NYSERDA--97-11

Effectiveness of Duct Sealing and Duct Insulation in Multi-Family Buildings

Final Report 97-11
July 1997

New York State
Energy Research and Development Authority

NYSERDA

The New York State Energy Research and Development Authority (NYSERDA) is a public benefit corporation created in 1975 by the New York State Legislature.

NYSERDA has major programs in energy and environmental research, radioactive and hazardous waste management, tax-exempt bond financing, energy analysis and planning, and energy efficiency grants. Its responsibilities include:

- Conducting a multifaceted energy and environmental research and development program to meet New York State's diverse needs;
- Helping industries, schools, hospitals, and not-for-profits implement energy efficiency measures;
- Providing objective, credible, and useful energy analysis to guide decisions made by major energy stakeholders in the private and public sectors;
- Managing the Western New York Nuclear Service Center at West Valley, including: (1) overseeing the State's interests and share of costs at the West Valley Demonstration Project, a federal/State radioactive waste clean-up effort, and (2) managing wastes and maintaining facilities at the shut-down State-Licensed Disposal Area;
- Participating in the Malta Rocket Fuel Area "Superfund" site clean-up and managing facilities at the site on behalf of the State;
- Coordinating the State's activities on nuclear matters, and designing, constructing, and operating State facilities for disposal of low-level radioactive waste, once siting and technology decisions are made by the State; and
- Financing energy-related projects, reducing costs for ratepayers.

NYSERDA derives its basic research revenues from an assessment levied on the intrastate sales of New York State's investor-owned electric and gas utilities. Additional research dollars come from limited corporate funds and a voluntary annual contribution by the New York Power Authority. More than 245 of NYSERDA's research projects help the State's businesses and municipalities with their energy and environmental problems. Since 1990, NYSERDA has successfully developed and brought into use more than 60 innovative, energy-efficient, and environmentally acceptable products and services. These contributions to the State's economic growth and environmental protection are made at a cost of less than $1 per New York resident per year.

Federally funded, the Energy Efficiency Services program is working with more than 220 businesses, schools, and municipalities to identify existing technologies and equipment to reduce their energy costs.

For more information, contact the Technical Communications unit, NYSERDA, Corporate Plaza West, 286 Washington Avenue Extension, Albany, New York 12203-6399; (518) 862-1090, ext. 3250; or on the World Wide Web at http://www.nyserda.org/

EFFECTIVENESS OF DUCT SEALING AND DUCT INSULATION IN MULTI-FAMILY BUILDINGS

Final Report

Prepared for

THE NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Norine H. Karins
Program Manager

with co-funding from

THE U.S. DEPARTMENT OF ENERGY
Washington, D.C.

Prepared by

STEVEN WINTER ASSOCIATES, INC.
Norwalk, CT 06854

Adrian Tuluca, R.A.
Project Manager

with

LAWRENCE BERKELEY NATIONAL LABORATORY
ENERGY PERFORMANCE GROUP
University of California
Berkeley, California

Mark Modera, Ph.D.
Project Manager

2024-EEED-BES-93

NYSERDA
Report 97-11

July 1997

NOTICE

This report was prepared by Steven Winter Associates, Inc. and its subcontractor Lawrence Berkeley National Laboratory in the course of performing work contracted for and sponsored by the New York State Energy Research and Development Authority and the U.S. Department of Energy, Office of Building Technology (hereafter the "Sponsors"). The opinions expressed in this report do not necessarily reflect those of the Sponsors or the State of New York, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Further, the Sponsors and the State of New York make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods, or other information contained, described, disclosed, or referred to in this report. The Sponsors, the State of New York, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

NYSERDA New York State Energy Research and Development Authority
William R. Howell, *Chairman*
F. William Valentino, *President*
Corporate Plaza West, 286 Washington Avenue Extension, Albany, NY 12203-6399
(518) 862-1090 • Fax: (518) 862-1091 • http://www.nyserda.org/

A NYSERDA Report in Brief

Report:	**Effectiveness of Duct Sealing and Insulating in Multifamily Housing Report 97-11**
Project Manager:	**Norine Karins**
Contractor:	**Steven Winter Associates**

Background: This report describes results of a research study aimed at evaluating the potential cost-effectivenss of sealing and insulating the accessible portions of duct systems exposed to unconditioned areas in multifamily buildings. Many multifamily buildings in New York State are heated, and sometimes cooled, with ducted air. The ducts leak, and often lose heat through conduction to the outside or to unconditioned spaces. Studies in single-family houses indicate 20-35% excess energy use for heating and cooling in ducted vs. non-ducted residences. A significant fraction of this extra energy use can be saved by sealing and insulating the duct systems. However, only a portion of the duct system can be accessed in multifamily housing.

Objectives: The project's objectives were to advance the theoretical knowledge on duct-air leakage, and also to help answer two practical questions. First, if accessible segments of the duct system are sealed and insulated, will the reduction in air leakage and conduction be appreciable? Second, will the sealing and insulation be cost- effective? The goals of the project were to ascertain the cost-effectiveness of sealing and insulating the accessible portions of the duct systems in multifamily residences.

R&D Results: A total of 25 apartments were tested in nine multifamily buildings in Cortland, Homer, Tully, and Ithaca, New York. The apartments were served by a total of 10 forced-air systems. All systems were natural-gas-fired furnaces. Two retrofit strategies were sequentially applied to the accessible ductwork in the unconditioned areas: sealing the leaks, and then insulating the ducts. Airflow and temperature measurements were performed before and after each retrofit strategy to evaluate the effect each had on system performance. Data were recorded, analyzed, and used to develop a prototypical multifamily residence. This prototype was used in energy and air infiltration-simulations. Simulations were then performed for two climates: New York City and Albany. Simulation results and average retrofit costs were used to calculate cost-effectiveness.

Test measurements reveal that airflow imbalances in apartments and systems changed between pre- and post-duct sealing. In any one apartment, duct-sealing reduced or increased the airflow imbalance. However, for the entire sample of apartments, the total airflow imbalance was reduced. A comparison between pre- and post-retrofit measurements reveals the improvements made in duct-air leakage, duct leakage area, and apartment airflow. On average, the leakage airflow was reduced by a minimum of 92 cfm for supply ducts, and a minimum of 223 cfm for return ducts.

The economic analyses revealed each retrofit's cost-effectiveness. Sealing proved cost effective in buildings with leaky or tight basements in both both Albany and New York. The simple payback was 3-4 years. In contrast, insulation was not cost-effective in buildings with tight basements (simple payback > 11 years) in either city.

However, the simple payback was no more than five years for buildings with leaky basements. In fact, in these buildings, the insulation increased the life-cycle savings by more than 60% over sealing alone.

Copies Available: To order copies of this report, contact the National Technical Information Service (NTIS): **(800) 553-6847**; (703) 487-4650 outside the U.S.; via Internet: **http://www.ntis.gov/ordering.htm**
NTIS product or order questions: **info@ntis.fedworld.gov**

For information on other NYSERDA reports, contact: New York State Energy Research and Development Authority, Corporate Plaza West, 286 Washington Avenue Extension, Albany, New York 12203-6399;
voice: (518) 862-1090, ext. 3241; fax: (518) 862-1091; e-mail: amt@nyserda.org; http://www.nyserda.org/

ABSTRACT

This research investigated the cost-effectiveness of sealing and insulating the accessible portions of duct systems exposed to unconditioned areas in multifamily housing. Airflow and temperature measurements were performed in 25 apartments served by 10 systems at 9 multi-family properties. The measurements were performed before and after each retrofit, and included apartment airflow (supply and return), duct system temperatures, system fan flow and duct leakage area. The costs for each retrofit were recorded.

The data were analyzed and used to develop a prototypical multifamily house. This prototype was used in energy simulations (DOE-2.1E) and air infiltration simulations (COMIS 2.1). The simulations were performed for two climates: New York City and Albany. In each climate, one simulation was performed assuming the basement was tight, and another assuming the basement was leaky. Simulation results and average retrofit costs were used to calculate cost-effectiveness.

The results of the analyses indicate that sealing leaks of the accessible ductwork is cost-effective under all conditions simulated (simple payback was between 3 and 4 years). Insulating the accessible ductwork, however, is only cost-effective for buildings with a leaky basement, in both climates (simple paybacks were less than 5 years). The simple payback period for insulating the ducts in buildings with tight basements was greater than 10 years, the threshold of cost-effectiveness for this research.

ACKNOWLEDGMENTS

The research benefitted from the technical review and management of Mr. Joseph Rizzuto and Ms. Norine Karins of the New York State Energy Research and Development Authority.

The Steven Winter Associates, Inc. team included major contributions from Adrian Tuluca, R.A., Ian Graham, and Devashish Lahiri, as well as technical support from Peter Stratton, Pawan Kumar, Jonathan Tham and Dennis O'Keefe. The Lawrence Berkeley National Laboratory team included Iain Walker, Ph.D., Mark Modera, Ph.D., and Darryl Dickerhoff.

We thank HSC Associates for their help in the field with insulating all the ductwork.

TABLE OF CONTENTS

TABLES

FIGURES

SUMMARY

Background

Many multi-family buildings in the State of New York are heated, and sometimes cooled, with ducted air. The ducts leak, and often lose heat through conduction to the outside or to unconditioned spaces. Studies in single-family houses (e.g., Modera et al, 1991) indicate 20%-35% excess energy use for heating and cooling in ducted vs. non-ducted residences. A significant fraction of this extra energy use can be saved by sealing and insulating the duct systems. However, only a portion of the duct system can be accessed in existing multi-family housing. This study endeavors to advance the theoretical knowledge on duct air leakage, and also to help answer two practical questions:

- If accessible segments of the duct system are sealed and insulated, will the reduction in air leakage and conduction be appreciable?
- Will the sealing/insulating be cost effective?

There are no *technical* obstacles to sealing accessible ducts, sealing furnaces, and to insulating exposed duct segments. However, the information on the cost-effectiveness of such measures is scarce.

- It is not clear how much air leaks through visible segments of the duct system, and how much leaks into the wall cavities.
- Further, it is unclear whether, by sealing the accessible segments of the duct system, the overall air leakage decreases, or whether most of the air simply finds a different leakage path out of the system.
- Also, it is not well established whether insulating the accessible duct and air handler segments has a significant effect on the heat loss of the entire system.

To assist in providing a technical and economic basis for retrofit activities, Steven Winter Associates, Inc. (SWA), with assistance from the Energy Performance of Buildings Group of Lawrence Berkeley National Laboratory (LBNL), performed testing and analysis of heat loss through air leakage and conduction from ducted air distribution systems in multi-family housing.

Goals

For the purpose of this investigation, a ducted system is defined as the furnace box and ducting.

The goals of the work were as follows:

- Ascertain the cost-effectiveness of sealing the accessible portions of the ducted system in multi-family residences.
- Ascertain the cost-effectiveness of insulating the accessible portions of the duct system in multi-family residences.
- Advance the knowledge of duct air leakage, and of its relationship to air infiltration rates in multi-family residences in the State of New York.
- Investigate the duct pressurization method as a means to estimate the reduction in duct leakage airflow and duct leakage area due to sealing.

Objectives

To attain these goals, the team obtained information about the following:

- Amount of air that leaks out of furnace boxes, and out of *all ducts* in each apartment
- Amount of air that leaks out of furnace boxes, and out of *those ducts that are readily accessible*
- Reduction in air leakage that can be practically obtained by sealing the furnace boxes and accessible ducts
- Room by room supply airflows
- Airflow imbalances between supply and return
- Pressure differentials from room-to-room when the fans are off and when the fans operate
- Comparison between total airflows obtained using flowhood and direct duct pressurization to verify and, if needed, to fine-tune the direct duct pressurization method
- Heat losses that occur through conduction in the *entire* duct system
- Heat losses that occur through conduction in those duct segments that are *exposed to the outdoor or to unconditioned spaces, and that are readily accessible*
- Reduction in conduction heat losses that can be achieved by insulating those duct segments that are exposed *to the outdoor or to unconditioned spaces, and that are readily accessible*

The team performed computer simulations to estimate the reduction in energy use that can be achieved by sealing and insulating the accessible portions of the duct system in existing multi-family buildings.

The team also characterized the cost-effectiveness (via simple payback and life cycle costing) of sealing and insulating the accessible portions of the duct system in existing multi-family buildings.

The study included a sample of 25 apartments. These apartments were located in 9 different buildings, and served by 10 different systems.

Research

To achieve the goals and objectives the research was performed in two phases. Each phase required several tasks:

1. Develop measurement protocol in phase one.
2. Select a minimum of 5 apartments for testing.
3. Perform detailed pre-retrofit and post-retrofit measurements in concert with a retrofit strategy, using the protocol.
4. Perform preliminary analysis on phase one results.
5. Revise measurement protocol for application in phase two, based upon the phase one results and phase two measurement requirements.
6. Select apartments for phase two testing.
7. Perform pre-retrofit and post-retrofit measurements in concert with retrofit strategies using the revised protocol.
8. Analyze the test results for both phases of testing.
9. Develop a prototype apartment building.
10. Perform air infiltration computer simulations.
11. Perform energy use computer simulations.
12. Perform a cost analysis, yielding simple payback and life-cycle costs.
13. Produce a final report.
14. Prepare a technical paper.

The 25 apartments tested (6 in phase one, 19 in phase two) were located in nine multi-family buildings from four adjacent towns: Cortland, Homer, Tully, and Ithaca. These buildings had five owners.

All apartments were located in buildings which had no less than three and no more than five dwelling units. All but one of the buildings were large single-family houses that had been converted to multi-family. The one exception was a building converted from a commercial use to mixed use: five dwelling units and a store-front commercial unit.

The apartments were served by a total of 10 forced air systems. All of these systems were natural gas fired furnaces. No cooling, central or otherwise, was provided in any of the apartments tested. Two retrofit strategies were sequentially applied to the accessible ductwork located in unconditioned areas: sealing the leaks, and then insulating the ducts. Airflow and temperature measurements were performed before and after each retrofit strategy, to evaluate the effect each strategy had on system performance.

The data collected were used to develop a prototype multi-family building. Based on this prototype, computer simulations projected energy savings for duct sealing and duct insulation. The cost effectiveness of these retrofit strategies was calculated in two locations: New York and Albany.

Results

Physically, the relationship between the surface area of the ducts and the total floor area of the buildings was fairly consistent across all buildings. On average the surface area of the exposed supply ducts was about 13% of the floor area served by the system. The surface area of the exposed return ducts was about 9% of the floor area, with somewhat more variation from building to building. In contrast, there was poor correlation between duct leakage area and duct surface area or floor area.

Also examined was the relationship between duct leakage and factors such as building owner, contractor, age, and observed condition of the ductwork. Based upon the sample, systems that are less than five years old appear to have less leakage, while the leakage in systems older than five years varies greatly. In addition, there appears to be a fairly predictable relationship between duct leakage and observed condition of the duct system. This is to say that, upon visual inspection, the researchers were reasonably accurate in predicting which systems would be leaky and which would not.

Test measurements reveal that airflow imbalances in apartments and systems changed between pre- and post-duct sealing. In any one apartment, duct sealing reduced or increased the airflow imbalance. However, for the entire sample of apartments, the total airflow imbalance was reduced.[1]

A comparison between pre and post retrofit measurements reveals the improvements made in duct air leakage, duct leakage area, and apartment airflow. In average, the leakage airflow was reduced by a minimum of 92 cfm for supply ducts, and a minimum of 223 cfm for the return ducts. This translates

---

1 Sealing alone cannot be relied upon to improve airflow imbalances. Imbalances may be designed or built into the system from the beginning, through poor design or construction. Therefore, proper airflow imbalance remediation must involve a formal balancing protocol, after sealing any duct leakage.

into about an 9% increase in supply air to the apartments and about 68% more air returned from the apartments. (If one of the systems with very poor return flow is not included in the calculation, the average increase in return airflow is about 17%.) The increase in return airflow has an impact not only on energy, but also on indoor air quality. The indoor quality will improve, because less basement air is introduced into the system.

Also, the sealing retrofit resulted in a reduction of 22% of the original leakage area. Therefore, the majority of the duct leakage is elsewhere in the duct systems (in walls or at registers).

Cost data were characterized on a per square foot basis. *Based upon exposed duct area*, the retrofit costs were $0.61/ft^2$ for sealing and $1.72/ft^2$ for insulating. The cost can also be expressed with respect to the floor area served by the system, because this research indicates that exposed duct area has a predictable relationship with respect to floor area. Therefore, *based upon floor area*, the costs are $0.12/ft^2$ for sealing and $0.34/ft^2$ for insulating. In either case the insulation had about three times the cost of sealing.

Computer simulations reveal that the air change rate for the living space increased after sealing in buildings with a leaky basement, and decreased after sealing in buildings with a tight basement. The simulations also reveal that the energy savings for sealing and insulating are about equal; about 3% each for a tight basement and about 5% each for a leaky basement. The energy savings in Albany are about twice those in New York.

The economic analyses revealed the cost effectiveness for each retrofit. Sealing proved to be cost effective in buildings with leaky or tight basements, for both Albany and New York. The simple payback (SPB) was 3 - 4 years.

In contrast, insulation was not cost-effective in buildings with tight basements, in either Albany or New York (SPB≥ 11 years). However, the SPB was no more than 5 years for buildings with leaky basements. In fact, in these buildings the insulation increased the life-cycle savings by more than 60% over sealing alone.

Chapter 1

PROJECT OVERVIEW

Air leakage occurs in duct systems for various reasons. Leaks may have been in the system since it was originally installed, because of loose fittings, gaps in duct connections, and poor transitions at building obstacles, such as stone foundation walls. Leaks may have developed over time due to fittings and duct connections slipping apart, or due to rusting through. Finally, leaks develop during changes to the duct system, when duct branches are added or removed without properly sealing the connections.

This study involved two retrofit techniques for duct systems: sealing the ductwork and insulating the ductwork. Both retrofits were applied to the exposed ductwork in unconditioned locations. The goals of the work were as follows:

- Ascertain the cost-effectiveness of sealing the accessible portions of the ducted system in multi-family residences.
- Ascertain the cost-effectiveness of insulating the accessible portions of the duct system in multi-family residences.
- Advance the knowledge of duct air leakage, and of its relationship to air infiltration rates in multi-family residences in the State of New York.
- Confirm the duct pressurization method as a means to estimate the reduction in duct airflow and duct leakage area due to sealing.

The retrofits were applied in sequence, sealing and then insulating, and were tested individually, to analyze the effect that each had on system performance. Airflow measurements were performed before and after sealing. After sealing, measurements characterizing the steady-state temperatures for the duct system temperatures were performed, then the ductwork was insulated and steady-state temperature were measured again.

THE APARTMENTS

The project involved testing of 25 apartments from nine multi-family buildings. As discussed below, these buildings had various owners, were located in different although adjacent towns, had different number of dwelling units, different types of occupants, different heating system configurations, and different heating system installers.

The towns where the testing took place (Cortland, Homer, Tully, and Ithaca) have the same general geographic location and the same climate. The apartments were located in buildings which had no less than three and no more than five dwelling units. All but one of the buildings were large single-family houses that had been converted to multi-family. The one exception was a building converted from commercial use to mixed use: five dwelling units and a store-front commercial unit.

The occupants of the apartments tested included older (retired) people, young and middle age adults, children (infancy through adolescents), and college students. Some occupants were on welfare; others worked or studied.

All apartments were served by natural gas-fired furnaces. The systems differed in the number of apartments that were served. Some systems served individual apartments; others served two or more apartments. In addition, some systems were connected to older existing ductwork, while other systems had new ductwork throughout.

Systems were was also fabricated by different installers. Some systems were installed by the landlords; others were installed by professional HVAC contractors. The apartments and HVAC systems are discussed further in chapter two.

As a result of this diversity, the duct systems tested cover a broad cross-section of conditions that can be encountered in multi-family residences.

TEST PROCEDURE

The twenty-five apartments tested were served by ten systems. The testing was performed in two phases.

Phase I

The first phase used a more detailed testing protocol and was applied to six apartments served by three systems. The testing protocol was designed to indicate how one could reduce the amount of work in phase two and still obtain useful information on the effect of duct sealing and duct insulation. It called for measuring the following:

- Total airflow through the system fan
- Airflow for each supply and return register
- Leakage airflow for the entire duct system using duct pressurization

- Leakage airflow for the supply duct work using duct pressurization
- Steady state system operating temperatures

One technical goal of both the first and second phase was to evaluate duct pressurization as a means for determining the air leakage rate from the duct system. This evaluation would compare the air leakage determined from the duct pressurization results and the air leakage determined by the difference between system fan flow and the sum of the register flows. It is known that the leakage area obtained through duct pressurization is not a good predictor of seasonal air leakage rates in any given system. The question was whether over a larger number of systems, from a statistical perspective, duct pressurization could yield reasonable estimates of air flow, and reasonable estimates of air flow reduction due to sealing.

A second goal of phase one was to measure the change in system fan flow subsequent to duct sealing. In general, as duct leaks are sealed the fan has to overcome greater friction in ducts and moves less air. When one measures the increase in supply air at registers after sealing, this increase is affected (diminished) by the fact that the fan moves less air. Therefore, the increase of airflow to apartments yields a *conservative* representation of how much leakage area was sealed. Phase one attempted to estimate how conservative this estimate was, since phase two did not include system air flow measurements, but only register measurements. A similar situation occurs with return air flows.

Phase one used duct pressurization as a method for determining the reduction in leakage area due to sealing. It used air flow measurements at supply and return registers, as well as for the entire system, to determine the effect of sealing on air supply to apartments, on airflow balance in apartments, and on total air moved by the fan. Temperature measurements were used to estimate the effect of duct insulation.

Phase II

The second phase involved 19 apartments served by seven systems, with a reduced test protocol measuring the following:

- Airflow for each supply and return register
- Leakage airflow for the entire duct system using duct pressurization
- Steady state system operating temperatures

Phase two used the duct pressurization as a method for determining the reduction in duct leakage area due to sealing. It applied airflow measurements at supply and return registers to determine the increase in supply air to apartments after sealing, and the airflow balance in apartments after sealing. Temperature measurements were used to estimate the effect of duct insulation.

The savings attributable to the retrofit strategies, sealing and insulating, was determined from the data collected in both phases. Also, the information collected was used to develop a prototype multi-family building. Computer simulations for airflow (COMIS) and energy (DOE-2.IE) were performed for the prototype building to generalize the cost effectiveness of each of the retrofit strategies.

RETROFIT PROCEDURE

Duct Sealing

The test personnel sealed the accessible leaks. The leaks were found during the initial inspection, while the test measurements were being made, and also during the sealing process.

The time needed to seal the leaks varied significantly from one installation to another. Systems with overall high leakage rates were characterized by large percentage differences between the static pressure at plenum and registers, as explained below. These systems usually had high leakage rates in accessible areas, and took longer to seal. One system had holes in the ducts, which had to be covered with sheet metal. During the sealing process the duct system was kept pressurized in order to monitor the effect of sealing specific leaks, and to aid in locating leaks. The sealing was stopped when no leakage sites were visible any longer, and when by sealing joints where leaks were not visible but possible (suspected) the team no longer reduced the differences in static pressures between registers and plenum.

The leaks were sealed using a commercial grade mastic. This mastic is formulated with an acrylic resin emulsion and contains fibers which provide reinforcement for the dried film. The mastic is water soluble until it cures, and when dry, is tough, flexible, fire resistant, and weatherproof. The application was performed by hand, trowel, and brush. No specialized equipment was required for a successful application. The application was performed according to the manufacturer's recommendations. (See appendix for technical specifications of the mastic.)

For large leaks the mastic was applied over an open mesh fiberglass tape, similar to fiberglass drywall tape. When the mastic would not seal a leak with one coat, it was applied in several coats. Long curing times were not required between coats for successful application of the product. The working temperature of the ductwork allowed the mastic to set quickly (less than half an hour), ready to accept a second coat.

Also, in none of the systems was the duct pressure so large that the mastic was forced out of a leak. As mentioned previously, the systems were pressurized, using the calibrated-fan, during the sealing process. This technique enabled the personnel to locate the leaks more easily. The air moving through a leak could be felt by hand, with a thin strip of paper, smoke stick, or the visible movement of the ubiquitous cobwebs around the ducts.

Finally, locating the leaks was facilitated by measuring the static pressure at each of the taped registers with the duct system pressurized. In a perfect duct system (i.e., no leaks) the static pressure is equal in all parts of the system when the system is pressurized and all registers are taped. However, a real system has leaks and the static pressure at the registers will vary with the amount of leakage in the branch; the greater the leakage in the branch the lower the static pressure at the register. Branches with small amounts of leakage have static pressures close to that at plenum. A register pressure which was significantly less than the rest indicated where the personnel should focus on searching for leaks. Register pressures which were uniformly less than the plenum pressure indicated that the there were leaks in a section common to all of the ductwork (i.e., in a main branch or at the plenum).

The time spent by the testing personnel and amount of material consumed (mastic, fiber-tape, brushes, etc.) while sealing the leaks for each duct system was recorded.

Duct Insulation

After all airflow measurements were performed pre and post-sealing, the duct systems were insulated. Two inch (2 in.) fiberglass duct-wrap with a foil-faced vapor barrier was installed. The installation was performed by an HVAC subcontractor according to the manufacturer's recommendations. (The appendix contains manufacturer specifications for the insulation used.)

This retrofit consisted of insulating all exposed metal duct (supply and return), except for the metal panning on joists. Metal panning on floor joists was only used to form return ductwork. The small temperature difference across the return ducts leads to a relatively small amount of conduction heat loss. Because of this small loss, an argument can be made for not insulating the returns at all; however, in this study both supply and return were insulated for completeness.

The subcontractor billed the insulation work on a time and materials basis.

Chapter 2

CHARACTERIZATION OF THE APARTMENTS

The project involved the testing of 25 apartments from nine multi-family buildings. These apartments were representative of different owners, locations (towns and properties), building types, number of dwelling units per property, occupants, heating system configurations, and heating system installers.

APARTMENTS

The apartments tested were located in nine properties from four adjacent towns: Cortland, Homer, Tully, and Ithaca. These properties had five owners.

All apartments were located in buildings which had no less than three and no more than five dwelling units. All but one building were large single-family houses that had been converted to multi-family. The one exception was a building converted from a commercial use to mixed use: five dwelling units and a store-front commercial unit.

The properties will be referred to by number (1-9) in this report. At property five there were two apartments served by separate systems; these systems are referred to as 5.1 and 5.2 throughout the report.

Table 2-1 : General Characteristics of Multi-Family Houses Tested

Property	Owner	Built	Apartments Total	Apartments Tested	Floor Area of Tested Apartments* (ft^2)	Number of Systems Tested
1	A	1890	5	1	1332	1
2	B	1978 (addition)	5	2	1167	1
3	B	1920-30	3	3	2890	1
4	B	1920-30	4	4	2271	1
5	A	1920	3	2	2583	2
6	C	1890	5	4	2162	1
7	B	1920-30	4	4	2614	1
8	D	1860	4	4	3248	1
9	E	1890	4	1	1103	1

* The figures represent the sum of the floor areas of all apartments tested in the building.

Table 2-1 indicates that some of the apartments in a building were not tested. There were several reasons for this, including:

- Apartments were not served by an air system. For instance, some attic apartments were heated with electric baseboards.
- The configuration of the duct system was unsuitable for this study. For instance, several apartments had dedicated furnaces sharing a common return plenum but had separate supply plenums.
- The ductwork did not pass through unconditioned areas, or was inaccessible in the unconditioned areas. For instance, the ductwork ran above a suspended ceiling that was below the original ceiling, and therefore in a quasi-conditioned space which would not have been accessible without major inconvenience to the occupants.

The table also lists the number of systems tested per building. This information indicates that the study involved six (6) systems that served multiple apartments, and four (4) systems that served individual apartments.

HVAC SYSTEMS

All systems tested provided heating only; none provided central cooling. Also, no window or through the wall air conditioning units were in any of the apartments.

The lack of mechanical cooling equipment could be attributed to several factors, including:

- The property owners are not required to provide cooling.
- The building occupants may not have ability or desire to make the financial investment.
- Summer design data for this area indicates that cooling is not a major concern. For Ithaca and Cortland (the other towns are very close to these locations) the 5% summer design dry-bulb temperature is 82°F and the 1% design dry-bulb temperature is only 88°F.

Heating was supplied by natural gas fired furnaces for all systems tested; two of these furnaces were high-efficiency condensing type. None of the systems used electric or fuel oil furnaces, and none used heat pumps. (The weather conditions in this part of New York, with relatively long cold winters followed by relatively mild summers, are not particularly suited to using heat pumps.)

The following two tables summarize the measured exposed duct areas. The apartment floor area includes the total area of all the apartments served by the system.

Table 2-2: Phase I - Exposed Duct Surface Area

Property	Apartment Floor Area* (ft^2)	Exposed Duct Surface Area (ft^2)			Exposed Duct Surface Area/ Apartment Floor Area	
		total	supply	return	supply	return
1	1332	312	206	106	0.15	0.08
2	1167	391	167	224	0.14	0.19
3	2890	368	179	189	0.06	0.07
Mean	1796	357	184	173	0.12	0.11
Max	2890	391	206	224	0.15	0.19
Min	1167	312	167	106	0.06	0.07
Std. Dev.	776	33	16	49	0.04	0.05

* The figures represent the sum of the floor areas of all apartments tested *and served by a single system.*

The exposed surface area of ducts scaled with the floor area conditioned by the system. The ratio of *exposed supply* duct surface area to apartment floor area was similar for four of the systems at about 12%. (This was also true for the other 20 systems in this study, per Table 2-3.) The anomaly was the system of property #3, which had a smaller than average duct system.

Table 2-3: Phase II: Exposed Duct Surface Area

System	Apartment Floor Area* (ft^2)	Exposed Duct Surface Area (ft^2)			Exposed Duct Surface Area / Apartment Floor Area	
		total	supply	return	supply	return
4	2271	423	290	133	0.13	0.06
5.1	1413	258	155	103	0.11	0.07
5.2	1170	236	140	96	0.12	0.08
6	2162	380	212	168	0.10	0.08
7	2614	628	332	296	0.13	0.11
8	3248	576	433	143	0.13	0.04
9	1103	286	201	85	0.18	0.08
Mean	1997	398	252	146	0.13	0.07
Max	3248	628	433	296	0.18	0.11
Min	1103	236	140	85	0.10	0.04
Std. Dev.	744	143	98	67	0.02	0.02

* The figures represent the sum of the floor areas of all apartments tested *and served by a single system.*

The results in Table 2-3 show that in these systems the conditioned average floor area was about 2,000 ft^2, and that the *exposed supply* duct surface area was about 13% of the floor area. The *exposed return* duct surface area was about 7% of the floor area. The ratio of supply duct surface area to floor area is relatively consistent from system to system, and consistent with the systems in phase one. For the returns, however, there was a wider range of return surface area ratios. This was because the systems have fewer returns; therefore placement of each register relative to the furnace becomes critical when determining the size of return ducts.

All ductwork in accessible and unconditioned spaces was exposed to unconditioned basements. There was no accessible ductwork in unconditioned crawlspaces or attics. As mentioned before, most buildings were converted from single to multi-family use. In addition, many of the duct systems were converted to reflect this change in use, and often to upgrade the older distribution systems. As a result, all except two of the duct systems (#2 and #9) had new ductwork connecting to at least part of an existing duct system.

The supply and return ducts were fabricated predominantly from galvanized sheetmetal. However, sheet aluminum was used to fabricate all the ductwork in one system (#6), and part of the return ductwork of another (#3). Sheetmetal panning fastened to the bottom of floor joists was commonly used to form parts of the return ductwork in many of the systems. One system (#2) had plywood panning forming some of the supply ductwork. In three systems (#2, #5 and #8) plywood was used to fabricated whole sections of supply and return ductwork. Flexduct was used in parts of two systems (#2 and #4).

Interviews were conducted with the building owners to collect information about who installed the system and when. Testing personnel inspected two of owner C's properties, with three systems. Four of owner B's properties with six systems were inspected. For owner A, six properties with 19 systems were inspected. In addition to the buildings tested in this study, 6 other properties with 23 systems were inspected. The inspection process provided insight as to the quality of construction available in the area. This experience allowed a qualitative comparison of the installations encountered. The following table contains a *qualitative* assessment of the overall condition of the ductwork, provides information on the year the system was installed, and on the contractor, if known.

The information presented in Table 2-4 indicates that the systems were installed by at least four different contractors. Based upon the systems tested and inspected in this study, the quality of an installation (rated by the researchers based on a visual inspection) may have some relationship with the property owner. One contractor installed systems for two different owners. The quality of the installation was consistent with the workmanship found at other properties of each owner. However, the sample is too small to draw any conclusions.

Table 2-4: Quality of Installation for Systems Tested

Property	Owner	System Installed	Furnace Size (Btu/hr)	Contractor	Opinion on Quality of Installation*	Remarks
1	A	1983-84	75,000	-	1	Large leaks in the basement
2	B	1978	90,000	-	3	Plywood ductwork; all new ductwork
3	B	1980's	125,000	-	4	Loose fitting register boots
4	B	1989	105,000	X	5	Only some small leaks
5.1 5.2	A	1985	105,000 105,000	X	2	Rust holes in ducts and large return leak at foundation wall
6	C	1985	105,000	Owner	3	Sheet aluminum ductwork; a broken duct
7	B	1993	100,000	Y	4	Condensing furnace
8	D	1970's	220,000	-	2	Disconnected duct, section of plywood duct
9	E	1989	40,000	Z	4	Condensing furnace; all new ductwork

* - Quality of installation, as observed by researchers, using a scale where 1.00=worst and 5.00=best

The age of the installation correlated with the quality of the installation, where the quality was rated by researchers based on visual inspection, as noted above. The installations that appeared to be in the best condition were those installed most recently (#4 and #9 in 1989, and #7 in 1993). The installations judged to be in worse condition were older, although here the line of demarcation is less clear.

In conclusion, no systematic correlation could be established between the owners, contractors, or size of the HVAC systems and the observed condition of the duct system. The age of the HVAC system correlated to some extent with the observed condition, with new systems (built within 5 years) being in best condition. Older systems varied in observed quality, partly because of retrofits. For systems in this study that were older than 5 years, one could not have consistently predicted in advance, before the site inspection, whether the duct systems would appear to be in good condition or otherwise. Chapter 4 addresses whether a correlation exists between these variables (owner, contractor, age, observed duct condition) and the opportunity for duct sealing. The opportunity for duct sealing is measured by the leakage area reduction and by increases in supply/return airflows after retrofit.

Chapter 3

METHODOLOGY AND TEST MEASUREMENTS

AIR FLOW MEASUREMENTS

Two methods were used in this study to characterize duct leakage: airflow and pressure measurement tests, and duct pressurization tests. Temperature measurements were taken to determine the conduction heat losses.

Flow and Pressure Measurements

A fan-assisted flowhood system was used to measure the supply and return airflows at each of the registers in an apartment. A calibrated-fan was used to measure the airflow through the system fan. Each procedure measures the airflow directly.

System Components

A device known as a calibrated-fan was used for all airflow measurements. A calibrated-fan is a variable speed fan with an integral vacuum pressure-sensing element. The sensing element is located in the inlet path of the air flowing through the fan. Calibration equations, determined for the fan, define the relationship between the measured vacuum pressure and the corresponding airflow.

The calibrated-fan is the main component of a system consisting of the following equipment:

- Calibrated-fan
- Electric fan speed controller
- Flexible extension duct
- Digital manometer
- Flowhood (used for register airflows only)

The accuracy of the calculated airflow is ±3% of the calculated flow for the calibrated-fan and the digital manometer used (see appendix for the technical specifications of the equipment).

Register Airflow

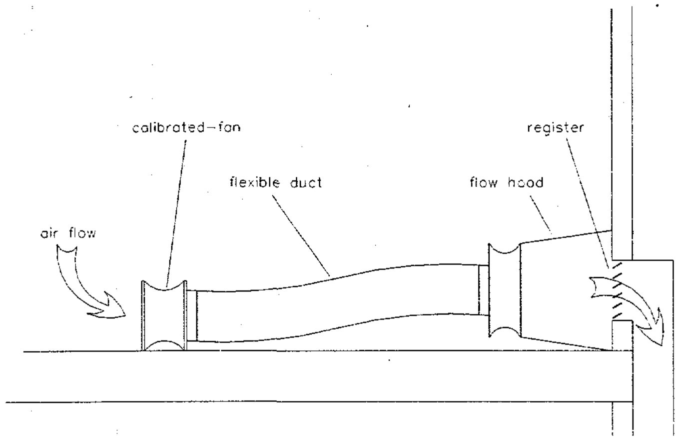


Fig. 3-1: Equipment configuration for register flow measurement

A calibrated-fan assisted flowhood arrangement was used to accurately measure the airflow through the apartment registers. This is the same method used by others to measure the low airflows associated with residential systems.[2] Although flowhoods are capable of measuring airflows directly, the measurement error is typically a minimum of 6 cfm. Since the airflow found in residences may be as low as 25 cfm, the 6 cfm error can result in measurement error of about 25%. In contrast, the measurement error for the calibrated-fan system is 3%.

The calibrated-fan system for measuring the register flows is a depicted in the Figure 3-1. Under normal operating conditions the pressure at the register is equal to the room pressure. The measurement system changes this pressure by increasing the resistance to airflow. These changes affect the airflow through the register. Varying the speed of the calibrated-fan until the hood pressure matches the room pressure compensates for the presence of the instrumentation.

Simply stated, the calibrated-fan compensates for the changes caused by the instrumentation, and thus enables accurate measurement of the register airflow.

When the hood pressure equaled the room pressure the calibrated-fan (vacuum) pressure was recorded, and the register flow was calculated. A set of register flow measurements was made pre-sealing, and another set was made post-sealing.

---

2 Jump, D.A. and Modera, M. 1994, "Energy Impacts of Attic Duct Retrofits in Sacramento Houses", Proceedings of ACEEE 1994 Summer Study, Asilomar, CA.

System Fan Flow

The calibrated-fan was also used to measure the system fan flow. Measuring the system fan flow involved forcing all of the airflow through the calibrated-fan. This was accomplished by blocking off the air path into the system fan from the return plenum (using duct tape and cardboard). The calibrated-fan was then connected to the fan housing, via the fan-access opening; Figure 3-2 illustrates this connection. The airflow measured at the calibrated-fan represents the airflow through the system fan, because the calibrated-fan is the only source for air.


Fig. 3-2: Fan flow test setup

The resistance to airflow of the instrumentation will not equal the resistance to airflow of the return ductwork. This means that the supply plenum pressure will change. The operating pressure in the supply plenum was measured and recorded prior to connecting the calibrated-fan. When the measured plenum pressure, during the test measurement, equals the normal operating pressure, the system fan flows are equal. The calibrated-fan speed is adjusted until the pressures match. When the plenum pressure is matched, the calibrated-fan pressure is recorded, and the fan flow is calculated.

The system fan flow was measured pre-sealing and again post-sealing/pre-insulating during the first phase only.

Duct Pressurization

Duct pressurization is a method for characterizing the leakage area in a duct system. Duct pressurization measures duct leakage area in the same way as a blower door test measures leakage in a house. Simply stated, the measurement process involves pressurizing the ductwork to a prescribed pressure and recording the airflow at that pressure. The leakage area is then determined for a representative system pressure.

The duct system is pressurized using a calibrated-fan connected to the system fan box. The air leakage through the duct system is described by equation (1):

$$Q_{leakage} = C(\Delta P_{duct})^n \quad (1)$$

Where:

C is the constant flow coefficient $[m^3/s \cdot Pa^n]$

n is the flow exponent [dimensionless]

ΔP is the pressure difference across the duct [Pa]

With a series of flow measurements made at different duct pressures the leakage characteristics of the duct system can be determined. Values for "C" and "n" are calculated from a curve-fit made to the data collected.

The effective leakage area (ELA) can be described as a function of the duct pressure, when "C" and "n" are known.

$$ELA_{25} = \frac{Q_{25Pa}}{(2\ \Delta P_{25Pa}\ /\ \rho)^{0.5}} \tag{2}$$

Where:

Q_{25Pa} is the calculated duct leakage at 25Pa $[m^3/s]$

ΔP_{25Pa} is equal to a 25Pa reference duct pressure

ρ is the density of air $[Kg/m^3]$

For duct systems a reference pressure equal to 25Pa is used, because system duct pressures are typically between 10Pa and 50Pa.[3]

Thus, the equivalent leakage area values, at 25 pascals, (ELA_{25}) can be calculated from a flow coefficient, C, and flow exponent, n, derived from a power law fit to the measured leakage flows and pressures. The flow exponent can be a guide to the type of leak in a system. With $n \cong 0.5$ the leaks are most likely to be sharp edged (orifice like) holes, and as the leakage paths become longer and have smaller diameters, the parameter n tends towards a value of 1.0.

In summary, the duct pressurization measurements provide an indication of the magnitude and shape of the leaks in a system. Characterizing different systems at the same duct pressure allows comparison of the relative leakage areas.

---

[3] Modera, M.; Dickerhoff, D.; Jansky, R.; and Smith, R,; 1991 "Improving the Energy Efficiency of Residential Air Distribution Systems in California, Final Report, Phase I", Lawrence Berkeley Laboratory Report, LBL-30886, Berkeley, CA

The duct pressurization tests were performed with the system fan off, and with the registers sealed. Sealing was accomplished by taping over the grilles. The static pressure in the duct was monitored at the supply plenum using a pitot tube. The ducts were pressurized with the calibrated-fan connected to the fan-access opening (as for the fan flow measurement, described above).

