Title
Field Measurement of the Interactions Between Heat Pumps and Attic Duct Systems in Residential Buildings

Permalink
https://escholarship.org/uc/item/0p0508nm

Authors
Modera, Mark P., Lawrence Berkeley National Laboratory
Jump, David A., Lawrence Berkeley National Laboratory

Publication Date
1994-11-01

LBL-36047
UC-1600

Field Measurement of the Interactions Between Heat Pumps and Attic Duct Systems in Residential Buildings

Mark P. Modera and David A. Jump

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

November 1994

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Existing Buildings Research Program and Building Equipment Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, by the California Institute for Energy Efficiency, and by the Sacramento Municipal Utility District.

ww

Field Measurement of the Interactions Between Heat Pumps and Attic Duct Systems in Residential Buildings

Mark P. Modera
Indoor Environment Program
Lawrence Berkeley Laboratory
Berkeley, CA 94720

David A. Jump
Indoor Environment Program
Lawrence Berkeley Laboratory
Berkeley, CA 94720

November, 1994

ABSTRACT

Research efforts to improve residential heat-pump performance have tended to focus on laboratory and theoretical studies of the machine itself, with some limited field research having been focused on in-situ performance and installation issues. One issue that has received surprisingly little attention is the interaction between the heat pump and the duct system to which it is connected. This paper presents the results of a field study that addresses this interaction. Field performance measurements before and after sealing and insulating the duct systems were made on three heat pumps. From the pre-retrofit data it was found that reductions in heat-pump capacity due to low outdoor temperatures and/or coil frosting are accompanied by lower duct-system energy delivery efficiencies. The conduction loss reductions, and thus the delivery temperature improvements, due to adding duct insulation were found to vary widely depending on the length of the particular duct section, the thermal mass of that duct section, and the cycling characteristics of the heat-pump. In addition, it was found that the use of strip-heat back-up decreased after the retrofits, and that heat-pump cycling increased dramatically after the retrofits, which respectively increase and decrease savings due to the retrofits. Finally, normalized energy use for the three systems which were operated consistently pre- and post-retrofit showed an average reduction of 19% after retrofit, which corresponds to a change in overall distribution-system efficiency of 24%.

NOMENCLATURE

C_P	is the specific heat of air, [kJ/kg K]
E	is HVAC energy consumption [J]
$F_{conduction}$	is the fractional conduction loss of air traveling through the duct system [-]
L	is the space conditioning energy load of a house [J]
$\dot{m}$	is the mass flow rate of air [kg/s]
T_{att}	is the attic temperature [°C]
T_{reg}	is the temperature at a supply register [°C]
T_{room}	is the temperature at the thermostat [°C]
$T_{ret\text{-}plen}$	is the temperature in the return plenum [°C]
$T_{sup\text{-}plen}$	is the temperature in the supply plenum [°C]
T_{out}	is the outside temperature [°C]
ΔT	temperature difference [K]
η_{del}	is the distribution-system delivery efficiency (EQ 1) [-]
η_{dist}	is the overall distribution system efficiency (EQ 3) [-]
η_{HP}	is the heat pump equipment efficiency [-]

Subscripts:

ducts	with duct system in place
no-ducts	without duct system in place
i	supply register index
n	total number of supply registers
post	post-retrofit period
pre	pre-retrofit period

INTRODUCTION

Research efforts to improve residential heat-pump performance have tended to focus on the machine itself, with some field research having been focused mainly on the impact of control strategies and sizing (Miller and Jaster 1985, Kao et al. 1987). A summary of field performance data on unitary heat pumps was compiled by Burke et al. (1986). More recently, Proctor and Pernick (Proctor 1990, Proctor and Pernick 1992) examined installation issues associated with residential heat pumps. An issue that has received surprisingly little attention is the interaction between the heat pump and the duct system to which it is connected. Over the past five years, inefficiencies in residential duct systems have been identified as a major source of energy loss in sunbelt homes (Cummings 1990, Davis and Roberson 1993, Modera and Jansky 1992, Modera 1993, Olson et al. 1993, Parker et. al 1993, Proctor 1991). This research has indicated that approximately 30-40% of the energy delivered to the duct systems passing through unconditioned spaces is lost through air leakage and conduction through the duct walls (Modera 1993, Olson et al. 1993), and that duct sealing can significantly impact those energy losses (Cummings et al. 1990, Davis and Roberson 1993, Proctor 1991). These duct losses can be particularly important for heat pumps, as: 1) duct losses can lead to increased use of electric resistance back-up, and 2) conduction losses (and leakage losses on the return side) decrease the temperature of the air leaving the registers, exacerbating the problem of “cold blow”.

This paper presents the results of a field measurement study that addresses the interactions between duct systems and residential heat pumps. The issues examined include both the impacts of the ducts on the performance of the heat pump, and the impact of the heat pump on the duct system. Field performance measurements before and after sealing and insulating the duct systems were made on three heat pumps.

