurements can lead one to believe that the building air flow balance is positive when in fact in may be negative. This bias can cause TAB personnel to sometimes determine that spaces and buildings are at positive pressure when in fact they are depressurized. It may also cause them to adjust the speed of exhaust fans, make-up air fans, and the size of outdoor air openings in order to decrease net air flow into the building under the mistaken belief that the building is at positive pressure.

The fourth point is that the air flow measurement approach to building air flow balance also produces error because duct systems leak. Supply ducts, return ducts, exhaust ducts, make-up air, and outdoor air ducts can all have air leakage. When this leakage occurs within the primary building air barrier, measurements done at grills and registers do not provide an accurate picture of the air flows across the building envelope. Figure 4.16 illustrates potential air flows within a building, including supply, return, outdoor air, exhaust air, and make-up air flows, and duct leakage which may occur in each of these.

It is important to understand how duct leakage can distort the picture obtained from measurements of air flows. Let's look at Figure 4.16 in some detail to understand how duct leakage affects building net air flow. Looking at the exhaust system in specific, note that there are seven different air flows indicated; EAin is air going into the exhaust grill, EA out is the air flow discharging, three possible leak sites on the suction side, and two possible leak sites on the discharge side. If one measures air flow entering the exhaust grill, this measurement will not truly reflect air flow out of the building if EAleak1, EAleak2, EAleak3, or EAleak4 are occurring. If one measures air flow discharging at the roof level, EAout, this is likely to accurately reflect the exhaust air flow leaving the building, unless leak EAleak5 is occurring (duct leak on the discharge side going to outdoors).

These types of leaks occur frequently in commercial buildings. Consider hotels, for example. It is common for a building shaft to be used as part of the exhaust duct system, with a large exhaust fan attached at the top of the shaft. Grills or short ducts go from the rooms to this shaft. Air is drawn from the building through exhaust grills and through leakage from this shaft to the building. Test and balance personnel may measure the exhaust flow rate into the grill (typically in the bathroom), but not account for the leakage. Therefore, the actual exhaust rate from the building may be much greater than indicated from the exhaust grill measurements. In one hotel tested in this project (building #68), air flow into the exhaust grills in 40 guest rooms which composed the entire building totalled 1324 cfm. Measurement of air flow from the exhaust fans at the roof totalled 2799, or more than twice as much. In other words, there is 1475 cfm of air flow that is not accounted for. The majority (we believe) falls under the category of EAleak1 (air leaking from conditioned space) but there is also an EAleak4 component as well (air leaking from outdoors into the exhaust shaft).

Figure 4.16


EAout
SAleak3
OA
OAleak2
EAleak5
EAleak3
OAleak
AirHandler
SAleak2
RAleak2
RAleak
EAleak4
EAleak2
SA
SAleak1
RAleak1
RA
OAleak1
EAin
EAleak1

The importance of not accounting for this leakage, from a TAB perspective, is that TAB personnel may conclude that the building air flow balance is positive (keeping the building at positive pressure in hot and humid climates is important for moisture control) when in actual fact the building is operating at negative pressure. This is truly important because the authors have had first-hand experience with TAB contractors who believed they had achieved positively pressurized buildings when in fact the building was operating at negative pressure and the subject building subsequently had serious moisture problems related to uncontrolled air flow. It is also possible, that misinterpretation of true building air flow balance can lead TAB personnel to improperly adjust the flow rate of exhaust fans and outdoor air and cause a building to go to negative pressure when prior to their testing it was in fact operating at positive pressure. The same misinterpretation can occur with make-up air, supply and return ducts, and with outdoor air.

Consider two examples of duct leaks that were occurring in the outdoor air ductwork in one recently tested commercial building. In one case, an outdoor air duct on the first floor stopped short of the grill at the exterior wall of the building leaving a 2 inch gap. As a consequence, about 75% of the "outdoor air" was actually being pulled from the building. In the other case, outdoor air ducts went from two second floor air handlers to panels in exterior walls where there were supposed to be exterior outdoor air grills. However, there were no grills -- just a solid brick wall! Nevertheless, the TAB contractor had done a traverse on the ducts and found flows of 1037 cfm and 897 cfm! In actual fact, this air flow did exist, but virtually all the air was being drawn from the mechanical room from leaks in the ducts and around the wall panels. (Note that the TAB contractor could not see that there was no grill because metal panels covered the access to where the exterior grills were supposed to be.) Therefore, in this building, outdoor air was being overestimated by over 2000 cfm. As a consequence, the building was operating with less ventilation and more depressurization than was thought based on the TAB report.

Pitot tube traverse measurements are subject to error under two conditions. 1) Measurements will be in error where insufficient straight duct section is available. 2) Measurements may be in error when they do not account for duct leakage just as was true for air flow hoods.

We recommend, therefore, that determination of whether a space is at positive or negative pressure with respect to outdoors or to another zone is best made by direct measurement of pressure differentials using a sensitive manometer. The alternative -- which is much more difficult and often impossible -- would be to carefully measure air flows at the point where they cross the building envelope, thereby accounting for any duct leakage which exists.

The fifth point is that building air flow imbalance can also occur because of return air design problems, such as centrally located returns in conjunction with closed interior doors and restricted return air through fire walls. The resulting pressure imbalance can cause unbalanced air flow across the building envelope and thus cause even greater air flow imbalance. (Stated another way, the high pressure in some zones pushes air out of the building while the negative pressure in other zones draws air into the building, and these flows are likely to be unbalanced.)

The sixth point is that building air flow imbalance can occur when building cavities are used as portions of air distribution systems. Pressure differentials in these cavities, especially negative pressure, can move considerable amounts of air across the building envelope and thus change or even reverse net building air flow and pressure. TAB contractors should examine the level of depressurization that exists in building cavities used as portions of the air distribution systems. For example, if the ceiling space is used as a return plenum, sufficient return grills should be provided in the ceiling so that the ceiling space is not at serious depressurization with respect to outdoors. In most cases in this study, the ceiling plenum was only about 1 pascal negative with respect to the occupied space. In one case, however, the ceiling space was at -6 pascals with respect to outdoors. Simply adding 10 drop-in ceiling grill panels in place of ceiling tiles reduced the ceiling to -0.8 pascals with respect to the occupied space.

Reiterating, it is important for TAB personnel to not only measure and adjust air flows, but to also measure pressure differentials between indoors and outdoors and between various zones/building cavities and outdoors.

4.13 Strip Malls Have Special Problems

Strip malls, where building units are attached to each other in series, represent a special case and have special problems because of connectivity. While adjacent units are separated from each other by interior walls, which are generally fairly airtight, above the ceiling level these adjacent units are often well connected, either by having common attic spaces or significant leak paths through fire walls. Unbalanced air flows caused by mechanical systems can move air between adjacent units and cause energy and air quality problems. In one case, a government office (building #42) located next to a cocktail lounge experienced air quality problems, including tobacco smoke and smells of cleaners resulting from air transport between units. Above the suspended t-bar ceilings, the ceiling spaces are well connected to each other by openings in the fire wall that totalled over 30 square feet in size. In addition, the bathroom exhaust fans from the bar discharged into the ceiling space of the office. Once in the ceiling space, air contaminants were transported into the office space by means of large return leaks.

In two other cases, investigated outside of this project, substantial air quality problems were experienced because of uncontrolled air flow in strip malls. In one case, a book store unit located next to a print shop smelled of printing chemicals. Upon investigation, it was found that the return air duct for the book store passed through the print shop and it had considerable duct leakage. In the other case, a national chain pizza parlor was located next to a dry cleaning/laundromat facility. The pizza restuarant moved out within one year because of complaints of smells from the cleaners. The cause was depressurization of the pizza store by the kitchen exhaust fans.

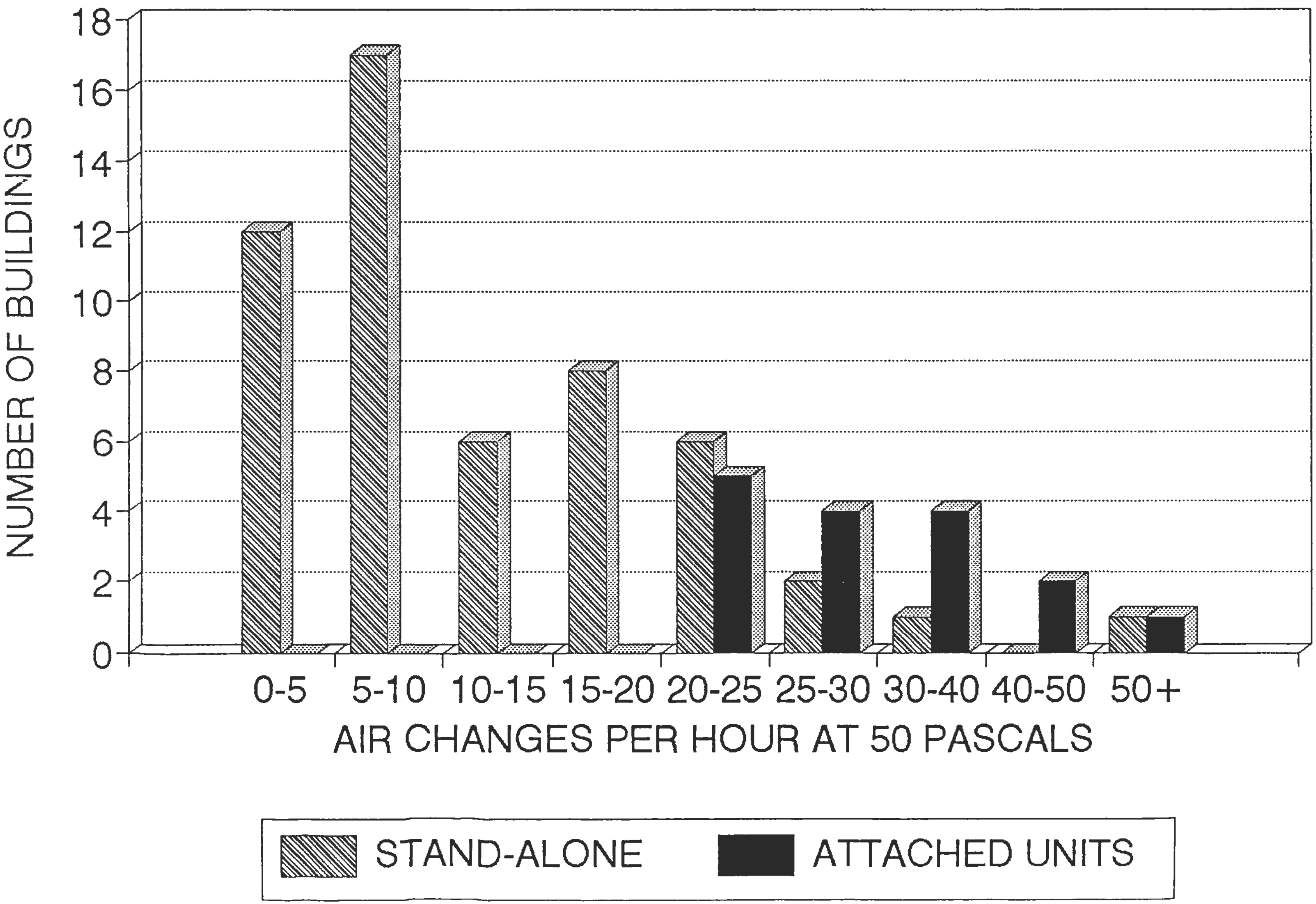
Wind driven pressure differences can also induce substantial pressure differentials and uncontrolled air flows, though these uncontrolled air flows are not unique to strip malls. When wind blows against a building it generates positive pressure on the windward side and substantial depressurization on top of the flat roof. In one strip mall, one-foot round roof vents were scattered intermittently across the flat roof, venting the ceiling space to outdoors. On one particularly windy day, opening of the front door to a retail store unit caused five or six ceiling tiles to lift and float several inches above the ceiling level until the door closed (this event was captured on video tape). In another case, a unit with a residential style attic and eve vents located only on one side, pressure in the entire office space went to +40 pascals with respect to outdoors during the approach of a gusty thunderstorm. When strong wind blew toward the vented side of the attic, pressure in the attic went to a very large positive pressure, and since the suspended t-bar ceiling was very leaky, that positive pressure extended down into the occupied space as well.

As seen by the blower door, strip mall units tend to be considerably more leaky than stand-alone buildings. Seventeen of the 70 buildings were attached (i.e., connected to other buildings units), primarily in strip malls. ACH50 averaged 31.2 in 16 attached units (no blower door test was done in one unit) and 12.6 in 53 stand-alone buildings. This means strip mall units are 2.5 times more leaky than stand-alone units, based on the limited sample examined in this study. These 17 units are located in five different strip malls. It is telling that the tightest measurement from all these units was 21.2 ACH50. Figure 4.17 shows distribution of building airtightness for stand-alone and attached units. The difference between stand-alone and attached units is striking.

An important reason why the blower door "sees" so much leakage in attached units is that they are often well or fairly well connected to each other above the ceiling level. Since the ceilings are almost always quite leaky, the blower door then "sees" leaks that are in ceiling spaces of adjacent units, which in turn are well connected to other ceiling spaces and all the occupied spaces below those ceiling spaces. Since much of the leakage seen by the blower door is "far away", located in units that may be one, two, or even more units away, the infiltration and energy impacts of this leakage may be somewhat smaller than that which occurs in stand-alone buildings.

Figure 4.17

AIRTIGHTNESS OF STAND-ALONE VERSUS ATTACHED COMMERCIAL BUILDINGS



5. ENERGY AND DEMAND SAVINGS FROM REPAIR OF UAF

Repair of duct leakage in residences has been identified as an extremely cost-effective retrofit measure. In 46 central Florida homes, duct repair reduced cooling energy consumption by 17.2%, or 7.0 kWh per day. The average cost of repair was estimated to be $200. Given estimated annual space conditioning energy use savings of $110, this retrofit pays for itself in less than two years (Cummings, Tooley, and Moyer, 1991).

We expected that repair of duct leakage and other forms of uncontrolled air flow in small commercial buildings would be cost-effective as well. From the sample of 70 small commercial buildings tested, 20 were chosen to be monitored for energy savings from repair of uncontrolled air flow. Cooling energy savings analysis was successfully done in 19 of the 20 buildings. In the remaining building (#12), analysis was complicated by the facts that cooling energy use could not be directly metered (cooling energy was provided to the building by a university-wide chilled water distribution system) and electric reheat was used to control building humidity.

5.1 Selection of Buildings for Repair

Twenty buildings were monitored for energy savings from repair of uncontrolled air flow over single cooling seasons. Two were monitored during the summer of 1993. Seven were monitored during the summer of 1994. Eleven were monitored during the summer of 1995. The plan was to monitor cooling energy use for a period of four to six weeks, make repairs during the middle of the summer, then monitor for another four to six weeks.

Only a portion of the 70 buildings tested were good candidates for repair. By "good candidate" we mean that it appeared that repair could be readily done (and within the project budget) and would achieve reasonably large energy savings. Based on our assessment of potential savings, it appears that 45, or 65%, of the 70 buildings would make good repair candidates. By contrast, it was estimated from an earlier residential duct leakage study, that duct repair would be justified in about 85% of central Florida residences. Additional research is needed to determine the repair cost and the savings which can be achieved in a wider range of buildings and attempted repairs. Additional development work is needed to identify repair options for the wide range of uncontrolled air flows, such as airtightening t-bar suspended ceilings, adding make-up air, and down-sizing or reducing the run time of exhaust fans. When these additional tasks are completed, then a better estimate of what proportion of buildings are good repair candidates can be made.

An important task for future research, therefore, will be to develop screening criteria and procedures by which to determine the energy savings which could be expected from specified UAF retrofits and thereby determine which buildings should be retrofitted.

Table 5.1 summarizes some building and HVAC characteristics of the twenty buildings in which repairs were done. Compared to the larger sample of 70 buildings, the 20 monitored buildings were about two years older, 23% smaller, 24% more leaky, and had ducts that were 13% tighter.

When deciding whether considerable energy savings were likely to occur from duct repair, we considered the size of the duct leakage and where the ducts were located. If ducts were located in the occupied space or within a ceiling return plenum, we anticipated little or no savings. If they were located in a ceiling space inside both the building's air and thermal barriers, then again, little or no savings were anticipated. However, if they were located outside the thermal barrier (insulation on the

TABLE 5.1
Building Airtightness, Duct Airtightness, Infiltration Rates, Air Flows, and Pressures Before Repair

BUILDING	Bldg CFM50	Bldg ACH50	Bldg C	Bldg n	Bldg r	Duct CFM25	ach AHON	ach AHOFF	OA & MA cfm	RLFlow cfm	Exh cfm	dP ON
2 Auditorium	10265	6.84	1230.18	0.54	0.9993	N/A	1.83	0.20	206	2700	686	1.1
3 Dentist 1	8826	21.37	876.95	0.59	0.9867	846	0.75	0.33	0	206	337	0.1
9 Dentist 2	3265	15.24	865.77	0.34	0.9948	396	3.91	0.26	911	232	325	5.2
12 Sports Building	22383	8.46	1763.55	0.65	0.9932	N/A	0.78	0.21	1426	592	2052	-0.3
20 City Hall	3296	7.44	331.16	0.59	0.9988	1632	0.60	0.32	0	284	209	0.2
21 Health Clinic 2	9005	24.83	714.22	0.65	0.9958	2576	0.84	0.17	0	1292	386	1.8
25 Sports Complex	12987	31.45	913.76	0.68	0.9983	788	0.71	0.50	0	555	155	1.5
29 Mfg Office 2	16727	24.89	929.37	0.74	0.9925	1418	1.10	0.65	1297	602	357	-0.5
31 Bar and Grill	6651	17.50	628.79	0.60	0.9999	655	2.34	0.64	0	505	987	0.8
37 Realty 2	2241	9.30	214.79	0.60	0.9972	571	0.20	0.19	0	0	730	-14.3
39 Realty 3	5879	17.51	409.45	0.68	0.9952	1276	0.59	0.34	0	414	76	-0.5
40 Safety Class	10646	25.97	1243.23	0.55	0.9964	1268	0.61	0.33	0	2034	0	2.0
45 School Supply	9133	21.49	696.39	0.66	0.9924	418	0.57	0.24	0	288	0	0.0
46 Court Office	32886	52.83	704.52	0.98	0.9951	830	0.46	0.42	0	600	0	0.0
53 Metal Bldg Co	3545	7.04	268.64	0.66	0.9977	1453	0.28	0.18	0	567	67	-2.1
54 Realty 4	7673	21.84	387.61	0.76	0.9977	885	1.15	0.67	0	92	416	0.1
56 Plastic Fabricate	2401	50.02	236.84	0.59	0.9998	186	N/A	0.15	0	193	0	-0.6
59 Carpet Store	5338	18.38	309.70	0.73	0.9939	158	0.63	0.61	0	0	194	-0.8
60 Mfg Office 3	1281	12.20	118.17	0.61	0.9992	251	1.28	0.35	0	106	0	-0.6
61 Mfg Office 4	3592	20.41	360.65	0.59	0.9953	793	1.01	0.45	0	128	0	-0.2
AVERAGE	8901	20.75	660.19	0.61	0.9960	911	1.03	0.36	192	570	349	0.1

ceiling tiles), then significant savings would be anticipated from duct repair. [Note that the savings would still depend upon roof thermal factors -- how much R-value exists in the roof construction, the thermal mass of the roof (concrete roof construction, for example, has high mass), the reflectivity of the roof surface, the presence of gravel (which does not transfer heat readily downward), and any shading of the roof surface.]

In the selection process, it was important that the magnitude of the savings be sufficiently large that the signal (energy savings) to noise (occupant use and weather variables) ratio be large enough that clear indication of savings would result. In 17 of the selected buildings, we expected significant energy savings. In three others, only moderate energy savings were expected (buildings numbers 45, 59, and 60).

5.2 Repairs

Various types of repairs were done. The primary focus, however, was airtightening of the air distribution system (ADS), including ducts and building cavities used as ducts. The breakdown of repairs was; duct repair (16 buildings), repair of building cavities used as ducts (9 buildings), improved return air pathways (4 buildings), reduction of outdoor air (3 buildings), tightening of the building shell (3 buildings) and reduced attic exhaust (1 building). These are indicated by "x" in Table 5.2.

Note that two major types of uncontrolled air flow repairs were not addressed in the repair side of this project even though considerable savings could be expected from them. These were 1) airtightening of the ceiling/roof assembly of the building when that portion of the building is excessively leaky and 2) balancing exhaust air flows. The latter could be achieved by some combination of reducing exhaust air flows and increasing intake air flows (make-up air and outdoor air). A significant number of the 50 buildings not included in the repair sample had excessive building leakage or exhaust/intake imbalance which should be remedied. These were not dealt with to any significant extent because of project budget limitations and lack of knowledge about the best repair solutions.

In most buildings, more than one type of retrofit was used. The breakdown of repair packages implemented in this project is as follows.

- Twelve retrofits involved only repair of the ADS.
- Four involved airtightening the ADS and improving return air.
- One involved airtightening the ADS, improving return air, and reducing outdoor air.
- One involved airtightening the ADS, changing out an old, inefficient air conditioner (done independently by the building owner), and turning off an attic exhaust fan.
- One involved tightening the building shell and reducing outdoor air.
- One involved reducing the amount of outdoor air.

Among the 20 repair candidates, some repairs that should have been done were not done because of diagnostic error (we did not see that the measure should be done) or because there were insufficient funds to accomplish the repair. Repairs not done that should have been done, indicated by "o" in Table 5.2, include return air (2 buildings), tightening of building shell (5 buildings), adding make-up air (1 building), and reduction of exhaust (1 building).

TABLE 5.2

Types of Uncontrolled Air Flow Repair That Were Implemented (X), and Were Not Implemented (O)

	BUILDING	DUCT LEAKS	BUILDING CAVITIES	RETURN AIR	OUTDOOR AIR	BUILDING SHELL	MAKE UP AIR	REDUCED EXHAUST
2	AUDITORIUM		X					
3	DENTIST 1	X				X		
9	DENTIST 2				X			
12	SPORTS BUILDING		X	O				O
20	CITY HALL	X				X		
21	HEALTH CLINIC 2	X	X	X				
25	SPORTS COMPLEX	X	X					
29	MANUF OFFICE 2				X	X		
31	BAR AND GRILL	X				O	O	
37	REALTY 2	X						X
39	REALTY 3	X	X	O				
40	SAFETY CLASS	X	X	X	X	O		
45	SCHOOL SUPPLY	X				O		
46	COURT OFFICE	X				O		
53	METAL BLG CO	X	X	X				
54	REALTY 4	X	X	X				
56	PLASTIC FABRICATE	X	X			O		
59	CARPET STORE	X						
60	MANUF OFFICE 3	X						
61	MANUF OFFICE 4	X						

After repairs were complete, airtightness, pressure differential, and air flow tests were repeated. Table 5.3 summarizes some building and HVAC characteristics of the twenty buildings after repairs were done. Three tables compare the buildings and duct systems before and after uncontrolled air flow retrofits. Table 5.4 compares pre-repair and post-repair building and duct system airtightness and shows percent tightening which occurred. On average, these buildings became 13.9% more airtight. For buildings in which duct system airtightening was done, the duct systems became 58% more airtight. Table 5.5 compares pre-repair and post-repair building and duct system airtightness, building ventilation rates, and return leak air flows. The average building ventilation rate with the mechanical systems operating (ach AHON) decreased by 10% from 1.03 ach to 0.93 ach. The building ventilation rate (infiltration rate) with all mechanical systems turned off increased substantially, from 0.35 ach to 0.46 ach in the 14 buildings for which both pre-repair and post-repair numbers were available. In 11 of the buildings, infiltration was approximately equal or less after repair. In three cases, however, post-repair infiltration was dramatically higher (1.13 ach compared to 0.42 ach pre-repair). Substantially higher wind speed associated with hurricane Opal explained the disparity in one case (building #45). Investigation of wind speed and other variables provided no explanation for the substantial disparity in the other two instances. Table 5.6 compares pre-repair and post-repair outdoor air+make-up air, return leak flow, and normal building operating pressure.

Repair of uncontrolled air flow was planned for the middle of summer so that approximately comparable weather would occur during the pre-repair and post-repair periods. Schedule conflicts, however, and the initial lack in availability of candidates caused monitoring starts later than anticipated for some sites. Most repairs occurred in July and August, but three buildings were repaired in September and two were repaired in October. (Note that summer weather occurs May through October in central Florida.)

For each repair candidate, a repair plan was developed, including what would be repaired, what materials would be needed, and estimates of repair time. Repair typically occurred 5 to 6 weeks after monitoring began. A team of two to three persons with considerable experience in repair of residential duct leakage usually did repairs. In two cases, repairs were done by HVAC contractors with the guidance of the research team.

5.3 Monitoring

The following variables were monitored by datalogger on 15-minute intervals.

- air conditioner(s) energy use
- room, ceiling space (or attic), and outdoor temperature
- air conditioner temperatures (return and supply temperatures are recorded only when the cooling system was operating)
- indoor relative humidity.

At many of the sites carbon dioxide levels and indoor pressure differentials were monitored, especially in tight buildings and those in which repair of uncontrolled air flow would significantly reduce ventilation. Outdoor environment conditions of dewpoint temperature and solar radiation were collected at several central locations, generally within 15 miles of the monitored buildings. The number of sensors and meter locations were planned based on size, airtightness, number of air conditioners, and location of thermostats, ducts, and air handlers. Monitoring equipment was assembled partly in the lab and partly in the field.

TABLE 5.3
Building Airtightness, Duct Airtightness, Infiltration Rates, Air Flows, and Pressures After Repair

Building	Bldg CFM50	Bldg ACH50	Bldg C	Bldg n	Bldg r	Duct CFM25	ach AHON	ach AHOFF	OA & MA cfm	RLFlow cfm	EXH cfm	dP ON
2 Auditorium	N/A	N/A	N/A	N/A	N/A	N/A	1.47	0.18	206	N/A	686	0.4
3 Dentist 1	9857	23.86	650.96	0.69	0.9986	396	0.66	0.3		98	337	0.7
9 Dentist 2	3265	15.24	865.77	0.34	0.9948	396	0.30	0.26	0	232	325	0.4
12 Sports Building	17749	6.71	1350.48	0.66	0.9917	N/A	0.48	N/A	1426	569	2052	-1.3
20 City Hall	2304	5.20	298.28	0.52	0.9966	795	0.79	0.35	0	188	209	0.0
21 Health Clinic	9208	25.39	774.06	0.63	0.9994	227	0.68	0.28	0	30	386	0.3
25 Sports Complex	11900	28.82	1316.61	0.56	0.9945	154	0.70	0.54	0	84	155	0.6
29 Mfg Office 2	4330	6.44	282.98	0.70	0.9979	1418	0.69	0.41	589	238	357	0.8
31 Bar & Grill	6317	16.62	646.10	0.58	0.9973	272	2.47	N/A	0	57	987	-2.0
37 Realty 2	2033	8.43	213.47	0.58	0.9852	112	0.33	0.15	0	0	730	-0.6
39 Realty 3	4869	14.50	413.05	0.63	0.9911	700	0.67	N/A	0	123	76	0.4
40 Safety Class	8744	21.33	763.72	0.62	0.9890	621	0.92	0.24	0	478	0	0.2
45 School Supply	8991	21.15	585.82	0.70	0.9941	190	1.12	0.86	0	0	0	0.3
46 Court Office	32072*	52.83*	N/A	N/A	N/A	292	1.49	1.23	0	215	0	1.3
53 Metal Bldg Co	3419	6.79	273.43	0.65	0.9907	833	0.25	0.18	0	249	67	-2.0
54 Realty 4	7580	21.57	518.59	0.69	0.9904	289	0.96	N/A	0	131	416	-2.0
56 Plastic Fabricate	2208**	46.00**	N/A	N/A	N/A	55	1.6	0.76	0	18	0	1.1
59 Carpet Store	4974	17.13	315.12	0.71	0.9950	86	0.71	1.31	0	0	194	-0.1
60 Mfg Office 3	1119	10.66	84.78	0.66	0.9968	138	1.11	N/A	0	52	0	-0.2
61 Mfg Office 4	2795	15.88	254.7	0.61	0.9996	554	0.7	0.24	0	71	0	0.0
AVERAGE	7565	19.19	565.17	0.62	0.9943	418	0.90	0.48	111	149	349	-0.1

* Pre-repair test data is used here because no building shell tightening was done and duct repairs were done inside the primary air barrier.
** Test not available. Ceiling is primary air barrier and ducts are located outside this air barrier, so the change between pre and post duct CFM was subtracted from the pre- building total CFM50.

TABLE 5.4
Building and Duct Airtightness Before and After Repair

Building	Pre Bldg CFM50	Post Bldg CFM50	Percent Reduction	Pre Bldg ACH50	Post Bldg ACH50	Percent Reduction	Pre Duct CFM25	Post Duct CFM25	Percent Reduction
2 Auditorium	10265*	N/A	N/A	6.84*	N/A	N/A	N/A	N/A	N/A
3 Dentist 1	8826	9857	-11.7	21.37	23.86	-11.7	846	396	53.2
9 Dentist 2	3265	3265*	0.0	15.24	15.24**	**	396	396	**
12 Sports Building	22383	17749	20.7	8.46	6.71	20.7	N/A	N/A	N/A
20 City Hall	3296	2304	30.1	7.44	5.20	30.1	1632	795	51.3
21 Health Clinic 2	9005	9208	-2.3	24.83	25.39	-2.3	2576	227	91.2
25 Sports Complex	12987	11900	8.4	31.45	28.82	8.4	788	154	80.5
29 Mfg Office 2	16727	4330	74.1	24.89	6.44	74.1	1418	1418*	**
31 Bar and Grill	6651	6317	5.0	17.50	16.62	5.0	655	272	58.5
37 Realty 2	2241	2033	9.3	9.30	8.43	9.3	571	112	80.4
39 Realty 3	5879	4869	17.2	17.51	14.50	17.2	1276	700	45.1
40 Safety Class	10646	8744	17.9	25.97	21.33	17.9	1268	621	51.0
45 School Supply	9133	8991	1.6	21.49	21.15	1.6	418	190	54.5
46 Court Office	32886	32886	0.0	52.83	52.83	0.0	830	292	64.8
53 Metal Bldg Co	3545	3419	3.6	7.04	6.79	3.6	1453	833	42.7
54 Realty 4	7673	7580	1.2	21.84	21.57	1.2	885	289	67.3
56 Plastic Fabricate	2401	2208	8.0	50.02	46.00	8.0	186	55	70.4
59 Carpet Store	5338	4974	6.8	18.38	17.13	6.8	158	86	45.6
60 Mfg Office 3	1281	1119	12.6	12.20	10.66	12.6	251	138	45.0
61 Mfg Office 4	3592	2795	22.2	20.41	15.88	22.2	793	554	30.1
AVERAGE	8829	7608	12.5	20.75	19.19	12.5	911	418	58.2

*This average excluded from column average to make values comparable.
** Pre-repair test data is used here because no repairs were made relating to this measurement. These numbers not included in averages.

TABLE 5.5
Building and Duct System Airtightness, Infiltration Rates, and Return Leak Airflow Rates Before and After Repair

Building	Before Repair					After Repair				
	Bldg ACH50	Duct CFM25	ach AHON	ach AHOFF	RLFlow cfm	Bldg ACH50	Duct CFM25	ach AHON	ach AHOFF	RLFlow cfm
2 Auditorium	6.84	N/A	1.83	0.20	2700	N/A	N/A	1.47	0.18	N/A
3 Dentist 1	21.37	846	0.75	0.33	206	23.86	396	0.66	0.30	98
9 Dentist 2	15.24	396	3.91	0.26	232	15.24	396	0.30	0.26	232
12 Sports Building	8.46	N/A	0.78	0.21	592	6.71	N/A	0.48	N/A	569
20 City Hall	7.44	1632	0.60	0.32	284	5.20	795	0.79	0.35	188
21 Health Clinic 2	24.83	2576	0.84	0.17	1292	25.39	227	0.68	0.28	30
25 Sports Complex	31.45	788	0.71	0.50	555	28.82	154	0.70	0.54	84
29 Mfg Office 2	24.89	1418	1.10	0.65	602	6.44	1418	0.69	0.41	238
31 Bar & Grill	17.50	655	2.34	0.64	505	16.62	272	2.47	N/A	57
37 Realty 2	9.30	571	0.20	0.19	0	8.43	112	0.33	0.15	0
39 Realty 3	17.51	1276	0.59	0.34	414	14.50	700	0.67	N/A	123
40 Safety Class	25.97	1268	0.61	0.33	2034	21.33	621	0.92	0.24	478
45 School Supply	21.49	418	0.57	0.24	288	21.15	190	1.12	0.86	0
46 Court Office	52.83	830	0.46	0.42	600	52.83	292	1.49	1.23	215
53 Metal Bldg Co	7.04	1453	0.28	0.18	567	6.79	833	0.25	0.18	249
54 Realty 4	21.84	885	1.15	0.67	92	21.57	289	0.96	N/A	131
56 Plastics Fabricate	50.02	186	N/A	0.15	193	46.00	55	1.60	*	18
59 Carpet Store	18.38	158	0.63	0.61	0	17.13	86	0.71	1.31	0
60 Mfg Office 3	12.20	251	1.28	0.35	106	10.66	138	1.11	N/A	52
61 Mfg Office 4	20.41	739	1.01	0.45	128	15.88	554	0.70	0.24	71
AVERAGE	20.75	911	1.03	0.36	570	19.19	418	0.93	0.46	149

* Comparable test not available.

TABLE 5.6
Building Airflows and Pressure Differentials Before and After Repair

BUILDING	Pre OA+MA cfm	Post OA+MA cfm	Percent Reduction	Pre RLFlow cfm	Post RLFlow cfm	Percent Reduction	Pre dP ON	Post dP ON
2 Auditorium	206	206	0.0	2700	N/A	N/A	1.1	0.4
3 Dentist 1	0	0	0.0	206	98	52.3	0.1	0.7
9 Dentist 2	911	0	100.0	232	232	*	5.2	0.4
12 Sports Building	1426	1426	0.0	592	569	3.9	-0.3	-1.3
20 City Hall	0	0	0.0	284	188	33.9	0.2	0.0
21 Health Clinic 2	0	0	0.0	1292	30	97.7	1.8	0.3
25 Sports Complex	0	0	0.0	555	84	84.9	1.5	0.6
29 Mfg Office 2	1297	589	54.6	602	238	60.5	-0.5	0.8
31 Bar and Grill	0	0	0.0	505	57	88.7	-0.8	-2.0
37 Realty 2	0	0	0.0	0	0	0.0	-14.3	-0.6
39 Realty 3	0	0	0.0	414	123	70.2	-0.5	0.4
40 Safety Class	0	0	0.0	2034	478	76.5	2.0	0.2
45 School Supply	0	0	0.0	288	0	100.0	0.0	0.3
46 Court Office	0	0	0.0	600	215	64.1	0.0	1.3
53 Metal Bldg Co	0	0	0.0	567	249	56.1	-2.1	-2.0
54 Realty 4	0	0	0.0	**	131	**	0.1	-2.0
56 Plastic Fabricate	0	0	0.0	193	18	90.7	-0.6	1.1
59 Carpet Store	0	0	0.0	0	0	0.0	-0.8	-0.1
60 Mfg Office 3	0	0	0.0	106	52	50.8	-0.6	-0.2
61 Mfg Office 4	0	0	0.0	128	71	44.2	-0.2	0.0
AVERAGE	192	111	7.7	595	149	57.3	0.1	-0.1

* No repairs were made relating to this measurement.
** The pre test measurement underestimated the return leak.

5.3.1 Data Transfer

All data was stored as 15 minute averages except energy use which was stored as total kilowatt hours every 15 minutes. Data transfer occurred through a modem and phone line. A central computer system called each datalogger daily and downloaded site data to disk storage. Data transfer was scanned for errors by comparing to prescribed value boundaries. If bad data was detected, a second attempt to download data from the datalogger occurred. Suspect data was marked.

Computer programs were created to call each site's datalogger, download data, and plot up to eight graphs containing up to 20 variables every twenty-four hours. These plots were automatically produced overnight and then reviewed daily to see that equipment was working well and to identify any unusual circumstances. Such circumstances could be unusual thermostat settings for a particular time of day, air conditioning turned off, faulty sensor, or in a real case, hurricane Erin's damage to some sensors. When there was an indication of trouble, the site would be visited to repair or replace faulty equipment.

5.4 Energy Savings

Energy savings from the repair of uncontrolled air flow has been determined by comparing cooling system energy consumption for periods before and after repair. In order to filter out variations caused by weather and changes in thermostat settings, cooling energy consumption (kWh) was plotted against the temperature difference between indoors and ambient. Thermostats were controlled in three manners. 1) At seven sites, thermostat settings remained constant over 24 hours (building #s 29, 31, 40, 45, 46, 56, and 61). 2) At ten sites, thermostat settings were raised (typically to 80°F or higher) after hours. 3) At two sites, air conditioners were turned off at the end of business (building #s 2 and 3).

When comparing energy use before and after repair, all data was examined to make sure the most comparable days (in terms of weather and occupancy factors) were used for the analysis. For 15 of the buildings, the analysis includes only weekdays. Weekends were excluded in most cases because of increased variability in building use on weekends. The analyses for the remaining four buildings used all days (buildings 29, 31, 40, and 56). Days with unusual cooling system operation or weather conditions that were not common to both periods were excluded from the data analysis. Examples of unusual operation would be if the thermostat was not raised to its typical after-hours setting or if the air conditioner was turned off for a period during the day. With no control over weather and, in some cases, relatively limited time for monitoring, some sites have less data than desired.