The desired duct pressure was achieved by varying the calibrated-fan speed. The air flowing through the calibrated-fan represents the leakage at the chosen duct pressure. Duct and calibrated-fan pressure were recorded, and the airflow calculated.

Duct pressurization leakage was measured for all of the systems tested. Supply and return leakage was only measured during the first phase. The return leakage was defined as the difference between the total and supply leakage. Measuring the supply leakage involved isolating the return ductwork from the supply ductwork. This was accomplished by blocking the air path from the return plenum into the system fan housing (as in the fan flow measurement, described above).

Duct pressurization tests were performed pre-sealing and again post-sealing/pre-insulating.

TEMPERATURE MEASUREMENTS

Temperature measurements were performed to determine the energy savings due to insulating the ductwork.

A set of steady-state temperature measurements was made post-sealing/pre-insulating and another post-insulating. These measurements characterized the effect that the insulation had upon reducing duct conduction losses.

Temperature Measurements

Air temperature measurements were made at several locations:

- supply and return plenums
- supply and return registers

The fractional heat loss is calculated by dividing the weighted average of temperature drops along all ducts by the temperature rise across the furnace or heat pump. The temperature drops along the duct branches are weighted proportionately to the airflow at each diffuser.

The measurement procedure involved turning the system on, allowing it to reach a steady-state condition, and recording register and plenum temperatures. The time of each measurement was also recorded. (Recording the time allows coordinating the register temperature with the plenum temperature.) One person went through the house measuring the register temperature and recording the time, while another person recorded the plenum temperature every minute until all of the registers were measured.

TEST PROTOCOLS

The team performed a full battery of tests on 6 apartments to advance the theory of duct leakage measurements and to refine the testing method for the remaining apartments:

- The flowhood tests measured the amount of air moving through each supply and return register.
- The calibrated fan was used to measure the amount of air moved by the HVAC system fan.
- The direct duct pressurization tests measured the amount of air moved by the pressurization fan, at specified pressure levels, in the entire duct system, and also in the supply ducts only. From these data, the effective leakage areas were calculated.

The flowhood tests were used to detect whether any systematic bias occurred with the airflows measured using the duct pressurization tests. The flowhood tests also yielded information on the room-by-room distribution of flows and pressures. These data indicated what supply/return flow imbalances existed, and supported the calculation of air exchange rates, for use with the energy simulations.

For the remaining apartments, the team performed duct pressurization tests for the entire duct system, as well as flowhood tests at all supply and return registers (but without direct measurement of the airflow through the fan).

The flowhood tests and the duct pressurization tests (for all 25 apartments) were performed with the accessible duct system both unsealed and sealed. Temperature measurements were performed in all apartments, both with and without duct insulation. Duct insulation was applied after the duct system was sealed.

Test protocols for each phase were developed by Lawrence Berkeley National Laboratories and Steven Winter Associates, Inc., and approved by the client. The protocols provided the testing personnel with detailed instructions regarding all steps in the data collection process. The protocols included data and testing checklists, tenant questionnaires, step-by-step measurement system configuration, and tables to record the measurements. The test protocols are provided in the appendix.

Chapter 4

SUMMARY OF TEST RESULTS

SYSTEM IMBALANCES

During the first phase of the testing, space pressure differences were measured at several locations for each apartment in order to assess the effect of system imbalances.

At Property 1, apt. 1, the indoor to outdoor pressure difference (Pin-Pout) post retrofit was 1.1 Pa with the fan off and 0.5 Pa with the fan on, indicating a slight depressurization of the apartment.

At Property 2, apt. 1, (Pin-Pout) measured at a window was -0.7 Pa with the fan off and +1.7 Pa with the fan on. This shows that the apartment was pressurized by about 1 Pa by the heating system operation. In Apt. B the inside to outside pressure difference measured at a window was affected by fluctuating wind pressures such that the variation in measured pressure was the same with the fan on or off (-1 to +3 Pa).

Fluctuations in wind speed and direction during the winter period when the tests were performed (and possibly the operation of heating systems in adjoining apartments) produced pressure changes that were the same size, or larger, than the pressures caused by fan operation. The only way to eliminate this difficulty would have been to perform long term measurements (averaged over several months, or at least over several weeks) to obtain the average effect of fan operation. Since the project scope did not include monitoring, the system imbalances were estimated through register airflow measurements.

There was an average of 3.8 supply registers per apartment, but only 1.2 return registers. In general, there was a supply register for every room, but the return registers were centrally placed within the apartment. In fact, five of the apartments had no return registers, and the maximum number of returns was three in any apartment. This meant that there was a strong likelihood for pressure imbalances between rooms of the apartments. Large leaks in the returns also implied that the apartments would typically be pressurized with respect to their surroundings due to the imbalance between supply and return flows. Supply and return register measurements indicate the amount of imbalance in each apartment, and in each system. The following tables shows the airflow imbalance for each apartment and for the entire system. In this study the airflow imbalance is defined as the following:

$$Airflow\ Imbalance = \frac{Supply - Return}{Supply},\ when\ Supply \geq Return \tag{3}$$

$$Airflow\ Imbalance = \frac{Supply - Return}{Return},\ when\ Supply < Return \tag{4}$$

Table 4-1: Airflow Imbalance by Apartment, Pre and Post Sealing

	Pre-Sealing			Post-Sealing		
	Supply (cfm)	Return (cfm)	Imbalance[1]	Supply (cfm)	Return (cfm)	Imbalance[1]
Property 1						
Apt #1	526	111	0.79	494	259	0.48
Property 2						
Apt #1	293	117	0.60	308	146	0.53
Apt #2	216	141	0.35	218	282	-0.23
Property 3						
Apt #1	203	116	0.43	280	128	0.54
Apt #2	219	317	-0.31	269	373	-0.28
Apt #3	452	0	1.00	532	0	1.00
Property 4						
Apt #1	205	64	0.69	210	63	0.70
Apt #2	413	674	-0.39	426	742	-0.43
Apt #3	101	0	1.00	102	0	1.00
Apt #4	162	0	1.00	165	0	1.00
Property 5						
Apt #1	981	227	0.77	1,050	1,077	-0.03
Apt #2	710	669	0.06	787	842	-0.07
Property 6						
Apt #1	198	198	0.00	241	224	0.07
Apt #2	271	144	0.47	284	200	0.30
Apt #3	53	108	-0.51	54	191	-0.72
Apt #4	449	0	1.00	486	0	1.00
Property 7						
Apt #1	239	159	0.33	244	172	0.30
Apt #2	362	234	0.35	383	249	0.35
Apt #3	189	75	0.60	199	79	0.60
Apt #4	312	88	0.72	321	100	0.69
Property 8						
Apt #1	258	378	-0.32	308	553	-0.44
Apt #2	257	971	-0.73	273	956	-0.71
Apt #3	594	193	0.68	683	244	0.64
Apt #4	387	0	1.00	443	0	1.00
Property 9						
Apt #1	821	594	0.28	852	643	0.25
Mean all	355	223	0.57	385	301	0.53
Maximum all	981	971	1.00	1,050	1,077	1.00
Minimum all	53	0	0.00	54	0	0.03
Std. Dev. all	225	251	0.30	241	317	0.31
Mean w/return	366	279	0.47	394	376	0.42
Maximum w/return	981	971	0.79	1,050	1,077	0.72
Minimum w/return	53	64	0.00	54	63	0.03
Std. Dev. w/return	240	252	0.23	258	312	0.22
Mean significant [2,3]	332	171	0.47	360	340	0.37
Maximum significant	981	378	0.79	1,050	1,077	-0.72
Minimum significant	53	108	0.00	54	128	-0.03
Std. Dev. significant	272	88	0.24	283	304	0.23

1 $Imbalance = \frac{Supply - Return}{Supply}$, when $Supply \geq Return$ $Imbalance = \frac{Supply - Return}{Return}$, when $Supply < Return$

2 The calculation of the mean, maximum, minimum and standard deviation uses absolute values for imbalances

3 "Significant" applies to apartments where the change in the absolute value of the imbalance is greater than 5%.

Table 4-1 shows that the airflow imbalance in the apartments, prior to sealing, was predominantly caused by more supply airflow to the apartment than return airflow from the apartment. (The imbalance figures are mostly positive.) Actually, five apartments had no return registers, eliminating the possibility of improving the imbalance through sealing. Imbalance caused by a situation where the return airflow is greater than the supply airflow occurred in only five of the 25 apartments.

The mean airflow imbalance for all apartments, using the absolute values of the figures in Table 4-1, was 57%. Post retrofit this average was changed to 53%, a 4% improvement. *The mean imbalance for the apartments that have both supply and return registers was 47%. Post retrofit this average was changed to 42%, a 5% improvement.*

The table also shows that most apartments still had more supply than return airflow after sealing the ductwork. However, three apartments changed from greater supply to greater return airflow. In Property 5, apt. 1, the supply to return balance was significantly improved, from 77% too little return air to only 3% too much. In Property 2, apt. 2, the supply to return balance was also improved, from 35% too little return air to 23% too much. Finally, in Property 5, apt. 2, the balance was essentially unchanged, from 6% to little return air too 7% too much. Five apartments had excess return air pre and post-sealing, with the imbalance being reduced in three.

Overall, the imbalance between supply and return airflow was reduced in 11 apartments, was unchanged in 7 apartments (5 of which had no return and therefore could register no change) and increased in 7. As noted above, the mean imbalance for all apartments improved from 57% to 53%. For the group of apartments that have both supply and return registers, the mean airflow imbalance improved from 47% to 42%. Thus, when the effect of sealing is measured through the relative imbalance between supply and return airflows, there was a modest overall improvement for the entire group of apartments. (The same conclusion is reached when the simple difference between supply and return airflow is examined. The difference is reduced a total of 1033 cfm in 9 apartments and increased a total of 596 cfm in 16 apartments, for a net overall reduction of 437 cfm.)

Another means of evaluating the change is to consider only airflow imbalances that are significant. The definition is arbitrary, but "significant" can be defined to be at least higher than 5%, which is the accuracy of the measurement technique. Using this criterion, a significant change occurs in only 9 apartments. Of these, 5 show an improvement and 4 a worse imbalance than before. The mean imbalance for the 9 apartments *that registered significant changes in airflow imbalance* changed from 51% to 42%, a 9% improvement.

In conclusion, sealing the duct system reduces the relative imbalance between supply and return airflows in apartments by a modest amount, from a statistical perspective. For any given apartment the effect is not predictable. The effect is determined by the magnitude, position and shape of leaks in both supply and return ducts.

Sealing did not have a major effect on whether apartments were pressurized or depressurized either. Of 25 apartments, 3 changed from pressurization to depressurization; of these 3, the depressurization was significant[4] in only one apartment.

Thus, it can be stated that the advantages of sealing do not manifest themselves in reduced airflow imbalances or in better pressurization of the apartments. The advantages of sealing are discussed later in the report, and are related to increased airflows in both supply and return, and thus to lower energy use and better indoor air quality. (The latter results from decreased airflow from basement into living spaces.)

Table 4-2: Airflow Imbalance by System, Pre and Post Sealing

	Pre-Sealing			Post- Sealing		
System	Supply (cfm)	Return (cfm)	Imbalance[1]	Supply (cfm)	Return (cfm)	Imbalance[1]
1	526	111	0.79	494	259	0.48
2	509	258	0.49	526	428	0.19
3	874	641	0.27	1,081	785	0.27
4	881	739	0.16	902	805	0.11
5.1	981	227	0.77	1,050	1,077	-0.03
5.2	710	669	0.06	787	842	-0.07
6	971	450	0.54	1,065	615	0.42
7	1,102	556	0.50	1,147	601	0.48
8	1,497	1,542	-0.03	1,708	1,753	-0.03
9	821	594	0.28	852	643	0.25
Mean[2]	887	579	0.39	961	781	0.23
Maximum	1,497	1,542	0.79	1,708	1,753	0.48
Minimum	509	111	0.03	494	259	0.03
Std. Dev.	287	398	0.27	346	410	0.18

1 $Imbalance = \frac{Supply - Return}{Supply}$, when $Supply \geq Return$ $\qquad Imbalance = \frac{Supply - Return}{Return}$, when $Supply < Return$

2 The calculation of the mean, maximum, minimum and standard deviation uses absolute values for imbalances

4 In the small buildings tested, depressurization is undesirable. However, in larger apartment buildings a negative imbalance (depressurization) is actually considered desirable, to avoid spreading odors to common areas.

The airflow imbalance by system, illustrated in Table 4-2, indicates that the systems are more balanced than the individual apartments. Pre-sealing, the *mean* airflow imbalance for all apartments varied between 47% to 57%, depending on whether "imbalance" refers to all apartments, or only those apartments with both supply *and* return registers. For all systems, the *mean* airflow imbalance before sealing is only 39%. Post-sealing, the airflow imbalance in apartments is even higher than that at a system level: 42% to 53% for apartments and only 23% for systems. The figures on system imbalances, however, are presented for information purposes only, because they are not indicative of comfort or energy efficiency. For any given system, the excess supply from one apartment may balance the excess return of another when the data are added together. This type of airflow balancing is energy inefficient and contributes to discomfort. It is driven to a large extent by outside air infiltration and outside air exfiltration, and depends on the air leakage across the interior walls. However, for all its failings, the airflow imbalance of systems is still an indicator of the effectiveness of the sealing retrofit, as long as this indicator is used in conjunction with the apartment-by-apartment imbalance analysis. Table 4-2 confirms the apartment-by-apartment findings: the airflow imbalance in each system modestly decreased or remained practically unchanged after sealing. For all systems combined, the airflow imbalance modestly decreased, from 39% to 23%.

Computer simulations using COMIS, a multi-zone infiltration and ventilation modeling program, were performed to model the airflow balance for a prototype multi-family building. The preceding data were used to characterize the airflows to and from apartments in the prototype. Data from prior research were used to characterize typical partition leakage values for the prototype.

AIR LEAKAGE

Phase I

During the first phase of testing, the duct leakage was determined in two ways. The first method measured the air delivered to all apartments through the supply registers, and the air returned from all apartments through return registers. These figures (air supplied to all apartments and air returned from all apartments) were compared with the air moving through the system fan. The differences indicate how much air leaks through the supply and return ducts. The second method involved pressurizing the duct system with the calibrated fan (the registers were sealed). The relationship between duct pressure and corresponding calibrated fan flow was then used to estimate the leakage airflow at a specified duct pressure.

The following table contains the results for both methods. The duct pressure used for the pressurization method was half the plenum pressure; this pressure can be used to predict the leakage, assuming that the leaks are evenly distributed along the duct system.

Table 4-3: Summary of Duct Leakage Testing, Phase I

Property #	Pre/Post duct sealing	System fan flow cfm	Supply leakage flow, calculated from flowhood tests and total fan flow tests cfm [% of fan flow]	Return leakage flow, calculated from flowhood tests and total fan flow tests cfm [% of fan flow]	Supply leakage flow calculated from duct pressurization tests cfm [% of fan flow]
1	Pre	643	117 [18]	532 [83]	225 [35]
	Post	528	34 [6]	269 [51]	161 [30]
2	Pre	590	81 [14]	332 [56]	107 [18]
	Post	481	0 [0]	53 [11]	-
3[1]	Pre	n/a	n/a	n/a	276 [31]
	Post	n/a	n/a	n/a	136 [14]

[1] Due to the physical constraints of the duct system, the pitot static probe could not be located in such a way as to produce reliable results. The dimensions of plenum and location of the supply duct branches created a flow pattern in the duct system which resulted in unreliable plenum pressure measurements. Repeated attempts to achieve reliable results failed; therefore the fan flow measurement and related results could not be determined.

The data from Table 4.3 indicate the following:

- The return ducts have more leakage airflow than the supply ducts. The average return leakage before sealing was 70% of the total system fan flow. *This means that less than one-third of the air entering the system fan was coming from the apartments.* After sealing, the average leakage airflow into the return ducts was reduced to 32%; *the leakage was cut by half.*
- Before sealing, the supply ducts leaked an average of 16% of the air delivered by the system fan. After sealing, the leakage airflow from the supply duct was reduced to an average of 3%.
- Sealing the ductwork resulted in an average reduction in system fan flow of 18%.
- The leakage airflows calculated based upon duct pressurization tests and upon average duct pressures differed from the figures obtained with flowhood and total fan flow tests by more than 300%. These data confirm that, while duct pressurization is useful in characterizing the leakage *area* of a duct system, *duct pressurization is not useful for predicting the leakage airflow of any given system.* However, as will be shown later, the duct pressurization technique is useful in estimating the leakage airflow of a large group of apartments, in a statistical sense.

Table 4-4 presents the reduction in supply and return leakage airflows based upon flowhood measurements and on fan flow measurements. Table 4-5 contains the changes in supply and return airflow through the apartment registers.

Table 4-4: Changes in Leakage Airflow, According to Flowhood and Fan Flow Measurements, Phase I

Property	Change in Leakage Flow from Supply Ducts (cfm)	Change in Leakage Flow into Return Ducts (cfm)
1	83	263
2	81	279
3[1]	Not calculated	Not calculated

1 Per footnote of Table 4-3, the fan flow could not be reliably measured for property #3. As a result, leakage flows and changes in leakage flows could not be calculated.

Table 4-5: Changes in Airflow at Registers, According to Flowhood Measurements, Phase I

Property	Change in Supply Flow (cfm)	Change in Return Flow (cfm)	Supply Increase/ Pre-Supply Flow	Return Increase/ Pre-Return Flow
1	-32	148	-0.06	1.33
2	17	170	0.03	0.66
3	207	144	0.24	0.22

The total supply airflow at the registers for property #1 actually decreased. This can occur when the static pressure across the system fan increases enough to reduce the airflow into the apartment. An increase of this nature happens when large leaks in the return ducts, located close to the fan, are sealed. Note that the reduction in supply airflow to the apartment actually reduced (improved) the airflow imbalance in the apartment, and thus had a positive impact on system performance.

A comparison of the results in Tables 4-4 and 4-5 indicates that, for properties 1 and 2, the change in register flow yields a very conservative estimate for the change in leakage flow. In fact, the percent difference between the change in register flow and decrease in leakage flow is an average of 90% for supply and 42% for return. Consequently, changes in register flows yield very conservative estimates of the reduction in leakage flows. (This becomes important when analyzing the data of phase two, where system fan flows were not measured.)

Phase II

Fan flows were not measured in the second phase. The flowhood measurements of airflow at registers cannot be used to estimate duct leakage explicitly. This report will therefore use the flowhood measurements to focus on *changes* in leakage flow due to the retrofit.

Duct pressurization tests were used to characterize leakage areas for each duct system. Table 4-6 summarizes the results of the duct pressurization testing in terms of leakage area at 25 pascals (0.1 in of water) for the whole duct system (i.e., supply and return combined). This leakage area is designated as ELA_{25}. Twenty-five pascals was chosen as reference pressure because it is a typical average pressure in a duct system; it is between a maximum pressure difference of about 50 Pa at plenums and the small pressure differences at registers. The ELA_{25} values were normalized with floor area and exposed surface area of the ducts to determine if there is a consistent quantity of duct leakage area per unit floor area, or per exposed (accessible) duct surface area. Such quantity would be useful in design or in energy estimation calculations.

Table 4-6: Summary of Duct Leakage Area [ELA_{25}] PRE Retrofit

Property	ELA_{25} (in^2)	Floor Area, FA (ft^2)	Exposed Duct Area, EDA (ft^2)	ELA/FA (in^2/ft^2)	ELA/EDA (in^2/ft^2)
4	62	2271	423	0.027	0.147
5.1	104	1413	258	0.074	0.396
5.2	117	1170	236	0.100	0.497
6	288	2162	380	0.133	0.758
7	245	2614	628	0.094	0.393
8	216	3248	576	0.066	0.374
9	60	1103	286	0.054	0.211
Mean	156	2000	398	0.078	0.397
Maximum	288	3248	628	0.133	0.758
Minimum	60	1103	236	0.027	0.147
Std. Dev.	92	803	151	0.034	0.199

Table 4-7. Summary of Duct Leakage Area [ELA_{25}] POST Retrofit

Property	ELA_{25} (in^2)	Floor Area, FA (ft^2)	Exposed Duct Area EDA (ft^2)	ELA/FA (in^2/ft^2)	ELA/EDA (in^2/ft^2)
4	46	2271	423	0.020	0.108
5.1	80	1413	258	0.056	0.302
5.2	76	1170	236	0.065	0.324
6	237	2162	380	0.110	0.625
7	210	2614	628	0.080	0.336
8	156	3248	576	0.048	0.272
9	43	1103	286	0.038	0.149
Mean	121	2000	398	0.060	0.302
Maximum	237	3248	628	0.110	0.625
Minimum	46	1103	236	0.020	0.108
Std. Dev.	80	803	151	0.029	0.167

The ELA_{25} values were calculated from flow coefficient, C, and flow exponent, n, from a power law fit to the measured leakage flows and pressures. The flow exponent can be a guide to the type of leak in a system. With $n \cong 0.5$ the leaks are most likely to be sharp edged (orifice like) holes, and as the leakage paths become longer and have smaller diameters n tends towards one. The average flow exponent for these duct systems was 0.52 (pre retrofit) and 0.56 (post retrofit). These values of flow exponent show that most of the duct leakage is through sharp edged holes. The change in flow exponent due to the retrofit reflects the sealing of large orifice like leaks.

The high standard deviations in Tables 4-6 and 4-7 show that there was poor correlation between leakage area and duct surface area, or between leakage area and floor area. Therefore, there is no general prediction to be made about the leakage area in a given system. The amount of leakage depends upon fabrication standards and subsequent maintenance of each system.

All systems had large leakage areas, with an average of 156 in^2 pre-retrofit and 121 in^2 post-retrofit. This indicates that the sealing retrofit resulted in a reduction of 22% of the original leakage area. The leaks that were sealed during the retrofit were only those accessible in the basement. Therefore, the majority of the duct leakage is elsewhere in the duct systems (in walls, in ceilings, or at registers). The leakage area at registers is usually unimportant, since the air has very low pressure at that location. Therefore, the fact that a system has a relatively large leakage area after sealing does not necessarily mean that there is significant airflow leakage after sealing. However, the leakage areas of other hidden portions of the ducts could be more significant but cannot be economically reached (i.e, without opening floors and walls).

As mentioned previously, using leakage area to estimate leakage flows requires knowledge of the pressure difference across the leaks. Due to the variation of pressure between plenums and registers, the pressure across leaks is dependent on their location. The uncertainty in estimating leak location and pressure difference is large and therefore *individual* leakage flow estimates using this method are poor. The leakage area of a given system is useful as an indicator of the care used in installing the ducts, and therefore can be employed to assess whether a system could benefit from sealing. However, when expressed as an average of many systems assessed in aggregate, the leakage area can yield a useful estimate of leakage flow reduction for all these systems combined. This is discussed in the last paragraph of this subsection.

Using a flowhood to measure all of the register flows is a more accurate method for estimating the absolute value of leakage flows, but to this end the system fan flow must also be measured. The system fan flows were not measured during the second phase of testing. In absence of data on system fan flow, the flowhood measurements of register airflows can be used to calculate the *change* in supply and return flows due to duct sealing. The difference between the register flows before and after retrofit can be used to estimate the reduction in air leakage through ducts. If the system fan flow were not to change due to the retrofit, then this would be a true measure of the leakage flow reduction. However, the system fan flow decreases after sealing, (because the static pressure in the ducts increases after sealing) and therefore the difference in register flows yields a *conservative* estimate of the change in leakage. (Refer to discussion of Tables 4-4 and 4-5 for an illustration on how conservative this approach is.)

Table 4-8 summarizes, in columns B and C, the changes in flow due to the duct sealing retrofit, i.e., summarizes the *minimum* reduction in leakage flow. Columns D and E express the increases in register airflows as a fraction of the pre-retrofit register flows. This illustrates the relative importance of flow reductions due to leak sealing, i.e., by what percentage can the supply and return flow be increased at registers by sealing the ducts.

Table 4-8: Changes in Register Airflow, According to Flowhood Measurements, Phase II

A	B	C	D	E
Property	Increase in Supply Flow (cfm)	Increase in Return Flow (cfm)	Supply Increase/ Supply Flow	Return Increase/ Return Flow
4	21	66	0.02	0.09
5.1	69	850	0.07	3.74
5.2	77	173	0.11	0.26
6	94	165	0.10	0.37
7	46	45	0.04	0.08
8	303	211	0.22	0.14
9	31	49	0.04	0.08
Mean	92	223	0.09	0.68
Maximum	303	850	0.22	3.74
Minimum	21	45	0.02	0.08
Std. Dev.	97	285	0.07	1.35

These results show that sealing the duct leaks in the basement increased the supply flows by an average of 9% and the return flows by an average of 68%. If the results from system 5.1 were to be taken out of the calculation (as representing an extreme condition), the supply flows were increased in average by 9% (same as before), and the return flows were increased on average by 17%. The supply flows were increased by an average of 92 cfm and return flows by 223 cfm. The fractional flow increase for return (Column E) is much larger than the fractional flow increase for supply (Column D). This is because the return ducts were much leakier than the supply ducts, and as a result the return airflow at registers increased more than the supply airflow after the sealing retrofit was completed. In general, the large variation in flow increase was due to the different potential for leak sealing in each system. Some very leaky systems had large, easily accessible holes that were sealed during the retrofit and these systems show the largest change. Conversely, some systems had less initial leakage or more inaccessible leakage.

For comparison, changes in airflow between pre- and post-retrofit were also calculated by using the measured duct pressures, shown below in Table 4-9, and ELA_{25} from Tables 4-6 and 4-7. Because the ELA_{25} was calculated for the whole duct system, the estimated leakage flow was for the whole duct system. The system pressure was estimated by averaging the pressures at the supply plenum, return plenum and the registers.

Table 4-9: System Operating Pressures[1, 2]

Property	Supply, Pa [in H_2O]		Return, Pa [in. H_2O]	
	PRE	POST	PRE	POST
5.2	42	74	96	107
6	11	15	21	21
7	28	40	81	81
8	60	72	39	42
9	39	40	54	47
Mean	36 [0.15]	48 [0.19]	58 [0.23]	59 [0.24]
Maximum	60 [0.24]	74 [0.30]	96 [0.38]	107 [0.44]
Minimum	11 [0.04]	15 [0.06]	21 [0.08]	21 [0.08]
Std. Dev.	16 [0.07]	22 [0.09]	27 [0.11]	31 [0.12]

1 Table 4-9 summarizes the measured operating system pressures for both supply and return. These operating pressures were used to estimate leakage flows from ELA. The sealing of the duct system had the effect of raising the supply plenum pressures by about one third. The pressure changes across the fan reduced fan flows. The systems showed a wide range of system pressures from about 10 Pa to 100 Pa reflecting a wide range of fan performance and duct system flow resistance. This wide range of pressures meant that it was not possible to infer any general performance criteria from these results. These results showed that individual system installation dominates over general system specifications in determining duct system pressures.

2 System operating pressures were not measured at properties #4 or #5.1. These data were not required by the measurement protocol for phase II. The system operating pressure was required during phase I, to perform system fan flow measurement. Since fan flow was not measured in phase II the operating pressure was not needed. The data presented were collected as time permitted.

Averaging all the duct systems together, the pressurization technique gives a mean total change of 251 cfm compared to 239 cfm for the flowhood test. Therefore, the use of the average pressure between registers and plenums gave a reasonable result when averaged over many systems. However, the differences for each individual system between the two test methods are large, with an average difference of 64%. When the two measurements agreed, it was because the pressure chosen to calculate flow from ELA_{25} happened to be the correct "average" pressure to produce the correct leakage flow. Even though ELA_{25} may be determined quite precisely, the uncertainty in pressure across the leaks creates a large uncertainty in leakage flow calculation.

Duct Operating System Temperatures

Air temperatures were measured at supply and return plenums, at registers, in the basement and outdoors. The plenum temperature measurements were recorded at the end of the furnace cycle to minimize thermal mass effects. The register temperatures were taken at about the same time as the plenum temperatures, within a 5 minute period. Basement temperatures and outdoor air temperatures were taken at the same time as plenum temperatures. Table 4-10 summarizes the plenum, basement and outside air temperatures pre- and post-insulation.

Table 4-11 summarizes the average register temperature for each system. The average was calculated by weighing the temperatures measured at each register with the airflow measured at that register. The two sets of measurements were made: (a) after sealing but before installing the duct insulation and (b) after the duct insulation was installed. Since the process of insulating the duct system took at least several hours, and sometimes more than a day depending on the work schedule of the insulation contractor, the outside air temperatures changed during that time period.

Table 4-10: Plenum Temperatures and Temperatures of Basement and Outdoor Air

Property	Supply Plenum Temp. °C		Return Plenum Temp. °C		Basement Temp. °C		Outside Temp. °C	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	65	82	14	17	8	10	-5	1
2	76	88	16	20	8	10	-11	0
3	60	63	20	22	17	13	-6	0
4	72	70	23	26	20	11	0	3
5.1	62	65	23	24	6	12	6	18
5.2	57	64	17	20	7	16	7	16
6	73	76	21	23	19	19	5	17
7	77	68	22	23	13	15	7	12
8	80	88	24	26	23	20	-1	14
9	53	50	24	24	15	15	16	20
Mean	68	71	20	22	14	14	2	10
Maximum	80	88	24	26	23	20	16	20
Minimum	53	50	14	17	6	10	-11	0
Std. Dev.	21	23	7	7	7	5	7	8

Table 4-11: Flow-weighted Average Register Temperatures

Property	Supply Plenum Temp. °C		Return Plenum Temp. °C	
	Pre	Post	Pre	Post
1	43	58	20	25
2	50	61	24	25
3	47	54	21	24
4	56	61	28	22
5.1	51	57	27	30
5.2	44	54	21	23
6	49	59	25	27
7	46	51	28	26
8	60	66	26	27
9	43	47	25	25
Mean	49	57	25	25
Maximum	60	66	28	30
Minimum	43	47	20	22
Std. Dev.	5	5	3	2

A change in outside air temperature results in a change in the basement air temperature, because outside air infiltrates into the basement. In turn, a different basement temperature translates into colder or warmer return air temperatures, and in colder or warmer temperatures at registers. As a result, the temperature measurements need to be interpreted.

Table 4-12: Effect of Duct Insulation on Basement Temperature

A	B	C	D	E	F
Property	Basement Temp. °C		Outside Temp. °C		Delta T Adjusted °C
	Pre	Post	Pre	Post	
1	8	10	-5	1	4
2	8	10	-11	0	9
3	17	13	-6	0	10
4	20	11	0	3	12
5.1	6	12	6	18	6
5.2	7	16	7	16	0
6	19	19	5	17	12
7	13	15	7	12	3
8	23	20	-1	14	18
9	15	15	16	20	4
Mean	14	14	2	10	8
Maximum	23	20	16	20	18
Minimum	6	10	-11	0	0
Std. Dev.	7	5	7	8	5

Table 4-12 presents an estimate of the maximum decrease in basement temperature due to duct insulation. The measured basement temperatures usually increased after duct insulation, but this increase was caused by warm outside air temperatures after insulating.

For instance, table 4-12 shows that the pre-insulation temperature of the basement in property 1 was 46°F (8°C). This temperature increased to 50°F (10°C) after the insulation retrofit; however, the outside air temperature also increased, from 23°F (-5°C) to 33°F (1°C). If the outside air temperature were to remain constant, it can be reasonably assumed that the basement temperature would not drop more than about 6°F (4°C). This drop is calculated by subtracting the increase in outside air temperature from the increase in basement temperature, i.e., 4°F -10°F = -6°F (2°C-6°C=-4°C). Indeed, as the basement temperature decreases the conduction heat losses to outside also decrease, so the drop in basement temperature is somewhat reduced and the 6°F (4°C) would be a conservative estimate. The reality is more complex though. The HVAC system may have operated for longer or shorter periods of time before the post-retrofit measurement was made, the occupants may have opened or closed the doors and windows more or less often, and infiltration into the basement may have changed to some extent. For all these reasons, there is great uncertainty related to any drop in temperature calculated for a given apartment. However, on average there should be a detectable trend, if it is assumed that there was some random change in at least some of the variables (system run time, occupant behavior). On average, Table 4-12 shows a 14°F (8°C) maximum drop in basement temperature. This number is indicative of the *order of magnitude* of the temperature drop, and was used to verify whether the computer analyses gave results within a credible *range*.

Experimentally, the drop in basement temperature could have been accurately measured in a laboratory installation, or could have been derived from results of long-term monitoring (needed because basements have large thermal storage capacities). For this work, however, the drop in basement temperature was estimated with computer analyses, and calibrated based on the measured data.

Similarly, the plenum and register temperatures were used to calibrate the DOE-2.1 model. For these temperatures any tabulated spreadsheet-type calculation would have been so inaccurate as to be meaningless. The effect of duct insulation is therefore fully analyzed only in the energy simulation section.

Column F in Table 4-12 shows that the basement temperature can be lower by a mean value of 8°C with a standard deviation of 5°C after insulating the accessible ducts. Also, maximum and minimum differences in basement temperature are 18°C and 0°C, respectively. Again, these numbers represent a simplified attempt to characterize the trend in basement temperature between pre- and post-insulating.

CORRELATION BETWEEN OBSERVABLE CHARACTERISTICS OF THE DUCT SYSTEM AND ITS AIR LEAKAGE

Chapter 2 of this report addressed the possible correlation between characteristics of the duct system that could be known before the site inspection, and the researchers' subjective impression of the duct system after the site inspection. Specifically, chapter 2 showed that, for the systems examined, one could not have predicted, before site inspection, the condition of the duct system. The property type, the owner, the contractor, the age of the system, or the furnace size were inconclusive predictors on whether a duct installation seemed to be in good or poor condition. (See Table 2-1 and the related discussion.) This chapter examines whether there can be a correlation between the above variables and the increase in supply/return airflows after sealing.

Table 4-13: Quality of Installation for Systems Tested

Property	Owner	System Installed	Furnace Size (Btu/hr)	Contractor	Opinion on Quality of Installation*	Supply Increase/ Supply Flow	Return Increase/ Supply Flow
1	A	1983-84	75,000	-	1	-0.06	1.33
2	B	1978	90,000	-	3	0.03	0.66
3	B	1980's	125,000	-	4	0.24	0.22
4	B	1989	105,000	X	5	0.02	0.09
5.1	A	1985	105,000	X	2	0.07	3.74
5.2	A	1985	105,000	X	2	0.11	0.26
6	C	1985	105,000	Owner	3	0.10	0.37
7	B	1993	100,000	Y	4	0.04	0.08
8	D	1970's	220,000	-	2	0.22	0.14
9	E	1989	40,000	Z	4	0.04	0.08

- Quality of installation, as determined by researchers with visual inspection, where 1.00=worst and 5.00=best

Table 4-13 shows a reasonably good relationship between the researchers' opinion of the quality of the installation, based on a visual inspection, and the percentage increase in supply and return flows. The installations that appeared to be in best condition (#3, 4, 7, and 9) also had the lowest increase in supply flow and return flow. The installations that appeared to be the worst (#1, 5, and 8) had highest or among the highest increases in supply or return airflows. Thus, it can be concluded that a visual inspection of a site can give a reasonably good indication of the opportunity to seal leaks. A similar, but more tenuous relationship can be inferred between age of installation and leaks. New systems (less than 5 years old) presented little opportunity for improvement; older systems did not have a clear correlation between age and opportunity for improvement.

In conclusion, it appears that sealing of ducts is likely to be unproductive in newer installations (5 years of age), but could be of interest in older ones, regardless of actual age, since so many other factors are at play. Also, it appears that a visual inspection of the duct system can give a reasonably good indication of the opportunity for duct sealing, regardless of any other factors.

COST OF RETROFIT STRATEGIES

The retrofits were performed in two stages: sealing, and then insulating. The sealing was performed by the test personnel, and the insulating by a local HVAC subcontractor. The reason for the division of labor was based upon project scheduling. Scheduling the contractor to do only a few hours work of sealing work, without the benefit of having located the leaks themselves would have been counterproductive.

During sealing and insulating the teams kept track of the time and materials required for the retrofit. The actual costs, including all applicable taxes, were also recorded, and are presented in the table below. Note, the time rate for the test personnel was assumed to be the same as that of the contractor. This was deemed reasonable in that this work would eventually be offered as a part of this trade.

The sealing costs do not reflect the diagnostic and testing done prior to sealing. Although the work done prior to actually sealing did help to some extent in locating the leaks, the advantage was minimal. The major leaks were evident during the initial inspection. The "hidden" leaks were not discovered until the sealing was being done, and required a dedicated effort to locate. Also, it was assumed that in the future this retrofit would be performed by personnel in the HVAC industry. Such personnel would have the advantage of knowing where to look for leaks, because they are the ones who install the system in the first place.

Table 4-14 indicates that for both retrofits the cost is predominantly in the labor. Namely, the labor represents 91% of the cost for sealing, 73% of the cost for insulating, and 77% of the combined total, sealing plus insulating. Also, the data show the relative expense of the two strategies: sealing and insulating being 26% and 74% of the total cost, respectively. Additionally, using the average area of exposed ductwork (385 ft^2) the average retrofit cost is $2.33 per square-foot of exposed ductwork (0.61/ft^2 for sealing and 1.72/ft^2 for insulating).

Table 4-14: Cost of Retrofitting

	Sealing			Insulating			Sealing & Insulation		
Property	Labor ($)	Material ($)	Total ($)	Labor ($)	Material ($)	Total ($)	Labor ($)	Material ($)	Total ($)
1	179.55	12.42	191.97	434.70	99.97	534.67	614.25	111.47	726.64
2	699.30	45.36	744.66	302.40	112.15	414.55	1001.70	145.84	1159.21
3	176.00	14.58	190.58	739.20	259.99	999.19	915.20	254.23	1189.77
4	113.40	14.58	127.98	529.20	185.76	714.96	642.60	185.50	842.94
5.1	94.50	22.68	117.18	324.00	123.34	447.34	418.50	135.20	564.52
5.2	94.50	22.68	117.18	324.00	123.34	447.34	418.50	135.20	564.52
6	189.00	24.84	213.84	583.20	222.91	806.11	772.20	229.40	1019.95
7	264.60	24.84	289.44	583.20	253.04	836.24	847.80	257.30	1125.68
8	189.00	24.84	213.84	680.40	283.82	964.22	869.40	285.80	1178.06
9	132.30	14.58	146.88	324.00	148.61	472.61	456.30	151.10	619.49
Mean	213.22	22.14	235.36	482.43	181.29	663.72	695.65	189.10	899.08
Std. Dev.	169.50	9.10	177.32	154.15	65.41	215.50	205.29	59.19	251.17
Max	699.30	45.36	744.66	739.20	283.82	999.19	1001.70	285.80	1189.77
Min	94.50	12.42	117.18	302.40	99.97	414.55	418.50	111.47	564.52

Other data in this study (see HVAC Systems, in Chapter 2) indicate that the exposed duct area is proportional to the floor area served by the system. Therefore, it is consistent with the results of this study to normalize the cost of the retrofits with respect to average floor area (1937 ft^2). This calculation yields a total retrofit cost of $0.46/$ft^2$ of the floor area served by a system.

Therefore, either exposed duct area or total apartment floor area can be used to estimate the cost for sealing and insulating the duct system.

CONCLUSIONS OBTAINED FROM TEST RESULTS

The test results indicate that the duct air leakage varies significantly between systems. These variations do not correlate with duct system area, or apartment floor area. The leakage is predominantly a factor of installation quality and system maintenance.

The systems tended to have larger leaks in the return ducts than in the supply ducts. Although supply and return duct leaks are both responsible for energy losses, the return duct leaks have the added effect of entraining basement air. The basement air will introduce to the apartments any airborne contaminants that the basement contains (e.g., dust, mold, mildew, radon). Therefore, reducing the return leakage has the benefit of improving the indoor air quality in the apartments.

The test results show that sealing the accessible supply and return duct leaks had an effect in several areas:

- More air reached the spaces and more air was returned from the spaces due to the reduction in air leakage.
- In phase one, the return air leakage was reduced on average by 67%. The supply air leakage was reduced on average by 85% for the systems tested.
- On average, the supply airflow to the apartments increased by 9%, or 92 cfm.
- On average, the return airflow increased by 68% or 223 cfm. (If an extreme system is removed from the analysis, the return airflow increased by 17%, or 118 cfm.)
- Changes in supply and return airflow in the apartments corresponds with the *minimum* change in duct leakage.
- The leakage area of all systems was reduced on average by 22%.
- Duct insulation resulted in a temperature decrease in the basement of about 15°F on average. (This figure is uncertain and is provided only as order-of-magnitude.)

Duct sealing modestly improved the airflow balance in aggregate, but did not improve the airflow balance in each apartment. In a few instances it had the opposite effect. Thus, duct sealing cannot be relied upon to deliver this additional benefit.

The net effect of how these effects impact energy use were analyzed using computer models. The test results from this study were used, in concert with results from prior research, to develop a prototype multi-family building. The prototype was used to calculate generalized energy use savings.

Chapter 5

COMPUTER SIMULATIONS

Computer simulations were performed to quantify the results of the retrofit work for a prototype multi-family building. COMIS 2.1 and DOE-2.1E were used for the computer simulations.

COMIS 2.1 is a detailed multizone infiltration computer modeling program, developed by an international group, Conjunction of Multizone Infiltration Specialists, hosted by LBL (Feustel, H.E., *Preface to COMIS 2.1 User's Guide*, p.II, July 1, 1995). COMIS models complex building infiltration in multizone systems. The infiltration results from COMIS 2.1 were used in the building simulations performed using DOE-2.1E. DOE-2.1E is the Department of Energy's building simulation program. DOE-2.1E is currently the most complete and accurate tool for modeling the complex interaction of building systems.