THEORY

The formalism used to describe the various efficiencies associated with the complete heat pump system is described in more detail in Modera et al. (1992). In brief, two efficiencies for the duct system will be utilized: 1) the delivery efficiency (η_{del}), and 2) the overall distribution system efficiency (η_{dist}). The delivery efficiency represents the fraction of the heat pump's heating capacity that is actually delivered to the conditioned space via the supply registers, and includes the impact of leakage as well as conduction losses. It is important to note that these delivery efficiencies are not constant, but rather depend on the weather (via its impact on the temperatures in the buffer zones where the ducts are located), and on the capacity of the heat pump (which varies with outside temperature). The delivery efficiency can be defined for the entire distribution system, or for any particular duct. The system delivery efficiency is defined as:

$$\eta_{del} = \frac{\left(\sum_{1}^{n_{reg}} \dot{m}_i C_P (T_{reg(i)} - T_{room})\right)}{\dot{m}_{fan} C_P (T_{sup-plen} - T_{ret-plen})} \quad (1)$$

In addition, some components of the losses contributing to the delivery efficiency can be fairly well isolated. Specifically, the apparent conduction losses through the supply side ducts can be isolated reasonably accurately from leakage losses by means of the measured temperature drop through the supply ductwork and the temperature rise across the heat exchanger. As a modest amount of leakage on the supply side has a minimal impact on the temperature drop between the plenum and the registers, the fractional energy loss due to conduction is well approximated by:

$$F_{conduction} = \frac{(T_{sup-plen} - T_{reg})}{(T_{sup-plen} - T_{ret-plen})} \quad (2)$$

The overall distribution system efficiency (η_{dist}), includes all of the impacts of the distribution system on the HVAC energy consumption of the house, including the impact of the duct system on the loads, and on the efficiency of the heating/cooling equipment. In the case of a heat pump, where the indoor fan power is incorporated into the equipment efficiency, the distribution efficiency can be expressed as:

$$\eta_{dist} \equiv \frac{E_{no-ducts}}{E_{ducts}} = \eta_{del} \left(\frac{\eta_{HP_{ducts}}}{\eta_{HP_{no-ducts}}}\right) \left(\frac{L_{no-ducts}}{L_{ducts}}\right) \quad (3)$$

The the first term in parentheses in Equation 3 is meant to quantify all of the impacts of the duct system on the rated heat-pump performance, including changes in cycling of the equipment resulting from the addition of the duct system, as well as changes in heat-pump COP due to duct-system impacts on the entering flowrate or temperature seen by the heat-pump. The second term in parentheses includes the impact of the duct system on building infiltration rates, as well as recovery of duct losses to unconditioned spaces in the form of reduced loads associated with the building shell in contact with those spaces.

EXPERIMENTAL DESIGN AND METHODOLOGY

The field study results reported in this paper were obtained as part of a larger effort to investigate the impacts and costs of residential duct-system retrofits. The houses in the field study were chosen by the electric utility to have representative electricity consumption. An abbreviated description of the house characteristics is presented in Table 1.

Diagnostic tests were performed on the air distribution system both before and after the retrofits, and included measurements of: 1) air flows into return registers and out of supply registers, and 2) system-fan air flow. To measure the lower air flows found in residential systems, a flow capture hood was modified by attaching a calibrated fan to the free end and forcing all air across the fan's calibrated intake. The total pressure in the flow capture hood was maintained to be equal to the room pressure by adjusting the fan speed control. This insured that the pressure drop across the register would be the same during the measurement as it would be under normal system operation. System-fan air flows were measured with a constant injection tracer gas technique (ASTM Standard E741). Supply and return duct leakage airflows were determined from the difference between total supply and return register flows and the system fan flow. Total and static operational pressures were measured with a pitot tube.

In addition to the diagnostic tests, short-term monitoring (approximately 2 weeks before and after retrofit) of plenum, register, attic, house and outdoor temperatures, as well as heat-pump and strip-heat electricity demand was conducted. Fast-response thermistors were placed in each supply and return register, in the plenums and at the thermostat to monitor the temperatures during the four week monitoring period of the program. Four thermistors were placed in the supply plenum and their outputs were averaged. Thermistors were also placed outside, in the attic and in the crawlspace. The outside and attic temperatures were shielded with aluminum foil or reflective tubing to reduce radiation effects.

The power consumption of the heat-pump systems was monitored with clamp-on current transducers on the fan and compressor. The voltage output of each current transducer was calibrated with the actual power consumption measured by a wattmeter in a one-time test. It should be noted that although power factors are typically relatively stable, they can vary by 2-5% for a given machine based on changing operating conditions.

All sensors were connected to a central data acquisition system and computer which recorded the data on a 1-minute timestep and transferred each day's data to the laboratory nightly by cellular telephone. A quick scan of the plots in the morning was enough to uncover problems with the monitoring equipment as they arose. Details of the field measurement and retrofit protocols can be found in Jump and Modera (1994).

RESULTS

Four parameters derived from the field measurements are used to characterize the performance of the heat-pump systems: 1) the delivery efficiency of the full duct system (η_{del}), 2) the spatial (register to register) variability in the supply conduction component of the delivery efficiency ($F_{conduction}$), 3) the change in normalized HVAC energy consumption due to the retrofit (η_{dist}), and 4) the changes in equipment cycling and strip-heat use due to the retrofit.

