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Flexible Residential Test Facility: Impact of Infiltration and Ventilation on Measured Heating Season Energy and Moisture Levels

R. Vieira, D. Parker, P. Fairey III, J. Sherwin, C. Withers, and D. Hoak
BA-PIRC

September 2013

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Flexible Residential Test Facility: Impact of Infiltration and Ventilation on Measured Heating Season Energy and Moisture Levels

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Definitions

ACH50	Air changes per hour at 50 Pascals
BA-PIRC	Building America Partnership for Improved Residential Construction
C	Air leakage coefficient
CFM	Cubic feet per minute
CO_2	Carbon dioxide
ELA	Effective leakage area
EqLa	Equivalent leakage area
FSEC	Florida Solar Energy Center
kWh	Kilowatt hour
n	Exponent in the building leakage curve
Pa	Pascal
Qn	Normalized air distribution system leakage
RH	Relative humidity
T	Temperature

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Executive Summary

Perhaps no residential topic has been discussed as much among building scientists as air infiltration and required mechanical ventilation. Usually, envelope tightening is recommended as an efficiency strategy for retrofitting an existing home. In humid climates, reducing infiltration can reduce summer moisture loads. However, during drier weather when the air conditioner is not running, lower infiltration can lead to potential condensation. Even though severe cold weather is rare in the Deep South, the prevalence of single-pane windows can lead to condensation events.

As part of a long-term experiment exploring retrofit measures, the savings from reducing air infiltration, with and without the addition of mechanical ventilation, are being studied. In 2011–2012, two identical laboratory homes designed to model existing Florida building stock were sealed and tested to 2.2 ACH50. Then, one was made leaky with 70% leakage through the attic and 30% through the windows, to a tested value of 8 ACH50. Reduced energy use was measured in the tighter home (2.2 ACH50) in the range of 15.8%–18.6% relative to the leaky (8 ACH50) home.

Internal moisture loads resulted in higher dew points inside the tight home than in the leaky home. Window condensation and mold growth occurred inside the tight home. Even cutting internal moisture gains in half to 6.05 lb/day, the dew point of the tight home was more than 15°F higher than the outside dry bulb temperature. The homes have single-pane glass representative of older central Florida homes. There are a few factors that may limit the representation of the moisture results:

- The laboratory homes have very little moisture capacitance, as they contain no interior walls, no furnishings, and no carpeting (slab is exposed).
- There was neither mechanical ventilation nor operation of windows. The weather was largely comfortable for much of the test period and many residents would likely open up the homes for most periods during this time.
- The homes were only one year old when the testing took place. There is likely still some drying out of the slab and concrete block walls typical of new homes, not existing homes.

A second winter of testing was conducted in 2012–2013 with the tight home alternating between two-week periods with mechanical ventilation (63 CFM supply air continuously) and not having ventilation. The leaky east building remained the same with no ventilation. Both buildings used a schedule of 11 lb/day of internal moisture generation. Winter condensation was observed again when the supply ventilation fan was off. Inside window temperatures (measured for the second winter collection period) were lower than the inside dew point on cold winter nights. However, condensation was not observed when the ventilation fan was on, or in the leaky home. Heating energy use in the tight but ventilated home was 15% higher than in the leaky home with natural air infiltration only.

The results indicate that tight construction in humid climates will risk window condensation and high interior humidity levels without mechanical ventilation. To reduce condensation potential there are steps practitioners may take coincident with tightening an older home. If the efficiency

measures include window replacement, a low U-value for the window can be selected to avoid condensation. Also, mechanical ventilation can be introduced, which will likely reduce humidity in the home during winter. Judicious use of operable windows during mild periods with no space conditioning will also likely be helpful in reducing moisture problems.

1 Background

Perhaps no residential topic has been discussed as much among building scientists as air infiltration and required mechanical ventilation. Sherman and Walker (2012) write "Although there is no national regulation of airtightness, many jurisdictions, regulatory bodies, codes and standards associations are beginning to include requirements for limiting envelope… There is currently a range of allowable leakage levels that are not the same depending on which code or standard is being referenced." Rudd and Lstiburek (2008) review some of the issues with different mechanical ventilation through the years ranging from first cost to poor air distribution and high energy use. Ventilation requirements are becoming part of high performance programs and new energy codes, usually referencing ASHRAE 62.2 (2010), "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings." However, implementation methods are varied, and few studies have been done to show the persistence of ventilation equipment run time and delivery of recommended air quantity over time. In existing homes, air sealing techniques may take place without adding ventilation.

Usually envelope tightening is recommended as an efficiency strategy for retrofitting an existing home. For example, the Energy.Gov website (2012) has a link from its main home page to air sealing that indicates "Reducing the amount of air that leaks in and out of your home is a cost-effective way to cut heating and cooling costs, improve durability, increase comfort, and create a healthier indoor environment." The site recommends sealing and ventilation.

In humid climates, reducing infiltration can reduce summer moisture loads. However, during drier weather when the air conditioner is not running, lower infiltration can lead to condensation. Even though severe cold weather is rare in the Deep South, the prevalence of single-pane windows can lead to condensation events.

As part of a long-term experiment exploring retrofit measures, the savings from reducing air infiltration is being studied. This report looks at the wintertime result with and without any mechanical ventilation. A separate report examines summer results with and without mechanical ventilation.

1.1 Facility

The State of Florida provided funding for the design and construction of two reconfigurable, geometrically identical, full-scale, side-by-side residential building energy research facilities at the Florida Solar Energy Center (FSEC), as shown in Figure 1. The Building America Partnership for Improved Residential Construction (BA-PIRC) has instrumented these flexible research homes and will monitor them to conduct research on advanced building energy efficiency technologies under controlled conditions.

The purpose of the Flexible Residential Test Facility is to provide a controlled research environment that serves two main purposes. First, it is used to research and evaluate advanced energy efficiency technologies and operational strategies. Second, it serves as a venue to help validate building simulation programs and algorithms. Details of the buildings and their instrumentation are provided by Vieira and Sherwin (2012).

Figure 1. Completed flexible residential test structures on FSEC campus

Of particular significance to this report is the substantial effort that went into creating equal air leakiness in the 1,536 ft^2, 14,331 ft^3 of volume buildings. Initial construction created reasonably tight buildings (3.62 and 3.82 ACH50), but FSEC staff further sealed leakage points until each was able to achieve 2.2 ACH50. The air distribution systems were tightened to achieve 13 CFM25/100 ft^2. (Qn = 0.013) in each home. Each home was then configured with controllable duct leakage and air leakage. The air leakage was designed to create the type of distribution and diffusion of air leakage represented in a number of southern slab-on-grade homes:

- Both homes were configured with four controllable ceiling leakage sites providing ~70% of leakage area needed to achieve ~8 ACH50 (see Figure 2 and Figure 3). Seventy percent leakage through the ceiling was able to be verified using a calibrated flow hood to measure air through ceiling leak sites when the house was at –50 Pa with reference to the outside.
- The remaining 30% of leakage area was achieved using metal shims at all windows (Figure 4). The leakage rate of the leaky configuration of the east unit increased from 6.01 ACH50 to 7.99 ACH50 by adding the shims.