Energy Simulations

The energy use reduction attributable to duct insulation was computed using DOE-2.1E and COMIS simulations on a prototypical multi-family building. The prototype was derived from the data obtained in the apartments tested by the team, and also based on prior work performed by others related to multi-family housing. COMIS was employed to estimate the air leakage rates in the apartment building. This information was incorporated into DOE-2.1E. Three sets of simulations were performed:

- Accessible duct system not sealed and not insulated
- Accessible duct system (including furnace box) sealed, but not insulated
- Accessible duct system (including furnace box) sealed and insulated

The energy savings attributable to duct system sealing, and to duct insulation, were derived in two climate zones representative of the State of New York: New York City and Albany.

PROTOTYPE BUILDING

The prototype building was developed using the findings of this study and existing work performed by SWA and LBNL. In general, the prototype building is a two story structure with a flat roof and full unconditioned basement. The interior of the building contains four identical apartments and a two story central hallway. The entire building is served by a single natural gas fired furnace; each apartment receives the same airflow. See the plans and drawings on the following pages.

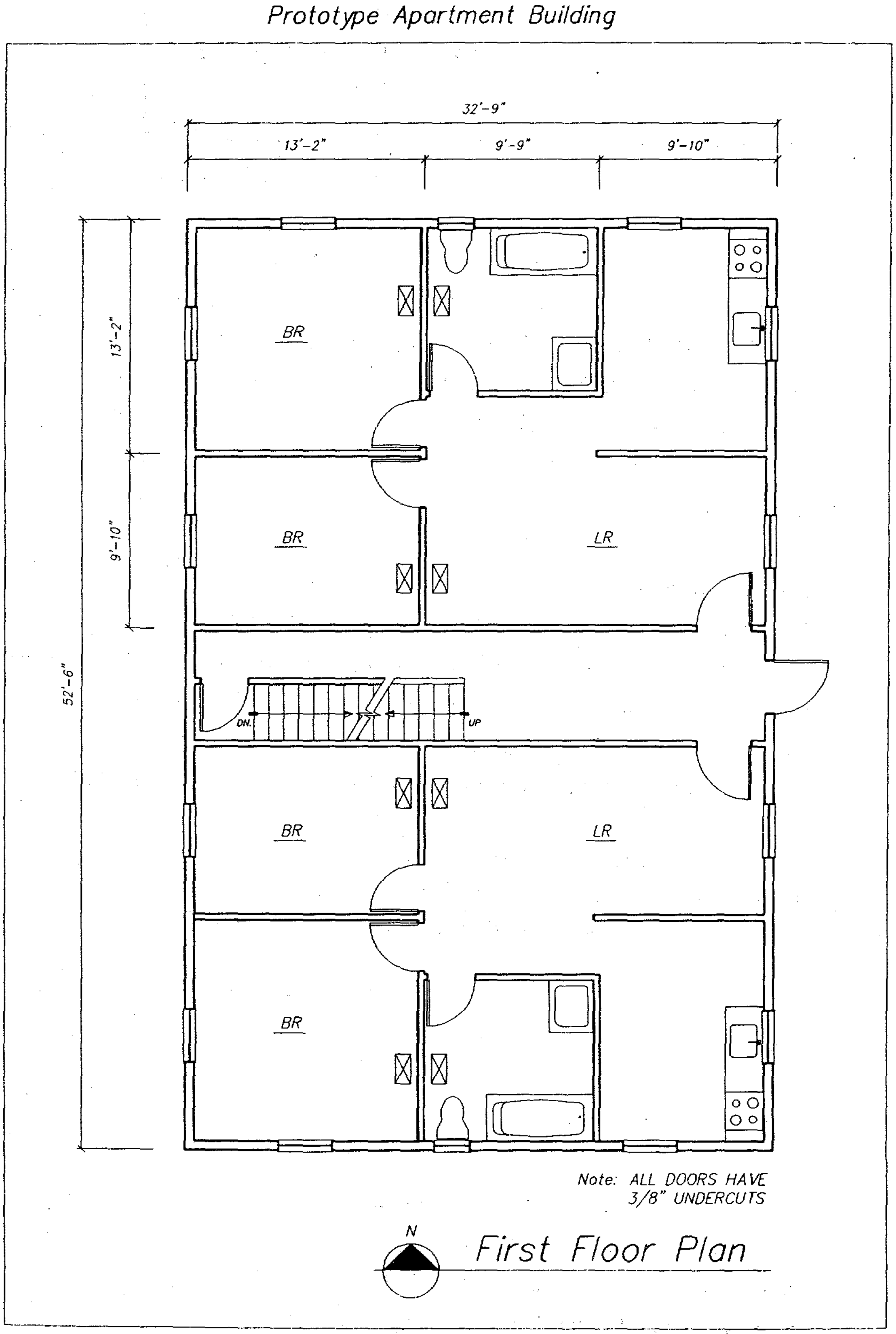


Fig. 5-1: Prototype Apartment Building - First Floor Plan

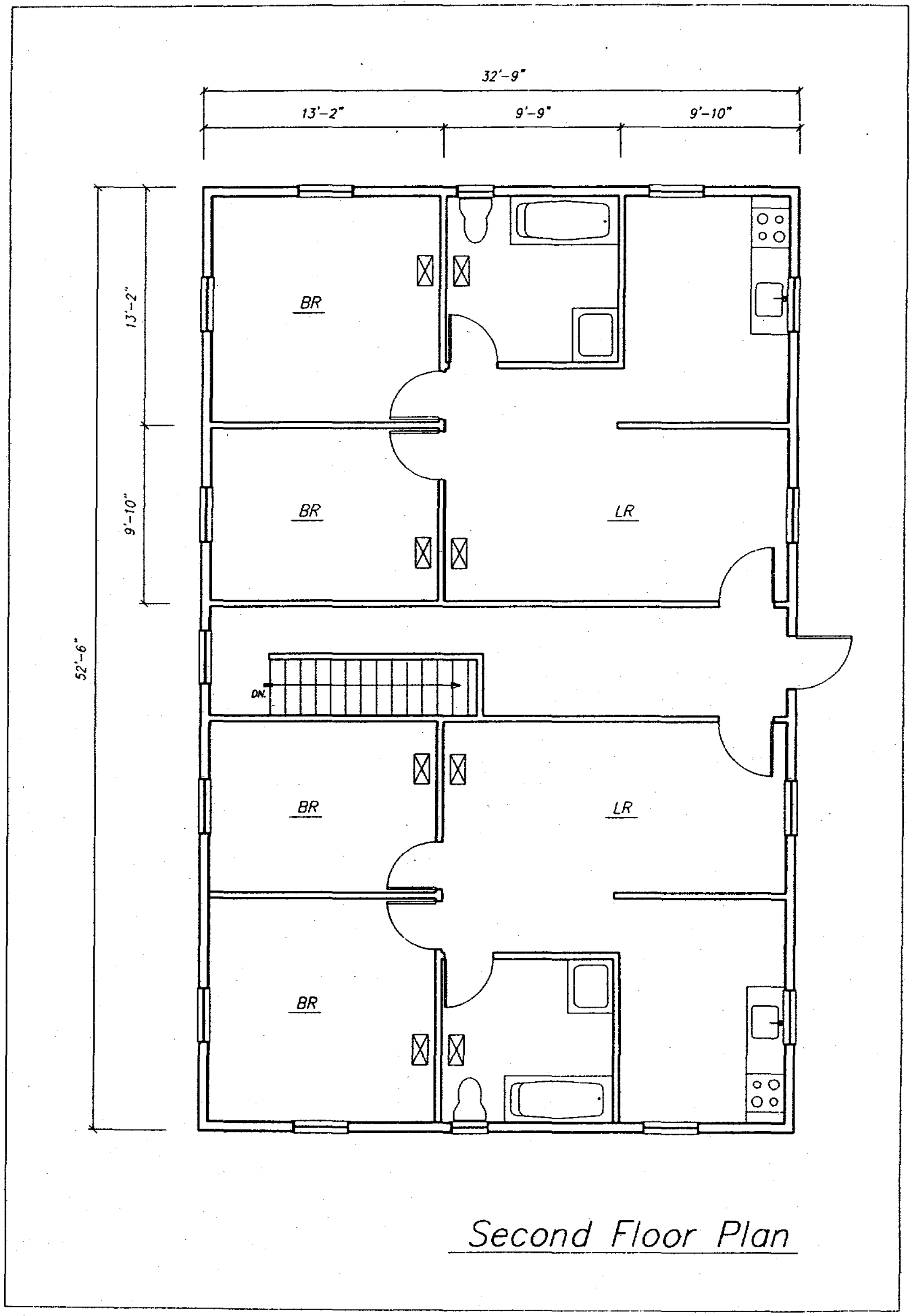


Fig. 5-2: Prototype Apartment Building - Second Floor Plan

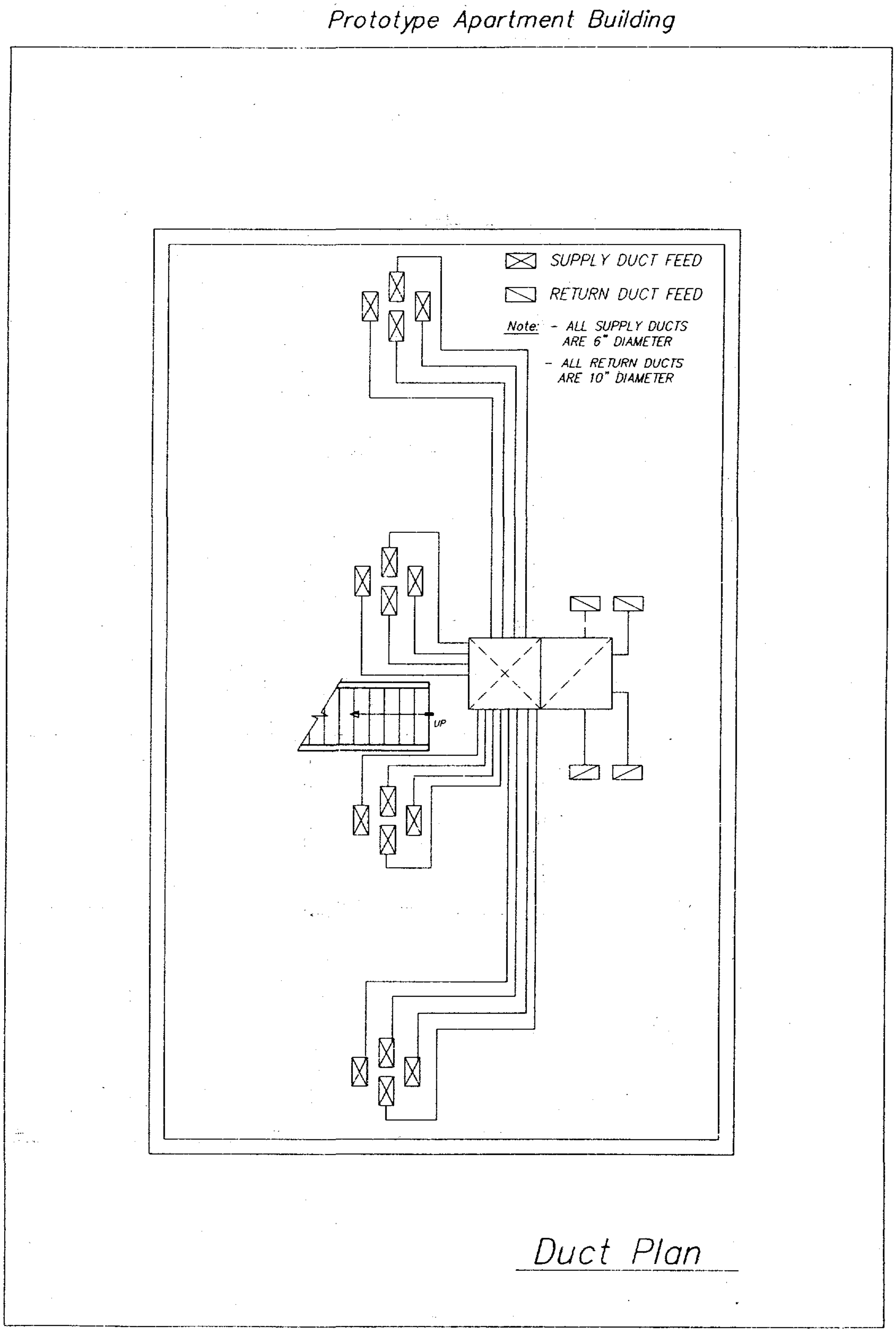


Fig. 5-3: Prototype Apartment Building - Duct Plan

Additionally, the following parameters were used in the COMIS simulations. They are expressed in SI units, because COMIS requires SI input. The English equivalent is provided for reference.

- *Envelope leakage:* 6 cm^2/m^2 (0.0864 in^2/ft^2), based upon previous a previous study, by SWA/LBNL, "Simplified Blower Door Techniques for Multifamily Buildings".
- *Basement leakage:* 1 cm^2/m (0.1440 in^2/ft) and 0.1 cm^2/m (0.0144 in^2/ft) of building perimeter, based on previous LBNL field testing data. The two values represent a leaky and tight basement, respectively. The leaky basement is representative of spaces examined that had broken windows and doors to the outside that did not close. In such basements one could see outside by looking below or above the sill plate. The tight basement is one with reasonably good construction practice.
- *Interior partition leakage:* 1 cm^2/m^2 (0.0144 in^2/ft^2), based on previous LBNL field testing data.
- *Interior door undercut leakage:* 100 cm^2 (15.5 in^2) per doorway; approximately 1cm x 100cm.
- *Wind pressure coefficients:* values from *1993 ASHRAE Handbook Fundamentals*, Ch. 14 - Airflow Around Buildings.
- *Space temperatures:* Apartment and hallways maintained a 20°C (68°F), and the basement assumed to be 10°C (50°F). The test data from this study indicate that significant stratification exists in the basements. The temperature may vary as much as 20°C (36°F) from the ceiling to the floor. The basement temperature is also highly dependent upon the outside temperature. The value assumed for the COMIS simulations is an estimated average temperature.

○ *Total building area:*	3,444 ft^2
○ *Basement area:*	1,722 ft^2
○ *Floor to ceiling height:*	8.2 ft
○ *Exterior wall construction:*	Vinyl siding
	¾" plywood
	2"x 4" wood studs @ 16"o.c. with R-11 fiberglass insulation
	½" gypsum board
○ *Interior wall construction:*	⅝" gypsum board
	2"x 4" wood studs @ 16"o.c.
	⅝" gypsum board
○ *Roof construction:*	Built-up roofing
	¾" plywood
	2"x 10" wood rafters@ 16" o.c. with R-19 fiberglass insulation
	⅝" gypsum board
○ *Windows and glazing:*	Vinyl frame windows

Double pane glass (¼" air space)

SC=0.88 U=0.60

3'-0" x 5'-0" nominal dimensions

Total window area = 465 ft^2

Window area/total floor area = 13.5%

- *HVAC system:* Natural gas fired furnace

  Input capacity: 165,600 Btu/hr

  Thermal Efficiency: 65%

  Pre-fan flow: 1650 cfm

  Post-fan flow: 1520 cfm

- *Exposed duct area:* Supply = 412 ft^2

  Return = 179 ft^2

  Total = 591 ft^2

The supply and return airflows to each of the apartments were based upon the data from this study. The average supply and return airflow was determined from all the data collected, and expressed in units of flow rate per unit floor area (cfm/ft^2). These values were then multiplied by the conditioned floor area (sum of the apartment areas only) of the prototype building to establish the supply and return flow rates to the spaces. The leakage airflow to and from the basement was assumed to be zero post-retrofit, and could be characterized as the difference between the pre and post-retrofit supply and return flow rates. The following table lists the values used in the COMIS simulations:

Table 5-1: Airflows Simulated in COMIS Model

	Supply		Return	
	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit
Conditioned Floor Area (ft^2)	3000	3000	3000	3000
Delivered Airflow (cfm)	1370	1490	846	1113
Apartment Airflow (cfm)	342.5	372.5	211.5	278.25
Register Airflow (cfm)	85.625	93.125	52.875	69.5625
Basement Airflow (cfm)	120	0	267	0

AIR INFILTRATION SIMULATIONS

COMIS 2.1, a multi-zone ventilation and infiltration modeling program, was used to calculate infiltration rates for the prototype building. Infiltration values were calculated for every hour of the year. The prototype building was simulated in two New York State locations, Albany and New York City. Hourly weather data for each location was used for the simulations.

COMIS is strictly a ventilation and infiltration modeling program; it does not perform energy use calculations. COMIS assumes that the space temperatures are maintained at their respective set-points, and does not consider how this is achieved. Therefore, COMIS does not simulate how intermittent system operation affects building infiltration. COMIS simulates the building infiltration either when the system is on or when the system is off, for a given hour; COMIS does not determine when the system is operating during only part of an hour. Energy simulations, such as DOE-2.1E, are required to determine part-load operation of the system. However, DOE-2.1E cannot be used in isolation from COMIS, since the air infiltration rate affects the building load (consequently affecting the part-load operation of the system) and the part-load operation of the system affects the air infiltration rate.

Consequently, determining the building infiltration rate requires an iterative solution. The solution applied in this project involves using two files which contain the infiltration values from the COMIS simulations. These simulations assume two operating scenarios:

1) The system is simulated as if it did not run for the entire year. This will yield the infiltration rates when the system is *off* (between the on-cycles).

2) The system is simulated as if it were run continuously for the entire year in a pre-retrofit state. This will yield the infiltration rates as affected by the supply/return airflow imbalance when the system is *operating* (during the on-cycles).

   or

   The system is simulated as if it were running continuously, using post-retrofit airflows. This will yield the infiltration values for the system operating under the post-retrofit airflow conditions. (The results will reflect the changes in the airflow imbalance.)

This iteration process performs calculations in the following sequence:

1) Begin the calculations with the infiltration values for the always-on operating condition.
2) Perform an energy simulation for these infiltration values to determine the part-load operation of the systems.
3) Use the part-load values from the energy simulation to proportionally combine the system-on and

system-off infiltration values, from the COMIS files, and place the results in a new file.

4) Perform an energy simulation with the new infiltration values to recalculate the part-load values.
5) Repeat steps 3 and 4 until the infiltration and operating conditions stop changing (or converge to an acceptable limit) between successive iterations.

The following table contains the average infiltration rates for the winter season (October 15 through May 15), calculated by COMIS. The living space values are the average air changes per hour (ACH) for the living space only; they do not include the basement infiltration. The basement values are the average ACH for the basement only; they do not include the living space infiltration.

Table 5-2 shows how for both leaky and tight basements the living space experiences lower air infiltration rates when the system is on by comparison to the periods when the system is off. The decrease is due to the pressurization that occurs in the apartments when the systems function. The pressurization, in turn, is determined by the higher airflow rates for supply than for return.

This table shows that the living space infiltration rates for the house with *leaky basement* increased after the sealing retrofit. Remember that the apartments had greater supply than return airflow. Imbalance in this direction tends to pressurize the apartment, reducing the infiltration rates. Since the retrofit reduced the airflow imbalance, the space pressure was also reduced and the infiltration rates increased.

It also follows that the infiltration in any basement, leaky or tight, would be reduced after the retrofit. In the basement the return ducts suck air into the system, depressurizing the space, while the supply ducts discharge air into the space, pressurizing it. The leakage area of return ducts is typically greater than the leakage area of supply ducts. Thus, the HVAC system sucks more air from the basement than it discharges into the basement, the basement is depressurized, which is the reverse condition of the living space above, which is pressurized. Sealing the ducts in the basement reduced the depressurization in the basement, and thus the infiltration rates into the basement.

Table 5-2 presents a different situation for the living space in the house with tight basement. In this case the air infiltration rates of the living space *decrease* after the sealing retrofit is performed. The reason for the reversal lays in the effect that basement depressurization has on the air infiltration rates of the living space. The leaky basement has such high air exchange rates (infiltration and exfiltration) that it is practically decoupled from the rest of the house in terms of air pressure. The pressure in the leaky basement is not very different from the pressure outside. Because of the high air exchange rates, the depressurization in the leaky basement caused by the return ducts is not great; it does not have a major effect on the air pressures in the living space above. The amount of air that crosses the living space floor into the leaky basement will not change much after duct sealing, because duct sealing does not significantly change the pressure in this basement. The dominant effect of duct sealing is a marked decrease in the pressurization of the living space. As a result, the living space in the house with leaky basement has higher infiltration rates post-sealing.

The situation for the living space in the house with tight basement changes. The air exchange rates of the tight basement are about 15-25% of those in the leaky one. The depressurization created by the duct leakage is greater. More air from the house is pulled into the basement across the living space floor and through stair wells. This is evidenced by the change in house air infiltration rates from system off to system on. In the *leaky basement* case (Albany), the air exchange rate of the living space with the system on is 65% of the air exchange rate of the living space with the system off (0.49 ach vs. 0.76 ach). For a tight basement, the air exchange rate of the living space with the system on is 70% of the one with the system off (0.55 ach vs. 0.79 ach). Pressurization of the apartments reduced to a lesser extent the air infiltration rates in the living space with tight basement than in the living space with leaky basement. This is because the pressurization in the apartments is accompanied by depressurization in the basement. In the tight basement the return ducts create greater depressurization, so they draw more air from the living space above. Consequently, the living space above has lower pressure with respect to the outdoors, and experiences a smaller reduction in air infiltration rates.

Duct sealing significantly changes the pressure in the tight basement, much more so than in the leaky basement. A tight basement with sealed ducts pulls significantly less air from the living space above than a tight basement with leaky ducts; this reduction is much greater than for the leaky basement. The effect is powerful enough to counteract and reverse the decrease in pressurization in the living space above (due to lower airflow imbalance between supply and return). The overall effect for the house with a tight basement is that the living space is more pressurized than before.

Consequently, duct sealing in a *leaky* basement of the Albany house was computed to *increase* the air infiltration rates by 18% (from 0.49 ach to 0.60 ach), while duct sealing in a *tight* basement of the same house was computed to *decrease* the air infiltration rates by 15% (from 0.55 ach to 0.47 ach).

Table 5-2: Summary of Air Infiltration Rates Obtained with COMIS

Average Winter Time Infiltration Rates					
City	System Operation	House with Leaky Basement		House with Tight Basement	
		Living Space (ACH)	Basement (ACH)	Living Space (ACH)	Basement (ACH)
Albany	Off	0.76	1.42	0.79	0.23
	On: Pre-sealing	0.49	1.64	0.55	0.38
	On: Post-sealing	0.60	1.38	0.47	0.20
New York	Off	1.03	2.15	0.81	0.27
	On: Pre-sealing	0.72	2.33	0.78	0.40
	On: Post-sealing	0.81	2.11	0.64	0.25

ENERGY USE SIMULATIONS

DOE-2.1E, the energy simulation program used for this work, is the most accurate and most complete energy simulation program currently in use in the U.S. for production purposes. The program is composed of four modules which execute sequentially. The four modules are as follows:

1) LOADS - This module is where the building geometry and orientation, wall and window constructions, infiltration values and schedules, and lighting, appliance, and occupancy loads and schedules are input. The program then computes the hourly building load based on the weather file and scheduled information. The results of this module can be passed to the SYSTEMS module.

2) SYSTEMS - This module is where the zone parameters, and heating and cooling distribution system are defined. The zone information includes space temperature schedules, and other information specific to a zone. The system information defines the type of distribution equipment (unit heaters, package systems, dual-duct, heating and ventilating, etc.) and the corresponding operating parameters (hot and cold deck temperatures, reheat, preheat, fan schedules, ventilation air and schedules, etc.). This module adjusts the results of the LOADS module, and calculates the energy requirements for the distribution systems. The results are then can be sent to the PLANT module.

3) PLANT - This module contains the central heating and cooling distribution equipment, if any, and the equipment parameters. The kind of equipment may include: boilers, chillers, cooling towers, generators, circulating pumps, etc. The parameters include: sizes, efficiencies, part load curves, temperature control set-points, etc. The results from the SYSTEMS module are used to determine

the load and corresponding fuel consumption required by the defined plant equipment. The results are then passed to the ECONOMICS module.

4) ECONOMICS - This module translates fuel consumption into energy costs. This module is capable of simulating virtually any utility rate, in steps no smaller than an hour.

A more detailed explanation of the structure and capabilities of the computer program is contained in the appendix.

Simulation Methodology

Although DOE-2.1E is a well-developed energy simulation program, it has limitations. The limitations which affect this work are as follows:

- The calculations are performed on an hourly basis. The program cannot account for system operation in steps smaller than one hour.
- The program assumes that the supply and return air flows to and from a space are equal. There are no provisions for imbalanced airflow.
- Supply conduction losses are not lost *into a space*. The program allows for the loss, but assumes the energy escapes from the building entirely.
- The program makes no explicit provisions for return conduction losses. The assumption is that no energy is lost from the return airstream.

However, the DOE-2 software allows the user to write customized functions to modify the standard calculation process. In other words, new program code was written to overcome the limitations listed, changing the energy balance to simulate the effects that duct leakage has on both system performance and building performance. How each of these limitations was overcome follows.

Hourly infiltration for energy simulations

As mentioned previously, the COMIS simulations used hourly infiltration data for an entire year to produce one set of results with the heating system operating all the time, and another set of results with the heating system not operating at all. These results had to be combined to yield a set of data for a heating system which cycles on and off as it meets the building load throughout the year. Determining when the system operates is complicated by the fact that the infiltration rates change depending on whether the system is on or off, and the system cycles on or off depending partly on the air infiltration rates.

Typically, the system cycles on and off several times in an hour. As described above DOE-2.1E is limited to conditions occurring on an hourly basis. This required that the infiltration values corresponding to on and off periods be combined on a time-weighted basis to account for the short cycling periods. The hourly fractional on-time and hourly infiltration values were solved using an iterative process.

This process involved a simulation using an initial set of infiltration values, performing the simulation to obtain the system on-time, recalculating the infiltration values and performing the simulation with the new values. This process was repeated until the maximum difference between infiltration value for two consecutive runs converged to within 1%.

Table 5-3 contains the results of the iterative process. These are the average air change rates for the heating season. The values include the effect that the system has on infiltration, as the system cycles on and off. As in Table 5-2, the living space values exclude the air infiltration in the basement, and the basement values are the air infiltration rates for the basement only.

Table 5-3: Summary of Air Infiltration Rates Determined Using Energy Simulations

Average Winter Time Infiltration Rates					
City		House with Leaky Basement		House with Tight Basement	
		Living Space (ACH)	Basement (ACH)	Living Space (ACH)	Basement (ACH)
Albany	Pre-sealing	0.64	1.52	0.72	0.30
	Post-sealing	0.69	1.41	0.65	0.22
New York	Pre-sealing	0.93	2.21	0.80	0.31
	Post-sealing	0.96	2.14	0.75	0.27

The results in this table follow the same trend as in Table 5-2, for the reasons described previously. In Albany the air infiltration rates *increased* between pre- and post-sealing by 8% in the building with a leaky basement, and *decreased* by 10% in the building with a tight basement. In New York the infiltration rates *increased* by 3% in the building with a leaky basement, and *decreased* by 6% in the building with a tight basement.

Airflow imbalance in the apartments

The airflow imbalance is caused by leaks in the duct system. If less supply air reaches the apartment, the apartment tends to be depressurized; if less air is returned from the apartment, the space tends to be pressurized. Depressurization will increase the infiltration rate while pressurization will decrease the infiltration rate. The effect that the infiltration rate has on the energy use of the building is accounted for with iterative runs using the COMIS results.

In addition, imbalanced airflow affects the energy use of the building in two other ways. These two ways are related to the amount of air which returns from the spaces to the furnace, and to the amount of air which leaks into the ductwork from the basement. The DOE-2 simulations are performed on spaces that have more supply airflow than return airflow. Since these spaces are over-pressurized, warm air exfiltrates. This exfiltrating air is not returned into the duct system and back to the furnace. To account for this effect on the energy balance, the DOE-2.1E code was revised: the energy which reaches the duct system from the apartments was reduced.

The warm air that exfiltrates from living spaces is replaced by cold air leaking into the return ductwork from the basement, reducing the temperature of the air that reaches the furnace. The mixed air temperature of the return air in the furnace was recalculated to account for this effect in the DOE-2 simulations.

Conduction losses from the ductwork to the basement

DOE-2.1E provides for conduction losses from the supply ductwork. However, DOE-2.1E does not explicitly provide for where this energy loss is directed. Without any changes, DOE-2.1E assumes the energy is just lost from the building. Additionally, the conduction through the return ductwork is not accounted for at all.

Again, the code was modified using custom written DOE-2.1E functions. These functions calculate the conduction losses based upon the hourly differences between the basement temperature and the air temperatures in the supply and return ductwork. This energy is then assigned to the basement.

DOE-2.1E incorporates each element in the revised energy balance to determine the hourly space temperature in the basement. This basement temperature is then used for the next hour in the energy balance equations. Therefore, the basement and duct system temperatures are coupled, and the effect that each has on the other is accounted for in the results. In other words, the change in basement temperature due to the retrofits is reflected in the overall energy use results.

ENERGY SIMULATIONS RESULTS

The operating temperatures after sealing increase as a result of the reduced airflow through the system fan, and thus reduced flow across the furnace heat exchanger. Also the reduced air leakage to the basement reduces the basement temperatures. Both of these conditions contribute to increasing the temperature difference across the ductwork. Therefore, the increased conduction losses reduce, to some extent, the savings achieved through sealing alone.

However, this is not to suggest that insulating is recommended without sealing the ducts. The insulation savings in Table 5-4 do not represent the savings which would occur if the insulation were installed without sealing; in fact the savings would be smaller. Insulation installed over a leaky duct system would not perform the same as when installed over a system with the leaks sealed. In the short-term, air from the leaks is forced through the insulation reducing the effective R-value. Long term, this air, carrying dust and dirt, would degrade the actual R-value of the insulation.

Table 5-4: Pre- and Post-Retrofit Energy Use and Energy Savings

		No Retrofit		Post Sealing		Savings vs. No Retrofit		Post Sealing and Insulation		Savings vs. Post Sealing		Savings vs. No Retrofit	
Location	Bsmnt Leakage	Gas (ccf)	Elec (Kwh)	Gas (ccf)	Elec (Kwh)	Gas (ccf)	Elec (Kwh)	Gas (ccf)	Elec (Kwh)	Gas (ccf)	Elec (Kwh)	Gas (ccf)	Elec (Kwh)
Albany	Tight	5346	19927	5171	19898	176	30	5029	19873	142	24	317	54
	Leaky	6683	21446	6361	21391	321	55	6048	21337	313	54	635	109
New York	Tight	3960	14761	3830	14739	130	22	3725	14721	105	18	235	40
	Leaky	4950	15886	4712	15845	238	41	4480	15805	232	40	470	81

The data in Table 5-4 indicate the range of energy savings achievable in the two climates. As the results show, the savings are reduced in a tight basement. More of the energy "lost" in a tight basement would tend to be "reclaimed" in one way or another, while the outside air moving through a leaky basement would carry the lost energy away.

The relative energy savings for each retrofit also changes with tight and leaky basements. The savings with respect to the no-retrofit case for both Albany and New York City energy use are about the same, at 10% and 6% for leaky and tight basements, respectively. The results are proportional in the two locations because the systems and leakage remains the same. The difference is simply the weather data. With regard to the weather data, only the winter data have an effect; cooling was not simulated, because no cooling was provided in any of the houses tested.

Also, the results indicate that duct insulation accounts for 49% of the energy savings in leaky basements, but only for 45% of the energy savings in tight basements. This shows that the basement temperature changes more in tight basements, and thus has an offsetting effect with respect to insulation savings.

CONCLUSIONS ON RESULTS FROM MODELING DUCT SEALING AND DUCT INSULATION

The computer simulations indicate that the air infiltration rates in the living spaces changes with the air leakage rates in the basement. Air infiltration rates in the living space may increase or decrease after sealing the ductwork, depending upon the amount of leakage in the basement. The variation in Albany was the greatest with the air infiltration increasing by 8% for a leaky basement and decreasing by 10% for a tight basement.

The energy use simulations indicate that the energy saved by each retrofit (sealing and insulation) is about equal. The energy savings for a house with a leaky basement are about double those for the house with a tight basement.

Chapter 6
ECONOMIC ANALYSIS

PROTOTYPE RETROFITTING COSTS

The cost of the retrofit strategies is based upon the average cost from the systems retrofitted in this study. As developed in Chapter 4, the average costs for sealing and insulating were $0.61/ft^2 and $1.72/ft^2, respectively. Again, these figures are based upon the exposed duct area.

The exposed duct area for the prototype was determined by developing the prototype duct plan. The duct plan represents a reasonable design for the locations of supply and return registers in the apartments. This plan yields exposed duct areas of 412 ft^2 and 172 ft^2 for the supply and return ductwork.

Based upon these calculations the cost for the retrofits are as follows:

Table 6-1: Cost Breakdown for Retrofit Strategies

	Supply	Return	Total
Sealing	$ 251.32	$ 104.92	$ 356.24
Insulation	$ 708.64	$ 295.84	$ 1,004.48
Both	$ 959.96	$ 400.76	$ 1,360.72

ENERGY COST AND SAVINGS

Typical rates for the two regions presented: New York City and Albany. The average utility prices used are as follows:

Table 6-2: Utility Prices

	Gas ($/Therm)	Electric ($/Kwh)
New York City	0.82	0.14
Albany	0.62	0.13

Based on these rates the total energy costs were calculated for the simulations performed, and are presented in Table 6-3.

Table 6-3: Total Energy Costs for Energy Simulations

Location		No Retrofit	Post Sealing	Savings vs. No Retrofit	Post Sealing & Insulation	Savings vs. Post Sealing	Savings vs. No Retrofit
	Basement Leakage	Total ($)	Total ($)	Total ($)	Total ($)	Total ($)	Total ($)
New York City	Tight	5314	5204	110	5115	89	199
	Leaky	6283	6082	201	5886	196	397
Albany, NY	Tight	5905	5792	113	5701	91	204
	Leaky	6931	6725	206	6524	201	407

The simple paybacks were calculated from the total energy cost and the first cost for each retrofit. These results are presented in Table 6-4.

Table 6-4: Total Retrofit and Energy Use Costs, and Simple Paybacks

Location		Sealing		Insulating		Sealing & Insulating	
	Basement Leakage	Total ($)	SPB (yrs)	Total ($)	SPB (yrs)	Total ($)	SPB (yrs)
Retrofit Cost		356		1004		1361	
New York City	Tight	110	3.2	89	11.3	198	6.9
	Leaky	201	1.8	196	5.1	397	3.4
Albany, NY	Tight	113	3.2	91	11.0	204	6.7
	Leaky	206	1.7	201	5.0	408	3.3

These results show that the paybacks are almost the same for each region. This is coincidental and occurs solely because of the relationship between utility rates and energy use. The downstate rates are about 32% more expensive for natural gas, but the upstate energy use is about 35% higher, due to the colder climate. The net result is that these two factors offset one another, and the simple payback is constant.

The results in the table also show that insulation is less cost-effective in tight basements. However, in leaky basements the simple paybacks are promising.

Finally, a life cycle costing analysis was performed with sealing only, and with sealing and insulation together. The analysis assumes:

- a life cycle of 18 years each for the sealant and the insulation,
- a 7% real discount rate, i.e., 7% higher than inflation, and

- DOE's fuel cost and inflation escalation schedules.

Table 6-5 contains the results for the life-cycle costs and life-cycle savings.

Table 6-5: Life-Cycle Analysis Results

Location	Basement Leakage	Retrofit	Life-cycle Cost ($)	Life-cycle Savings ($)
New York City	Tight	None	64,867	
		Sealing	63,975	892
		Sealing & Insulation	63,996	871
	Leaky	None	76,221	
		Sealing	74,279	1,942
		Sealing & Insulation	73,049	3,172
Albany, NY	Tight	None	58,545	
		Sealing	57,591	954
		Sealing & Insulation	57,611	934
	Leaky	None	69,185	
		Sealing	67,309	1,876
		Sealing & Insulation	66,139	3,046

For a tight basement the life-cycle savings are practically the same whether only sealing or both sealing plus insulation are performed. For a leaky basement, sealing plus insulation saves about 60% more than sealing only. These results are subject to change in the assumptions for both discount rate and energy inflation rates. The 7% real discount rate is equivalent to about 11%-12% nominal discount rate at the current inflation of 4%-5%. Additionally, some federal or state programs may offer more advantageous financing terms for such retrofits, resulting in more attractive life-cycle savings.

CONCLUSION ON RESULTS OF ECONOMIC ANALYSIS

The results indicate that duct sealing is cost-effective for all conditions simulated. In contrast, the results indicate that insulating the ductwork after sealing may not be cost-effective in houses with tight basements, but is cost-effective in houses with leaky basements. In fact, the *life-cycle cost increases* (albeit slightly) with the addition of insulation in tight basements, in both Albany and New York. In leaky basements the insulation decreases the life-cycle costs. The life-cycle cost savings increase by more than 60% for leaky basements when the ducts are insulated after they have been sealed.

APPENDIX A

TESTING PROTOCOL FOR PHASE I

SWA Monitoring Protocol for Multifamily Duct Field Study in Cortland, New York

revision date: 2/20/94

I. Arrival

A. Identify yourself (show ID)

B. record basic information:

Customer: ____

Address:______________________________Apart. ID#___________________________

phone number:____________________Date:______________________________________

Arrival Time:_____________________SWA Team:_________________________________

C. program description

Go over program description and measurements with apartment dweller. Briefly explain what SWA will be doing. Discuss what potential benefits apartment dweller may expect to realize. Answer any questions apartment dweller may have.