Pre-Retrofit Delivery Efficiency

Focusing first on the performance of the heat pump systems prior to retrofit, the continuous monitoring data provides field verification of the dependence of duct-system delivery efficiency on heating-equipment capacity. This effect can be seen in Figure 1, in which the pre-retrofit delivery efficiency of the duct system in House 8 is plotted over the last four hours of a day. This particular period was chosen because it includes resistance backup operation as well as exceptionally long heat-pump on-cycles. Figure 1 includes plots of the absolute instantaneous delivery efficiency of the system, as well as the percentage changes in the delivery efficiency, the temperature difference between the supply ducts and the attic, and the capacity of the heat pump, all relative to their values at a reference point approximately 20 minutes before 8 P.M. Focusing on the long cycle starting just before 10 P.M., it is clear that the heat-pump capacity drops significantly during this cycle (apparently due to frosting of the outside coil, $T_{out} = 2^oC$), and that the delivery efficiency also drops during this period. It is also clear that the drop in the temperature differential across the supply ducts due to the capacity reduction does not make up for the reduction in efficiency stemming from the capacity reduction. To better understand this, one should remember that only a fraction of the losses from the duct system scale with the capacity of the equipment, several losses (i.e. return side leakage and conduction, and a portion of supply-side conduction) being independent of the capacity of the equipment. The effect of increasing the equipment capacity (due to strip-heat usage) can be seen in the time period just before 9 P.M. in Figure 1. In this case the delivery efficiency quickly decreases when the strip heat is turned on (due to the time lag between the registers and the supply plenum), and then proceeds to increase above the heat-pump-only value, and to overshoot due to thermal time lag of the ducts.

Duct Retrofits and Conduction Losses

Measurements of instantaneous conduction losses ($F_{conduction}$) in House 8 illustrate the large variability in the efficiency at different registers connected to the same heat pump. Referring to Figure 2, which is a schematic layout of the duct system in that house, Figure 3 is a plot of $F_{conduction}$ (for the same time period in Figure 1) for three bedrooms which differ in their distance from the supply plenum. Figure 3 makes it clear that: 1) conduction losses can be dramatic, 2) there may be serious non-uniformity of heating in this house, and 3) “cold blow” is likely to be an issue, particularly in the master bedroom. Figure 3 also reflects the drop in percentage conduction losses associated with the use of the strip-heat slightly before 9 P.M.

The duct systems to which the three heat pumps were connected were all insulated and sealed as part of the duct retrofit protocol being tested. As part of the retrofit, all of the heat-pump duct systems received an additional 5.1 cm (2 inches) of batt insulation, and were sealed with mastic to various extents, the level of sealing depending on the initial leakage level and the accessibility of the leaks. The added insulation should increase the thermal resistance of the ducts by approximately 1 m^2K/W. For both the pre and post retrofit periods, the measured flowrate across the indoor coil, the percentage of the supply and return side flows that were passing through duct leaks (obtained by subtraction of fan and register flows), and the observed insulation value of the duct systems are summarized in Table 2.

Table 2 indicates that the duct systems to which the heat pumps were connected were fairly typical (see Modera 1993). Plastic flex-duct with one inch of fiberglass insulation is by far the dominant systemtype in the U.S. sunbelt, and 20% leakage on the supply and return side is consistent with leakage measurements from larger field studies (Cummings 1990, Davis and Roberson 1993, Modera 1993, Olson et al. 1993). Concerning the heating equipment, design air flowrates typically call for approximately 210 m^3/hr. per kW of heating capacity. Examination of Table 2 reveals that two of the three systems air flowrates were significantly lower than this.

The impact of the retrofit on conduction losses is illustrated for House 8 in Figure 4 and in Table 3. Figure 4, which presents post-retrofit conduction losses for weather conditions similar to those for Figure 3, illustrates that the conduction losses are disproportionately reduced for the higher-loss duct runs, and that heat pump cycling seems to increase dramatically after the retrofit. Table 3 presents a snapshot view of conduction losses and register temperatures at the end of system cycles under essentially identical attic temperature conditions. Table 3 makes it clear that the retrofit, in addition to improving the energy performance of the heat-pump, improved the uniformity of the heating, and reduced or eliminated the "cold-blow" effect.

Retrofit Impacts on Heat-Pump Operation

As was noted in the previous section, the duct-system retrofit seemed to increase the cycling of the heat-pump in House 8 (see Figures 3 and 4). Table 4 presents a more complete analysis of this effect, summarizing the average number of cycles per hour of the three heat pumps pre- and post-retrofit. Table 4, which includes the entire data set for all of the houses binned by indoor-outdoor temperature difference, makes it clear that the retrofit significantly increases heat-pump cycling. It should be noted however, that the increased cycling may reduce the probability of frosting of the exterior coil, which seemed to be occurring during the longer on-periods in Figure 3.

In addition to changing the cycling of the heat pumps, the duct-system retrofits also impacted the use of strip-heat back-up. To illustrate this effect, HVAC energy use for pre- and post-retrofit periods with essentially equal weather conditions were compared for House 6. The results, summarized in Table 5, show a significant impact of the retrofit on the use of strip-heat back-up. These results further illustrate that the sizing of the heat pump will have a significant impact on magnitude and direction of interactions with the duct system.