Figure 2. Ceiling penetration for planned leakage

Figure 3. Attic view of hole that diffuses airflow

Figure 4. Windows are shimmed to allow leakage

FSEC staff experimented with different configurations of holes and air pathway restrictions until they were able to achieve an "n" value in a range of 0.6–0.7 while bringing in 30% of the air through the windows and obtaining an ACH50 value near 8. An n value of 0.6–0.7 was established since this is the typical range found in measurements in homes across the United States. Once the air leakage design was established in the first home, the same design was copied in the second home to obtain matched leakage results.

Airtightness testing was repeated on both homes in the tightest house envelope configuration and in the leakiest house envelope configuration at 8 ACH50. The detailed test results are summarized in Table 1 and Table 2. These tests were done with a very tight duct system having only Qn = 0.013 (0.013 CFM25 leakage to outside per 100 ft^2 of conditioned space).

Table 1. Building Tightness Comparison of Tight House Configuration (Tight Duct System)

	ACH50	CFM50	C	n	r^2	EqLa	ELA
East Laboratory Tight	2.26	540 (± 0.7%)	36.0 (± 8.6%)	0.692 (± 0.023)	0.9990	55.8 (± 3.5%)	29.6 (± 5.5%)
West Laboratory Tight	2.18	520 (± 0.6%)	36.0 (± 8.9%)	0.683 (± 0.023)	0.9996	53.7 (± 3.7%)	28.5 (± 5.8%)

ACH50 Air changes per hour at 50 Pascals
CFM50 Cubic feet per minute at 50 Pascals
C Air leakage coefficient
n Exponent in the building leakage curve
r^2 The coefficient of variation as an indicator of the fit of the least squares equation to the data
EqLA Equivalent leakage area
ELA Effective leakage area

Table 2. Building Tightness Comparison of Leaky House Configuration (Tight Duct System)

	ACH50	CFM50	C	n	r^2	EqLa	ELA
East Laboratory Leaky	7.99	1,909 (± 1.8%)	177.3 (± 15.4%)	0.607 (± 0.047)	0.9940	197.1 (± 5.9%)	104.8 (± 9.6%)
West Laboratory Leaky	8.06	1,926 (± 1.1%)	182.3 (± 11.3%)	0.603 (± 0.031)	0.9962	198.8 (± 4.3%)	105.7 (± 7.1%)

1.1.1 Internal Gains

Due to the limited heating season in central Florida, internal gains can provide sufficient heat on some winter days, particularly in newer, tighter homes. Furthermore, internal moisture generation in a tight home without ventilation can create high moisture loads. The laboratories have automated (computer controlled) heat and moisture gains scheduled by time of day based on the Residential Energy Services Network lighting, appliance and miscellaneous energy usage amendment schedule (RESNET 2011, also see Parker et al. 2010). The hourly schedules utilized are shown in Figure 5, and more details of how they were derived and delivered are given in the report on the facility (Vieira and Sherwin 2012).

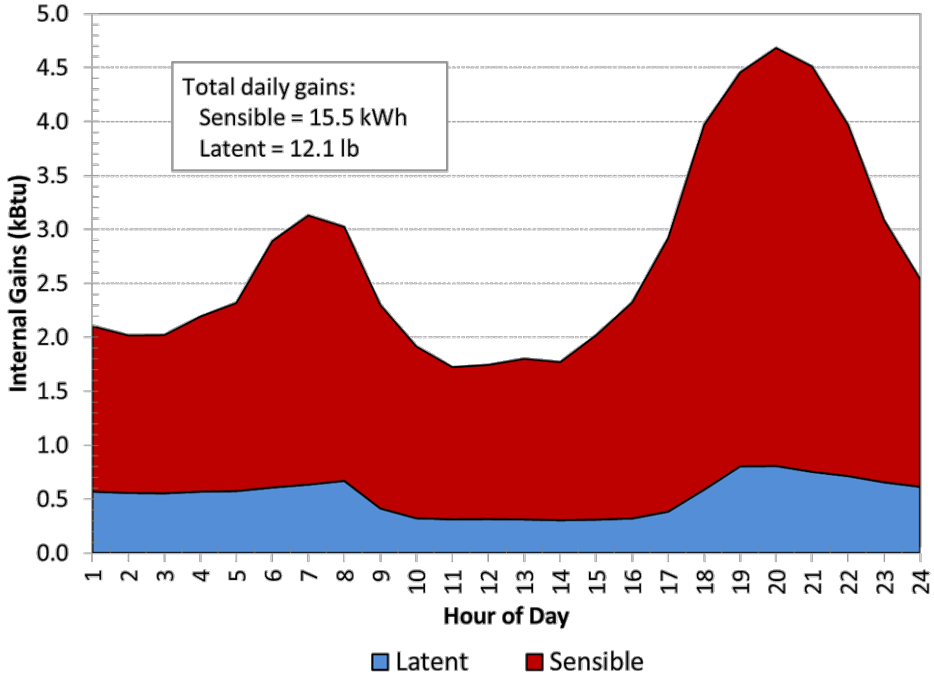

Figure 5. Daily load schedule for both homes

A second experiment was run whereby the latent loads were cut in half (6 lb/day), maintaining the same hourly profile but half the magnitude, in order to observe the effect on condensation and humidity levels.

2 Infiltration Experiment

2.1 House Leakiness

For the infiltration test, the west laboratory home served as the tight home and had the leakage sealed off at the ceiling plane. The leaky east laboratory home used the ceiling penetrations and window shims to obtain the results shown in Table 3.

Table 3. Leakage Measurements in Flexible Residential Test Facility for Experiment

Leakage Parameter	Leaky Home—East	Tight Home—West
CFM50	1,909	520
ACH50	7.99	2.18
C	177.3	36.0
n	0.607	0.683
R^2	0.9970	0.99983
ELA (in.^{2})	104.8	28.5
Specific Leakage Area	0.00053	0.000119

2.2 Data Collection

Details of the measurement capability are provided in the instrumentation plan (Vieira and Sherwin 2012). However, of particular interest for this experiment are the space and power measurements, which are presented in Table 4. Each of these values is taken every 10 seconds and averaged over 15 minutes, or for energy or consumption, summed over 15 minutes.

