FLORIDA SOLAR ENERGY CENTER®

Executive Summary: Evaluation of the Impact of Vacant Home Space Conditioning Strategies on Summer Relative Humidity, Energy, and Peak Load; Phase II

Authors

James B. Cummings, Charles R. Withers, Jr.,
Danny S. Parker, Carlos Colon

Original Publication

Cummings, J., Withers, C., Parker, D., Colon, C., "Executive Summary: Evaluation of the Impact of Vacant Home Space Conditioning Strategies on Summer Relative Humidity, Energy, and Peak Load; Phase II ", Submitted to: Craig V. Muccio, General Office of Florida Power & Light, FPL PO # 4500292934; C # 4600002848, FSEC Project # 20128099, December 18, 2006.

Publication Number

FSEC-CR-1626-06

A Research Institute of the University of Central Florida
1679 Clearlake Road, Cocoa, FL 32922-5703 • Phone: 321-638-1000 • Fax: 321-638-1010
www.fsec.ucf.edu

Executive Summary

The Vacant Home Space Conditioning Study was sponsored by Florida Power & Light (FPL) as part of its Conservation R&D Program and carried out by the Florida Solar Energy Center (FSEC). In the US, about one in four retiree "snowbirds" make Florida their destination to escape the northern cold. Snowbird residents number more than 900,000 in Florida during the winter. In some counties of FPL's territory these seasonal residents compose up to 15% of the population (Shih, 1981). This pattern of seasonal occupancy creates a need for space conditioning guidelines for vacant homes to avoid mold problems while minimizing both customer energy usage and electrical load during utility peak hours.

In 2004, a Phase I Snowbird project was carried out. Three homes on Florida's east coast in Brevard County were equipped with monitoring equipment for the experiments. The first was a 45-year-old 1100 ft^2 single-story, painted concrete block home on a concrete slab with a low pitch tar and gravel roof. The second house was a 40-year-old 1950 ft^2 split-level home, with block and frame construction. The third home was a 900 ft^2 single-wide mobile home manufactured in 1984. All three test-homes had 2.5-ton central air conditioning (AC) systems with heat pump, gas, and electric strip heating, respectively.

Five space conditioning strategies for vacant homes were assessed during hot, humid summer conditions and/or warm, humid fall weather conditions. The aim was to control relative humidity (RH), minimize energy use, and limit peak electrical demand. The five approaches were: 1) no space conditioning as the baseline, 2) AC thermostat set at 85^{o}F or 83^{o}F, 3) morning AC operation at 74^{o}F, 4) dehumidifier alone, and 5) space heating.

An important observation was that some homes require more aggressive action to control RH than others. Air infiltration was found to be an important factor in the struggle against high indoor RH. Air infiltration, usually measured in air changes per hour (ach), is the rate at which outside air enters the house. Homes that have higher infiltration rates require greater moisture removal rates to achieve RH control.

Conclusions from the Phase I Study (2004)

Not recommended. Two methods were identified as “not effective”.

- Letting the house “float” (no space conditioning) cannot reliably achieve RH below 65% most of the time.
- Setting the AC system to 85^{o}F, or even 83^{o}F, is not sufficient, especially on humid and cloudy days, to achieve RH control. Furthermore, this approach imposes maximum demand during the utility’s peak period of noon to 9 PM.

Recommended. Three methods were found to be “effective”. These methods show considerable promise, each showing the ability to control indoor RH with reasonable energy and peak demand impacts. None of these methods stands out as being substantially better than the others within the limited sample of homes.

- Running the AC system “flat out” for two (or more) hours in the early morning appears to work well in a majority of homes and under a wide range of weather conditions. In homes with high infiltration rates, AC operation time may need to be extended to adequately control RH. Lower thermostat settings may be necessary during cooler weather for light mass (i.e., manufactured) homes.