As indicated, cooling energy use is plotted versus temperature difference between indoors and ambient. While "ambient" usually means outdoors, in some cases the dominant thermal environment was a warehouse or attic space. In the plastic fabrication office, for example, which is located inside an unconditioned warehouse, energy consumption correlates better to "warehouse minus office space" temperature difference. Attic temperature can also have a strong impact on building cooling load, especially when poor insulation or air transport brings heat into the building. Energy use in realty office 3 (building #39), for example, correlates better to attic temperature than outside temperature, in large part because this attic had very little insulation. In these cases, warehouse or attic temperature was used as the reference temperature for the energy savings analysis.

The best-fit lines on the plots are produced by least-squares linear regression. The graphs for 20 building-retrofits are shown in Figures 5.1 - 5.4. Note that the energy savings for realty office 2

Figure 5.1

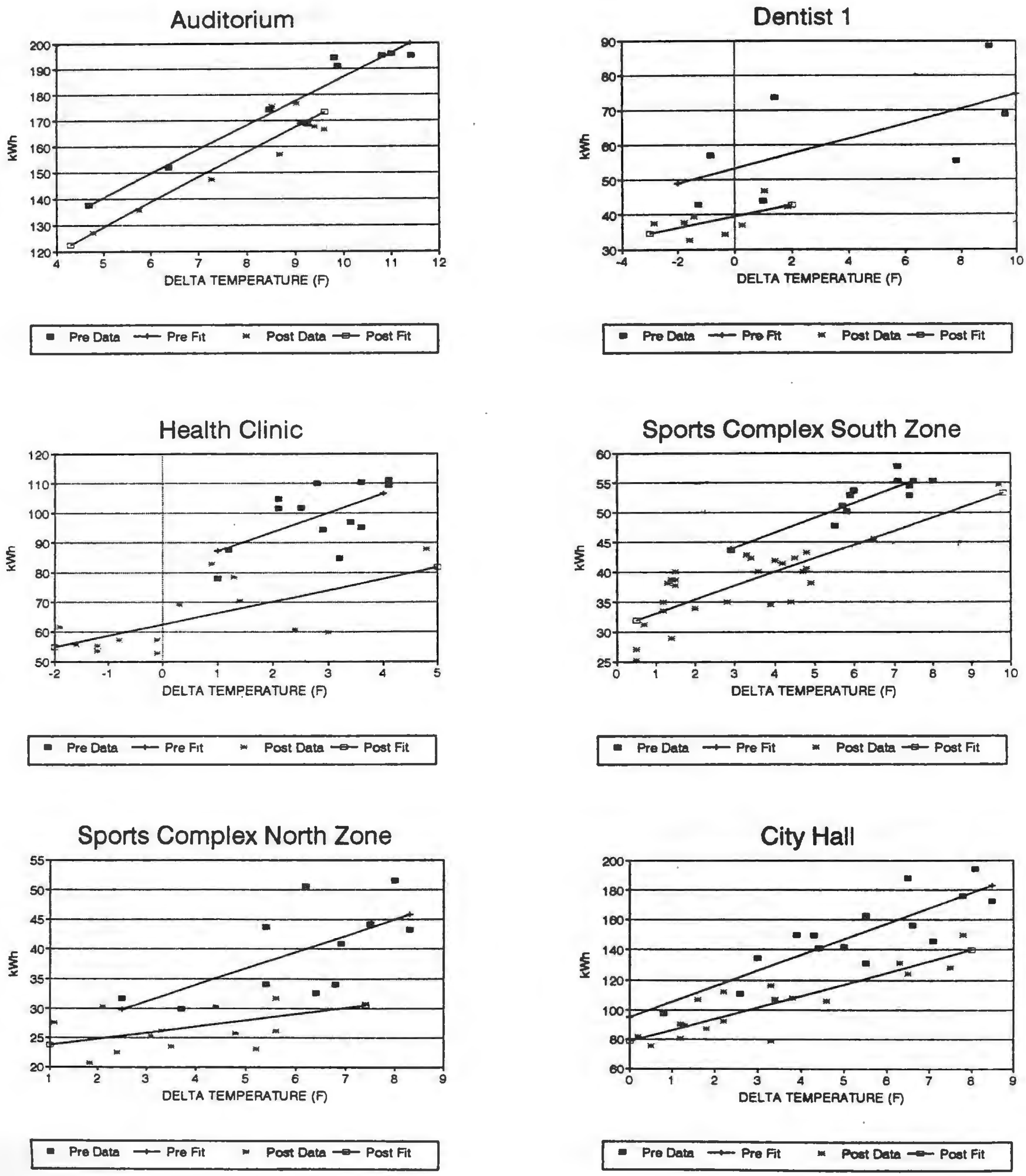
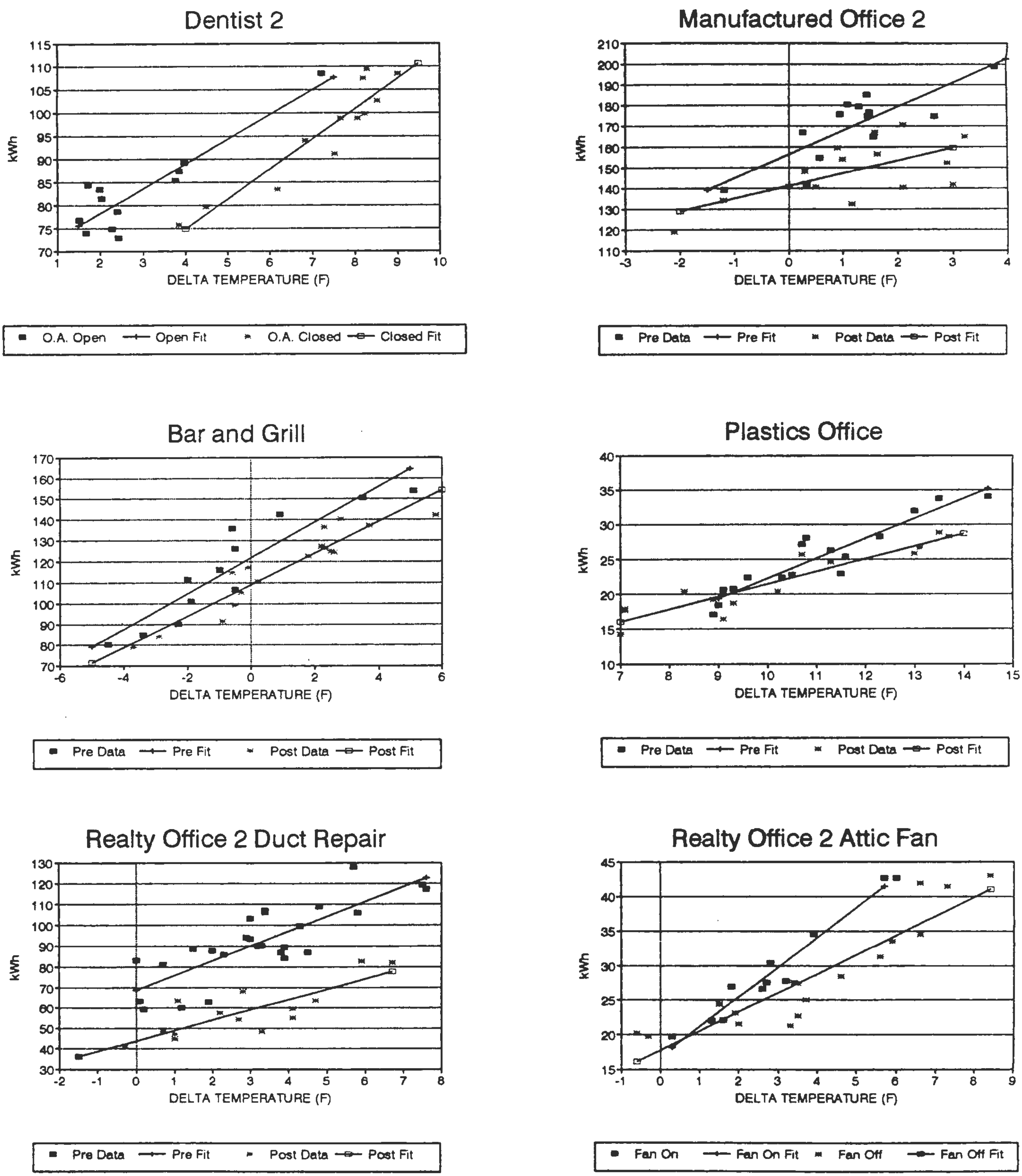
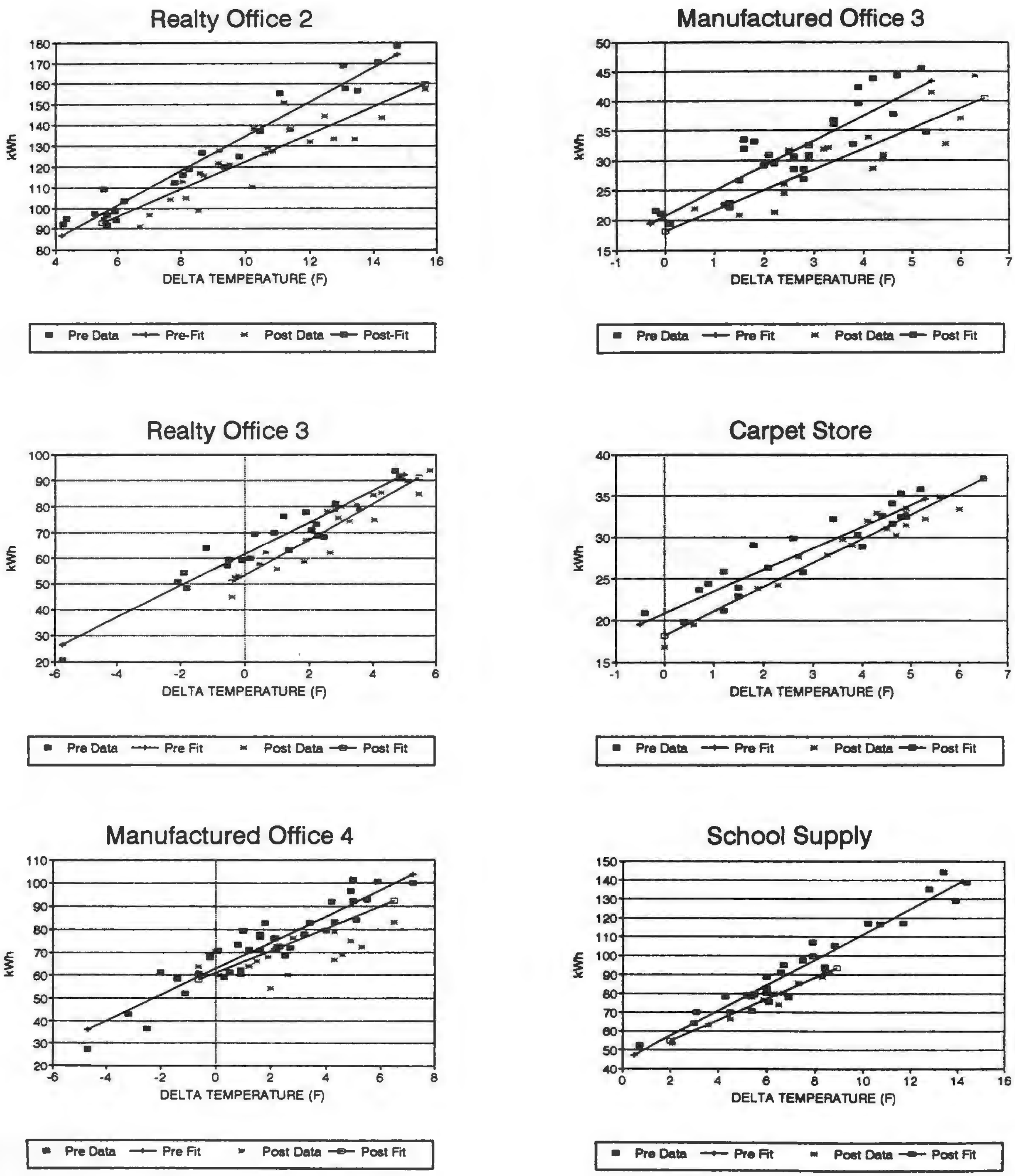

Auditorium
kWh
200
190
180
170
160
150
140
130
120
4 5 6 7 8 9 10 11 12
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Dentist 1
kWh
90
80
70
60
50
40
30
-4 -2 0 2 4 6 8 10
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Health Clinic
kWh
120
110
100
90
80
70
60
50
-2 -1 0 1 2 3 4 5
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Sports Complex South Zone
kWh
60
55
50
45
40
35
30
25
0 1 2 3 4 5 6 7 8 9 10
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Sports Complex North Zone
kWh
55
50
45
40
35
30
25
20
1 2 3 4 5 6 7 8 9
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
City Hall
kWh
200
180
160
140
120
100
80
60
0 1 2 3 4 5 6 7 8 9
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit

Figure 5.2



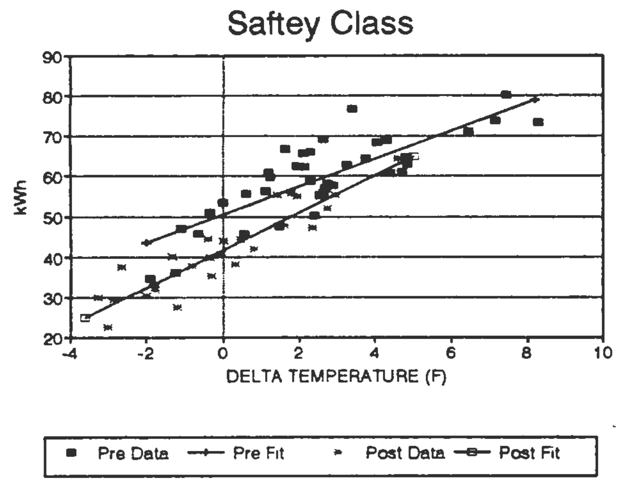
Dentist 2
kWh
DELTA TEMPERATURE (F)
O.A. Open
Open Fit
O.A. Closed
Closed Fit
Manufactured Office 2
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Bar and Grill
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Plastics Office
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Realty Office 2 Duct Repair
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Realty Office 2 Attic Fan
kWh
DELTA TEMPERATURE (F)
Fan On
Fan On Fit
Fan Off
Fan Off Fit

Figure 5.3

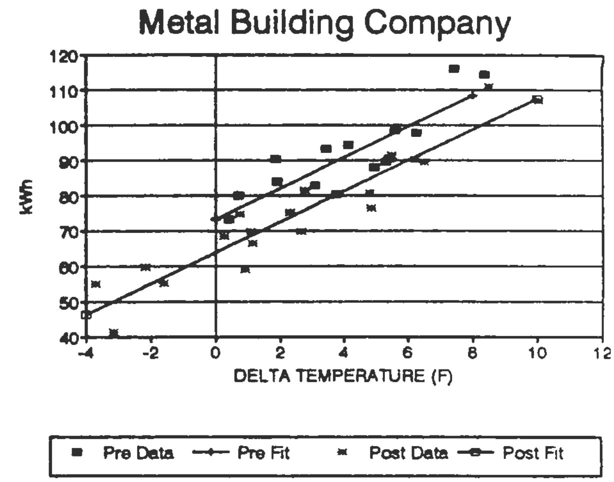


Realty Office 2
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre-Fit
Post Data
Post-Fit
Manufactured Office 3
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Realty Office 3
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Carpet Store
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
Manufactured Office 4
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit
School Supply
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit

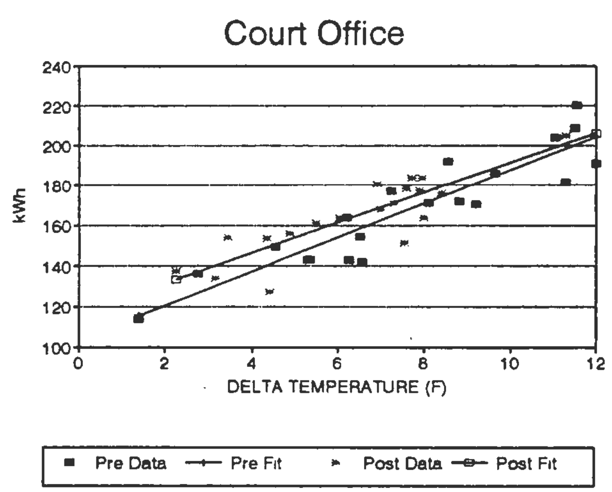
Figure 5.4



Saftey Class
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit



Metal Building Company
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit



Court Office
kWh
DELTA TEMPERATURE (F)
Pre Data
Pre Fit
Post Data
Post Fit

(building #37) is presented for two UAF retrofits. "Realty 2 duct" is savings from duct repair only. "Realty 2 fan" reflects cooling energy savings of 3.1 kWh/day and reductions in attic fan energy use of 11.2 kWh/day when the attic fan was turned off. Also note that the sports complex building (building #25) shows the north and south zones separately, because the two zones are separated by a common wall and a fire wall, the door between the zones was always closed, each zone had a separate cooling system, and the thermostats were controlled separately.

5.4.1 Percent savings and payback calculation

Seasonal energy savings are calculated in the following manner. The least-squares, best fit lines (energy use vs temperature differential) are used in conjunction with 10 year meteorological data from the FSEC weather station to calculate the expected cooling energy use for each day during a typical cooling season. Percent savings is based on a six month period May 1 through October 31. Daily energy use was summed over the entire six month period and divided by 184, the number of days in this period. Percent savings is calculated by dividing the difference between pre-repair and post-repair energy use divided by the pre-repair energy use.

To examine the cost-effectiveness of UAF repair, energy consumption for an 8-month cooling season was computed (again based on the kWh vs dT best fit curve and the daily 10-year weather database) from mid-March to mid-November. Adjustments were made to weekend energy use because 10 of 19 commercial buildings were less utilized on the weekends. We found that cooling energy use was 41.7 percent lower in these 10 buildings on the weekends, on average. Therefore, weekend cooling energy use in these 10 buildings was reduced by 41.7 percent for purposes of these computations.

Some heating energy savings will result from these UAF retrofits. But since we did not monitor heating energy use, we do not know what energy savings would be expected. Several factors make this difficult to predict. First, commercial buildings are more fully conditioned during day-time hours when temperatures are warmer. Second, they tend to have greater internal heat generation. Therefore, we have based annual savings only on an 8-month cooling season.

Some businesses pay only for electricity consumption. Others pay demand charges as well. In order to simplify the analysis, we have assumed a cost of $0.075 per kWh for all buildings. Simple payback was calculated by dividing the estimated repair cost by the energy savings.

On average, cooling energy consumption decreased from 87.4 kWh/day to 75.1 kWh/day, or 12.4 kWh/day. On average, cooling energy use declined by 14.7% from repair of UAF (Table 5.7). Based on the assumed $0.075/kWh electricity cost, projected annual cooling energy savings are $182. Given that the average projected retrofit cost is $454, simple payback is 2.5 years. This indicates that UAF repair can be a very cost-effective retrofit measure.

5.4.2 Two types of uncontrolled air flow were not repaired

Note that there were two major types of uncontrolled air flow repairs that were not addressed in the repair side of this project. These were 1) airtightening of the ceiling/roof assembly of the building when that portion of the building is excessively leaky and 2) balancing exhaust air flows, by some combination of reducing exhaust air flows and increasing intake air flows (make-up air and outdoor air).

TABLE 5.7
Cooling Energy Savings and Cost Payback

Building	Pre kWh/Day	Post kWh/Day	kWh/Day Saved*	Percent Savings	8 Month kWh Saved**	8 Month $ Saved**	Repair Cost $	Payback Years
2 Auditorium	130.2	119.6	10.6	8.1	2769	208	430	2.1
3 Dentist 1	54.0	39.9	14.1	26.1	2251	169	450	2.7
9 Dentist 2	88.4	74.0	14.3	16.2	3557	267	50	0.2
20 City Hall	137.4	109.9	27.5	20.0	4689	352	900	2.6
21 Health Clinic 2	96.7	72.0	24.7	25.6	4448	334	1300	3.9
25 Sports Complex	77.3	63.9	13.4	17.4	2779	208	450	2.2
29 Mfg Office 2	211.2	170.5	40.8	19.3	7620	571	1280	2.2
31 Bar & Grill	142.4	127.3	15.1	10.6	3129	235	975	4.2
37 Realty 2 Duct	99.6	69.1	30.6	30.7	5938	445	330	0.7
37 Realty 2 Fan	39.7	25.4	14.3	36.0	3208	241	50	0.2
39 Realty 3	117.7	108.9	8.8	7.5	1551	116	235	2.0
40 Safety Class	50.8	42.1	8.7	17.0	2496	187	460	2.5
45 School Supply	69.7	64.8	4.8	6.9	855	64	155	2.4
46 Court Office	137.8	147.0	-9.2	-6.6	-2762	-207	225	
53 Metal Bldg Co	87.2	77.8	9.4	10.8	2041	153	340	2.2
54 Realty 4	61.9	53.4	8.5	13.7	1854	139	675	4.9
56 Plastics Fabricate	22.8	21.8	1.0	4.3	260	19	225	11.5
59 Carpet Store	21.7	19.1	2.6	11.9	511	38	58	1.5
60 Mfg Office 3	31.4	26.9	4.5	14.3	732	55	260	4.7
61 Mfg Office 4	70.7	67.6	3.1	4.3	521	39	225	5.8
AVERAGE	87.4	75.1	12.4	14.7	2422	182	454	2.5

* kWh/day savings based on May-October.

** Annual cooling savings based on March 15- November 15, and assumes cost of $0.075/kWh.

Substantial exhaust imbalance problems exist in perhaps 20% of the total 70 building sample. These imbalances cause excessive space ventilation and elevated cooling energy consumption. In cases where the building has a leaky ceiling and a vented attic space, the energy penalties can be very large and therefore the energy savings from repair can be very large as well. These were not dealt with because of project budget limitations and/or lack of knowledge about the best methods to implement solutions. In one of the buildings which we monitored and in which we made extensive duct repairs (building #31), we tried to get the business/building owner to install make-up air but he felt he could not afford the cost.

Consider another example. A seven-year old convenience store (building #69) has a kitchen exhaust fan which draws 1546 cfm from this store from 5 AM to 7 PM seven days per week, depressurizing the building to -1.8 pascals. Since the floor and walls are tight (all masonry) and the ceiling is very leaky (suspended, t-bar construction), most of the passive make-up air originates from the vented attic space. Since this space is very hot and humid, unbalanced exhaust air adds tremendously to the building cooling load. Some "back-of-the-envelope" calculations will provide some perspective on the potential savings that may result.

Assume the following:

1 Exhaust fan operates from 5 AM to 7 PM seven days per week.
2. 80% of passive make-up air comes from attic.
3. During period from 5 AM to 7 PM, temperature and dewpoint temperature conditions are 85F/74F outdoors and 101F/78F in the attic space, 210 days per year
4. Cooling system COP (coefficient of performance) is 1.8.
5. A make-up air system is installed to match 80% of the exhaust air flow and assume that 75% of that unconditioned make-up air exhausts directly to outdoors and does not add load to the building.
6. Outdoor air, which is currently 11% of exhaust air flow, is increased to 25% of exhaust air flow as a result of cleaning filters. This would cause the building to operate at positive pressure most of the time.
7. The cost of installing make-up air is $2500.

Based on these assumptions, cooling energy savings are projected to be $2175 per year and the simple payback period is just over one year.

5.5 Description of Uncontrolled Air Flow Retrofits

Following is a building-by-building discussion of the nature and impacts of the retrofits. Building numbers refer to the master data table which may be found in Appendix B.

5.5.1 Auditorium (#2)

One large 25 ton air conditioning system serves this 5000 square foot, 90000 cubic foot building. Because of the height of the ceiling (18 feet) and size of the supply grills (6 foot diameter) and the fact that the ceiling "stucco" was asbestos, duct system airtightness was not measured. The supply ductwork was located on the roof in a protective enclosure which prevented access for inspection or repair. Large return leaks (26% return leak fraction) were drawing air from an exterior mechanical room which was vented to outdoors. Repair of the return leaks caused an 8% reduction in cooling energy use from 130.2 kWh/day to 119.6 kWh/day. Repairs were accomplished in five person-hours using $180 in materials. Energy savings pay for the estimated $430 repair cost in 2.1 years.

5.5.2 Dentist 1 (#3)

Two attic-mounted air handlers serve this 2754 square foot building. The ducts are located in the attic space. Substantial leakage existed in the ductwork. Repairs, however, sealed only 53% of the total leakage. Return leak fraction was reduced from an average of 5.2% to 2.7%. Many supply leaks remain. It is clear, in retrospect, that additional effort should have been put into duct repair. Ideally, duct repair would have been done with a duct test rig installed on the duct system (registers and grills masked off) so that airtightness could be periodically retested in order to gauge progress. However, in nearly all these buildings, retrofits were done during occupied hours, so the air conditioning system could not be readily turned off during the repairs. To optimize the repair process, it would be best to schedule these operations when the business is closed.

Relative humidity was largely unchanged as a result of the repairs (58% pre-repair and 60% post-repair). Carbon dioxide levels increased from an average 588 ppm to 709 ppm, since repair of the duct leaks diminished the building ventilation rate. Cooling energy use decreased by 26% from 54.0 kWh/day to 39.9 kWh/day. Repairs were accomplished in eight person-hours using $50 in materials. Energy savings pay for the estimated $450 repair cost in 2.7 years.

5.5.3 Dentist 2 (#9)

A two-stage, 10-ton air conditioner serves this 1512 square foot building. Unlike most retrofits in this project, no duct repair was done. Rather, the oversized outdoor air was reduced. When originally tested, this roof-top package unit had no outside air damper and total outdoor air flow was 25% of the total 3623 cfm air handler air flow. This equals 911 cfm, which is about 100 cfm per person or 3.9 air changes per hour. With this high infiltration rate, the owner experienced difficulty in controlling humidity in the occupied space. Because the building was thermally very inefficient, the ductwork was located on the roof in the hot sun, and room temperature was typically kept at 72°F, the air conditioning system operated nearly continuously during business hours.

Upon being informed of our findings, the building owner/occupant requested that outdoor air flow be reduced. Therefore, the pre-retrofit monitoring occurred with the outdoor air reduced to 65% of original flow, or 590 cfm. The post-retrofit monitoring occurred with outside air completely sealed. Before retrofit, building ventilation was 835 cfm or 93 cfm per person as measured by tracer gas decay. This ventilation consists of the 590 cfm of outdoor air plus approximately 232 cfm of return leakage, primarily from rooftop air handler panel leaks. After sealing off the outdoor air, ventilation decreased to 232 cfm (return leaks) or 26 cfm per person.

Both carbon dioxide levels and relative humidity were monitored. Carbon dioxide levels during business hours increased from an average 390 ppm with outside air 65% open to 570 ppm with outside air closed. (Note that 570 ppm is well below the 1000 ppm maximum recommended by ASHRAE 62-1989.) This indicates, as was also documented by tracer gas measurements, that ventilation exceeds 20 cfm/person. Relative humidity decreased from an average 59% to 54% because of the retrofit. One person-hour is figured for this retrofit and no materials. Cooling energy consumption decreased by 16.2% from 88.4 kWh/day to 74.0 kWh/day as a result of downsizing the outdoor air. Energy savings pay for the estimated $50 repair cost in 0.2 years.

5.5.4 City hall (#20)

Two five-ton roof top package air conditioners serve this 2952 square foot concrete block building. Most of the ductwork was located in the hot and dry ceiling space. It was hot and dry because the roof deck is the primary air barrier and the insulation is on top of the ceiling tiles. About 20% of the ductwork is located on the roof. Substantial duct leakage existed both below and above the roof.

All of the ductwork on the roof, both return and supply, was replaced by an HVAC contractor. Return and supply ducts within the building were sealed by research staff. Duct CFM25 decreased 51% from 1632 to 795. Much of the remaining duct leakage was in supply ducts located in the ceiling space and wrapped in exterior duct insulation. These leaks were not repaired because of the difficult access. Future research should focus on cost-effective methods to airtighten ductwork that is difficult to access and which has exterior insulation wrap. (Note that access to the ceiling space is through ceiling tiles which have insulation batts on top and that the ducts run through a maze of hangers (wires) which support the suspended ceiling.)

In addition to duct repair, the duct access hole (through the roof) was tightened thereby decreasing building leakiness from 7.4 ACH50 to 5.2 ACH50. Carbon dioxide levels increased slightly from an average 561 to 589 as a result of the repairs. Indoor relative humidity increased slightly from 47% pre-repair to 49% post-repair. Cooling energy consumption decreased by 20% from 137.4 kWh/day to 109.9 kWh/day. Total repair time was sixteen person-hours and $100 in materials. Energy savings pay for the estimated $900 repair cost in 2.6 years.

5.5.5 Health clinic 2 (#21)

Three air conditioning systems served this 2560 square foot strip mall space. Air handlers were located in mechanical closets which were used as return plenums and were depressurized to -12 pascals, -33 pascals, and -17 pascals. Illustration of the third system is shown in Figure 5.5. Because the closet ceilings were suspended t-bar construction and were very leaky, return leaks of 48%, 13%, and 48% were being drawn from the hot attic space above, which was as hot as 120°F. This means that, on average, these three systems were drawing 36% of their return air from the attic. Even with 10 tons of air conditioning, it is not surprising that this building was often uncomfortable. Repairs were made by "hard-ducting" the system, that is, installing continuous ducting from the air handlers to the return ductwork in the attic, so that the closets were no longer plenums. Significant supply leaks at register connections were also repaired.

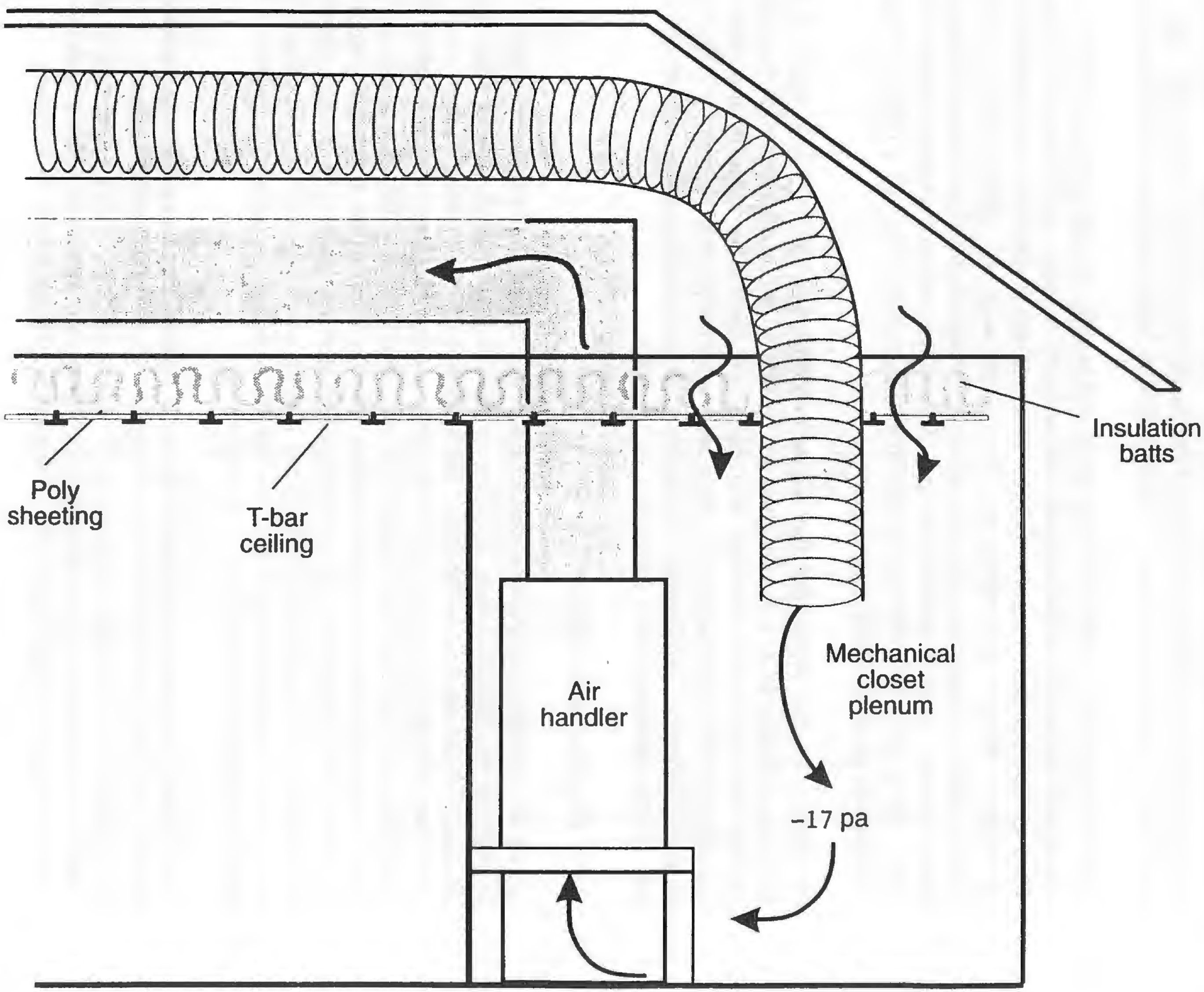
Duct CFM25 decreased 91% from 2576 to 227 (most of that leakage was in the return plenum closets). Relative humidity decreased from an average 57% to 52% as a result of repairs. Carbon dioxide levels increased from an average 498 ppm to 539 ppm. Cooling energy consumption decreased by 25.6% from 96.7 kWh/day to 72.0 kWh/day. Twenty person-hours and $300 in materials were used in this repair. Energy savings pay for the estimated $1300 repair cost in 3.9 years.

5.5.6 Sports building (#12)

Four air conditioning systems served this 16,713 square foot university building. Air handlers were located in two mechanical rooms which are located inside the ceiling space. Air handler #1 serves zone #1 plus a small portion of zone #2. Air handlers #s 2-4 serve the remainder of zone #2. These two zones are separated by a fire wall and doors between the two zones are closed most of the time.

Figure 5.5

Serious Return Leakage Through T-bar Ceiling of a Closet Used as a Return Plenum



Mechanical room #1 acts as a return plenum for air handler #1. The other three air handlers have "hard-ducted" returns. Air handler #1 draws air from the mechanical room and depressurizes the mechanical room to -10 pascals, and in turn the mechanical room draws air through "windows" from the ceiling space which is a return plenum. Exhaust fans in bathrooms and locker rooms depressurized zone 1 (the portion of the building served by air handler #1) to -1.7 pascals.

The ceiling plenum, which served only zone #1 had large leakage to outdoors. A three inch gap existed where the top of the exterior walls met the sloped roof deck. Considerable return leakage occurred through this gap in spite of the insulation batts which were stuffed into the gap. Not being an air barrier, these batts did not stop the air flow but rather filtered the air as it entered the building.

The uncontrolled air flow retrofit on this building consisted of sealing this gap, using foil-backed fibrous board and class 1 foam. A repeat of the building airtightness test found that 22% of the total building leakage was eliminated by this repair alone. Since cooling energy was delivered to this building by chilled water from a central plant, energy consumption was measured by monitoring air handler air flow rate, temperature drop, and humidity drop. Energy consumption of the electric reheat was monitored by a power meter, and it was found that reheat was consuming about $10,000 per year on air handler #1 alone!

Cooling energy savings were less than expected. Savings may have been reduced by and analysis made more complicated by the fact that electric reheat was used to control building humidity. The reheat is controlled by relative humidity, such that on cooler summer days the reheat operated more of the time, and therefore the cooling load did not respond as expected to changes in external weather conditions. Savings were also compromised by diagnostic failure. After the previously described repairs (sealing the return plenum) were made and only 7% energy savings were identified, we reevaluated our diagnosis and concluded that this building had an "exhaust air vs intake air" imbalance problem. Exhaust fans operate continuously and have larger air flow than the outdoor air. While we had stopped leak pathways and made the building more airtight, the driving forces of the exhaust fans were still operating and depressurization of zone #1 increased from -1.7 pascals to -3.4 pascals as a result of the this tightening.

The following observations and recommendations were given to the building owner based on the reevaluated diagnosis.

> "First, exhaust fans continue to draw 2230 cfm of air from the building, causing the average building pressure to be about -1.2 pascals (area weighted average of zones 1 and 2). This is consistent with the fact that exhaust fans are drawing about 750 cfm more air from the building than outdoor air ducts are bringing into the building (outdoor air = 1477 cfm and exhaust fan air = 2230 cfm).
>
> Second, a significant portion of the supply air from air handler #1 is delivered to zone 2 (about 3700 cfm), and the return air path is inadequate and is returning only about 1200 cfm (this means there is a net pumping of 2500 cfm of air from zone 1 to zone 2). Therefore, zone 2 (about 60% of the building) operates at about +0.2 pascals (all pressures with respect to outdoors), while zone 1 operates at about -3.4 pascals. Therefore, while zone 1 was made much more airtight (about 22% of the total building leak area was eliminated by the repair of the ceiling return plenum), it is now under much greater negative pressure (it was -1.7 pascals), and so considerable ambient air is still being drawn into the building.