Table 4. Heating, Ventilation, and Air Conditioning and Power Measurement Sensor Plan

Performance	Location	Type	Thermocouple Channels	Millivolt Channels	Pulse
Supply T/RH	Duct	T/RH Volts		2	
Return T/RH	Duct	T/RH Volts		2	
End of Supply T/RH	Duct	T/RH Volts		2	
Airflow	Duct	Volts		2	
		Total		**8**	

Interior Room Conditions	Location	Type	Thermocouple Channels	Millivolt Channels	Pulse
Center T/RH	Center	T/RH Volts		2	
Center mrt	Center	TC	1		
Ceiling Surface	Center	TC	1		
Tstat T/RH	Tstat	T/RH Volts		2	
		Total	**2**	**4**	

Power/Use Measurements	Location	Type	Thermocouple Channels	Millivolt Channels	Pulse
Air Handler		Pulse W-h			1
Condenser		Pulse W-h			1
Interior Fans		Pulse W-h			1
Interior Lights		Pulse W-h			1
Outdoor Lights		Pulse W-h			1
Water Heater		pulse W-h			1
Total Use		**pulse W-h**			**1**

3 Winter Infiltration Test Results Without Mechanical Ventilation

As shown in Figure 6, temperatures were mild in January 2012 with two cold spells. In order to ensure some heating, thermostats in the laboratories were set to 72°F. Temperatures inside the two laboratories remained close, as shown in Figure 7, which indicates the profile for an average of each hour over the test period shown. Note that during some warm days, the temperature increased beyond the winter set point. No cooling was used for this test.

The heat was supplied by electric resistance furnaces. The energy use for each home for each day is shown in Figure 8, and the 24-hour cycle for the average day is shown in Figure 9. Due to the mild weather, there are some days without heating. Overall, there is about an 18.6% savings from the tighter home. Note that neither home has mechanical ventilation, and the result is based on a small amount of heating use. Also, there were some moisture concerns in the tight home.

The average daily cycle (each hour averaged for the time period) is shown in Figure 6.

