SHORT-TERM MONITORING TO DIAGNOSE COMFORT PROBLEMS IN A RESIDENCE IN CENTRAL TEXAS

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ABSTRACT

This paper presents results from a project to resolve comfort problems created by high indoor humidity in a 3,400 sq.ft. house in Bryan, Texas. The case study house had been certified by the local utility to meet their energy efficiency standards. However, the resident of the house complained that the house felt too humid although the desired temperature conditions were being maintained. Several HVAC contractors had been previously hired to resolve the problem without success.

The field measurements undertaken to diagnose the problem are typical of those that could be undertaken by a house inspector and include an inspection of the construction of the house, short-term monitoring of temperature and humidity, blower door tests and whole-house pressurization tests. To perform the analysis both floors of the house were instrumented with portable data loggers and monitored for a period of two weeks to measure the temperature and relative humidity of the supply, return and ambient conditions. Analysis procedures applied to the house include comparing the measured data against the ASHRAE comfort zone (ASHRAE, 1997) which confirmed adequate zone temperatures with high humidity conditions, and inadequate supply air delivery temperatures for humidity removal. Combined results of the blower door tests and whole-house pressurization tests indicated a potential for leakage through the return air duct.

After the recommendations were presented to the homeowner, a new contractor was hired and retrofits applied on the house (i.e., cleaning the cooling coils, enlarging the compressor and relining of the return duct). Measurements were then repeated to determine that the problem had been fixed. This paper describes the case study residence, the measurements used to diagnose the problem, analysis methods, and presents results of the application of the analysis.

INTRODUCTION

Literature Review

A number of papers have been published on the methods used for monitoring, analysis, evaluation and diagnosis of residential environmental conditions including Haberl et al, (1998a; 1998b) and Parker et al. (1994). Several papers have studied the problems associated with humidity control in residential buildings including Beever (1996), Trowbridge and Peterson (1994) and Beckwith (1996). Several authors diagnosed problems associated with humidity control in residential buildings and made a number of recommendations to increase comfort of residences. Parker et al. (1994) monitored ten low-income houses in Florida for the purpose of verifying the effectiveness of energy conservation retrofits. The authors recommendations included return duct sealing which saved 12% of annual energy use (2.40 kWh/day equal to an absolute saving of 880 kWh/yr.), and evaporator coil enhancements among other requirements.

Haberl et al. (1998b) examined two side-by-side Habitat for Humanity houses in Houston. This study recommended that the most important ECRM was training the occupants in the proper use of the thermostat, and a careful inspection to make sure that all systems are properly installed and working. They found that in one of the two houses the HVAC system ran continuously for several months during their monitoring period accounting for indoor temperatures between 65 and 75 °F. They also noticed that the house often dropped below 65 °F when the HVAC system was in its heating mode. Their measured humidity ranges were 50-70% in the summer and 20% in the winter. Blower door tests performed on the energy efficient house resulted in an air change rate per hour of 0.75, which was due in part to air leakage through an open access panel into the attic.

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O'Neal et al. (1996) studied the effect of return air leakage on air-conditioners. They found that the effective capacity and effective Energy Efficiency Ratio (EER_{eff}) were reduced during high humidity conditions. Return air leakage amounts as small as 5% in high humidity areas produced a 20% reduction in both capacity and efficiency. They even found in an instance where an 8% leakage rate from a 140° F attic at 17% RH caused a reduction of capacity and EER of 28%. The lower capacity resulted in longer run times. They also concluded that the leakage of enough hot/moist air could reduce the effective dehumidification that the evaporator provides to the space.

Beckwith (1996) studied problems associated with DX systems. He stated that over-sizing resulted in high humidity levels where the systems meet the thermostat requirements but do not operate long enough to remove humidity. He suggested the use of a dehumidifying sub-cooling and de-superheater (SCADR) heat pipe system.

In contrast, Trowbridge and Peterson (1994) found that clammy and unpleasant conditions were sometimes due to undersized air-conditioners with evaporators that had inadequate latent heat removal capacity, and which operated all day. They suggested that humidity control could be achieved by a change in the ventilation system configuration that incorporates a humidistat and a thermostat, which would minimize initial and running cost.

Beever (1996) studied the use of a separate whole-house dehumidification system for independent humidity and temperature control, and concluded that temperature and humidity could effectively be controlled separately. In this study, one air conditioner was used to control the temperature and a separate whole-house dehumidification system was used to control the humidity with each working independently.

Methods have also been developed and refined for measuring the infiltration rates in a house. ASTM has published a standard methodology for measuring the leakage of residential systems to unconditioned spaces (ASTM, 1992). This standard includes two alternative leakage measurement techniques. One technique requires only the blower door test, whereas the other technique requires a flow capture hood and a blower door test.

Modera (1995) studied alternative techniques of measuring air distribution system leakages. He reported on the results of field measurements of 30 houses using a blower door test and a flow-capture hood. In this analysis, he showed that leakage measurements with the blower door analysis would be negatively biased by 30-50% if the duct pressure had not been incorporated in the analysis. Similarly flow-capture hood supply leakage measurements would be negatively biased by 33% if the envelop pressure differential had been used instead of the duct pressure differential.

Air infiltration into buildings are typically driven by interior to exterior temperature differences (air buoyancy) and wind. Both temperature differences and wind speeds tend to be at their lowest during summer months. Site measurement taken in U.S. locations using tracer gas decay techniques show lower that typically recommended summer air infiltration rates (air changes per hour or ACH) to be lower than those commonly believed. For instance, a large scale study during the heating season in the Pacific Northwest found an average winter air change rate of only 0.4 ACH (Parker et al., 1989). Summer air change rates in 23 tested homes during summer in Tennessee found rates averaging only 0.31 ACH (Gammage et al., 1984). A similar study by Cummings in Florida in summer conditions there found an average air change rate of 0.21 ACH in fifty tested homes (Cummings et al., 1989; 1990). One controversial element of this situation is that the typical summer infiltration rate in housing is often lower than that typically recommended by ASHRAE for residential ventilation (0.35 ACH). On the basis of the tracer tests described above, the likely average typical air change rates for summer range from 0.2 to 0.3.

In summary, there is plenty of advice in the previous literature concerning humidity control and the associated problems in residences. Although some of the previous literature focused on the effectiveness of conservation measures (Haberl et al. (1998b); Parker et al. (1994)), A number of papers did provide good advice on selected aspects of measuring and diagnosing comfort problems in residences in hot and humid regions. These papers showed return air leaks (O'Neal, 1996), over-sizing (Beckwith, 1996) or under-sizing (Trowbridge and Peterson, 1994) can cause humidity problems. Specially designed systems have been shown to be capable of independent temperature and humidity control (Beever, 1996). Methods have also been developed (ASTM, 1992) and refined (Modera, 1995) for measuring whole-house tightness with blower doors, as well as

Table 2. Results of the pressurization and depressurization tests of the case study house.