Third, air handler #1 receives very little "outdoor air". While air handlers 2, 3, and 4 receive 457 cfm, 538 cfm, and 420 cfm, respectively, air handler #1 receives only 62 cfm. Zone 1 has 500 cfm of exhaust air operating continuously, or 438 cfm net loss, and consequently, this further depressurizes zone 1.

Recommendations

Based on these observations, the following recommendations are made. The ultimate objective of these recommendations is to reduce humidity levels in the building so that the electric reheat may be turned off. Based on one week of reheat energy use data, we project that AH#1 reheat is using about $10,000 per year (assume $0.08/kWh), and the cooling energy required to meet the reheat cooling load may be about $3500. Therefore, if the humidity can be controlled without reheat, savings from AH#1 alone could be $13,500 per year.

First, we recommend creating a larger return window in mechanical room #1 to allow a greater amount of return air to get back to AH#1. This window should be about three times larger than the presently existing window. This will reduce pressure imbalance between the two zones.

Second, we recommend that several exhaust fan flow rates be reduced in the building. Following are the current exhaust flow rates (as measured) and what we suggest for reduced flow:

	current	proposed
locker room shower	850	850
locker room bathroom	600	300
coaches locker room	280	100
office area bathrooms	500	200
total	2230	1450

This would reduce exhaust flow from 2230 cfm to 1450 cfm. Furthermore, we suggest that the middle two (locker room bathroom and coachers locker room) be placed on occupancy sensor control with an appropriate (15, 30, or 60 minute) time delay.

Third, we recommend that the outdoor air be increased to air handler #1, to about 500 cfm. This would bring zone 1 to positive pressure. When these first three steps are taken, nearly all the air entering the building will enter through the outdoor air ducts and therefore, the air will be conditioned by the outdoor air cooling coil before it reaches the air conditioning system. This will produce much improved dehumidification control.

Fourth, we recommend that the flow rate on the air handlers be reduced -- to levels that are just adequate to meet the cooling load on the hottest afternoons. This might mean the flow rates would need to be reduced by 70%. This reduction in air flow would cause the average cooling coil temperature to be colder and therefore remove more moisture.

Alternatively, the control of the chilled water could be changed. Currently, the water temperature is modulated to adjust to the cooling load as sensed by the thermostats. The recommended change would be to cycle the chilled water. In this mode, the water would be sent through the coil at full coldness, and then cycled off when the thermostat senses the setpoint has been satisfied. If this is done, it will be important that the "on" cycles be of sufficient length to allow good dehumidification (say 15 minute on cycles, at the very least) and it will be important that the drain pan not hold much water, because this water will evaporate during the "off" cycle, thus adding moisture back to the room air."

By reducing the flow rate and run time of exhaust fans, and increasing the outdoor air so the building operates at a slight positive pressure, building ventilation rates would decrease and dehumidification would improve. Moisture removal from air coming into the building would be enhanced because it would all (or at least virtually all) pass through the cooling coils on the outdoor air intake ducts. This yields a superior latent removal performance compared to trying to remove the moisture after it has already mixed with the room air as it passes through the air handlers -- especially since the air handlers are considerably oversized.

These recommendations had not yet been implemented by the fall of 1995 when monitoring ended. When they are implemented, we expect that relative humidity, which typically runs around 57% with the aid of the electric reheat, could be kept under control without the use of reheat and annual HVAC savings of $15,000 to $25,000 per year could be anticipated.

5.5.7 Recreation center (#25)

Two air conditioners (4 tons and 5 tons) serve this 2708 square foot building. A suspended t-bar ceiling is below a residential-style ventilated attic space. Insulation batts are attached to the bottom members of the attic truss system 6" to 30" above the ceiling; some batts are missing and some have fallen. The air handlers are situated on enclosed support platforms located in closets. Return leaks of 12.2% (south zone) and 19.4% (north zone) exist in each return plenum because the plenums are built into the closet corners and the walls are partially open to the inside of the plenum. Air is drawn down closet walls from the attic space, from above the ceiling tiles but below the suspended insulation batts. Voids between insulation batts allowed this space to become as hot as 91°F when the attic space above the batts was 118°F. Return leaks created slight positive pressure in the building, pushing room air into the space above the ceiling and thus keeping it from being much hotter than outdoors. Return leak flow was a total of 555 cfm from the two systems. The inside of the support platform return plenums and through-the-wall grill penetrations were sealed using fiberglass mesh and mastic. Supply leaks were sealed at some grill to duct connections.

Duct CFM25 was reduced by 81% from 788 to 154. Relative humidity was largely unchanged; 53% pre-repair and 52% post-repair. Cooling energy use decreased by 17.4% from an average 77.3 kWh/day to 63.9 kWh/day. Repair time was 8 person-hours and materials cost was $50. Energy savings pay for the estimated $450 repair cost in 2.2 years.

5.5.8 University office 1 (#29)

Four roof-top package air conditioners serve this 5040 square foot manufactured office space. Ductwork is located in the ceiling space. Insulation batts are located at the bottom of the roof deck. The ceiling space is warm and humid because it is well ventilated to outdoors. Vented soffit is located at the eaves on three sides of this buildings. Only vertical insulation batts separated this ventilated soffit space (outside the building) from the ceiling space (inside the building), and these batts allowed substantial air flow. Building airtightness was 24.9 ACH50 largely because of the ceiling space ventilation. Two retrofits were employed; airtightening the ceiling space and reducing outdoor air.

After identifying that the ceiling space was leaky to outdoors, it was decided that tightening the ceiling space would be preferable to sealing the rather leaky ductwork. Though the ducts are located inside the building thermal barrier (insulation attached to the bottom of the roof deck), they are effectively outside the building air barrier. The retrofit consisted of sealing the exterior walls above the ceiling level with fibrous ductboard, mastic, and foam. Airtightening of the ceiling space resulted in reduction of building ACH50 by 74% to 6.4. The second retrofit was reduction of outdoor air from 1296 cfm (86 cfm per person) to 588 cfm (39 cfm per person). In addition, panel leaks on the package air conditioners were sealed with metal tape.

As a result of tightening the ceiling space and reducing the outdoor air, relative humidity in the occupied space declined from an average 53% to 48%. Relative humidity in the ceiling space declined from 50% to 41%. Cooling energy use decreased from an average 211 kWh/day to 170 kWh/day, or 19.3%. Repair time was 24 person-hours and $80 in materials. Energy savings pay for the estimated $1280 repair cost in 2.2 years.

5.5.9 Bar and grill (#31)

Two four-ton air conditioners serve this rather leaky (17.5 ACH50) 2400 square foot restaurant/bar. The air handlers and ductwork are located in the attic space. The ductwork was very leaky; 655 CFM25. Large return leaks (505 cfm) were drawing hot attic air into the building. There were substantial supply leaks as well, but return leaks dominated. A kitchen exhaust fan pulled 987 cfm of air from the building throughout most of the day, and there was no make-up air. The building was depressurized to -0.8 pascals when both exhaust and air handlers were operating.

Based on the size of the duct leaks and the fact that they were drawing in hot attic air, cooling energy savings of 30% or more could have been expected. To our surprise, monitored savings were only 10.6%. In hind-sight two problems were identified. First, only 58% of the duct leaks were sealed. Second, we had mis-diagnosed the building UAF problems, or more accurately we only got it half right. We believed that sealing the large return leaks would reduce the amount of hot attic being brought into the building. It turned out that for the most part this was not true because the exhaust fan would continue to draw nearly 987 cfm air into the building for 8 to 10 hours per day, mostly from the attic. (Most of the air would come from the attic since nearly all of the shell leakage of this slab-on-grade, concrete block building existed in the ceiling.) As a result of duct repair, building pressure went from -0.8 pascals to -2.0 pascals. After repair, less attic air was being drawn into return leaks, but more attic air was being pulled into the building by space depressurization.

We believe that substantially greater energy savings could have been realized if make-up air were installed in the kitchen. Alternatively, the large leak paths between the attic and occupied space (above the bar) could have been sealed. This would have reduced the amount of air drawn from the hot attic and increased the amount drawn from the relatively cooler outdoors. To make this second approach even more effective, a passive make-up air vent could be installed in the kitchen, in the proximity of the cooking area and the exhaust fan. This would minimize the impact of the make-up air by causing it to "short circuit" -- go almost directly from the make-up grill into the exhaust intake. This case illustrates how important correct diagnosis is and the importance of taking all uncontrolled air flows into account when specifying repairs.

As a result of these repairs, duct CFM25 decreased 59% from 655 to 272. Relative humidity in the occupied space declined from an average 63% to 57%. Cooling energy use decreased from an average 142.4 kWh/day to 127.3 kWh/day, or 10.6%. Repair time was 18 person-hours and materials totalled $75. Energy savings pay for the estimated $975 repair cost in 4.2 years. Calculations indicate that installation of make-up air could save over $1000 per year.

5.5.10 Realty office 2 (#37)

This was one of the most interesting retrofit cases. An old, inefficient (estimated 6.0 SEER) five-ton air conditioner served this 1845 square foot building. Major breaks and offsets of sections of supply duct located in the attic had occurred as a result of foil tape adhesive failure producing very large supply leaks. An attic exhaust fan was pulling 730 cfm from the attic space throughout the day. It was depressurizing the attic space, which has only two small eave vents, to -10.0 pascals and the occupied space to -10.6 pascals (Figure 5.6). (Note that these pressures were with the air handler also operating and that the supply leaks were depressurizing the occupied space relative to the attic space.) It is also interesting to note that a new roof was put on the building after our initial testing and before the duct repairs were done. A new attic exhaust fan was also installed and it depressurized the attic space to -16.0 pascals and the occupied space to -15.6 pascals. (Note that the attic space is now more depressurized than the occupied space because the supply leaks had been repaired at this stage.)

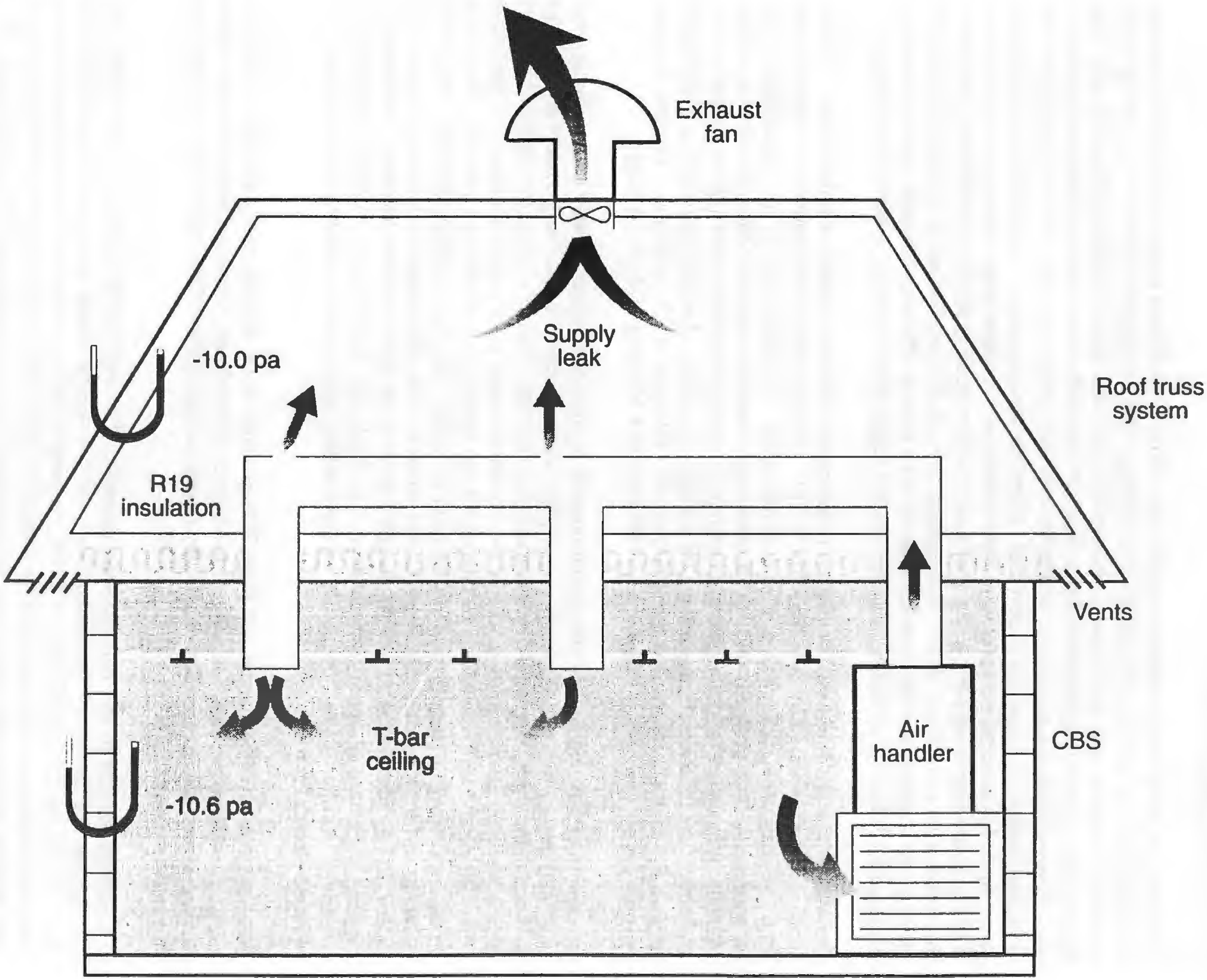
Retrofits to this building were completed in three phases. The first retrofit was duct repair. CFM25 in the ducts was reduced by 80% from 571 to 112. Cooling energy consumption declined 31% from 99.6 kWh/day to 69.1 kWh/day as a result of this repair. The second retrofit was replacement of the air conditioner by a 12 SEER unit. (This replacement was done entirely at the initiative and expense ($2800) of the owner.) Cooling energy consumption was reduced by 43% from 69.1 kWh/day to 39.7 kWh/day. The third retrofit was turning off the attic exhaust fan. Energy consumption (including the exhaust fan motor) was reduced by 36% from 39.7 kWh/day to 25.4 kWh/day. In total, the three retrofits cut cooling energy consumption 74% from 99.6 kWh/day to 25.4 kWh/day.

In addition to reducing cooling energy consumption by 36%, turning off the attic exhaust fan lowered building pressure from -16.0 pascals to -0.4 pascals and decreased the building ventilation rate from 0.79 ach to 0.24 ach. Carbon dioxide concentration increased from an average 620 ppm to 1150 ppm during weekday afternoon hours. Since concentrations above 1000 ppm is indicative of ventilation below 20 cfm/person, it would be recommended that additional ventilation be installed. One option would be to downsize the attic exhaust fan from its current 730 cfm to perhaps 200 cfm. This would draw hot air from the attic space, slightly depressurize the attic with respect to the occupied space, and ensure that air was flowing from the occupied space to the attic and not vice versa. Note that air entering the occupied space from outdoors has much less heat than air entering from the attic. Therefore, the direction of flow across the leaky ceiling plane is very important from a cooling load point-of-view.

Indoor relative humidity increased from 72% pre-duct repair to 76% post-duct repair. Relative humidity remained at 76% when the air conditioner was replaced. However, when the attic exhaust fan was turned off, indoor relative humidity decreased from 76% to 58%, as a result of the decrease in ventilation rate from 0.79 ach to 0.24 ach.

The energy savings in this building were dramatic. The total retrofit package -- duct repairs, AC change-out, and turning off the exhaust fan -- reduced cooling energy use by an estimated $1114 per year. Given the total retrofit cost of $3180, the simple payback period is 2.9 years. Looking at the individual measures, duct repair pays for itself in 0.7 years, AC change-out pays for itself in 6.5 years, and shutting off the attic exhaust fan pays for itself in 0.2 years (assume $50 service call). Duct repairs required six person-hours and $30 in materials.

Figure 5.6


Exhaust
fan
Supply
leak
-10.0 pa
Roof truss
system
R19
insulation
Vents
T-bar
ceiling
Air
handler
CBS
-10.6 pa

5.5.11 Realty office 3 (#39)

This building is a 50-year-old converted residence served by two air conditioners. Ductwork is located in the attic. The air handlers are in one closet and are located on support platforms that act as return plenums. Considerable return leakage (414 cfm as operated) comes from the attic by way of walls. It is interesting to note that the attic insulation had been compressed and badly soiled by rodent infestation, and the air drawn from the attic was contributing to indoor air quality complaints. The attic was a very difficult environment in which to spend any time because of the pungent odor.

A number of flaws lead to considerable return leakage associated with the support platforms that were enclosed to form return plenums. One plenum had two through-the-wall return grills and another return grill drawing air from inside the closet, thus making the closet act as a return plenum. There was a return transfer in the closet door, but it was undersized. As a result, the mechanical closet was substantially depressurized and was drawing air from the attic. The second plenum had one transfer through a wall and some leakage through a hole in the wood floor over a small crawlspace. Unsealed return transfers in the closet walls allowed hot attic air to be drawn down the walls from the attic.

Supply leakage was minor and due to time constraints was not repaired (repairs were begun after close of business, two hours were spent cleaning up a condensate leakage problem which interfered with the repair, and post-repair testing work was completed at 1 AM!). Leakage in the closet was also not repaired, due to oversight. Post repair testing showed that only 45% of the duct leakage had been sealed. Return leak fractions decreased from 10.5% to 5.2% on the west system and from 21.6% to 5.6% on the east system. Overall return leakage decreased by 66%.

Relative humidity in the occupied space did not change as a result of the repairs, remaining at 56%. Cooling energy use decreased by 7.5% from an average 117.7 kWh/day to 108.9 kWh/day. Repair time was 4 person-hours and $35 in materials. Energy savings pay for the estimated $235 repair cost in 2.0 years.

5.5.12 Safety class (#40)

Two roof-top air conditioners with combined capacity of 9 tons serve this 2460 square foot unit located in the same strip mall as the court office and school supply. This space had some of the worst uncontrolled air flows of the entire sample, yet repairs produced only modest savings. Following is a brief list of the failures.

1) For outdoor air, a grill had been installed in the return duct of the west system in the unconditioned ceiling space. This outdoor air was drawing 750 cfm of air into the return duct from the space between the insulation (located on the ceiling) and the roof deck. Since the roof deck was the primary air barrier of the building, this "outdoor air" was not providing significant ventilation and was drawing large amounts of unwanted heat into the space (Figure 5.7).

2) There were substantial other duct leaks, including a 1 inch by 30 inch leak at the west system air handler to main supply trunk duct connection which was **drawing air into that leak** (Figure 5.7)! Note that leaks in supply ducts sometimes draw air into the duct because of venturi forces.

3) Closed doors caused major pressure and flow imbalances since the returns and supplies were located in mutually exclusive zones. The return for one system was located in a closet positioned between the two main classrooms (Figure 5.8). This closet was depressurized to -13 pascals.

Figure 5.7

NSC Classroom

(West AC System)

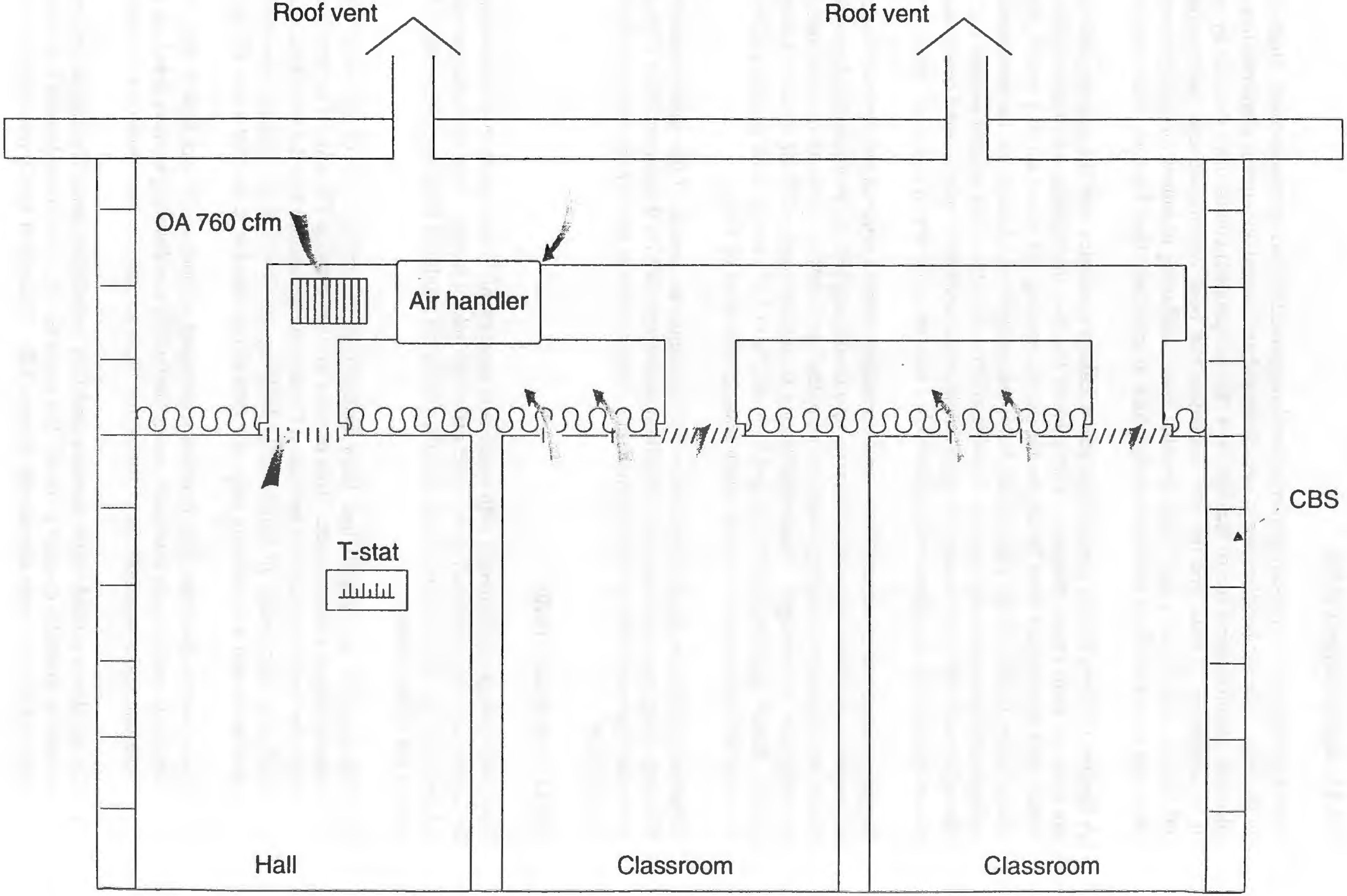
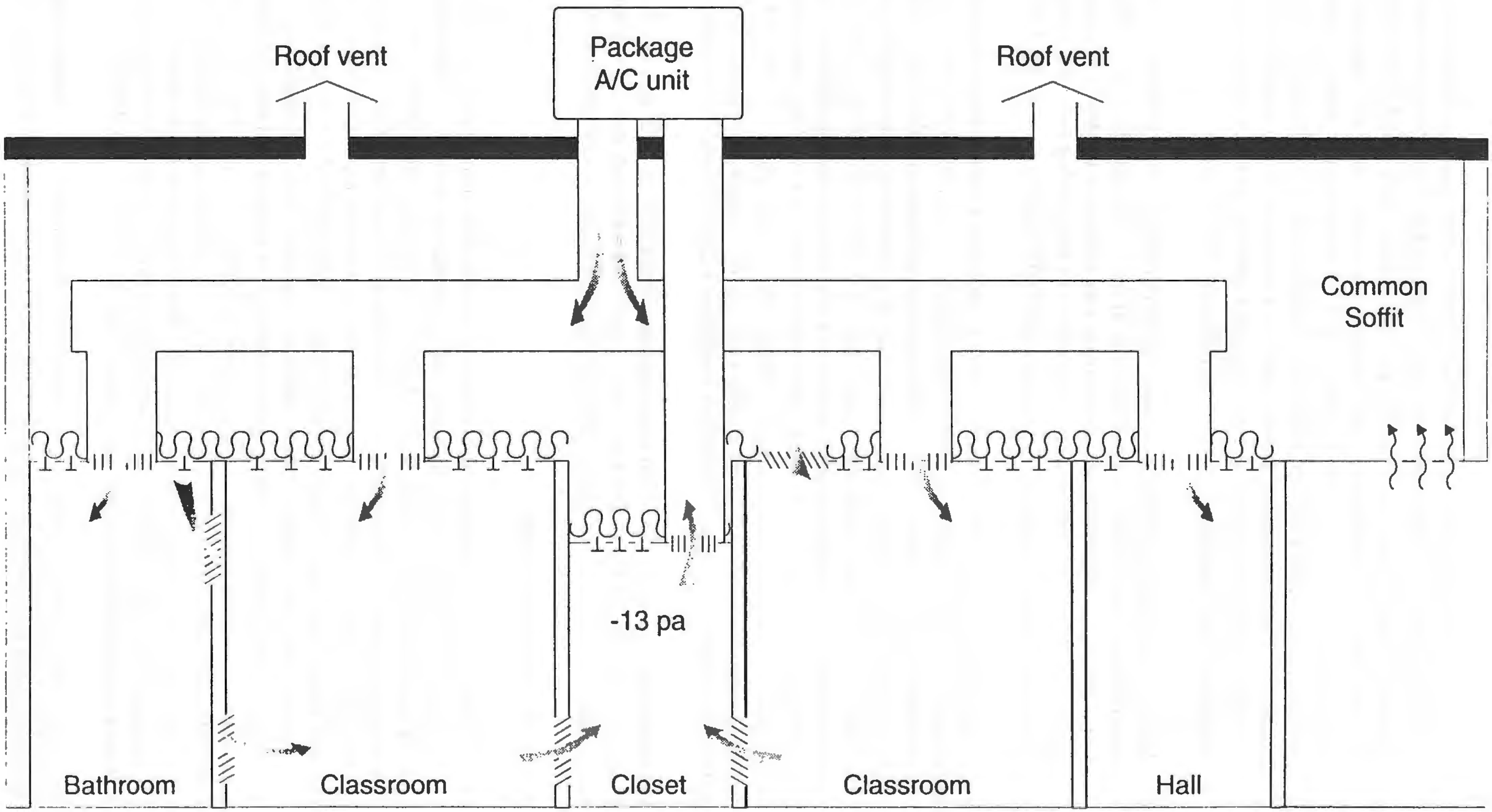


Figure 5.8

NSC Classroom

(East AC System)



Transfer grills were located in the doors going to the adjacent classrooms, allowing some return air flow. However, since this closet has a suspended, t-bar ceiling and was depressurized to -13 pascals, it was pulling considerable air from the unconditioned ceiling space above. The return for the other air conditioner was located in the hall while the supplies for that system were located exclusively in the classrooms. Thus, the classrooms were operating at positive pressure and the closet and hallway where the return grills were located were operating at negative pressure. Therefore, room air was moving from the room, through the suspended t-bar ceilings and batt insulation, through the ceiling space where it picked up heat, and then down through the insulation and suspended ceilings in the closet and hallway.

4) Each of the air conditioners served both classrooms, causing virtually identical cooling energy use whether one or both classrooms was in use. The east thermostat was located in one of the two classrooms while the west thermostat was located in the hallway, a space that had no supply registers. Since the west system thermostat was not sensing the cooling that was occurring in the classrooms, the majority of the cooling for both classrooms was done by the west system.

Repairs included sealing 51% of the duct leaks, installing return transfer ducts (two 2'x4' grills in each classroom), adding an additional return duct to the south classroom, installing an additional return transfer grill from the closet to the north classroom, airtightening the t-bar ceiling in the depressurized closet, and moving the thermostat from the hall to a classroom. Surprisingly, energy savings were only 17% when 50% savings could have been imagined. Two factors may explain the savings shortfall. 1) Moving the west thermostat shifted much of the cooling systems run time from the west unit to the less efficient east unit. 2) Considerable recapture of lost cooling may be occurring because the uncontrolled air flows occur primarily within the ceiling space. Though it is outside the primary thermal barrier (insulation located on the ceiling), it is inside the primary air barrier (the roof deck) and the roof deck may have significant insulation value (thermal resistance).

Relative humidity in the occupied space declined from 55% to 51% as a result of the repairs. Cooling energy use decreased by 17.0% from an average 50.8 kWh/day to 42.1 kWh/day. Repair time was 8 person-hours and $60 in materials. Energy savings pay for the estimated $460 repair cost in 2.5 years.

5.5.13 School supply (#45)

One 7.5-ton roof top package air conditioner serves this strip mall business. Supply leaks at panel connections and panel knockouts were sealed on the air handler. Difficulties were experienced in gaining access to the remaining duct leakage. Large return leaks were sealed by squeezing one person into the air handler on the return side and coating the interior of the plenum ductboard with mastic. Leakage in the remainder of the supply ductwork was not repaired because finding and repairing all the duct leaks would have been extremely time consuming, largely because of exterior insulation wrap. Finding the leak sites requires removing the insulation wrap and replacing it after sealing air leaks. Since access to the ceiling space requires standing on a ladder and moving the ladder from one ceiling tile location to another (with insulation batts on top), such a process is difficult and time consuming, especially considering the office furniture. The fact that the ceiling tiles have insulation batts and dust on them makes the process even more difficult and makes it likely that fibers and dust will fall onto people and furnishings below. In general, the ceiling access issue represents a significant barrier to efficient duct repair in a significant proportion of commercial buildings.

Repairs to this system decreased CFM25 by 55% from 418 to 190. Relative humidity in the occupied space declined from 48% pre-repair to 46% post-repair. Cooling energy use decreased 6.9% from an average 69.8 kWh/day to 64.8 kWh/day. Repair time was 2.5 person-hours and $30 in materials. Energy savings pay for the estimated $155 repair cost in 2.4 years.

5.5.14 Court office (#46)

Two roof-top air conditioners with combined capacity of 11.5 tons serve this 3735 square foot strip mall unit located next to the school supply store. Sixty-five percent of total leakage in this leaky duct system was sealed. Repairs were made to the return ducts at the grill connections and the east system return was sealed by coating the interior of the ductboard with mastic. The suspended ceiling had not been hung very securely, and over time the panels began to sag. As a result the supply grills pulled away from the ducts in some locations. The only supply side repair was at the supply-register-to-ceiling tile connections, since the ducts were wrapped metal. Even though 65% of the duct leakage was repaired, cooling energy consumption actually increased by 6.6 percent! (This was the only retrofit which did not show energy savings.)

In retrospect we have tried to determine why energy use would increase. The one factor that may provide some explanation is leakiness of the building shell. This office is the leakiest of the seventy buildings tested and has an ACH50 of 52.8. It may be that because the very leaky ceiling and vented roof deck allows wind to move air across it, air exchange may not change significantly as a result of duct repair. Note that the plastics office, which showed an unexpectedly small savings of 4% also had a very leaky building shell (ACH50=50.0). It may be that leaky buildings will often yield only small energy savings from duct repair. More research is required to answer that question.

Repairs decreased duct CFM25 by 65% from 830 to 292. Relative humidity in the occupied space declined slightly from 49% pre-repair to 47% post-repair. Cooling energy use increased by 6.6% from an average 137.8 kWh/day to 147.0 kWh/day. Repair time was 4 person-hours and $25 in materials.

5.5.15 Metal building company (#53)

Two cooling systems with total capacity of 9 tons serve this 3672 square foot metal building. Ceiling insulation is located both on top of the ceiling tiles and on the bottom of the sloped metal deck above. Some moderate sized supply leaks existed. The large duct leaks, however, occurred because the mechanical room for one of the larger of the two systems was used as a return plenum, and the ceiling of that room is suspended t-bar. Of the total 1453 CFM25 duct leakage in the two systems, 49% existed in the ceiling of that mechanical room.

Repairs consisted of repairing one major supply leak, sealing return ducts, airtightening the t-bar ceiling in the mechanical room, and reducing the mechanical room pressure from -19.1 pascals to -4.2 pascals by installing a louvered door in place of the solid door. Return leak fraction for the mechanical room decreased from 28% to 4% as a result. Cooling energy use declined by 10.8% as a result of the retrofit. Larger savings might have been expected, except that the building has two thermal barriers -- insulation on top of the ceiling and insulation at the roof deck. All of the duct leakage occurs inside the building air barrier and inside one of the two thermal barriers. If the roof deck insulation had not been there, these duct leak repairs might have produced energy savings of 25% or more. Another way of saying this is that this building was saved from the full consequences of uncontrolled air flow by having a second thermal barrier at the roof deck.

A general lesson can be stated here. If the ductwork and ceiling spaces are located inside the primary air barrier and thermal barrier, then the consequences of uncontrolled air flow are largely obviated.

Repairs to this system decreased CFM25 by 43% from 1453 to 833. Relative humidity in the occupied space was at 41% before and after repairs. Cooling energy use decreased from an average 87.2 kWh/day to 77.8 kWh/day, or 10.8%. Repair time was 5 person-hours and $90 in materials. Energy savings pay for the estimated $340 repair cost in 2.2 years.

5.5.16 Realty office 4 (#54)

Two air conditioning systems serve this 2635 square foot building. The air handlers are located in closets which act as return plenums. The east closet was depressurized to -19 pascals and the west closet to -16 pascals, but only when the closet doors were closed. The ceiling of the east closet was moderately leaky (one foot square tongue-in-groove ceiling tiles) and the ceiling of the west closet was gypsum board. The east closet door was closed at all times thereby causing substantial return leaks. The west closet door was open all the time, so there was no return leakage into that mechanical closet and no tightening of the closet was done. The east mechanical closet was repaired primarily by tightening the ceiling and walls. Some supply leaks were repaired. Repairs decreased duct CFM25 from 885 CFM25 to 289 CFM25. Relative humidity in the occupied space increased from 54% pre-repair to 55% post-repair. Cooling energy use decreased 13.7% from an average 61.9 kWh/day to 53.4 kWh/day. Repair time was twelve person-hours and $75 in materials. Energy savings pay for the estimated $675 repair cost in 4.9 years.

5.5.17 Plastic fabrication office (#56)

This was the most simple yet most perplexing retrofit. While large duct leaks were repaired, energy savings was a meager 4%. A single two-ton air conditioner serves the small 360 square foot office space of this plastics manufacturing warehouse facility. The office itself, the air handler, and the ductwork are all located inside an unconditioned warehouse space. Significant leakage existed at the return support plenum and filter access causing 26% of the return air to originate in this hot warehouse. Supply leaks also exist at the supply register connections. Total duct leakage was reduced by 70% from 186 CFM25 to 55 CFM25. Return leaks declined from 26% to 2%. The small energy savings was a surprise.

Several factors were examined to determine why the savings were so small. The temperature drop from the return to supply increased from 10.0°F to 12.2°F when repaired. Based on this, the authors would expect at least an 18% reduction in cooling energy use. Variations in room temperature were examined; the thermostat setting remained constant throughout the monitoring period. A later experiment was done by adding a new return duct leak (19% return leak fraction); this increased energy used by 2.8%, a surprisingly small change.

One variable which may offer explanation is the extreme leakiness of the space; ACH50 equals 50.0. This office was the second leakiest of all sites monitored, nearly three times as leaky as the average for the entire 70 building sample. It may be that shell leaks allow considerable air transport between the occupied space and the warehouse, even when the duct leaks are not operating. An additional factor may be that since most of the shell leakage is to the unconditioned warehouse, perhaps some of the energy lost from duct leaks is recovered by cooling and drying the warehouse space.

Relative humidity in the occupied space increased from 54% pre-repair to 55% post-repair. Cooling energy use decreased 4.3% from an average 22.8 kWh/day to 21.8 kWh/day. Repair time was four person-hours and $25 in materials. Energy savings pay for the estimated $225 repair cost in 11.5 years.

5.5.18 Carpet store (#59)

A 3-ton air conditioner serves this 1584 square foot converted automotive service station. The air handler and return are completely within the conditioned space. Moderate supply leaks exist. This site was chosen even though the potential for savings was not expected to be great. Only supply grill connections and one elbow seam were repaired. These repairs reduced total duct leakage by 45.6%, from 158 CFM25 to 86 CFM25. Relative humidity decreased from 53% pre-repair to 51% post-repair. Cooling energy use decreased 11.9% from an average 21.7 kWh/day to 19.1 kWh/day. Repairs were completed in one person-hour using only $8 in materials. Energy savings pay for the estimated $58 repair cost in 1.5 years.

5.5.19 Manufactured office 3 (#60)

One ground-mounted 3-ton package air conditioner served this single-wide commercial trailer. Duct repairs were made to the main return duct at the air handler and the floor register, and to supply register connections in the floor. Some package air conditioner panel leaks could not be sealed. Duct CFM25 decreased 45% from 251 CFM25 to 138 CFM25. Relative humidity increased from 54% pre-repair to 57% post-repair. Cooling energy use decreased 14.3% from an average 31.4 kWh/day to 26.9 kWh/day. Repairs were completed in five person-hours using only $10 in materials. Energy savings pay for the estimated $260 repair cost in 4.7 years.