D. insure that the apartment has a central forced-air distribution system

E. obtain apartment dweller permissions to:

1. control heater/air conditioner operation for the day
2. extinguish pilot lights and shut off gas appliances
3. close windows and control exterior and interior doors
4. have access to entire apartment including attic, garage, basement etc.
5. cover air grilles
6. operate blower door and duct blaster units inside the home
7. repair and insulate air distribution system

II. Building Characteristics and Apartment Dweller Information

A. shielding description (trees, shrubs, neighboring buildings etc.)

1. take photograph of front of building

B. building description:

age (yr. built)	square footage	number of stories	number of apartments

C. miscellaneous (if possible)

1. monthly energy costs
   a) electricity:______________________
   b) gas:____________________________
2. Are you satisfied with the performance of the heating/cooling system?_____
   ____
3. Are there any rooms that are not well heated or cooled?
   a) Which ones?____
4. Are your utility bills high in winter or summer?____________________
5. Is the air handler fan noticeably loud when operating?__________________

D. construction

1. walls: wood-frame, brick facing, stucco, wood facing, other__________
2. wall insulation: R-_____, attic insulation: R-_____
3. roof construction: shingle, shake, tar shingle, tile, other________
4. window type: single- double- or triple-pane, fixed, casement, sliding, double-hung

E. internal resistance (optional)

1. label doorways with capital letters
2. record undercut of internal doorways (height)
3. record doorway position schedule (ask apartment dweller if possible)

Table 1: Internal Resistances

Door	Room	crack width	crack height	normal position
A				
B				
C				
D				
E				
F				
G				
H				

III. Equipment Characteristics

A. fill in table:

Table 2: HVAC Equipment Info.

characteristic	Heating	Cooling	notes
fuel			
manufacturer			
model #			
serial #			
year manufactured			
year installed			
rating			
location			
general condition			

1. photograph heating installation
2. sketch heating system location in floor plan, page 32 and page 31 or page 29

B. **thermostat (optional)**

1. type: single-setpoint, setback, programmable
2. manufacturer:__________________________
3. model number: ____________________________
4. serial number: ___________________________
5. photograph thermostat
6. sketch thermostat location in floor plan
7. operation and setpoint schedule: (check settings or ask apartment dweller)

Table 3: Thermostat Settings

	summer	winter
Day		
Evening		
Night		

8. current setpoint and time of day: ____________________
9. displayed temperature: ________________________
10. anticipator setting and range: (e.g. 0.5 in range 0-1)__________________
11. fan operation settings (i.e. speed selection if variable): _______________

C. distribution system characteristics

Table 4: HVAC/Duct Location Summary

	air handler	compressor	supply ducts	return ducts	zoned? # zones
location					

Table 5: Air Distribution System Summary

	supply ducts	supply plenum	return ducts	return plenum	air handler
material[a]					
R - value					
thickness					
condition[b]					

a. duct construction: sheet metal square, sheet metal spiral, aluminum spiral, flat aluminum, fiberglass, flexible plastic with metal spiral, other
b. check for asbestos

D. Connections to plenums: duct tape, mastic and fiber, other: ______________

1. connections to junction boxes: duct tape, mastic and fiber, other: __________
2. connections to register boots: duct tape, mastic and fiber, other: __________
3. duct sealing type, condition: ____
4. take a photograph of a typical duct section
5. sketch duct system layout on page 32, use floor plan as template
6. indicate in sketch duct dimensions, diameters
7. fan thermostat settings (usually heating only)
   a) low: ________
   b) high: ________
   c) limit: ________
8. fan rating
   a) amps: ______________________flow: ________________________
   b) pressure differential: ______________________________________
   c) measure actual power consumption (optional): ____________

____

E. **distribution system leakage sites**

1. visual inspection of leakage sites
   a) return: ______________________________
   b) registers: ______________________________
   c) air-handling unit: ______________________________
   d) air filter: ______________________________
   e) ducts (small leaks): ______________________________
   f) ducts (large leaks, disconnected ducts): ______________________________

F. record observations here:

IV. Sketches

A. use same scale and dimensions so that sketches can be overlaid

B. include building orientation, foliage class, %window glazing etc.

C. label rooms and supply and return registers: kit, mba, mbr, br1, br2, din, lnd, den, ba1, etc.

D. label internal doors: A, B, C, etc.

E. label external doors: I, II, III, IV, etc.

F. describe attic and crawlspace venting (size of grilles, location)

G. indicate normal direction wind impinges on building

H. mark location of fireplace, water heater, washer, dryer, dishwasher

I. mark location of ventilation / exhaust fans or grilles (bathrooms, laundry, etc.)

J. checklist of sketches:

1. ❒ building floor plan, incl. dimensions
2. ❒ duct system layout

V. Photograph Checklist

A. ❒ front of building

B. ❒ attic venting, if there is ductwork in the attic

C. ❒ heating installation

D. ❒ cooling installation (optional)

E. ❒ thermostat

F. ducts:

1. ❒ connections to plenums
2. ❒ connections to junction boxes, register boots
3. ❒ deteriorated ducts
4. ❒ other obvious problems/leakage sites

G. **Air Distribution System**

1. sketch distribution system layout and location
   a) air handler dimensions including plenums
   b) supply and return duct lengths, dimensions and insulation
2. label air filter location
3. note location of in-line fans and dampers, if any, check for zoning
4. fill in Table 6 (Optional if sketch is good):

Table 6: Air Distribution System Characteristics

supply or return duct/plenum	length	dimensions	insulation	damage
SP				
sd1				
sd2				
sd3				
sd4				
sd5				
sd6				
sd7				
sd8				
sd9				
sd10				
RP				
rd1				
rd2				
rd3				
rd4				

VI. Attic

A. basic equipment to take into attic that has ducts

1. camera
2. hand light
3. extension cords
4. measuring tape
5. pressure sensor
6. pencil and attic plan page of protocol for sketch

VII. Blower Door Test (OPTIONAL)

A. this test is to determine the envelope ELA

B. setup for depressurization

1. set up blower door in main doorway or doorway with plenty of clearance
2. connect tube to "A" side reference port on the digital manometer, run other end outside. This is the apartment pressure measurement side. Use the 200 Pa scale
   a) make sure outside end of tube is well away from the blower door fan
3. connect tube to "B" side reference port on the digital manometer, connect other end to port on blower door fan housing. This is the fan pressure measurement side. Note: when reading this pressure, switch scale to 2000 Pa before switching to this channel.
4. make sure manometer is away from blower door fan when operating
5. use 5, 10 second or long term averaging when reading manometer for pressures
6. make an inside and outside temperature reading, record this in Table 7
7. make sure all windows and doors to outside are closed
8. make sure all fireplace dampers are closed
9. make sure all internal doors are open

C. depressurization test

1. turn on blower door fan and depressurize the apartment to -50 Pa
   a) if fan pressure is less than 20 Pa for -50 Pa apartment pressure, stop fan and install flow ring A on fan inlet. If condition not remedied, install ring B etc.
   b) measure and record the pressure in surrounding apartments
2. record the apartment pressure and fan pressure in Table 7
3. decrease fan speed until apartment pressure is about -40 Pa, record apartment and fan pressure in Table 7
4. repeat above step in increments of about 10 Pa until -10 Pa reached, record info. in Table 7

D. zero measurement

1. cover inlet side of blower door with no-flow plate. record apartment (including surrounding apartments) and fan pressures in Table 7

E. calculate and record ACH information in Table 8

F. Measure the envelope leakage of the entire building (optional)

G. leave blower door installed for combination test (blower door + duct blaster)

VIII. Register and Leakage Flow Measurements

A. register flows are to be measured by the duct blaster augmented flowhood

B. setup - supply register flows

1. put together flowhood (either 24" × 24" or 16" × 16"), when finished, stand it upright with base upward
2. duct tape adapter (flexible duct to cardboard cutout) to cardboard cutout, tape round cardboard cutout to flowhood base with duct tape. (this is likely done already)
3. connect flexible duct to adapter using velcro strap
4. attach other end of flexible duct to fan housing attachment using velcro strap
5. insert white honeycombed foam flow conditioner into fan housing attachment
6. use weather stripping to connect fan housing attachment to inlet side of duct blaster fan, install with ring 1 between flow attachment and fan, make sure flow ring opens into fan
7. connect a tube to the side "A" input pressure port on the digital manometer, connect the other end of the tube to the forward tube coming out of the flow measurement section of the flowhood (the end nearest the wide end of the flowhood, i.e. the tube nearest the oncoming flow) (for total pressure). Side "A" measures ΔP_{flow}
8. make sure manometer is clear of duct blaster fan when making measurements
9. connect tube to side "B" inlet pressure port on the digital manometer, connect other end of tube to the pressure tube port on the fan housing attachment on the duct (this connection is a "tee" connection with other tubes attached to it)
10. connect a tube to the side "B" reference pressure port on the digital manometer, connect the other end of this tube to the port on the duct blaster fan housing
11. make sure all flexible duct is as straight and as uncompressed as possible when making flow measurements.
12. doors and windows to apartment and basement should all be closed
13. plug in duct blaster fan
14. turn on air handler fan

C. **measure flows from each supply register**

1. place flowhood over supply register
2. adjust duct blaster fan speed until flowhood luffs and pressure on channel "A", ΔP_{flow} is 0. record ΔP_{flow} if too difficult to reach 0. note, use 5 or 10 second or long term averages when making readings
   a) If $\Delta P_{fan} < 20$ Pa, turn off duct blaster and install ring 2 in place of ring 1. Use ring 3 if problem not remedied.

D. **record ΔP_{fan}, calculate Q in Table 12 (pre-retrofit) or Table 21 (post-retrofit). note, use the calibration for the installed flow ring**

E. **measure flows into each return register**

1. remove pressure measurement tube from fan housing attachment and from digital manometer
2. remove fan housing attachment from duct blaster and take out honeycombed flow conditioner
3. reconnect fan housing attachment to exhaust side of duct blaster fan (opposite side)
4. leave inlet side open with no flow ring installed
5. make sure pressure measurement tube is still connected from fan housing to B side reference port on manometer.
6. place flowhood over a return register
   a) if flowhood does not cover entire grille, cover about 1/2 to 3/4 of it and make one measurement, then cover the remaining area for a second measurement and the total flow will be a sum of the two measurements
7. adjust duct blaster fan speed until flowhood luffs and pressure on channel "A", ΔP_{flow} is 0. record ΔP_{flow} if too difficult to reach 0. note, use 5 or 10 second or long term averages when making readings
   a) If $\Delta P_{fan} < 20$ Pa, turn off duct blaster and install ring 1 in place of the open fan. Use ring 2 etc. if problem not remedied.
8. record ΔP_{fan}, calculate Q in Table 12 or 21. note, use the calibration for the installed flow ring

IX. Operating Pressures

A. turn on air handler fan

B. using digital manometer

1. connect tubing to input side of manometer
2. connect pitot tube to other end of tube
3. stick pitot tube in register
4. record static pressure difference between supply, return registers and apartment interior
5. connect tube to dynamic port on pitot tube
6. record total pressure difference between supply, return registers and apartment interior
7. fill in the Table 14 for pre-retrofit or Table 23 for post-retrofit

X. Interior Room Pressures (Optional)

A. use digital manometer to determine pressures across closed doors when fan is operating

1. make sure fan is on, doors to outside are closed
2. measure ΔP to apartment interior

B. measure pressure across the envelope with the interior doors open with and without the furnace fan on

C. fill in Table 15 for pre-retrofit or Table 24 for post-retrofit

XI. Duct Blaster Tests

A. IF ACCESS AT FAN COMPARTMENT DOOR IS GOOD:

1. **MEASURE OPERATING PRESSURE OF DUCT SYSTEM IN SUPPLY PLENUM (LEAVE SENSOR IN PLACE IN SUPPLY PLENUM FOR ALL SUBSEQUENT TESTS IN THIS SECTION)**
   a) measure pressure difference between supply plenum and basement with air handler fan on all external doors and windows closed, record value in Table 13 for pre-retrofit and Table 22 for post-retrofit
2. **SEAL ALL REGISTERS AND GRILLES, REMOVE FILTER, AND INSTALL DUCT BLASTER INTO FAN ACCESS DOOR**
3. **PRESSURIZE (AND OPTIONALLY DEPRESSURIZE ALSO) THE DUCT SYSTEM TO 30 PA (AND SEVERAL OTHER PRESSURES TO MIMIC OPERATING PRESSURES IN THE DUCT SYSTEM)**
4. **MEASURE THE PRESSURE AT RETURN PLENUM, ALL RETURN REGISTERS, SEVERAL SUPPLY REGISTERS**
   a) record plenum and register pressures in Table 14 for pre-retrofit or Table 23 for post-retrofit
5. **RECORD DUCT BLASTER FLOW AND PRESSURES (MEASURE TEMPERATURE AT DUCT BLASTER ENTRANCE)**
   a) record duct blaster fan pressure and plenum pressure and determine flow in Table 9 for pre-retrofit or Table 18 for post-retrofit
6. **IF IT IS NOT CLEAR WHERE ALL OF THE LEAKAGE IS GOING, USE BLOWER DOOR IN APARTMENT TO ISOLATE LEAKAGE SECTIONS (BY MAKING PRESSURE IN ZONE EQUAL TO THAT IN DUCTS, SEE APPENDIX) (Use Table 11 for pre-retrofit and Table 20 for post)**
7. **SEAL THE SUPPLY SIDE FROM THE RETURN SIDE AT THE FILTER**
8. **MEASURE SUPPLY SIDE ONLY LEAKAGE**
   a) record duct blaster fan pressure and supply plenum pressure and determine flow in Table 10 for pre-retrofit or Table 19 for post-retrofit
9. **UNSEAL SUPPLY REGISTERS**
10. **MEASURE FAN FLOW WITH DUCT BLASTER AT SEVERAL SUPPLY PLENUM PRESSURES ON AND AROUND PREVIOUSLY MEASURED OPERATING POINT**
    a) record duct blaster fan pressure and determine fan flow in Table 13 for pre-retrofit or Table 22 for post-retrofit
    b) calculate total flow to make sure it is greater than the sum of supply or return register flows by a reasonable amount

11. **IF IT IS NOT CLEAR WHERE ALL OF THE LEAKAGE IS GOING, USE BLOWER DOOR TO ISOLATE LEAKAGE SECTIONS (BY MAKING PRESSURE IN ZONE EQUAL TO THAT IN DUCTS, SEE APPENDIX) (Use Table 11 for pre-retrofit and Table 20 for post)**

B. **IF ACCESS IS NOT GOOD (SEE APPENDIX)**

XII. Conduction Losses

A. **use digital thermometer to measure the temperatures in the duct system and surroundings**

1. make sure furnace is on and operating under steady-state conditions (i.e., force a long on period),
2. measure the temperatures at each supply register, each return register, the supply plenum, the return plenum, outdoors, and the basement.
3. record the time and sensor used for each measurement (check
4. perform post-retrofit return plenum and register measurements before and after insulating

B. **fill in Table 16 for pre-retrofit or Table 25 for post-retrofit**

C. **characterize the dynamic performance of the system (optional)**

1. record the temperatures at one or two supply registers (near and far from the plenum) and the supply plenum on a minute by minute basis over an entire cycle.
2. fill in Table 17 for pre-retrofit or Table 26 for post-retrofit

XIII. Clean up

A. remove all equipment

B. vacuum all traces of insulation or dirt tracked through the apartment

Table 7: Envelope Leakage Data (Optional)

T_{out}, °C =				T_{in}, °C =		
test	nominal apartment pressure, Pa	actual apart. pressure, Pa	fan pressure Pa	flow ring	flow, cfm	flow, m^3/hr
depressurization	-50 Pa					
	-40 Pa					
	-30 Pa					
	-20 Pa					
	-10 Pa					
no-flow plate	0 Pa					

Table 8: Preliminary Results

$CFM50 = CFM(50/\Delta P)^{.65}$, ft^3/min	
$ELA_4{}^a = 0.353 * CFM50$, cm^2	
ACH50 = 60*CFM50/(APART. VOL.)	
$ACH = ACH50/24^b$	

a. estimation only, regression will yield better ELAs
b. Sacramento only

Blower Door Calibration formulas:
open fan: $Q = 490.2\Delta P^{4945}$
ring A: $Q = 180.7\Delta P^{4948}$
ring B: $Q = 57.2\Delta P^{5065}$
ring C: $Q = 20.7\Delta P^{5275}$

ΔP in Pa, Q in cfm. Conversion: $m^3/hr = 1.699 * cfm$

Table 13: Duct Blaster Fan Total Airflow (PRE-RETROFIT)

test #	ΔP_{duct}, Pa normal	ΔP_{duct}, Pa w/ duct blaster	ΔP_{fan} Pa	Q cfm	$T_{into\ DB}$ °C
1					
2					
3					
4					
5					
6					
7					

Table 17: Duct Temperature Cycling Characteristics (PRE-RETROFIT)

Surroundings	Supply Register		Supply Plenum	
time/ Temp (^oC)	time	Temp. (^oC)	Time	Temp. (^oC)

Table 22: Duct Blaster Fan Total Airflow (POST-RETROFIT)

test #	ΔP_{duct}, Pa normal	ΔP_{duct}, Pa w/ duct blaster	ΔP_{fan} Pa	Q cfm	$T_{into\ DB}$ ^oC
1					
2					
3					
4					
5					
6					
7					

Table 26: Duct Temperature Cycling Characteristics (POST-RETROFIT)

Surroundings	Supply Register		Supply Plenum	
time/ Temp (°C)	time	Temp. (°C)	Time	Temp. (°C)

Plan View of Apartment:

Plan View of Attic:

Plan View of Basement:

XIV. APPENDIX

A. **(INADEQUATE ACCESS OPTION) this test is to determine the total duct leakage and the duct leakage to outside for both the supply and return sides (also can be used to isolate leakage to basement from leakage to outside or apartments)**

B. **setup for supply side leakage measurements, depressurization or pressurization only**

1. separate and seal the air distribution system at the fan
2. seal all supply and return registers except a large flow supply register
   a) do not remove grilles, seal over them instead using cardboard or metal plates and/or blue tape
3. connect duct blaster feed to open supply register, seal tightly
4. make sure duct blaster inlet is open to room
5. connect a tube to the side "A" input pressure port on the digital manometer, place the other end of the tube in a supply register nearest the supply plenum. Push the tube into the register as far as possible in an attempt to locate the end of it in the plenum. Do not place the end of the tube near the duct blaster inlet! This is the duct pressure measurement side. Use the 200 Pa scale
   a) if access to the supply plenum exists and is not difficult to use, put other end of duct supply side tube in supply plenum
6. connect a tube to the side "B" reference pressure port, connect the other end of this tube to the pressure port on the duct blaster fan housing. This is the duct blaster fan measurement side. Use the 2000 Pa scale
7. when reading manometer, do not place it near the duct blaster fan inlet
8. use 5, 10 second or long term averaging when reading manometer for pressures
9. measure temperature inside apartment, record it in Table 10 for pre-retrofit or Table 19 for post-retrofit
10. open an external door or large window in apartment and basement

C. **depressurize supply side ducts and plenum - total supply duct leakage test**

1. turn on duct blaster
2. pressurize ducts to 30 Pa or to highest possible pressure up to 30 Pa
   a) if duct blaster fan pressure is less than 20 Pa for 30 Pa duct pressure, stop fan and install flow ring 1 on fan inlet. If condition not remedied, install ring 2 etc.
3. record the duct pressure and fan pressure in Table 10 for pre-retrofit or Table 19 for post-retrofit

4. turn off duct blaster fan

D. apartment blower door + duct blaster test - supply side to outside plus basement leakage test - only if it is not clear where the leakage is going

1. close the open apartment door or window
2. using the one channel electronic manometer, connect the high side pressure port to the tube running outside the apartment
3. turn on blower door fan and depressurize the apartment to about 30 Pa on the single channel apartment manometer
4. turn on the duct blaster and depressurize the Supply ducts until the reading on side "A" of the digital manometer is zero
5. record the apartment pressure, the duct to inside pressure difference and the duct blaster fan difference in Table 11 for pre-retrofit or Table 20 for post-retrofit
6. turn off duct blaster and blower door fans

E. setup for return duct leakage measurements, depressurization or pressurization only

1. open an external door or window in apartment and basement
2. disconnect duct blaster feed duct from the supply register
3. remove seal from main return register
4. connect duct blaster feed to open return register, seal tightly
5. make sure duct blaster fan inlet is open to room
6. remove duct pressure tube from supply duct
7. make sure duct pressure tube is still connected to the side "A" input pressure port on the digital manometer, place the other end of the tube in the return plenum or in another register nearest the return plenum. Push the tube into the register as far as possible in an attempt to locate the end of it in the plenum. Do not place the end of the tube near the duct blaster inlet! This is the duct pressure measurement side. Use the 200 Pa scale
8. make sure the fan pressure tube is still connected to the side "B" reference pressure port, with the other end of this tube connected to the pressure port on the duct blaster fan housing. Use the 2000 Pa scale
9. when reading manometer, do not place it near the duct blaster fan inlet.
10. use 5, 10 second or long term averaging when reading manometer for pressures
11. measure temperature inside apartment, record it in Table 9 for pre-retrofit or Table 18 for post-retrofit

F. depressurize return side ducts and plenum - total return duct leakage test

12. turn on duct blaster
13. pressurize ducts to 30 Pa or to highest possible pressure up to 30 Pa
    c) if duct blaster fan pressure is less than 20 Pa for 30 Pa duct pressure, stop fan and install flow ring 1 on fan inlet. If condition not remedied, install ring 2 etc.
14. record the duct pressure and fan pressure in Table 9 for pre-retrofit or Table 18 for Dost-retrofit
15. turn off duct blaster fan apartment

G. blower door + duct blaster test - return side to outside leakage test - only if it is unclear where the leakage is going

1. close the open apartment door or window
2. using the one channel electronic manometer, connect the high side pressure port to the tube running outside the apartment
3. turn on blower door fan and depressurize the apartment to about 30 Pa on the single channel apartment manometer
4. turn on the duct blaster and pressurize the supply ducts until the reading on side "A" of the digital manometer is zero
5. record the apartment pressure, the duct to inside pressure difference and the duct blaster fan difference in Table 11 for pre-retrofit or Table 20 for post-retrofit
6. turn off duct blaster and blower door fans

H. total duct system leakage to basement test

1. leave duct blaster feed connected to main return duct, leave digital manometer setup as is
2. open an external door or window in apartment and basement
3. remove the seal at the air handler fan

I. depressurize total duct system - total duct leakage test

1. turn on duct blaster
2. pressurize ducts to 30 Pa or to highest possible pressure up to 30 Pa
    a) if duct blaster fan pressure is less than 20 Pa for 30 Pa duct pressure, stop fan and install flow ring 1 on fan inlet. If condition not remedied, install ring 2 etc.
3. record the duct pressure in supply plenum and fan pressure in Table 11 for pre-retrofit or Table 20 for post-retrofit
4. turn off duct blaster fan

J. **basement blower door + duct blaster test - total duct system to basement leakage test (optional)**

1. install a blower door between the basement and outside
2. close the open basement door or window
3. using the one channel electronic manometer, connect the high side pressure port to the tube running outside the basement
4. turn on blower door fan and depressurize the basement to about 30 Pa on the single channel envelope manometer
5. turn on the duct blaster and depressurize the supply ducts until the reading on side "A" of the digital manometer is zero
6. record the basement pressure, the duct to basement pressure difference and the duct blaster fan difference in Table 11 for pre-retrofit or Table 20 for post-retrofit
7. turn off duct blaster and blower door fan

K. **clean up**

1. remove all register seals
2. clean all tape marks from grilles
3. remove duct blaster and blower door equipment

L. **Procedure to estimate supply and return leakage areas when it is impossible to isolate each side (optional):**

1. measure total and to outside duct ELAs
   a) pressurize ducts from the return side
   b) leave all registers sealed
2. open a known dimensioned hole in the supply side
   a) can be an entire small supply grille or a partial large one
3. use duct blaster ring 1 (largest) on return side for known dimensioned hole on return side (ring 1 = 6 5/8 " dia.)
4. turn on air handler fan
5. monitor pressures in supply and return plenums, one or two sealed supply registers, and at the return register
6. try not to exceed 200 Pa in duct system (don't rupture ducts!)

APPENDIX B

TESTING PROTOCOL FOR PHASE II

SWA Monitoring Protocol for Multifamily Duct Field Study in Cortland, New York

1. Arrival

A. Identify yourself (show ID)

B. Record basic information:

Customer:____

Address:______________________________ Apart. ID#________

Phone number:__________________________ Date:____________

Arrival Time:___________________________ SWA Team:_______

C. Program description

Go over program description and measurements with apartment dweller. Briefly explain what SWA will be doing. Discuss what potential benefits apartment dweller may expect to realize. Anser any questions apartment dweller may have.

D. Ensure that the apartment has a central forced-air distribution system.

E. Obtain apartment dweller permissions to perform the following:

1. control heater/air conditioner operation for the day
2. extinguish pilot lights and shut off gas appliances
3. close windows and control exterior and interior doors
4. have access to entire apartment including attic, garage, basement, etc.
5. cover air grilles
6. operate blower door and duct blaster units inside the home

II. Building Characteristics and Apartment Dweller Information

A. Shielding Description (trees, shrubs, neighboring buildings, etc.)

1. Take photograph of front of building

B. Building description:

age (yr. built)	square footage	number of stories	number of apartments

C. Miscellaneous (if possible)

1. monthly energy costs

   a) electricity:____________

   b) gas:_________________

2. Are you satisfied with the performance of the heating/cooling

   system: ____

   ____

3. Are there any rooms that are not well heated or cooled?

   a) Which ones?____

4. Are your utility bills high in winter or summer?_________________

5. Is the air handler fan noticeably loud when operating?____________

D. Construction

1. walls: wood-frame, brick facing, stucco, wood facing, other________

2. wall insulation: R-______, attic insulation: R-______

3. roof construction: shingle, shake, tar shingle, tile, other________

4. window type: single- double- or triple-pane, fixed, casement, sliding, double-hung

E. Internal resistance (optional)

1. label doorways with capital letters

2. record undercut of internal doorways (height)

3. record doorway position schedule (ask apartment dweller if possible)

Table 1: Internal Resistances

Door	Room	Crack width (in)	Crack height (in)	Normal position
A				
B				
C				
D				
E				
F				
G				
H				

III. Equipment Characteristics

A. Fill in table:

Table 2: HVAC Equipment Info.

Characteristic	Heating	Cooling	Notes
fuel			
manufacturer			
model #			
serial #			
year manufactured			
year installed			
rating			
location			
general condition			

1. Photograph heating installation
2. Sketch heating system location in floor plan, page 38

B. Thermostat (optional)

1. type: single-setpoint, setback, programmable
2. manufacturer:____________________
3. model number:____________________
4. serial number:____________________
5. photograph thermostat
6. sketch thermostat location in floor plan
7. operation and setpoint schedule: (check settings or ask apartment dweller)

	Summer	Winter
Day		
Evening		
Night		

8. current setpoint and time of day:____________
9. displayed temperature:____________________
10. anticipator setting and range: (e.g. 0.5 in range 0-1)__________
11. fan operation settings (i.e. speed selection if variable):_________

C. Distribution System Characteristics

Table 4: HVAC/Duct Location Summary

	air handler	compressor	supply ducts	return ducts	zoned?/# zones
location					

Table 5: Air Distribution System Summary

	supply ducts	supply plenum	return ducts	return plenum	air handler
material[a]					
R-value					
thickness					
condition[b]					

a. duct construction: sheet metal rectangular, sheet metal round, sheet metal spiral, aluminum spiral, aluminum rectangular, fiberglass, flexible plastic with metal spiral, plywood, other

b. check for asbestos

D. Connections to plenums: duct tape, mastic and fiber, other:________

1. connections to junction boxes: duct tape, mastic and fiber, other:____
2. connection to register boots: duct tape, mastic and fiber, other:_____
3. duct sealing type, condition:________________________________
4. take a photograph of a typical duct section
5. sketch duct system layout on page 38
6. indicate in sketch duct dimensions, diameters

7. fan thermostat settings (usually heating only)

   a) low:___

   b) high:___

   c) limit:___

8. fan rating

   a) amps:______________flow:_____________

   b) pressure differential:____________________

   c) measure actual power consumption (optional):_______________

   ____

E. Distribution system leakage sites

1. visual inspection of leakage sites

   a) return:____

   b) registers:____

   c) air-handling unit:_______________________________________

   d) air filter:____

   e) ducts (small leaks):_____________________________________

   f) ducts (large leaks, disconnected ducts):______________________

F. Record observations here:

IV. Sketches

A. Use same scale and dimensions so that sketches can be overlaid

B. Include building orientation, foliage class, % window glazing, etc.

C. Label rooms and supply and return registers: kit, mba, mbr, br1, br2, din, lnd, den, bal, etc.

D. Label internal doors: A, B, C, etc.

E. Label external doors: I, II, III, IV, etc.

F. Describe attic and crawlspace venting (size of grilles, location)

G. Indicate normal direction wind impinges on building

H. Mark location of fireplace, water heater, washer, dryer, dishwasher

I. Mark location of ventilation/exhaust fans or grilles (bathrooms, laundry, etc.)

J. Checklist of sketches:

1. ☐ building floor plan, incl. dimensions

2. ☐ duct system layout

V. Photograph Checklist

A. ☐ **front of building**

B. ☐ **attic venting, if there is ductwork in the attic**

C. ☐ **heating installation**

D. ☐ **cooling installation (optional)**

E. ☐ **thermostat**

F. ducts:

1. ☐ connections to plenums
2. ☐ connections to junction boxes, register boots
3. ☐ deteriorated ducts
4. ☐ other obvious problems/leakage sites

G. Air Distribution System

1. Sketch distribution system layout and location:
   a) air handler dimensions including plenums
   b) supply and return duct lengths, dimensions and insulation
2. Label air filter location.
3. Note location of in-line fans and dampers, if any; check for zoning.
4. Fill in Table 6 on page 10.

Table 6: Air Distribution System Characteristics

supply or return duct/plenum	length (ft)	dimensions (in)	insulation	damage
SP				
sd1				
sd2				
sd3				
sd4				
sd5				
sd6				
sd7				
sd8				
sd9				
sd10				
RP				
rd1				
rd2				
rd3				
rd4				
rd5				
rd6				
rd7				
rd8				

VI. Attic

A. Basic equipment to take into attic that has ducts

1. camera
2. hand light
3. extension cords
4. measuring tape
5. pressure sensor
6. pencil and attic plan page of protocol for sketch

VII. Blower Door Test (OPTIONAL)

A. This test is to determine the envelope ELA

B. Setup for depressurization

1. Set up blower door in main doorway or doorway with plenty of clearance

2. Connect tube to "A" side reference port on the digital manometer, run other end outside. This is the apartment pressure measurement side. Use the 200 Pa scale.

   a) Make sure outside end of tube is well away from the blower door fan.

3. Connect tube to "B" side reference port on the digital manometer, connect other end to port on blower door fan housing. This is the fan pressure measurement side. Note: when reading this pressure, switch scale to 2000 Pa before switching to this channel.

4. Make sure manometer is away from blower door fan when operating.

5. Use 5, 10 second or long term averaging when reading manometer for pressures.

6. Make an inside and outside temperature reading. Record this in Table 7.

7. Make sure all windows and doors to outside are closed.

8. Make sure all fireplace dampers are closed.

9. Make sure all internal doors are open.

C. Depressurization test

1. Turn blower door fan and depressurize the apartment to -50 Pa.

   a) If fan pressure is less than 20 Pa for -50 Pa apartment pressure, stop fan and install flow ring A on fan inlet. If condition not remedied, install ring B, etc.

   b) Measure and record the pressure in surrounding apartments.

2. Record the apartment pressure and fan pressure in Table 7.

3. Decrease fan speed until apartment pressure is about -40 Pa. Record apartment and fan pressure in Table 7.

4. Repeat above step in increments of about 10 Pa until -10 Pa reached and record info. in Table 7.

D. Zero measurement

1. Cover inlet side of blower door with no-flow plate. Record apartment (including surrounding apartments) and fan pressures in Table 7.

E. Calculate and record ACH information in Table 8.

F. Measure the envelope leakage of the entire building (optional).

G. Leave blower door installed for combination test (blower door + duct blaster).

VIII. Register and Leakage Flow Measurements

A. Register flows are to be measured by the duct blaster augmented flowhood

B. Setup - supply register flows

1. Put together flowhood (either 24" x 24" or 16" x 16"). When finished, stand it upright with base upward.

2. Duct tape adapter (flexible duct to cardboard cutout) to cardboard cutout, tape round cardboard cutout to flowhood base with duct tape. (This is likely done already.)

3. Connect flexible duct to adapter using velcro strap.

4. Attach other end of flexible duct to fan housing attachment using velcro strap.

5. Insert white honeycombed foam flow conditioner into fan housing attachment.

6. Use weather stripping to connect fan housing attachment to inlet side of duct blaster fan. Install with ring 1 between flow attachment and fan and make sure flow ring opens into fan.

7. Connect a tube to the side "A" input pressure port on the digital manometer. Connect the other end of the tube to the forward tube coming out of the flow measurement section of the flowhood (the end nearest the wide end of the flowhood, i.e. the tube nearest the oncoming flow) (for total pressure). Side "A" measures ΔP_{flow}.

8. Make sure manometer is clear of duct blaster fan when making measurements.

9. Connect tube to side "B" inlet pressure port on the digital manometer. Connect other end of tube to the pressure tube port on the fan housing attachment on the duct. (This connection is a "tec" connection with other tubes attached to it.)

10. Connect a tube to the side "B" reference pressure port on the digital manometer. Connect the other end of this tube to the port on the duct blaster fan housing.

11. Make sure all flexible duct is as straight and as uncompressed as possible when making flow measurements.

12. Doors and windows to apartment and basement should all be closed.

13. Plug in duct blaster fan.

14. Turn on air handler fan.

C. Measure flows from each supply register

1. Place flowhood over supply register.

2. Adjust duct blaster fan speed until flowhood luffs and pressure on channel "A", ΔP_{flow} is 0. Record ΔP_{flow} if too difficult to reach 0. Note: Use 5 or 10 second or long term averages when making readings.

   a) If $\Delta P_{fan} < 20$ Pa, turn off duct blaster and install ring 2 in place of ring 1. Use ring 3 if problem not remedied.

D. Record ΔP_{fan} and calculate Q in Table 12 (pre-retrofit) or Table 21 (post-retrofit). Use the calibration for the installed flow ring.

E. Measure flows in each return register.

1. Remove pressure measurement tube from fan housing attachment and from digital manometer.

2. Remove fan housing attachment from duct blaster and take out honeycombed flow conditioner.

3. Reconnect fan housing attachment to exhaust side of duct blaster fan (opposite side).

4. Leave inlet side open with no flow ring installed.

5. Make sure pressure measurement tube is still connected from fan housing to B side reference port on manometer.

6. Place flowhood over a return register.

   a) If flowhood does not cover entire grille, cover about 1/2 to 3/4 of it and make one measurement, then cover the remaining area for a second measurement and the total flow will be a sum of the two measurements.

7. Adjust duct blaster fan speed until flowhood luffs and pressure on channel "A", ΔP_{flow} is 0. Record ΔP flow if too difficult to reach 0. Note: Use 5 or 10 second or long term averages when making readings.

   a) If $\Delta P_{fan} < 20$ Pa, turn off duct blaster and install ring 1 in place of the open fan. Use ring 2, etc. if problem not remedied.

8. Record ΔP_{fan} and calculate Q in Table 12 or 21. Use the calibration for the installed flow ring.

IX. Operating Pressures

A. Turn on air handler fan.

B. Use digital manometer to perform the following:

1. Connect tubing to input side of manometer.
2. Connect pitot tube to other end of tube.
3. Stick pitot tube in register.
4. Record static pressure difference between supply, return registers and apartment interior.
5. Connect tube to dynamic port on pitot tube.
6. Record total pressure difference between supply, return registers and apartment interior.
7. Fill in the Table 14 for pre-retrofit or Table 23 for post-retrofit.

X. Interior Room Pressures (Optional)

A. Use digital manometer to determine pressures across closed doors when fan is operating.

a. Make sure fan is on and that doors to outside are closed.

b. Measure ΔP to apartment interior.

B. Measure pressure across the envelope with the interior doors open with and without the furnace fan on.

C. Fill in Table 15 for pre-retrofit or Table 24 for post-retrofit.

XI. Duct Blaster Tests

A. IF ACCESS AT FAN COMPARTMENT DOOR IS GOOD:

1. **Measure Operating Pressure of Duct System in Supply Plenum (Leave Sensor in Place in Supply Plenum for All Subsequent Tests in this Section)**

   a) Measure pressure difference between supply plenum and basement with air handler fan on and all external doors and windows closed, record value in Table 13 for pre-retrofit and Table 22 for post-retrofit.

2. **Seal All Registers and Grilles. Remove Filter, and Install Duct Blaster into Fan Access Door.**

3. **Pressurize (and Optionally Depressurize Also) the Duct System to 30 Pa (and Several Other Pressures to Mimic Operating Pressures in the Duct System)**

4. **Measure the Pressure at Return Plenum, All Return Registers and Grilles, Several Supply Registers**

   a) Record plenum and register/grilles pressures in Table 14 for pre-retrofit or Table 23 for post-retrofit.

5. **Record Duct Blaster Flow and Pressures (Measure Temperature at Duct Blaster Entrance) -- Total System**

   a) Record duct blaster fan pressure and plenum pressure and determine flow in Table 9 for pre-retrofit or Table 18 for post-retrofit.

6. **If it Is Not Clear Where All of the Leakage Is Going, Use Blower Door to Isolate Leakage Sections by Making Pressure in Zone Equal to That in Ducts (See Appendix). Use Table 11 for pre-retrofit and Table 20 for post.**

7. **Seal the Supply Side from the Return Side at the Filter**

8. **Measure Supply Side Only Leakage**

   a) Record duct blaster fan pressure and supply plenum pressure and determine flow in Table 10 for pre-retrofit or Table 19 for post-retrofit.

9. **Unseal Supply Registers**

10. **Measure Fan Flow with Ductblaster at Several Supply Plenum Pressures on and Around Previously Measured Operating Point**

    a) Record duct blaster fan pressure and determine fan flow in Table 13 for pre-retrofit or Table 22 for post-retrofit.

    b) Calculate total flow to make sure it is greater than the sum of supply or return register flows by a reasonable amount.

11. **If it Is Not Clear Where All of the Leakage Is Going, Use Blower Door to Isolate Leakage Sections by Making Pressure in Zone Equal to That in Ducts (See Appendix). Use Table 11 for Pre-retrofit and Table 20 for Post.**

B. IF ACCESS IS NOT GOOD, SEE APPENDIX.

XII. Conduction Losses

A. Use digital thermometer to measure the temperatures in the duct system and surroundings

1. Make sure furnace is on and operating under steady-state conditions (i.e., force a long on period).

2. Measure the temperatures at each supply register, each return register, the supply plenum, the return plenum, outdoors, and the basement.

3. Record the time and sensor used for each measurement.

4. Perform post-retrofit return plenum and register measurements before and after insulating.

B. Fill in Table 16 for pre-retrofit or Table 25 for post-retrofit.

C. Characterize the dynamic performance of the system (optional)

1. Record the temperatures at one or two supply registers (near and far from the plenum) and the supply plenum on a minute by minute basis over an entire cycle.

2. Fill in Table 17 for pre-retrofit or Table 26 for post-retrofit.

XIII. Clean up

A. Remove all equipment.

B. Vacuum all traces of insulation or dirt tracked through the apartment.

Table 7: Envelope Leakage Data (Optional)

T_{out} °C =			T_{in} °C=			
test	nominal apartment pressure, Pa	actual apartment pressure, Pa	Fan pressure Pa	flow ring	flow, cfm	flow, m^3/hr
depressurization	-50 Pa					
	-40 Pa					
	-30 Pa					
	-20 Pa					
	-10 Pa					
no-flow plate	0 Pa					

Table 8: Preliminary Results

CFM50 = CFM $(50/\Delta P)^{0.65}$, ft^3/min	
ELA_4[a] = 0.353 * CFM50, cm^2	
ACH50 = 60*CFM/50(APART. VOL)	
ach = ach50/24[b]	

a. estimation only; regression will yield better ELAs
b. Sacramento only

Blower Door Calibration formulas:

ΔP in Pa, Q in cfm. Conversion: m^3/hr = 1.699*cfm

open fan: $Q = 490.2\Delta P^{0.4945}$
ring A: $Q = 180.7\Delta P^{0.4948}$
ring B: $Q = 57.2\Delta P^{0.5065}$
ring C: $Q = 20.7\Delta P^{0.5275}$

DATE: **PRE-RETROFIT**

Table 9: Total Duct Leakage Measurements (PRE-RETROFIT)

T_{intoDB}, °C =						
Time	duct pressure, Pa	duct bl. fan pressure, Pa	flow rings	flow cfm	flow, m^3/hr	ELA_{25}

Table 10: Supply Duct Leakage Measurements (PRE-RETROFIT)

T_{intoDB}, °C =						
Time	duct pressure, Pa	duct bl. fan pressure, Pa	flow rings	flow cfm	flow, m^3/hr	ELA_{25}

Table 11: Basement/Outside Duct Leakage Measurements[a] (optional)(PRE-RETROFIT)

T_{in}, °C =							
Time	envelope pressure, Pa	duct pressure, Pa	duct bl. fan pressure, Pa	flow rings d.b.	flow rings b.d.	flow, cfm	ELA_{25}[b]

a. Duct blaster calibration formulas: open fan: $Q = 104.38\Delta P^{0.5}$, ring 1: $Q = 39.25\Delta P^{0.5}$, ring 2: $Q= 15.31\Delta P^{0.5}$, ring 3: $Q = 6.26\Delta P^{0.5}$. Conversion: $m^3/hr = 1.699 * cfm$

b. Estimation of duct leakage are: $ELA_{25} = 3.49 * Q/\Delta P^{0.65}$, Q in m^3/hr, ΔP in Pa

Table 12: Register Flowrates (PRE-RETROFIT)

supply or return duct/plenum	T_{flow} °C	ΔP_{fan} Pa	flow ring	Q[a] cfm	Q m^3/hr
SP					
sd1					
sd2					
sd3					
sd4					
sd5					
sd6					
sd7					
sd8					
sd9					
sd10					
RP					
rd1					
rd2					
rd3					
rd4					

a. Duct blaster calibration formulas: open fan: $Q = 104.38\Delta P^{0.5}$, ring 1: $Q = 39.25\Delta P^{0.5}$, ring 2: $Q= 15.31\Delta P^{0.5}$, ring 3: $Q = 6.26\Delta P^{0.5}$. Conversion: m^3/hr = 1.699 * cfm

Table 13: Duct Blaster Fan Total Airflow (PRE-RETROFIT)

test #	ΔP_{duct}, Pa normal	ΔP_{duct}, Pa w/duct blaster	ΔP_{fan} Pa	Q cfm	T_{into}DB °C

Table 14: Air Distribution System Pressures (PRE-RETROFIT)

location	ΔP_{static}	ΔP_{total}	Leak Test ΔP_{plen}	Leak Test ΔP_{reg}
SP				
sr1				
sr2				
sr3				
sr4				
sr5				
sr6				
sr7				
sr8				
RP				
rr1				
rr2				
rr3				
rr4				

Table 15: Interior Room Pressures (PRE-RETROFIT)

door/room	pressure	room	pressure
apartment to out (fan on)		E	
A		F	
B		G	
C		apartment to out (fan on)	
D		apartment to out (fan off)	

Table 16: Steady-State Duct System Temperatures (PRE-RETROFIT)

description	time	Temp.(°C)	description	time	Temp.(°C)
Tsup1			Tret1		
Tsup2			Tret2		
Tsup3			Tret3		
Tsup4			Tret4		
Tsup5			Tret5		
Tsup6			Tret6		
Tsup7			Tret7		
Tsup8			Tret8		
Tbasement			Tbasement		
T			T		
T			T		
T			T		
T			T		
T			T		
Tsupplen			Tretplen		

Table 17: Duct Temperature Cycling Characteristics (PRE-RETROFIT)

Surroundings	Supply Register		Supply Plenum	
time/Temp (°C)	Time	Temp. (°C)	Time	Temp. (°C)

DATE: **POST-RETROFIT**

Table 18: Total Duct Leakage Measurements (POST-RETROFIT)

T_{intoDB}, °C =						
Time	duct pressure, Pa	duct bl. fan pressure, Pa	flow rings	flow cfm	flow, m^3/hr	ELA_{25}

Table 19: Supply Duct Leakage Measurements (POST-RETROFIT)

T_{intoDB}, °C =						
Time	duct pressure, Pa	duct bl. fan pressure, Pa	flow rings	flow cfm	flow, m^3/hr	ELA_{25}

Table 20: Basement/Outside Duct Leakage Measurements[a] (POST-RETROFIT)

T_{in}, °C =							
Time	envelope pressure, Pa	duct pressure, Pa	duct bl. fan pressure, Pa	flow rings		flow, cfm	ELA_{25}[b]
				d.b.	b.d.		

a. Duct blaster calibration formulas: open fan: $Q = 104.38\Delta P^{0.5}$, ring 1: $Q = 39.25\Delta P^{0.5}$, ring 2: $Q= 15.31\Delta P^{0.5}$, ring 3: $Q = 6.26\Delta P^{0.5}$. Conversion: $m^3/hr = 1.699 * cfm$

b. Estimation of duct leakage are: $ELA_{25} = 3.49 * Q/\Delta P^{0.65}$, Q in m^3/hr, ΔP in Pa

Table 21: Register Flowrates (POST-RETROFIT)

supply or return duct/plenum	T_{flow} °C	ΔP_{fan} Pa	flow ring	Q[a] cfm	Q m^3/hr
SP					
sd1					
sd2					
sd3					
sd4					
sd5					
sd6					
sd7					
sd8					
sd9					
sd10					
RP					
rd1					
rd2					
rd3					
rd4					

a. Duct blaster calibration formulas: open fan: $Q = 104.38\Delta P^{0.5}$, ring 1: $Q = 39.25\Delta P^{0.5}$, ring 2: $Q= 15.31\Delta P^{0.5}$, ring 3: $Q = 6.26\Delta P^{0.5}$. Conversion: $m^3/hr = 1.699 * cfm$

Table 22: Duct Blaster Fan Total Airflow (POST-RETROFIT)

test #	ΔP_{duct}, Pa normal	ΔP_{duct}, Pa w/duct blaster	ΔP_{fan} Pa	Q cfm	T_{into}DB °C

Table 23: Air Distribution System Pressures (POST-RETROFIT)

location	ΔP_{static}	ΔP_{total}	Leak Test ΔP_{plen}	Leak Test ΔP_{reg}
SP				
sr1				
sr2				
sr3				
sr4				
sr5				
sr6				
sr7				
sr8				
RP				
rr1				
rr2				
rr3				
rr4				

Table 24: Interior Room Pressures (POST-RETROFIT)

door/room	pressure	room	pressure
apartment to out (fan on)		E	
A		F	
B		G	
C		apartment to out (fan on)	
D		apartment to out (fan off)	

Table 25: Steady-State Duct System Temperatures (POST-RETROFIT)

description	time	Temp.(°C)	description	time	Temp.(°C)
Tsup1			Tret1		
Tsup2			Tret2		
Tsup3			Tret3		
Tsup4			Tret4		
Tsup5			Tret5		
Tsup6			Tret6		
Tsup7			Tret7		
Tsup8			Tret8		
Tbasement			Tbasement		
T			T		
T			T		
T			T		
T			T		
T			T		
Tsupplen			Tretplen		

Table 26: Duct Temperature Cycling Characteristics (POST-RETROFIT)

Surroundings	Supply Register		Supply Plenum	
Time/Temp (°C)	Time	Temp. (°C)	Time	Temp. (°C)

Plan View of Apartment:

Plan View of Attic (if applicable):

Plan View of Basement:

Plan View of Ducts with Dimensions:

XIV. Appendix

A. (INADEQUATE ACCESS OPTION) This test is to determine the total duct leakage and the duct leakage to outside for both the supply and return sides (also can be used to isolate leakage to basement from leakage to outside or apartments)

B. Setup for supply side leakage measurements, depressurization or pressurization only

1. Separate and seal the air distribution system at the fan.

2. Seal all supply and return registers except a large flow supply register.

   a) Do not remove grilles. Seal over them instead, using cardboard or metal plates and/or blue tape.