Table 5 illustrates two other interactive effects of duct retrofits. The first is the impact of the duct retrofit on the attic temperature, which is seen to decrease by approximately 1.5°C due to the reduced duct losses to the attic as a result of the retrofit. The second is the change in return plenum temperature resulting from the reduction in heat losses and entrainment of cold attic air on the return side. This increase in entering temperature should decrease the efficiency of the heat pump.

Retrofit Impacts on HVAC Energy Use and Distribution Efficiency

Given the various counteracting interactions between the duct retrofits and the heat pumps that have been quantified, the key issue at this point is to quantify the overall impacts of the retrofits on overall HVAC energy use and overall distribution-system efficiency (η_{dist}). To accomplish this, the energy consumption was determined on an hourly basis by integrating power demand over each hour, and T_{room} - T_{out} was averaged on the same hourly basis. Both the energy consumed in each hour and the hourly averaged temperature differentials were plotted as a function of the hour of the day. Each of these scatterplots was then fit with a cubic spline, and the ratio of the two fitted curves calculated for each hour of the day for both pre- and post-retrofit data. The normalized energy savings was then calculated as $[(E/\Delta T)_{pre}-(E/\Delta T)_{post}]/(E/\Delta T)_{pre}$ for each hour of the day. The 24-hour average values for these savings, and their coefficients of variation (standard-deviation/mean-value), are summarized in Table 6.

DISCUSSION

The fact that average delivery efficiencies before and after retrofit are not reported in this paper merits some discussion. The reason for their absence is the complexity introduced by duct-system thermal mass on the calculation of delivery efficiency and conduction losses. More specifically, although there were often long heat-pump on-cycles from which steady-state delivery efficiencies could be determined for the pre-retrofit periods, obtaining these numbers for the post-retrofit periods was much more problematic. The problems stemmed from the fact that the higher duct-system efficiencies in the post-retrofit periods translate into shorter heat-pump on-times, and that the improved ducts have longer time constants. The implication of these combined effects is that there is little or no steady-state operation in the post-retrofit periods, which implies that delivery efficiencies tend to be underestimated, and conduction losses tend to be overestimated for these periods.

Although a straight-forward analysis of the data indicated that delivery efficiencies generally increased due to the retrofits, the negative bias of the post-retrofit delivery efficiencies became apparent when the delivery efficiency improvements were compared with the distribution efficiency improvements. A more sophisticated dynamic analysis procedure for the data is presently under development.

One other point worth raising relative to duct dynamics is that there is a delicate balance of factors that determine whether or not the overall negative impact of duct dynamics will increase or decrease after the retrofits. On the one hand, the number of cycles and the total thermal mass of the ducts are increased, both of which would tend to increase dynamic losses in the post-retrofit situation. On the other hand, a larger fraction of the duct energy storage is likely to be returned to the conditioned space between cycles due to the improved thermal resistance between the duct system and its surroundings.

CONCLUSIONS

Based upon the results presented above, it is safe to conclude that duct-system performance significantly impacts the performance of heat pumps, and that the operating characteristics of heat pumps significantly impact duct-system performance. First, the measurements presented made it clear that the efficiency of the duct system varies inversely with the capacity of the heat-pump, including capacity changes associated with frosting and strip heat use. Our field measurements also made it clear that the reduction in load associated with improved duct systems has two counteracting impacts on heat-pump performance. On the one hand, the reduced load results in less strip-heat use, resulting in a higher heating-plant efficiency. On the other hand, the reduced loads increase cycling of the heat-pump compressor, which reduces its efficiency. These results point out the importance of taking into account duct-system efficiency when sizing heat pumps.

The field test results also allow us to conclude that duct-system efficiency improvements can result in significant HVAC energy savings for residential heat-pump systems. Including all of the interactions between the heat pump, the house, and the duct-system improvements, the overall weather-normalized energy savings for the two-week monitoring periods ranged between 14 and 24%.

In addition to the energy benefits of improving duct-system efficiencies, our results suggest that significant thermal-comfort benefits can be accrued as a result of the retrofits performed. One benefit that should occur for any heating or cooling system, and which was documented for the systems reported here, is an improvement in the uniformity of register temperatures during system operation, and by implication an improvement in the uniformity of thermal conditions in different zones. There appears to be another thermal comfort benefit of duct repair which is particular to heat pumps. Namely, as heat pumps have been known to suffer from uncomfortable air delivery temperatures, any increases in delivery temperatures can be seen as a thermal comfort benefit. Our results suggest that delivery temperatures can be increased by 1-2 K as a result of the duct system retrofit. Finally, another comfort issue that may be somewhat resolved by duct-system efficiency improvements is perception of cold drafts. As increased duct insulation should increase the temperature of thermosiphon flows through the duct system and into the rooms during the off-cycle, the occurrence of drafts (or perceived drafts) may also be reduced by the retrofit. This effect will be examined as part of future analyses of the data collected.