Pressurization	*ACH/hr @ 50 Pa*
Nothing taped	0.37
With kitchen vents tapped	0.37
With kitchen vents, dryer vents taped	0.37
With kitchen vents, dryer vents, bathroom vents taped	0.36
With kitchen vents, dryer vents, bathroom vents, and return grills taped	0.34
Depressurization	*ACH/hr @ 50 Pa*
With kitchen vents, dryer vents, bathroom vents, and return grills taped	0.20
With kitchen vents, dryer vents, bathroom vents taped	0.24
With kitchen vents, dryer vents taped	0.26
With kitchen vents tapped	0.28
Nothing taped	0.29

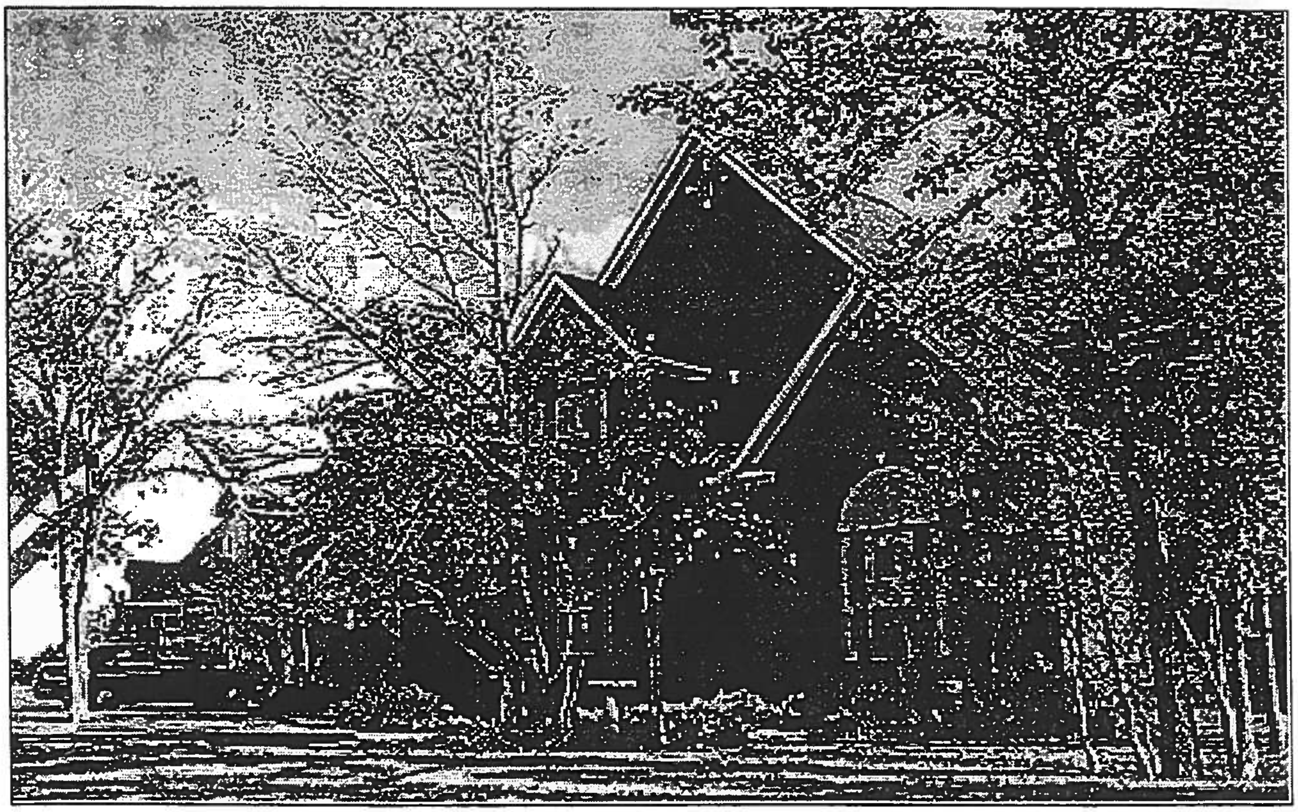

Figure 1. Front Elevation of the case study house

Finally, several studies have attempted to quantify air change rates in samples of houses, which found large variations in measured exchange rates, including Grot and Clark (1979), Grimsrud et al. (1982), Palmiter and Brown (1989) and Parker et al. (1994). ASHRAE also has made recommendations of 0.35 air changes/hr with at least 15 cfm/occupant (ASHRAE 1989).

Case Study House.

The house examined in this paper is a 3,400 sq.ft. two-story residence located in Bryan, Texas. The house is a four-bedroom dwelling with a cathedral ceiling and an 18-foot high ceiling in the entrance hall. The first floor consists of a living room, dining room and kitchen, a study, one bedroom and a bathroom. A laundry room, attached double car garage and external patio are also on the first floor. The second floor has three bedrooms and a sitting area. Two people presently occupy the house. Figure 1 is a photo of the case study house.

The building is approximately four years old and was constructed to meet the energy conservation program requirements for the City of Bryan (COB, 1999). The conservation program requires wall construction to be R-15, the ceiling insulation of R-30, and R-6 insulated ductwork. The house must have an air-conditioning unit with a minimum Seasonal Energy Efficiency Ratio (SEER) of 12 (and a minimum 450 sq.ft. /ton), and a minimum Annual Fuel Utilization Efficiency (AFUE) value of 80% for the furnace.

The normalized annual electric energy consumption of the case study house (rank no. 14) is compared to other houses in the neighborhood as shown in Figure 2a, and the size of the house is compared against the other houses in the neighborhood in Figure 2b. Clearly, the case study house is an average energy user when compared against 22 similar houses in the neighborhood, although it is one of the larger houses in the neighborhood that meets the conservation standard.

PROBLEM REPORTED BY THE HOMEOWNER

A complaint from the homeowner concerning the cold and clammy indoor conditions prompted the investigation. The homeowner stated that these conditions persisted despite operating the bathroom exhaust fan continuously in an attempt to remove excess moisture. He also set the thermostat at a lower temperature, approximately 68 °F, in an attempt to maintain comfort, however he reported no noticeable improvement in the indoor comfort conditions. Prior to the inspection, the homeowner had contracted work to be performed on the house's air conditioning system. The contractor's solution was to install a larger compressor on the air-conditioner without replacing the evaporator. However, the comfort problems persisted after the first retrofit was performed.

Based on an initial walk-through inspection and a discussion with the homeowner, it was determined that a more detailed examination of the house's HVAC system and house tightness was warranted. Therefore, it was recommended to monitor the house for several weeks, run tests to determine the house tightness, analyze the data, and provide recommendations to resolve the problem. A nameplate inspection revealed the house had 5.5 tons of air-conditioning (2 tons upstairs and 3.5 tons downstairs). This provided 618 sq.ft. /ton of air conditioning, which is higher than the 450 sq.ft. /ton required for HVAC systems in the City of Bryan's conservation program. It was also determined that the remaining requirements for the conservation program were also met.

The HVAC units for the house were split systems with the condensers located at ground level on one side of the house. Both evaporators were located in the attic above the second floor, a rise of almost 25 feet for the refrigerant (one of the reasons the original contractor installed a larger compressor). The return grill for the second floor system was located approximately 10 feet from the unit in the ceiling of the second floor. Supply ductwork was insulated R-6 flexible ductwork. The return duct was rigid, 1" foil-faced ductboard. The return grill for the first floor unit was located near the front of the house in the first floor hallway. This required the return air to rise 25 feet upward through a drywall framed chase, then through an additional 10 feet of the rigid ductboard to the evaporator where it was then conditioned and redistributed to the first floor through a combination of flexible ducts and framed chases in the walls of the second floor where it was delivered to diffusers in the ceiling of the first floor. A visual inspection of the ductwork in the attic revealed no obvious leaks.