- Dehumidifier on a timer is effective and reliable in controlling RH at a reasonable energy cost. Dehumidifier run time must be determined based on the size and airtightness of the house, generally using a trial and error approach. A floor fan (or two) can be plugged into the same timer to distribute the heat and dryness produced by the dehumidifier.
- Heating the house to about 89^{o}F lowers indoor RH quite effectively for nearly all hours of the summer without removing moisture from the room air. Energy use is moderate for the period June through September, but increases substantially in spring and fall.

Energy consumption. Each of the recommended approaches was found to use only modest amounts of energy, on the order of $20-$40 per month (assuming space heating with a heat pump and $0.12 per kWh). Energy consumption for approaches using the AC system or a dehumidifier increased substantially with higher natural infiltration rates. An important lesson; a tight house envelope saves considerable energy when conditioning an unoccupied building, especially when using either the AC system or dehumidifier to remove moisture from the indoor air. Space heating uses considerably more energy than the other two approaches during cooler months (e.g., May and October). Humidistat control may substantially reduce heating energy use. The Phase II study examined humidistat control of both space heating and dehumidifiers. Space heating is about four times more energy efficient using a heat pump compared to strip heat. With either heat source, the peak demand to the utility is minimal since no space heating was required from 12 - 9 PM on hotter than average summer days for all three homes. Thermostat programming could, of course, be used to disable the heating system during the utility's peak demand period.

Overview of the Phase II Study (2005)

A total of four homes were studied. Three were either stand-alone homes or a duplex. The other was a condominium located on the third floor of a four-story building. Condo units were expected to respond differently to various RH control measures. An important objective of the Phase II experiments was to explore RH control strategies for residential units embedded in a larger building, where heat originating from outdoors is minimal. Table ES-1 summarizes information about the four houses.

Table ES-1. Characteristics of four residences used in the Phase II study.

HOUSE #	Building Type	County	Size (ft^2)	# Stories	Duct $Q_{25,out}$	RLF (%)	ACH50	Natural Infiltration (ach)
1	Duplex	Brevard	1722	1	199	13.2	6.6	0.17
2	Stand alone	Brevard	2317	2	270	13.1	7.6	0.36
3	4 story condo	St. Lucie	1136	1	NA	0.0	17.1	0.35 *
4	Stand alone	Brevard	1100	1	60	0.8	8.5	0.05

* Tracer gas decay calculation yields natural infiltration of 0.26 ach. However, taking into account measured and estimated tracer gas in adjacent "conditioned" spaces, natural infiltration from outdoors and adjacent conditioned spaces is estimated to be 0.35 ach. Note that adjacent "conditioned" spaces were typically only slightly conditioned.

In Houses 1 – 3, five different experiments were performed (see Table ES-2). In House 4, three different experiments were performed, each with three different imposed infiltration rates.

Another important objective of the Phase II experiments was to examine the RH impacts of varying infiltration rates, and from that develop guidance regarding how long systems that are controlled on a schedule should operate. The infiltration rates imposed on House 4 were generally in the range of 0.15 ach, 0.30 ach, and 0.45 ach, with some variations.

Table ES-2. Experiments carried out in the four residences.

HOUSE #	AC ON at 71°F from 3-5 AM	AC ON at 80°F from 9 PM-noon	Dehumidifier with Timer	Dehumidifier with Humidistat	Space Heating at 89°F
1	X	X	X	X	X
2	X	X	X	X	X
3	X	X	X	X	X
4	X	X	X		

Infiltration Rates. Tracer gas decay tests were performed. The natural infiltration rate in these houses ranged from 0.05 to 0.36 ach. Natural infiltration is the exchange of outdoor and indoor air caused by the natural forces of wind and temperature difference with all mechanical air moving systems turned OFF. When the air handler was turned ON, the infiltration rate increased typically by a factor of 2 or 3 in Houses 1, 2, and 3. This substantial increase in infiltration during AH operation has the effect of drawing hot and humid air into the residence, but only during the period when the AH operates. During the portion of the day that indoor conditions "float" (no mechanical system operation), the lower natural infiltration rate will be in effect.