3. Connect duct blaster feed to open supply register; seal tightly.

4. Make sure duct blaster inlet is open to room.

5. Connect a tube to the side "A" input pressure port on the digital manometer; place the other end of the tube in a supply register nearest the supply plenum. Push the tube into the register as far as possible in an attempt to locate the end of it in the plenum. Do not place the end of the tube near the duct blaster inlet. This is the duct pressure measurement side. Use the 200 Pa scale.

   a) If access to the supply plenum exists and is not difficult to use, put other end of duct supply side tube in supply plenum.

6. Connect a tube to the side "B" reference pressure port, connect the other end of this tube to the pressure port on the duct blaster fan housing. This is the duct blaster fan measurement side. Use the 2000 Pa scale.

7. When reading manometer, do not place it near the duct blaster fan inlet.

8. Use 5, 10 second or long term averaging when reading manometer for pressures.

9. Measure temperature inside apartment and record it in Table 10 for pre-retrofit or Table 19 for post-retrofit.

10. Open an external door or large window in apartment and basement.

C. Depressurize supply side ducts and plenum - total supply duct leakage test

1. Turn on duct blaster.

2. Pressurize ducts to 30 Pa or to highest possible pressure up to 30 Pa.

   a) If duct blaster fan pressure is less than 20 Pa for 30 Pa duct pressure, stop fan and install flow ring 1 on fan inlet. If condition is not remedied, install ring 2 etc.

3. Record the duct pressure and fan pressure in Table 10 for pre-retrofit or Table 19 for post-retrofit.

4. Turn off duct blaster fan.

D. Apartment blower door and duct blaster test - Supply side to outside plus basement leakage test. (Only if it is not clear where the leakage is going.)

1. Close the open apartment door or window.

2. Using the one channel electronic manometer, connect the high side pressure port to the tube running outside the apartment.

3. Turn on blower door fan and depressurize the apartment to about 30 Pa on the single channel apartment manometer.

4. Turn on the duct blaster and depressurize the supply ducts until the reading on side "A" of the digital manometer is zero.

5. Record the apartment pressure, the duct to inside pressure difference, and the duct blaster fan difference in Table 11 for pre-retrofit or in Table 20 for post-retrofit.

6. Turn off duct blaster and blower door fans.

E. Setup for return duct leakage measurements, depressurization or pressurization only.

1. Open an external door or window in apartment or basement.

2. Disconnect duct blaster feed duct from the supply register.

3. Remove seal from main return register.

4. Connect duct blaster feed to open return register; seal tightly.

5. Make sure duct blaster fan inlet is open to room.

6. Remove duct pressure tube from supply duct.

7. Make sure duct pressure tube is still connected to the side "A" input pressure port on the digital manometer; place the other end of the tube in the return plenum or in another register nearest the return plenum. Push the tube into the register as far as possible in an attempt to locate the end of it in the plenum. Do not place the end of the tube near the duct blaster inlet. This is the duct pressure measurement side. Use the 200 Pa scale.

8. Make sure the fan pressure tube is still connected to the side "B" reference pressure port, with the other end of this tube connected to the pressure port on the duct blaster fan housing. Use the 2000 Pa scale.

9. When reading manometer, do not place it near the duct blaster fan inlet.

10. Use 5, 10 second or long term averaging when reading manometer for pressures.

11. Measure temperature inside apartment and record it in Table 9 for pre-retrofit or Table 18 for post-retrofit.

F. Depressurize return side ducts and plenum - total return duct leakage test.

1. Turn on duct blaster.
2. Pressurize ducts to 30 Pa or to highest possible pressure up to 30 Pa.
   a) If duct blaster fan pressure is less than 20 Pa for 30 Pa duct pressure, stop fan and install flow ring 1 on fan inlet. If condition not remedied, install ring 2 etc.
3. Record the duct pressure and fan pressure in Table 9 for pre-retrofit or Table 18 for post-retrofit.
4. Turn off duct blaster fan.

G. Apartment blower door and duct blaster test - return side to outside leakage test (only if it is unclear where the leakage is going).

1. Close the open apartment door or window.
2. Using the one channel electronic manometer, connect the high side pressure port to the tube running outside the apartment.
3. Turn on blower door fan and depressurize the apartment to about 30 Pa on the single channel apartment manometer.
4. Turn on the duct blaster and pressurize the supply ducts until the reading on side "A" of the digital manometer is zero.
5. Record the apartment pressure, the duct to inside pressure difference, and the duct blaster fan difference in Table 11 for pre-retrofit or in Table 20 for post-retrofit.
6. Turn off duct blaster and blower door fans.

H. Total duct system leakage to basement test

1. Leave duct blaster feed connected to main return duct, leave digital manometer setup as is.
2. Open an external door or window in apartment or basement.
3. Remove the seal at the air handler fan.

I. Depressurize total duct system - total duct leakage test

1. Turn on duct blaster.

2. Pressurize ducts to 30 Pa or to highest possible pressure up to 30 Pa.

   a) If duct blaster fan pressure is less than 20 Pa for 30 Pa duct pressure, stop fan and install flow ring 1 on fan inlet. If condition not remedied, install ring 2 etc.

3. Record the duct pressure in supply plenum and fan pressure in Table 11 for pre-retrofit or Table 20 for post-retrofit.

4. Turn of duct blaster fan.

J. Basement blower door duct blaster test - total duct system to basement leakage test (optional)

1. Install a blower door between the basement and outside.

2. Close the open basement door or window.

3. Using the one channel electronic manometer, connect the high side pressure port to the tube running outside the basement.

4. Turn on blower door fan and depressurize the basement to about 30 Pa on the single channel envelope manometer.

5. Turn on the duct blaster and depressurize the supply ducts until the reading on side "A" of the digital manometer is zero.

6. Record the basement pressure, the duct to basement pressure difference, and the duct blaster fan difference in Table 11 for pre-retrofit or in Table 20 for post-retrofit.

7. Turn off duct blaster and blower door fan.

K. Clean up.

1. Remove all register seals.

2. Clean all tape marks from grilles.

3. Remove duct blaster and blower door equipment.

L. Procedure to estimate supply and return leakage areas when it is impossible to isolate each side (optional):

1. Measure total and to outside duct ELAs.

    a) Pressurize ducts from the return side.

    b) Leave all registers sealed.

2. Open a known dimensioned hole in the supply side.

    a) Can be an entire small supply grille or a portion of a large one.

3. Use duct blaster ring 1 (largest) on return side for known dimensioned hole on return side (ring 1 = 6-5/8" diameter).

4. Turn on air handler fan.

5. Monitor pressures in supply and return plenums, one or two scaled supply registers, and at the return register.

6. Try not to exceed 200 Pa in duct system. (Don't rupture ducts!)

APPENDIX C

TECHNICAL SPECIFICATIONS AND MANUFACTURERS INFORMATION

MINNEAPOLIS

DUCT BLASTER™

OPERATION MANUAL

MANUFACTURED BY THE ENERGY CONSERVATORY

Direct impacts of duct leakage to the outside can include:

- Infiltration rates have been found to increase by 2 or 3 times whenever the air handler is operating due to household pressurization or depressurization from duct leaks.
- Supply leaks cause conditioned air to be dumped directly into unconditioned spaces rather than delivered to the house. In addition to the energy loss associated with delivering conditioned air to the outside, supply leaks can result in other significant problems including attic ice dam formation (in cold climates), and moisture problems in warm humid climates (from house depressurization).
- Return leaks pull unconditioned air directly into the HVAC system reducing both efficiency and capacity. For example, if 10 percent of the return air for an air conditioning system is pulled from a hot attic (120 F), system efficiency and capacity could be reduced by as much as 30 percent. In humid climates, moist air being drawn into return leaks can overwhelm the dehumidification capacity of air conditioning systems. In cold climates, return leaks can cause house pressurization leading to moisture being driven into wall cavities and attics.
- In mild climates, duct leakage can greatly increase the use of electric strip heaters (in heat pump applications) during winter operation.
- Household depressurization (from supply leaks) can cause pressure induced spillage of combustion products into the house, and can increase entry of soil gases.

DUCT LEAKAGE TO THE INSIDE

Much less is known about the energy and system efficiency impacts of duct leakage inside the house. A recent study of new houses in Minnesota has shown that the duct systems are very leaky, but that very little of that leakage was connected directly or indirectly to the outside. One of the primary causes of duct leakage in Minnesota houses was found to be very leaky basement return systems which use panned under floor joists as return ductwork. Because most of the duct leakage was occurring within the conditioned space of the house, the energy efficiency penalty from this leakage is thought to be much less significant. (Note: In Minnesota, basements are typically considered heated space.)

However, the Minnesota study did find that leaky return systems can cause the basement (where the furnace and water heater are located) to depressurize to the point where combustion products from the water heater or furnace would spill into the house. Negative pressures from return leaks can also contribute to increased moisture and radon entry into houses. In addition, comfort problems were experienced due to the return duct system drawing most of its air from the basement rather than the rooms of the house. These problems all suggest that controlling duct leakage to the inside may be just as important as leakage to the outside.

CHAPTER 3

SYSTEM COMPONENTS:

The Minneapolis Duct Blaster consists of the following components:

- Duct Blaster Fan
- Pressure Measurement Gauges (Magnahelic or Digital)
- Fan Speed Controller
- Flexible Extension Duct
- Flow Conditioner (Depressurization Attachment)
- Duct Blaster Carrying Case

3.1 Duct Blaster Fan

The Duct Blaster fan consists of a molded fiberglass fan housing with a variable speed motor. The Duct Blaster fan will move up to 1,500 CFM at zero pressure drop (free air), and approximately 1,350 CFM against 50 Pascals of back pressure. With the flexible extension duct attached, the fan will move 1,250 CFM (free air) and 1,000 CFM against 50 Pascals of back pressure. Fan flow is determined by measuring the slight vacuum created by the air flowing over the flow sensor attached to the end of the motor. The Duct Blaster fan can accurately measure flows between 30 and 1,500 CFM using a series of three calibrated Low-Flow Rings which are attached to the fan inlet. The Duct Blaster fan motor is not reversible, however, the fan can be installed to either pressurize or depressurize the duct system. The components of the Duct Blaster fan are shown in Figure 1.

The Duct Blaster fan meets the flow calibration specifications of both the CGSB Standard 149.10-M86 and ASTM Standard E779-87. The Minneapolis Duct Blaster has a fan flow accuracy of +/- 5 percent using standard magnahelic gauges and an accuracy of +/- 3 percent using the Energy Conservatory Digital Gauge. These calibration specifications include inaccuracies due to production tolerances of the fan and calibration errors of the fan gauges.

DETERMINING FAN FLOW AND USING THE LOW-FLOW RINGS:

Fan pressure readings are easily converted to fan flow readings in cubic feet per minute (CFM) using Table 1 (Flow Conversion Table), or by using the calibration formulas in Appendix B. Be sure to use the flow conversion or calibration formula which corresponds to the configuration of the Low-Flow Rings connected to the Duct Blaster fan inlet. When depressurizing a duct system, you must use the flow conditioner in order to measure fan flow.

The Duct Blaster fan has 4 different flow capacity ranges depending on the configuration of Low-Flow Rings in the fan inlet. Table 2 below shows the flow range of the fan under each of the 4 inlet configurations. All three Low-Flow Rings (#1, #2 and #3) can be attached to the inlet side of the fan. To attach Ring 1, place it against the inlet of the fan so that the outer edges of the ring roughly line up with the outer edge of the inlet flange on the fan. Be sure the nozzle located in the middle of the ring is pointing inward toward the fan motor (Figure 2).

Secure the outer edge of Ring 1 and the fan flange together by pushing the black connecting trim over both edges all the way around the fan flange (Figure 3). Rings 2 and 3 are installed in exactly the same manner as Ring 1. Use of the Low-Flow Rings is discussed in more detail below.

Fan pressure readings of less than 25 Pa should never be taken with the Duct Blaster Fan using the magnahelic gauges. Below 25 Pa, the fan pressure signal becomes too small to measure accurately. To solve this problem and to allow accurate flow measurements over the entire measurement range, the Minneapolis Duct Blaster comes with 3 Low-Flow Rings which attach to the fan inlet (Figure 1). The Low-Flow Rings restrict the opening to the fan, forcing a given amount of air to enter the fan at a higher velocity thereby increasing the fan pressure signal. Table 2 shows the fan flow capacity ranges for all four fan inlet configurations.

TABLE 2: FAN FLOW RANGES

Fan Configuration	Flow Range	Minimum Fan Pressure (Magnahelic Gauges)
Open	1,500 - 500 CFM	25 Pa
Ring 1 installed	800 - 200 CFM	25 Pa
Ring 2 installed	300 - 75 CFM	25 Pa
Ring 3 installed	125 - 30 CFM	25 Pa

When choosing Duct Blaster Fan inlet configurations, always use the configuration which provides the desired flow capacity with the highest fan pressure signal. High fan pressure readings can always be read more accurately by the gauges than low fan pressure readings. For example, if you running the fan in the "open" configuration (no Low-Flow Rings installed), and can pressurize the duct system to 50 Pa with respect to (WRT) outside, but record a fan pressure of only 10 Pa, you need to install Ring 1 in order to achieve proper accuracy. After installing Ring 1 and readjusting the fan speed to achieve a duct reference pressure of 50 Pa, record the new higher fan pressure reading. Use this new reading as your measurement of fan pressure and flow. If fan pressure readings fall below 25 Pa during a duct leakage test, install the Ring with the next smaller size nozzle opening. (Ring 1 has the largest nozzle, Ring 3 has the smallest nozzle).

Conversely, if you are trying to pressurize a duct system with a Low-Flow Ring installed and the fan running full speed (i.e. high fan pressures), but you can not achieve enough pressure in the duct system, remove the Low-Flow Ring or install a Ring with a larger nozzle opening in order to increase fan flow.

Note 1: When using an Energy Conservatory digital pressure gauge, fan pressure readings down to 10 Pa can be taken due to the increased accuracy of the digital gauge.

Note 2: When taking Duct Blaster Fan pressure measurements, do not stand directly in front of the fan assembly or place any objects directly in front of the fan. This may affect the flow readings and result in erroneous measurements. For best accuracy, stand at least 12 inches from the side of the fan inlet when conducting a duct leakage test.

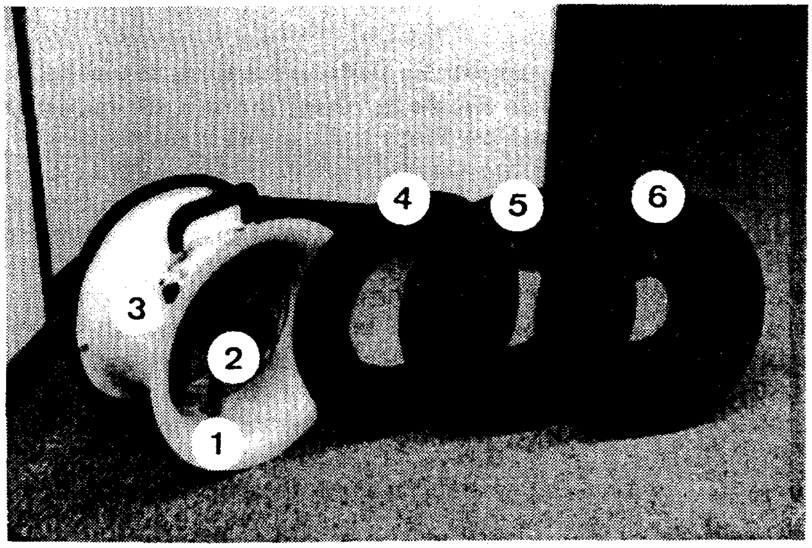


Figure 1

1. Fan Inlet
2. Flow Sensor
3. Power Receptacle and Fan Pressure Tap
4. Low-Flow Ring 1
5. Low-Flow Ring 2
6. Low-Flow Ring 3

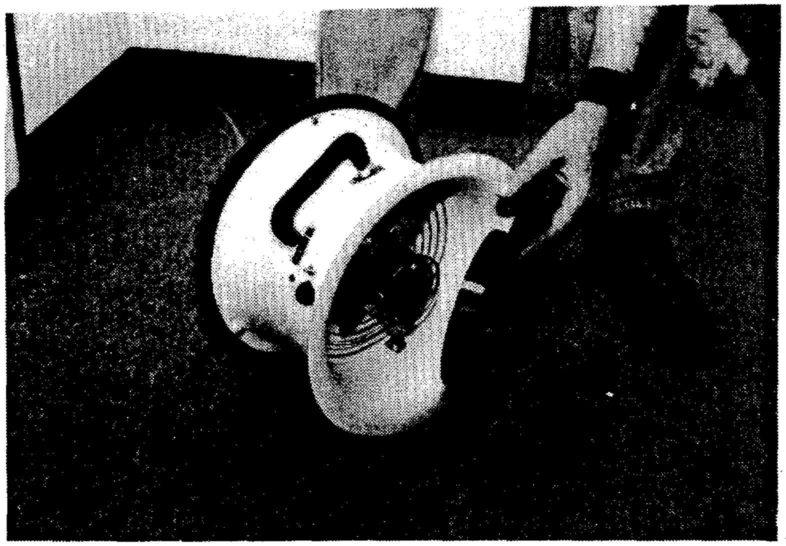


Figure 2

Figure 3

3.2 Pressure Measurement Gauges

The Minneapolis Duct Blaster can be purchased with either a set of 3 magnahelic pressure gauges, or with a 2 channel digital pressure gauge from The Energy Conservatory. The pressure gauge(s) are used to measure both the fan flow and a corresponding reference pressure in the duct system being tested.

MAGNAHELIC GAUGES:

If you purchased the magnahelic gauges, they are mounted on a black ABS plastic gauge board. The magnehelic gauges are ***differential pressure gauges,*** meaning they measure the pressure difference between the top and bottom pressure taps on the gauge. If the pressure measured by the top tap is higher than the pressure at the bottom tap, the gauge will register a positive pressure reading.

The top 60 Pa gauge is used to measure the duct reference pressure (i.e. duct pressure relative to the house or duct pressure relative to the outside). The two bottom gauges will be used to measure the air flow through the Duct Blaster fan. The two bottom gauges each have five separate scales on the gauge face, one scale which reads in units of Pascals (the bottom scale), and four scales which read in cubic feet per minute (CFM) for the various configurations of the Duct Blaster fan inlet. Fan pressure readings in Pascals can be easily converted into flows (CFM) by using Table 1, the laminated flow table provided with your manual, or the calibration formulas found in Appendix B. Fan flow in CFM can also be read directly off the gauge using the appropriate flow scale on the gauge faceplate. For example, if Ring 1 is installed in the fan inlet, flow in CFM can be read from the Ring 1 scale. Two fan pressure gauges are provided to cover the entire range of possible fan pressures with the necessary precision and accuracy. The fan pressure gauges are interconnected so that they simultaneously measure the fan pressure signal. Always use the middle fan pressure gauge (125 Pa) to read fan flow when it is less than full scale. Hose connections made to the magnahelic gauges will depend on the type of test being conducted and are discussed in more detail in Chapter 5 and 6.

The gauge board can be attached to any door by using the C-clamp attached to the back of the board. The gauge board can also be easily attached to a horizontal surface (book shelf or desk top) by rotating the clamp 90 degrees before securing the board.

DIGITAL GAUGE:

If you purchased a digital gauge with your Duct Blaster, please read the operating instructions provided with the gauge before proceeding. The digital gauge (model DG-2) has two separate measurement channels which allow you to monitor two different pressure signals and to display either pressure reading on the gauge. The position of the **CHANNEL** selection knob determines which pressure channel (**A** or **B**) is currently being monitored by the gauge and shown on the display.

The DG-2 gauge is a ***differential pressure gauge*** which measures the pressure difference between either of the bottom reference pressure taps and its corresponding top input pressure tap. The input or signal taps (marked "INPUT") should be connected to the input pressure signals you are measuring. The bottom reference taps (marked "REFERENCE") should always be connected to the reference pressure you are measuring against. Hose connections to the digital gauge will be explained in more detail in Chapter 5 and 6.

The digital gauge is typically shipped in a separate padded case which is stored in the Duct Blaster carrying case. Also included with the digital gauge is a small black ABS plastic gauge board to which the digital gauge can be attached using the velcro strips mounted on the back of the gauge. The gauge board can be attached to any door by using the C-clamp attached to the back of the board. The gauge board can also be easily attached to a horizontal surface (book shelf or desk top) by rotating the clamp 90 degrees before securing the board.

3.3 Fan Speed Controller

The Duct Blaster fan is controlled by a variable speed fan controller. The speed controller is clipped onto the gauge board supplied with your Duct Blaster unit, but can be removed from the board by sliding the controller clip off.

Connect the female plug from the controller to the male power receptacle on the fan (Figure 4). To connect the female plug, line up the plug with the three brass pins on the fan receptacle and push the plug completely onto the brass pins. Now secure the plug to the fan by pushing the locking ring from the female plug against the fan and turning the ring clockwise until it locks in place. The remaining controller cord (power cord) should be plugged into any standard household 110 Volt outlet. Be sure the fan controller knob is turned all the way counter-clockwise to the "off" position before plugging into the house outlet. If the controller is attached to the gauge board, it can be unclipped by sliding the silver clip on the back of the controller off the board.

3.4 Flexible Extension Duct

The flexible extension duct (Figure 5) consists of a 8 foot long section of 10" round flexible duct with one square and one round black ABS plastic transition piece attached at either end. The flexible extension duct is used to connect the Duct Blaster fan to the distribution system. The round transition piece connects to the either the fan exhaust flange (pressurization testing) or the fan inlet flange (depressurization testing), while the square transition piece can be attached directly to a supply or return register, or installed at the air handler door. The extension duct allows the fan air flow to be easily directed to any room register while leaving the fan on the floor or on a table.

The flexible extension duct is connected to the fan flange using black connecting trim. To connect the round transition piece to the Duct Blaster fan, first place the transition piece against the fan flange so that the outer edges of the transition piece roughly line up with the outer edge of the fan flange. Secure the outer edge of the transition piece and the fan flange together by pushing the black connecting trim over both edges all the way around the fan (Figure 6).

Attached to the side of the round transition piece are a series of hoses which are interconnected to a single pressure tap. This pressure tap is only used when using the flow conditioner along with the round transition piece.

3.5 Flow Conditioner

The flow conditioner is used when conducting a duct leakage test in the depressurization mode (i.e. sucking air out of the duct system), or when using the Duct Blaster as a powered flow hood to measure flows through supply registers. The flow conditioner consists of a round one-inch wide white foam disk which is inserted into the round transition piece (part of the flexible extension duct) before the round transition piece is connected to the inlet flange of the Duct

Blaster fan. The flow conditioner conditions the air flow upstream of the fan flow sensor to provide an accurate fan pressure reading.

To install the flow conditioner, first line up the crescent shaped key slot on the outside of the white foam disk with the key indentation inside the round transition piece. Insert the flow conditioner all the way into round transition piece until it is pushed beyond the three snap pins (located on the side of the transition piece) and up tightly against the ridge stop. When fully engaged, the snap pins will hold the flow conditioner in place during fan operation. Once the flow conditioner is installed in the round transition piece, the round transition piece can be installed onto the inlet of the fan. To remove the flow conditioner, release one of the snap pins by pushing it flush with the transition piece and then gently pull out the flow conditioner.

Importantly, you must always install one of the Low-Flow Rings (1, 2 or 3) along with the flow conditioner on the inlet of the fan. The Low-Flow Ring is needed to provide additional flow conditioning before the measured air stream passes over the flow sensor on the Duct Blaster fan. Because of this limitation, the maximum flow which can be measured with the flow conditioner is approximately 700 CFM. First place one of the Low-Flow Rings against the fan inlet flange (use the Ring which will supply the range of flow you are trying to measure - with the Ring nozzle pointing inward toward the fan), then place the round transition piece with the flow conditioner installed against the Ring. Secure both the Ring and the round transition piece to the inlet flange using the black connecting trim.

3.6 Duct Blaster Carrying Case

The entire Minneapolis Duct Blaster system can be stored in the lightweight fabric carrying case provided with your system. A shoulder strap on the carrying case provides a simple "hands-free" method for carrying the system to and from testing locations.

MINNEAPOLIS DUCT BLASTER™

CALIBRATION FORMULAS

FAN CONFIGURATION:	CALIBRATION FORMULAS
OPEN FAN:	FLOW (CFM) = 104.38 x (Fan Pressure)$^{.5000}$
RING 1 INSTALLED:	FLOW (CFM) = 39.25 x (Fan Pressure)$^{.5000}$
RING 2 INSTALLED:	FLOW (CFM) = 15.31 x (Fan Pressure)$^{.5000}$
RING 3 INSTALLED:	FLOW (CFM) = 6.26 x (Fan Pressure)$^{.5000}$

MINNEAPOLIS DUCT BLASTER™

Specifications:

	(without flex duct)	(w/ flex duct installed)
Maximum Flow:	- 1,500 CFM @ 0 Pa - 1,350 CFM @ 50 Pa	- 1,250 CFM @ 0 Pa - 1,000 CFM @ 50 Pa

Flow Range:
- 1,500 - 30 CFM (standard)
- 1,500 - 15 CFM (w/ digital gauge)

Flow Measurement System:
- Integral Flow Measuring Nozzles
- Flow Calibration Meets both ASTM Standard E779-87 and CGSB Standard 149.10-M86
- Flow Calibration Accuracy: +/- 5% (magnahelic gauges)
+/- 3% (digital gauge)

Pressure Gauges:
- 3 Magnahelic Gauges (standard)
- 2 Channel Digital Gauge (optional)

Dimensions:
- Fan: 10" Diameter, 8" Long
- Flexible Extension Duct: 8 Feet Long w/ 10" Flex Duct
- Magnahelic Gauges w/ Board: 16" Long, 5" Wide, 2 1/4" Deep
- Digital Gauge: 7 1/2" Long, 4" Wide, 1 1/4" Deep

Weight:
- Fan: 7 lbs (8.5 lbs w/ 3 low-flow nozzles)
- Flexible Extension Duct: 3 lbs
- Magnahelic Gauges w/ Board: 4 1/2 lbs - Digital Gauge: 1 lbs

Fan Controller:
- Variable Speed Solid State - (4 amp max current)

THE ENERGY CONSERVATORY

DIGITAL PRESSURE GAUGE

Model DG-2

(For Units Shipped After 3-22-93)

The Energy Conservatory Digital Pressure Gauge provides highly accurate measurement of low differential pressures. The auto zeroing and time averaging features make it ideal for measuring small pressure changes associated with forced air heating and cooling systems, exhaust devices, radon mitigation systems and combustion safety testing. The DG-2 gauge allows you to measure two separate pressure signals and to display either pressure reading on the gauge. The DG-2 gauge comes with a complete two year parts and labor warranty and includes a soft-shell protective carrying case, and two 10 foot lengths of plastic hose.

Specifications:

Range: 0 - 199.9 Pascal (Low-Range)
0 - 1999 Pascal (High-Range)

Resolution: 0.1 Pascal (Low-Range) 1 Pascal (High-Range).

Accuracy: +/- 1% of reading, or +/- 2 counts (whichever is greater) up to 1000 Pa.

Weight: 16.0 oz.

Operating Temperature Range: 32 F to 120 F.

Storage Temperature Range: -10 F to 160 F.

Battery: One 9 Volt (alkaline or rechargeable ni-cad). Battery will last approximately 48 hours on continuous High-Range resolution, or 24 hours on continuous Low-Range resolution.

Low Battery Indicator: "BAT" appears in lower right display ("BAT" blinks only as auto zero function is operating). Battery should be replaced immediately following "BAT" display to prevent errors in pressure readings.

Display: LCD, 0.5" digit height.

Controls: MODE switch (Off, 1 Sec. Average, 5 Sec. Average, 10 Sec. Average, Long Term Average) and RANGE indicator (0-1999 Pa, 0-199.9 Pa).

AUTO ZERO function operates automatically whenever the gauge is turned on.

CHANNEL switch allows either pressure signal A or B to be displayed.

Over Pressurization Safety: Built-in over pressurization safety protects sensor from momentary overpressurization. "OP" appears on display.

5158 Bloomington Ave. S. • Minneapolis, Minnesota 55417 • (612) 827-1117/FAX (612) 827-1051

RCD Corporation®

Product Data Sheet

NOW IN TUBES

RCD® #6 Mastic

Description: **RCD # 6 Mastic** is a fibrous adhesive-sealant used in the fabrication, sealing, and coating of thermal insulation on air ducts, equipment, fittings, piping, and vessels. This mastic is formulated with an acrylic resin emulsion and contains fibers which provide reinforcement of the dried film. It dries to a tough, flexible, fire resistant, and weatherproof film. **RCD # 6 Mastic** contains no lead, mercury, asbestos, or solvents.

Performance: **RCD # 6 Mastic** is an elastomeric mastic which spreads easily and permanently seals the exterior of thermal insulation, providing excellent outdoor durability. This mastic will not run or sag when properly applied and is mold and mildew resistant. Since this product contains fibers it can be used without a reinforcing membrane if desired. It adheres to most substrates, including, but not limited to: glass and mineral fiber, polyurethane foam, cellular glass, polystyrene foam, calcium silicate insulation, sheet aluminum, aluminum foil, foil skrim, galvanized steel, wood, gypsum board, concrete, and masonry. This mastic is ideal for repairing damaged insulation and leaking ductwork, and for retrofitting ductwork or equipment. **RCD # 6 Mastic** has been tested to ASTM E-84 for flame spread and smoke density, and was found to be in compliance with the requirements of NFPA - 90A and 90B.

Tools & Materials:

- Brush, caulking gun, or trowel (may also be palmed).
- 30:1 or 40:1 airless spray equipment.
- Optional: a reinforcing membrane of fiberglass, polyester, or nylon.

Application: **RCD # 6 Mastic** is easily applied to most construction surfaces. Surfaces must be free from dirt, oil, and grease. No thinning or mixing is necessary; it can be used directly from the pail. Brush, trowel, palm, or spray a tack coat of 2 gal./100 sq. ft. (if a reinforcing membrane is used, embed it into the tack coat so that all of the mesh is filled). Then apply a finish coat of 2 gal./100 sq. ft. Using these procedures will ensure a high quality, weather proof, and long lasting coating. Allow at least 4 hours drying time during threatening weather.

Precautions: Do not thin. Protect from freezing. Rotate stock. Do not apply below 35°F or above 120°F. High humidity will retard drying. *Keep out of the reach of children. If there is contact with eyes, flush with clean water and contact physician.*

Warranty: **RCD #6 Mastic** is warranted to do the work for which it is designed as set forth above. We do not make any claims for **RCD #6 Mastic** beyond our warranty of its performance. Recommendations for storage, use and application of **RCD #6 Mastic** are set forth above. Since we have no control over these recommendations it is necessary that we make a condition of sale of our product. We will refund the purchase price or replace within ninety (90) days from date of sale any material found to be defective in any way by our laboratories. Under no circumstances are we responsible beyond the purchase price of our product. No damages or charges of any kind, either for labor or otherwise suffered or incurred by the customer in repairing or replacing defective products, or occasion by them, will be allowed. The retention of the product after (90) days from the date of shipment shall be deemed conclusive evidence that the warranty has been fulfilled.

This express warranty excludes all implied warranties, including merchantability and fitness.

SPECIFICATION DATA

wet film coverage	50 sq. ft./gal. at 1/16"; 25 sq. ft. at 1/8"
weight per gallon	10.3 lbs.
solids by weight	61%
type	acrylic resin emulsion
color	cream
dry time at 50% humidity and 70° F	to touch 1–2 hours, through 4 hours
adhesive cure	72 hours
service temperature limits	-10° F. to 200° F.
viscosity	95,000 – 110,000 cps.
packaging	11 oz. tubes, 1 gal., 2 gal., & 5 gal. plastic pails
clean up	soap & water

Surface Burning Characteristics

(based on 100 for untreated red oak) applied to asbestos-cement board

ASTM E-84 flame spread	5
ASTM E-84 smoke developed	0

tests performed by Applied Research Laboratories, Inc.

ARL Listed Product per UL-181 for application to aluminum backed ductboard, vinyl flex duct and galvanized steel connectors.

RCD Corp. • 2310 Coolidge Ave. • Orlando, FL 32804 • 407-422-0089

NIIAW

Revised 1/93

Material Safety Data Sheet

May be used to comply with OSHA's Hazard Communication Standard, 29 CFR 1910.1200. Standard must be consulted for specific requirements.

U.S. Department of Labor
Occupational Safety and Health Administration
(Non-Mandatory Form)
Form Approved
OMB No. 1218-0072

IDENTITY *(As Used on Label and List)*: RCD Corporation #6 Mastic

Note: Blank spaces are not permitted. If any item is not applicable, or no information is available, the space must be marked to indicate that.

Section I

Manufacturer's Name: RCD Corporation	Emergency Telephone Number: 407-422-0089
Address *(Number, Street, City, State, and ZIP Code)*: 2310 Coolidge Ave. Orlando, FL 32804	Telephone Number for Information: 407-422-0089
	Date Prepared: May 7, 1991
	Signature of Preparer *(optional)*

Section II — Hazardous Ingredients/Identity Information

Hazardous Components (Specific Chemical Identity; Common Name(s))	OSHA PEL	ACGIH TLV	Other Limits Recommended	% *(optional)*

Section III — Physical/Chemical Characteristics

Boiling Point	212 F.	Specific Gravity (H_2O = 1)	1.30
Vapor Pressure (mm Hg.)	same as water	Melting Point	
Vapor Density (AIR = 1)	N.I.	Evaporation Rate (Water = 1)	1.0

Solubility in Water: Miscible

Appearance and Odor: Cream colored. Viscous liquid with a pleasant odor.

Section IV — Fire and Explosion Hazard Data

Flash Point (Method Used)	Flammable Limits	LEL	UEL
None Tag open cup	None		

Extinguishing Media: For dried material use water.

Special Fire Fighting Procedures: Self-contained breathing apparatus should be used when fighting fires.

(N.I.=No Information Av

Unusual Fire and Explosion Hazards: None

(N.A.=Not Applicable)

RCD #6

Section V — Reactivity Data

Stability	Unstable		Conditions to Avoid None
	Stable	X	

Incompatibility (*Materials to Avoid*)
None

Hazardous Decomposition or Byproducts
None

Hazardous Polymerization	May Occur		Conditions to Avoid None
	Will Not Occur	X	

Section VI — Health Hazard Data

Route(s) of Entry: Inhalation? Skin? Ingestion?

Health Hazards (*Acute and Chronic*)

Carcinogenicity: NTP? IARC Monographs? OSHA Regulated?

Signs and Symptoms of Exposure
None Known

Medical Conditions
Generally Aggravated by Exposure

Emergency and First Aid Procedures
Wash from skin with soap and water. If splashed in eyes flush with copious amounts of water and seek medical advice.

Section VII — Precautions for Safe Handling and Use

Steps to Be Taken in Case Material Is Released or Spilled
Mop up or absorb with inert materials (sand) and place in containers.

Waste Disposal Method
Deposit in a approved landfill in accordance with Local, State and Federal Agencies.

Precautions to Be Taken in Handling and Storing
Normal handling of non-hazardous materialy

Other Precautions
Protect from freezing. Keep out of reach of children.

Section VIII — Control Measures

Respiratory Protection (*Specify Type*)
N.A.

Ventilation	Local Exhaust Normal	Special	
	Mechanical (*General*)	Other	

Protective Gloves Rubber Gloves	Eye Protection Chemical Safety Goggles

Other Protective Clothing or Equipment

Work/Hygienic Practices

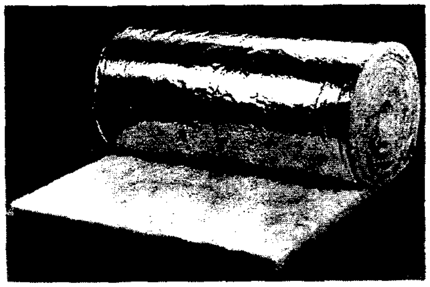
☆U.S. Government Printing Office: 1987—181-504/84352

SCHULLER

Air Handling Systems

Manville® Microlite®

Fiber Glass Duct Wrap Insulation



Type: Flexible Blanket
Temp. Limit: 350°F (177°C) Unfaced
250°F (121°C) Faced

Description
Manville Microlite duct insulation is a lightweight, highly resilient, blanket-type thermal and acoustical insulation made of glass fibers, bonded with a thermosetting resin.

Available Forms
Microlite insulation is available in a variety of densities, thicknesses, widths and roll lengths. It can be supplied plain or with various vapor barrier facings to meet service conditions. Faced Microlite blanket is supplied with a 2-inch stapling tab.

Uses
Microlite is recommended as thermal insulation for the exterior of rectangular and round sheet metal ducts in heating or cooling systems operating at a maximum temperature of +250°F (121°C) for faced material or +350°F (177°C) plain. It is also ideal for exteriors of plenums or other spaces or surfaces where temperatures must be controlled.

Advantages
Reduces Heat Transfer.
For warm air ducts, Microlite blanket reduces heat loss, increases system efficiency and cuts down fuel costs. For air conditioning systems it permits more accurate temperature control of cooled air during distribution, conserves power and helps prevent condensation.

Fire Safety.
Microlite insulation meets the requirements of NFPA 90A and 90B Standards and FHA on a *composite* basis (insulation, adhesive and facing) as well as the plain form. The kraft paper used in the FSK laminate is treated to reduce fire hazard. The UL Surface Burning Characteristic index is shown on page 15.

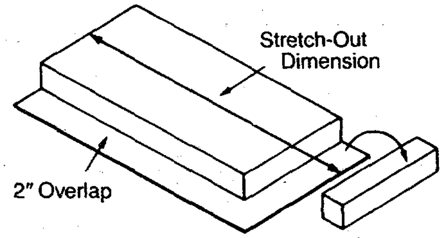
Resilient and Flexible.
The resilience of Microlite blanket minimizes the insulation's packing down and losing its effectiveness. The performance of any duct wrap is dependent upon installation. Care should be taken to minimize compression during installation. The flexibility of Microlite blanket makes it easy to apply, more manageable in difficult working areas, and more conformable to curved surfaces.

Strong, and Easy to Apply.
Microlite has high tensile strength and won't pull apart during normal handling. It can easily be pulled over duct corners, past hangers, through narrow openings, and formed around elbows, tees, etc. Microlite is lightweight and easy to cut with an ordinary knife, and is readily attached to duct surfaces with adhesive or mechanical fasteners.