DIAGNOSTICS

The inspection of the house included an examination of the ductwork in the attic, return air ductwork and vents, supply air diffusers, whole-house pressurization tests, blower door tests, and an examination of the air-conditioner condenser and evaporator coils. Mold and mildew had grown on diffusers in the kitchen, which helped confirm the

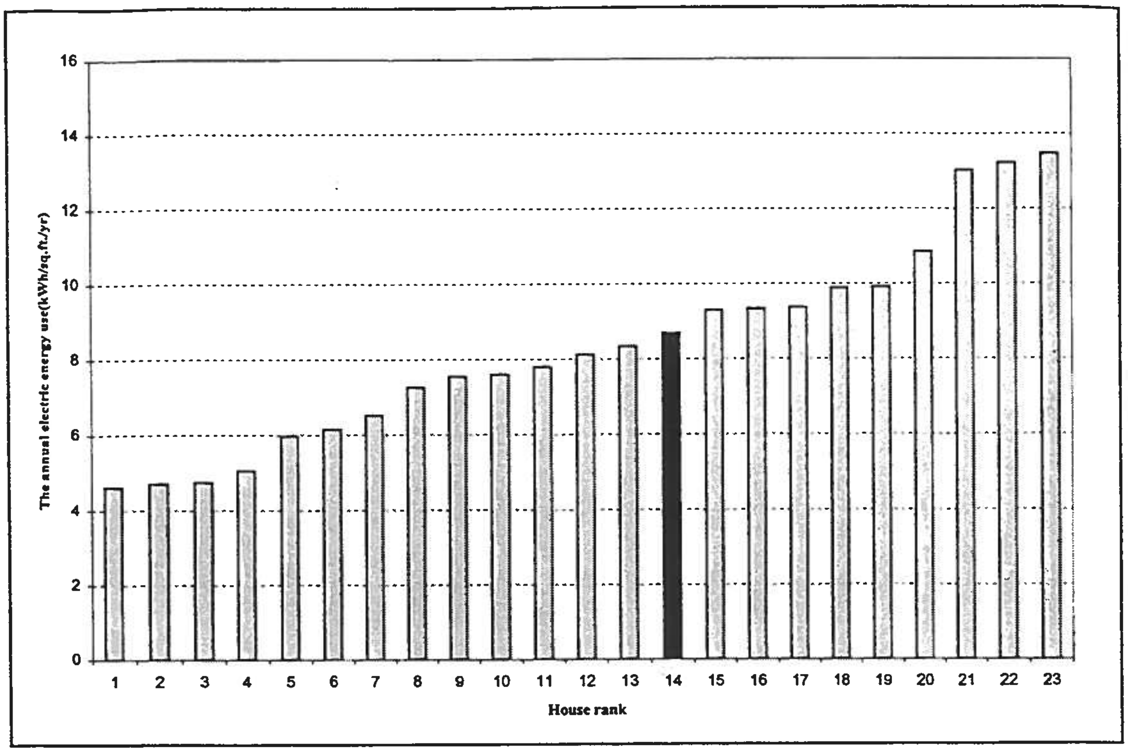

Figure 2a Comparative EUI indices for case study house. This figure shows the Energy Utilization Indices (EUI) for the case study house (rank14) compared against 22 houses of similar construction in the neighborhood.

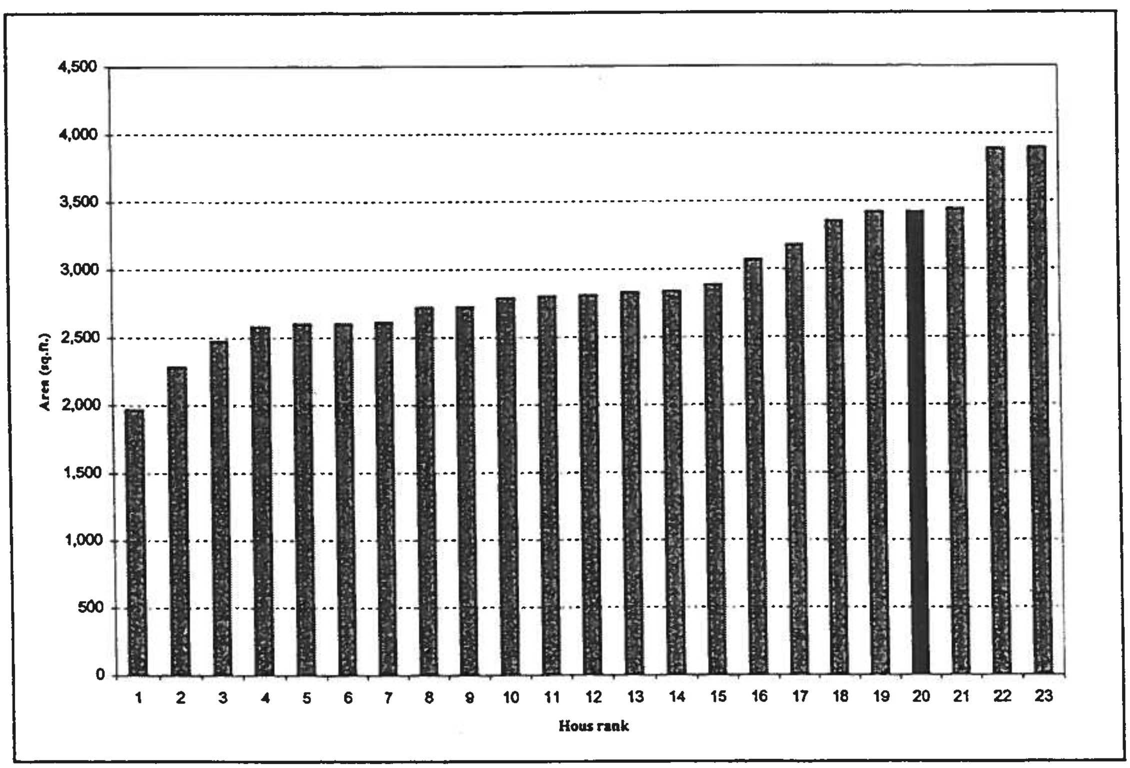

Figure 2b Comparative area of case study house. This figure shows the conditioned area of the case study house (rank 20) and the other 22 similar houses in the neighborhood.

damp conditions described by the homeowner. An inspection of the home's ductwork revealed that there was a large separation in the drywall joints of the chase which allowed hot, humid attic air to be drawn into the air-conditioner system with the return air.

The house was then monitored for two weeks using four portable temperature and relative humidity data loggers (Onset, 1998). Figures 3 and 4 show the portable data loggers in place at a diffuser (Figure 3) and a thermostat (Figure 4). These were installed at a ceiling diffuser in the dining room and at the thermostat on the first floor. Similar data loggers were installed at a diffuser in the second floor sitting area and the thermostat on the second floor. The measurements from these sensors provided time series data of the indoor conditions (i.e., temperature and relative humidity data) for both first and second floors (supply and room temperature). Simultaneous measurements of outdoor temperature and relative humidity data were collected from a nearby weather station (Kootin-Sanwu et al., 2000).

A whole-house pressurization test was also performed with a motor specially designed for this purpose. Pressure difference measurements of the whole-house were taken with reference to the outdoor pressure. Finally, a blower door test was performed on the house using the ASTM *Standard* E 779 (ASTM, 1992) procedure to characterize the house tightness.

RESULTS

Pre-retrofit Temperature and Humidity Measurements. During the monitoring period, the indoor temperature on the first floor (at the thermostat) was maintained at approximately 68 °F. The supply air temperature from the diffusers on the first floor was found to vary between 55 °F and 65 °F. Outdoor temperatures for the same period ranged between 65 °F and 85 °F as shown in Figure 5. Several additional features are worth noting in Figure 5. First, during the monitoring period there were periods when the homeowner turned the air-conditioning system off on the first floor. During these periods the zone temperature (i.e., "the room temperature", located in the hallway in the front of the house) rose only a few degrees. However, the supply temperature (which measures to the ceiling temperature of the dining area when the blower is shut off) rose 5-7 °F above the thermostat set-point, indicating uneven heat gain on the first floor when the air conditioner was switched off.

Second, although there are instances where the supply air dips to 55 °F, the average temperature of 60- 62 °F from the diffuser indicates inadequate moisture removal in the air-conditioning coil. Finally, the cycling of the air-conditioning is evident during the afternoon and evening periods, indicating the unit was more than adequate to meet the load during the mild evening hours. A closer look at the data also indicates a small rise in the average supply temperature as the load dropped in the early hours of the morning, which is due to an increase in cycling.

Relative humidity measurements for the same period are shown in Figure 6. The indoor relative humidity measured at the first floor thermostat varied between 55% and 65%. The relative humidity of supply air at the diffusers on the first floor was found to vary in the range of 50-100%. Outdoor relative humidity readings for the same period ranged between 40-95%. The temperature and relative humidity on the second floor was maintained at similar conditions to the first floor. A closer look at Figure 6 indicates that the highest room relative humidity (as measured at the first floor thermostat) rose during the daytime when the system was shut off, which would be consistent with the homeowner's comments about leaving on an exhaust fan (i.e., this actually raised the indoor humidity). A second consistent rise in the room relative humidity can also be seen each evening as the cooling load dropped off and the air-conditioner cycled to meet the load.