During the tracer gas decay test, the return leak fraction was also measured. This is the portion of the return air that originates from outside the conditioned envelope of the building. Both return and supply duct air leakage contributes to the higher infiltration rate with the air handler operating, and also reduces the ability of the cooling system to produce low RH in the space.

Experimental Results

The first approach, *AC set at 71°F from 3-5 AM* (fan AUTO), was examined in all four houses. Generally, this approach yielded good results.

- In House 1 (duplex), this approach provided good RH control during June, October, and November test periods. RH levels averaged 57% (67% peak), 57% (67% peak), and 57% (60% peak), respectively. Energy use was 5.5, 7.6, and 0.1 kWh per day, respectively. The AC essentially did not run during the cool November period. A relatively low infiltration rate (0.17 ach) also helps maintain interior dryness during the AC OFF periods.
- House 2 (2-story), this approach provided unacceptable RH control during June/July and October test periods. RH levels averaged 64% (69% peak) and 68% (72% peak), respectively. Energy use was 5.8 kWh per day during each test. Two factors contribute to this failure. First, large duct leaks reduce the effectiveness of the AC system while running. Second, the relatively high infiltration rate (0.36 ach) allows substantial moisture flows into the house. It is probably evident how return leaks bring additional heat and water vapor into the house, and thereby reduce the effectiveness of the AC

system as a dehumidifier. Supply leaks, however, also cause high moisture content air to be drawn into the house. When the supply air leaks to the attic, for example, it causes depressurization of the house, which in turn causes hot and humid air to be drawn into the house. Furthermore, supply leaks significantly reduce total latent and sensible cooling capacity, making the AC system less effective at lowering house RH. In House 3 (condo), this approach provided unacceptable RH control during a June test period (Figures ES-1 and ES-2). RH level averaged 66.5% (78% peak). Energy use was 6.3 kWh per day. The relatively high infiltration rate (0.35 ach) allows substantial moisture flows into the house from outdoors and from adjacent spaces (split unknown). Expanding the AC run time from two to four hours yielded a significant improvement (to acceptable RH control) during a June/July time period (Figures ES-3 and ES-4). The expanded AC run time was insufficient, however, to provide acceptable RH control during a September test period (Figures ES-5 and ES-6). RH levels averaged 61% (70% peak) and 62% (76% peak), respectively. Energy use for the expanded AC operation was 10.4 and 10.5 kWh per day, respectively. An interesting pattern is observed for the condominium building, which affects RH in the condo unit. On sunny (which are also typically hotter) days the RH level in the building drops, because most of the condo units are set to 80^{o}F. The drier air produced by AC systems located in other condo units throughout the building causes a substantial drop in RH in the test condo unit. Conversely, during cloudy weather, RH levels in the test condo rise substantially.

- In House 4 (1-story), this approach provided good RH control at all levels of infiltration. When we include a test performed in the 2004 Phase I project (0.05 ach), tests are now available for four levels of infiltration 0.05, 0.15, 0.30, and 0.36 ach. These four tests occurred during September (2004) and June, October/November, and September 2005, respectively. There is a general pattern of rising indoor RH as infiltration increases (with the exception of the cooler test period falling in October/November). RH levels averaged 48% (58% peak), 56% (64% peak), 60% (63% peak), and 59% (63% peak), respectively. Energy use was 7.2, 5.2, 2.2, and 5.5 kWh per day during these tests, respectively.

<u>The second approach</u>, *AC set at 80^{o}F from 9 PM - noon (or 9 PM to 7 AM)* (fan AUTO) was examined in all four houses. Generally, this approach yielded good results but it has some disadvantages.