Durable.
The glass fibers in Microlite duct insulation are incombustible. Being non-cellular and non-hygroscopic, they resist the effects of moisture. The fibers will not deteriorate, are unaffected by oil, grease and most acids and does not promote the growth of fungi or bacteria.

Application Recommendations
The "R-Value" will vary depending upon how much the insulation is compressed during installation.

Prepare overlap by removing approximately 2" of insulation from facing.



Before applying duct wrap, sheet metal duct shall be clean, dry and tightly sealed at all joints and seams.

Wrap insulation around duct with facing to the outside so the 2" flap completely overlaps facing and insulation at the other end of stretch out. Insulation shall be snugly butted.

Seams shall be stapled approximately 6" on center with outward clinching staples, then sealed with pressure-sensitive tape matching the facing and designed for use with duct insulation. The underside of duct work 24" or greater shall be secured with mechanical fasteners and speed clips spaced approximately 18" on center. The protruding ends of the fasteners should be cut off flush after the speed clips are installed, and then sealed with the same tape as specified above.

Adjacent sections of duct wrap insulation shall be snugly butted with the circumferential 2" tape flap overlapping and secured as recommended for longitudinal seam. In lieu of pressure sensitive tape two coats of vapor retarder mastic reinforced with one layer of 4" wide open weave glass fabric may be used.

In order to obtain the advertised installed "R-Values," the duct wrap insulation shall be cut to a stretch-out per the following table.

Duct Wrap Stretch-Outs

Labeled Thickness	Installed Compressed Thickness	Round	Square	Rectangular
1.0"	0.75"	P+7.0"	P+6.0"	P+5.0"
1.5"	1.125"	P+9.5"	P+8.0"	P+7.0"
2.0"	1.5"	P+12.0"	P+10.0"	P+8.0"
2.5"	1.875"	P+14.5"	P+12.5"	P+9.5"
3.0"	2.25"	P+17.0"	P+14.5"	P+11.5"

Stretch-outs include 2" for overlap.
P = Perimeter of duct to be installed.

SCHULLER

Air Handling Systems

Manville® Microlite®

Fiber Glass Duct Wrap Insulation Specification Data

Physical Properties

Temperature (maximum) Unfaced	350°F (177°C)
Faced	250°F (121°C)
Moisture adsorption	Less than 0.2% by volume
Alkalinity	Less than 0.6% expressed as Na_2O
Corrosivity (with steel, copper or aluminum)	Does not accelerate
Capillarity (after 24 hours)	Negligible
Odor	None
Shrinkage	None
Resistance to fungi and bacteria	Does not promote

Underwriters Laboratories Surface Burning Characteristics

All products meet the Surface Burning Characteristics requirements of NFPA 90A and 90B Standards and FHA, as tested by UL. Faced materials are tested as composite products (insulation, adhesive and facing). UL Guide No. 40 U8.3. Card R3711. Fire Hazard Classification 25/50.

(UL labels supplied on packages when requested on order.)

Facing Information

FSK Aluminum Foil
Reinforced with fiber glass scrim laminated to UL rated kraft.

Class I Vinyl
Gray and white. Meets NFPA 90A and 90B. UL rated.

Permeance

FSK (Facing) .02 perms
Class I Vinyl 1.3 perms

(Per ASTM E 96, Procedure A for facing material prior to lamination. After lamination, permeance values may be higher.)

Thermal Conductivity (ASTM C 518)

Type	k* Compressed Thickness BTU·in/(hr·ft²·°F)	W/m·°C	k Labeled Thickness BTU·in/(hr·ft²·°F)	W/m·°C
75	.27	.039	.29	.042
100	.25	.036	.27	.039
150	.24	.035	.25	.036

Conductivity at 75°F (24°C) Mean Temperature.
*Tested with material thickness compressed 25%.

Installed R-Values

Type	Labeled Thickness (in)	(mm)	Installed "R"† (hr·ft²·°F)/BTU	m²·°C/W	Out of Pkg. "R" (hr·ft²·°F)/BTU	m²·°C/W
75	1½	38	4.2	.74	5.2	.92
	2	51	5.6	.99	6.9	1.22
	3	76	8.3	1.46	10.3	1.81
100	1½	38	4.5	.79	5.6	.99
	2	51	6.0	1.06	7.4	1.30
150	1½	38	4.7	.83	6.0	1.06
	2	51	6.3	1.11	8.0	1.41

†Installed R-Value calculated with a material thickness compressed to a maximum of 25% following recommended duct wrap stretch-outs (see "Guide Specifications" Vapor Barrier Duct Insulation data page, AHS-116).

Compliance with Government Specs and Other Standards

HH-I-558B*, Form B, Type I, Class 6
Designation B-2 Type 75
Designation B-3 Type 100
Designation B-4 Type 150

*The above Class and Designation have been deleted in HH-I-558C and substituted by ASTM C 553-92.

ASTM C 553-92**
Type II Types 75, 100, 150

**To 350°F unfaced; 250°F faced.

MIL-I-22023D△, Types I and II
Class 2 Type 75
Class 3 Type 100
Class 4 Type 150

△This standard has been replaced by ASTM C 1139-90.

ASTM C 1139-90
Type I† Grade 1 Type 75 Unfaced
Grade 2 Type 100 Unfaced
Grade 3 Type 150 Unfaced

Type II† Grade 1 Type 75 Faced
Grade 2 Type 100 Faced
Grade 3 Type 150 Faced

†Type I to 350°F; Type II to 250°F.

ASTM E 84 All Types

ASTM C 1136††
Type II FSK Jacket

††Replaces HH-B-100B, Type II.

Canada: CGSB 51-GP-11M

Standard Thickness and Packaging

Type	Thickness (in) (mm) 100′ roll	75′ roll	50′ roll
75	1½ (38)	2 (51)	3 (76)
100	1½ (38)	2 (51)	
150			1½, 2 (38, 51)

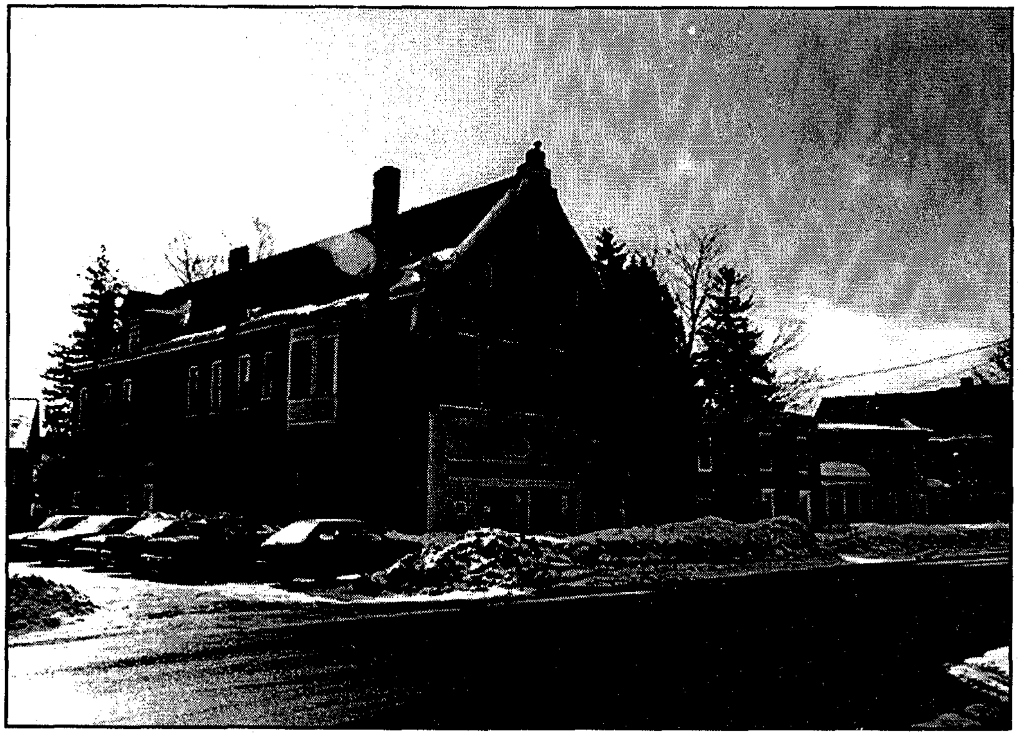
Note: All types and thicknesses are available in widths from 24″ through 96″ with or/without facing. Additional thicknesses and other lengths available on special order. Contact zone sales office for availability.

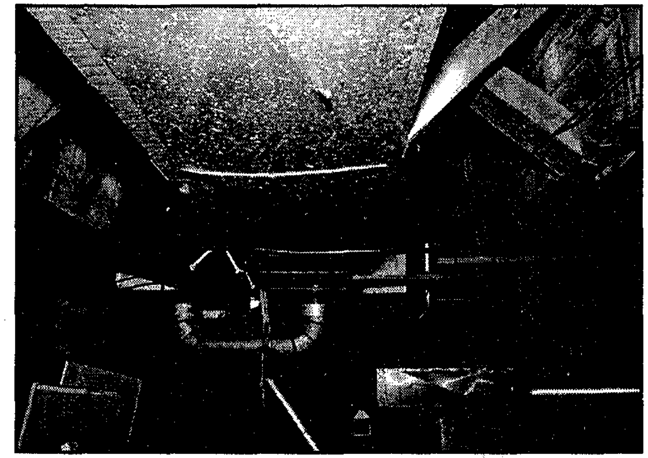
When ordering material to comply with any government, ASTM or listed specification, a statement of that fact must appear on the purchase order. Government regulations and other listed specifications require specific lot testing, and prohibit certification of compliance after shipment has been made. There may be additional charges associated with specification compliance testing.

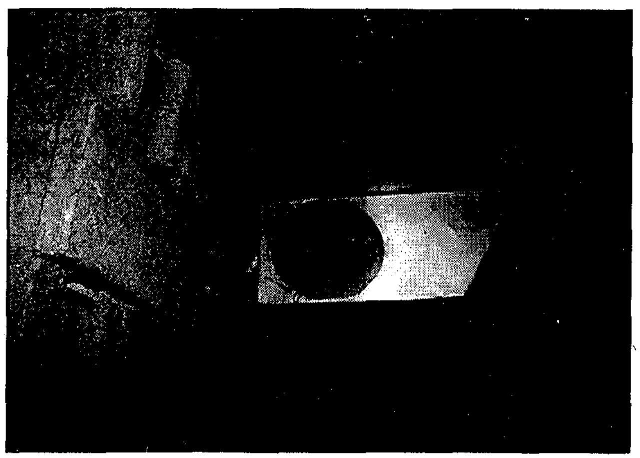
For Guide Specifications, see Manville® Spec-Line™ folder (MID-101), or Specification No. 3.1, AHS-116.

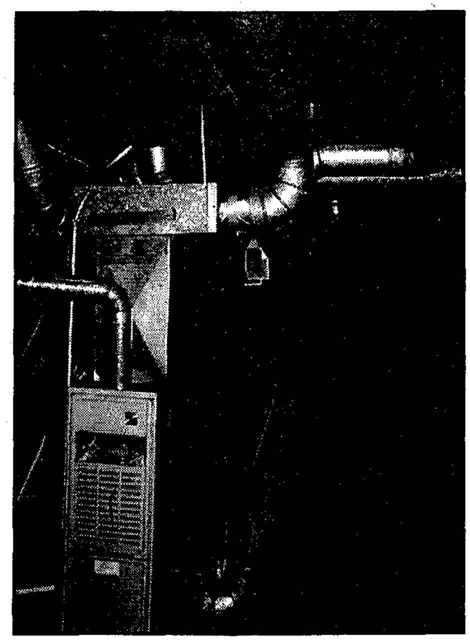
APPENDIX D

PROPERTIES AND SYSTEMS TESTED

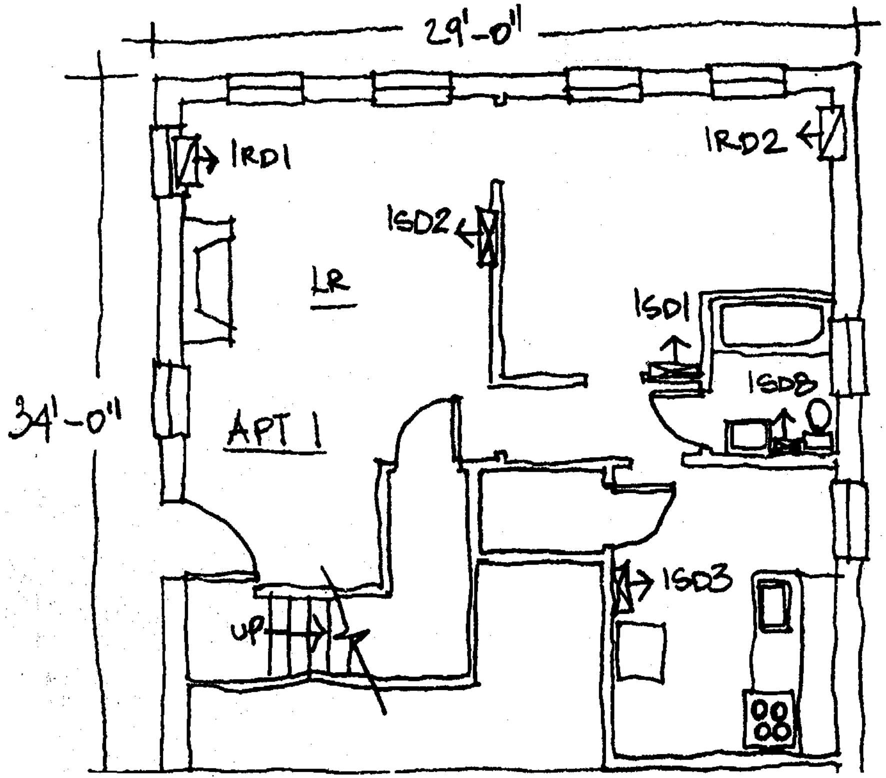

Property #1 - Front Elevation.


Property #1 - Duct used as a jumper to connect joist space to complete run.

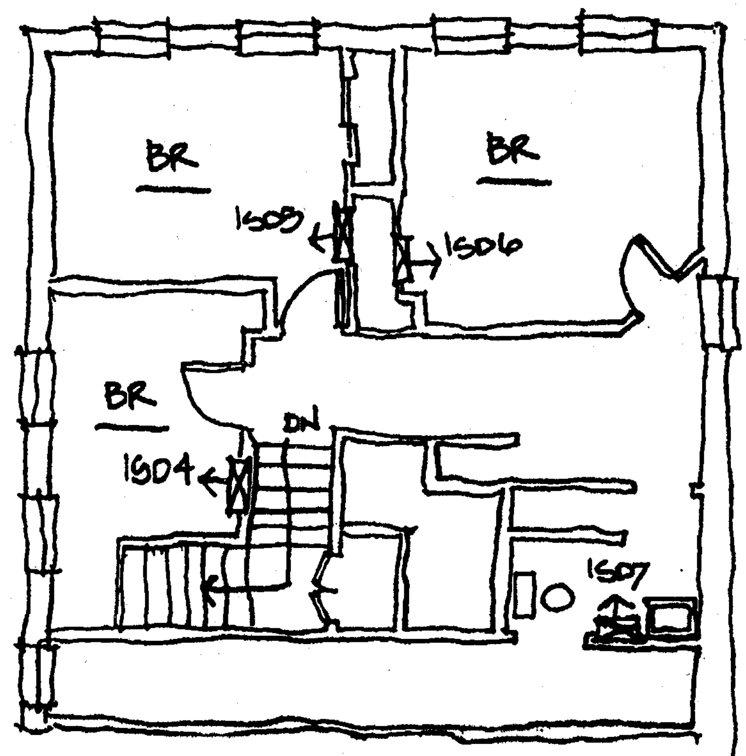

Property #1 - Open ductwork to Apt. 1.


Property #1 - Heating System for Apt. #1.

Property #1
Apartment #1

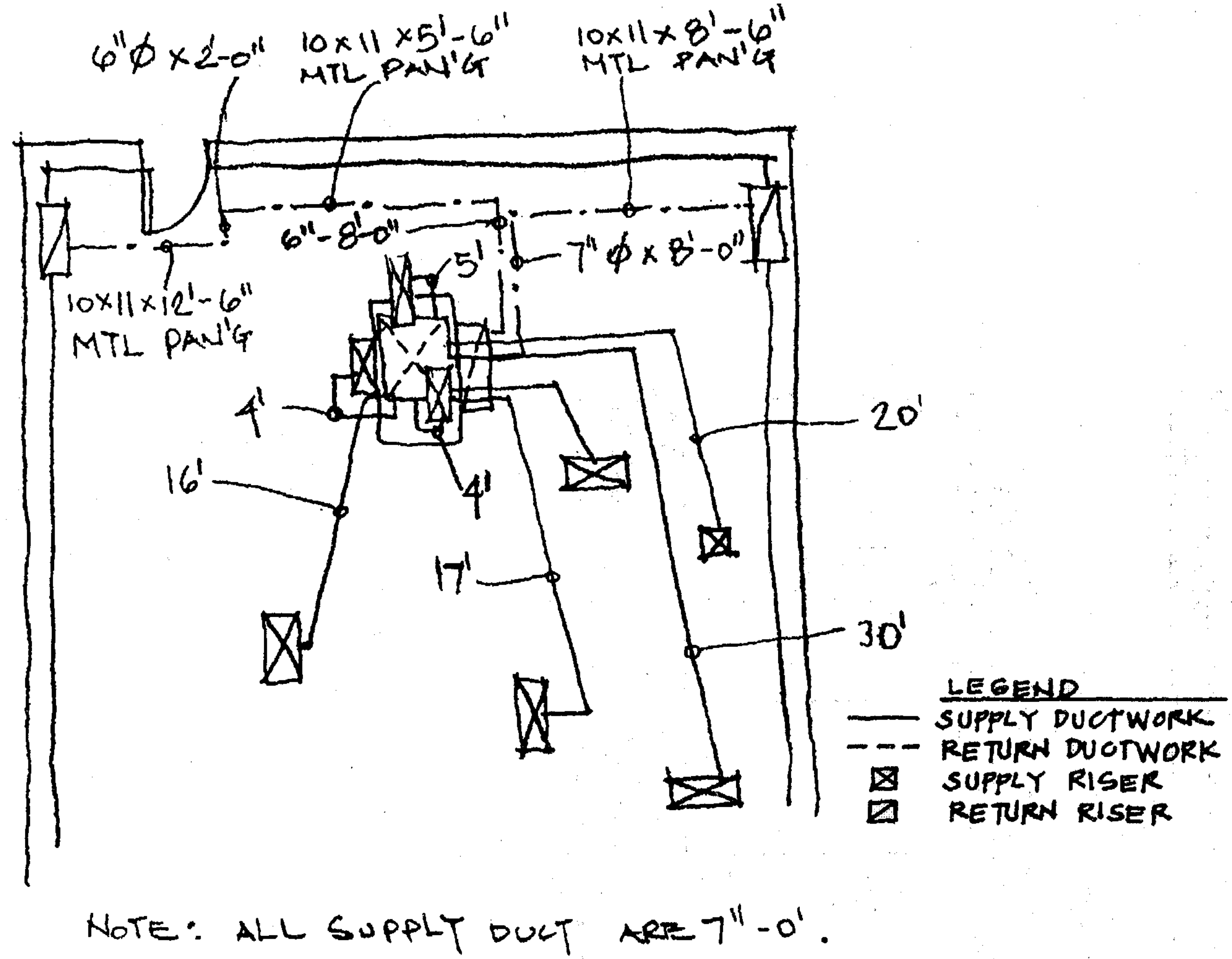


First Floor



Second Floor

Property #1



Duct Plan

PROPERTY #1

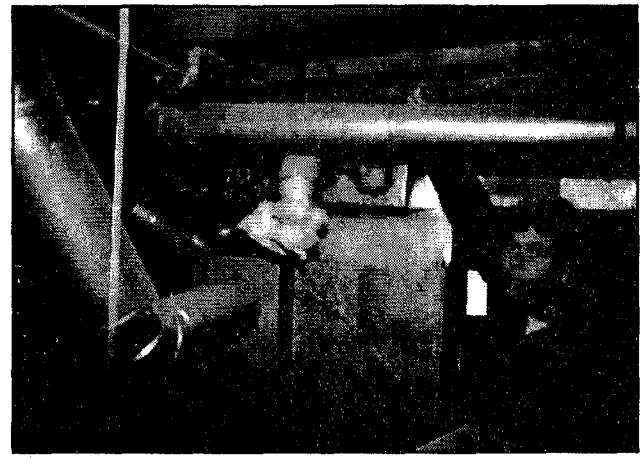
Total System Airflow

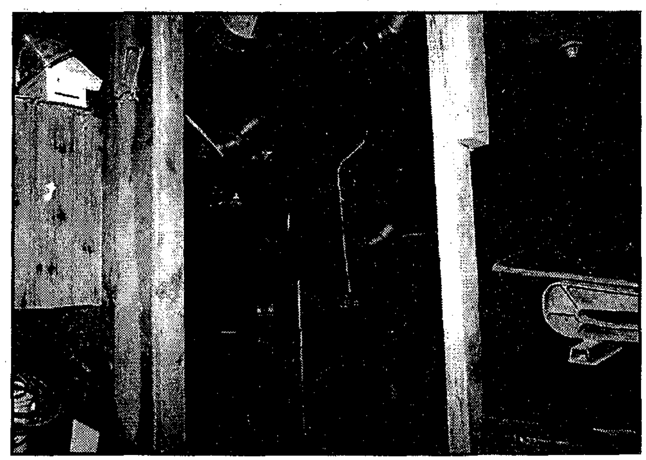
	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	526.0	111.0	494.0	259.0
Totals	526.0	111.0	494.0	259.0

Apartment Airflows

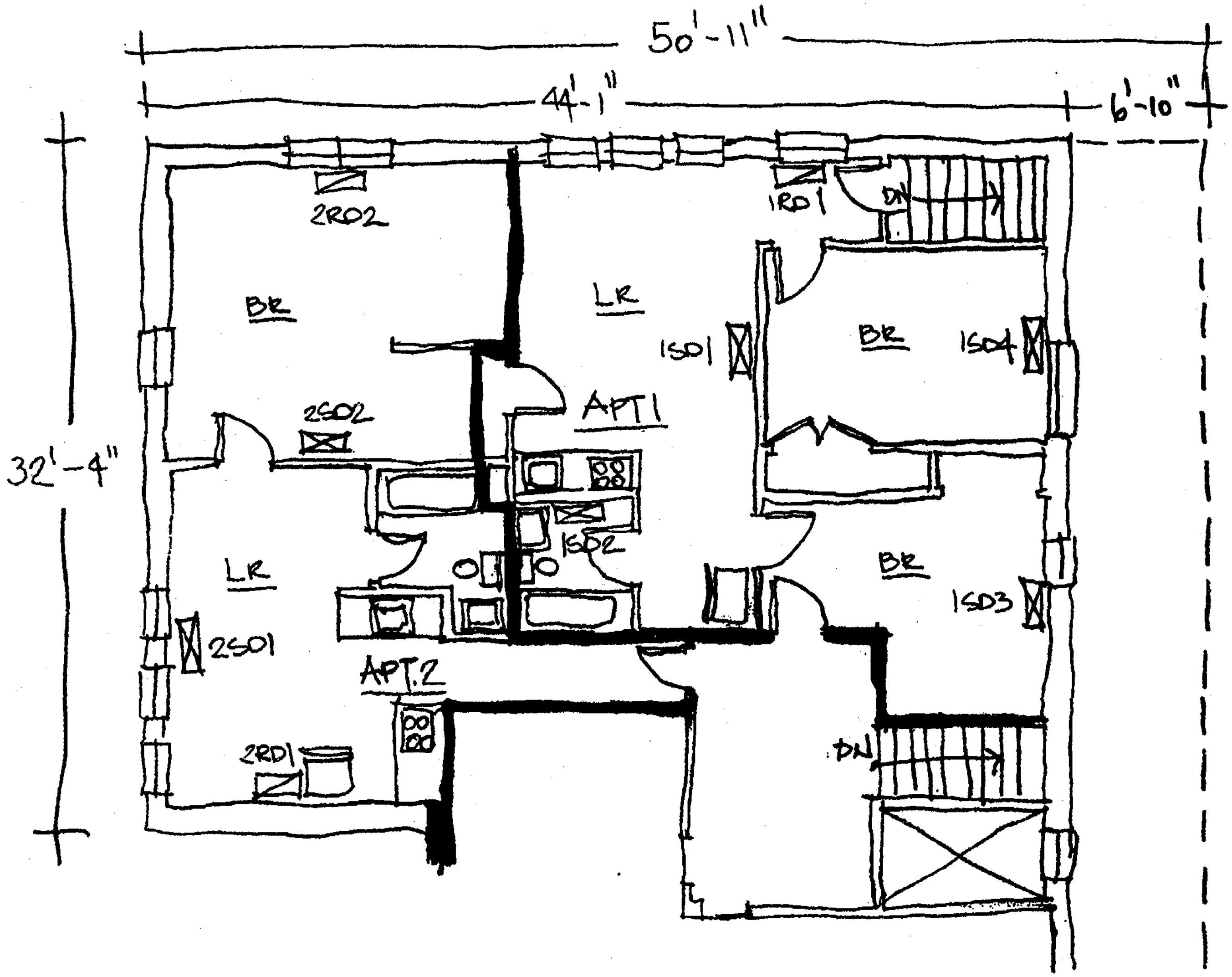
Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	77.0		76.0	
SD2	79.0		77.0	
SD3	89.0		87.0	
SD4	50.0		44.0	
SD5	55.0		53.0	
SD6	74.0		66.0	
SD7	27.0		14.0	
SD8	75.0		77.0	
RD1		17.0		63.0
RD2		94.0		196.0
Totals	526.0	111.0	494.0	259.0


Property #2


Property #2 - Fiberglass insulation used to close ductwork.

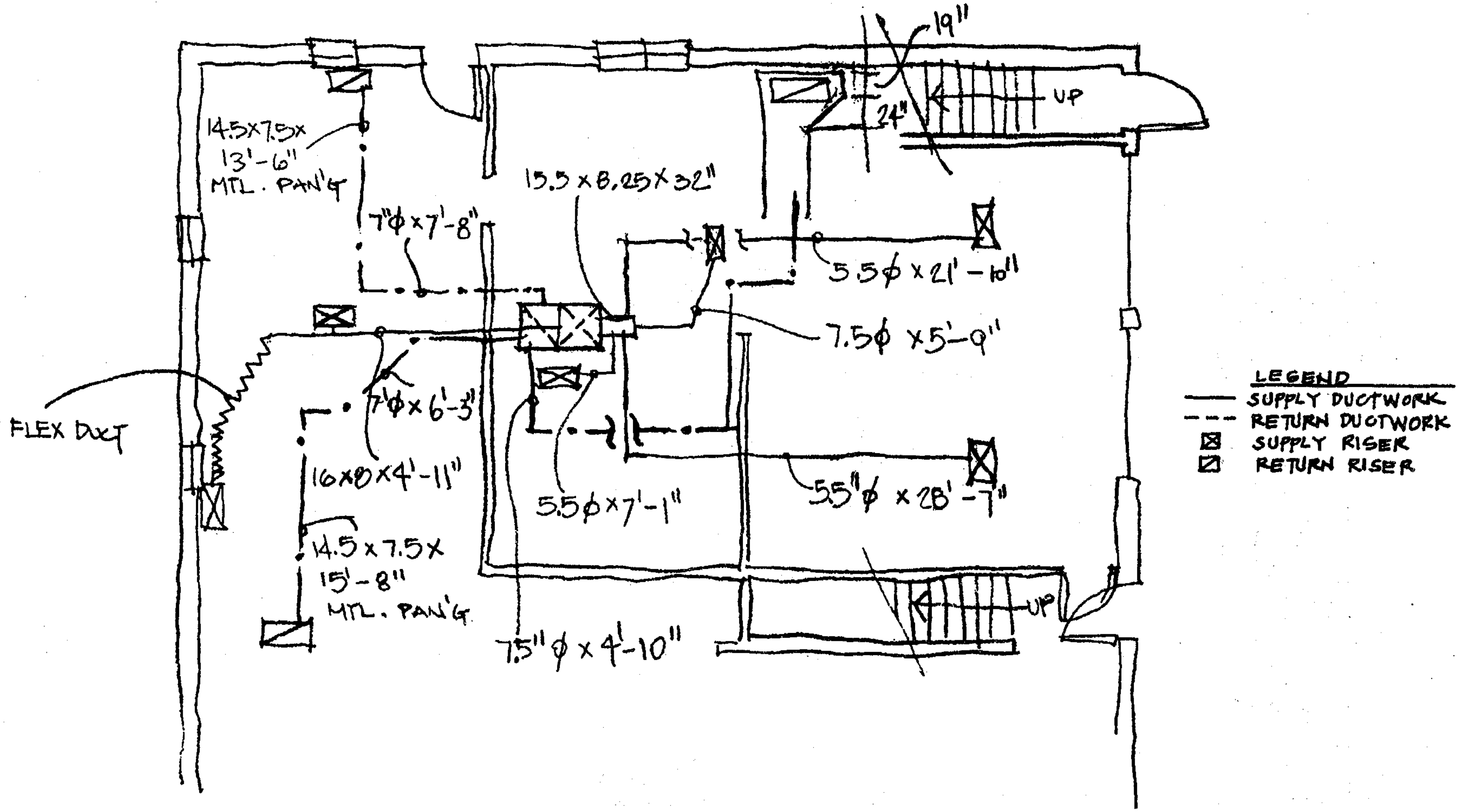

Property #2 - Heating system.

Property #2
Apartments #1-2



First Floor

Property #2



Duct Plan

PROPERTY #2

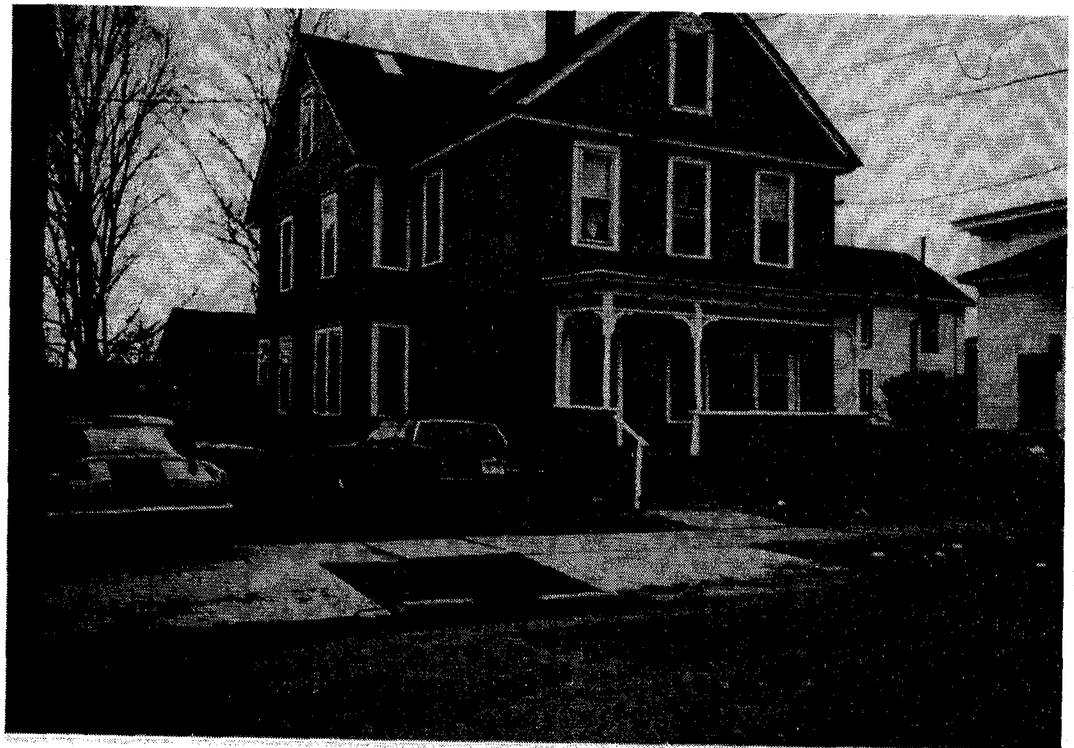
Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	293.0	117.0	308.0	146.0
Apt. #2	216.0	141.0	218.0	282.0
Totals	509.0	258.0	526.0	428.0

Apartment Airflows

Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	134.0		143.0	
SD2	55.0		55.0	
SD3	52.0		55.0	
SD4	52.0		55.0	
RD1		117.0		146.0
Totals	293.0	117.0	308.0	146.0

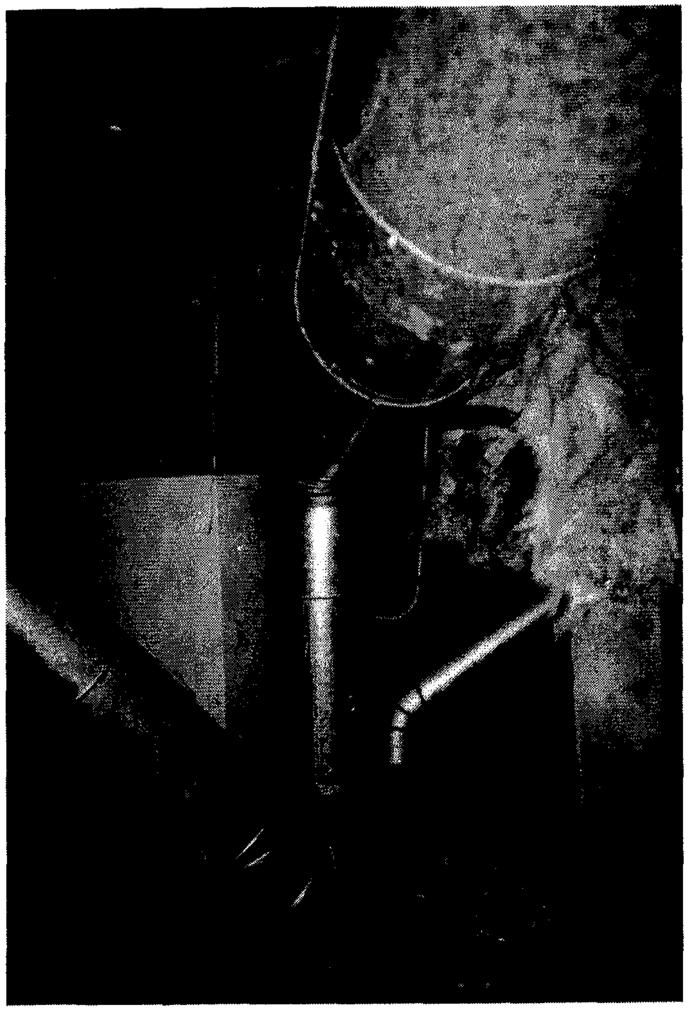
Apt. #2	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	76.0		78.0	
SD2	140.0		140.0	
RD1		65.0		123.0
RD2		76.0		159.0
Totals	216.0	141.0	218.0	282.0



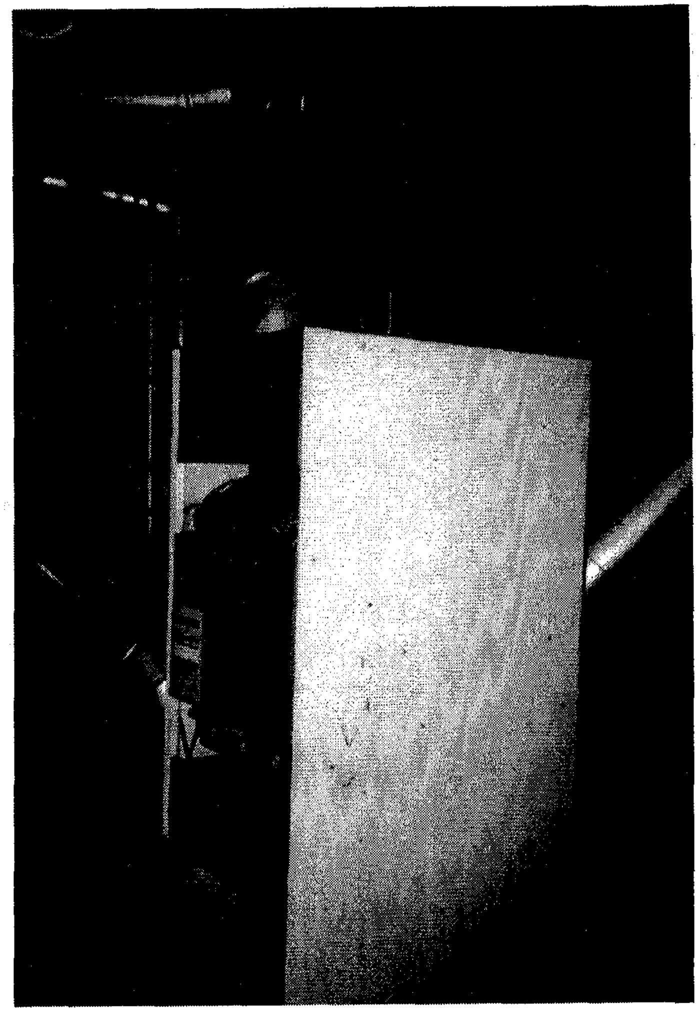
Property #3

Property #3 - Loose register boot connection.

Property #3 - Poorly fitted register boot connection. Duct insulation filled the gaps around the boot.

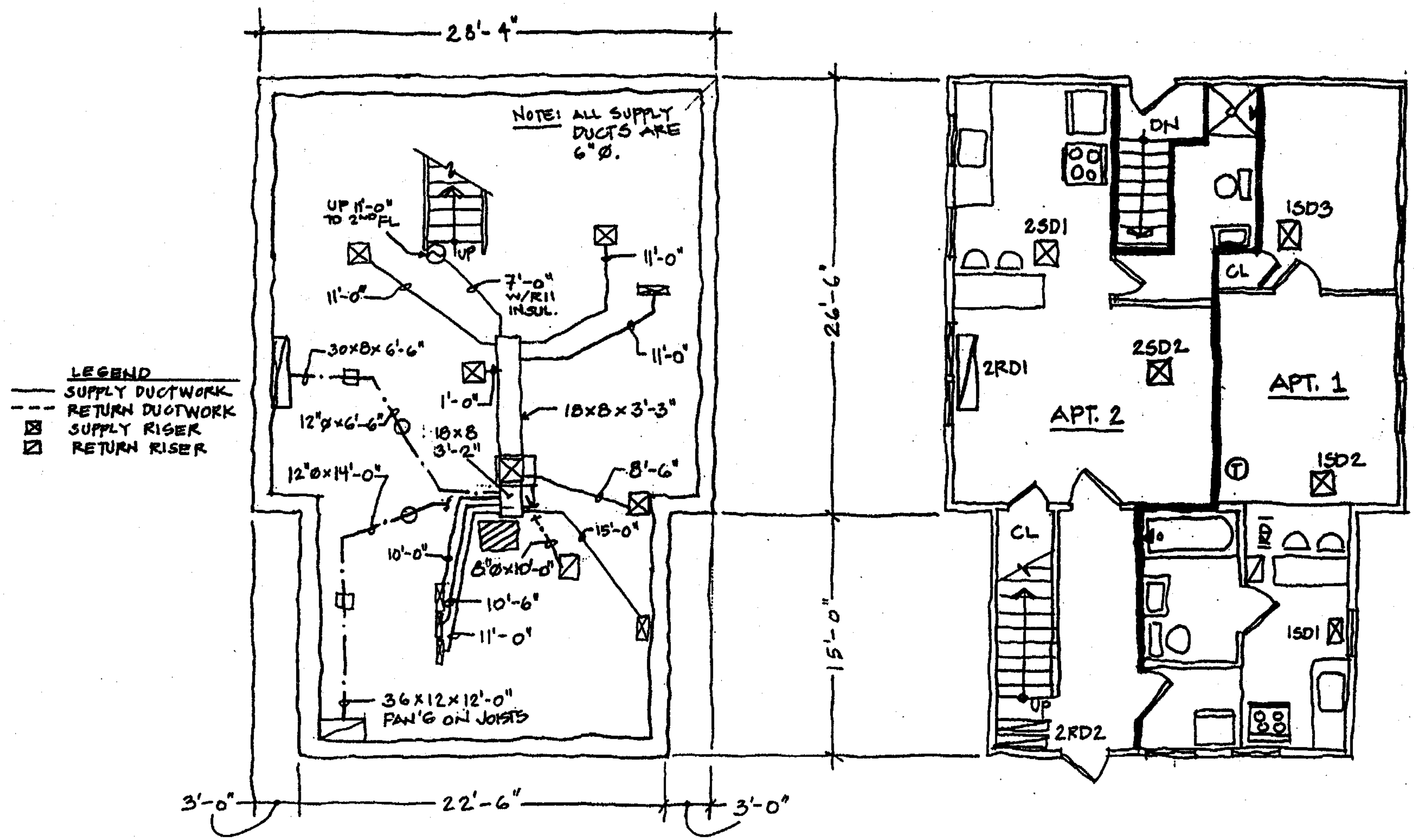


Property #3 - Return duct and return plenum.



Property #3 - Furnance.