5.5.20 Manufactured office 4 (#61)

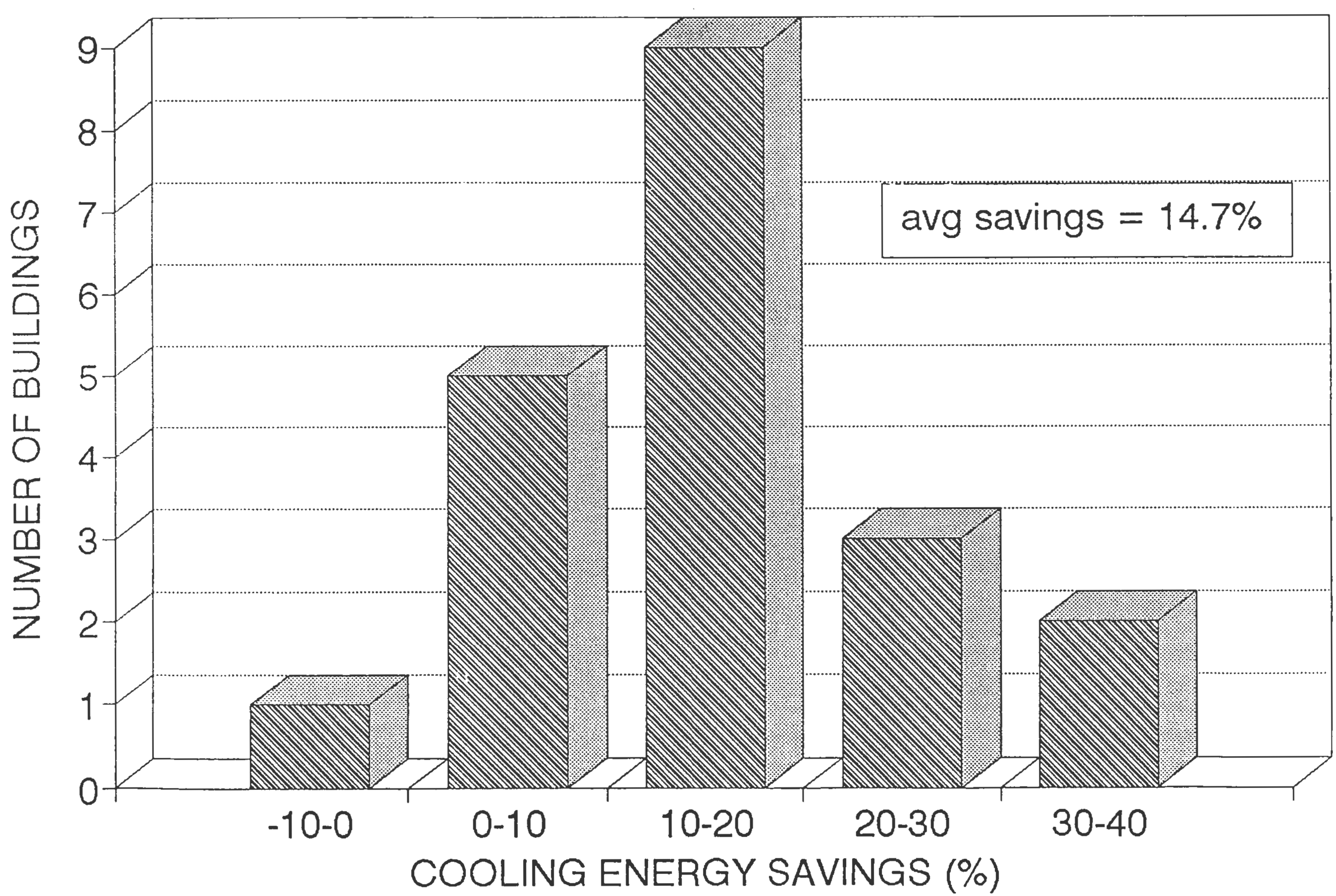
The two wall-mounted air conditioning package units serve this modular office. Part of the exterior wall cavity is used for return air for both systems. Return leakage was repaired in the wall cavity and at the duct board connections at the air handler. Supply ducts were located in the small space between the ceiling and roof deck, and were therefore largely inaccessible. Therefore, only supply leaks accessible through the registers were repaired. Only 30% of the total duct leakage (as seen by the duct test rig) was repaired. As a consequence, energy savings was only 4%. Greater savings would be expected if the ductwork was more accessible.

Duct CFM25 decreased 30% from 793 CFM25 to 554 CFM25. Relative humidity decreased from 46% pre-repair to 45% post-repair. Cooling energy use decreased 4.3% from an average 70.74 kWh/day to 67.6 kWh/day. Repairs were completed in four person-hours using only $25 in materials. Energy savings pay for the estimated $225 repair cost in 4.7 years.

5.6 Discussion of Energy Savings

Energy savings were found in 18 of 19 buildings in which uncontrolled air flow was repaired. In one building, energy use **increased** by 6.7%. In the 18 which showed energy use reduction, savings ranged from 4.3% to 36% (Figure 5.9). For 19 buildings (including the one which showed an increase in energy use), cooling energy consumption declined by an averaged 14.7%, or 12.4 kWh/day during the hottest six months of the cooling season. Over an eight month period, savings would be $0.75/day savings or $182 per year (based on 7.5 cents/kWh). Since the average repair cost was $454, the average simple payback period was 2.5 years.

Figure 5.9 COOLING ENERGY SAVINGS RESULTING FROM REPAIR OF UNCONTROLLED AIR FLOW



While 14.7% savings is substantial and the payback periods are attractive, it is the authors opinion that greater energy savings could be available. In retrospect, we see that only 59% of the duct system leaks were sealed (in buildings where the ducts were the target of repair). With added attention to achieving more complete repair, we estimate that 70% or more of the leakage could have been sealed.

There are several reasons why we believe that considerably more repair savings can be achieved:

1) Some repairs were not as comprehensive as they could have been because of project budget limitations.

2) For efficiency reasons, we usually attempted to retest the building and HVAC systems on the same day as repairs were done. This places additional demands on time available for repairs.

3) Business owners are sensitive to interference with the normal activities of their employees or their customers. Therefore, there was usually some pressure on repair personnel to finish quickly and considerable resistance to turning off the HVAC systems so that duct test rigs could be installed (the duct test rig could then be used to monitor duct airtightening progress).

4) In buildings that have ceiling spaces (as opposed to attic spaces), repairs are generally done by lifting ceiling tiles. The process of finding the leaks and then making the repairs is made more complicated by the need to move ladders incrementally around the room while avoiding furniture and people. Scheduling repairs outside of business hours is the best way to avoid these problems. When ducts are located in an attic space, repair is considerably easier because persons can move around within the attic space without significant bother to persons in the occupied space.

5) Additional savings may also be available with repair technologies which have not yet been developed. A prime example is very leaky ceiling planes in many commercial buildings. When methods are developed to either airtighten suspended ceilings or move the air barrier to another building plane (preferably where the thermal barrier is located), then considerably more savings will result. New aerosol deposition technologies which are currently under development may prove to be useful in sealing ducts located in ceiling spaces, especially those with exterior insulation wrap.

6) There is a learning curve associated with repair of uncontrolled air flow. There is a learning curve for diagnosis -- accurately determining what is going on and what should be done. There is also a learning curve for repair -- what to repair, what repair technologies can be used (for example, how to airtighten ceilings), and how to accomplish the repair. In this project, staff were on the early stages of the learning curve regarding diagnosis and repair of uncontrolled air flow. In several cases, repair was incomplete because of incomplete understanding of the interacting relationships between 1) duct repair and exhaust fans and 2) interacting relationships between duct repair and very leaky building shells. Having completed repairs on 20 buildings, the authors now better understand these interacting relationships and can prescribe (and train) improved retrofits. There is still more to be learned, especially in the areas of exhaust/intake imbalance, building envelope airtightening, improved return air, and proper sizing of ventilation.

If more of the duct leakage had been repaired and more complete addressing of the exhaust fan and building leakage had occurred, then savings would have been considerably greater. If it is assumed that 75% of duct leaks can be repaired and that repair technologies for providing make-up air and airtightening buildings is available, then we project that about 25% cooling energy savings could have been realized in these 19 buildings.

5.6.1 Commercial savings compared to residential savings

While the energy savings in these commercial buildings was less than that found in residences on a percentage basis (14.7% for commercial versus 17.2% for residential duct repair), the savings are larger in absolute terms, 12.4 kWh/day savings versus 7.2 kWh/day savings. Even normalizing to building size, the savings are larger in commercial buildings. In 48 residences, pre-repair cooling energy consumption was 24.6 kWh/day per 1000 square feet and savings were 4.24 kWh/day per 1000 square feet (Cummings, Tooley, Moyer, 1991). By comparison, in these 19 commercial buildings (average floor area = 2541 square feet), pre-repair cooling energy consumption was 34.4 kWh/day per 1000 square feet (or 40% greater than in residences) and savings were 4.84 kWh/day per 1000 square feet.
From an electrical demand point of view, commercial buildings cooling energy consumption is focussed more intensely on daytime periods of weekdays, which is also the time when most utilities experience peak demand. Therefore, it might be expected that commercial buildings UAF retrofit programs should provide disproportionate benefit to demand management. In the following section we will look at the monitored demand savings which resulted from repair of uncontrolled air flow.

5.7 Peak Electrical Demand Analysis

Compared to residences, commercial building cooling energy consumption is more concentrated during weekday daytime hours, because that is the period of maximum occupancy. In 63% of the 20-building sample, thermostats were raised or turned off during evening or weekend hours. In the remaining 37%, set-points remained constant throughout the entire week. Based on questionnaire results, the average business was occupied from 7:30 AM to 6 PM on weekdays and open about 4 hours per weekend, for a total of 56.5 hours per week. By contrast, average residential occupancy may be on the order of 130 hours per week (of a total 168 hours per week). Therefore, internal heat generation and cooling systems operation is much more focussed on weekday, daytime periods, which also coincides with periods when summer electrical demand is at a peak.

Reduction in peak electrical cooling demand was analyzed for these 19 buildings. Peak electrical demand was evaluated by selecting pre-repair and post-repair days which are approximately comparable, and then creating 24-hour composite energy use plots. Following is a discussion of the criteria used for selecting days for analysis.

5.7.1 Criteria for selecting peak demand days

Analysis of power demand reduction was done by choosing the warmest sets of days for which comparable pre-repair and post-repair outside temperature, solar radiation, and "outdoor - indoor temperature difference" data were available. Typically the sample size was six to twelve days. These sets of days were then converted to composite days -- that is, the data is averaged for each hour of the day. This results in 24 values, for temperature, power, and solar radiation for both pre-repair and post-repair periods. Since the FSEC VAX computer, which collects all off-site data, operates using Eastern Standard Time, **the results are plotted in Eastern Standard Time.** A business which operates from

9 AM to 5 PM DST will be reflected on the peak demand reduction graphs as operating from 8 AM to 4 PM EST.

Florida utilities experience summer peak demand in the window of 2 PM to 6 PM EST, with a maximum around 3:30 EST. In the 19 buildings monitored for energy savings, business hours typically ran from 7 AM to 4 PM EST, though some deviated from that. For our analysis, we identified the peak demand period for each building, usually a two or three hour period, and used that period for comparison of electrical demand. In 10 of the 19 cases, the period 1 PM to 3 PM EST was the peak. The average peak demand period for these 19 buildings was 1:10 PM to 3:16 PM EST (which is 2:10 PM to 4:16 PM DST).

5.7.2 Peak demand results

The results of the peak demand analysis before and after repairs are shown in Table 5.8. The number of days used for comparison are shown as "# Days". On average, 8.7 days of pre-repair and 9.7 days of post-repair data were included in the peak demand analysis. The temperature and solar radiation data are 24-hour averages while peak demand is the cooling energy consumption rate for the indicated peak demand period. Solar radiation appears as a low number because it is a 24 hour average.

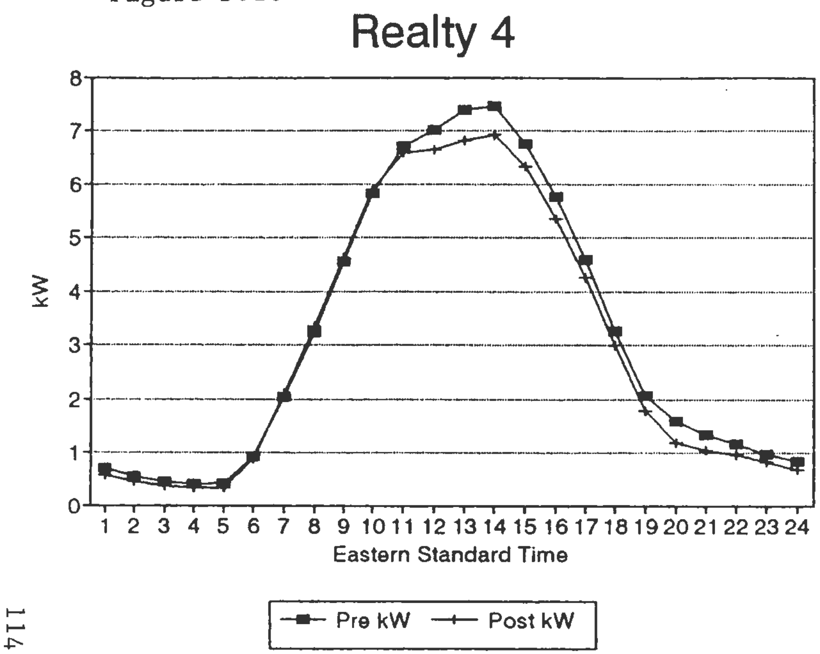
Composite 24 hour demand profiles were developed for the 18 buildings for which sufficient pre-repair and post-repair data was available. These are presented as Figures 5.10 - 5.14.

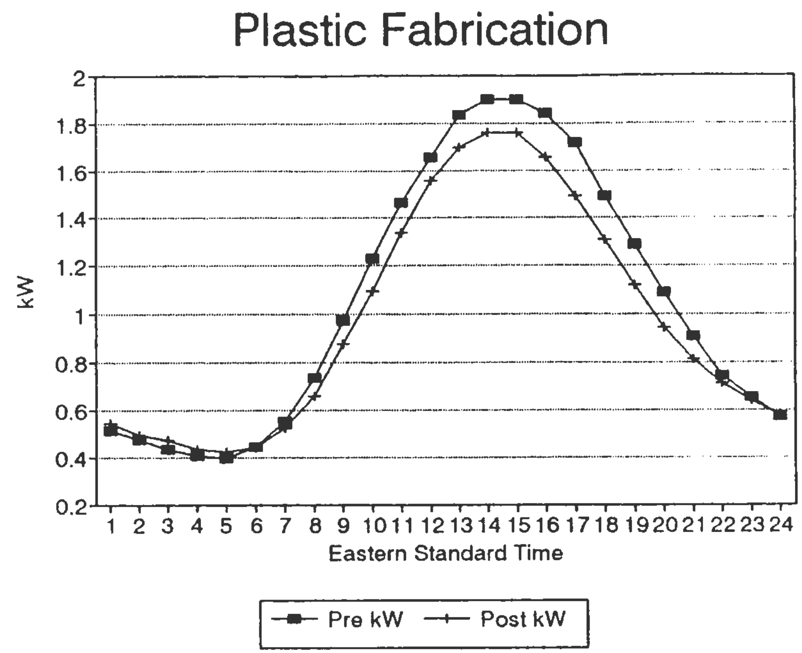
If more than one retrofit was employed at a building, they were all done at the same time and monitored as if one repair. The exception to this was Realty 2 (building #37). In this case, three retrofits were implemented in three phases and the energy savings due to each was monitored. The first was duct repair, the second was replacing an old inefficient air conditioner with a new high efficiency one (this measure was taken at the initiative and expense of the business owner), and turning off an attic ventilation fan. The demand reduction shown in Table 5.8 for this building represents only the duct repair and turning off the attic exhaust fan (measures related to uncontrolled air flow), and does not include the demand savings from installing the new air conditioner. Note that it also includes the fan power savings (0.468 kW) when the attic fan was turned off.

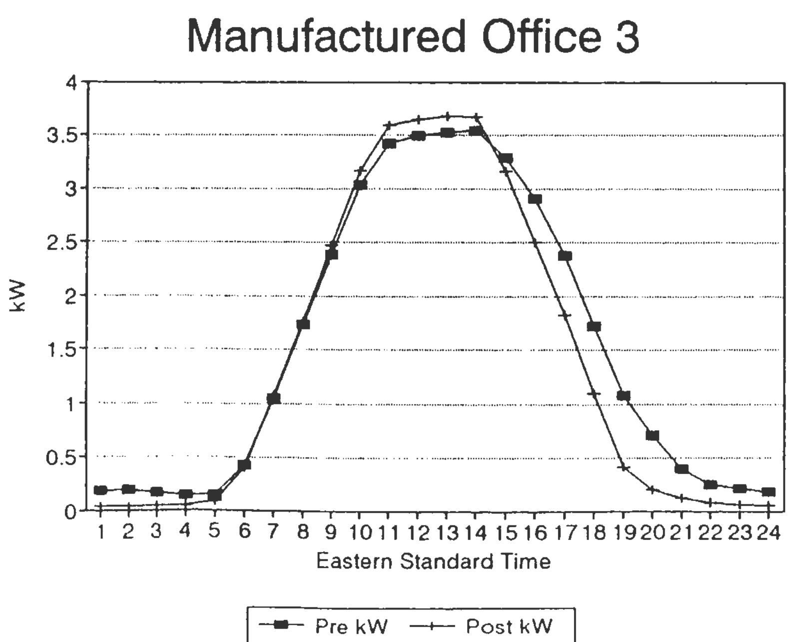
The demand savings from all three phases of retrofit in Realty 2 are shown in Table 5.9 and Figure 5.12. (Note that the second retrofit phase, replacement of the air conditioning system is not an uncontrolled air flow retrofit.) Repairing the substantial duct leaks reduces peak demand by 1.07 kW. Replacing the air conditioning system reduces peak demand by 1.84 kW. Turning off the attic exhaust fan, which was depressurizing the entire building to -15 pascals, lowered cooling energy demand by 0.28 kW and fan power by 0.47 kW. In total, peak electrical demand was reduced by 3.66 kW. Since the cost of the three retrofits was $3180, avoided demand cost was $870 per kW. Since the uncontrolled air flow retrofits (only duct repair and turning off the attic exhaust fan) cost was $380, avoided demand cost was $104 per kW.

For the entire sample of 18 buildings (data for buildings 3 and 12 was insufficient for analysis), average demand savings were 0.71 kW, or 9.4% of total cooling demand. Since the average cost of these retrofits was $454, this means the cost of avoided electrical generating capacity was $767 per kW, approximately in line with the cost of building new generation capacity. When one considers the combined demand savings and energy savings, repair of uncontrolled air flow can be seen as a very cost-effective measure.

Figure 5.10


Realty 4
kW
Eastern Standard Time
Pre kW
Post kW


Plastic Fabrication
kW
Eastern Standard Time
Pre kW
Post kW


Manufactured Office 3
kW
Eastern Standard Time
Pre kW
Post kW

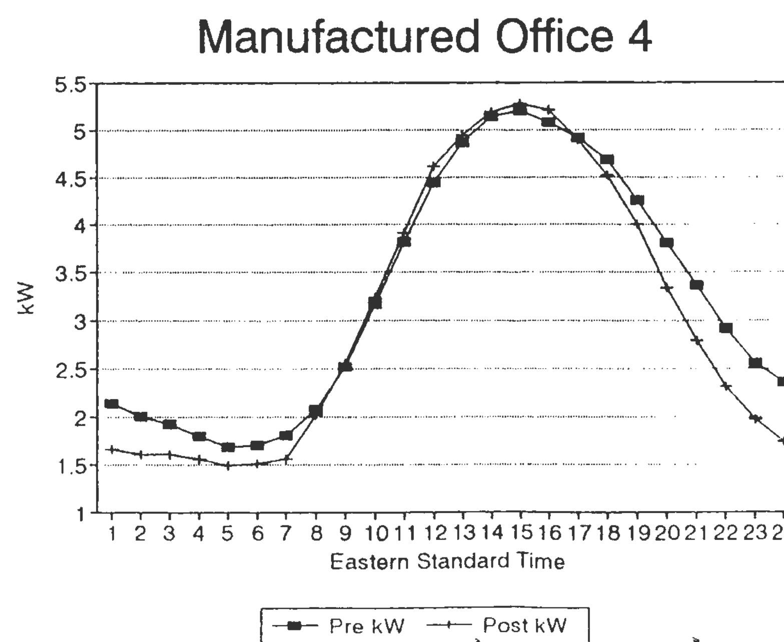

Manufactured Office 4
kW
Eastern Standard Time
Pre kW
Post kW

Figure 5.11

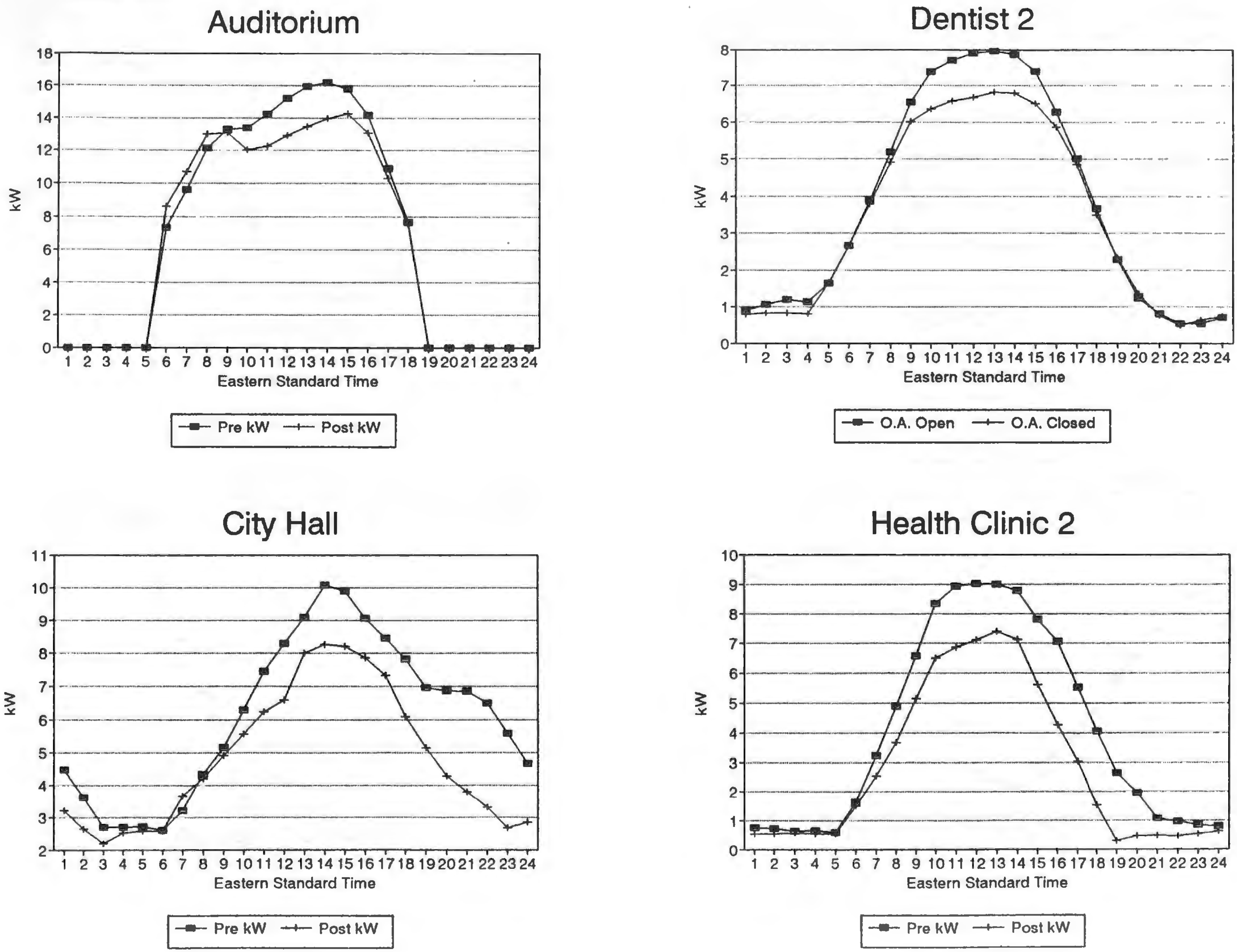
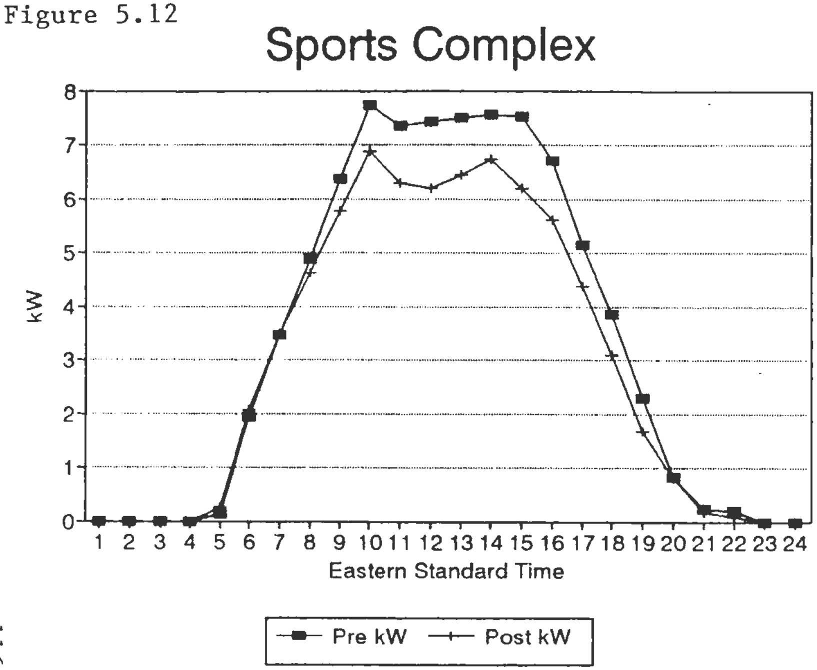
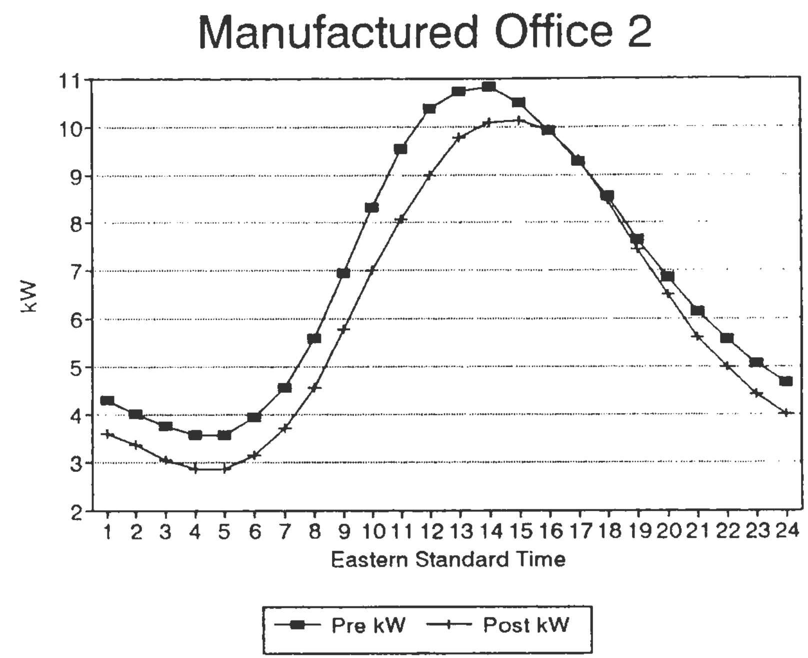
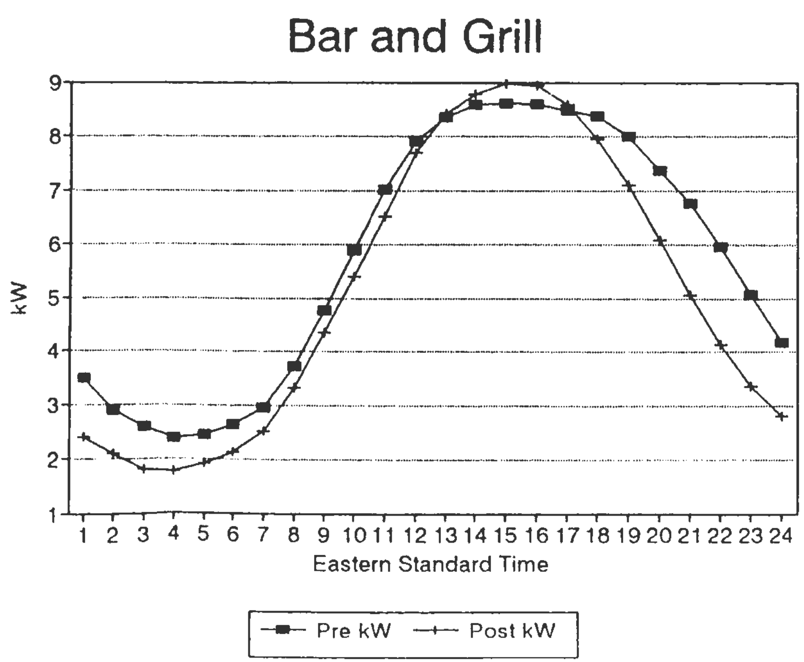

Auditorium
kW
Eastern Standard Time
Pre kW
Post kW
Dentist 2
kW
Eastern Standard Time
O.A. Open
O.A. Closed
City Hall
kW
Eastern Standard Time
Pre kW
Post kW
Health Clinic 2
kW
Eastern Standard Time
Pre kW
Post kW

Figure 5.12


Sports Complex
kW
Eastern Standard Time
Pre kW
Post kW


Manufactured Office 2
kW
Eastern Standard Time
Pre kW
Post kW


Bar and Grill
kW
Eastern Standard Time
Pre kW
Post kW

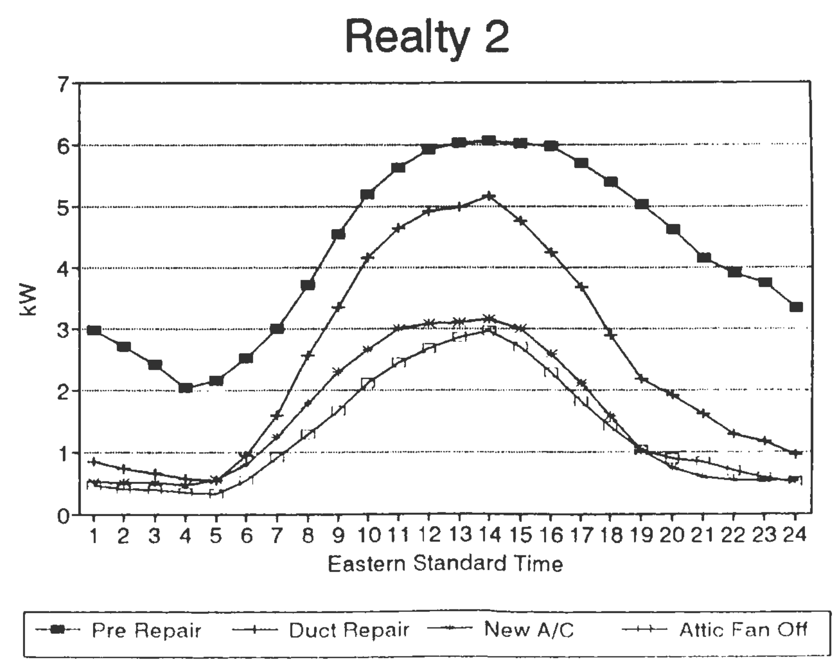
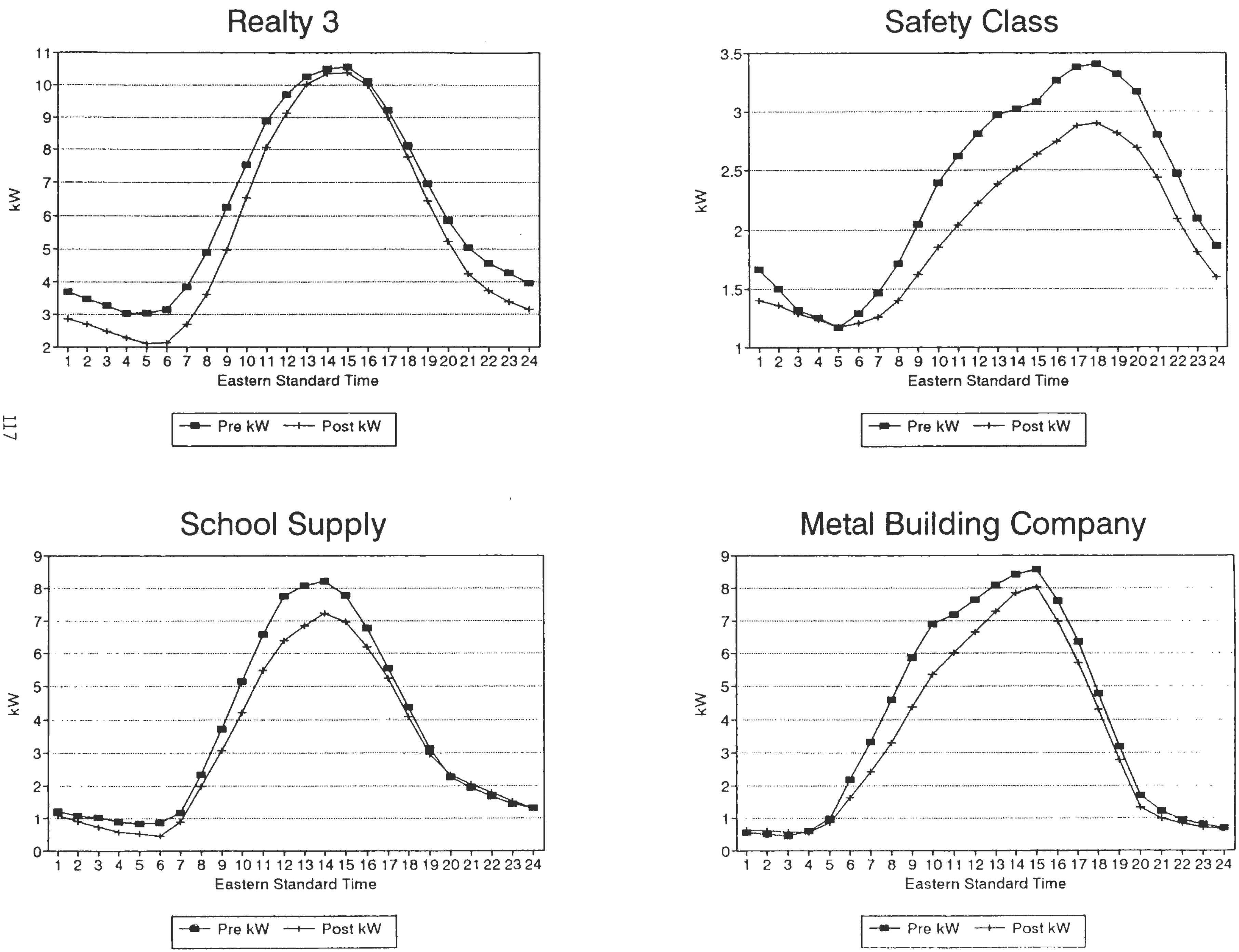
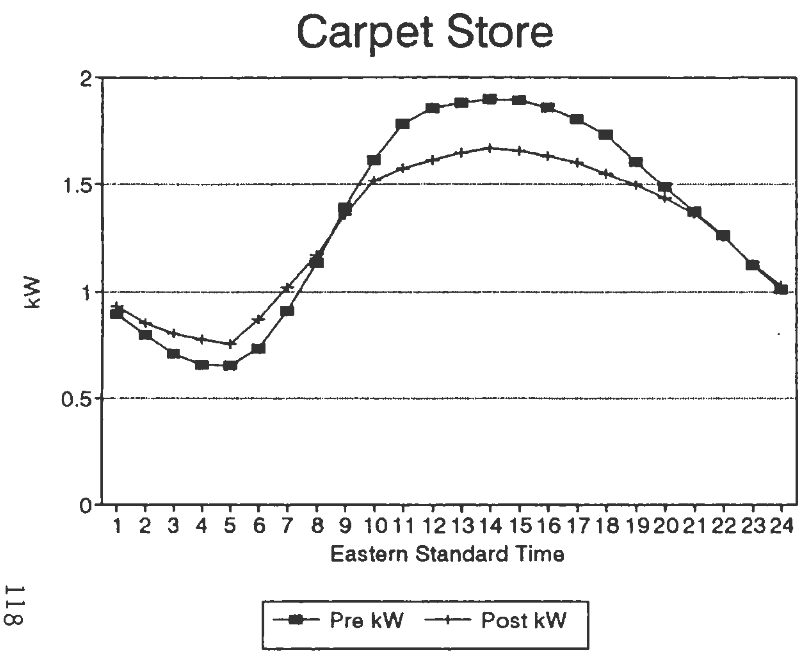

Realty 2
kW
Eastern Standard Time
Pre Repair
Duct Repair
New A/C
Attic Fan Off

Figure 5.13

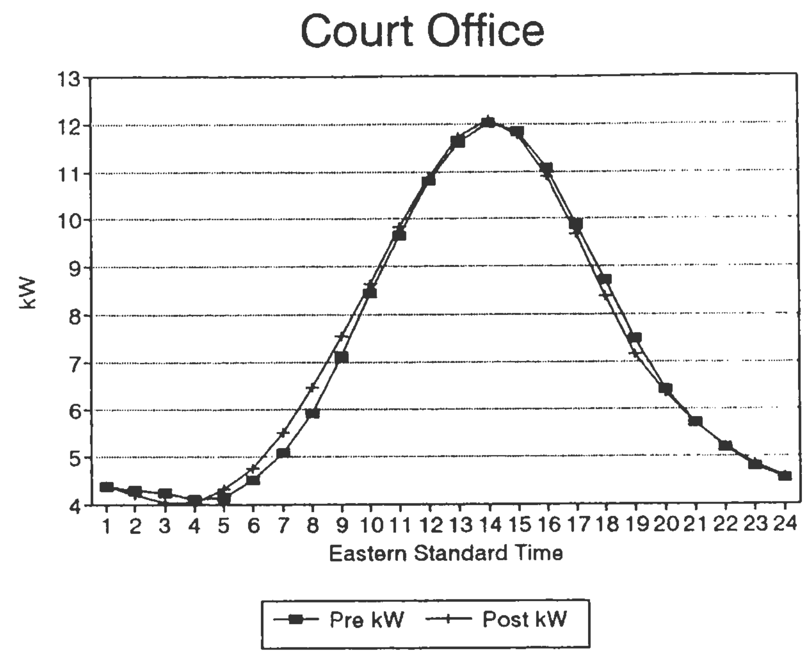


Realty 3
kW
Eastern Standard Time
Pre kW
Post kW
Safety Class
kW
Eastern Standard Time
Pre kW
Post kW
School Supply
kW
Eastern Standard Time
Pre kW
Post kW
Metal Building Company
kW
Eastern Standard Time
Pre kW
Post kW

Figure 5.18



Carpet Store
kW
2
1.5
1
0.5
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Eastern Standard Time
Pre kW
Post kW



Court Office
kW
13
12
11
10
9
8
7
6
5
4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Eastern Standard Time
Pre kW
Post kW

TABLE 5.8

Cooling Energy Peak Demand (kW) Before and After Repair for Periods Indicated.