These same data are presented on a psychrometric plot in Figures 7-9. Figure 7 shows the first floor temperature and humidity as measured at the thermostat. The ASHRAE comfort zone is also shown on the psychrometric chart (i.e., 60 % RH upper humidity bounds, 68-78 °F effective temperature, and 36 °F dewpoint lower humidity bounds). From Figure 7, it is clear that the first floor was colder and more humid than recommended ASHRAE conditions. Figure 8 shows the conditions of the supply air for the same period. In a similar fashion to Figure 5, Figure 8 indicates that the supply air to the first floor was not being cooled enough for adequate moisture removal. Figure 9 shows the outdoor temperature and humidity for the same period. This figure shows the significant variation in the outdoor conditions during the pre-retrofit period. This is quite a contrast to the very tightly controlled indoor condition for the first floor (Figure 7).

In Figure 10 the temperature difference is shown between the supply air and the return air (i.e., Room - Supply temperature). During the monitoring period, the data show a temperature difference of 5-7 °F between the return air and the supply air during the periods of air-conditioning operation. This is well

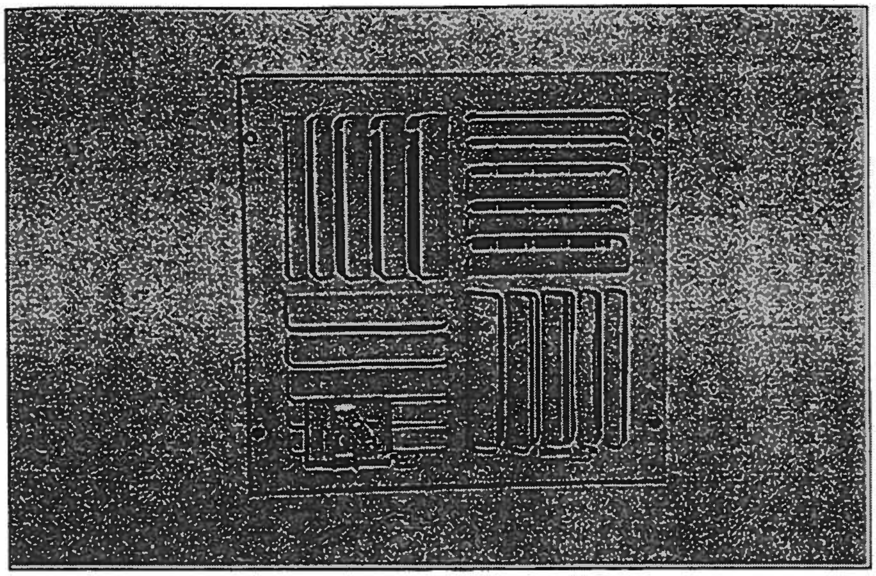

Figure 3. Portable measurement equipment at the diffuser. This photo shows the data logger attached to the ceiling diffuser in the case study house.

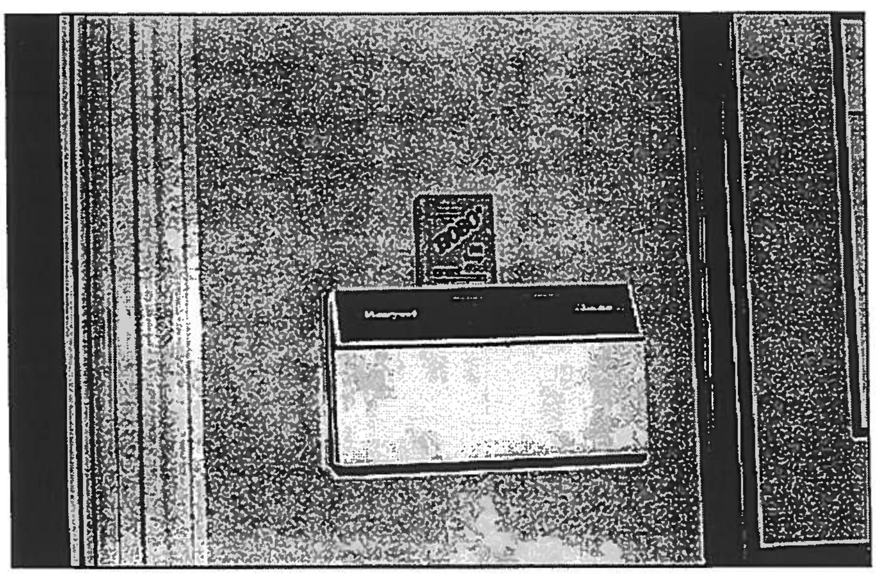

Figure 4. Portable measurement equipment at the thermostat. This photo shows the data logger measuring room temperature and relative humidity in the case study house.

below the necessary 10 to 20 °F temperature difference needed for proper humidity control.

Whole-house Pressurization Test. The results of the whole-house pressurization test are presented in Table 1. In these series of tests, the whole-house indoor-outdoor pressure difference was measured with a very sensitive pressure meter (i.e., 1 Pascal = 0.004 in H_20). During these tests the HVAC's blower was repeatedly cycled on and off using the various modes (i.e., heat, cool, fan-only) on a calm day (i.e., no wind). These results indicate a slight pressurization of the house when the HVAC's blower was operating (all other fans were shut off, including all exhaust fans). This pressurizing of the house when the blower is on often indicates a leak in the return air plenum which motivated the inspection of the 25 foot return air chase between the first and second floor. This inspection revealed that the contractor had failed to tape the drywall joints inside the return air chase, which allowed hot and humid attic air to be drawn in with the return air through a visible 1/8" to ¼" separation in the drywall running the length of the chase up into the attic, thus pressurizing the house. Excessive return leakage in between floor chases like the one described are one of the reasons that this design is not allowed within Florida's energy code. Only hard duct returns are acceptable. This likely the primary problem for the entire building.

Table 1. Results of the whole-house pressurizationtest.

Operation	Pressure (Pa)
Air conditioner on	+ 0.2
Air conditioner off	0.0
Heater on	+ 0.2
Fan-on only	+ 0.3

Blower Door Test. A blower door test was performed on the house. The fan flows were measured at house pressures of 5, 12.5, 20, 27.5, and 35 Pascal for five different tightness configurations and a curve-fit was performed on the data. The five tightness configurations were: 1.) with no tape on any vents; 2.) with the kitchen vents sealed; 3.) with kitchen and dryer vents sealed; 4.) with kitchen vents, dryer vents and bathroom vent sealed; 5.) with kitchen vents, dryer vents, bathroom vents and return air ducts sealed. Table 2 shows the results of the pressurization and depressurization blower door tests.

Several trends are evident from the blower-door pressurization/depressurization tests. First, the house appears to be a tight house, which is well within the values previously reported, and it satisfies the ASHRAE *Standard 62*. (i.e., 0.35 ACH/hr). Second, the decrease in depressurization values compared to the pressurization values indicates that the back-flow flappers on the exhaust fans were working on the exhaust fans, although some leakage still seems to be occurring. Finally, the large ACH change in both pressurization and depressurization that occurred with the taping of the return grills was a good indication that there was significant leakage in the return air passage for the HVAC that served the first floor.

Recommendations to the Homeowner. The observations from the monitoring and inspection lead us to believe that several problems were contributing to the high humidity conditions. First, the supply air was not cold enough for proper dehumidification which could be caused by an evaporator coil with inadequate latent heat removal, and return air leakage, or some combination of the above. Second, the constant use of a bathroom fan may be drawing in more humid air through infiltration. Third, part of the homeowner's discomfort may be due to uneven heat gain on the first floor. Based on these observations we recommended that the return air duct be re-sealed and the evaporator coils either cleaned or replaced with newer coils with a higher latent heat removal capacity.