REFERENCES

ASTM Standard E741-83, 1994, "Standard Test Method for Determining Air Leakage Rate by Tracer Dilution", ASTM Book of Standards, American Society of Testing and Materials, Vol 04.07.

Burke, J.C., Fitzgerald, K.F., Frantzis, L., 1985, "Summary and Evaluation of Field Performance Data on Unitary Heat Pumps", Oak Ridge National Laboratory Report ORNL/Sub/85-00219/1.

Cummings, J.B., Tooley, J.J. Jr. and Dunsmore, R., 1990. "Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes", Proceedings of ACEEE Summer Study, Pacific Grove, CA, August 1990, American Council for an Energy Efficient Economy, 1001 Connecticut Ave. N.W., Suite 535, Washington D.C. 20036.

Davis, B.E. and Roberson, M.R., 1993, "Using the 'Pressure Pan' Technique to Prioritize Duct Sealing Efforts: A Study of 18 Arkansas Homes", *Energy and Buildings*, Vol. 20, No. 1(1993) pp 57-64.

D.A. Jump and M.P. Modera, 1994, "Impacts of Attic Duct Retrofits in Sacramento Houses", Proceedings of ACEEE Summer Study, Pacific Grove, CA, Lawrence Berkeley Laboratory Report, LBL-35375.

Kao, Y.K., Mulroy, W.J. and D.A. Didion, 1987, "Field Performance of Three Residential Heat Pumps in the Heating Mode", NBSIR 87-3528. Gaithersburg, MD: National Bureau of Standards.

Miller, R.S., and Jaster, H. 1985, "Performance of Air-Source Heat Pumps", Electric Power Research Institute, Palo Alto, CA, EPRI EM-4226 Project 1495-1 Final Report, November 1985.

M.P. Modera, J. Andrews, E. Kweller, 1992, "A Comprehensive Yardstick for Residential Thermal Distribution Efficiency", Proceedings of ACEEE Summer Study, Pacific Grove, CA, Lawrence Berkeley Laboratory Report, LBL-31579.

Modera, M.P. and Jansky R., 1992., "Residential Air Distribution Systems: Interactions with the Building Envelope", Proceedings of ASHRAE/DOE Conference *Thermal Performance of the*

Exterior Envelopes of Buildings V, Clearwater FL, Lawrence Berkeley Laboratory Report LBL-31311.

Modera, M.P. 1993, "Characterizing the Performance of Residential Air Distribution Systems", *Energy and Buildings*, Vol. 20, No. 1 pp 65-75, Lawrence Berkeley Laboratory Report LBL-32532.

Olson, J.R., Palmiter, L., Davis, B., Geffon, M. and Bond, T., 1993. "Field Measurements of the Heating Efficiency of Electric Forced-Air Systems in 24 Homes", Bonneville Power Administration, DOE/BP-23303-1.

Parker, D., Fairey, P. and Gu, L., 1993, "Simulation of the Effects of Duct Leakage and Heat Transfer on Residential Space-Cooling Energy Use", *Energy and Buildings*, Vol. 20, No. 2, pp 97-114.

Proctor, J.P. and Pernick, R.K., 1992. "Getting it Right the Second Time: Measured Savings and Peak Reduction from Duct and Appliance Repairs", Proceedings of ACEEE Summer Study, Pacific Grove, CA, August 1992 American Council for an Energy Efficient Economy, 1001 Connecticut Ave. N.W., Suite 535, Washington D.C. 20036.

Proctor, J.P., Davids, B., Jablonski, F., and Peterson, G., 1990 "Pacific Gas and Electric Heat Pump Efficiency and Super Weatherization Pilot Project: Final Report", Proctor Engineering Group, 5725 Paradise Dr. Corte Madera, CA, 94925.

J. Proctor, "Pacific Gas and Electric Appliance Doctor Pilot Project: Final Report Summer 1990 Activity", January 8, 1991, Proctor Engineering Group, 5725 Paradise Drive, Suite 820, Corte Madera, CA 94925.

TABLE 1. Basic Characteristics of the Three Houses/Systems Tested

House ID	Year of Construction	Floor Area [m^2]	Duct Surface Area [m^2]	Nominal HP Heating Capacity [kW]
6	1988	200	41	14
8	1985	135	30	7
10	1957	223	47	12.3

TABLE 2. PRE_ AND POST_ RETROFIT DUCT SYSTEM CHARACTERISTICS FOR THREE HEAT-PUMP SYSTEMS

Parameter	Retrofit Status	House 6	House 8	House 10
Flowrate Across the Heat-Pump Indoor Coil [m^3/h @ 20°C/kW (cfm @68°F/ton) nominal heating capacity]	Pre-	142 (292)	187 (385)	118 (242)
Return Register Flow/ Fan Flow [%]	Pre-	76	97	65
	Post-	93	89	87
Supply Register Flow/ Fan Flow [%]	Pre-	79	86	58
	Post-	85	90	72
Nominal Duct System Insulation Value[a] [m^2 K/W]	Pre-	0.7	0.7	0.7
	Post-	1.8	1.8	1.8

[a] All ducts were manufactured plastic flex-duct with 5 cm of insulation.