Outdoor Temperature, Solar Radiation, and dT (T outdoors - T indoors) are 24 Hour Averages.

Building	Pre Repair					Post Repair					Peak Demand Period E.S.T.	Peak Demand Reduction kW	Percent Reduction
	# Days	T out	dT	Solar (W/m^2)	Peak kW	# Days	T out	dT	Solar (W/m^2)	Peak kW			
2 Auditorium	7	81.6	4.0	208.3	15.96	9	81.0	3.0	205.1	13.89	1-3	2.07	13.0
9 Dentist 2	4	80.7	4.7	176.5	7.90	3	80.3	5.3	218.0	6.77	12-2	1.13	14.3
20 City Hall	3	79.9	4.1	259.4	9.70	3	80.0	3.2	216.0	8.17	1-3	1.53	15.8
21 Health Clinic 2	3	80.8	3.2	220.3	8.93	3	80.3	3.3	200.9	7.20	12-2	1.73	19.4
25 Sports Complex	4	79.3	2.3	262.2	7.53	5	80.3	0.6	227.1	6.48	1-3	1.05	13.9
29 Mfg Office 2	12	76.0	1.2	168.1	10.68	15	75.8	1.1	176.1	9.99	1-3	0.69	6.5
31 Bar & Grill	6	78.8	1.3	203.5	8.53	9	76.7	1.8	186.0	8.74	1-5	-0.21	-2.5
37 Realty 2	15	81.4	5.0	299.8	6.50	14	82.0	5.2	289.7	4.68	1-3	1.82	28.0
39 Realty 3	9	81.4	8.6	279.4	10.39	17	82.6	8.4	248.5	10.24	2-4	0.15	1.4
40 Safety Class	11	80.6	1.2	229.7	3.37	13	80.2	1.2	233.8	2.86	5-7	0.51	15.1
45 School Supply	16	81.9	6.1	227.5	8.01	13	81.9	6.1	280.7	7.01	1-3	1.00	12.5
46 Court Office	6	82.7	7.6	258.9	11.82	8	82.8	7.3	261.0	11.86	1-3	-0.04	-0.3
53 Metal Bldg Co	15	81.0	4.2	261.0	8.18	14	79.8	4.1	247.2	7.53	1-4	0.65	7.9
54 Realty 4	7	82.2	2.5	283.6	7.21	7	82.2	2.6	230.9	6.69	1-3	0.52	7.2
56 Plastic Fabricate	13	79.7	11.5	285.9	1.87	10	79.8	11.3	287.8	1.71	1-4	0.16	8.6
59 Carpet Store	10	83.3	4.5	271.0	1.89	12	84.1	4.5	216.4	1.66	1-3	0.23	12.2
60 Mfg Office 3	8	81.9	4.1	278.3	3.45	10	82.4	4.7	263.2	3.51	1-3	-0.06	-1.7
61 Mfg Office 4	17	79.6	2.2	280.0	5.14	9	81.0	2.1	278.1	5.22	2-4	-0.08	-1.6
AVERAGE	9	80.7	4.3	247.4	7.61	10	80.7	4.2	237.0	6.90	1-4	0.71	9.4

TABLE 5.9
Cooling Energy Peak Demand (kW) Before and After Repair for Realty 2 for Periods Indicated.
Outdoor Temperature, Solar Radiation, and dT (T outdoors - T indoors) are 24 Hour Averages.

BUILDING	Pre Repair					Post Repair					Peak Demand Period E.S.T.	Peak Demand Reduction kW	Percent Reduction
	# Days	T out	dT	Solar (W/m^2)	Peak kW	# Days	T out	dT	Solar (W/m^2)	Peak kW			
37 Realty 2 duct repair	10	81.6	5.1	297.5	6.5*	6	81.3	4.8	283.9	5.4*	1-3	1.07	16.5
37 Realty 2 new a/c	6	81.3	4.8	283.9	5.4*	5	81.1	4.9	302.1	3.6*	1-3	1.84	34.1
37 Realty 2 attic fan off	5	81.1	4.9	302.1	3.6*	8	82.7	5.7	295.6	2.9	1-3	0.75	20.8
AVERAGE	7	81.4	4.9	294.5	5.2	6	81.7	5.1	293.9	3.9	1-3		
CUMULATIVE												3.66	71.4

* Peak demand includes AC and attic fan power.

The average 24-hour outdoor temperature on these days was 80.7F, or about 3F cooler than the hottest summer days. Therefore, we could expect even greater demand reduction on the hottest summer days when the utilities are experiencing their system-wide peak demand.

Thirteen of the 18 buildings had 6% or greater peak cooling energy demand reduction, ranging from 6.5% to 28% and averaging 13.4%. Five of the 18 buildings had less than 2% peak demand reduction, ranging from +1.4% to -2.5% and averaging -0.9% savings. Essentially, we can say that five buildings showed no demand reduction while 13 buildings showed an average 13.4% demand reduction. Let's look at the five that had no demand reduction to see what factors could account for the poor results.

One of them, the Bar and Grill (building #31) had a significant UAF problem which was not dealt with because of diagnostic oversight, as discussed earlier in this report in the energy savings section. That problem was a large exhaust fan, with no designed make up air, pulling attic air into the building for about eight hours per day. Three of the other four buildings had very little insulation in the ceiling/attic spaces. This insulation deficit tends to cause a sharp (solar radiation induced) spike in cooling load during the hot hours of the day. Transport of heat from the hot attic/ceiling space operates in parallel to the conductive heat transfer through the poor insulation. Therefore, addition of insulation in these buildings may have produced both substantial energy savings and demand savings. The fifth is the court office (building #46). We cannot identify reason why energy and demand savings did not occur.

5.8 Energy Savings and Peak Demand Savings Conclusions

Repair of uncontrolled air flow in 19 buildings produced cooling energy savings of 14.7%. It is estimated that better diagnosis and more complete repair would yield 25% cooling energy savings. The average cost of repair was $454. Average daily cooling energy savings were 12.4 kWh per day. Projected annual savings, excluding the heating season, were $182. The energy savings pay for the repairs in 2.5 years.

Peak electrical demand savings from uncontrolled air flow repairs in 18 buildings produced peak demand savings of 9.4% or 0.71 kW. Based on an estimated $700 cost of bringing new generation capacity on line, the average retrofit (cost = $454) displaces the need for about $500 in new capacity.

When energy and demand savings are considered together, the cost benefits of uncontrolled air flow retrofits are extremely promising. If, for example, a utility were willing to pay half the cost of the retrofit ($227), then the utility would in essence be getting new system capacity at a cost of $320/kW and the customer would be obtaining $182/year energy savings which provides a 1.2 year simple payback. Add to this possible comfort and indoor air quality benefits, such a program is a win-win situation for all parties.

6. CHARACTERISTICS OF A GOOD BUILDING

Virtually all commercial buildings have air flow control problems. In this sample of 70 small commercial buildings, only one building was identified as a "good building", in which there was essentially no uncontrolled air flow. A good building is hard to find!

6.1 A Good Hardware Store

The one building examined in this study that had good control of air flow was a hardware store. What made this a good building? This two-year old, 4600 square foot hardware store had essentially no duct leakage. It is, perhaps, no coincidence that the HVAC contractor that installed the space conditioning system had been through the Florida Solar Energy Center duct repair school. All the ductwork was assembled with mastic and embedded fabric. A building cavity, an enclosed support platform, was used as the return ductwork, but it was carefully isolated from wall cavities which could cause it to leak from outdoors or attic. While duct CFM25 was a fairly large 422, virtually all of this was leakage from the return plenum and air handlers to the conditioned space. The lack of duct leakage is confirmed by the fact that return leak fraction was 0.0% and infiltration went from only 0.15 ach to 0.19 ach when the air handler was turned on.

Pressure pan tests were done, also confirming duct tightness. When the building was at -50 pascals (wrt outdoors), delta-pressure across the pan was on the order of 0.3 pascals for nearly all the registers, indicating that there was virtually no duct leakage. (See Section 3.6.2 for an explanation of the pressure pan test.)

In fact, the only serious problem noted was that building ventilation was too small. Even if there were no significant pollutant sources, additional ventilation would still be needed; either 0.35 ach or 20 cfm per person, which ever is greater. Since containers of pesticides, chemicals, and other products are sold in the store and emit contaminants into the air, even higher levels of ventilation are required.

The interior was almost completely open, except for two small office spaces and two bathrooms. Therefore, there is almost no pressure imbalance due to closed doors. The building shell is quite airtight, with ACH50 of 4.3. It is tight because it has a concrete slab floor, concrete block walls with stucco exterior, and a gypsum board ceiling. The same construction with a t-bar ceiling (and vented attic) might have been ACH50 of 15 or more. Insulation in the attic space is located on top of the gypsum board, so the primary air and thermal barriers are in the same plane.

What are the characteristics of a good building? How can we design and build a good building? Following is our best assessment of how to achieve a good building.

6.2 Criteria for a good building

Uncontrolled air flow can have serious negative consequences in buildings. These consequences can include too much or too little ventilation, too high or too low humidity, occupant thermal discomfort, elevated energy use, damage to building materials, microbial growth, backdrafting of combustion equipment, transport of pollutants, and indoor air quality problems. Therefore, it is important to design, build, commission, and maintain buildings so that air flows are under control. How can this be done?

6.2.1 Tight ducts

Ducts should be airtight, especially those located outside either the building air barrier or the building thermal barrier, or which can draw air from outside those barriers. SMACNA (Sheet Metal and Air Conditioning Contractors National Association) has developed a duct leakage classification chart (Figure 6.1). Class 6 ductwork (which can apply to sealed metal ductwork, ductboard ducts, and flex ducts) is rated to leak at 1.2 cfm per 100 square feet of duct surface area when depressurized to -25 pascals (this can also be stated as 1.2 CFM25). By contrast, the air distribution systems measured in this project had leakage of about 80 CFM25 per 100 square feet, or 70 times more leakage than expected by the standard. Based on work being done in North Carolina, the SMACNA duct tightness standards can be achieved when contractors receive training and feedback.

In general, building cavities should not be used as ducts, unless provisions are made to ensure that these cavities are quite airtight to outdoors or that pressure differentials between that building cavity and outdoors is small. In general, building cavities are quite leaky, so connecting them to the pressures induced by the air handler blower generally produces substantial air leakage. If special measures are taken to airtighten the building cavity, then major leakage can be avoided.

Building cavities may also be used as ducts without significant penalty, even if they are moderately leaky, if they operate at approximately neutral pressure with respect to outdoors. Consider the example of building number 6. Building airtightness of 3.7 ACH50 and outdoor air of 870 cfm produces positive pressure in the building of +4.2 pascals. The ceiling space of the first floor is used as a return plenum, and it is depressurized to -1.0 pascals with respect to the occupied space. Therefore, the ceiling space is at +3.2 pascals with respect to outdoors. Or consider building number 17, a special education school. It has a similar situation where the occupied space operates at +2.0 pascals wrt outdoors while the ceiling return plenum operates at +1.2 pascals wrt outdoors. Though this 16,700 square foot plenum has leakage equal to 8234 CFM25, it experiences relatively little leakage because it is under only small pressure. In fact, because it is at a smaller absolute pressure than the occupied space, it leaks less than if it were not a plenum.

In general, ceiling spaces may be used as return plenums without serious penalty if the roof deck is fairly airtight and has a good thermal barrier, and the pressure in the plenum is designed to be small in absolute terms with respect to outdoors.

In general, all other types of building cavities used as ducts or plenums may create substantial problems, primarily because these cavities often operate at significant depressurization. When mechanical rooms or mechanical closets are used as return plenums, that space is often seriously depressurized (on the order of -10 pascals to -40 pascals). This can cause several types of problems, including drawing air in from outdoors or an attic space, drawing radon from the ground below the slab, drawing sewer gases from drain lines, and drawing humid outdoor air into wall cavities where moisture accumulation may occur. Walls, chases, or shafts used as ducts can cause air to drawn in from outdoors or from the attic space. Panned floor joists, though not common in Florida commercial buildings, can draw contaminated air (radon, pesticides, and high humidity air) into the building from the crawl space.

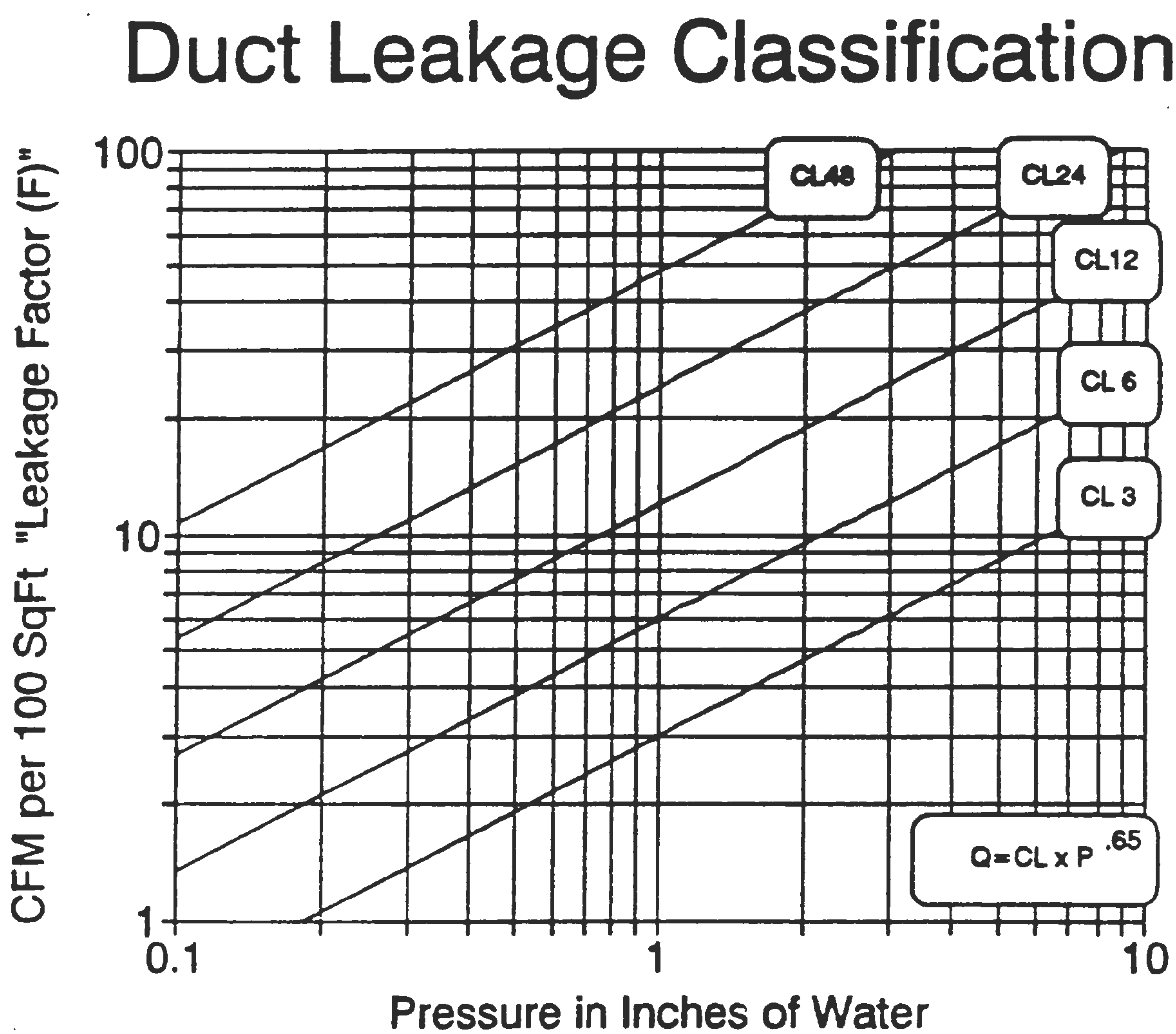


Figure 6.1 SMACNA Duct Leakage Classification Chart. (Adapted from HVAC "Air Duct Leakage Test Manual," 1st Edition, 1985, with permission of SMACNA, Sheet Metal and Air Conditioning Contractors National Association.

6.2.2 Tight building envelope

Building envelopes should be reasonably airtight. As indicated previously, many commercial buildings are very leaky, and the majority of the leakage in most cases is in the ceiling/attic/roof assembly. Because suspended t-bar ceilings are leaky, it is the airtightness of the ceiling space or attic space to outdoors that determines, to a large extent, what the overall building airtightness will be. Since most commercial buildings use suspended t-bar ceilings, and will probably continue to do so, because of cost, flexibility, and accessibility factors, the best solution is to make the roof deck the primary air barrier. This means that the roof deck should not be ventilated and the wall above the ceiling should not be vented, either intentionally or unintentionally. It should be noted that installation of insulation batts in the vertical plane between the ceiling space and soffitted eave space does not constitute an air barrier. Though the backing on the insulation batts is airtight, batts are not installed in a manner that achieves a continuous air barrier.

The combination of an attic space and suspended t-bar ceiling creates the potential for an energy disaster, especially when driving forces exist to move air from the hot attic space into the occupied space. Since attics are ventilated and the ceiling is very leaky, the ceiling/roof plane of the building is very leaky. Even if the remainder of the building is very airtight, this combination produces a very leaky building. One solution would be installation of insulation at the roof deck and eliminating the attic ventilation. In this way the attic space would be inside the air and thermal barriers of the building, and would remain cool and dry.

6.2.3 Thermal barrier at air barrier

In many commercial buildings, the thermal barrier is not located at the primary air barrier. As a consequence, either naturally or mechanically driven air flow may occur through or around the insulation system. To achieve good energy efficiency, a good building should have the air barrier and thermal barrier located in the same plane. In most commercial buildings, this would mean the roof deck will be the air barrier (no venting of the ceiling space) and the insulation will be integral to the roof construction or attached to the bottom of the roof deck. If the air barrier is at the roof and the thermal barrier is at the ceiling tiles or attached to the bottom of the roof trusses (suspended or "floating"), then the ceiling space will be hot and dry. If the air barrier is at the ceiling and the thermal barrier is located at the roof deck, the ceiling will be warm and humid. Air leakage from the ceiling/attic space to the occupied space will have undesirable impacts.

If the ceiling space or attic space is enclosed within both the air and thermal barriers of the building, then this space will remain cool and dry. This has important implications for many forms of uncontrolled air flow. Duct leakage that occurs to and from this space will cause minimal energy penalties. When interior doors are closed (with central returns), air drawn into the occupied space by depressurization of the central zone will draw air from a cool and dry space and thus cause minimal energy penalties. Depressurization of the occupied space by the operation of exhaust fans will draw air from a cool and dry space rather than a hot and humid space and thus cause minimal energy penalties.

6.2.4 Balanced return air

Adequate return air pathways should be provided. Without adequate return air pathways, air flow and pressure imbalances can result and cause comfort, energy, demand, moisture, and air quality problems.

Providing adequate return air pathways can mean several things. 1) If return ducts are run to the individual rooms or zones which can be closed off from other portions of the building, the returns should be sized to approximately match the supply air to that space. 2) If returns are not provided to individual rooms or zones which can be closed off from other portions of the building, then pathways need to be provided for return air to get back to the central return location(s). These pathways can be transfers through the wall, through the door, or a transfer duct between two ceiling registers. 3) If a ceiling space is used as a return plenum and fire walls subdivide the plenum, then properly sized "cross-over windows" need to be provided in the fire walls (with fire dampers) in order to allow the passage of return air and avoid pressure imbalance. A pressure differential across fire walls of 1 pascal would seem to be a reasonable target for avoiding excessive pressures and infiltration.

6.2.5 Balancing exhaust and intake air flows

Exhaust and intake air flows should be balanced so that buildings operate at positive (or at least neutral) pressure, especially in hot and humid climates. An important first step in achieving air flow balance is sizing exhaust fans so they are no larger than needed. Another way to achieve downsizing is targeted ventilation -- spot ventilation (locating the exhaust fans right at the source that is to be removed from the building) or source containment ventilation (enclosing the space where the source is located, and then exhausting that zone). Another sizing strategy is use of multiple speed fans that can be set to a lower setting when full exhaust is not needed.

When large exhaust fans operate in buildings, make-up air or outdoor air should be provided, otherwise the building will operate at negative pressure. Negative pressure can draw dust and pollutants into buildings, draw untreated humid air into the building general, draw humid air into building cavities (especially wall cavities) where moisture accumulation can occur on cool surfaces, and cause backdrafting of combustion equipment. Providing mechanically induced intake air can alleviate these problems. Providing intake air by means of **make-up air** (especially when the make-up air is not conditioned) can dramatically reduce cooling/heating energy consumption and greatly reduce the building ventilation rate. Providing intake air by means of **outdoor air** allows filtering and dehumidifying (or humidifying during dry conditions) the air before it enters the building. Both methods can alleviate the negative pressure, moisture problems, and indoor air quality consequences. Make-up air, however, where it can be used, has the advantage of greatly reducing building ventilation rates, downsizing of cooling/heating equipment, and large energy and demand savings.

An important aspect of balancing exhaust and intake air flows is control over the exhaust fans and control over the intake fans. Exhaust fans should be designed so they operate only when needed. Unless the exhaust fan operation is needed all the time, it should be controlled so it operates only when needed. Options for control include timers that activate the fans only during portions of the day; on/off switches under the control of the occupants; sensors that activate the fans in response to some other equipment or activity occurring; sensors that detect levels of humidity, carbon dioxide, or other substance; or occupancy sensors with timed delay.

Control of intake air is also important. Make-up air fans are usually interlocked with the exhaust fan control, so they operate whenever the exhaust fans operate. This ensures proper exhaust/intake balance. Outdoor air is not so reliable. In many cases, the air handlers cycle on and off in response to building cooling/heating loads, and thus outdoor air cycles on and off as well. In other cases, the air handlers are variable air volume (VAV). Air handler and outdoor air flow rates vary according to load and building thermostat schedule. In either case, outdoor air can vary and therefore building pressure and air flow balance can vary.

If outdoor air is to be used to balance exhaust air flow, consider the following. It is generally not a good idea to operate the air handler blower continuously, for several reasons. First, it uses considerable fan power. Second, duct air leakage and conduction heat gains (losses) can add considerably to cooling/heating loads and draw considerable humidity into the building (humid climates). Third, continuous fan operation causes re-evaporation of moisture from the cooling coil and drain pan, causing considerable reduction in cooling system dehumidification performance. This last point can be very important, since high humidity can lead to severe building and air quality problems.

We suggest that the best solution for using outdoor air to balance exhaust air flow is to remove the "V" from HVAC. That is, provide ventilation through a separate system that is not used for normal heating and cooling of the space. A dedicated space conditioning unit can be used to provide continuous outdoor air. It would cool/dehumidify or heat the incoming air, but would operate in response to operation of the exhaust fans.

If this approach is not used, a two-stage cooling system can be used. This could involve designating one of the cooling systems to be the first stage unit. It would have a large outdoor air fraction (perhaps 35% or more) and would operate at a lower temperature setting (cooling mode) than the other units, so it would be operating virtually all the time. The other cooling units would not have outdoor air and would "cycle on" depending upon the need for additional cooling. This can also be achieved by use of two-stage air conditioning systems, where the air handler operates whether one or two compressors are running.

Be aware of the interacting relationships between attic exhaust fans and building ventilation rates, energy consumption, comfort, humidity, and pressure. As was noted in Realty 2 (building #37), an attic exhaust fan can depressurize not only the attic but the entire building, especially in cases where the ceiling is suspended t-bar. This space depressurization can lead to excessive ventilation rates, high relative humidity (humid summer weather), low relative humidity (winter weather), moisture problems in building cavities, increased space conditioning energy use, and combustion safety problems.

6.2.6 Effective test and balance

The probability of obtaining a good building is increased if commissioning is implemented. Test and Balance (TAB) is a form of commissioning of the HVAC systems. There are problems with standard TAB practice, as discussed in section 4.12, including errors in air flow measurement, not taking duct leakage into account when determining the building air flow balance, and not assessing and correcting some return air flow imbalance problems (especially those related to centralized returns and firewalls in ceiling plenums). Good TAB practice should be aware of the limitations of air flow measurements, evaluate and correct return air problems, and check building and zone pressure relationships with digital micromanometers (preferably with time averaging capabilities).

6.2.7 Maintenance requirements

A good building will only remain a good building if operated and maintained properly. Note that this is a big issue in most building -- filters, coils, condensate drain lines, etc. in a large majority of commercial buildings are not well maintained. Dirty filters can reduce system efficiencies, reduce air flow rates, create building air flow imbalance, and increase duct leakage. Improperly sized filters can cause dirt by-pass. Dirty coils can reduce system air flow rates, efficiency, and capacity. Poorly designed, damaged, or missing condensate traps can lead to re-entrainment of moisture back into the conditioned space. This can lead to high relative humidity, dampness in duct systems, and microbial growth that can cause indoor air quality complaints.

To achieve good operation and maintenance practice, operations and maintenance documents and training should be provided to facilities maintenance personnel.

To assist facilities managers and HVAC contractors in assessing the performance of HVAC systems, various types of low-cost monitoring equipment could be installed in new buildings to enhance both maintenance and trouble-shooting. These can include temperature probes in return and supply ducts, zone humidity sensors, carbon dioxide sensors (to indicate relative ventilation rates), and zone pressures.

6.2.8 Balanced air flow in modified buildings

If buildings are modified, air flow imbalance may result. These modifications can include change-out of HVAC equipment which can lead to changes in air flow rates, outdoor air damper settings, and air flow resistance of filtration. Building modifications, such as erecting or moving interior walls, can cause restrictions to return air flow, returns being in the wrong zone, pressure imbalance, and thermostats being located outside of that cooling zone. There are an almost infinite number of ways that a building or HVAC system can be modified, and in many cases the modifications create uncontrolled air flow.

Some provision needs to be made for commissioning modifications. Just as a new building needs commissioning, modifications to buildings need a process for assuring that air flows are under control. Therefore, building modification plans need a TAB specification, and facilities managers need to be trained to oversee the TAB process and be familiar with any air flow changes that result.

7. RECOMMENDATIONS FOR IMPLEMENTATION OF PROJECT FINDINGS

A contract deliverable is to "work closely with the advisory group in developing a marketing and implementation plan," (project contract). Section 7 of this report, then, is the resulting implementation plan. This plan is based on the experience of the research team and advice from the advisory committee.

Where do we go from here? What should be done with the information gained in this project? We suggest three pathways: 1) development of technology transfer materials, 2) additional research, and 3) development of standards related to uncontrolled air flow.

7.1 Technology Transfer

With regard to technology transfer, much has been learned in this project, and therefore there is much that needs to be communicated to those involved in designing, building, commissioning, operating, maintaining, diagnosing, and repairing commercial buildings.

We propose, therefore, that a training and technology infrastructure be developed. This effort would include the following:

7.1.1 Develop protocols and additional testing methods

In this project, protocols were developed to identify and quantify uncontrolled air flows, building and distribution system airtightness, and pressure differentials. Also incorporated and developed were testing methods which can accurately and comprehensively characterize air flows, airtightness, and pressure differentials. These test protocols and test methods have been employed in a research manner to gain a comprehensive picture of what is going on in buildings. It is necessary to identify protocols and test methods that work from a field diagnostics point of view. The basic issue is, how can we accurately and quickly come to an understanding of what is going on and specifically what is going wrong in this building, so that a diagnosis of what is wrong and what to do can be made? A diagnostic protocol will almost certainly be less extensive than the research protocols that were used in this project.

7.1.2 Develop materials that can be used in training

Training manuals for improved design and construction of <u>new buildings</u> should be produced. Training manuals for diagnosis and repair of uncontrolled air flow in <u>existing buildings</u> should be produced. Visual presentation materials, such as diagrams, slides, and overhead transparencies, should be developed. Over 800 slides and several hours of hi-8 video were taken during the project and they can be developed into standard presentation packages. Additionally, the airtightness, air flow, and pressure differential interactions which occur in commercial buildings can be very effectively demonstrated using table-top and even larger scale models. A number of different models should be developed illustrating various building construction configurations and the air barrier and thermal barrier permutations which can exist in real buildings. These models make excellent classroom demonstration tools and can also be used effectively in air flow and pressure diagnostic labs.

More advanced training materials could also be developed on video tape or on interactive computer technology.

7.1.3 Develop curriculum and training courses

Various types of course curriculum could be developed, covering various topics of the uncontrolled air flow issue and addressed to the various groups, including engineers, architects, builders, HVAC contractors, consultants, IAQ specialists, utility personnel, and government agency staff. A range of training seminars could be offered in Florida and around the country. More extensive training (perhaps two weeks in length) could be developed and offered in several locations around the country.

The monetary cost of energy waste, indoor air quality problems, sick buildings, lawsuits, vacated buildings, and reduced worker productivity in this country is staggering, probably running into the 10's of billions of dollars per year. There is a strong need for large numbers of well trained, qualified building scientists to design new buildings that work well and diagnose and repair problems that occur in existing buildings. At this time, there are only a small number of persons around the country who understand the complex interactions of building airtightness, pressure differentials, air flows, moisture transport and accumulation, air contaminant transport and sources, and understand building systems, construction, and materials well enough to make effective diagnoses. Therefore, it would be of great benefit to implement comprehensive training programs that could produce a cadre of well equipped building scientists.

Several approaches could be taken. A variety of short-courses could be developed to satisfy continuing education requirements for trade groups, professional groups, and others responsible for buildings including code officials, facilities managers, indoor air quality specialists. These can be offered in various cities around Florida and the nation. Another approach would be to incorporate the emerging knowledge and tools of applied building science into trade, technical, and professional training programs. A third approach would be to develop extended training/retraining programs for persons for persons looking for new careers, such as those displaced from their jobs as a result of industrial and military downsizing. Such programs could run for say six months and provide comprehensive building science training. The result would be high quality jobs that would benefit the individual graduates and society.

7.1.4 Papers, seminars, and conferences

Information, test methods, and protocols developed in this project can also be disseminated to researchers, practitioners, and others in the building science community by means of publishing papers, developing and holding seminars around the state and the country, and developing and hosting conferences.

7.1.5 A proposal has been developed

In response to the need for technology transfer of the information and skills developed in this project, a proposal has been produced to develop an uncontrolled air flow technology transfer program. This proposal is included in Appendix C.

7.2 Additional research is needed

With regard to research, the work done in this project has uncovered many valuable insights into the way commercial buildings operate and how they can be improved. There are, however, many issues which need further investigation, including more field research, more controlled laboratory-type work (side-by-side buildings, for example, which can modified to study energy and moisture impacts of parametric analysis), and computer model verification and simulation work. Following are areas requiring further investigation.

7.2.1 Energy impacts of uncontrolled air flow

In this project, uncontrolled air flow was repaired in 20 buildings. Energy savings and peak demand savings were monitored. However, there are a great many variables which determine the level of energy waste that results from various forms of UAF, and questions remain.

WHAT IS THE ENERGY PENALTY IF:

1. The ducts leak but are in the occupied space?
2. The ducts leak but are located in a ceiling space used as a return plenum?
3. The ducts leak but are located in a ceiling space which is inside the primary air and thermal barrier of the building?
4. The ducts leak but are located in a ceiling space that is inside the primary air barrier but outside the primary thermal barrier of the building?
5. The ducts leak but are located in a ceiling space that is outside both the primary air and primary thermal barriers of the building?
6. The ducts leak but are located in a vented attic space?
7. Exhaust fans depressurize a building and draw air from a ceiling space that is outside the building thermal barrier?
8. Exhaust fans depressurize a building and draw air from a ceiling space that is outside the building air and thermal barriers?
9. Exhaust fans depressurize a building and draw air from a vented attic space when the ceiling is suspended t-bar?

WHAT ENERGY SAVINGS CAN RESULT FROM:

10. Providing make-up air in buildings, especially restaurants, depending upon the airtightness of the ceiling, the thermal conditions that exist in the space above the ceiling, and whether the building is brought to the point where it operates under positive pressure?
11. Providing improved return air pathways, either by providing return air transfers or improved return cross-over windows through fire walls?
12. Changing the pressure in ceiling return plenums?

The monitoring of 20 buildings in this project begins to answer some of these questions. However, because commercial buildings have such a large number of permutations of air barrier and thermal barrier locations, duct locations, exhaust fan sizes, and return air imbalance problems, much more investigation is needed before the energy consequences of UAF and repair of UAF can be fully understood. In addition to field investigations, lab investigations and computer modelling should be done to be able to look at the many permutations.

7.2.2 Exhaust fans

The impacts and interactions of exhaust fans need to be further investigated. It appears that exhaust fans are oversized in some commercial buildings. In other buildings, some of the existing exhaust fans may not be needed. Research is needed to determine when and how much exhaust air is needed in various types of buildings.

Control strategies need to be examined. In some cases, exhaust fans operate 24 hours per day when only needed for a portion of the day. In other cases, they operate 10 or 14 hours per day, when a lesser number of hours might be appropriate. In other cases, a multiple speed fan might be practical depending upon variations in activities (i.e., cooking, showering). Improved control strategies could be developed that cause the exhaust systems to better respond to actual ventilation need.

Make-up air needs to be better understood and implemented by designers and contractors. Methods for injecting the make-up air into the building to minimize energy use, occupant discomfort, and HVAC equipment size need development and dissemination. Issues of when make-up air should be conditioned, or not, need to be further investigated. Some restaurants condition their make-up air while others do not. Obviously, if make-up air can be designed to work well without being conditioned, potential energy savings can be great.

We need to investigate how to get buildings to positive pressure. This is especially important in hot and humid climates, where moisture accumulation in building materials and high relative humidities are often large problems. (Note that in cold climates, positive pressure can lead to moisture problems.) Make-up air is usually sized at only 50% to 70% or so of the exhaust air flow rate. So additional intake air is needed. This can be provided by outdoor air. But there can be problems if the air handlers do not operate continuously (cycle according to load), since the outdoor air only operates when the air handler is running. In other cases, the air handlers are VAV and the outdoor air is variable as well. As a consequence, intake air may be sufficient only a portion of the time. Keeping the air handler running continuously can create problems as well, including considerable additional fan energy use, duct leak and conduction energy losses, and poor dehumidification performance of the AC unit. (Cummings et al., 1995).

Research effort should go into building designs that allow improved pressure control within the building (building airtightness and air flow balance) and within specific zones of the building (distribution balance) and which can concentrate ventilation in zones that have the greatest source control requirements. There is potential for considerable energy savings and improvement to indoor air quality through enclosing zones of the building which have the greatest air contaminant sources and developing spot ventilation for those sources. This could apply to heat, humidity, combustion gases, odors, volatile organic compounds, and other contaminants in restaurants, sports facilities, and light industrial buildings. There is need to develop building design criteria to allow differential control of pressure within and between specific zones of the buildings, such as depressurizing bathrooms, kitchens, industrial production areas while the building operates at positive pressure with respect to outdoors.

7.2.3 Return air design

Return design problems are one of the most common forms of UAF. It is common for return grills to be centrally located and closed interior doors to block return air. Serious pressure imbalances often result. It also occurs that main returns are located in closable rooms. Even more serious pressures are likely to result from this HVAC configuration. It is common for firewalls to restrict return air flow because of missing, undersized, or blocked return crossover windows. Serious air flow and pressure imbalances can result.

There is need to develop improved **methods** for providing return air. There is need to develop **standards** for good return air practice. And there is need for improved **test and balance procedures** to ensure that return air and pressure differential imbalances do not exist in buildings.