Retrofit Measures. Following a meeting with the homeowner where the recommendations of the study were presented the homeowner hired a new contractor who was given a copy of the report and asked to perform their own analysis on the house. The contractor performed his own tests and then decided to clean the evaporator coils, reseal the return chase and further increase the size of the air-conditioning system from 5.5 to 6.5 tons (reducing the tonnage/sq. ft. from 618 to 523).

Post-retrofit Measurements. Measurements were then repeated to confirm the success of the retrofits as shown in Figures 11 – 14. Although, these measurements were taken during a much hotter period of the year they still show a marked improvement in the comfort conditions. In Figure 11, supply temperatures dropped to the 57-60°F range. Relative humidity dropped well below 60% as shown in Figure 12. The homeowner appears to have increased the set point as well (possibly in response to the drier conditions). Figure 13 also confirms the post-retrofit conditions are well within the recommended ASHRAE comfort range. Figure 14 indicates an improvement of the supply-return temperature difference as well.

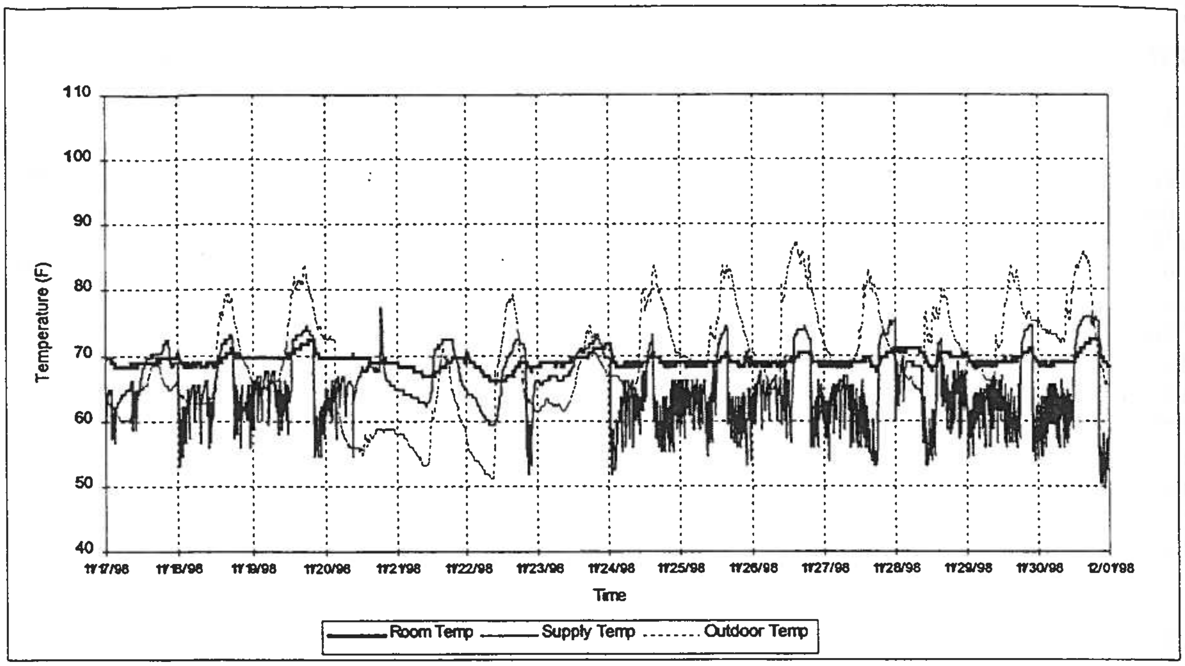

Figure 5. Room, supply, and outdoor air temperatures (F) for the first floor of the house for the pre-retrofit period of 11/17/98 to 12/1/98.

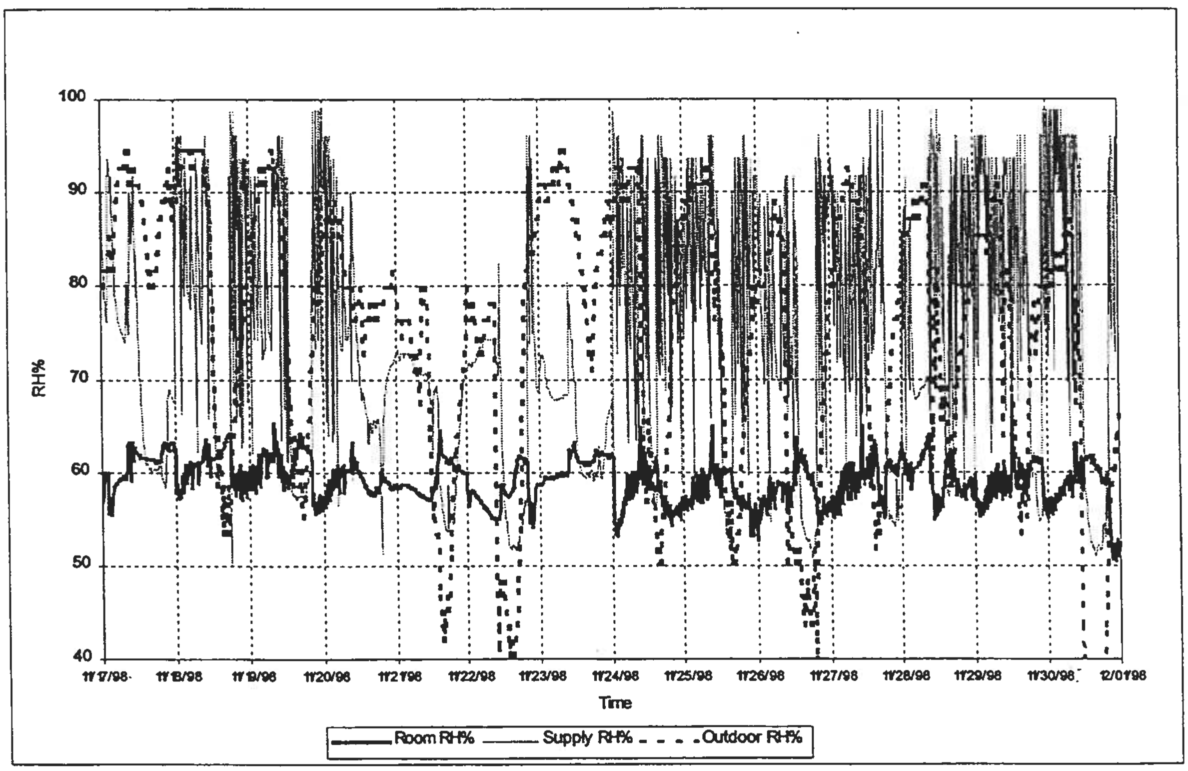

Figure 6. Room, supply, and outdoor air relative humidities (%) for the first floor of the house for the pre-retrofit period of 11/17/98 to 12/1/98.

CONCLUSIONS

This paper presents results from a project to resolve comfort problems created by high indoor humidity in a house in Bryan, Texas. The case study house had been certified by the local utility to meet their energy efficiency standards. However, the resident of the house complained that the house felt too humid although the desired temperature conditions were being maintained. Several HVAC contractors had been previously hired to resolve the problem without success. Field measurements, typical of those taken by a home inspector, revealed that the house was suffering from a combination of problems, including a leaking return duct and dirty evaporator coils. Following the retrofit of the air conditioning system measurements were repeated to confirm that the problems had been repaired.

Several insights have been gained from this project that may be useful for future projects:

1) Simple comfort problems in a house are often caused by a complex series of problems.

2) Measurements and inspections, typical of those that could be performed by a home inspector, are capable of identifying potential duct leakage and/or comfort problems with air-conditioning systems. Simple time series measurements using inexpensive stick-on loggers can be very helpful in confirming comfort problems and can help diagnose the problems. Whole-house pressurization and blower-door tests are also useful diagnostics in determine leakage rates and possible leakage pathways.