- In House 1 (duplex), this approach was examined at three thermostat setpoints.
  - This approach with an 80^{o}F setting provided good RH control during a July test period. The RH level averaged 57% (62% peak). Energy use was 5.9 kWh per day. Temperature, RH, and power results are shown in Figures ES-7 and ES-8.
  - When the thermostat setpoint was raised to 82^{o}F, the AC system continued to provide good RH control. RH levels averaged 58% (62% peak), 61% (65% peak), 61% (67% peak), and 60% (64% peak) during July, August, October, and November test periods, respectively, at the 82^{o}F setting. Energy use was 3.1, 1.5, 0.0, and 0.0 kWh per day during these tests, respectively. No AC operation occurred during the latter two test periods. Temperature, RH, and power results are shown in Figures ES-9 and ES-10.
  - When the thermostat setpoint was raised to 84^{o}F, the AC system provided good RH control. The RH level averaged 60% (64% peak). The AC system ran little during this typical July/August test period. Energy use was 0.5 kWh per day. An

assessment was made that the 84^{o}F thermostat setting would certainly not provide adequate RH control during cooler and more cloudy weather.
    - A relatively low infiltration rate (0.17 ach) helps maintain interior dryness when the AC system is OFF.
- In House 2 (2-story), this approach was examined at three thermostat setpoints.
    - This approach with an 80^{o}F setting provided good RH control during a July test period with 15 hour per day operation. The RH level averaged 58% (65% peak). Energy use was 14.1 kWh per day. This approach with an 80^{o}F setting provided very good RH control during a July test period with 10 hour per day operation. The RH level averaged 55% (61% peak). Energy use was 13.7 kWh per day.
    - When the thermostat setpoint was raised to 82^{o}F, the AC system provided marginal RH control during an August test period. The RH level averaged 62% (65% peak). Energy use was 4.0 kWh per day. During a cool and cloudy period in September, the AC system provided unacceptable RH control. The RH level averaged 70% (76% peak). Energy use was 1.5 kWh per day. Because of the relatively high natural infiltration rate of this house, considerably more AC run time is required compared to House 1 in order to control indoor RH. Figure ES-11 illustrates that an 82^{o}F setting results in little to no AC run time during cloudy and humid weather, and very elevated indoor RH.
    - When the thermostat setpoint was raised to 84^{o}F, the AC system provided good RH control. The RH level averaged 59% (63% peak). This was an exceptionally hot and sunny period in late July. Energy use was 4.0 kWh per day. An assessment was made that the 84^{o}F thermostat setting would certainly not provide adequate RH control during cooler and more cloudy weather, and would most likely not even provide adequate RH control during average summer weather conditions.
    - Conclusion: In this instance, use of the AC system to control indoor RH requires high levels of energy consumption. The reason: a high infiltration rate (0.36 ach) introduces considerable moisture into the house. During less sunny periods, the 80^{o}F setting is required to obtain reasonable RH control. During sunny weather, the high solar loads cause the AC to run for extended periods, creating excessive energy use. If this house were more airtight, then the thermostat could be raised to 84^{o}F and most likely still maintain reliable indoor RH.
- In House 3 (condo), this approach was examined at several temperature settings.
    - At an 80^{o}F setting (24 hours per day), this approached produced unacceptable RH control during a July test period (Figure ES-12). The RH level averaged 71% (72% peak). Since the AC did not turn ON during this one-week test period, energy use was 0.0 kWh per day.
    - At a 77^{o}F setting, this approached also produced unacceptable RH control during a July test period (Figures ES-13 and ES-14). The RH level averaged 75% (81% peak). This was a generally cloudy period with exceptionally high outdoor dew point temperatures. Energy use was 3.6 kWh per day. The modest AC operation time was totally unable to match the high rate of moisture introduction produced by the relatively high infiltration rate (0.35 ach).
    - At a 74^{o}F setting, this approach did produce acceptable RH control during a July test period (Figures ES-15 and ES-16). The RH level averaged 58% (70% peak).

This was a moderately sunny period with high outdoor dew point temperatures. Energy use was 11.3 kWh per day. The greatly increased AC operation time was able to match the high rate of moisture introduction produced by the relatively high infiltration rate (0.35 ach).