7.2.4 Duct repair

Duct repair methods and materials standards are being developed for residential buildings, through utility repair programs, state energy and building code offices, Underwriters Laboratories, trade associations, and through independent training programs. A similar effort is needed for commercial buildings. While there are similarities between residential and commercial duct systems, there are significant differences as well. Guidelines should also be developed regarding which ducts should be repaired; those in the conditioned space, those located in ceiling return plenums, those inside both the air and thermal barrier, those inside the air barrier but outside the thermal barrier, those located in ceilings spaces that are outside the air and thermal barriers, and those located in attics. It may make sense to set different duct airtightness standards for ducts in different thermal environments.

There area also differences of application. In residences, ducts are often in attics, crawl spaces, or basements. In each of these locations, persons can typically move around and make repairs. In commercial buildings, ducts are most often located in a ceiling space and the only access is through the ceiling tiles. This requires moving about on a ladder or mobile platform and may be more difficult than the same work in residences. The ducts may also be more often externally insulated which may make for more difficult repair. Work needs to be done to develop efficient and effective repair methodologies and technologies for commercial buildings.

Currently, duct airtightness testing with duct test rigs is quite accurate but also very time consuming. Alternative methods which use pressure differential, such as the pressure pan and blocked-return building pressure methods, cannot be consistently used in commercial buildings because ducts are often located within the primary building air barrier (but may be outside the primary thermal barrier). Additional work needs to be done to develop diagnostic methods and test methods for determining duct system leakage and identifying when ducts should be repaired.

7.2.5 Commissioning

Various methods have been used over the years to commission buildings. These include the code inspections process and Test and Balance. More recently, moves are underway to rate the energy efficiency of new and existing buildings. Various HERS (home energy rating system) and BERS (building energy rating system) programs are under development across the United States, including in Florida. Perhaps no other part of the building commissioning or rating process is more important than testing for proper control of air flows and pressures.

In order for Test and Balance and BERS programs to be effective, these programs need to take into account the full range of uncontrolled air flow issues identified in this project. Some of the problems related to Test and Balance identified in section 4.12 of this report need to be addressed. Persons involved in TAB need additional training to be able to understand the complex building system interactions which occur in buildings and which result in UAF. Standard methods for TAB work need to be examined and perhaps modified.

The same applies to BERS programs. They must incorporate an understanding of UAF. They must include appropriate test methods so that air flow and pressure differentials may be accurately characterized. And again, training programs for building testers and raters must include the basics of building science so that practitioners can understand what is occurring in buildings and why, and recognize the patterns and causes of building failure modes.

An ideal "best practice" inspection/commissioning process should be developed, including pressure mapping, airtightness testing, and air flow measurement. This standard can become the basis from which various forms of building commissioning practice can derive their own diagnostic procedures.

The code inspection standards and process should be examined in light of uncontrolled air flow. The issues of how to inspect for appropriate compliance with UAF portions of buildings codes when the mechanical systems are not yet powered needs to be examined. Training seminars and courses should be provided to building inspectors on the types and nature of UAF and methods for identifying unbalanced air flows and pressures.

Finally, the commissioning process should not be concluded without education and documentation. By this we mean, facilities managers should be trained in the use and maintenance of their buildings. An "owners manual" should be developed for each building and given to the building facility manager and to all future facility managers, to assist them in understanding how to properly run and maintain their facilities.

7.2.6 Building airtightness

One of the largest sources of uncontrolled air flow in commercial buildings is a leaky envelope. Most specifically, the ceilings of small commercial buildings are very leaky.

Research needs to done to characterize the energy savings that result from making leaky commercial buildings more airtight, in various climates. In this project, building envelope airtightening was done in several buildings but these retrofits were done in conjunction with other forms of UAF repair as well. No clear indication of energy savings from building tightening exists.

Energy savings depend upon climate and the "climate" inside buffer zones (attics, crawl spaces, etc.) where UAF may originate. The energy impacts of UAF, therefore, should be evaluated under a full range of climates, building designs, and pressure differential configurations.

Research should be done on various types of ceiling systems, to characterize their potential airtightness and thermal characteristics. Light fixtures, ceiling mounted speakers, and other ceiling penetrations should be evaluated in order to understand the source (causes) of ceiling leakiness and how to make them more airtight. New ceiling tiles, t-bar support framework, and gasketting options can be investigated to determine ways to make ceilings more airtight.

Research should also be done to determine when and in what climates, if ever, ceiling spaces or attic spaces located above commercial buildings should be ventilated. Best practice for making commercial building airtight might be to make to the roof deck/ceiling space airtight to outdoors, locate the insulation system at the roof deck, and then not worry that the ceiling is not particularly airtight.

Research should also focus on the fact that when buildings are made quite airtight, there may be unwanted consequences in lowered ventilation and pressure imbalances. Tight buildings will need greater amounts of mechanically provided ventilation air. However, the mechanically induced ventilation will, in turn, produce greater pressure differentials than would occur in a leaky building. Investigation should take place to develop guidelines for building airtightness; how tight is too tight? Small imbalances in air flow in tight buildings can produce large pressure imbalances which in turn can lead to moisture accumulation problems, mining of pollutants, combustion safety problems, and indoor air quality problems. Therefore, in the process of making commercial buildings tighter, it will be important to develop the means and guidelines to maintain acceptable pressure differentials in buildings.

7.2.7 Improved insulation systems in commercial buildings

As indicated in section 4.8, there are a number of problems with ceiling/roof insulation. UAF can flow through insulation located on top of ceiling tiles as a result of exhaust fans, duct leaks, restricted return air through fire walls, or closed interior doors. Insulation batts located on ceiling tiles are often thrown or pushed aside when persons access the ceiling space, leaving voids. Insulation may be attached to the bottom of trusses and it is common for these batts to have partially (or even completely) fallen onto the ceiling. Insulation may be located at the roof deck, but the ceiling space is vented to outdoors. In these cases, the insulation may stop significant heat conduction, but ventilation transported heat (or cold) by-passes the thermal barrier.

Research needs to be done to characterize the energy penalties associated with different insulation failure modes and the commensurate energy savings which result from setting it right. Development work needs to be done to determine the best new construction insulation practices. Work also needs to be done to develop cost-effective retrofit measures and good installation practice.

7.2.8 Development of "best practice" commercial building construction

In this project, a number of building failure modes related to air flows, pressure differentials, building airtightness, duct airtightness, and insulation have been identified. Based on this understanding, some elements of "best practice" have been developed. (See section 6.)

However, considerable additional work is required to determine the best ways to design and construct buildings that work in an optimal manner in terms of energy, comfort, and health. Some of the best practices will come out of the research work indicated in 7.2.1 - 7.2.7. The issues will not be only "make the building tight", but how to make the building tight. Not only "operate the building at positive pressure", but methods to achieve balanced air flow and pressure, and how to keep it there. Not only that "HVAC systems should be controlled to minimize energy use, optimize ventilation, and achieve comfort", but how this should be done. Not only "provide adequate ventilation", but how to optimize spot ventilation to remove sources and general ventilation to provide outdoor air to occupants.

A set of guidelines for "best practice" commercial buildings construction will be useful in many ways. It can be incorporated into existing architectural and engineering degree programs. It can be taught in seminars, conferences, and training programs. Test and balance practice can incorporate an understanding of best practice in their training and as a standard to which they will strive to attain when testing and balancing a building.

7.3 Development of standards related to uncontrolled air flow

Best practice needs to be converted to standards. These standards could be basis for code officials to make buildings inspections. These standards could be the basis for test and balance practice, both conceptual and measurement methods. These standards could be the basis for building energy rating system (BERS) programs.

Standards also need to be set for duct fabrication methods and materials and duct repair methods and materials. Standards also need to be developed for best diagnostic test methodologies; how to measure duct airtightness, how to measure building airtightness, how to identify the primary building air barriers, how to evaluate the effectiveness of insulation systems, how to check combustion system safety, and how to measure air flow and pressure dynamics in buildings that employ VAV systems.

State and national building, energy, and air quality codes should be reviewed and perhaps modified to take into account uncontrolled air flow. For example, state radon construction codes will need to consider the variety of pressure differential, contaminant transport, and contaminant mining factors which can result from uncontrolled air flow in buildings.

8. CONCLUSIONS

Going into this project, it was anticipated that considerable uncontrolled air flow would be found in small commercial buildings. What was found -- the extent and variety of building failures related to duct leakage, return air restrictions, barriers to air flow within HVAC systems and buildings, and exhaust/intake air imbalance -- is remarkable. While driving forces (large air moving systems) and barriers (obstructions to air flow) create most of the uncontrolled air flows, a rather major finding of this project is that the building shell of a large majority of small commercial buildings is very leaky. A significant minority of these building are very airtight (ACH50 less than 5), but the greatest majority are quite loose, with ACH50 greater than 20. And the source of this building leakiness is suspended t-bar ceilings.

About 80% of the tested buildings have t-bar ceilings and these ceilings are on the order of 10 times more leaky than typical gypsum board ceilings. Since the ceilings of small commercial buildings are almost always very leaky, the airtightness of the overall building hinges upon how airtight the space above the ceiling is to outdoors.

8.1 Uncontrolled Air Flow is Greater in Commercial Buildings Than in Residences

The magnitude of uncontrolled air flow in commercial buildings is greater, in general, than that found in residences. Residences have substantial duct leakage but duct leaks in commercial buildings are about three times larger (per 1000 square feet). Residences have air flow and pressure imbalances related to closed interior doors, but commercial buildings have this problem as well, and with leaky ceilings, the amount of attic or ceiling space air drawn in by this imbalance is potentially much greater in commercial buildings. Additionally, in larger commercial buildings, fire walls separate zones of the building and commonly restrict return air flow through the ceiling return plenum creating imbalances. Residences have exhaust fans, but these are usually fairly small and operate only intermittently. By contrast, in many commercial buildings, exhaust fans are considerably larger and typically operate more continuously.

In general, these 70 commercial buildings experienced greater pressure differentials, both positive and negative, than residences under normal operating conditions. Seventeen of 70 buildings experienced pressures of greater than +3 pascals or -3 pascals. There is a significant bias toward negative pressure. Thirty-six of the 70 buildings operated at negative pressure (air handler on and exhaust fans in normal operating mode) while only 27 registered positive pressure when measured (seven were at neutral pressure). On average, these 70 buildings operated at -1.1 pascals with respect to outdoors.

Two other types of HVAC air flows exist in small commercial buildings which are not normally found in residences, outdoor air and make-up air. Twenty-nine of the commercial buildings in this study have outdoor air to provide ventilation. Five of the commercial buildings in this study, all restaurants, have make-up air to provide air flow balance to large exhaust fans.

The size of HVAC equipment is much larger in commercial buildings, compared to residences, even normalizing for building size. Air conditioning systems average 3.38 tons per 1000 square feet in this sample of small commercial buildings compared to about 1.8 tons per 1000 square feet in residences. Exhaust fans, especially in restaurants, hotels, and sports facilities, tend to be much larger than in residences.

Commercial buildings HVAC systems tend to operate a greater proportion of the time, at least during occupied hours. In some small commercial buildings, the air handlers run continuously even when the compressor cycles off. Exhaust fans tend to operate more continuously. In summary, small commercial buildings have more HVAC equipment, larger HVAC equipment, larger air flows, and more continuous operation. As a consequence, the drivers of uncontrolled air flow are greater than are found in residences.

Commercial buildings are generally larger than residences, and sometimes they are more complex. Complexity is the more important factor in understanding uncontrolled air flow. Many small commercial buildings are fairly simple in terms of the interior layout (one story, open spaces, and doorways that remain open much of the time). In others, however, there are greater numbers of subdivisions within the building, created by walls, firewalls, and multiple stories. HVAC systems that move air across the boundaries between those subdivisions can create pressure imbalances, beyond what would normally be found in residences.

8.2 Knowledge of Uncontrolled Air Flow Needs to be Transferred

Therefore, a greater level of understanding is required to design, build, commission, maintain, and diagnose buildings so that good air flow control is achieved. Degree programs in architecture and mechanical engineering need to incorporate more information on control of air flows in buildings. HVAC and building contractors need more complete understanding of how to reduce leakage from the air distribution system, how to achieve good return air flow, and control strategies for exhaust and intake air systems. Test and balance methods and training need to be reviewed and perhaps modified to take uncontrolled air flow into account, including improved methods to assure that the building air flow balance is positive and that the building (all of it) operates at positive pressure. Facilities managers need better training on how their buildings work and how to properly maintain HVAC systems (including filters), and should be given "owners manuals" on how all the systems operate and how they should be maintained. Finally, those involved in diagnosing building systems, building degradation problems (especially moisture related), energy problems, and indoor air quality problems need training on uncontrolled air flow and how to use diagnostic methods and tools for determining the air flow and pressure balances within the building and with respect to outdoors.

8.3 Energy Consequences of Uncontrolled Air Flow Are Large

Energy penalties resulting from uncontrolled air flow can be substantial. Repairs of uncontrolled air flows in 20 small commercial buildings achieved 15% reduction in cooling energy use. Savings could have been greater if more complete repairs had been accomplished. Time and money constraints limited repairs in some buildings, and in other cases limited access time (sometimes repairs were not complete until 1 AM to accommodate business schedule) and diagnostic errors lead to incomplete repairs. If all the uncontrolled air flows in these 20 buildings had been corrected, we estimate that cooling energy savings may have reached 25%. A 25% reduction in energy use indicates that uncontrolled air flow is increasing cooling energy use by 33% compared to eliminating uncontrolled air flows.

8.4 Non-Energy Consequences May Be Larger

While energy waste is a major consequence of uncontrolled air flow, the non-energy consequences of building degradation and indoor air quality problems are substantially larger. A number of new buildings (less than one year) in this study had extensive mold/mildew growth on walls with sheetrock becoming soft. Other reports indicate that some hotels in Florida have had to have more than 50% of their sheetrock replaced even before opening because of moisture damage, much of it caused by uncontrolled air flow. A number of larger office buildings in Florida, including court houses, have had multi-million dollar retrofits designed to solve indoor air quality problems which appear to be linked to uncontrolled air flow.

Uncontrolled air flow can create an uncomfortable working environment for employees and customers. High temperatures in the entire building or zones of the building can result from uncontrolled air flow and lead to worker dissatisfaction and potentially reduced productivity. High humidity, which can result from excessive ventilation caused by various forms of uncontrolled air flow, can also lead to discomfort and reduced productivity. It can also affect building equipment, paper products, and lead to mold and mildew growth.

Indoor air quality and sick buildings can lead to large human and monetary consequences, much greater than those associated with energy or comfort. Uncontrolled air flow is clearly not the only cause of indoor air quality problems, but it may be a major cause or contributor, especially in hot and humid climates. It can lead to air quality problems by reducing ventilation rates for the building as a whole or zones of the building, by transporting contaminants from polluted zones, by mining of pollutants (from soil, sewers, and combustion equipment), or even by causing air pollution (especially moisture related). Poor air quality can lead to worker dissatisfaction and increased sick leave. Increased levels of complaints can lead to the label of "sick building", with increasing levels of worker anxiety and reduced productivity. Costs escalate even more when buildings must be evacuated, either temporarily or (almost) permanently, and when major lawsuits are brought.

8.5 Need for Training

Solving uncontrolled air flow problems requires training. Those who have had some role in creating these uncontrolled air flow problems -- architects, engineers, HVAC contractors, builders, test and balance firms, and facilities managers -- cannot be counted on to eliminate these problems without changes in their ways of thinking and doing things.

Several things can be done to get the word out to these people.

1. Develop training manuals
2. Develop other visual communication materials (slides, overhead transparencies, and video tapes)
3. Develop scale models (table-top or larger) which can be used to demonstrate uncontrolled air flow and pressure differentials, to implement training labs, and teach the use of some diagnostic tools and methods
4. Publish papers containing the findings of this uncontrolled air flow research
5. Hold short courses and seminars
6. Develop and hold conferences on uncontrolled air flow in buildings

7. Incorporate uncontrolled air flow understanding, diagnostic methods, and diagnostic tools into the curriculum of architecture and engineering degree programs, technical training degree programs, and continuing education programs.

A proposal incorporating the first six items on this list is contained in Appendix C.

Intensive and in-depth training programs were developed in Florida (six day course at the Florida Solar Energy Center) and North Carolina (10 day course at the North Carolina Alternative Energy Corporation) to train persons involved with diagnosis and repair of residential duct systems. The size and complexity of commercial buildings and number of different types of uncontrolled air flow in commercial buildings is considerably greater than that represented in residences. Therefore, the extent of training required for diagnosing and repairing uncontrolled air flow commercial buildings will need to be even greater.

8.6 Need for More Research

While this research project has been a good start to identifying and uncovering uncontrolled air flow in small commercial buildings, there is a great deal more to do. Following is a partial list.

1) Characterization of small commercial buildings in other parts of the country.
2) Identification of the consequences of uncontrolled air flow in different climates are two important tasks.
3) Gain a thorough understanding of the impacts of uncontrolled air flow on energy use. There are many forms of uncontrolled air flow and many different building configurations which determine the energy impact of those air flows. For example, energy savings from duct repair will depend upon whether the ducts are located within the conditioned space, outside the conditioned space but inside the air and thermal barriers of the building, outside the thermal barrier but inside the building air barrier, or outside both.
4) Develop optimal methods for repairing or correcting uncontrolled air flows.
5) Develop methods to best provide intake air to provide balance to exhaust systems, and architectural designs which allow containment of pollution sources and improved spot removal.
6) Develop improved methods and design guidelines for controlling HVAC systems so that ventilation air is adequate but not excessive, source ventilation is provided only when it is needed, and cooling systems provide optimal space dehumidification in humid climates.

8.7 Importance of This Research

This research has looked at 70 small commercial buildings in central Florida and identified that air flows in commercial buildings are greatly out of control. Only one building was identified by the research team as having no significant uncontrolled air flows. In a majority of these 70 buildings there are severe air flow and pressure imbalance problems. In some of these cases, the uncontrolled air flow occurs without significant consequences. In others, the consequences can be severe.

The range of problems that are associated with uncontrolled air flow and the monetary costs which are occurring as a result of uncontrolled air flow are very large indeed. While this may seem like bad news, in fact it can be viewed as good news because it represents a great opportunity to make things better -- to save energy, reduce peak electrical demand, improve comfort, achieve improved ventilation, better control indoor relative humidity, solve moisture degradation problems, diminish indoor air quality problems, and occasionally avoid the occurrence of sick buildings. Because the consequences of uncontrolled air flow are so great, the benefits of getting this information out to those responsible for commercial buildings is also great. Potentially, this information can lead to better buildings, which are more efficient, comfortable, and healthful for occupants, which in turn can lead to more productive environments for people to carry out the business of life.

If we cannot control air flows in buildings, we cannot control indoor air quality and the thermal environment. On the other hand, if we design, construct, and maintain buildings so that air flow and pressure differentials can be controlled, then we have a good chance of having buildings with comfortable and healthy indoor environments.

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APPENDIX A

EXAMPLE UNCONTROLLED AIR FLOW FORMS

An important part of developing diagnostic methods was developing forms to contain and process the information. These forms were developed on a spread sheet. Data can be input directly into a computer in the field as the testing is proceeding. For example, with the blower door form, the spreadsheet computes the values for C, n, r, CFM50, ACH50, etc. instantaneously as soon as the second data point is input, and then updates each time a new set of values is input. Given this format, the quality of the data can be instantly evaluated and if a problem exists, can be corrected and the test repeated. Following are forms and data recording formats used in this project.

Uncontrolled AirFlow Project - FSEC

General Information

Date: 29-Mar-95

Code: DESING

Business Name:	~~Design Molding Tooling~~	Phone:	
Address:	[illegible]	Contact:	Jon
Address:			
City:	Titusville	ZipCode:	32780
Type Business:	Plastic fabrication		
Year built:	1982	Last retrofit:	
Original use:	same		
Construction:	Metal building		

Conditioned Space

1st floor area:	3000	Height:	12.5	Volume:	37500		
2nd floor area:	12000	Height:	17	Volume:	204000		
3rd floor area:		Height:		Volume:			
4th floor area:		Height:		Volume:			
Total floor area:	15000			Tot. Vol:	241500	# floors:	2

Unconditioned Space

Area:		Height:		Volume:	

Description:

1

Indoor Air Survey

Carbon Dioxide		ppm
Carbon Monoxide		ppm
Formeldehyde		ppm
VOC's		ppm
Temperature		F
Relative Humidity		%
Time		

Business Schedule

Building Open		Business Hours	
From:	8	From:	8
To:	4:30	To:	4:30
Day / week:	5	Day / week:	5

Occupancy

Average:	5	Maximum:	7

Comments

Last year 18 employees - Aerospace recession hit!

1

2 Both 1st and 2nd floors are ground level - floor 1 is the office/warehouse and floor 2 is the shop area

3

4

5

C:\QPW\FSEC\DESING.WB1 29-Mar-95

UAF - Building Airtightness

DESING

Building Description

3000	Floor area [sqft]	78	Inside Temp	Date:	29-Mar-95
12.5	Ave Building Height [ft]	80	Outside Temp	Time:	9:50 *start*
37500	Building volume	1.002	Air Density Factor		
15	Max building height [ft]	a	Wind sheilding (a)ve, (m)in, ma(x)		
0.825	Height factor	24.2	"N"		
40750	Surface Area		Average number of people		

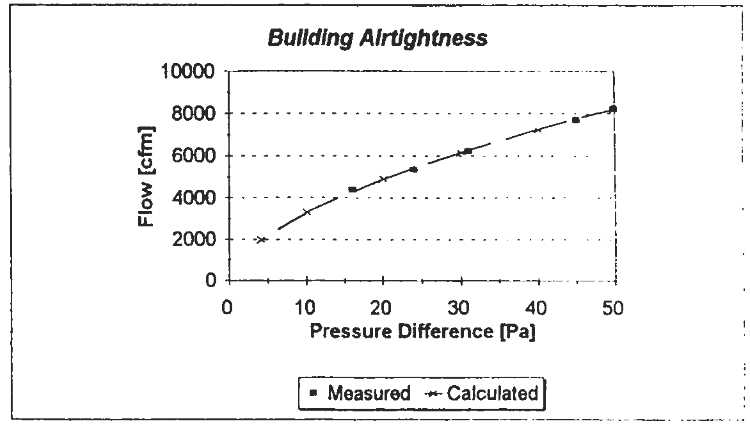
Blower Door Data

Door Location: north | north | |

	Building Press	Fan Id # 3512 Fan Press	Fan Config	Fan Flow	Fan Id # 3512 Fan Press	Fan Config	Fan Flow	Fan Id # Fan Press	Fan Config	Fan Flow	Fan Id # Fan Press	Fan Config	Fan Flow	Sum Flows	Temp. Comp.	Calc cfm
1	50.0	118.0	o	5187	41.0	o	3075							8262	8278	8228
2	45.0	94.0	o	4635	41.0	o	3075							7711	7725	7752
3	31.0	36.0	o	2884	49.0	o	3359							6243	6254	6280
4	24.0	126.0	o	5358		o	0							5358	5368	5434
5	16.0	84.0	o	4385		o	0							4385	4393	4321
6			o	0		o	0							0	0	

Calculations

0.57	n	8228	CFM50	13.2	ACH50
901.79	C	1069.7	FLA	0.5	ach (ACH50/N)
0.9985	r	3313	CFM10	339	cfm (estimated)
		973.8	EqLA	13.0	SLA
		1974	CFM4		cfm needed for 15cfm / person
		559.7	ELA	219	cfm @ .35 ach
				2.7	CFM50 / sqft
		1334.3	cfm @ 2pa	0.02	C/SurfaceArea



Comments

This is office and warehouse total

C:\QPW\FSEC\DESING.WB1 29-Mar-95

UAF - Building Airtightness

DESING

Building Description

12000	Floor area [sqft]	78	Inside Temp	Date:	29-Mar-95
17	Ave Building Height [ft]	80	Outside Temp	Time:	start
204000	Building volume	1.002	Air Density Factor		
19	Max building height [ft]	a	Wind sheilding (a)ve, (m)in, ma(x)		
0.7	Height factor	28.6	"N"		
19080	Surface Area		Average number of people		

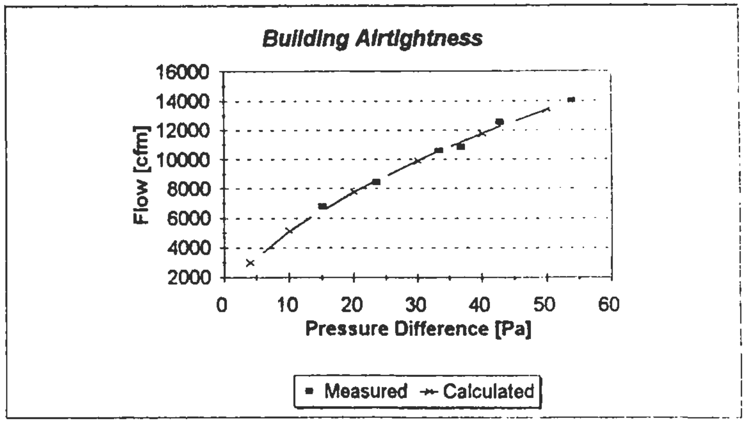
Blower Door Data

Door Location: east | east | south |

	Building Press	Fan Id # 3512 Fan Press	Fan Config	Fan Flow	Fan Id # 3512 Fan Press	Fan Config	Fan Flow	Fan Id # 3512 Fan Press	Fan Config	Fan Flow	Fan Id # Fan Press	Fan Config	Fan Flow	Sum Flows	Temp. Comp.	Calc cfm
1	53.9	111.3	o	5039	63.0	o	3803	117	o	5165				14008	14034	14038
2	42.8	29.8	o	2626	98.2	o	4737	116	o	5143				12507	12530	12238
3	36.8	32.1	o	2725	31.5	o	2700	127	o	5379				10803	10823	11187
4	33.4	122.3	o	5280	122.8	o	5290		o	0				10570	10590	10560
5	23.6	126.2	o	5362	40.4	o	3053		o	0				8415	8431	8589
6	15.2	50.8	o	3419	49.0	o	3359		o	0				6778	6791	6611

Calculations

0.59	n	13424	CFM50	3.9	ACH50
1309.90	C	1745.2	FLA	0.1	ach (ACH50/N)
0.9908	r	5153	CFM10	470	cfm (estimated)
		1514.6	EqLA	4.9	SLA
		2988	CFM4		cfm needed for 15cfm / person
		847.1	ELA	1190	cfm @ .35 ach
				1.1	CFM50 / sqft
		1978.4	cfm @ 2pa	0.07	C/SurfaceArea



Comments

This is machine shop and molding injection area

UAF - Building Airtightness

DESING

Building Description

360	Floor area [sqft]	78	Inside Temp	Date:	29-Mar-95
8	Ave Building Height [ft]	80	Outside Temp	Time:	start
2880	Building volume	1.002	Air Density Factor		
8	Max building height [ft]	a	Wind sheilding (a)ve, (m)in, ma(x)		
1	Height factor	20.0	"N"		
1032	Surface Area		Average number of people		

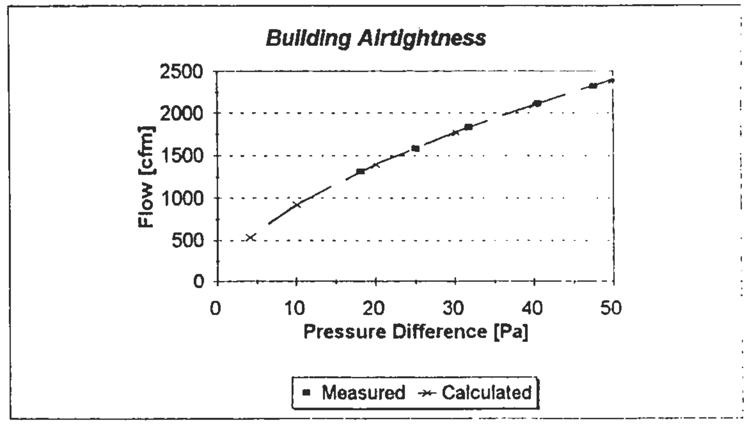
Blower Door Data

Door Location: office /wrhse | north | |

	Building Press	Fan Press (Fan Id # 3512)	Fan Config	Fan Flow	Fan Press (Fan Id # 3512)	Fan Config	Fan Flow	Fan Press (Fan Id #)	Fan Config	Fan Flow	Fan Press (Fan Id #)	Fan Config	Fan Flow	Sum Flows	Temp. Comp.	Calc cfm
1	47.5	174.0	a	2321			0							2321	2325	2329
2	40.5	144.8	a	2119			0							2119	2123	2119
3	31.7	108.5	a	1837			0							1837	1840	1833
4	25.0	80.3	a	1583			0							1583	1586	1593
5	18.1	55.1	a	1314			0							1314	1316	1316
6			a	0			0							0	0	

Calculations

0.59	n	2401	CFM50	50.0	ACH50
236.84	C	312.1	FLA	2.5	ach (ACH50/N)
0.9998	r	926	CFM10	120	cfm (estimated)
		272.1	EqLA	29.4	SLA
		538	CFM4		cfm needed for 15cfm / person
		152.6	ELA	17	cfm @ .35 ach
				6.7	CFM50 / sqft
		357.0	cfm @ 2pa	0.23	C/SurfaceArea



Comments

This is office ONLY ~~when the warehouse is at the same building pressure~~.

(SUPPLY & RETURN TAPED)

A-5

UAF - Duct System

DESING

Duct Description

office	System tested
Total	Duct Tested <SA, RA, OA, EA>
Return Grill	Mounting location
Return	Reference Tap Location
	Supply Static Pressure

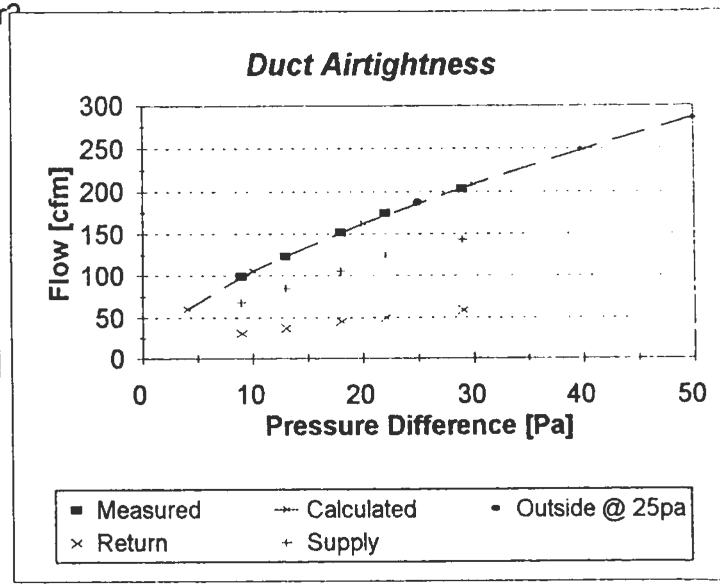
78	Inside Temp
80	Outside Temp
1.002	Air Density Factor

Date: 29-Mar-95
Time: 10:40 start

Duct Blaster Data

Single <S> or Dual <D> Duct Blaster? d

		Return			Supply					
		Fan Id # 239			Fan Id # 239					
	Duct Press	Fan Press	Fan Config	Fan Flow	Fan Press	Fan Config	Fan Flow	Sum Flows	Temp. Comp.	Calc cfm
1	29.0	89.0	3	59	526	3	144	203	203	204
2	22.0	64.0	3	50	395	3	124	174	175	172
3	18.0	53.0	3	46	287	3	106	152	152	152
4	13.0	36.0	3	38	187	3	86	123	123	125
5	9.0	25.0	3	31	118	3	68	99	99	99
6										



Duct Blaster Data - Outside

		Fan Id #			
	Duct Press	Fan Press	Fan Config	Fan Flow	Temp. Comp.
1					0

Calculations

Total

0.62	n
25.63	C
0.9984	r

286	CFM50
186	CFM25

Return

83	CFM50
54	CFM25

Supply

201	CFM50
131	CFM25

Outside

186	CFM25

Comments

Filter at the airhandler was covered with ductmask to help split
the system

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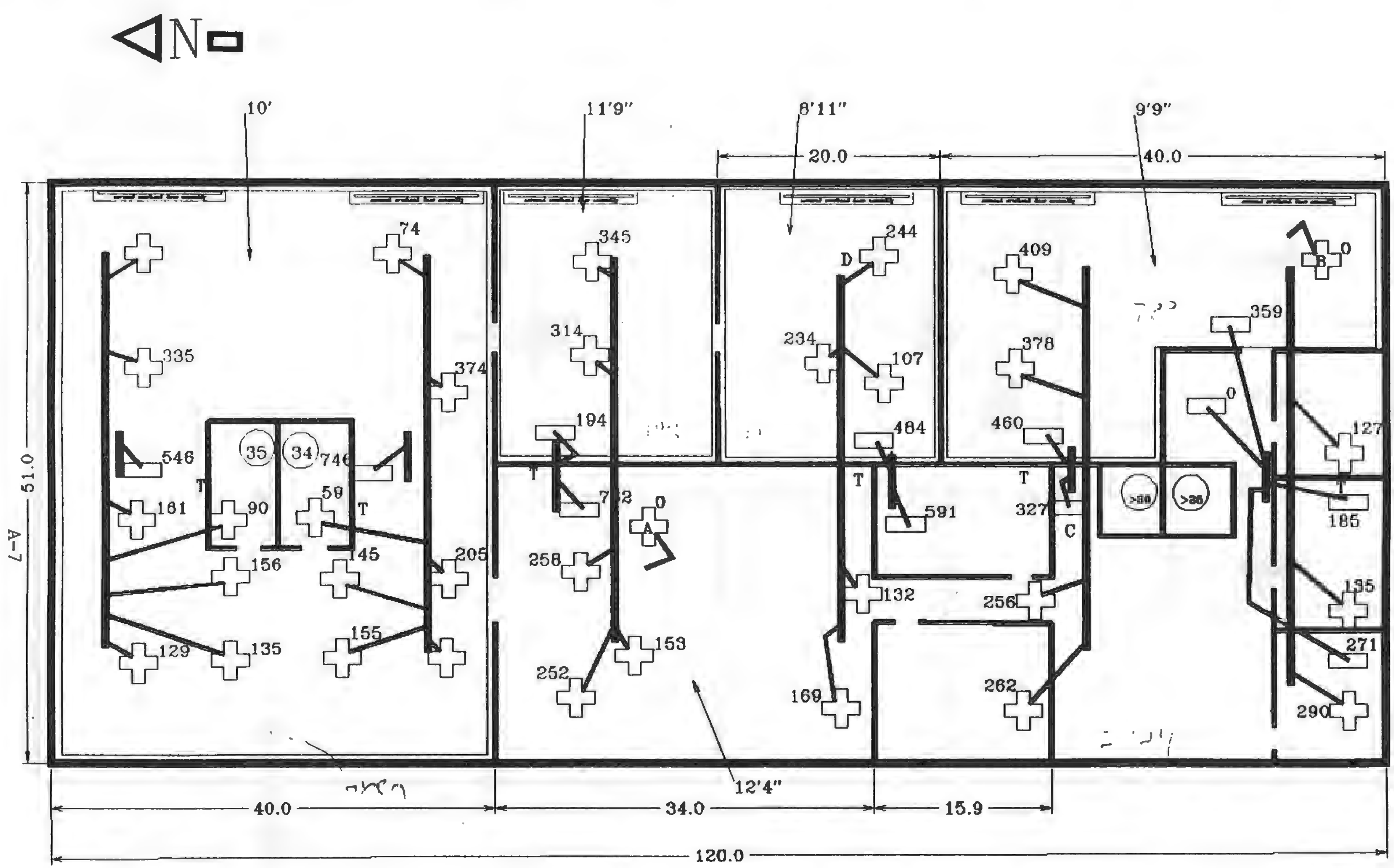