3) The diagnostic measures that are typically employed by contractors in this area usually include the traditional refrigerant temperature-pressure measurements, compressor power draw, and equipment inspections (i.e., coil conditions, ductwork, piping, etc.). In the case study house these traditional measurements confirmed the potential problems that had been identified by the home inspection measures.

4) Home inspectors (or utility customer service representatives, realtors, etc.) could provide additional information to homeowners by using simple site measurements and inspections that could be performed inexpensively, yet provide meaningful results. Such inspections are often called for at the time of sale of a house. In the case study house, such inspections could have alerted the homeowner to potential problems before they purchased the house.

ACKNOWLEDGMENTS

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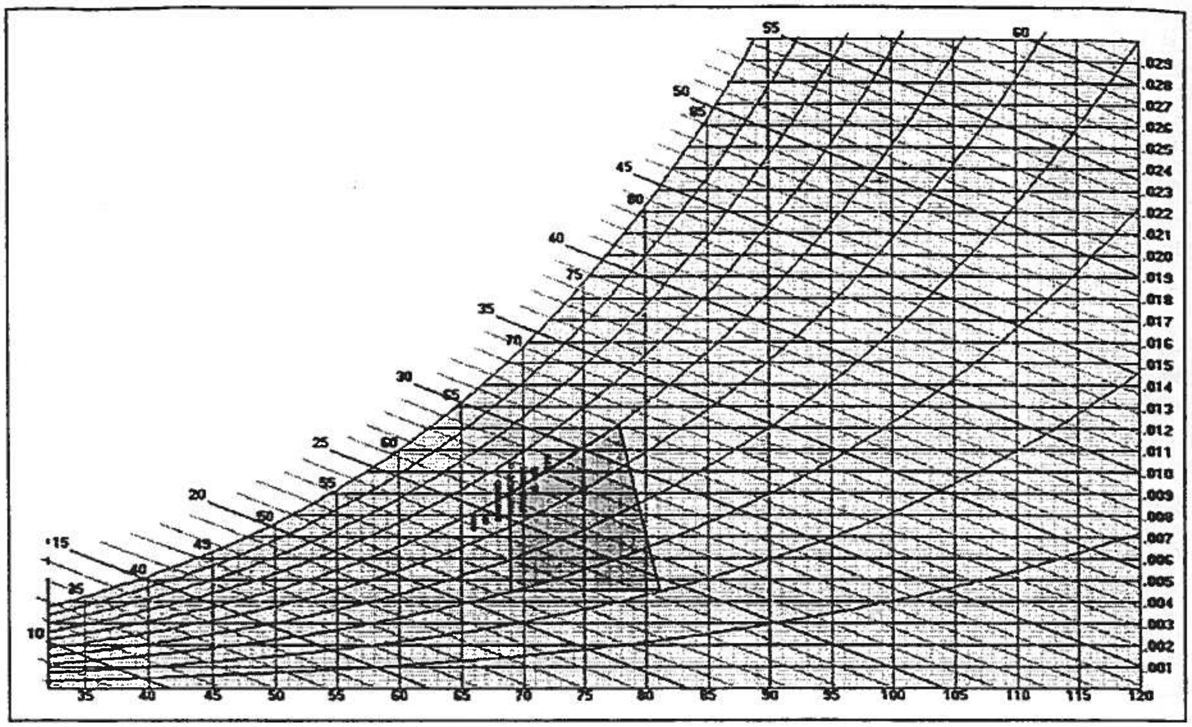

Figure 7. First floor temperature and relative humidity as measured at the 1st floor thermostat for the pre-retrofit period of 11/17/98 to 12/1/98.

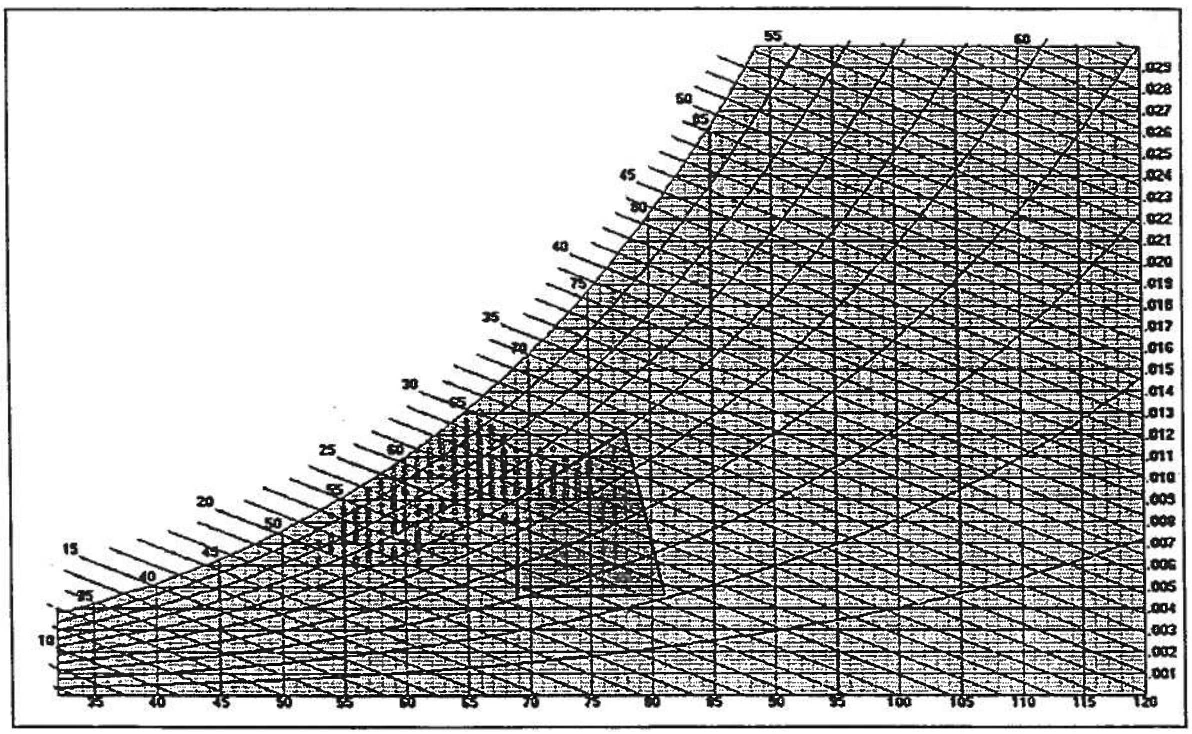

Figure 8. Supply air temperature and relative humidity for the first floor of the house for the pre-retrofit period of 11/17/98 to 12/1/98.