    - It is clear that dwelling units located inside of larger, multi-story buildings behave differently from stand-alone houses (or even duplexes). Because this embedded condo unit receives little heat (sensible cooling load) from outdoors, use of cooling load (such as with the AC at 80^{o}F (or 74^{o}F in condo) from 9 PM to 7 AM) to drive the AC system operation is the reverse of what is needed. This is especially true in this building where other condo units are set to 80^{o}F, and therefore operate considerably during hot and sunny weather. The entire building RH drops substantially during sunny and warmer weather. The dryer air produced throughout the building causes a substantial drop in RH in the test condo unit. In this building, best practice would require a control strategy that runs the AC much more on cloudy and cooler days.

- In House 4 (1-story), this approach provided marginal-to-very good RH control depending upon the weather patterns and various infiltration rates. Again, weather conditions are more dominant than the infiltration rate.
    - At 0.15 ach, this approach yielded very good RH control. The RH level averaged 53% (62% peak).
    - At 0.30 ach, this approach yielded exceptionally good RH control during a hot and sunny period in July. The RH level averaged 50.5% (56% peak).
    - At 0.30 ach, this approach yielded marginal RH control during a moderately cloudy and very humid period in October (including 60 mph winds from Hurricane Wilma). The RH level averaged 63% (66% peak).
    - At 0.45 ach, this approach yielded good RH control during typical August weather. The RH level averaged 57% (63% peak).
    - Because of limited attic insulation, and the continuous exhaust operation that was causing the house to draw air largely from the attic, AC operation in this house is exceptionally sensitive to solar radiation levels. We conclude, therefore, that "AC at 80^{o}F from 9 PM to 7 AM" is not an energy efficient way to control RH. An alternative approach that provides a fixed amount of AC operation per day (such as the "AC at 71^{o}F from 3 AM to 5 AM") would be much better. Even better, an approach that operates the AC system in response to indoor RH would be best. See "conclusions" at the end of the Executive Summary for an improved RH control approach.

<u>The third approach</u>, *dehumidifier on a timer from 8 - 11 AM*, was examined in all four houses. Generally, good results can be obtained with sufficient dehumidifier run time. The length of required dehumidifier run time is largely a function of the natural infiltration rate of the house.

- In House 1 (duplex), this approach provided good RH control during a September test period (Figures ES-17 and ES-18). RH levels averaged 62% (67% peak). Energy use was 1.9 kWh per day. A relatively low infiltration rate (0.17 ach) also helps maintain interior dryness during the dehumidifier OFF periods.
- In House 2 (2-story), this approach provided marginal RH control during a test period in August. RH levels averaged 66% (68% peak). Energy use was 2.2 kWh per day,

including floor fan energy. A relatively high natural infiltration rate (0.36 ach) causes indoor RH levels to increase fairly rapidly during the dehumidifier OFF periods. Because of the higher natural infiltration rate, dehumidifier run time would need to be increased to an estimated 5 hours per day to achieve acceptable RH levels, which would require 3.7 kWh per day energy use.

- In House 3 (condo), this approach provided acceptable RH control during a test period in July/August when the dehumidifier operation time was increased to six hours per day (Figure ES-19). RH levels averaged 57% (64% peak). Energy use was 3.7 kWh per day, including floor fans. A relatively high natural infiltration rate (0.35 ach from outdoors and adjacent spaces combined) causes indoor RH levels to increase fairly rapidly during the dehumidifier OFF periods. Note that operation of the dehumidifier pushes up the indoor temperature from 80°F to 82.5°F as a result of the heat given off by the dehumidifier (electrical energy heat and moisture condensation heat). About 5 percentage points of the RH reduction occurring in this condo unit is the result of heating of the indoor space.
- In House 4 (1-story), this approach provided marginal to good RH control depending upon the weather patterns and various infiltration rates.
  - When we include a test performed in the 2004 Phase I Project (0.05 ach), results are then available for five levels of infiltration 0.05, 0.15, 0.22, 0.30, and 0.45 ach. Figure ES-20 shows the temperature, RH, and power response for 3 hours per day dehumidifier operation with the ventilation rate set to 0.22 ach. These five tests occurred during August/September (2004), October, September, August, and August/September, respectively. There is no general pattern of rising indoor RH as infiltration increases. Again, weather conditions are more dominant than the infiltration rate. RH levels averaged 56% (63% peak), 65.5% (67% peak), 63% (68% peak), 59% (62% peak), and 63.5% (65% peak), respectively. Energy use was 2.1 kWh per day for each of these test periods, including floor fans.
  - Following are estimates that have been developed by project staff for dehumidifier runtimes required to achieve acceptable RH for House 4.
    - 1.5 hours per day for 0.05 ach.
    - 2.5 hours per day for 0.15 ach.
    - 3.5 hours per day for 0.30 ach.
    - 4.5 hours per day for 0.45 ach.