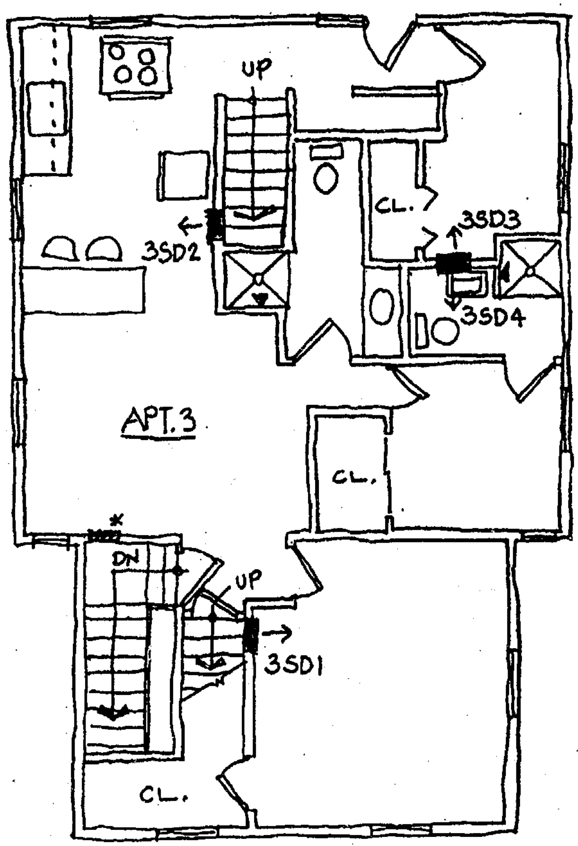
Property #3
Apartments #1-2



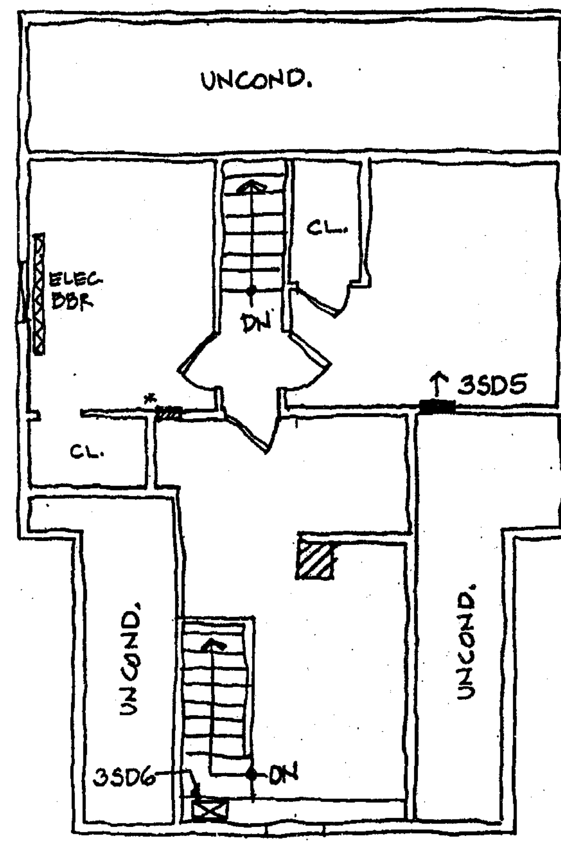
Duct Plan

First Floor

Property #3
Apartment #3



Second Plan



Third Floor

*- UNCONNECTED WALL REGISTER

PROPERTY #3

Total System Airflow

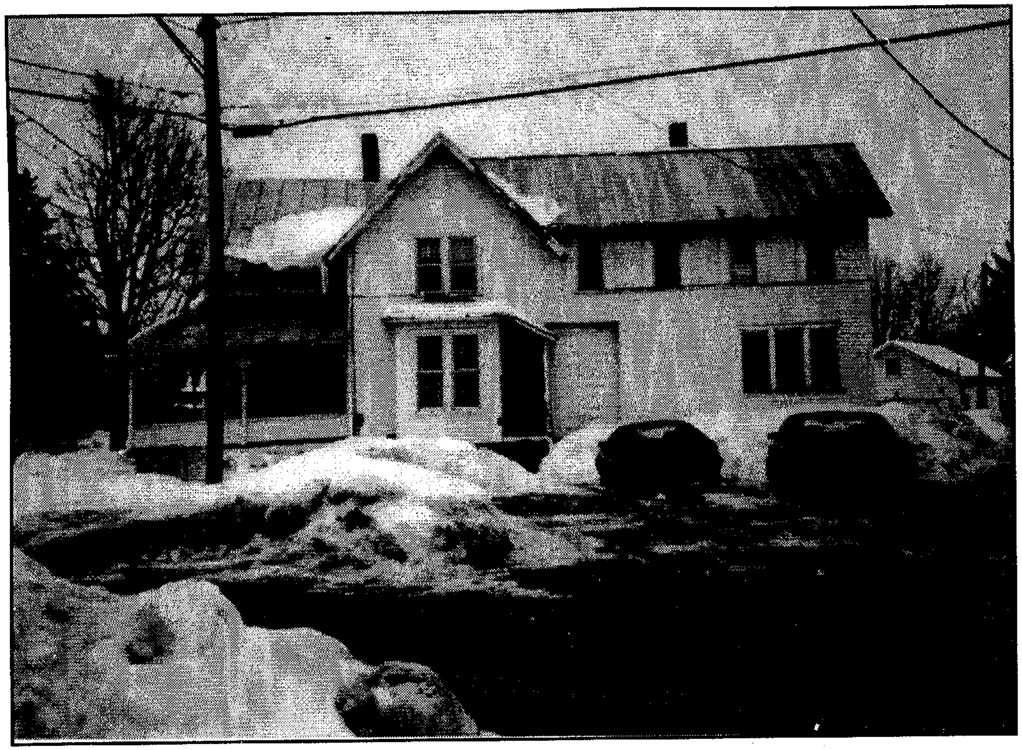
	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	203.0	116.0	280.0	128.0
Apt. #2	219.0	525.0	269.0	657.0
Apt. #3	452.0	0.0	532.0	0.0
Totals	874.0	641.0	1081.0	785.0

Apartment Airflows

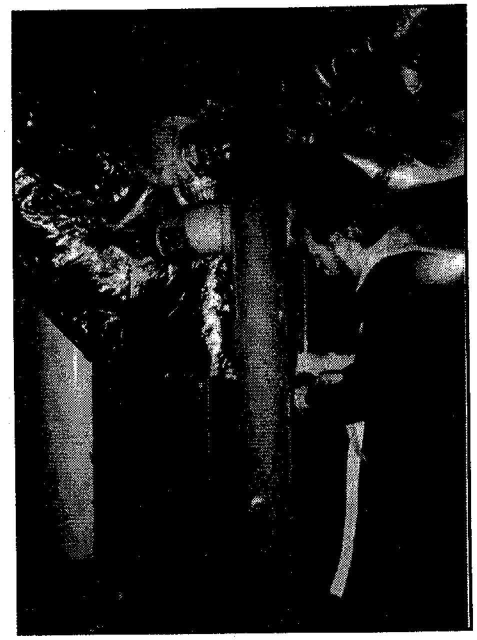
Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	52.0		61.0	
SD2	87.0		100.0	
SD3	64.0		119.0	
RD1		116.0		128.0
Totals	203.0	116.0	280.0	128.0

Apt. #2	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	148.0		189.0	
SD2	71.0		80.0	
RD1		317.0		373.0
RD2		208.0		284.0
Totals	219.0	525.0	269.0	657.0

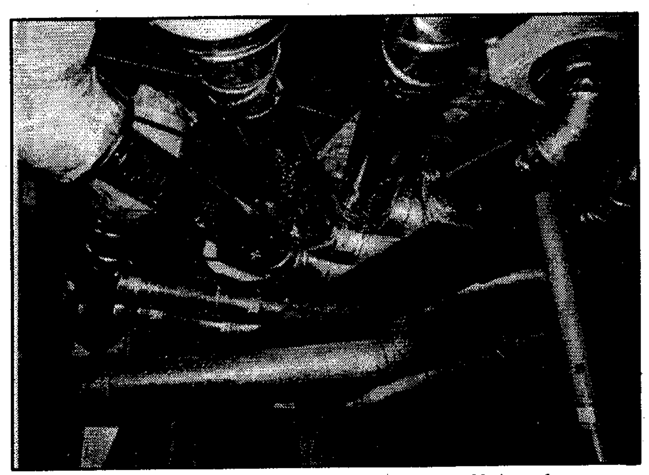
Apt. #3	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	96.0		122.0	
SD2	110.0		120.0	
SD3	59.0		64.0	
SD4	48.0		57.0	
SD5	47.0		55.0	
SD6	92.0		114.0	
Totals	452.0		532.0	



Property #4

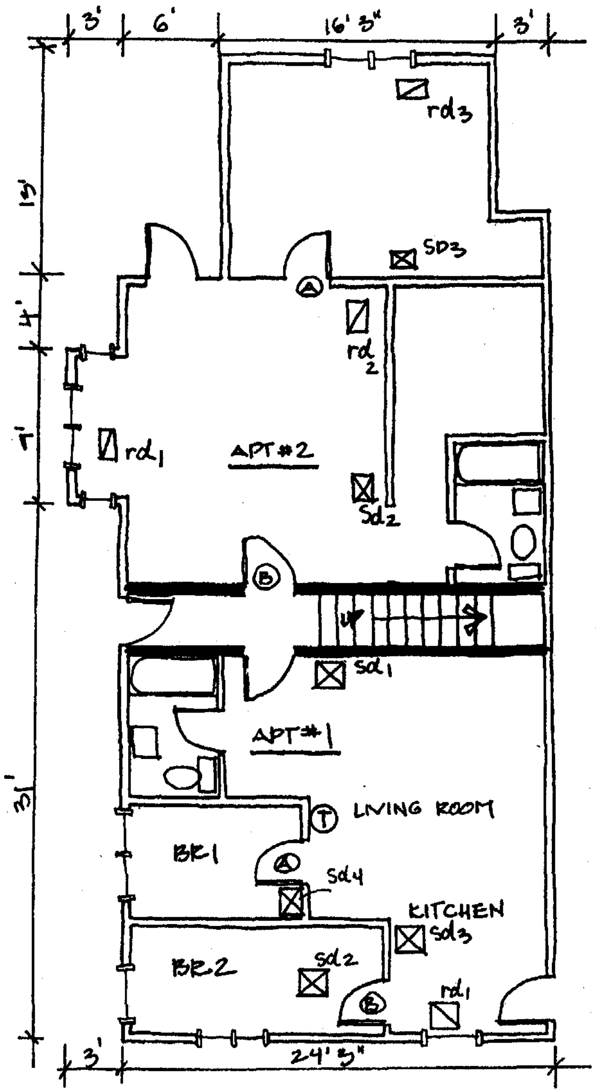


Property #4 - Heating System. Duct wrap insulation being installed to plenum.

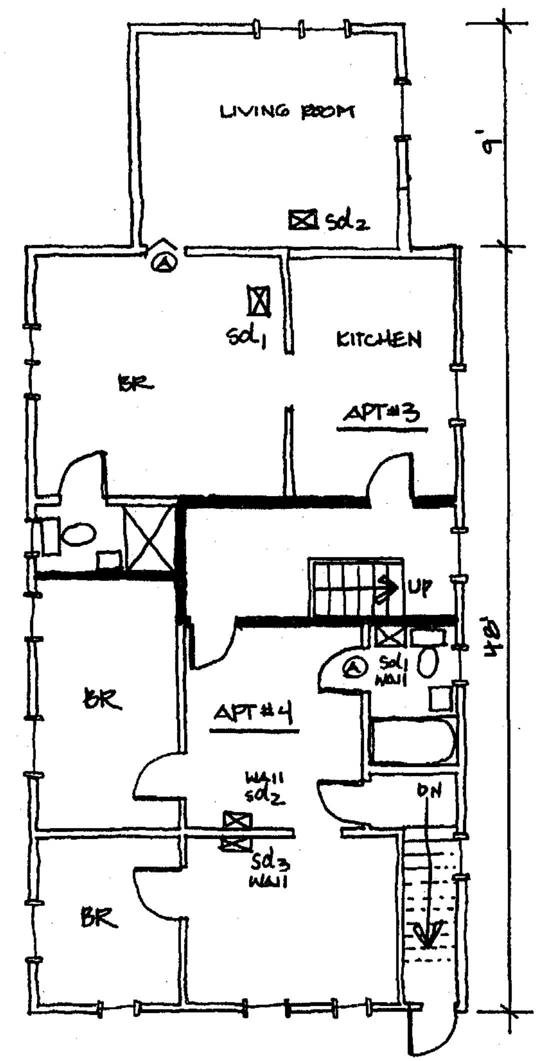


Property #4 - New supply duct branches off the plenum and connections to old ductwork.

Property #4
Apartments #1-4

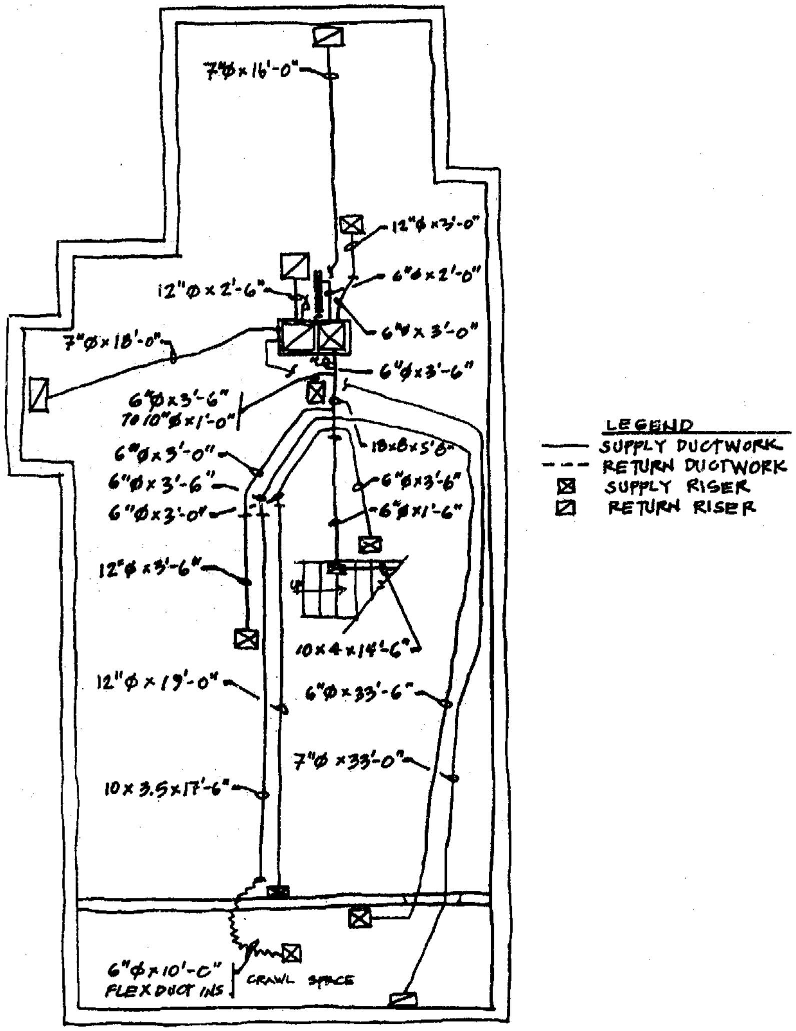


First Floor



Second Plan

Property #4



Duct Plan

PROPERTY #4

Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	205.0	64.3	209.8	63.3
Apt. #2	412.8	674.2	425.9	741.7
Apt. #3	101.0	-	101.5	-
Apt. #4	162.3	-	164.9	-
Totals	881.1	738.5	902.1	805.0

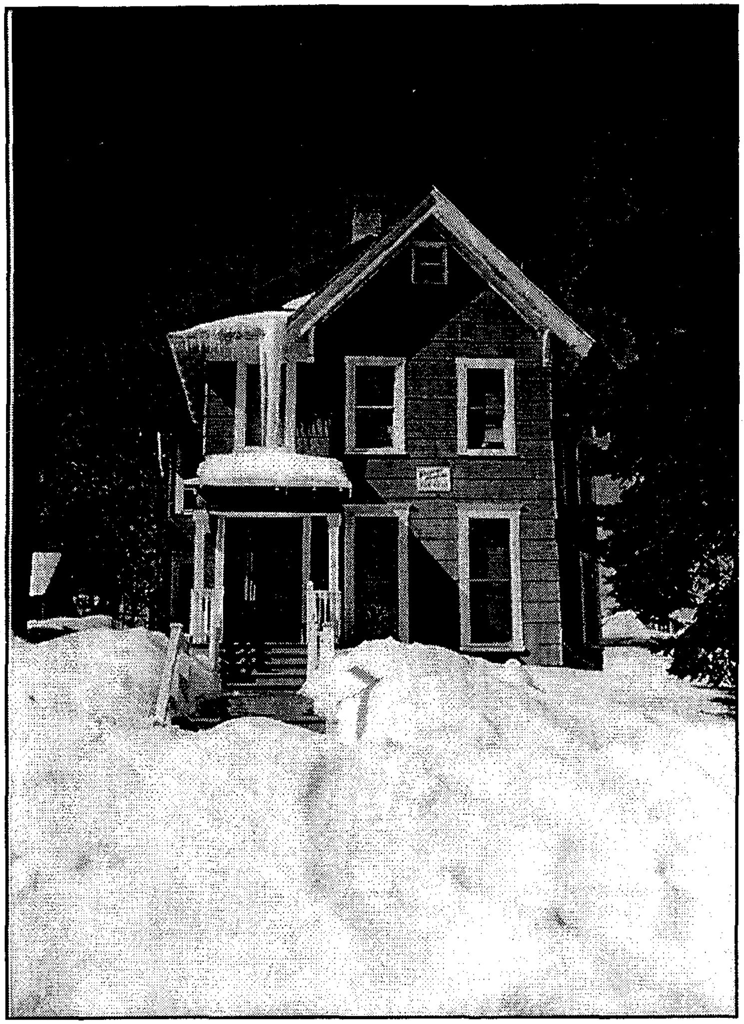
Apartment Airflows

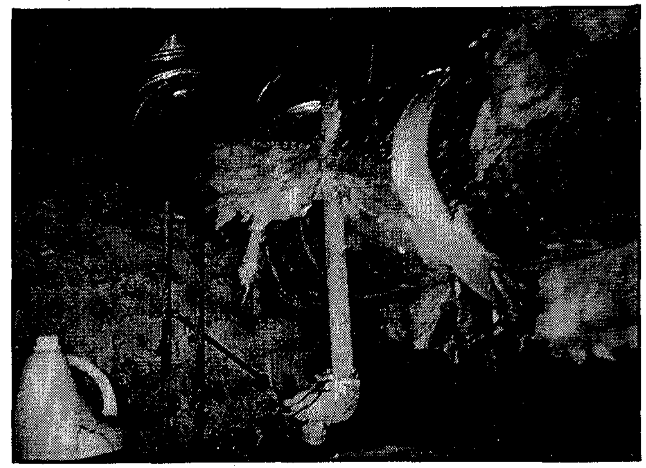
Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	88.8		90.3	
SD2	51.6		52.7	
SD3	64.6		66.8	
SD4	0.0		0.0	
RD1		64.3		63.3
Totals	205.0	64.3	209.8	63.3

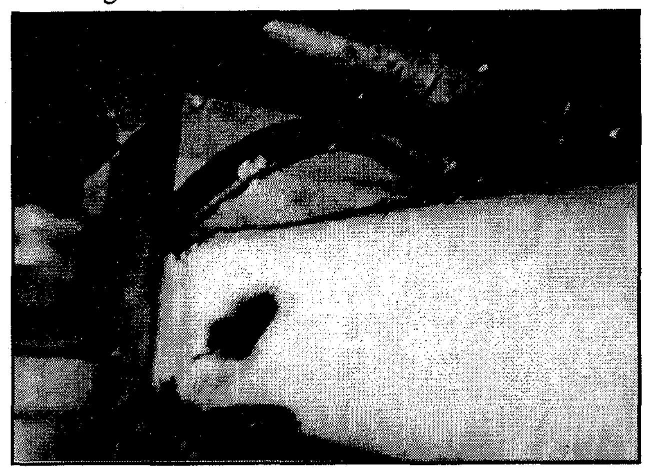
Apt. #2	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	132.9		137.2	
SD2	95.4		99.2	
SD3	184.5		189.5	
RD1		95.1		100.0
RD2		472.6		536.3
RD3		106.5		105.4
Totals	412.8	674.2	425.9	741.7

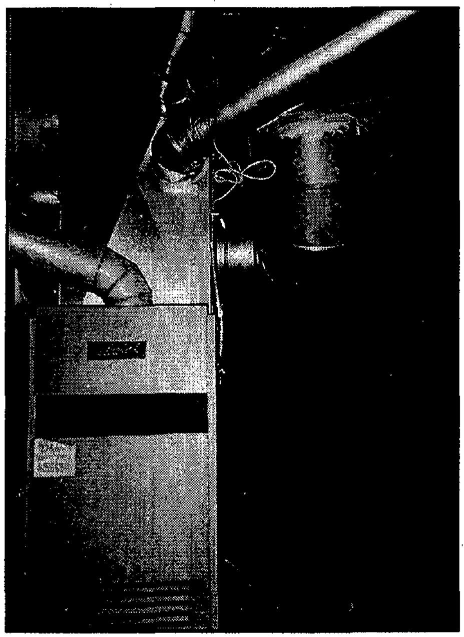
Apt. #3	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	88.2		86.3	
SD2	12.8		15.2	
Totals	101.0		101.5	

Apt. #4	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
SD1	83.3		84.9	
SD2	35.7		47.4	
SD3	43.3		32.6	
Totals	162.3		164.9	

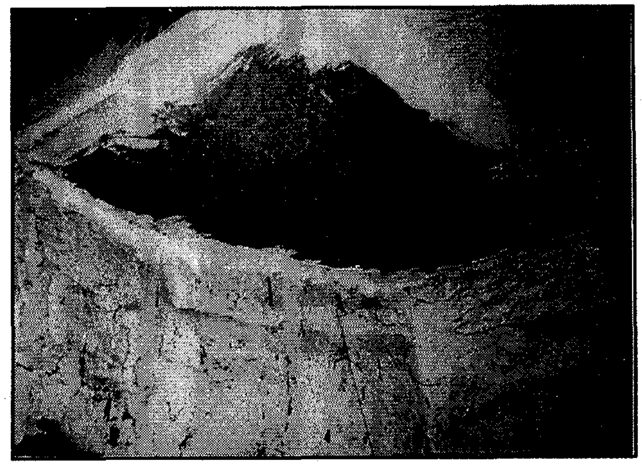

Property #5 - Front Elevation.


Property #5 - Disconnected ductwork; A-ttempts at insulating ductwork.


Property #5 - Holes in ductwork due to rusting.

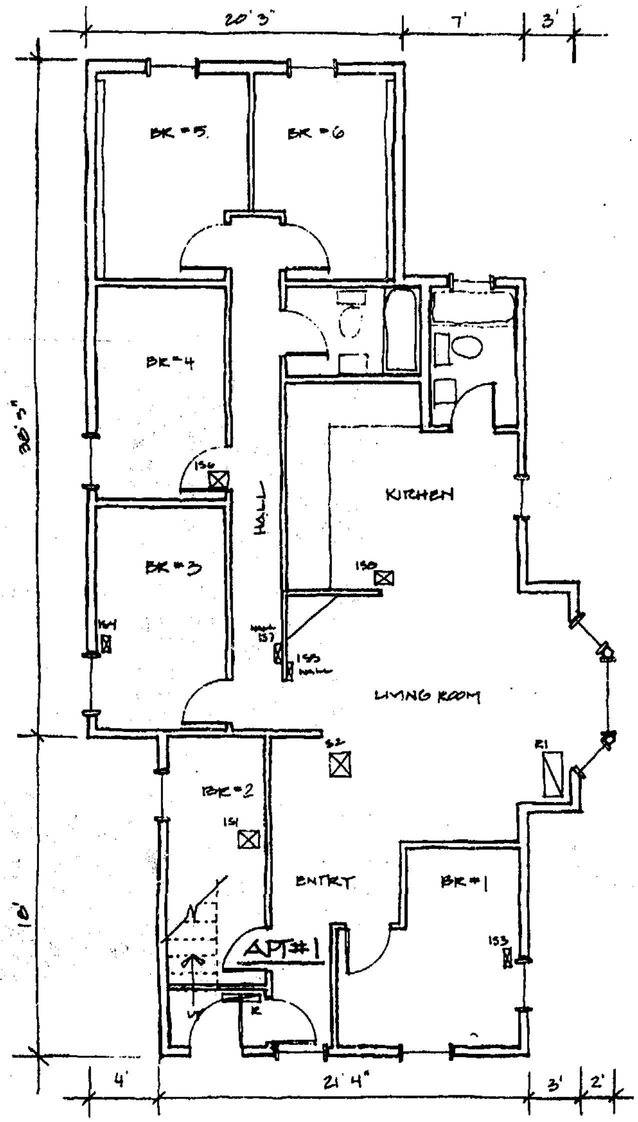


Property #5 - Heating system for Apt #1.

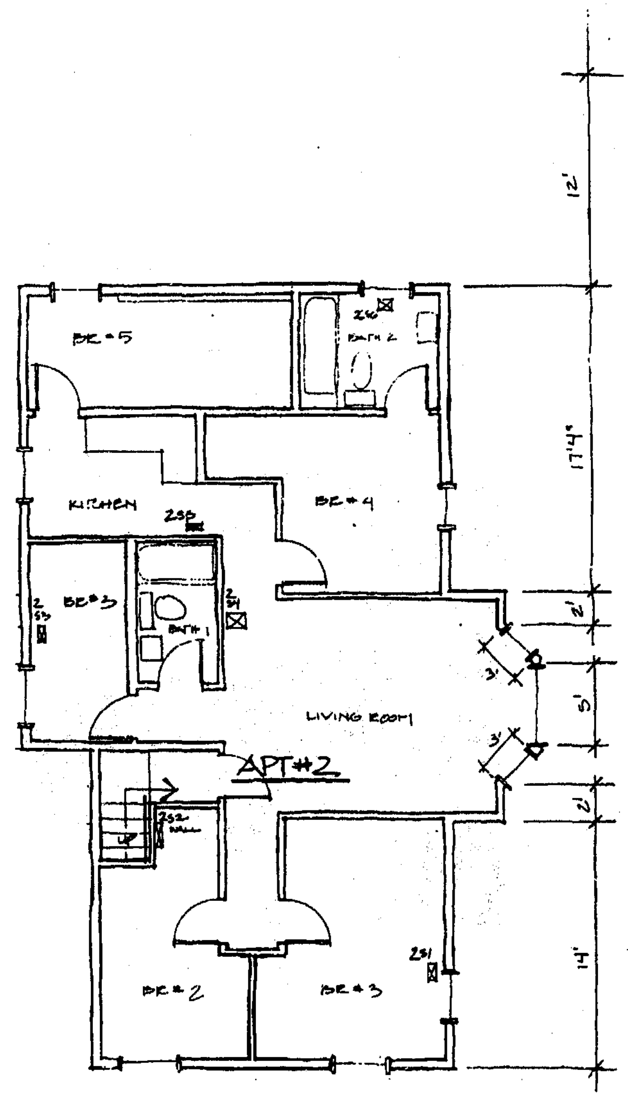


Property #5 - Return ductwork after sealing.

Property #5
Apartments #1-2

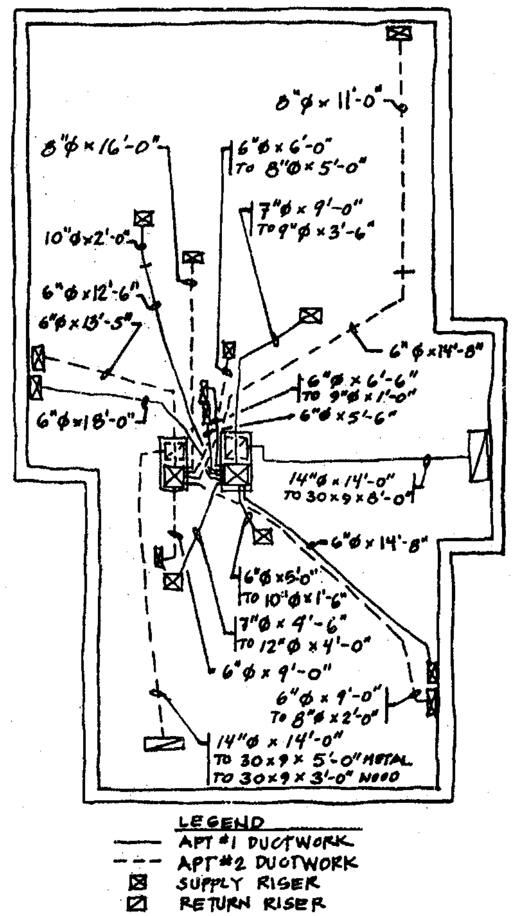


First Floor



Second Plan

Property #5



Duct Plan

PROPERTY #5.1

Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	883.2	227.1	946.6	1077.4
Totals	883.2	227.1	946.6	1077.4

Apartment Airflows

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
1S2	126.6		142.6	
1S3	120.2		128.2	
1S4	107.8		115.0	
1S5	95.9		125.1	
1S6	178.8		169.2	
1S7	48.2		59.1	
1S8	205.7		207.4	
1R1		227.1		1077.4
Totals	883.2	227.1	946.6	1077.4

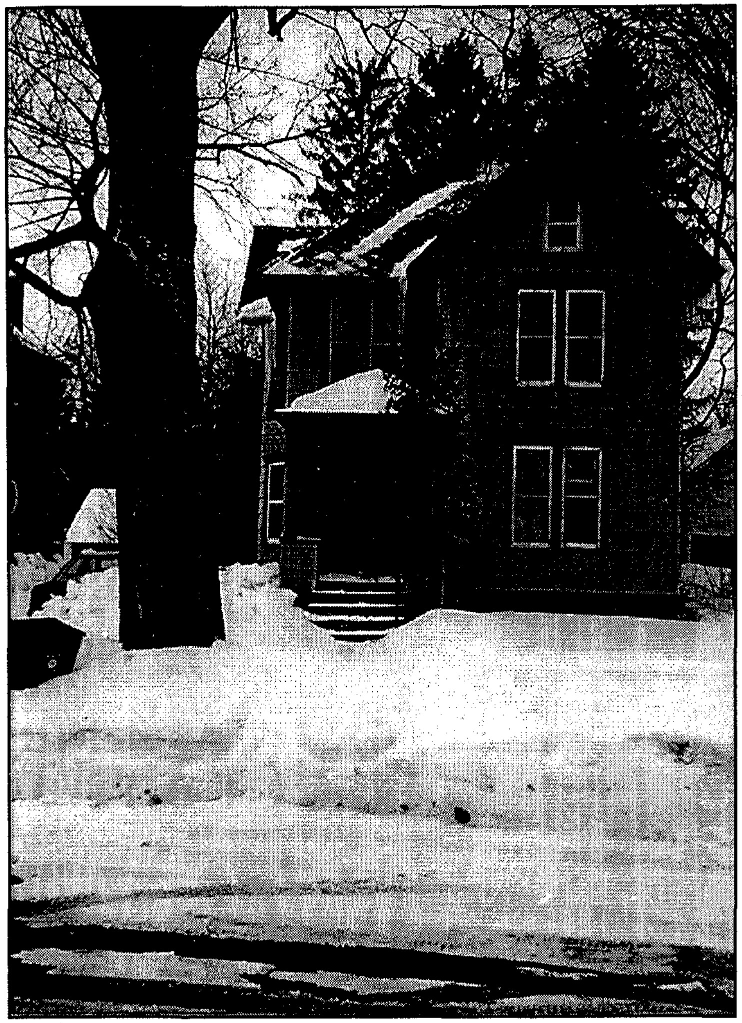
PROPERTY #5.2

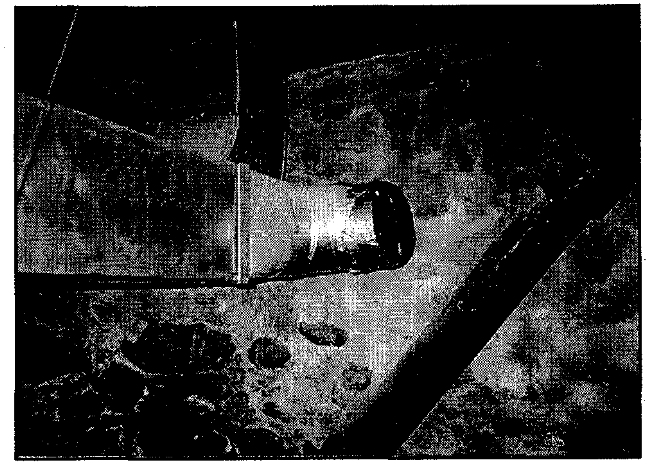
Total System Airflow

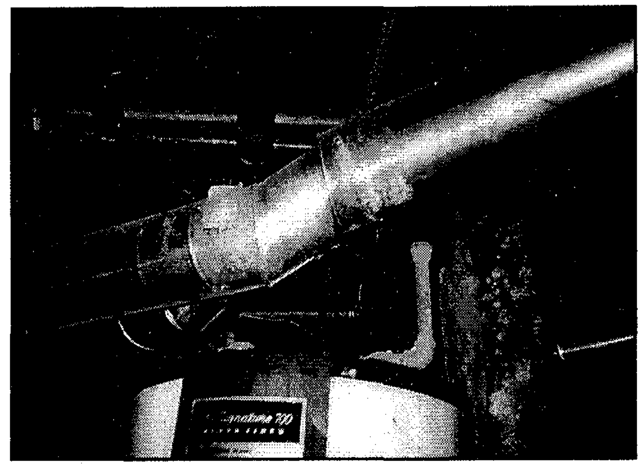
	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #2	583.3	668.8	645.6	842.3
Totals	583.3	668.8	645.6	842.3

Apartment Airflows

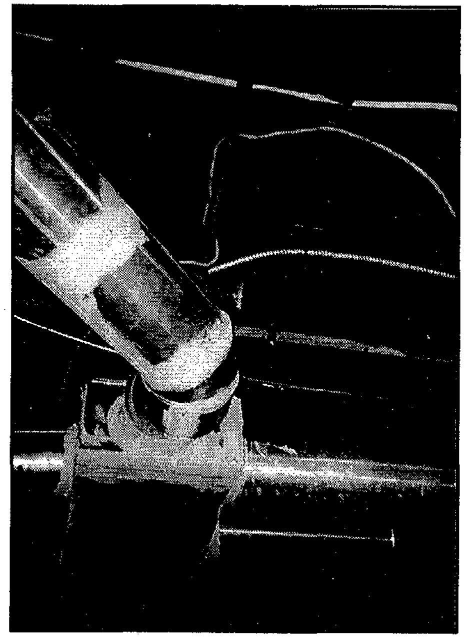
	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
2S3	54.6		61.4	
2S4	185.0		206.2	
2S5	179.5		188.0	
2S6	164.2		190.0	
2R1		668.8		842.3
Totals	583.3	668.8	645.6	842.3

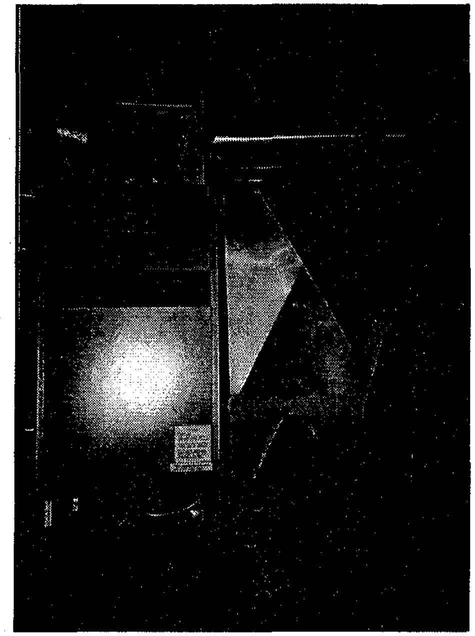

Property #6


Property #6 - Ductwork sealed with duct tape.

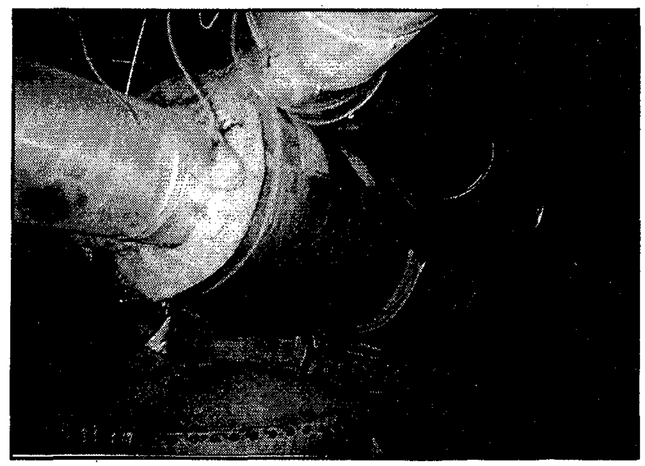

Property #6 - Broken duct.


Property #6 - Duct connection after retrofitting.

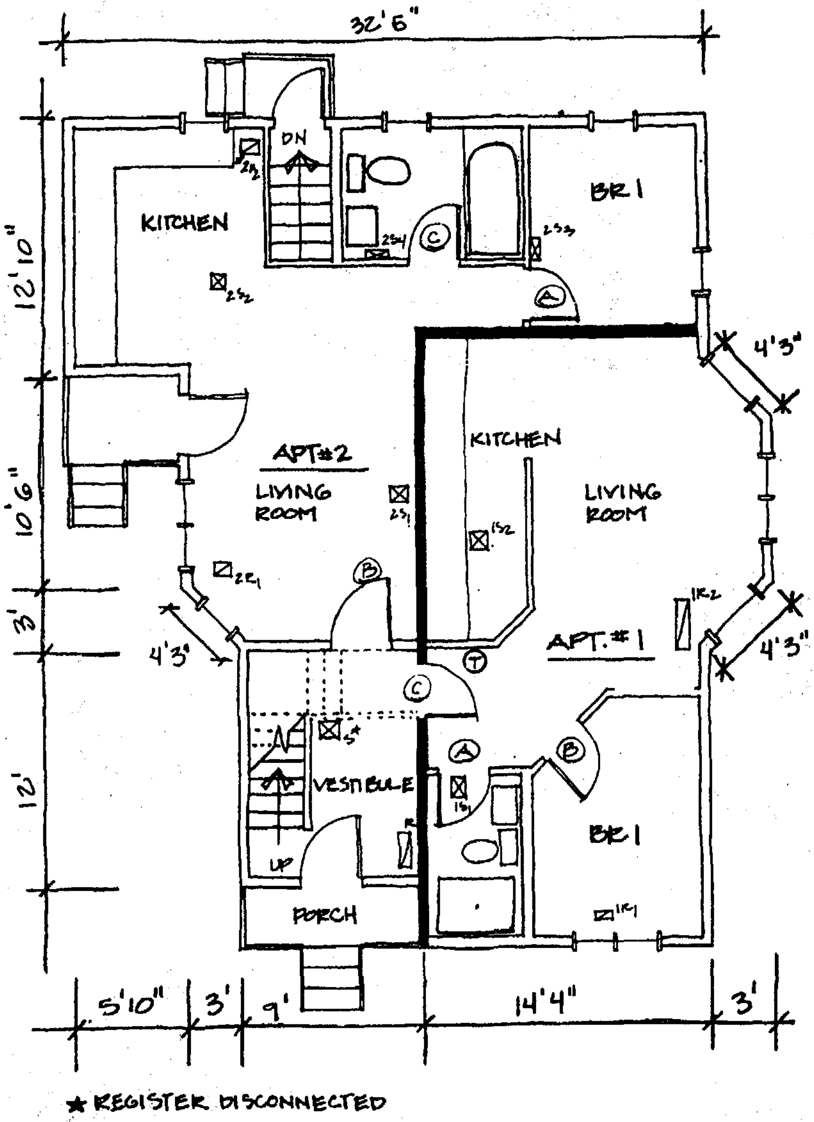

Property #6 - Ductwork after sealing.


Property #6 - Heating system.

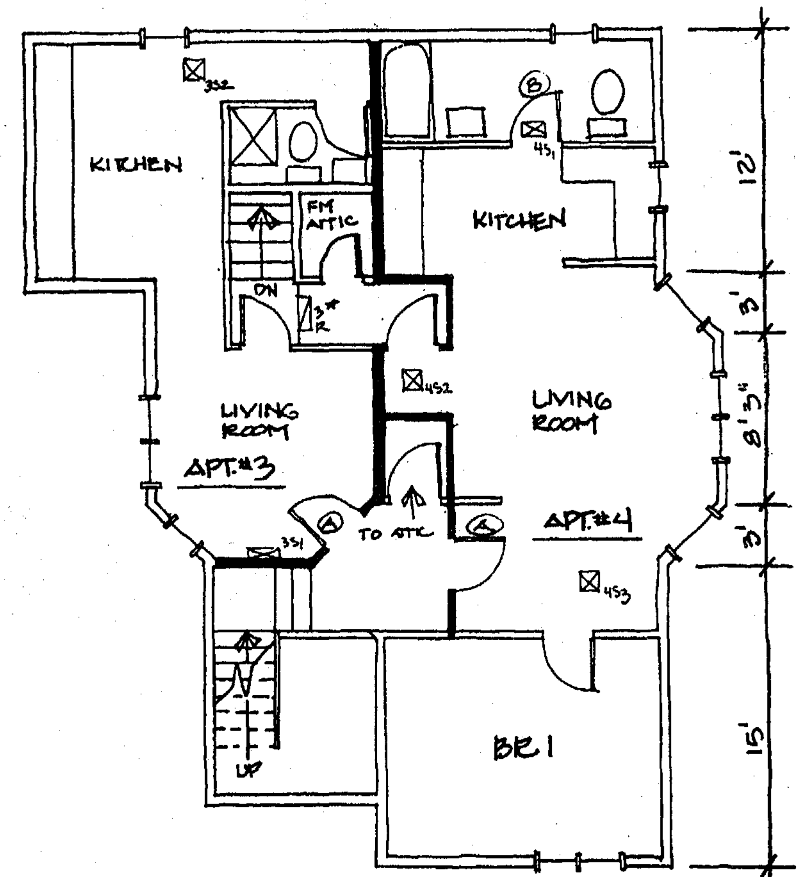

Property #6 - Disconnected ductwork. Duct connection before retrofitting.