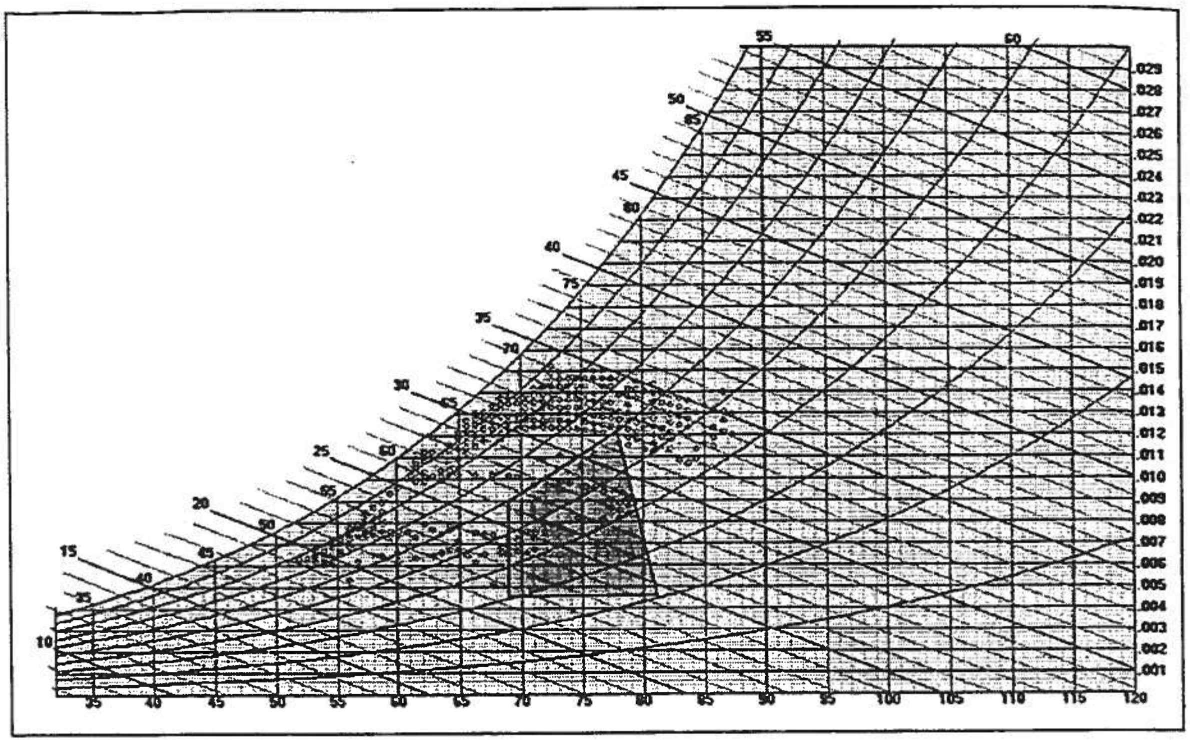

Figure 9. Outdoor air temperature and relative humidity for the period of 11/17/98 to 12/1/98.

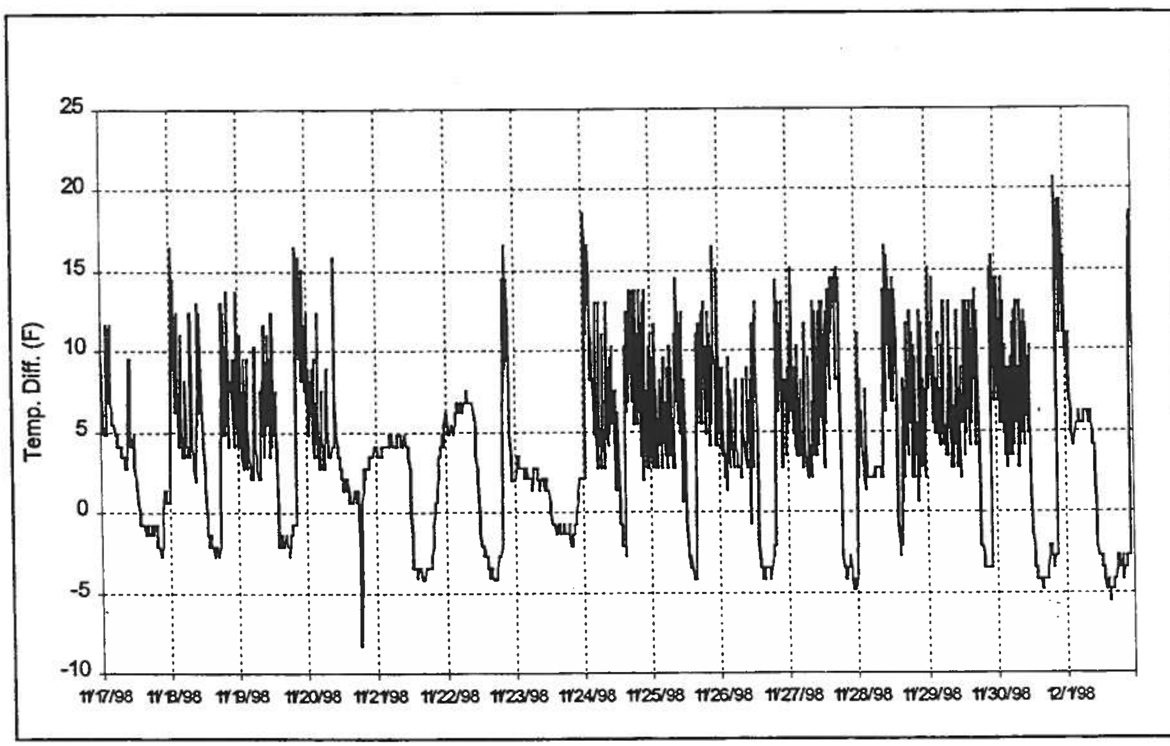

Figure 10. The first floor difference in temperature between the return air and supply air the case study house during the pre-retrofit period.

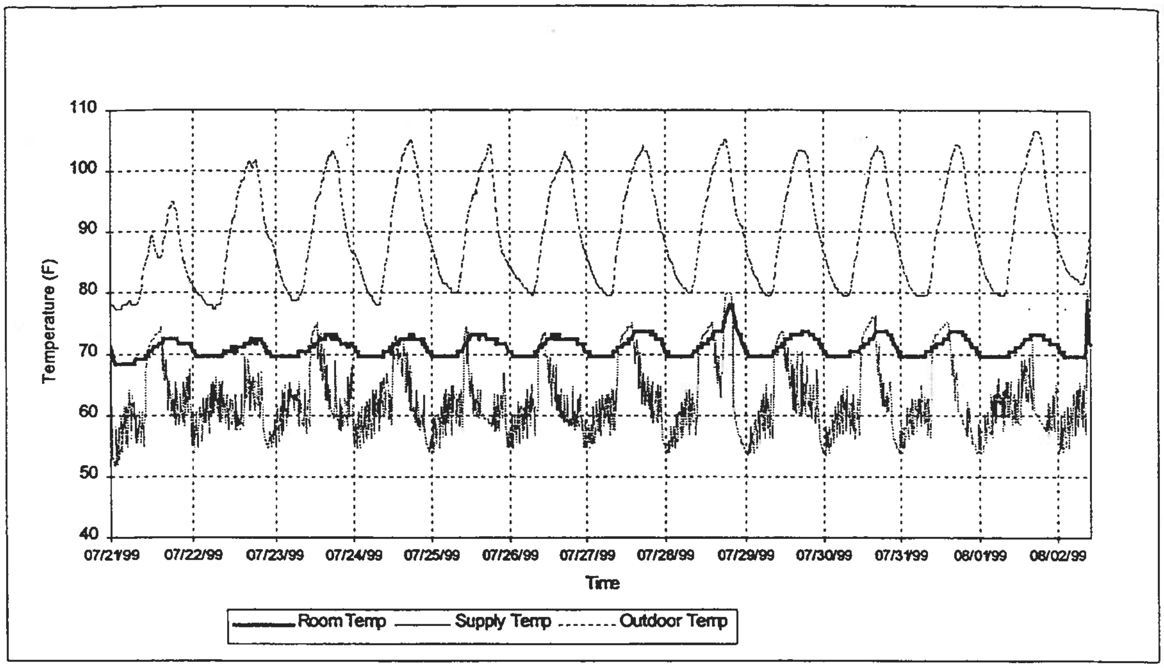

Figure 11 Room, supply, and outdoor air temperatures (F) for the first floor of the house for the post-retrofit period of Jul 21 - Aug 2, 1999.