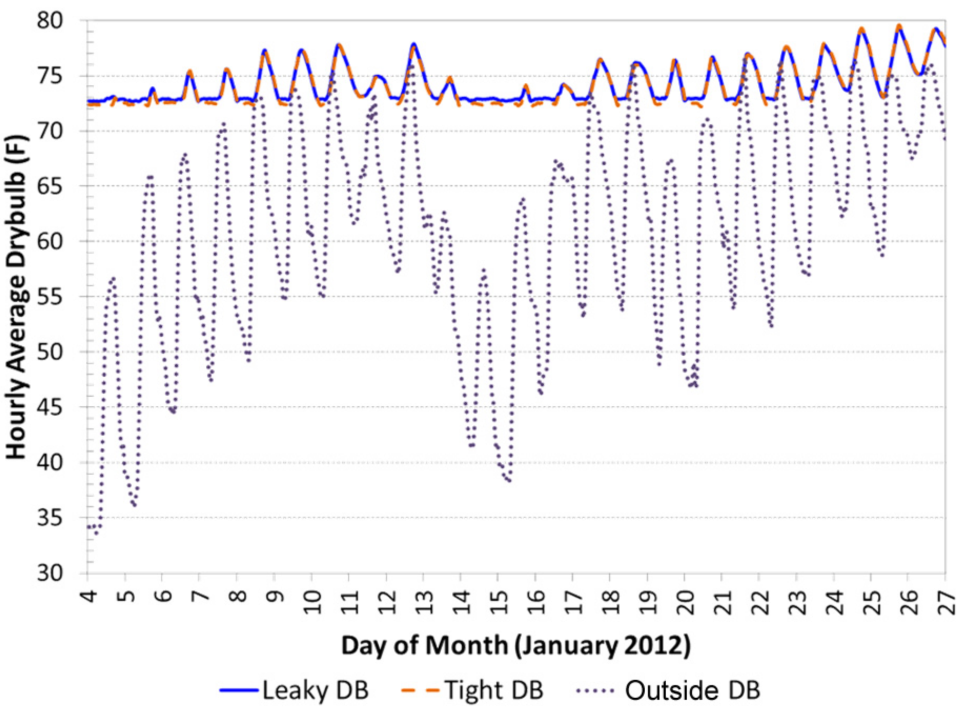

Figure 6. January outdoor and indoor temperatures

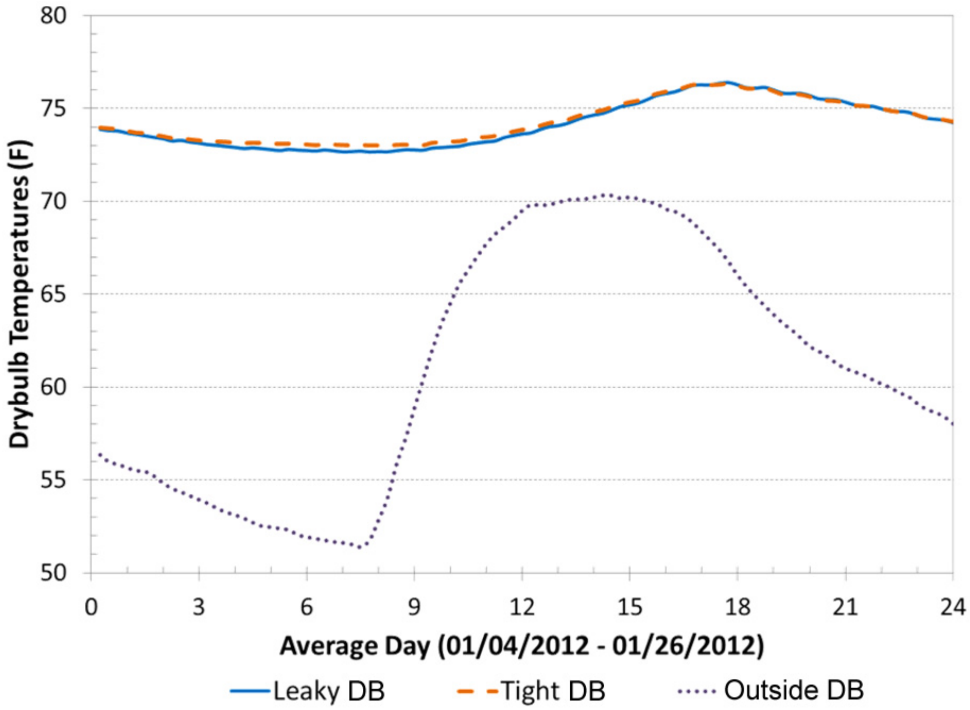

Figure 7. Twenty-four hour average cycle during January test period

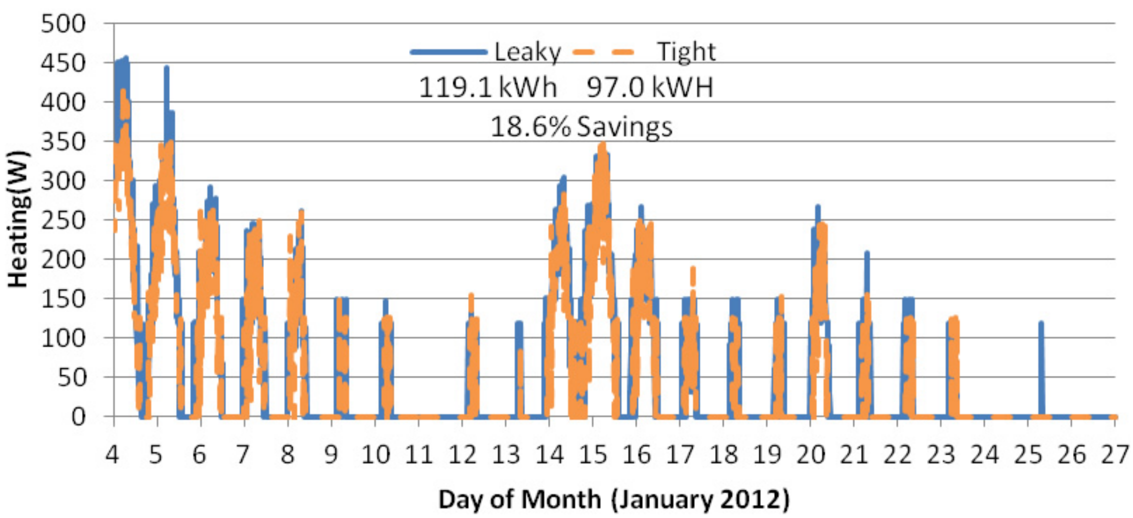

Figure 8. Comparison of leaky and tight home heating energy use for January 2012 by day of month

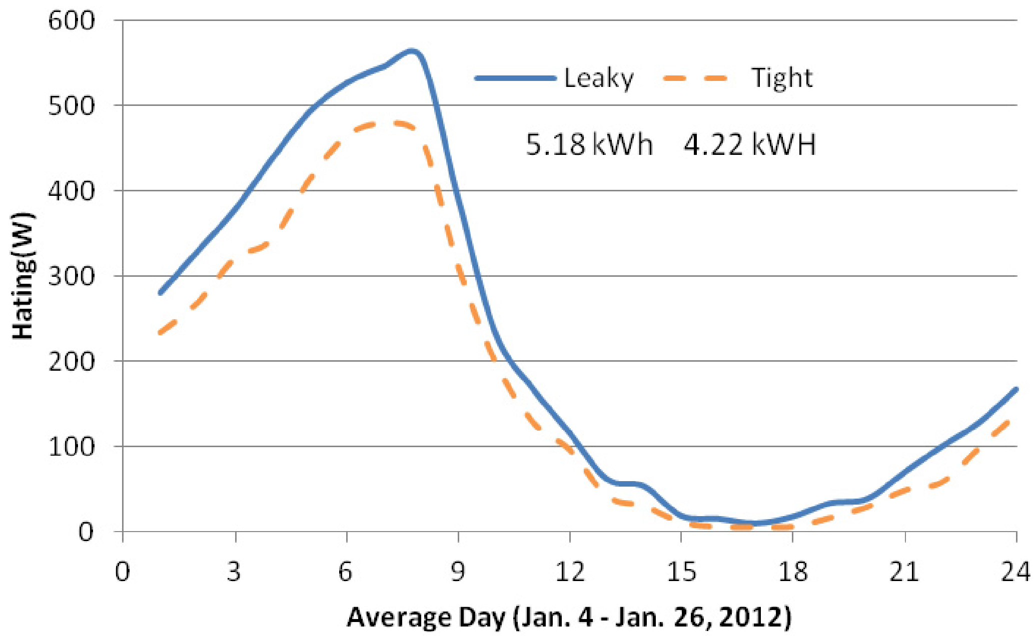

Figure 9. Average day heating energy use during January for leaky and tight homes

3.1 Tight Home Moisture Problems

Figure 10 plots the dew point inside each home and outdoors during January. Because of internal moisture generation, the moisture level in the homes is higher than outside. The leaky home dew point is 1°–2°F higher than outside typically, while the tight home dew point is ≥ 10°F higher than outside. This resulted in significant hours when the dew point temperature inside the tight home was likely higher than the window temperature. Unfortunately, the laboratory did not have a thermocouple measuring window temperature (one is being added). However, the resulting condensation was significant during cold spells (see Figure 11 to Figure 16). The windows are single-pane, typical of most existing residential central Florida homes.

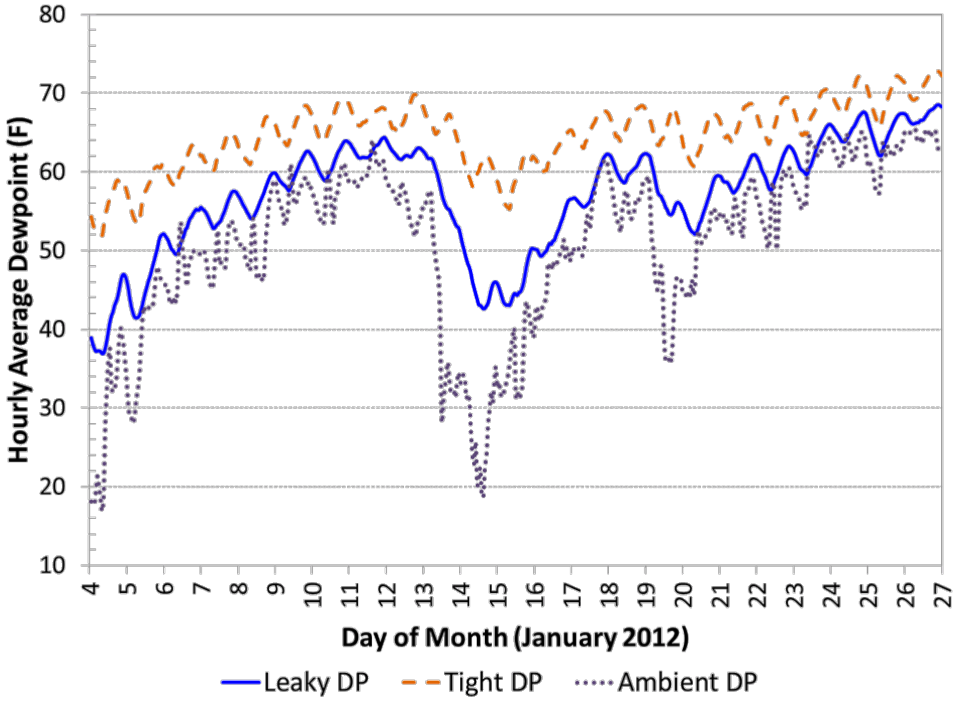

Figure 10. Dew points for tight and leaky homes for January 2012

Figure 11. Condensation occurs on all windows of tight building

Figure 12. Leaky building had no observed condensation

Figure 13. There appeared to be more condensation on the glass portion than on the screened portion of each tight home window

Figure 14. Considerable condensation accumulated

Figure 15. Tight home condensation residue by sliding glass doors

Figure 16. Mold surrounding a tight home window

3.2 Results With Reduced Internal Moisture Generation

Immediately following the January test period, the laboratory homes were dried out by eliminating internal moisture generation and air conditioning as much as possible. Internal moisture generation was cut in half from 12.10 lb/day to 6.05 lb/day. On February 8, the heating systems in both laboratory homes were reactivated. A cold snap on February 11–14 (see Figure 17) allowed additional measurements under the revised internal moisture generation schedule.