Property #6 - One duct insulated.

Property #6
Apartments #1-2

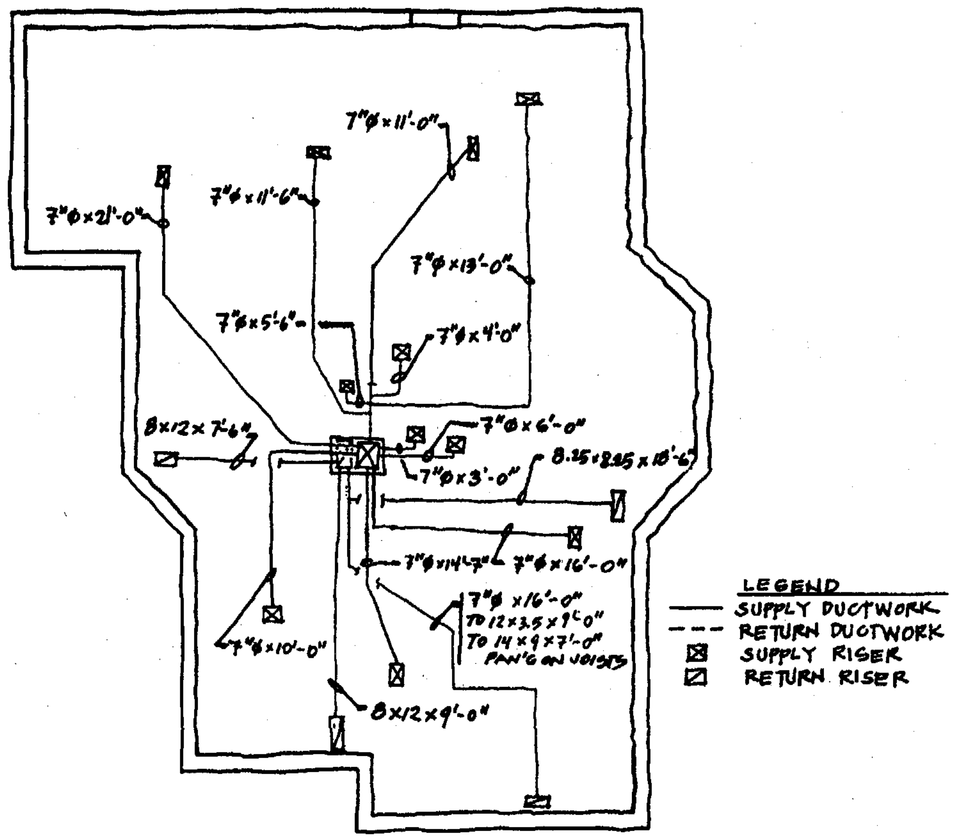


First Floor



Second Plan

Property #6



Duct Plan

PROPERTY #6

Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	198.0	198.3	241.4	224.1
Apt. #2	270.9	143.5	284.0	199.9
Apt. #3	53.1	108.3	54.2	191.0
Apt. #4	448.6	-	485.9	-
Totals	970.6	450.1	1065.5	615.0

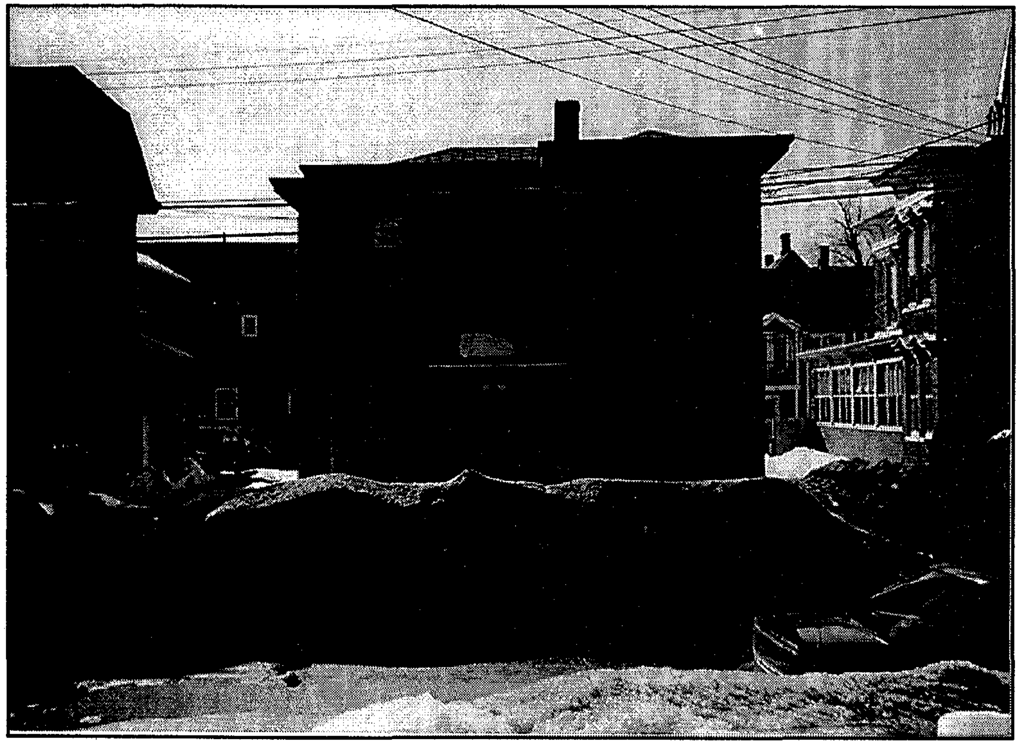
Apartment Airflows

Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
1S1	71.8		96.2	
1S2	126.2		145.2	
1R1		53.0		59.9
1R2		145.3		164.2
Totals	198.0	198.3	241.4	224.1

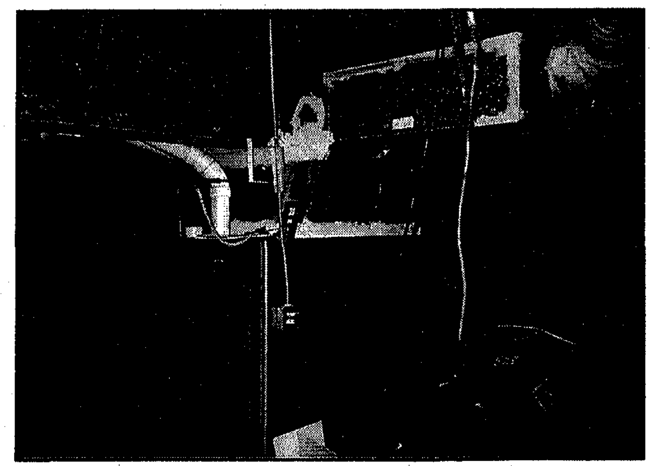
Apt. #2	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
2S1	78.1		87.3	
2S2	59.2		62.8	
2S3	87.4		86.5	
2S4	46.2		47.4	
2R1		143.5		199.9
Totals	270.9	143.5	284.0	199.9

Apt. #3	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
3S1	22.3		23.3	
3S2	30.8		30.9	
3R1		108.3		191.0
Totals	53.1	108.3	54.2	191.0

Apt. #4	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
4S1	172.5		181.6	
4S2	124.2		121.9	
4S3	151.9		182.4	
Totals	448.6		485.9	

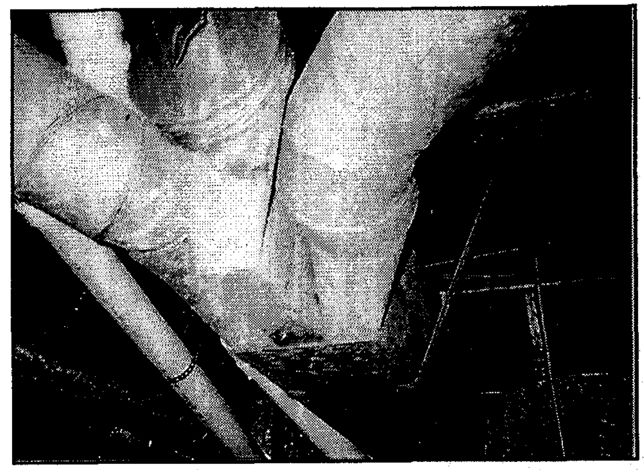


Property #7



Property #7 - Heating system; High efficiency condensing furnace.

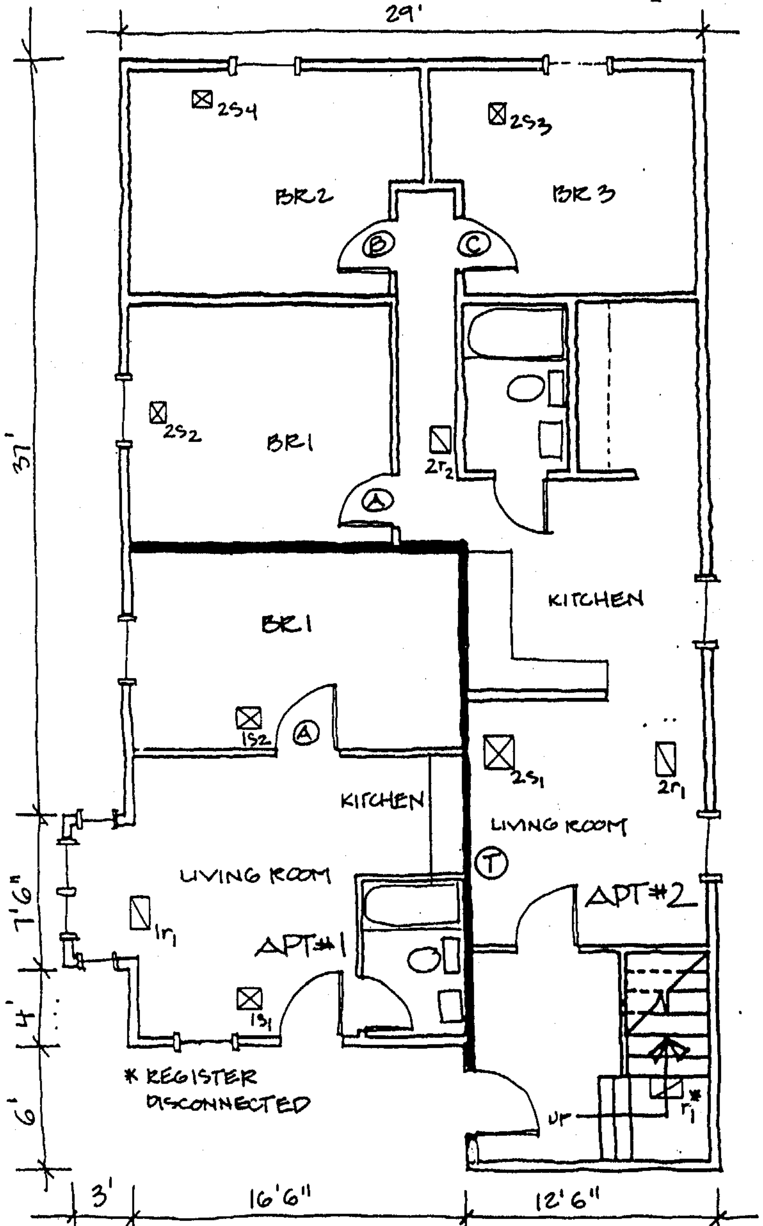
Property #7 - Ductwork sealed with duct tape.



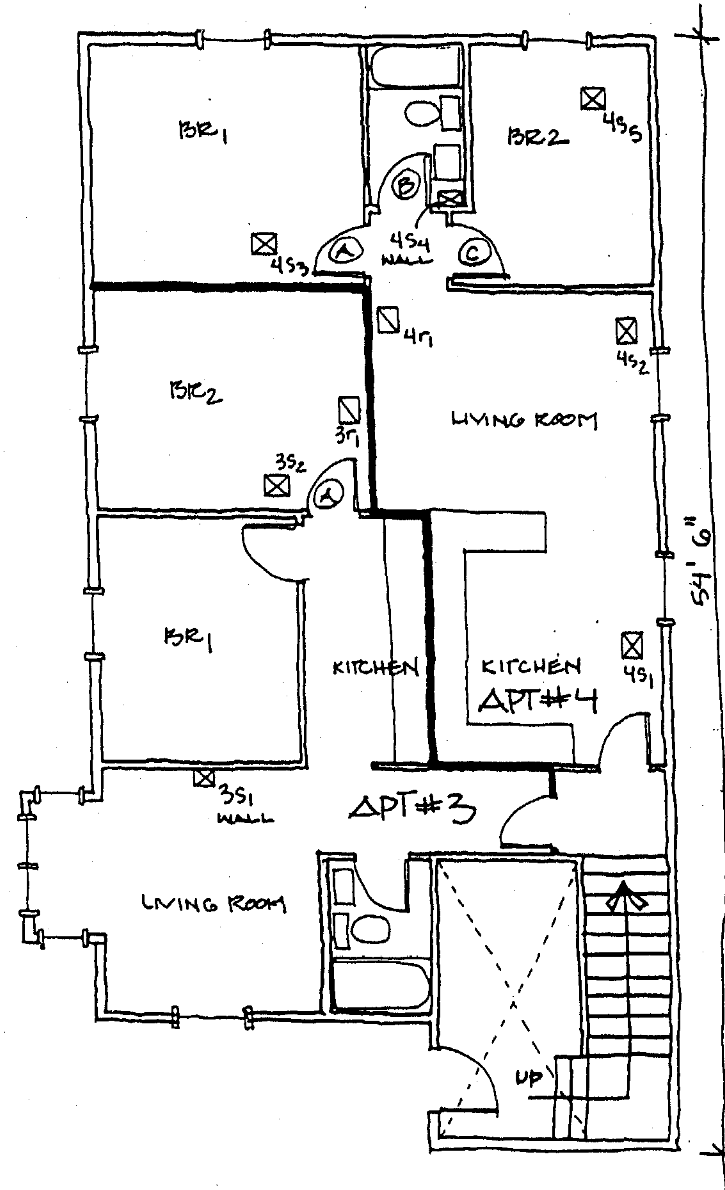
Property #7 - Supply duct branches.

Property #7 - End of return duct at the foundation wall.

Property #7
Apartments #1-4

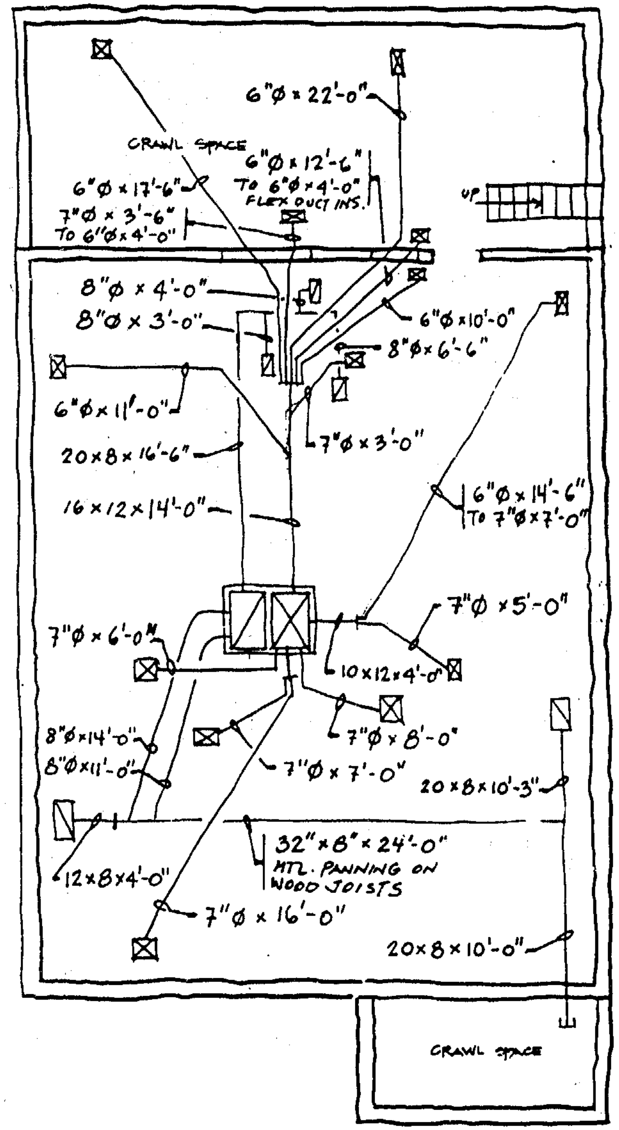


First Floor



Second Floor

Property #7



Duct Plan

PROPERTY #7

Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	239.0	159.0	244.3	172.2
Apt. #2	361.8	233.6	383.0	249.1
Apt. #3	189.0	74.7	199.1	79.3
Apt. #4	311.9	88.2	320.8	100.2
Totals	1101.7	555.5	1147.2	600.8

Apartment Airflows

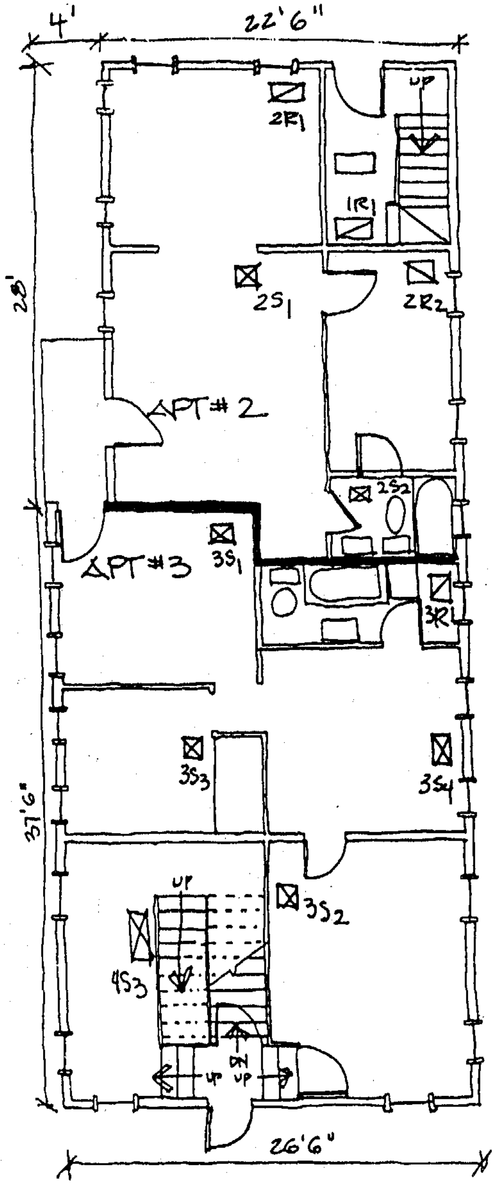
Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
1S1	167.9		177.4	
1S2	71.1		66.9	
1R1		159.0		172.2
Totals	239.0	159.0	244.3	172.2

Apt. #2	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
2S1	37.7		40.0	
2S2	109.0		120.1	
2S3	105.1		111.8	
2S4	110.0		111.1	
2R1		120.8		197.6
2R2		112.8		51.5
Totals	361.8	233.6	383.0	249.1

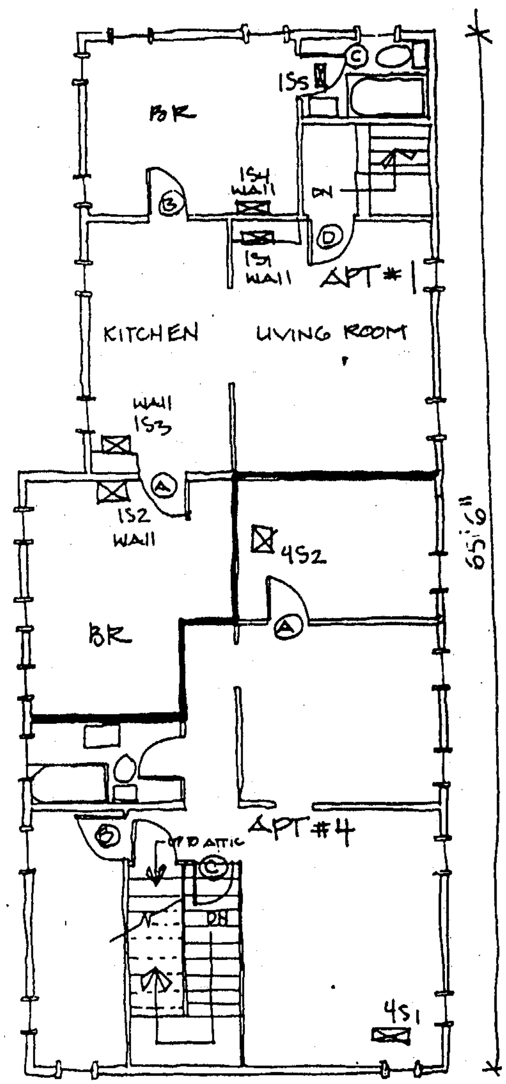
Apt. #3	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
3S1	155.1		162.0	
3S2	33.9		37.1	
3R1		74.7		79.3
Totals	189.0	74.7	199.1	79.3

Apt. #4	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
4S1	18.6		14.9	
4S2	102.3		103.8	
4S3	65.0		67.5	
4S4	87.0		93.5	
4S5	39.0		41.1	
4R1		88.2		100.2
Totals	311.9	88.2	320.8	100.2

Property #8
Apartments #1-4

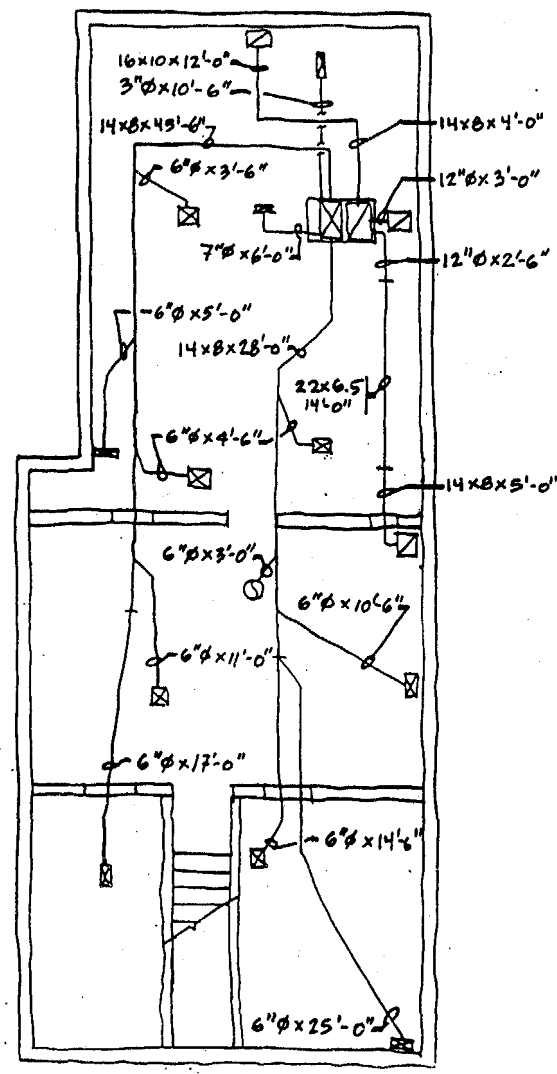


First Floor



Second Floor

Property #8



Duct Plan

PROPERTY #8

Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	258.4	378.3	307.5	552.7
Apt. #2	257.3	970.6	273.3	956.3
Apt. #3	594.4	193.1	683.4	244.0
Apt. #4	386.9	-	443.3	-
Totals	1497.0	1542.0	1707.5	1753.0

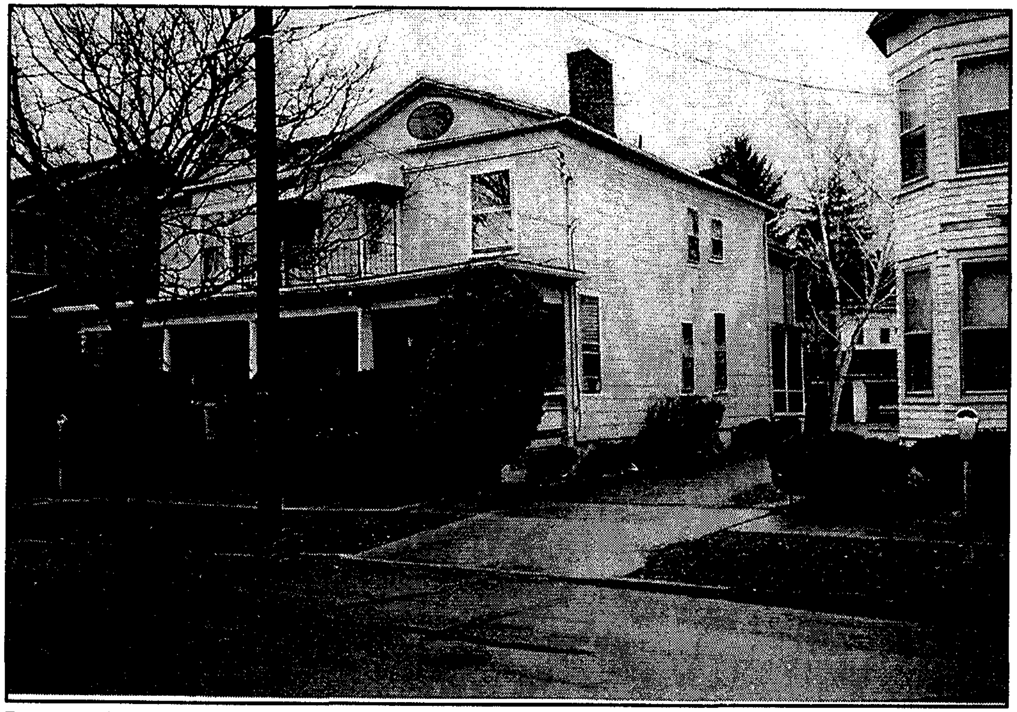
Apartment Airflows

Apt. #1	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
1S1	13.1		15.3	
1S2	33.0		37.9	
1S3	71.5		84.2	
1S4	140.8		156.4	
1S5	0.0		13.7	
1R1		378.3		552.7
Totals	258.4	378.3	307.5	552.7

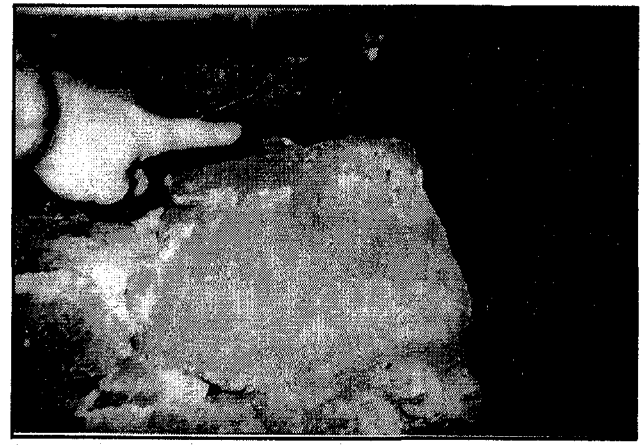
Apt. #2	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
2S1	154.3		161.7	
2S2	103.0		111.6	
2R1		121.3		125.8
2R2		849.3		830.5
Totals	257.3	970.6	273.3	956.3

Apt. #3	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
3S1	182.2		188.9	
3S2	110.3		168.8	
3S3	139.9		148.0	
3S4	162.0		177.7	
3R1		193.1		244.0
Totals	594.4	193.1	683.4	244.0

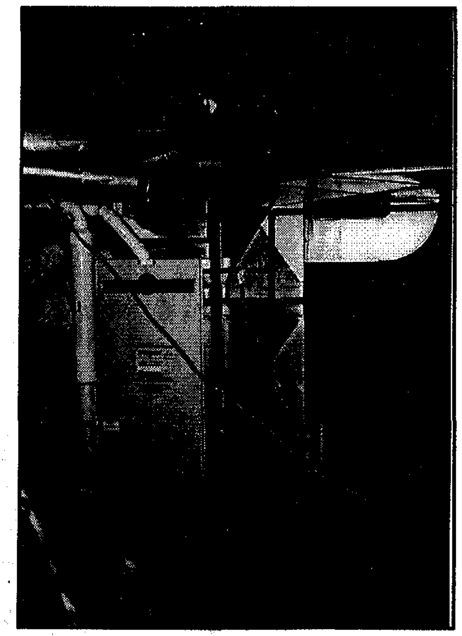
Apt. #4	Pre-Sealing		Post-Sealing	
Registers	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
4S1	36.8		41.9	
4S2	216.1		252.5	
4S3	134.0		148.9	
Totals	386.9	0.0	443.3	0.0



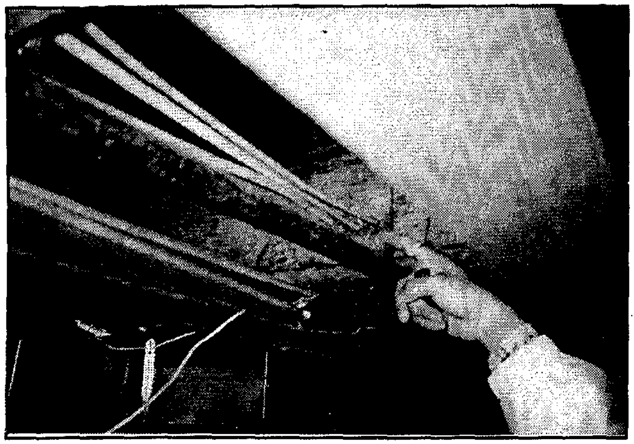
Property #9 - Front and side elevations.

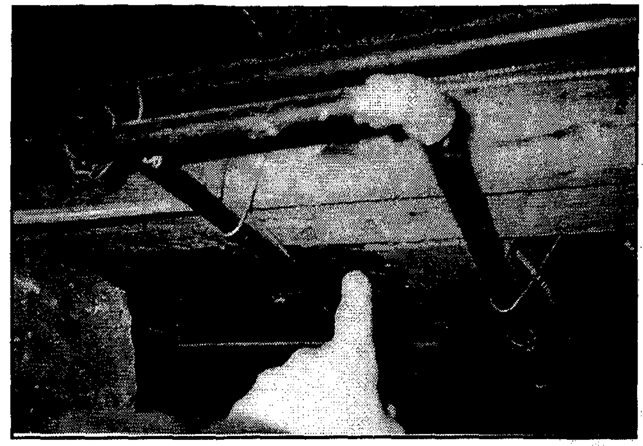


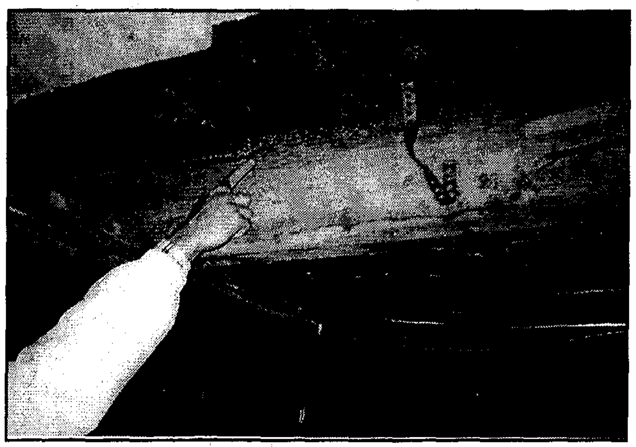
Property #9 - Return leak at the foundation wall.

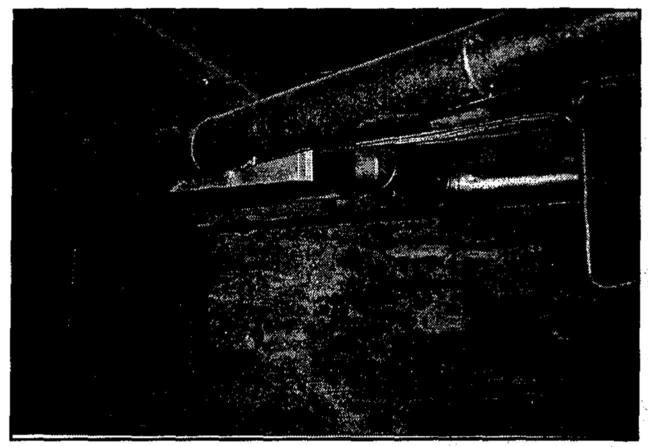


Property #9 - Heating System; High efficiency condensing furnace.

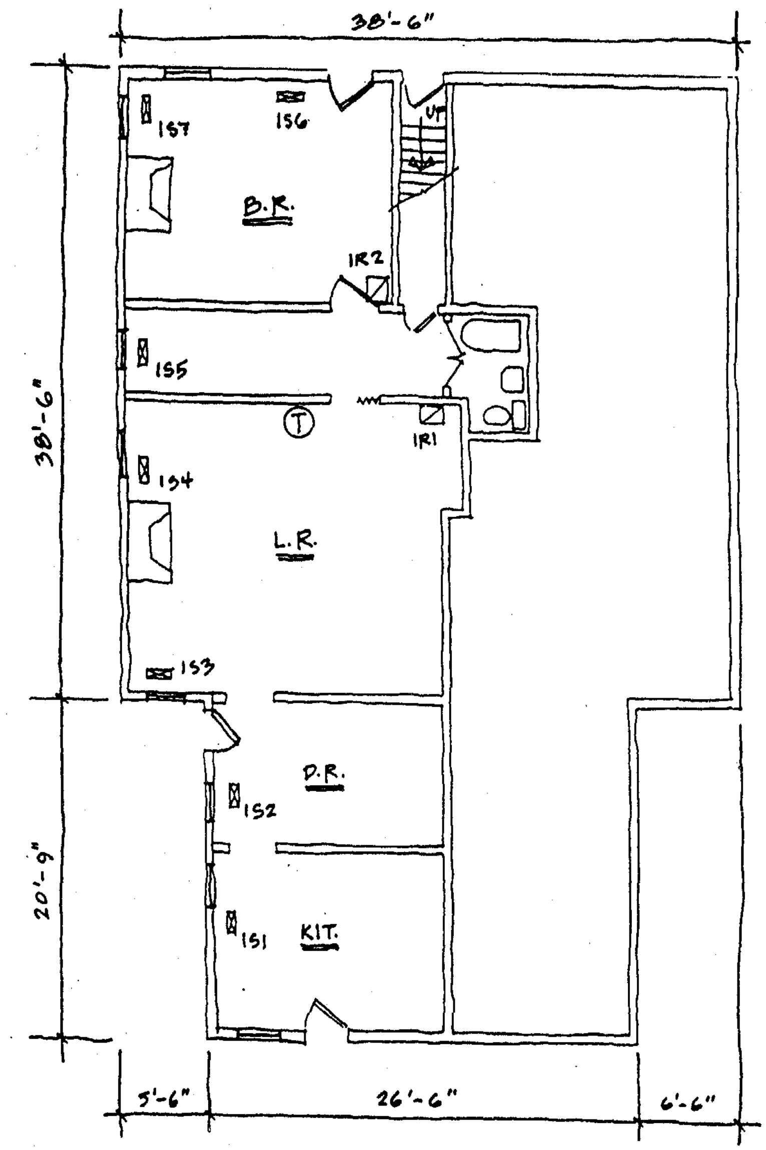

Property #9 - Holes in floor joist to run electrical systems.


Property #9 - Gaps in panning.


Property #9 - Gaps in wood flooring makes panning less effective.

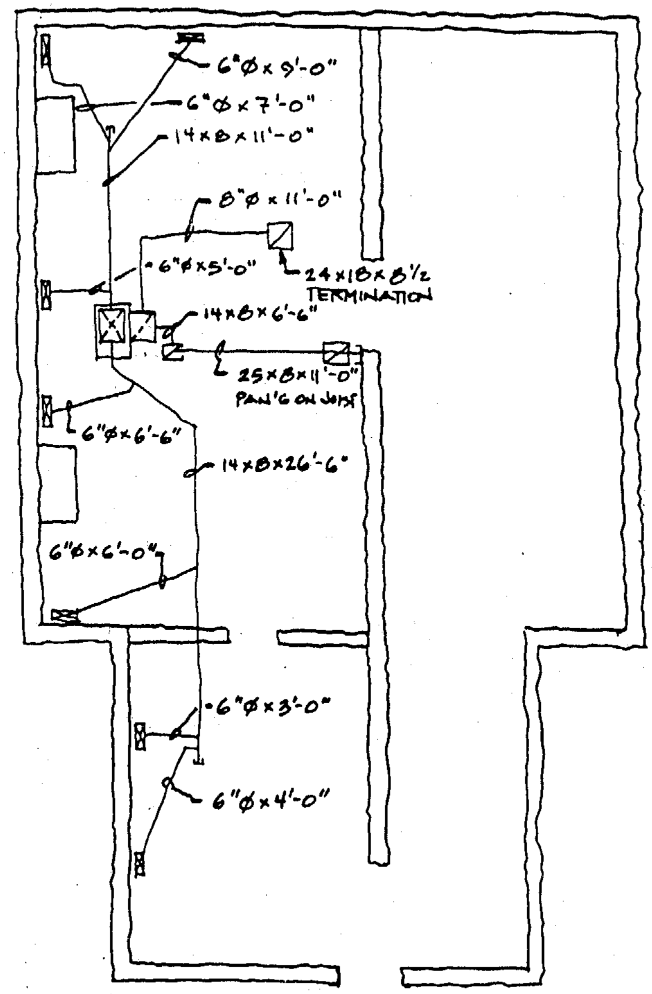

Property #9 - Supply duct branches.

Property #9
Apartment #1



First Floor

Property #9



Duct Plan

PROPERTY #9

Total System Airflow

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
Apt. #1	579.5	594.0	602.0	643.3
Totals	579.5	594.0	602.0	643.3

Apartment Airflows

	Pre-Sealing		Post-Sealing	
	Supply (cfm)	Return (cfm)	Supply (cfm)	Return (cfm)
1S3	128.7		143.6	
1S4	120.9		125.2	
1S5	87.4		93.4	
1S6	126.7		124.9	
1S7	115.8		114.9	
1R1		353.9		394.5
1R2		240.1		248.8
Totals	579.5	594.0	602.0	643.3

APPENDIX E

REFERENCES

REFERENCES

ASHRAE *Handbook of Fundamentals*, 1993

SMACNA *HVAC Duct Leakage Test Manual*, 1985

Cummings, J.B.; Tooley, J.J. Jr., 1989. "Infiltration and pressure differences induced by forced air systems in Florida residences," *ASHRAE Trans.,1989,* Vol. 95, Part 2.

Grot, R.A., and Harrje, D.T., 1981. "The transient performance of a forced warm air duct system," *ASHRAE Trans., 1981,* Vol. 88, Part 1.

Jakob, F.E., Locklin, D.W., Fischer, R.D., Flanigan, L.J., and Cudnik, R.A., 1986a. "SP43 Evaluation of System Options for Residential Forced-Air Heating," *ASHRAE Trans.*, 1986, Vol. 92, Part 2.

Jakob, F.E., Fischer, R.D., Flanigan, L.J., Locklin, D.W., Herold, K.E., and Cudnik, R.A., 1986b. "Validation of the ASHRAE SP43 Dynamic Simulation Model for Residential Forced-Warm-Air Systems," *ASHRAE Trans.*, 1986, Vol. 92, Part 2.

Lambert, L.A., Robison, D.H., 1989. "Effects of Ducted Forced-Air Heating Systems on Residential Air Leakage and Heating Energy Use," *ASHRAE Trans., 1989,* Vol. 95, Part 2.

Locklin, D.W., Herold, K.E., Fischer, R.D., Jacob, F.E. and Cudnik, R.A., 1987. "Supplemental Information from SP43 Evaluation of Systems Options for Residential Forced-Air Heating," *ASHRAE Trans., 1987,* Vol. 93, Part 2.

Modera, M.P., 1989. "Residential Duct System Leakage: Magnitude, Impacts, and Potential for Reduction," *ASHRAE Trans., 1989,* Vol. 95, Part 2.

Modera, M., Dickerhoff, D., Jansky, R., and Smith, R., 1991. "Improving the Energy Efficiency of Residential Air Distribution Systems in California, Final Report, Phase I," Lawrence Berkeley Laboratory Report, LBL-30886, Berkeley, CA

Parker, D.S., 1989. "Evidence of Increased Levels of Space Heat Consumption and Air Leakage Associated with Forced-Air Heating Systems in Houses in the Pacific Northwest," *ASHRAE Trans., 1989,* Vol. 95, Part 2.

Orlando, J.A., and Gamze, M.G., 1980. "Analysis of Residential Duct Losses," Final Report, GRI-79/0037, Gamze-Korobkin-Caloger, Inc., Contract No. 5011-341-0156, Chicago

Robison, D.H., Lambert, L.A., 1989. "Field Investigation of Residential Infiltration and Heating Duct Leakage," *ASHRAE Trans., 1989,* Vol. 95, Part 2.