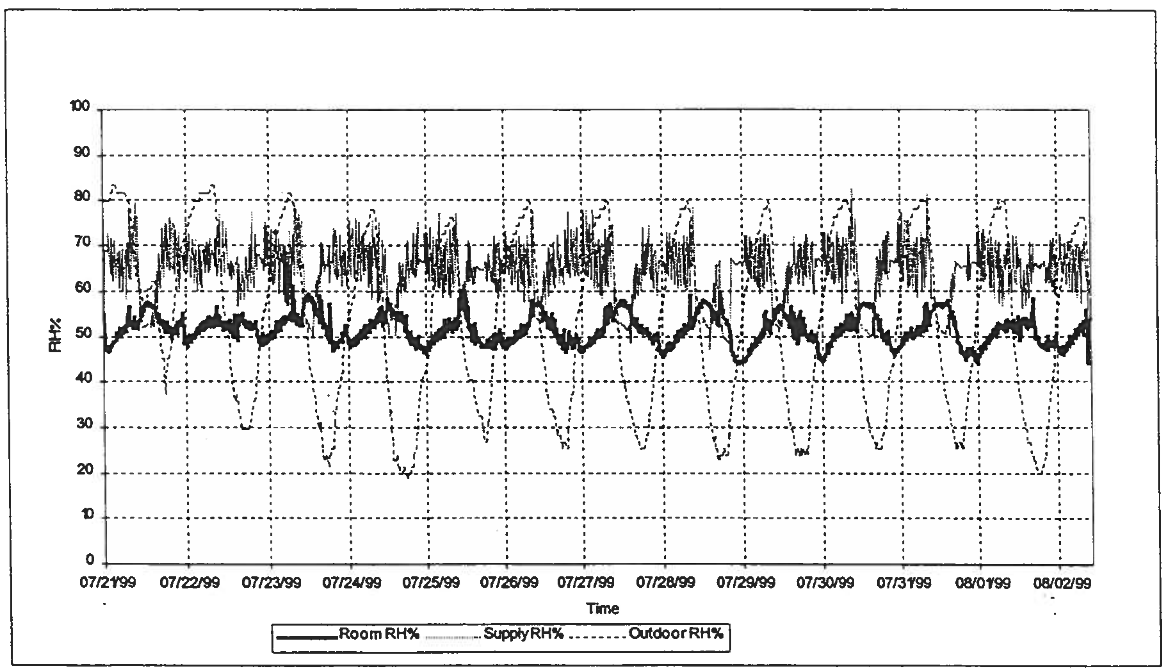

Figure 12 Room, supply, and outdoor air relative humidity (%) for the first floor of the house for the post-retrofit period of Jul 21 - Aug 2, 1999.

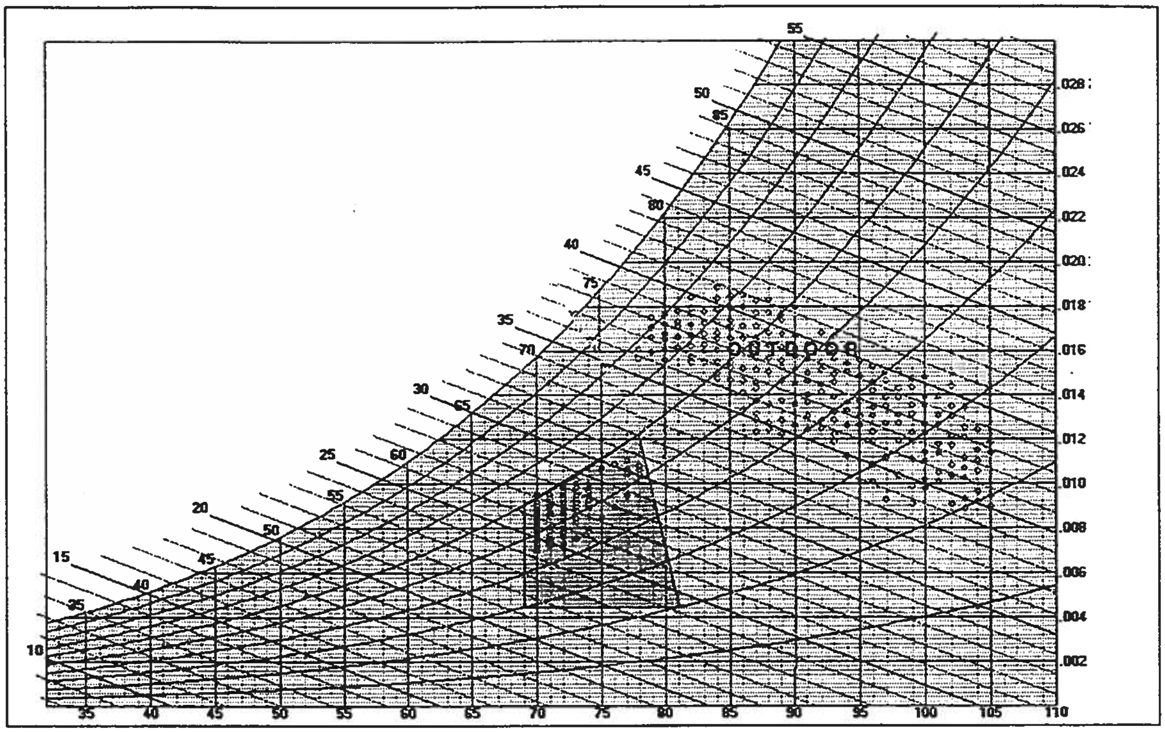

Figure 13 Room and outdoor air conditions for the post-retrofit period of Jul 20 - Aug 2, 1999.

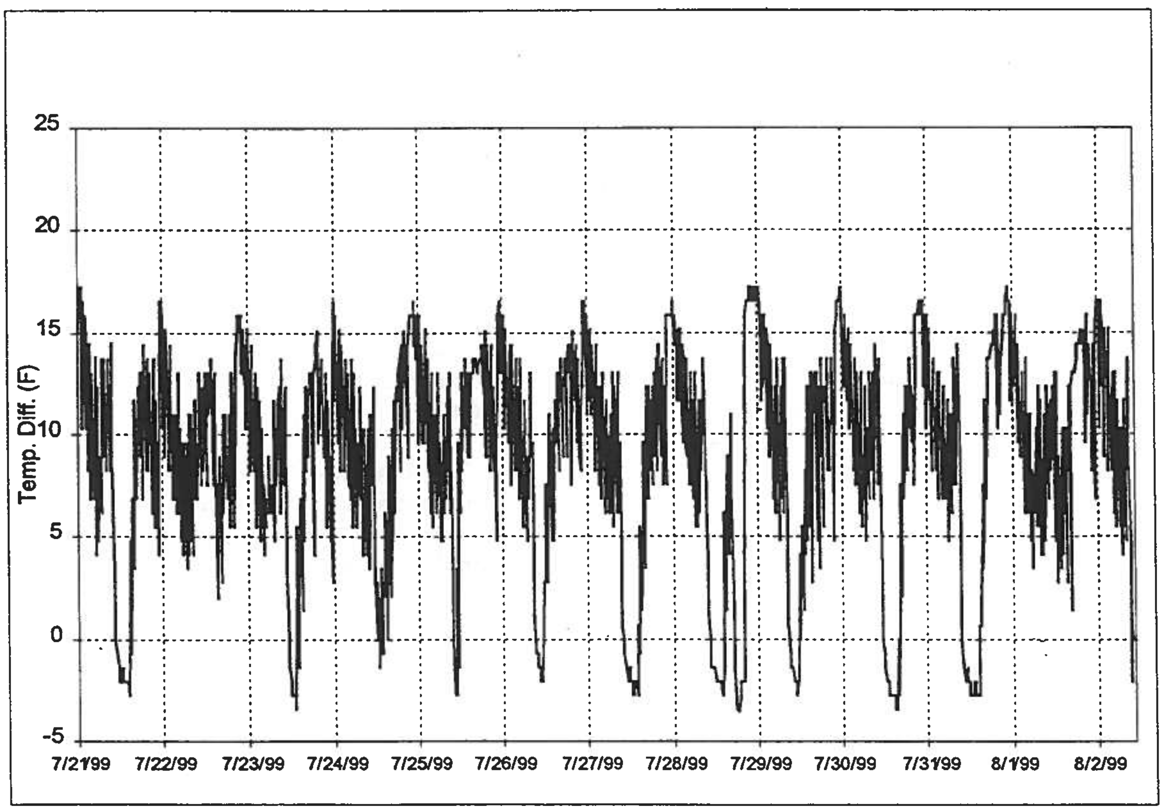

Figure 14 The first floor difference in temperature between the return air and supply air at the case study house for the post-retrofit period.