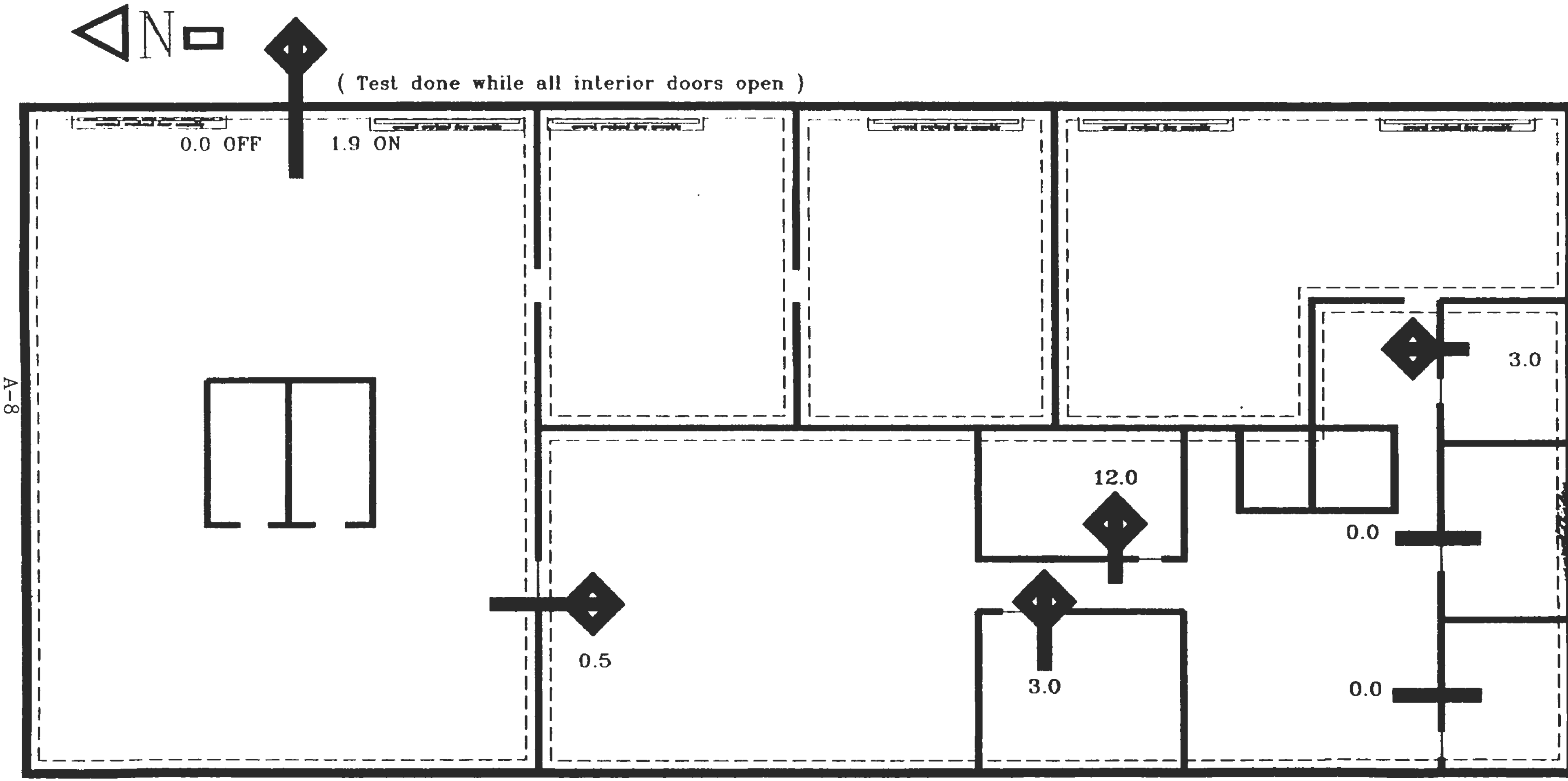
A: Duct never connected–no connector in main

B: 12" flex dropped from main supply duct
Measured flow from main = 785 cfm

C: Return main flex 50% disconnected from unit

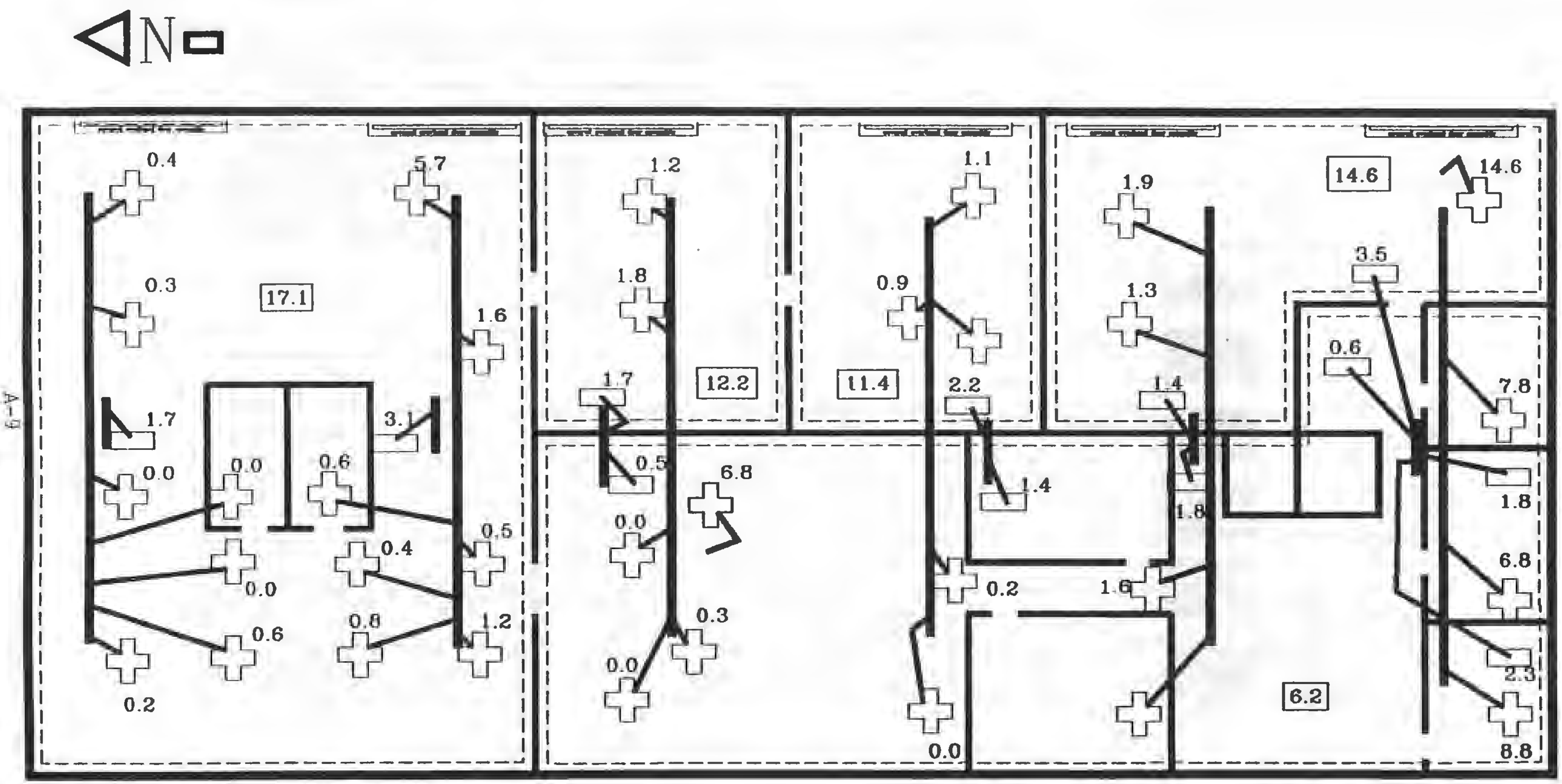
D: Flex duct with many kinks

11/22/93



Pressures created with Air Handlers operating

11/22/93



11/22/93

Pressure Pan readings with building depressurized to 25 pascals

Pressure across ceiling tiles

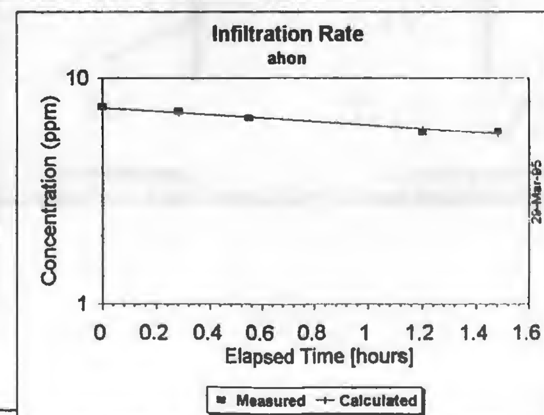
Building Infiltration

					Date: 29-Mar-95	start / end
Type of Test:	ahon		Tracer Gas:	N2O	Outside Temp:	/ 78 °F
Tracer Gas Analyzer #:	1	068381	TG Injection @:	12:11	Inside Temp:	77 / 77 °F
Info Equipment:	Miran 101		Approx Winds:		ach=	0.179
Equipment On @:	11:50		Wind Direction:		r=	0.971

#	Time	PPM -1-	PPM -2-	PPM -3-	PPM -4-	PPM -5-	PPM -6-	PPM -7-	PPM -ave-	zero corr.	PPM corr.	Calc PPM
1	12:40 PM	8.4	8.4	9	10.3	2.5	6.1		7.5		7.5	7.4
2	12:57 PM	8.9	8.5	8.5	7.4	3.4	5.9		7.1		7.1	7.0
3	01:13 PM	8.2	7.6	7.6	5.7	5.1	5.5		6.6		6.6	6.7
4	01:52 PM	6.8	6.8	6.5	4.5	5.1	4.9		5.8		5.8	5.9
5	02:09 PM	6.7	6.25	6.2	4.9	5.6	5.1		5.8		5.8	5.6
*												
*												
*												
*												
*												
*												
*												
*												
*												
*												
*												

Sample Location ID

1 south zone
2 north zone
3 bathroom hall
4 office
5 office hall
6 warehouse
7



Comments

pressure difference wrt out = -0.6

Name: ____________

Equipment: South zone

Flow = 1606 cfm

Date: 29-Mar-95

Time: 12:52 start

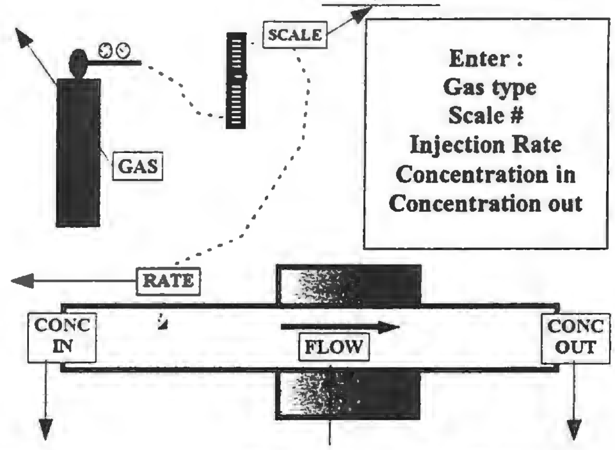
end

SF6 <1> / N2O <2>

	Gas	Scale: #2 / #3	Rate <0-100>
1	1	2	100
2	1	2	85
3	1	2	70
4	1	2	55
5	1	2	

Scale#2 – small

Scale#3 – larger



	ppm in	cfm	ppm out
1	1.4	1585	100
2	2.1	1602	85
3	2.2	1612	70
4	2.2	1624	55
5			

Equipment: North zone

Flow = 11058 cfm

Date: 29-Mar-95

Time: 13:03 start

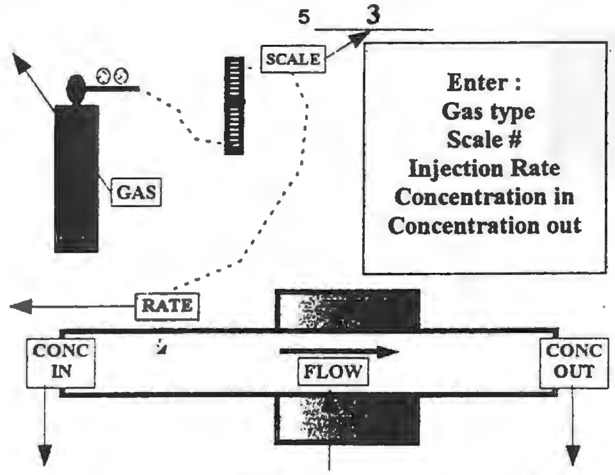
end

SF6 <1> / N2O <2>

	Gas	Scale: #2 / #3	Rate <0-100>
1	1	3	78
2	1	3	99
3	1	3	89
4	1	3	51
5	1	3	

Scale#2 – small

Scale#3 – larger



	ppm in	cfm	ppm out
1	2.2	11118	18.1
2	3.5	10484	25.1
3	4.4	10618	23.5
4	5.3	12013	14.7
5			

C:\QPW\FSEC\DESING.WB1 29-Mar-95

Return Leak Fraction

Date: 03/29/95

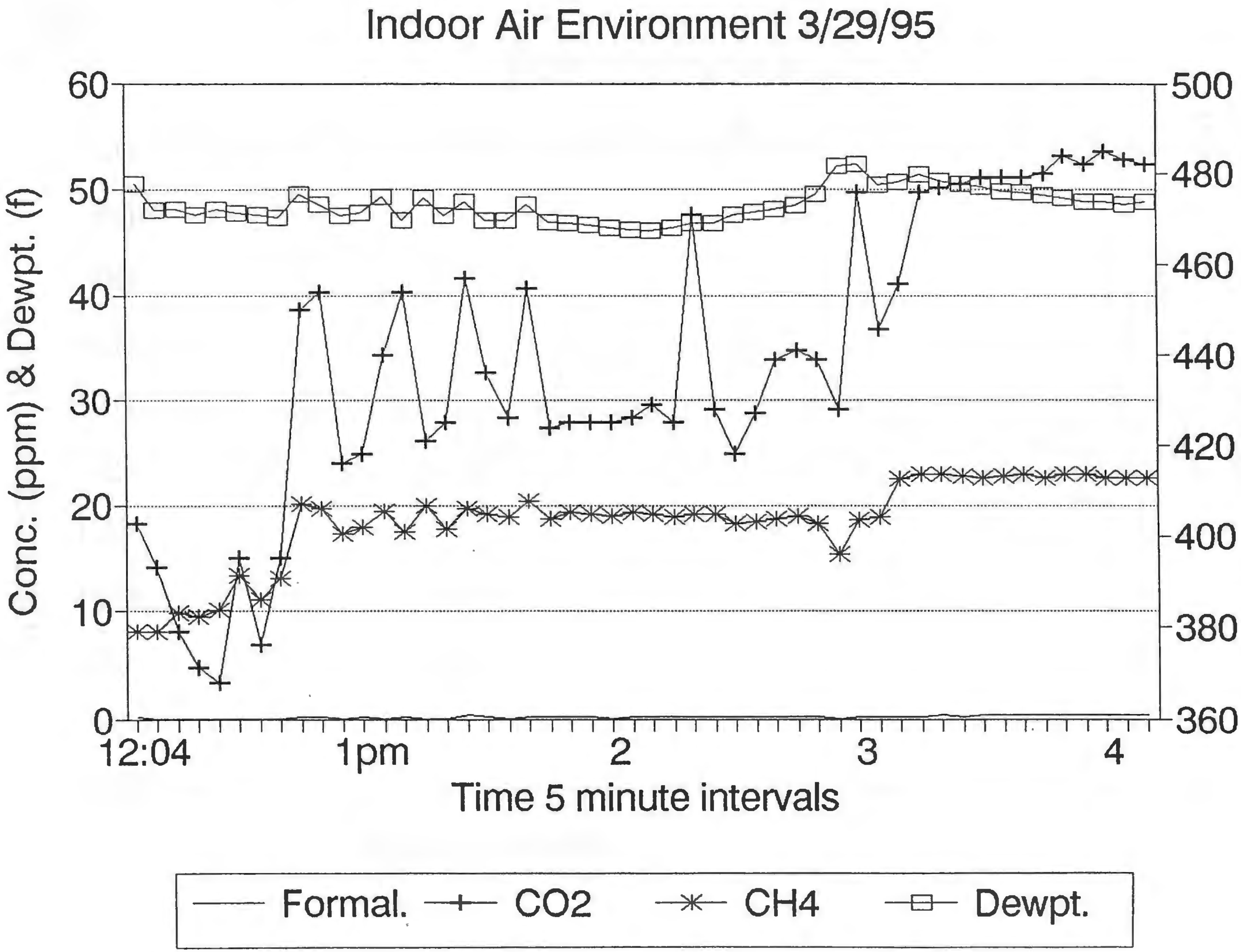
Name:

System: office

RLF 25.6%

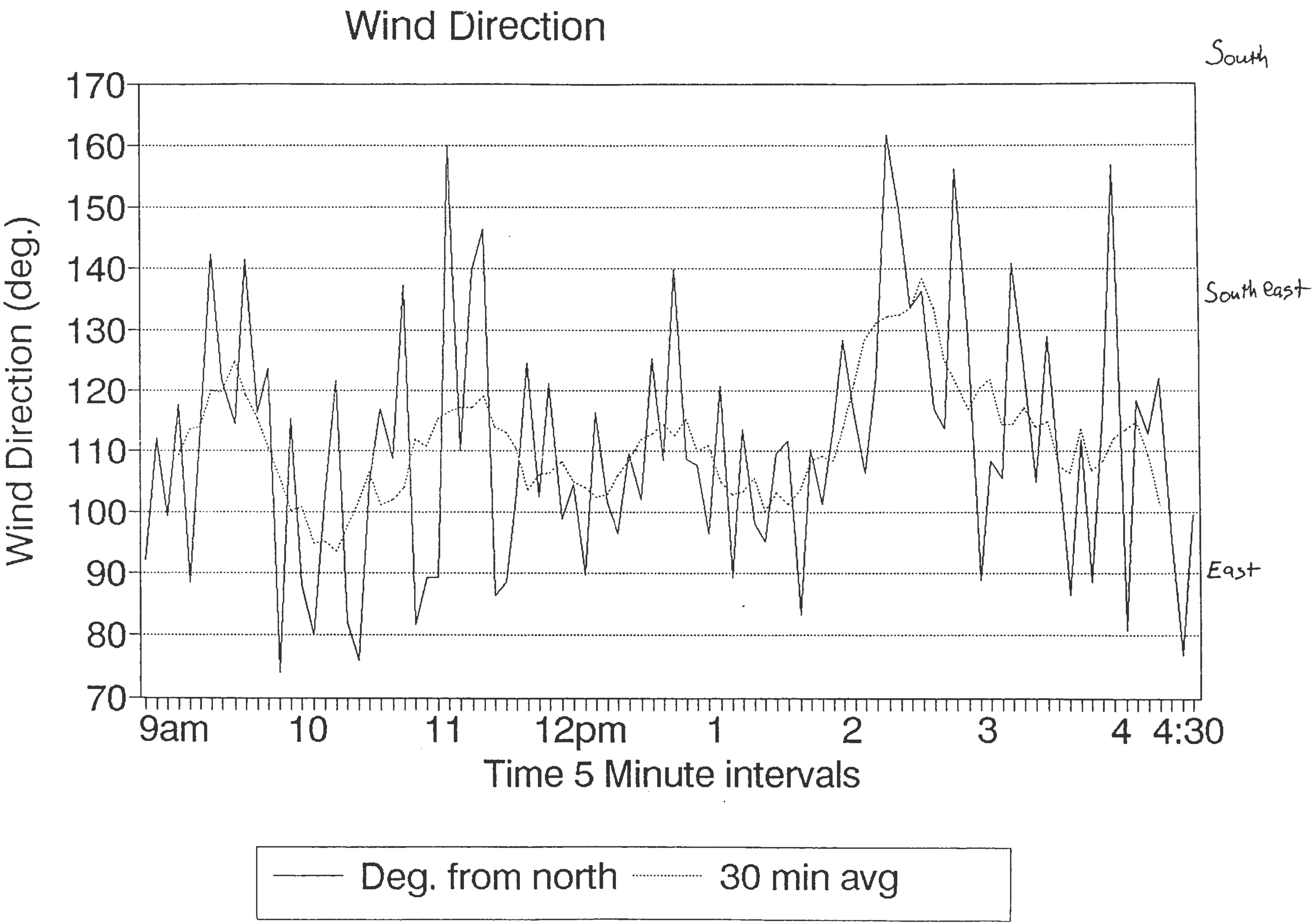
	Return	Supply	Return	Buffer	rlf	Time
1	19.6	16.0	18.2	4.4	**19.1%**	12:23
2		14.1	17.4	4.4	**27.6%**	
3		13.0	16.0	4.4	**30.1%**	

Comments



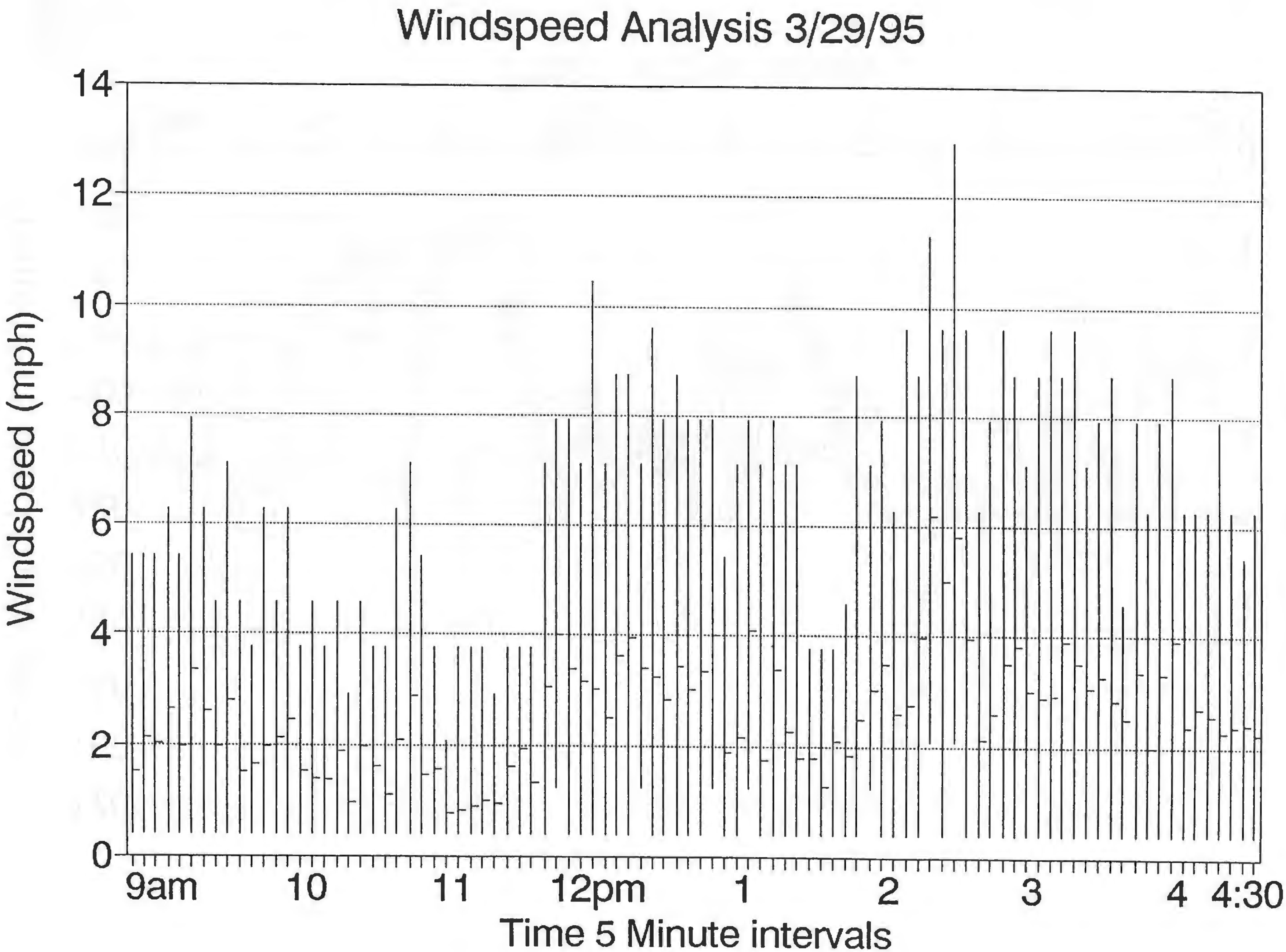
Indoor Air Environment 3/29/95
Conc. (ppm) & Dewpt. (f)
60
50
40
30
20
10
0
CO2 (ppm)
500
480
460
440
420
400
380
360
12:04
1pm
2
3
4
Time 5 minute intervals
Formal.
CO2
CH4
Dewpt.

A-13



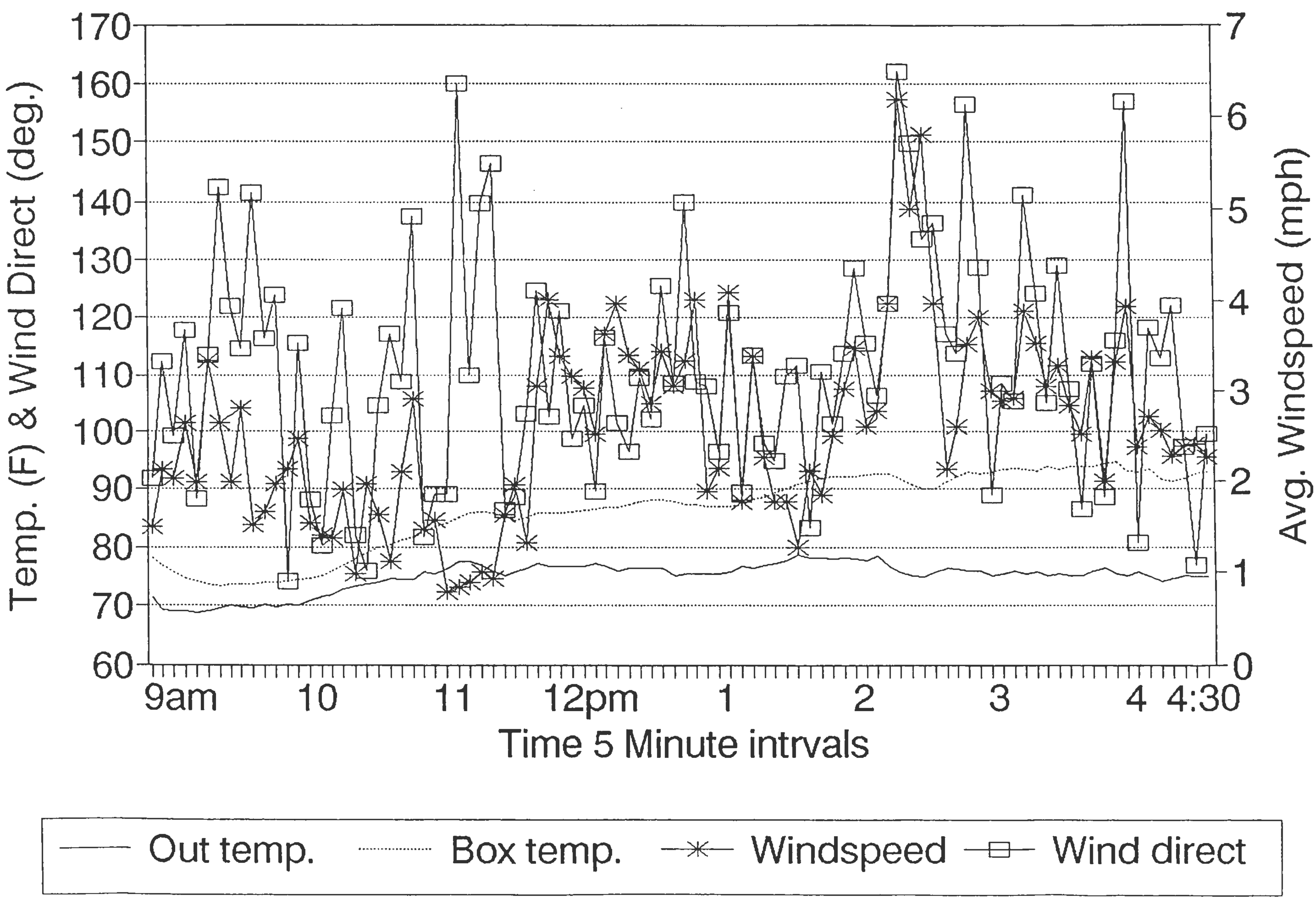
Wind Direction
South
South east
East
170
160
150
140
130
120
110
100
90
80
70
Wind Direction (deg.)
9am
10
11
12pm
1
2
3
4
4:30
Time 5 Minute intervals
Deg. from north
30 min avg

A-14


Windspeed Analysis 3/29/95
Windspeed (mph)
0
2
4
6
8
10
12
14
9am
10
11
12pm
1
2
3
4
4:30
Time 5 Minute intervals

A-15

Weather Data 3/29/95



APPENDIX B

MASTER DATA TABLE

STUDY OF UNCONTROLLED AIR FLOW IN NON-RESIDENTIAL BUILDINGS

A large portion of the data collected in this project is included in this master table. Following is nomenclature for the table, explaining headings and the number and letter symbols used in the table. Each building has a number assigned which represents the order in which the buildings were tested.

NOMENCLATURE FOR UNCONTROLLED AIR FLOW MASTER TABLE

BUILDING USE

1. SMALL OFFICE (0 - 10,000 SF)
2. MEDIUM OFFICE (10,000 - 50,000 SF)
3. SMALL RETAIL (0 - 10,000 SF)
4. MEDIUM RETAIL (10,000 - 50,000 SF)
5. MEDICAL OFFICE
6. EDUCATION
7. RESTAURANT/BAR
8. ASSEMBLY/RECREATION
9. COMMERCIAL BUILDING
10. LIGHT INDUSTRIAL/WAREHOUSE

STAND ALONE

0 = ALONE; building unit is unattached to any other unit
1 = ATTACHED; building unit is attached to one or more other units

SLAB/CRAWL

0 = SLAB ON GRADE
1 = CRAWL SPACE

CONVERT USE

CC = CONVERTED FROM PREVIOUS COMMERCIAL
CR = CONVERTED FROM RESIDENTIAL
N = NOT CONVERTED; PRESENT USE IS ORIGINAL USE

AC TONS

IS TOTAL BUILDING INSTALLED COOLING CAPACITY

TONS PER 1000 SF

IS COOLING CAPACITY PER 1000 SQUARE FEET OF FLOOR AREA

AH LOCATION

A = ATTIC
CL = CLOSET
CS = CEILING SPACE
EG = EXTERIOR GROUND
EMR = EXTERIOR ACCESS MECHANICAL ROOM
EW = EXTERIOR WALL
MR = MECHANICAL ROOM
OS = OCCUPIED SPACE
R = ROOF TOP
W = WAREHOUSE

DUCT LOCATION

0 = NO DUCTS
1 = IN CONDITIONED SPACE
2 = IN UNCONDITIONED SPACE
3 = OUTDOORS

DUCT TYPE

D = DUCTBOARD
F = FLEX DUCT
M = METAL
N = NONE

BUILDING CAVITY DUCT

CH = CHASE USED AS DUCT
CL = CLOSET USED AS PLENUM
CS = CEILING SPACE USED AS PLENUM
MR = MECHANICAL ROOM AS PLENUM
N = NONE
O = OTHER CAVITY USED AS DUCT
SP = SUPPORT PLATFORM ENCLOSED AS PLENUM
WCD = WALL CAVITY AS DUCT

OCCUPANCY

IS TYPICAL FULL UTILIZATION, NOT AVERAGE OCCUPANCY; in a church, for example, typical full utilization might be 200 persons on a typical Sunday morning, while the average over all hours of the week might only be 5 persons.

FLOOR AREA

IS SUM OF BUILDING FLOOR AREA

OCCUPIED VOLUME

IS VOLUME BETWEEN FLOOR AND CEILING IN PORTIONS OF THE BUILDING NORMALLY CONDITIONED AND OCCUPIED BY PERSONS

THERMAL VOLUME

IS THE VOLUME BETWEEN THE FLOOR AND THE CEILING/ROOF THERMAL BARRIER; if the thermal barrier is located at the ceiling the thermal volume will be equal to the occupied volume; if the thermal barrier is at the roof deck or some place in between the roof deck and the ceiling, then the thermal volume will be larger than the occupied volume.

AIR VOLUME

IS THE VOLUME INSIDE THE BUILDING'S PRIMARY AIR BARRIER, THAT IS THE VOLUME BETWEEN THE FLOOR AND THE PRIMARY AIR BARRIER; if the ceiling is the primary air barrier then the air volume will be equal to the occupied volume; if the air barrier is at the roof deck then the air volume will be larger than the occupied volume.

ROOF SLOPE

F = FLAT
S = SLOPED

ABOVE CEILING (description of space above the ceiling)

A = ATTIC
C = CEILING SPACE
N = NO SPACE ABOVE CEILING
W = WAREHOUSE

CEILING MATERIAL

S = SUSPENDED CEILING TILES
P = CEILING PANELS, NOT ON SUSPENDED T-BAR
G = GYPSUM BOARD
N = NO CEILING OTHER THAN THE BOTTOM OF THE ROOF DECK

BARRIER CONFIGURATION (AB = air barrier, TB = thermal barrier)

1 = PRIMARY AB AND TB ARE LOCATED AT THE ROOF DECK WHICH IS ALSO THE CEILING
2 = PRIMARY AB AND TB ARE LOCATED AT THE ROOF DECK; SUSPENDED CEILING
3 = PRIMARY AB IS LOCATED AT THE ROOF DECK; PRIMARY TB IS LOCATED AT CEILING
4 = PRIMARY AB AND TB ARE LOCATED AT THE CEILING WHILE THE SPACE BETWEEN THE CEILING AND ROOF DECK IS GENERALLY WELL VENTILATED
5 = PRIMARY AB IS LOCATED AT THE CEILING; PRIMARY TB IS LOCATED AT THE ROOF DECK
6 = PRIMARY AB IS LOCATED AT THE ROOF DECK; PRIMARY TB IS LOCATED BETWEEN THE CEILING AND THE ROOF DECK
7 = PRIMARY AB IS LOCATED AT THE CEILING; PRIMARY TB IS LOCATED BETWEEN THE CEILING AND THE ROOF DECK

CEILING SPACE CONDITION (AB = air barrier, TB = thermal barrier)

0 = NO CEILING SPACE
1 = CEILING SPACE IS PLENUM; cool and dry
2 = INSIDE AB AND TB; cool and dry
3 = INSIDE AB, OUTSIDE TB; hot and dry
4 = OUTSIDE AB AND TB; warm and humid

CFM50

IS THE AIR FLOW RATE INTO THE BUILDING WHEN THE BUILDING IS DEPRESSURIZED TO -50 PASCALS (by a calibrated fan), WITH ALL MECHANICAL AIR MOVING SYSTEMS TURNED OFF AND EA, MA, AND OA OPENINGS SEALED OFF.

ACH50

IS THE AIR EXCHANGE RATE OF THE BUILDING (exchange with outside air) WHEN THE BUILDING IS DEPRESSURIZED TO -50 PASCALS (by a calibrated fan), WITH ALL MECHANICAL AIR MOVING SYSTEMS TURNED OFF AND EA, MA, AND OA OPENINGS SEALED OFF.

SURFACE AREA

THE EXTERIOR SURFACE AREA OF THE BUILDING, INCLUDING EXTERIOR WALL SURFACES UP TO THE HEIGHT OF THE CEILING/ROOF PRIMARY AIR BARRIER, AND THE SURFACE AREA OF THE CEILING/ROOF PRIMARY AIR BARRIER. THE FLOOR SURFACE AREA IS NOT INCLUDED.

C BUILDING AIR FLOW COEFFICIENT, DERIVED FROM A MULTI-POINT BLOWER DOOR TEST.

n BUILDING AIR FLOW EXPONENT, DERIVED FROM A MULTI-POINT BLOWER DOOR TEST. AIR FLOW THROUGH THE BUILDING ENVELOPE IS DEFINED AS A FUNCTION $Q = C\ (dP)^n$, WHERE Q IS AIR FLOW IN CFM AND dP IS PRESSURE DIFFERENTIAL BETWEEN INDOORS AND OUTDOORS IN PASCALS.

r CORRELATION COEFFICIENT; INDICATES THE GOODNESS OF FIT OF THE PRESSURE VS AIR FLOW DATA POINTS WITH THE BEST FIT LINE DEFINED BY $Q = C\ (dP)^n$.