<u>The fourth approach</u>, dehumidifier controlled by a humidistat, was examined in three of the four houses. Generally, it appears that a dehumidifier controlled by a humidistat can achieve acceptable RH control in all of the tested houses (including the condo), but problems remain in achieving the desired humidistat control setting and regarding humidistat drift problems.

- In House 1 (duplex), this approach provided marginal RH control during an August test period. RH levels averaged 64% (68% peak). Energy use was 0.6 kWh per day. A relatively low infiltration rate (0.17 ach) helps reduce the dehumidifier operation time by limiting the entry rate of outdoor water vapor. In order to achieve acceptable RH control, the humidistat would have to be set to a lower setting. The 62.5% setting that was used produced about 64% in the living room and 68% in the bedroom. It appears that a setting of 60%, for this particular humidistat, would likely achieve our objective of controlling RH at 65% or lower during most hours. Dehumidifier energy use would of course increase substantially with the lower RH setting, but would still be quite reasonable. Given that three hours of dehumidifier run time per day (with timer control and 2.1 kWh per day energy use) yielded 62% (67% peak), suggests that dehumidifier energy use of about 3 to 4 kWh per day would yield the desired RH control for this house.

- In House 2 (2-story), this approach provided unacceptable RH control during two test periods in September and October. RH levels averaged 68% (70% peak) and 68.5% (69% peak), respectively. Energy use was 2.4 and 1.5 kWh per day, respectively, including the floor fans. In order to achieve acceptable RH control, the humidistat would have to be set to a lower setting. The 62% setting produced an average RH of about 67% in the living room and 68% in the bedroom. It appears that a setting of 58%, for this particular humidistat, would likely achieve our objective of controlling RH at 65% or lower during most hours. Dehumidifier energy use would increase substantially with the lower RH setting, but would still be moderate. Given that three hours of dehumidifier run time per day (with timer control and 2.2 kWh per day energy use) yielded an average 66% RH (68% peak), suggests that dehumidifier energy use of about 5 to 10 kWh per day would yield the desired RH control for this house. The split-level house in the Phase I study, which had a high natural infiltration rate of 0.43 ach, required 15 hours per day to maintain acceptable RH. Given that House 2 (Phase II) has a lower natural infiltration rate and operates at higher temperatures (because of the extensive east and west window areas), it is likely that 8-10 hours per day (5.9 to 7.3 kWh per day) would be required for this house. Even at 10 hours per day, the monthly energy cost (at $0.12 per kWh) would only be $26.
- In House 3 (condo), this approach provided marginal RH control during a period in August (Figure ES-21). RH levels averaged 64% (70% peak). While the humidistat was set to 57%, actual room RH averaged63% (in the bedroom where the humidistat was located) for about one week, and then without explanation room RH jumped up to about 68%. This indicates that there is need for improved humidistats. Energy use was 1.8 kWh per day. Setting the humidistat to a lower level, such as 54% would likely allow the dehumidifier to meet our RH control objective of keeping RH at or below 65% most of the time. Given that six hour of dehumidifier operation (with timer control) was sufficient to yield acceptable RH control (58% average and 64% peak with 3.7 kWh per day energy use), we would expect that energy use with an appropriate humidistat RH setting would use on the order of 4 kWh per day. At $0.12 per kWh, this would still be a modest $15 per month energy cost.

<u>The fifth approach</u>, space heating controlled by a humidistat, was examined in three of the four houses. Generally, it appears that space heating controlled by a humidistat can achieve acceptable RH control in all of the tested houses (including the condo). Use of a humidistat (compared to use of a thermostat set to 89^{o}F) to control the heating system reduces energy use dramatically, especially during cooler months such as May, October, and November.