TABLE 3. Snapshot Comparison of Register Temperatures and Conduction Losses Pre and Post Retrofit for House 8

	Pre-Retrofit	Post-Retrofit
Time of Day	11:54 pm	9:36 pm
Zone Temperatures, °C:		
Outside	2.0	5.2
Attic	7.6	7.7
Inside	20.7	20.3
Register Temperatures, °C:		
Master Bedroom	26.0	31.1
Bedroom 1	27.8	31.5
Bedroom 2	28.7	32.3
Plenum Temperatures, °C:		
Supply Plenum	29.9	33.5
Return Plenum	21.4	21.4
Conduction Losses, %		
Master Bedroom	46	20
Bedroom 1	24	17
Bedroom 2	14	10

TABLE 4. **Impact of Retrofits on Equipment Cycling (Houses 6, 8 and 10)**

Parameter	Indoor/Outdoor Temperature Differential, [K]				
	5.6 - 8.3	8.3 - 11.1	11.1 - 13.9	13.9 - 16.7	16.7 - 19.4
Average Number of Pre-Retrofit Cycles/ Hour	0.89	1.16	1.05	1.07	0.60
Average Number of Post-Retrofit Cycles/Hour	0.88	1.23	1.49	1.53	1.32
Post/Pre Ratio	0.99	1.06	1.42	1.43	2.20

TABLE 5. **COMPARISON OF HVAC ENERGY USE PRE AND POST RETROFIT FOR HOUSE 6 BETWEEN 4-10 AM**

Parameter	Pre-Retrofit	Post Retrofit
Strip Heat Energy Use [kWh]	3.3	0.5
Compressor and Fan Energy Use [kWh]	13.8	12.0
Total HVAC Energy Use [kWh]	17.1	12.5
Average Attic Temperature [^{o}C]	8.0	6.7
Average Outside Temperature [^{o}C]	7.2	7.5
Average Return Plenum Temperature [^{o}C]	19.3	20.3

TABLE 6. **IMPACT OF RETROFITS ON HVAC ENERGY USE AND DISTRIBUTION EFFICIENCY**

House ID	Change in Temperature-Normalized Energy Use [%]		Mean Change in η_{dist} [%]
	Mean	Coefficient of Variation	
6	-20	37	25
8	-14	117	16
10	-24	19	32

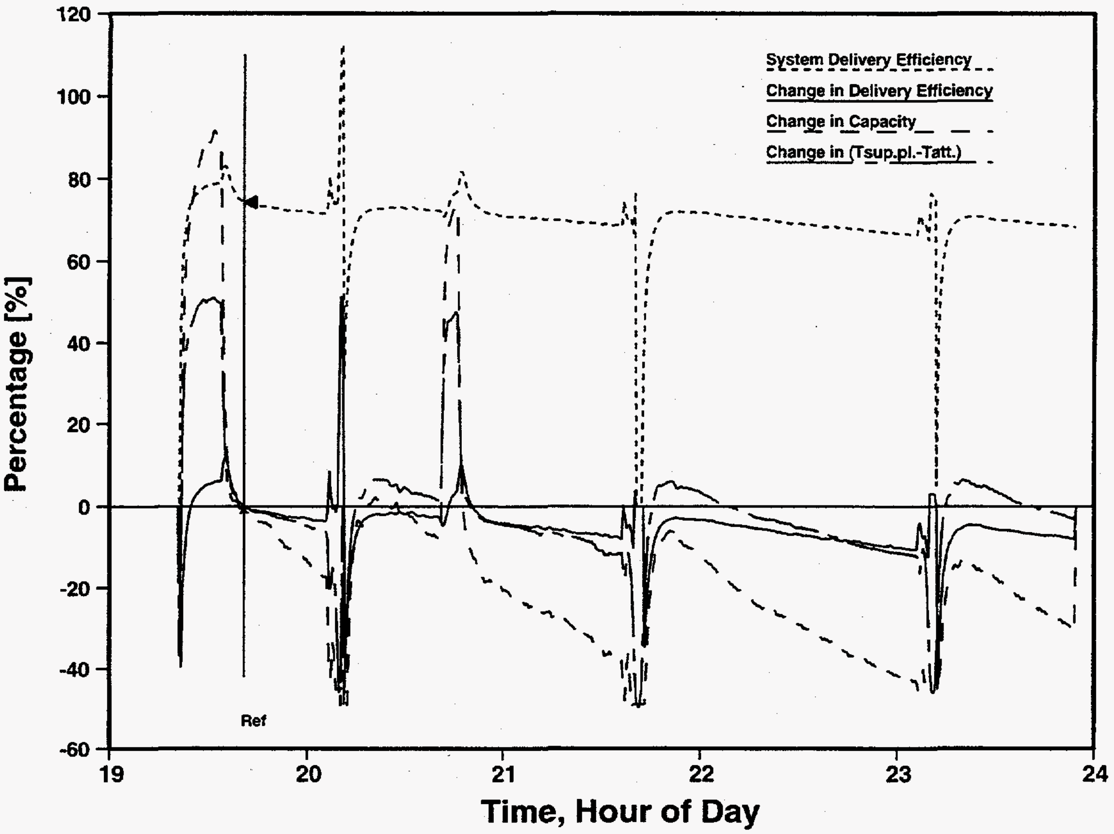

FIGURE 1. PRE-RETROFIT DUCT SYSTEM DELIVERY EFFICIENCY (η_{DEL}) AS A FUNCTION OF TIME FOR HOUSE 8. ALSO, PERCENTAGE CHANGES IN THAT EFFICIENCY, IN THE CAPACITY OF THE HEAT PUMP, AND IN THE TEMPERATURE DIFFERENTIAL ACROSS THE SUPPLY DUCTS, ALL WITH RESPECT TO THEIR VALUES AT 19:40.