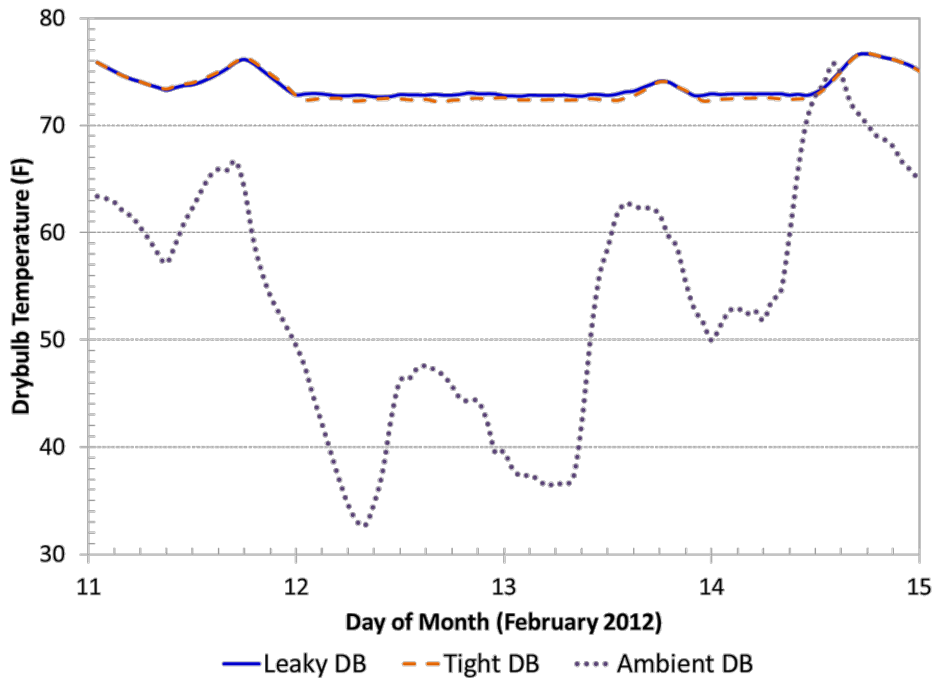

Figure 17. February outdoor dry bulb temperature during cold time period

The heating energy savings in the tight home were similar to the January tests but slightly less, with just 15.8% savings, as illustrated in Figure 18. The dew point temperatures inside the tight home were still considerably higher than in the leaky home (Figure 19). A peak difference between inside dew point and outside ambient of 19°F occurred during this cold spell (Figure 20). Condensation was observed during this cold spell even with the reduced moisture generation inside the home. However, the condensation was short-lived and did not create the mold as in earlier winter cold periods. Thermocouples were added to the glass and will be reported in future experiments.