DUCT CFM25

AIRTIGHTNESS OF THE DUCT SYSTEM. THIS IS THE AIR FLOW RATE THROUGH LEAKS IN THE AIR DISTRIBUTION SYSTEM, INCLUDING SUPPLY DUCTS, RETURN DUCTS, SUPPLY PLENUMS, RETURN PLENUMS, AND AIR HANDLERS WHEN THE AIR HANDLERS ARE TURNED OFF, THE REGISTERS AND GRILLS ARE MASKED CLOSED, AND THE SYSTEM IS DEPRESSURIZED TO -25 PASCALS.

ach AHON

IS TRACER GAS DECAY MEASUREMENT OF BUILDING AIR EXCHANGE WITH OUTDOORS WITH AIR HANDLERS ON CONTINUOUSLY AND EXHAUST FANS IN NORMAL MODE

ach AHOFF

IS TRACER GAS DECAY MEASUREMENT OF BUILDING AIR EXCHANGE WITH OUTDOORS WITH AIR HANDLERS OFF

OA & MA

IS THE SUM OF OUTDOOR AIR AND MAKEUP AIR FLOWS INTO THE BUILDING

RLflow

IS THE FLOW OF AIR INTO LEAKS IN RETURN DUCTS; this air may be drawn from outdoors, unconditioned zones, or conditioned zones of the building

EXH

IS THE FLOW RATE OF AIR LEAVING THE BUILDING THROUGH EXHAUST FANS

dP ON

IS PRESSURE IN THE BUILDING WITH RESPECT TO OUTDOORS WHEN THE AIR HANDLERS ARE TURNED ON AND THE EXHAUST FANS ARE IN THEIR NORMAL OPERATING MODE

	BUILDING	AGE BLDG	BLDG USE	STAND ALONE	TYPE CONSTR	NUMB STORY	SLAB CRAWL	ROOF GIRD	CONV USE	# AC UNITS	AC TONS	TONS P 1000SF	AH LOC	DUCT LOC	TYPE DUCT	B_CAV DUCT
1	RESEARCH OFFICE	31	1	0	MASONR	1	0	M	N	1	15	2.78	MR	1	M	MR/C
2	AUDITORIUM	31	8	0	MASONR	1	0	M	N	1	25	5.00	EMR	3	M	WCD
3	DENTIST 1	4	5	0	MASONR	1	0	W	N	2	10	3.63	A	2	D	N
4	CHURCH	26	8	0	MAS/FRA	2	0	W	N	4	25	2.37	MR	1	M	WCD
5	CHURCH HALL	37	8	0	MASONR	1	0	W	N	1	15	4.43	EMR	2	M	N
6	VIDEO OFFICE	35	2	0	MASONR	2	0	M	CC	7			MR	1/2	M/D	SP/MR/C
7	BUSINESS TRAIN	28	6	0	MASONR	1	0	M	N	6	28	1.66	MR/R	2	D	MR
8	ENGINEER OFFICE	15	1	1	MAS/FRA	1	0	M	N	1	2.5	2.84	R	2	D	N
9	DENTIST 2	37	5	0	MASONR	1	0	W	N	1	10	6.61	R	3	D	N
10	ARCHITECT	10	1	0	MASONR	1	0	M	CC	6	21	3.43	R	2	D/F	N
11	HVAC SUPPLY	36	3	0	MAS/MET	1	0	W	CR	2	8.5	4.74	CL/OS	2	D/F	CL
12	SPORTS BUILDING	9	8	0	MASONR	1	0	M	N	4	58	3.47	MR	1/2	M/F	MR/C
13	DAY CARE	26	6	0	MASONR	1	0	W	N	4	8	3.09	A/OS	0/2	D	N
14	MANUF CLASS	6	6	0	MANUF	1	1	W	N	2	6	3.57	EW	2	D	WCP
15	HEALTH CLINIC 1	10	5	0	MASONR	1	0	M	N	1	6	2.87	EMR	2	D/F	N
16	MANUF OFFICE 1	8	1	0	MANUF	1	1	W	N	7	21	4.27	EW	1	D/F	WCP
17	SCHOOL	21	6	0	MASONR	1	0	W	N	1	28	1.68	EMR	1	M	C
18	STADIUM COMPLEX	10	8	0	MASONR	2	0	M	N	5	129	5.74	R	1	M	C
19	PIZZA RESTAURANT	21	7	0	FRA/MAS	1	0	W	CC	2	7.5	3.86	CL/EG	2/3	D/F	CL
20	CITY HALL	27	1	0	MASONR	1	0	M	N	2	10	3.39	R	2/3	D	N
21	HEALTH CLINIC 2	9	5	1	FRAME	1	0	W	N	3	10	3.91	CL	2	F/D	CL
22	SUB RESTAURANT	2	7	0	MASONR	1	0	W	N	3	27	7.71	R	2	D/F	N
23	MAIL WAREHOUSE	12	10	0	METAL	1	0	M	N	1	6	1.96	OS	1	D	N
24	LIBRARY	7	8	0	MASONR	1	0	M	N	5	26	3.01	R	1	D/F	N
25	SPORTS COMPLEX	9	8	0	MASONR	1	0	W	N	2	9	3.32	CL	2	D/F	SP
26	REALTY 1	2	1	1	FRAME	1	0	W	N	1	2	2.08	CL	2	D/F	N
27	FOOD OFFICE	2	1	1	FRAME	1	0	W	N	1	2	2.08	CL	2	D/F	N
28	FOOD WAREHOUSE	2	10	1	FRAME	1	0	W	N	2	4	2.08	CL	2	D/F	N
29	MANUF OFFICE 2	13	1	0	MANUF	1	1	W/M	N	4	16	3.17	R	2	D/F	N
30	SAIL MANUF	55	10	0	FRAME	2	0	W	CC	1	5	1.54	OS	2	D	SP
31	BAR AND GRILL	10	7	0	MASONR	1	0	W	N	2	8	3.33	A	2	D	N
32	GOLF CLUB HOUSE	2	7	0	FRAME	1	0	W	N	3	15.5	3.56	A	2	D	N
33	CHICKEN REST 1	2	7	0	MASONR	1	0	M	N	4	35	11.07	R	2	D/F	N
34	HVAC CONTRACTOR	65	1	1	FRA/MAS	1	0	W	CC	2	6	3.34	CL/W	2	M/D/F	SP
35	CHICKEN REST 2	10	7	0	MASONR	1	0	M	CC	4	35	10.54	R	2	D/F	N
36	PRINTING 1	30	10	0	MASONR	1	0	M	N	6	40	2.48	R/OS	1	D	N
37	REALTY 2	24	1	0	MASONR	1	0	W	N	1	4	2.17	CL	2	D	SP
38	INTERIOR DECORAT	24	3	0	MASONR	1	0	W	N	2	7	1.77	CL	2	D	SP
39	REALTY 3	50	1	0	MASONR	1	1	W	CR	2	7	3.27	CL	2	D/F	SP/CL
40	SAFETY CLASS	30	6	1	FRA/MAS	1	0	M	CC	2	9	3.66	CS/R	2	M/D	MR
41	PET GROOMING	30	3	1	FRA/MAS	1	0	M	N	1	3	4.26	WH	2	M/D/F	N
42	GOV'NMENT OFFICE	30	1	1	FRA/MAS	1	0	M	N	3	20	3.15	R	2	M/F	OTHER
43	BAR	30	7	1	FRA/MAS	1	0	M	CC	2			R	2	D	N
44	SAFETY OFFICE	30	1	1	FRA/MAS	1	0	M	N	1	5	3.77	R	2	M	N
45	SCHOOL SUPPLY	30	3	1	FRA/MAS	1	0	M	N	1	7.5	2.94	R	2	M	N
46	COURT OFFICE	30	1	1	FRA/MAS	1	0	M	N	2	11.5	3.08	CS	2	M/D	N
47	MARSHAL ARTS	30	6	1	FRA/MAS	1	0	M	N	1	3	3.09	R	2	M/D	N
48	OFFICE SUPPLY	30	3	1	FRA/MAS	1	0	M	N	1	4	3.03	R	2	M/D	N
49	RETAIL VACANT	30	3	1	FRA/MAS	1	0	M	N	1	2	2.02	WH	2	M/D	N
50	RETAIL VACANT	30	3	1	FRA/MAS	1	0	M	N	1	3	3.03	WH	2	M/D	N
51	GAS COMPANY	45	1	0	MASONR	1	0	M/W	N	4	18	3.32	R/CL	2	D/F	SP
52	TAX SERVICE	32	1	0	MASONR	1	0	M	N	1	3.5	1.94	CL	2	M	CL
53	METAL BLDG CO	10	1	0	METAL	1	0	M	N	3	9	2.32	CL	1	M/F	CL
54	REALTY 4	20	1	0	MASONR	1	0	W	CC	2	7	2.66	CL	2	D/F	CL
55	PRINTING 2	18	10	0	METAL	1	0	M	N	5	18.5	1.85	EG/OS	1	D	N
56	PLASTIC FABRICATE	13	10	0	METAL	1	0	M	N	3	27	2.18	OS/W	1/2	D/F	SP
57	AMUSEMENT PARK	14	8	0	MASONR	2	0	W	N	6	21	2.98	CL	2	D/F	SP
58	HARDWARE STORE	2	3	0	MASONR	1	0	W	N	2	10	2.15	CL	2	D	SP
59	CARPET STORE	23	3	0	MASONR	1	0	W	CC	1	3	1.89	OS	2	D	N
60	MANUF OFFICE 3	11	1	0	MANUF	1	1	W	CC	1	3	3.57	EG	3	M/F	N
61	MANUF OFFICE 4	13	1	0	MANUF	1	1	W	CC	2	5	3.79	EW	2/3	D	WC
62	CHINESE RESTAURA	33	7	0	FRAME	1	0	W	N	3			MR	2	D/F	C
63	POLICE STATION	6	1	0	MASONR	1	0	M	N	6	29	4.37	MR	1	D/F	MR/C
64	SCHOOL WING 1	31	6	0	MASONR	1	0	M	N	2	20	1.97	MR	1	D	MR/CHA
65	SCHOOL WING 2	31	6	0	MASONR	1	0	M	N	1			CS	1	NONE	N
66	SCHOOL WING 3	31	6	0	MASONR	1	0	M	N	1	10	1.97	MR	1	D	MR/CHA
67	HOTEL COMPLEX	19	9	0	MASONR	1	0	M	N	8	73	4.86	R	2	D/F	C
68	HOTEL	19	9	0	MASONR	2	0	C	N	40	20	1.57	OS	0	NONE	WCP
69	CONV. STORE 1	7	3	0	MASONR	1	0	W	N	2	17.5	4.05	A	2	D/F	N
70	CONV. STORE 2	27	3	0	MASONR	1	0	C	N	1	4	1.59	OS	1	M	N
	AVERAGE	21.3		17		76	6			3.13	16.1	3.38				

	BUILDING	OCCU-PANCY	FLOOR AREA	OCCUP VOLUME	THERMAL VOLUME	AIR VOLUME	ROOF SLOPE	ABOVE CEIL	CEIL MAT'L	BARRIER CONFIG	CEIL COND	CFM50	ACH50	SURF AREA	C	n	DUCT CFM25	ach AHON	ach AHOFF	OA+MA cfm	RLflow cfm	EXH cfm	dP ON
1	RESEARCH OFFICE	30	5404	43232	59444	59444	F	C	S	2	1	1980	2.75	8124	146.77	0.67		0.583	0.18	743	0	279	2.8
2	AUDITORIUM	30	5000	90000	90000	90000	F	N	S	1	0	10265	6.84	8600	1230.18	0.54		1.834	0.198	206	2700	686	1.1
3	DENTIST 1	13	2754	24786	24786	24786	F	A	S	4	5	8826	21.37	4433	876.95	0.59	846	0.746	0.326	0	206	337	0.1
4	CHURCH	200	10538	217120	217120	217120	S	N	S	1	0	6056	1.67	12824	618.14	0.58	4471	0.234	0.159	0	210	50	-3.5
5	CHURCH HALL	40	3384	33840	37224	33840	S	A	S	7	5	9618	17.05	5830	850.62	0.62	1627	0.962	0.236	271	738	941	0.9
6	VIDEO OFFICE	15	12716	101728	127040	152592	F	C	S	3	1	6193	3.65	12931	587.59	0.6		0.443	0.382	870	493	100	4.2
7	BUSINESS TRAIN	17	16875	168750	236250	236250	F	C	S	5	2	27583	9.81	23375	2905.38	0.58		1.02	0.202	2620	470	103	1.3
8	ENGINEER OFFICE	2	880	7920	8800	7920	F	C	S	7	4	3926	29.74	2104	394.97	0.59	174	0.747	0.271	0	142	44	0
9	DENTIST 2	9	1512	12852	12852	12852	F	N	P	1	0	3265	15.24	2923	865.77	0.34	396	3.914	0.262	911	232	325	5.2
10	ARCHITECT	30	6120	67320	67320	102510	F	C	S	3	3	11195	9.98	9882	1586.51	0.5		0.965	0.476	391	1251	114	1.9
11	HVAC SUPPLY	5	1795	15258	15258	15258	S	A	S	4	5	7472	29.38	3241	588.27	0.65	436	1.219	0.997	0	129	0	0
12	SPORTS BUILDING	35	16713	158774	306649	306649	F	C	S	2	1	22383	8.46	22953	1763.55	0.65		0.777	0.205	1426	592	2052	-0.3
13	DAY CARE	40	2592	27100	28940	28940	S	N	N	1	0	12161	26.92	4651	793.98	0.7	399	0.892	0.672	0	72	0	0.8
14	MANUF CLASS	30	1680	13154	14835	14835	F	C	P	2	2	2051	9.36	3264	196.18	0.6	773	1.34	0.209	118	152	0	1
15	HEALTH CLINIC 1	10	2092	16736	16736	25104	F	C	S	3	3	4371	15.67	4540	678.85	0.49	971	0.677	0.421	306	485	143	-0.6
16	MANUF OFFICE 1	40	4920	36900	46740	46740	F	C	S	2	2	4898	7.96	7618	624.02	0.52	1829	0.736	0.176	143	323	269	-0.8
17	SCHOOL	140	16700	149770	219529	219529	S	C	S	2	1	18607	7.45	22337	1339.91	0.67	8234	0.856	0.08	2520	0	2649	2
18	STADIUM COMPLEX	60	22461	280960	308839	293710	F	N/C	N/S	1	2	17521	3.74	32304	1378	0.65		0.76	0.27	1870	3120	9201	-1.6
19	PIZZA RESTAURANT	15	1942	15536	15536	15536	F	C	G	4	5	4137	15.98	3542	497.73	0.54	116	1.94	1.95	0	109	3170	-1.5
20	CITY HALL	14	2952	26568	26568	35424	F	C	S	3	3	3296	7.44	5664	331.16	0.59	1632	0.595	0.317	0	284	209	0.2
21	HEALTH CLINIC 2	10	2560	21760	23040	21760	S	A	S	7	5	9005	24.83	4962	714.22	0.65	2576	0.839	0.17	0	1292	386	1.8
22	SUB RESTAURANT	50	3503	33279	42036	49042	F	C	S	6	3	2164	3.90	5802	202.97	0.6		5.3		4670	336	5603	-25
23	MAIL WAREHOUSE	5	3060	35190	35190	35190	F	N	N	1	0	11845	20.20	5613	1182.96	0.59		0.765		0	0	0	0.7
24	LIBRARY	13	8650	86500	123630	123630	F	C	S	2	2	2565	1.78	14084	225.68	0.62		0.352	0.05	599	331	402	2.1
25	SPORTS COMPLEX	5	2708	24776	28885	24776	S	A	S	7	5	12987	31.45	5055	913.76	0.68	788	0.706	0.504	0	555	155	1.5
26	REALTY 1	5	960	9600	10400	13280	S	A	S	6	3	5714	35.71	1920	564.75	0.59	133	0.524	0.313	0	11	58	-1
27	FOOD OFFICE	4	960	9600	10400	13280	S	A	S	6	3	5667	35.42	1920	541.11	0.6	142	0.578	0.357	0	32	84	-6.1
28	FOOD WAREHOUSE	4	1920	19000	20800	26560	S	A	S	6	3	7848	24.78	3835	1058.4	0.51		0.46		0	37	104	5.1
29	MANUF OFFICE 2	15	5040	40320	75600	75600	F	C	S	5	2	16727	24.89	7344	929.37	0.74	1418	1.1	0.646	1297	602	357	-0.5
30	SAIL MANUF	2	3240	24300	24300	24300	S	A	S	4	5	20385	50.33	4995	3077.51	0.48	331	1.266	0.973	0	24	0	-0.2
31	BAR AND GRILL	25	2400	22800	25200	22800	S	A	G	7	5	6651	17.50	4600	628.79	0.6	655	2.34	0.641	0	505	987	-0.8
32	GOLF CLUB HOUSE	15	4351	43768	47861	43768	S	A	G/S	7	5	8426	11.55	7034	933.63	0.56	1051	1.91		1107	746	3038	-6.1
33	CHICKEN REST 1	30	3161	28330	28330	41093	F	C	S	3	3	6995	14.81	5616	720.55	0.58	1282	11.2		8410		10606	-8
34	HVAC CONTRACTOR	4	1796	14368	14368	14368	S	W	S	4	5	6145	25.66	3548	639.02	0.58	654	1.496	1.552	0	139	0	-0.1
35	CHICKEN REST 2	30	3321	28760	28760	53136	F	C	S	3	3	3689	7.70	5564	295.95	0.64		5.9		6360	464	9272	-43
36	PRINTING 1	25	16100	177100	177100	177100	F	N	N/S	1	0	11993	4.06	22590	911.5	0.66		0.34	0.11	191	627	369	1.2
37	REALTY 2	8	1845	14465	15682	26174	F	A	S	6	3	2241	9.30	3272	214.79	0.6	571	0.197	0.185	0	0	730	-4.4
38	INTERIOR DECORAT	5	3956	31648	44505	44505	F	C	S	2	2	3056	5.79	5972	264.04	0.63		0.245	0.362	0	7	0	-2.1
39	REALTY 3	12	2142	20149	20992	20992	S	A	G	2	5	5879	17.51	4049	409.445	0.68	1276	0.591	0.336	0	414	76	-0.5
40	SAFETY CLASS	35	2460	24600	24600	24600	F	C	S	4	5	10646	25.97	4700	1243.23	0.55	1268	0.607	0.334	0	2034	0	2
41	PET GROOMING	1	704	7040	7040	7040	F	C	S	4	5	3394	28.93	1904	295.56	0.62	214	0.498	0.531	0	43.3	0	0.6
42	GOV'NMENT OFFICE	36	6358	50864	92191	92191	F	C	S	2	2	20201	23.83	9038	815.34	0.82	7037	1.386	0.717	1155	1951	422	0
43	BAR	20	2108	21080	21080	30566	F	C	S	3	3	15625	44.47	4988	1374.47	0.62	196	0.872	0.822	0		0	0
44	SAFETY OFFICE	4	1328	10491	10491	10491	F	C	S	4	5	7560	43.24	2863	487.3	0.7	347	0.937	0.511	0	37	0	-1.5
45	SCHOOL SUPPLY	4	2550	25500	25500	25500	F	C	S	4	5	9133	21.49	4824	696.39	0.66	418	0.57	0.24	0	288	0	0
46	COURT OFFICE	19	3735	37350	37350	54158	F	C	S	3	3	32886	52.83	6285	704.52	0.98	830	0.462	0.422	0	600	0	0
47	MARSHAL ARTS	7	972	9720	9720	9720	F	C	S	4	5	5012	30.94	2602	203.47	0.82	304	0.675	0.221	0	69	0	-2.1
48	OFFICE SUPPLY	3	1322	12425	12425	12425	F	C	S	4	5			2873			283	0.865	0.362	0	142	0	-1.7
49	RETAIL VACANT	3	990	9900	9900	9900	F	C	S	4	5	3504	21.24	2610	383.86	0.57	233		0.575	0		0	0.9
50	RETAIL VACANT	3	990	9900	9900	9900	F	C	S	4	5	5108	30.96	1620	529.79	0.58	183		0.75	0		0	0.8
51	GAS COMPANY	27	5428	45987	46686	56389	F/S	C	S	6	3	9404	12.27	9388	822.88	0.62	4581	0.621	0.388	1130	245	111	0
52	TAX SERVICE	5	1800	16920	21150	21150	F	C	S/G	2	2	1943	6.89	3821	171.08	0.62	487	0.199	0.384	0	133	0	-0.6
53	METAL BLDG CO	17	3872	30202	41308	41308	S	C	S	2	2	3545	7.04	6704	268.64	0.66	1453	0.279	0.178	0	567	67	-2.1
54	REALTY 4	8	2635	21080	22845	21080	S	A	S	7	5	7673	21.84	4363	387.61	0.76	885	1.145	0.673	0	92	416	0.1
55	PRINTING 2	21	10000	100689	115000	115000	F	C	S/N	2	2	20346	12.12	15635	1939.05	0.6		1.093	0.939	0	357	0	-0.6
56	PLASTIC FABRICATE	5	12360	206880	206880	206880	S	N	N/S	1	0	15825	4.59	18684	1544.31	0.59		0.179	0.147	0		0	-0.6
57	AMUSEMENT PARK	20	7052	74270	78972	74270	F	C	S	4	5	26544	21.44	11507	4138.58	0.48	1291	0.757	0.428	0	231	305	0.9
58	HARDWARE STORE	6	4656	55872	55872	55872	S	A	G	4	5	4002	4.30	8136	351.81	0.62	422	0.185	0.147	0	0	93	-0.1
59	CARPET STORE	3	1584	17424	17424	17424	S	C	S	4	5	5338	18.38	3564	309.7	0.73	158	0.63	0.613	0	0	194	-0.8
60	MANUF OFFICE 3	6	840	6300	6300	6300	F	N	P	1	0	1281	12.20	1950	118.17	0.61	251	1.278	0.348	0	106	0	-0.6
61	MANUF OFFICE 4	6	1320	10560	10560	10560	F	N	P	1	0	3592	20.41	2632	360.65	0.59	793	1.012	0.452	0	128	0	-0.2
62	CHINESE RESTAURA	90	7854	74613	106029	106029	S	C	S	2	2	10172	8.18	12679	357.65	0.86		2.197		0	0	6495	-4.6
63	POLICE STATION	40	6641	53128	79692	79692	F	C	S	2	1	3407	3.85	10973	561.84	0.46		1.133	0.221	648	0	1297	-4.6
64	SCHOOL WING 1	150	10136	96292	111496	111496	F	C	S	2	2	7063	4.40	15104	555.45	0.65		0.78		913		790	3.1
65	SCHOOL WING 2	35	2000	20000	30660	30660	F	C	S	2	2	1735	5.21	3800	227.18	0.52		1.53		473		0	10.4
66	SCHOOL WING 3	100	5068	48146	55748	55748	F	C	S	2	2	11882	14.81	8650	1474.43	0.53		2.13		2480		0	4.8
67	HOTEL COMPLEX	50	15033	184122	184122	184122	F	C	S	4	3	23309	7.60	23055	4035.76	0.45		1.717		5955		12907	-3
68	HOTEL	60	12750	102000	102000	102000	F	N	G	1	0	11520	6.78	12055	1010.8	0.62		2.1		842		2799	-4.2
69	CONV. STORE 1	8	4320	41904	41904	41904	S	A	S	4	5	11746	16.82	7094	1053.98	0.62	1346	1.9		165	228	1620	-1.8
70	CONV. STORE 2	3	2520	29484	29484	29484	S	N	N	1	0	836	1.70	4915	65.97	0.65		0.14	0.17	0	0	0	-1.8
	AVERAGE	26.2	5030	52125	61455	63489						9131	16.70	7828	857.57	0.61	1212	1.25	0.43	697	418	1149	-1.12

APPENDIX C

Development of Technology Transfer Program for Improved Air Flow in Commercial Buildings

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Florida Solar Energy Center

December 5, 1995

1. NEED FOR TECHNOLOGY TRANSFER ABOUT UNCONTROLLED AIR FLOW

Important understanding of the nature, extent, and impacts of uncontrolled air flow in commercial buildings has been gained through research conducted by the Florida Solar Energy Center and funded by the Florida Energy Office through a project entitled **Study of Uncontrolled Air Flow in Non-Residential Buildings**. This project has found that uncontrolled air flow is a widespread and substantial problem affecting a large majority of commercial buildings. Of a total of 70 small commercial buildings tested in the Florida project, only one was identified by the researchers to have no significant uncontrolled air flow.

Some of the observed impacts of uncontrolled air flow include increased energy use, higher peak electrical demand, occupant comfort problems, elevated humidity, microbial growth, transport of contaminants from polluted zones into occupied spaces, mining of pollutants from the soil or combustion equipment, and indoor air quality problems. The consequences of uncontrolled air flow vary considerably from one case to another. Some buildings that have uncontrolled air flow experience almost no apparent consequences. In many other cases, there are substantial impacts, including some or all of the above listed consequences. Whether the uncontrolled air flow produces significant problems is usually just a matter of luck.

The energy savings associated with repair of uncontrolled air in small commercial buildings are truly enormous. Monitored repairs indicate that repair of uncontrolled air flow saves about 15% to 20% of annual cooling energy costs, on average. Based on the number of United States buildings with less than 25,000 square feet, energy savings from repair of uncontrolled air flow in small commercial buildings could yield as much as $3.5 billion per year. Clearly many jobs would be created as well.

Uncontrolled air flow in commercial buildings may have even greater financial impacts as a result of indoor air quality problems. Environmental illness or sick buildings may result from elevated humidity, inadequate ventilation, or elevated air contamination sources. Poor indoor air quality can result in greater occupant complaints, more sick leave, and reduced worker productivity. In some cases, buildings have to be evacuated because a significant number of persons have complained of sickness. Renovations to a sick building can run into the millions of dollars. Litigation can add even greater financial penalties. **While not easy to quantify, annual losses resulting from indoor air quality problems in commercial buildings caused by uncontrolled air flow may exceed 10 billion dollars nationwide.** Furthermore, these problems are on the increase.

Following is a brief discussion of some of the major findings from the Commercial Uncontrolled Air Flow Project which would form the basis for much of the proposed training.

1.1 Types of Uncontrolled Air Flow in Commercial Buildings

There are a number of major flaws that exist in standard small commercial buildings construction practice, related to building leakage, duct system leakage, and pressure imbalances. These include:

1) Duct systems in commercial buildings are leakier, on average, than residential duct systems.

2) Building cavities, such as mechanical rooms, ceiling spaces, and enclosed support platforms, are used as part of the air distribution system. Since building cavities are almost always quite leaky, this results in considerable air distribution system leakage.

3) Ceilings are typically very leaky (constructed with t-bar and ceiling tiles) and therefore often allow considerable air flow between the conditioned space and the ceiling space or attic space. Depending upon the temperature and humidity conditions of the air above the ceiling, there may be substantial energy and/or comfort penalties.

4) Closure of interior doors often causes pressure imbalances in small commercial buildings, just as was found in residential buildings, when returns are centrally located. The impacts may be greater in commercial buildings because the ceilings are often very leaky. While residential ceilings are constructed of gypsum board, and are consequently fairly airtight, commercial building ceilings are typically loose ceiling tiles, which are on the order of 10 times leakier than gypsum board ceilings. As a result, room air is easily pushed into the ceiling spaces above closed rooms and ceiling space air (often unconditioned) is drawn into the central and hallway portions of the building.

5) Return air pressure imbalance sometimes occur as a result of firewalls. In buildings that use the ceiling space as a return plenum, return air pathways (cross-over windows) through the firewalls are often undersized, resulting in some zones being pressurized and some zones being depressurized.

6) Commercial buildings often experience depressurization problems associated with exhaust fans. In hot/humid climates it is important for buildings to operate at positive pressure so that the relatively dry interior air bathes walls and other building cavities as it leaves the building, thus preventing moisture build-up (adsorption or condensation) on building surfaces and materials. Some buildings have large exhaust fans, especially restaurants, which may draw 5,000 cfm, 10,000 cfm, or even more air from the building. Attempts to balance the building air flow by means of "make-up air" and outdoor air often fail due to undersizing of these fans or cycling of the outdoor air.

7) Commercial buildings often provide "outdoor air" to ventilate the space and assist in producing positive pressure in the building. In some cases, outdoor air is oversized, which may lead to excess ventilation, higher humidity, mold/mildew, and energy waste.

8) In some cases, ventilation rates are less than required levels, sometimes leading to indoor air quality complaints, especially in building with large contaminant sources. Correcting problems of insufficient ventilation may lead to increased energy consumption. The costs associated with worker complaints and potentially reduced worker productivity, however, may cost much more than the additional energy. It also requires correct design so that the added ventilation produces positive building pressure. Adding ventilation that produces space depressurization can lead to a wide range of problems, as discussed in the following section.

1.2 Consequences of Uncontrolled Air Flow

Uncontrolled air flow in commercial buildings has a number of potential consequences. There are four **primary consequences** of uncontrolled air flow; 1) elevated infiltration, 2) pressure imbalances, 3) mining of contaminants (drawing pollutants from the soil, sewer system, or combustion equipment), and 4) transporting of heat, cold, or contaminants from unconditioned or polluted zones into the occupied space. There are a number of **secondary consequences** of uncontrolled air flow that follow from the primary consequences, including increased energy use, higher peak electrical demand, elevated relative humidity, mold/mildew growth in building cavities or in the building proper, occupant discomfort, and indoor air quality problems.

Duct leakage. Leakage in ducts or in building cavities used as ducts can cause energy waste, spikes in cooling system electrical demand, pressurization or depressurization of the building, or distribution imbalance so that individuals or zones do not receive sufficient air. Duct leakage can also contribute to excessive infiltration rates, which can produce elevated humidity levels and indoor air quality problems.

Leaky ceilings. T-bar ceilings (ceiling panels supported by a t-bar metal framework), used in nearly all commercial buildings, range from leaky to very leaky. Leaks occur because of cracks on four sides of each ceiling panel, because some tiles or portions of tiles are missing, and because fluorescent light fixtures are leaky. Because the ceiling often does not represent a significant barrier to air flow, the airtightness of the roof assembly (including walls and eaves above the ceiling level) becomes a very important factor in the building's overall airtightness. If the roof assembly is tight, then that commercial building may be airtight or even extremely airtight. On the other hand, if the ceiling space is vented to outdoors (intentionally or unintentionally), then the building may be quite leaky or even very leaky. As a consequence, it may be difficult to control flow of unconditioned air into the occupied space, either resulting from the dynamics of wind or the induced pressures of closed interior doors or exhaust systems. This can cause building cooling and heating loads to exceed design. It may also lead to high infiltration, high humidity, and mold/mildew growth.

Air distribution system air flow imbalance. In many commercial buildings, walls and closed doors create barriers to air flow. Often, returns are located in the central body of the building, while supplies are provided to individual rooms. When interior doors are closed, high pressure is created in the closed rooms and depressurization occurs in the central zone. As a result, conditioned air is pushed from the closed rooms into the ceiling space and in turn ceiling space air is drawn into the central zone. If the ceiling space is inside the building air barrier and the building thermal (insulation) barrier, then the impacts of this uncontrolled air flow may be minimal. On the other hand, if the space above the ceiling is unconditioned, such as an attic or a ceiling space where the insulation is located on top of the ceiling tiles, then there may be serious energy penalties.

In buildings where the ceiling is a return plenum, fire walls may restrict the flow of return air, and create pressure imbalances in the building. Pressure differences as great as 17 pascals have been measured between adjacent zones separated by fire walls. The impacts of these pressure imbalances depend upon the airtightness of the building shell and where the air flows originate.

These pressure imbalances can create substantial infiltration, cause humid outdoor air to be drawn into building cavities, precipitate mold/mildew problems, and cause combustion appliances venting problems.

Exhaust and make-up air imbalance. A significant number of commercial buildings have large exhaust fans which have the potential to significantly depressurize the building. In seven restaurants, pressure measurements found that all of these buildings operate at negative pressure, often in spite of make-up air and outdoor air. This is an area where architects, engineers, test and balance personnel, HVAC contractors, and builders need to understand the relationships between sizing of exhaust fans and make-up air fans, cycling of outdoor air (outdoor air stops working when the air handlers cycles off), and building airtightness.

Excess or deficient ventilation. Some buildings have excessive ventilation either because of oversized exhaust equipment or oversized outdoor air. In hot/humid climates this can lead to high relative humidity, mold/mildew problems, occupant discomfort, and high energy costs. Some buildings have less ventilation than required based on occupancy or pollutant sources. This can lead to build up of air contaminant levels, occupant discomfort and complaints, and potential reductions in worker productivity. In rare cases, inadequate ventilation can lead to problems of low humidity, in the 30% to 35% range, even in hot/humid climates.

1.3 Who Needs to Hear the Message about Uncontrolled Air Flow

There are a number of trade, construction, and professional groups who need this information in order **to design and construct buildings that work**. Specifically, those who need to better understand air flows in buildings and how to bring them under control include air conditioning contractors, building contractors, architects, mechanical engineers, and test and balance firms.

There are a number of groups that need this information **for diagnosing and correcting uncontrolled air flow problems in existing buildings**. These would include air conditioning contractors, energy consultants, indoor air quality consultants, building facility managers, and mechanical engineering firms.

Correct diagnosis and repair of uncontrolled air flow in commercial buildings requires intensive training. The interactions between air flow, building tightness, and pressure differentials cannot be easily be understood and identified without training in building systems interactions and diagnostic tools and methods. Without appropriate training, incorrect diagnosis, leading to wrong repair, will yield little energy savings, solve few indoor air quality problems, and potentially create new problems.

2. THE FLORIDA SOLAR ENERGY CENTER HAS A HISTORY OF SUCCESSFUL TECHNOLOGY TRANSFER

The importance of in-depth training for practitioners involved in diagnosing and repairing duct leaks in residences has been widely recognized. Training is even more important for commercial buildings because uncontrolled air flow in commercial buildings is more complex. Pressure imbalances and resulting indoor air quality problems in commercial buildings appear to be increasing, and therefore there is even greater need for highly trained individuals to be able to deal with these problems.

At the Florida Solar Energy Center (FSEC) we are receiving an increasing number of calls related to high bill complaints, comfort problems, high humidity levels, and mold/mildew in both homes and commercial buildings. In many cases, we suspect that uncontrolled air flow may be at the root of their problem. Even if uncontrolled air flow is not the root problem, it is essential that a diagnostician be capable of measuring air flows and pressures when determining the cause. When we receive many of these calls, especially related to commercial buildings, we are at a loss to know to whom we should refer these individuals. In other words, there is desperate need for training for a wide range of contractors, consultants, and professionals so that the growing problems of uncontrolled air flow can be correctly diagnosed and repaired in Florida and nationwide.

Recent history demonstrates that FSEC can successfully transfer important understanding and technology to the marketplace and have significant impacts on energy consumption in Florida buildings. In 1988, when the Florida Energy Office first provided funding for FSEC to research duct leakage in homes (with Lakeland Electric and Natural Florida Retrofit, Inc.), there were only a handful of persons in the state that owned and used blower doors. With state funding, duct repair training materials, a manual and video, and a duct school were developed. Now there are more than 500 contractors across the state that have been trained in building science, diagnostic methods, use of diagnostic tools, and duct repair. Duct repair programs have begun at numerous utilities in Florida and across the nation as a result of this training.

It is estimated that over the past four years, nearly 100,000 homes within Florida have had duct repairs and are now saving about $10 million per year in utility bills. This new duct repair industry has created an estimated 300 full-time new jobs. We believe that the benefits from commercial buildings training and tech transfer will exceed that of residential duct repair. We feel that if we can develop training materials, develop training curriculum, develop courses, write papers, and hold seminars and conferences, then a significant change will occur in the way buildings are designed, built, commissioned, maintained, diagnosed, and repaired.

3. PROPOSED WORK

We propose the following work:

1. Develop training courses, training materials including manuals, audio visual materials, and training models
2. Develop course curriculum
3. Offer a range of building science courses
4. Develop and sponsor national seminar and conferences on uncontrolled air flow
5. Publish a number of papers that will alert a national audience to the important issues related to uncontrolled air flow in commercial buildings.

A number of different courses could be offered. The following topics could be developed into individual classes or grouped together to form several larger courses.

1) How do buildings actually work
2) What failure modes exist in buildings
3) What impacts result from uncontrolled air flow
4) How do uncontrolled air flows create energy and IAQ problems
5) What is the cause of uncontrolled air flow
6) How to diagnose uncontrolled air flow problems
7) How to use diagnostic tools and equipment
8) How to repair uncontrolled air flow problems
9) How to design buildings which have optimized air flow control.

Courses would be developed for specific audiences -- designers, contractors, energy consultants, IAQ consultants, etc. We propose to develop training materials, including slides, transparencies, and a diagnostic/repair training manual for those involved in diagnosis and repair of **existing buildings**. We propose to develop a training curriculum, including a course outline, assemble materials for specific lectures, and prepare instructors for extensive courses.

We also propose to develop training materials for courses and classes on improved building and HVAC design, control, and commissioning for **new buildings**. This training would be directed toward design professionals, HVAC contractors, and test and balance contractors.

We propose to develop course curriculum for three or more classes (one-to-four day classes, depending upon the topic). This would include: 1) material to be covered, 2) list and content of lectures, 3) diagnostic labs, 4) repair training sessions, and 5) class agenda.

To aid in technology transfer, we propose to publish a minimum of six or more professional papers related to research findings and training development on uncontrolled air flow in commercial buildings. Publishing research results will help to disseminate the these findings to the research community (and practitioners as well) and establish the basis for further funding in this area of research. Additionally, we propose to host national symposia or conferences on the topic of uncontrolled air flow in commercial buildings and its impacts on energy, demand, and indoor air quality.

4. DELIVERABLES

1. We will produce a training document on diagnosis and repair of uncontrolled air flow in existing small commercial buildings. This document will incorporate how buildings work, an understanding of failure modes, diagnostic methods, how to use diagnostic tools, and how to determine effective retrofits.

   A good deal of work will go into defining and refining the steps of commercial building diagnosis. In our research, we developed many test methods and tools that serve to obtain a complete picture of what is occurring in buildings. In addition, we used a number of methods and tools, some of which are time-consuming and expensive, from a research perspective. Now we will streamline those methods into optimized protocols which yield the maximum information at the least expenditure of time and money, and using tools that cost no more than is necessary.

   Considerable effort will go into developing illustrations and curricula that make clear the types of uncontrolled air flows that exist in buildings, diagnostic test methods, and repair techniques.

2. We will produce design guidelines and a training document for new commercial buildings, including envelope airtightness, duct system location and construction, distribution system balancing, ventilation systems design and controls, location and characteristics of building air and thermal barriers, achieving pressure and air flow balance, and optimization of air and heat flows in commercial building construction. Considerable preparatory work will be done to develop best practice solutions which will eliminate many of the uncontrolled air flow problems which are wide-spread in commercial buildings. Considerable illustrations will be used in this document as well.

3. Curricula for at least three courses. Possible courses: 1) diagnosis and repair of uncontrolled air flow, 2) design of commercial buildings and air moving systems to optimize energy and indoor air quality, and 3) advanced diagnostic methods and tools in commercial buildings. Prepare diagnostic lab training aids (displays, etc.) to teach diagnostic methods, building system interactions, and repair of uncontrolled air flow.

4. Develop audio visual materials, including slides, dynamic training models, and overhead transparencies, to be used in training.

5. Write and publish six or more professional papers related to uncontrolled air flow in commercial buildings.

6. Host one or more national symposia/conferences on uncontrolled air flow and its effects on energy, ventilation, and indoor air quality.

5. SCHEDULE

We propose that this project run for 28 months.

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