- In House 1 (duplex), this approach provided acceptable RH control. Heat is provided by a gas furnace.
  - During a September test period, with the humidistat set to 62%, the room RH level averaged 62% (65% peak) (Figure ES-22). Energy use was 105,000 Btu per day. In order to achieve acceptable RH control, the humidistat would have to be set to a slightly lower setting. If the system had been a heat pump with a COP of 4

(at summer temperatures), the heating energy use would have been 7.7 kWh per day (or $28 per month).
    - During a test period in October/November, with the humidistat set to 62%, the room RH level averaged 60% (62% peak). Energy use was 12,400 Btu per day over the entire period. The heating system was operational for only one of the 26 test days, because outdoor dew point temperatures were low enough to control indoor RH to below the humidistat setpoint. If the system had been a heat pump with a summer weather COP of 4, the heating energy use would have been 0.9 kWh per day (or $3.30 per month). This illustrates how a humidistat can eliminate most of the heating requirement during cooler portions of the snowbird season.
    - It is interesting that the indoor RH level closely matched the humidistat setting during these heating experiments. It may be that the humidistat is sensitive to room temperature, and that at higher temperatures (such as 88^{o}F to 90^{o}F) the humidistat dial settings are more accurate. This was not investigated in this project.
- In House 2 (2-story), this approach provided marginal RH control. Heating is provided by a gas furnace.
    - During an August test period, with the humidistat set to 62%, the room RH level averaged 65% (67% peak). Energy use was 0 Btu per day, because the heating system never came ON. Because the weather was very hot and sunny, and because this house has extensive window area on the east and west sides, the interior temperature was sufficiently hot (averaging about 89^{o}F on the first floor) that RH stayed below the humidistat setpoint the entire 10-day period.
    - During a five-day period in October, with the humidistat set to 62%, the first floor and second floor RH levels averaged 66% (73% peak). Heat energy use was 6,859 Btu per hour on an average basis (7,929 Btu per hour including AH fan energy) over the five-day period. The heating system was operational for only four of the five test days, because outdoor dew point temperatures were low enough to control indoor RH to below the humidistat setpoint on the fifth day (Figure ES-23).
    - It is interesting that the indoor RH level more closely matched the humidistat setting during these heating experiments. It may be that the humidistat is sensitive to room temperature, and that at higher temperatures (such as 88^{o}F to 90^{o}F) the humidistat dial settings are more accurate. This was not investigated in this project.
    - This house illustrates the fact that the humidistat can eliminate heating system operation during both cooler days when outdoor dew point temperatures are dropping, and hot and sunny days when indoor temperatures are already in the range of 88^{o}F to 90^{o}F.
- In House 3 (condo), this approach provided acceptable RH control. Heating is provided by electric resistance.
    - During a September test period, with the humidistat set to 62%, the room RH level averaged 62% (64% peak) with an average room temperature of about 85^{o}F. Energy use was 15.9 kWh per day.
    - During a test period in October, with the humidistat set to 62%, the room RH level averaged 62% (67% peak). Energy use was 21.1 kWh per day over the entire

period. One can see in Figure ES-24 that once the outdoor dew point temperature dropped significantly, the humidistat shut OFF the heating system, thereby saving considerable energy.

- Given an average heating energy use of 18.5 kWh per day between the two test periods, the heating energy use would be $67 per month. If the system had been a heat pump with a summer weather COP of 4 (instead of electric resistance heat), the heating energy use would have been 4.6 kWh per day (or $17 per month).
- Furthermore, if all snowbirds in this condo building were to use this space heating approach (instead of the AC at 80^{o}F), then the heating energy use for this condo unit would be much less, perhaps less than $10 per month, because all (or most) of the building heating systems would be operating simultaneously.

Selecting System Operation Time for Various Infiltration Rates

Experiments carried out at House 4 were done at various infiltration rates. A calibrated exhaust fan drew air from the house continuously at a controlled rate for each test period.