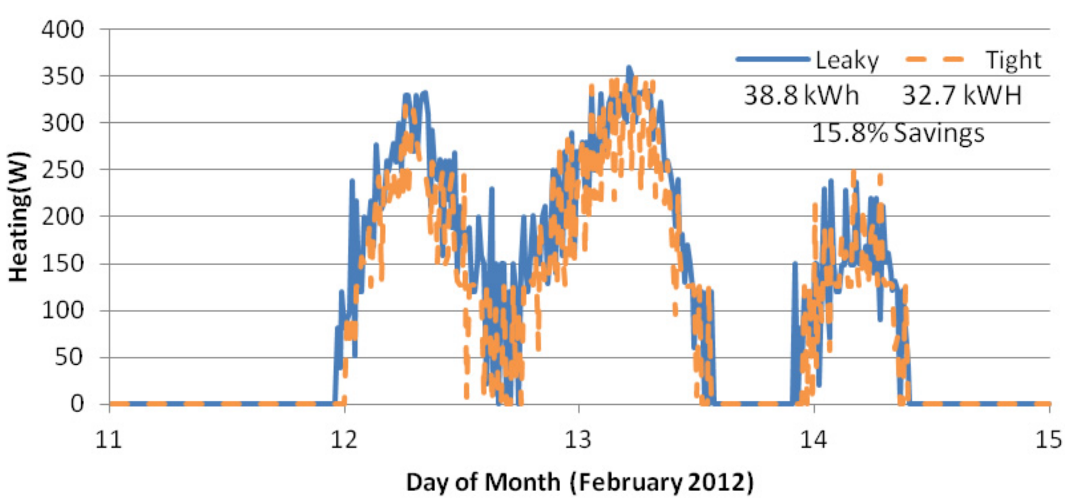

Figure 18. Heating energy use during February cold time period

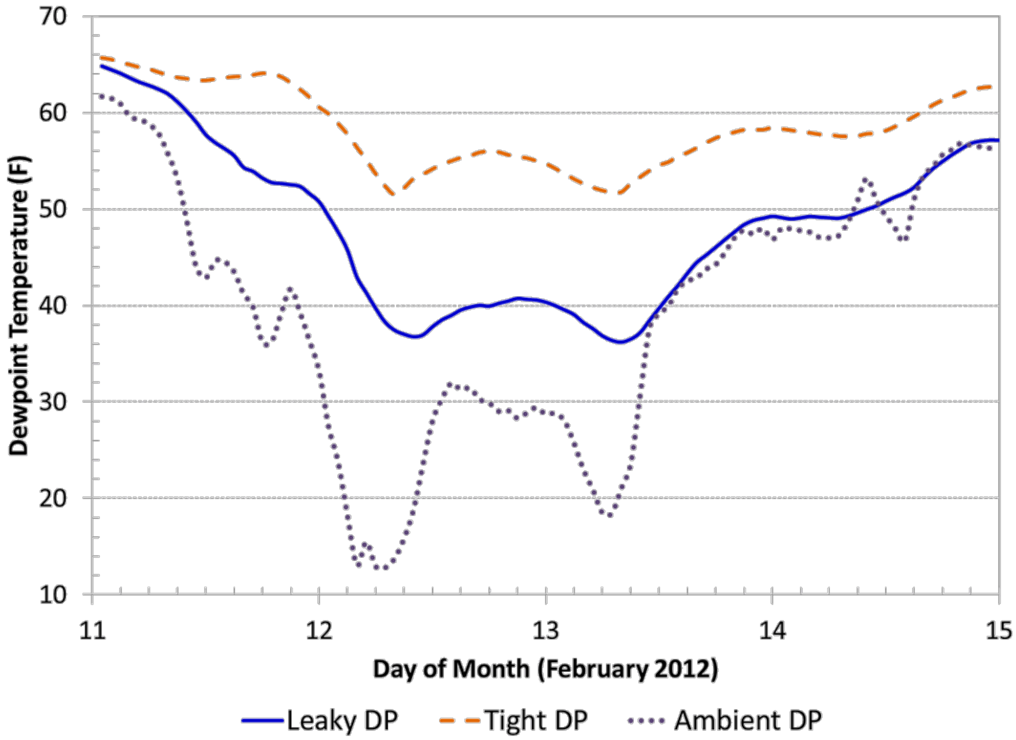

Figure 19. Dew point temperatures for February experiment

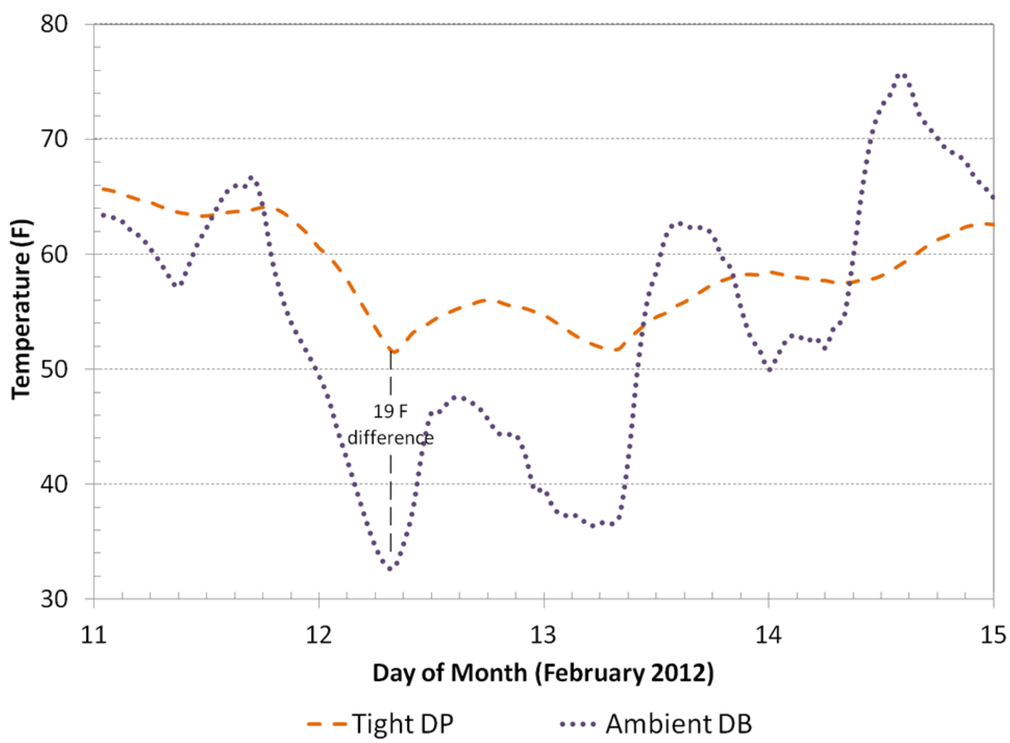

Figure 20. Tight house interior dew point temperature and outside dry bulb temperature. The large difference can lead to condensation on the interior of the single-pane windows.

4 Winter Infiltration Test Results With Mechanical Ventilation in Tight Building

For the winter of 2012–2013, a supply fan set for 63 CFM continuously was placed in the tight west building. The leaky east building remained the same with no ventilation. Both buildings used a schedule of 11 lb/day of internal moisture generation. This second winter of data was run with the fan on for about a 2-week cycle and then off for about a 2-week cycle. This allowed for repeating results from the first winter. Window temperature measurements were also added for the second winter.

4.1 Infiltration Measurements

Carbon dioxide (CO_2) dosing and measurement equipment were installed to measure infiltration in the two homes. The dosing equipment consisted of two parallel CO_2 tanks located in the garage and precisely metered on their release by digital flow meters that are recorded by instrumentation. Measurements came from Vaisala CO_2 transmitters with a full-range accuracy of $\pm$ 2%.

Ambient outdoor CO_2 sensors were also installed. Because the buildings are unoccupied, it is possible to measure the in situ building infiltration rate using the CO_2 gas emission rate as a tracer gas. The rise in the concentration of indoor CO_2 can be used to then estimate the building infiltration and ventilation rate with outdoor air. An initial problem with this setup was experienced when it became apparent that the outdoor CO_2 sensor had to be quite remote from the homes to prevent the effluent CO_2 from the leaking buildings from corrupting the reference outdoor CO_2 measurement. This tended to be more a problem with the ventilated west home, so the sensor outside the east home has been used as the ambient level for all analysis.

4.2 2012–2013 Winter Results

There were 60 days of good winter data collected continuously from December 24, 2012 through February 21, 2013. On February 22, the east oven controller that is used to deliver internal loads started to experience inconsistencies, and data from an early March cold period cannot be included. Figure 21 shows the ambient conditions during this period. Keeping in mind this is central Florida, there were four periods of heating. Figure 22 shows the daily watt-hours of electric resistance heating used in each unit as well as the status of the mechanical ventilation system in the tight building. A value of 1 represents the fan on all day, 0 off all day. For transition days, it depends on when the fan was turned on or off. For example, if the fan was turned off at 8:00 a.m., a value of 0.33 is shown. Only two transition days occurred on days with heating. Figure 23 shows the matching measured air exchange rate using the CO_2 sensors. The average values are shown in Table 5.