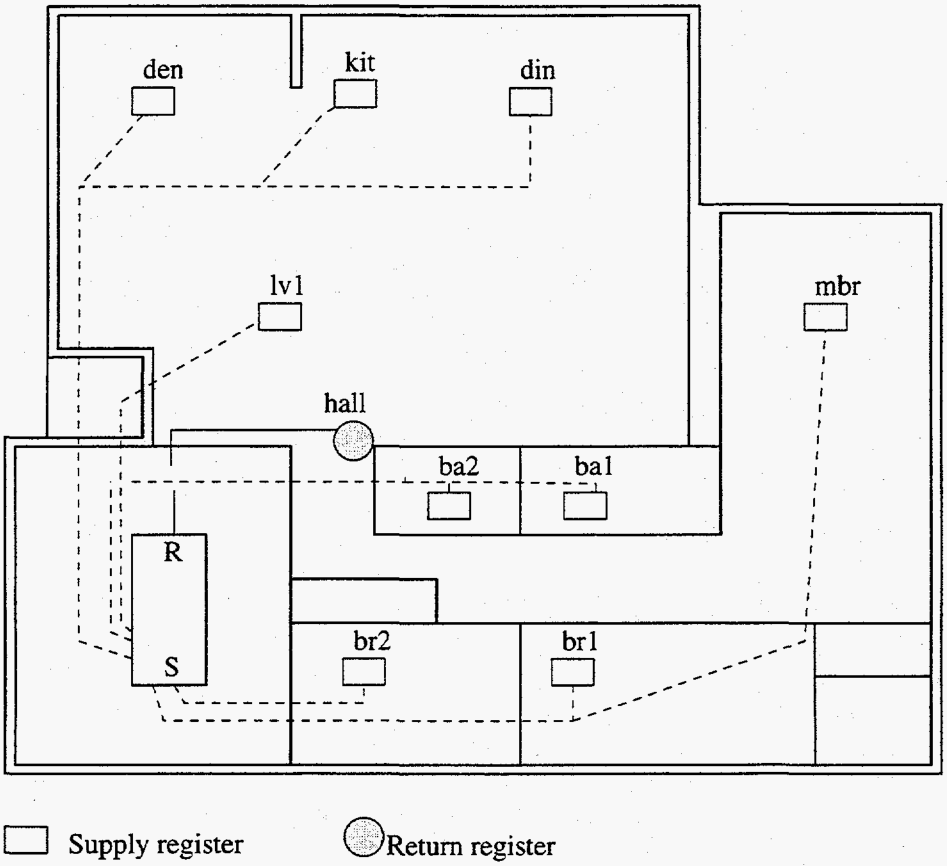

FIGURE 2.SCHEMATIC OF DUCT SYSTEM LAYOUT IN HOUSE 8.