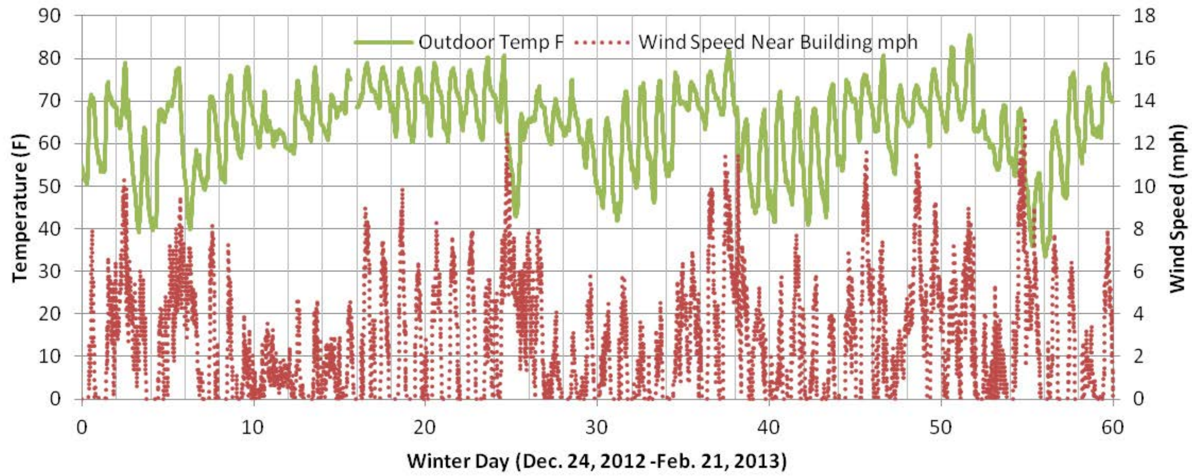

Figure 21. Ambient conditions winter 2012–2013

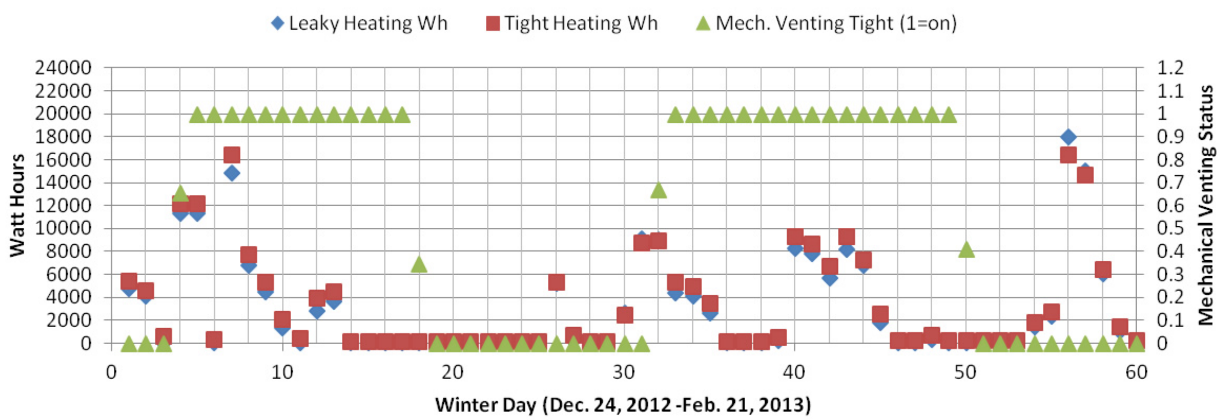

Figure 22. Heating energy use winter 2012–2013

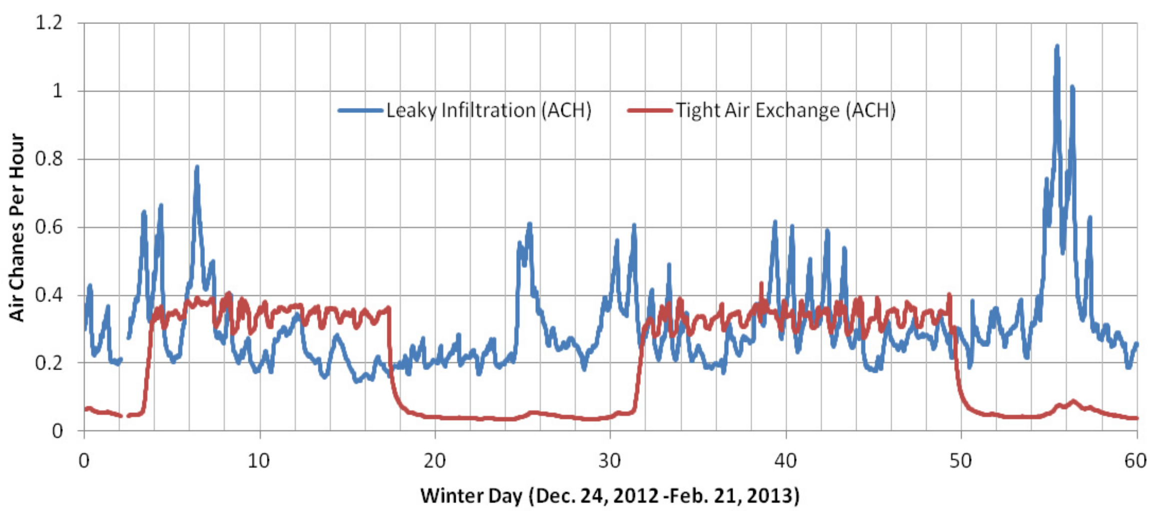

Figure 23. Air exchange rate winter 2012–2013

Table 5. Average Measured Air Exchange Winter 2012–2013

Ventilation Status	Data Points (15-min Measurements)	Leaky Home—East ACH Average From CO_2 Measurements	Tight Home—West ACH Average From CO_2 Measurements
Off	2,624	0.320	0.053
On	3,096	0.292	0.334

The measured heating energy use consistently shows greater heating use in the ventilated unit when the ventilation is on. The results for when the ventilation system is off are not as clear during the two cold spells in 2012–2013 as they were in 2011–2012. To estimate savings from one house to the next, only days with 1,000 Wh of heating were included to eliminate any significant measurement error during low standby time. Days of ventilation transition were not included. This left 11 days of heating when the vent fan was off. The total heating used in the leaky unit those days was 70.205 kWh, and the tight unit used 70.398 kWh with no significant difference.

There were 16 days of significant heating when the homes were ventilated. The total heating used in the leaky unit those days was 95.6 kWh, and the tight ventilated unit used 110.2 kWh or a 15.3% increase in heating energy use in the tight ventilated home relative to the leaky home.

A key preliminary finding was that while the impact of air infiltration on heating was unclear in the 2013 winter season, there were clear indications that mechanical ventilation led to an approximately 15% increase in space heating.

4.3 Condensation During Winter 2012–2013

As anticipated, condensation was observed in the tight unit during times of non-venting and not in the leaky home (see Figure 24 of condensation forming on January 23). Condensation was not observed in the tight unit during times of ventilation.

Figure 24. Unvented tight house north-facing window condensation January 23, 2013

Dew point and window temperature data are shown for two such days, January 23 and February 17 in Figures 25 and 26. The dew point temperature in the tight west home is ≥ 10°F higher than the leaky east home. The tight home window temperature is at times lower than the dew point leading to the observed condensation. Two interior window temperature measurements are shown from the same North-facing window, one from the lower portion of the single-hung window that was semi-protected by a window screen, and one from the upper half that did not have a screen.

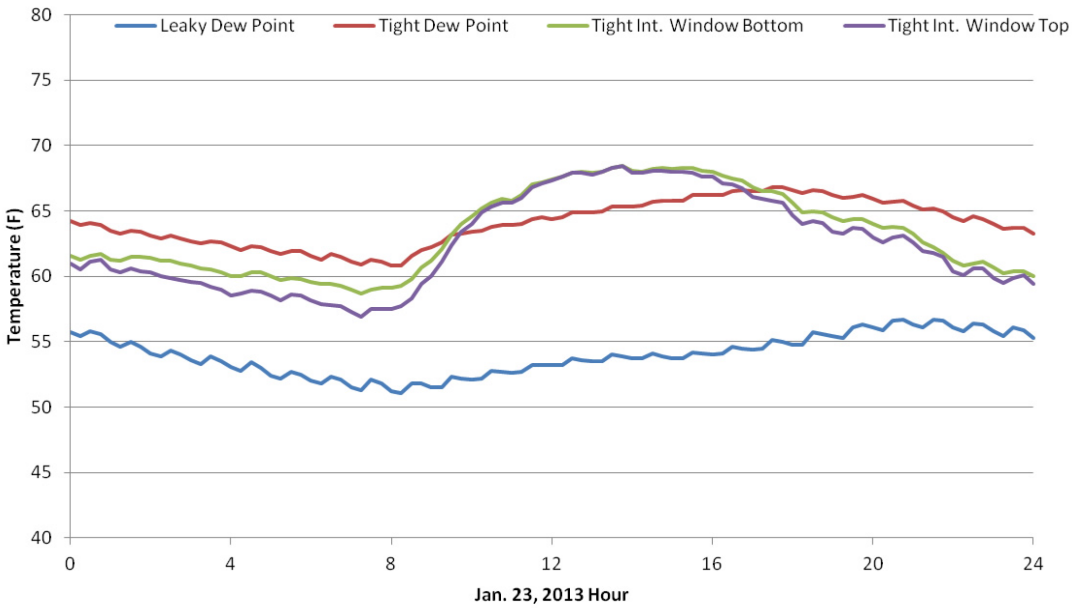

Figure 25. Unvented tight house dew point and window temperatures January 23, 2013

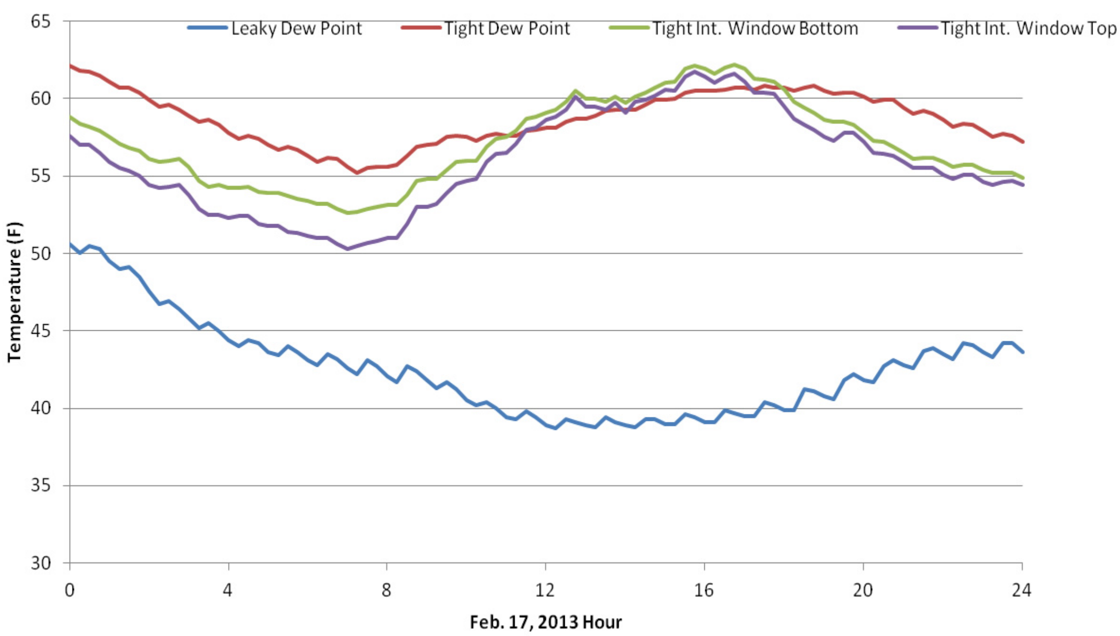

Figure 26. Unvented tight house dew point and window temperatures February 17, 2013

All of the temperatures are consistently 3°–4°F below the inside dew point during the night, such that condensation can form. Note that at night the temperature of the upper glass is cooler than the lower glass, indicating some thermal insulation influence from the insect screen. During the day the temperatures become more even, perhaps due to more indirect solar heating on the top portion of the window.

5 Conclusions

Two identical laboratory homes designed to model existing Florida building stock were sealed and tested to 2.2 ACH50. Then, one was made leaky with 70% leakage through the attic and 30% through the windows, to a tested value of 8 ACH50. Two winters of data were recorded. In the first winter, there was no mechanical ventilation in either home. In the second winter, a mechanical ventilation system was operated in the tighter home during most of the cold periods.

For the first winter, reduced energy use was measured in the tighter home (2.2 ACH50) in the range of 15.8%– 18.6% relative to the leaky (8 ACH50) home. Internal moisture loads resulted in higher dew points inside the tight home than the leaky home. The homes have single-pane glass representative of older central Florida homes. Window condensation and mold growth occurred inside the tight home. Even cutting internal moisture gains in half to 6.05 lb/day, the dew point of the tight home was more than 15°F higher than the outside dry bulb temperature. There are a few factors that may limit the representation of these results regarding condensation:

- The laboratory homes have very little moisture capacitance, as they contain no interior walls, no furnishings, and no carpeting (slab is exposed).
- There was neither mechanical ventilation nor operation of windows. The weather was largely comfortable for much of the test period, and some residents would likely open up the homes for most periods during this time.
- The homes were only one year old when the testing took place. There is likely still some drying out of the slab and concrete block walls not typical of older homes.

The results presented alter just one variable—the air infiltration rate. To reduce condensation problems, there are steps practitioners may take coincident with tightening an older home. If the efficiency measures include window replacement, a low U-value for the window can be selected to avoid condensation. Also, mechanical ventilation can be introduced, which will likely reduce humidity in the home during winter. Judicious use of operable windows during mild periods with no space conditioning will also likely be helpful in reducing moisture problems.

For the second winter, condensation was observed again when the supply ventilation fan was off. Inside window temperatures were lower than the inside dew point on cold winter nights. However, condensation was not observed when the ventilation fan was on, or in the leaky home. This indicates that tight construction in humid climates will risk window condensation and high interior humidity levels without mechanical ventilation.

Heating energy use in the tight, but ventilated home was 15% higher than in the leaky home with natural air infiltration only. This may argue for heat recovery ventilation for such systems to offset heating related impacts.

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