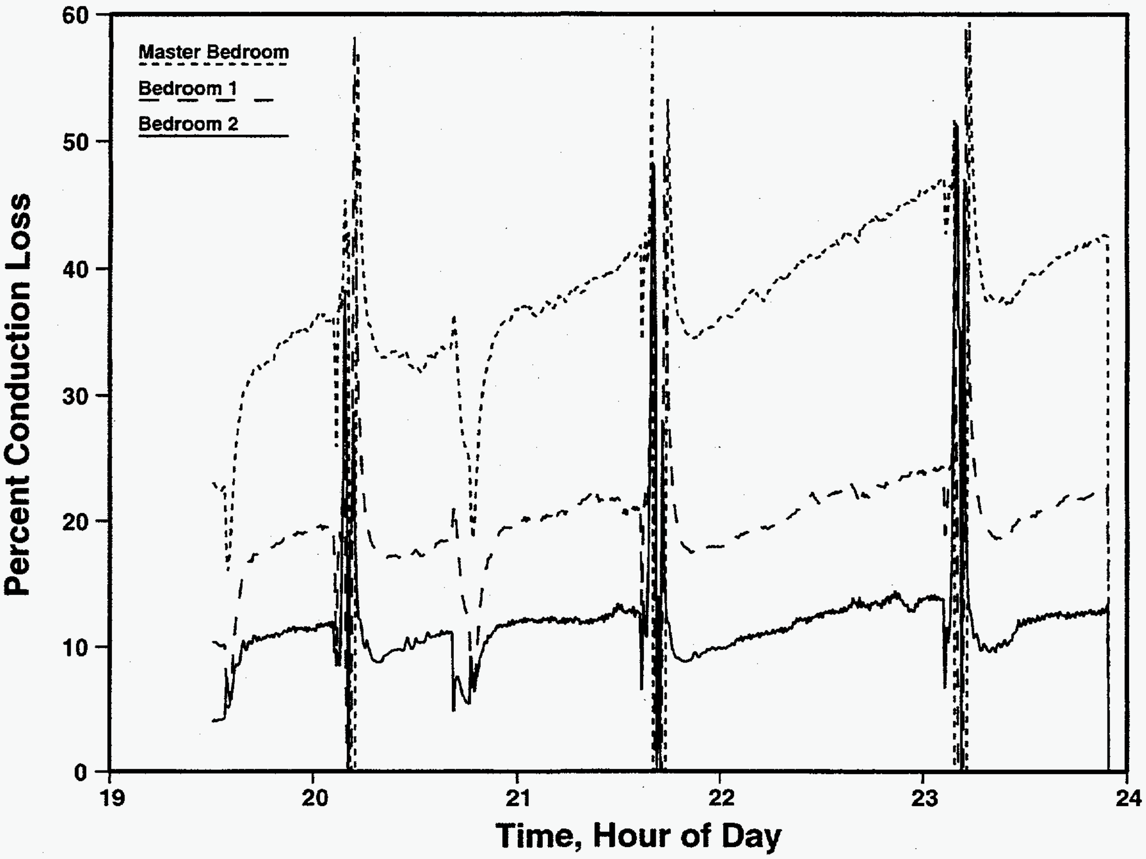

FIGURE 3.PRE-RETROFIT PERCENTAGE CONDUCTION LOSSES, $F_{CONDUCTION}$, FOR THREE REGISTERS IN HOUSE 8.

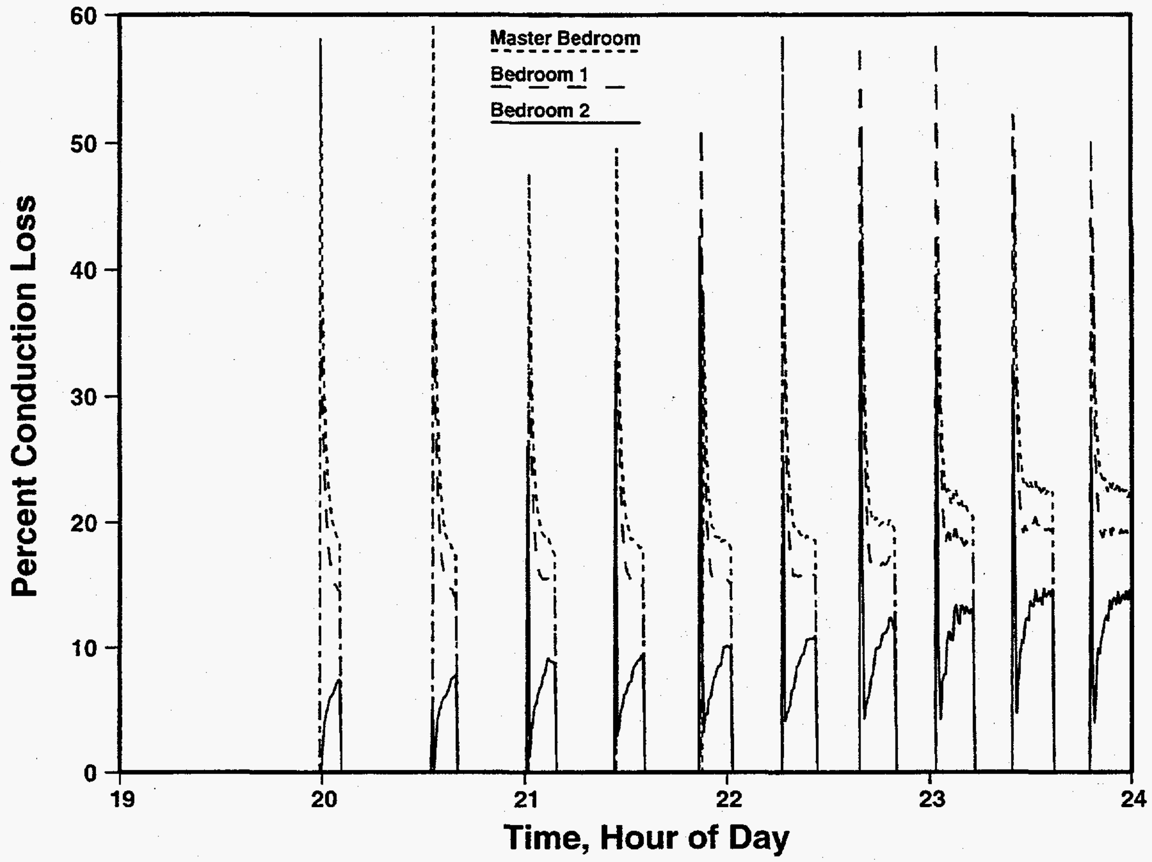

FIGURE 4.POST-RETROFIT PERCENTAGE CONDUCTION LOSSES, $F_{CONDUCTION}$, FOR THREE REGISTERS IN HOUSE 8.