<u>The first approach</u>, *AC set at 71^{o}F from 3-5 AM* (fan AUTO), showed a reasonably clear pattern of response to changes in infiltration. In general, indoor RH increases with increasing infiltration. With ach at 0.05, 0.15, 0.30, and 0.36 ach, the resulting indoor RH was 48%, 56%, 60%, and 59%. Based on these results, the authors suggest the following AC run times for the various infiltration rates for this house; 0.5 hours per day for 0.05 ach, 1.3 hours per day for 0.15 ach, 1.9 hours per day for 0.30 ach, and 3.0 hours per day for 0.45 ach.

<u>The second approach</u>, *AC set at 80^{o}F from 9 PM - noon (or 9 PM to 7 AM)* (fan AUTO), showed a less clear pattern of RH response to changes in infiltration. Changes in indoor RH appear to be more closely related to weather and less to infiltration. With ach at 0.15, 0.30, 0.30, and 0.45 ach, the resulting indoor RH was 53%, 50.5%, 63%, and 57%. In the first approach, "AC set at 71^{o}F from 3-5 AM", the AC run time is not related to weather. The AC unit runs 2 hours each day largely independent of the weather (except during very cool November weather). In the second approach, "AC set at 80^{o}F from 9 PM - noon (or 9 PM to 7 AM)", AC run time is highly dependent upon weather. Consequently, the AC system removes much more water vapor from the indoor air on hot and sunny days than cool and cloudy days

<u>The third approach</u>, *dehumidifier on a timer from 8 - 11 AM*, showed little RH response correlation to changes in infiltration. With ach at 0.15, 0.22, 0.30, and 0.45 ach, the resulting indoor RH was 65.5%, 63%, 59%, and 63.5%. It is difficult to draw guidance from this information regarding the length of dehumidifier operation time required for good RH control, as a function, that is, of infiltration rate.

Recommendations With Technical Discussion

Five methods of controlling RH in residences were tested. The following recommendations are made.

AC at 71^{o}F from 3-5 AM (fan AUTO). Generally two hours per day (early morning) of AC operation yields good RH control for homes with relatively low infiltration rates. House 4 was specifically examined with various infiltration rates. Even at 0.36 ach, indoor RH remained under control at this house. This house may not be entirely representative, however, for two reasons. First, the 2.5-ton AC system is relatively oversized. Therefore, two hours of AC operation yields more cooling per square foot than in most of the other houses tested. Second, because of the poor insulation levels in the attic, this house heats up rapidly on sunny days. Based on analysis from all six houses tested (including Phase I homes), the authors conclude that for homes with infiltration below 0.25 ach, two hours per day will meet the RH control targets. At 0.35 ach, 3 hours. At 0.45 ach, 4 hours. In the Phase I study, the split level house had an air change rate of 0.43 ach, and it required 4 hours per day to barely maintain the desired RH control. Our general recommendation can also be stated, that AC at 71^{o}F from 3-6 AM will be sufficient for most homes, and one hour less (3-5 AM) for tight homes and one hour more (3-7 AM, or 3 - 5 AM plus 10 AM - 12 noon) for homes with higher than average infiltration rates.

AC at 80^{o}F from 9 PM - 7 AM (fan AUTO). For the three non-condo units, this approach works effectively during a majority of the summer. For the condo unit, AC at 74^{o}F provides adequate RH control. Based on examination of the data, the authors project that AC at 75^{o}F from 9 PM to 7 AM would provide sufficient AC run time in the condo to control RH.

This approach, however, falls short on two counts. First, it fails to provide good RH control during periods of cool and cloudy weather. Second, it wastes considerable energy by running the AC system excessively during hot and sunny weather. House 2 provides illustrations of extreme performance variation. During a hot and sunny period in July with the AC set to 84^{o}F, the average room RH averaged 59%. By contrast, during a cool and cloudy period in September with the AC set to 82^{o}F, indoor RH averaged 70%. In order to achieve RH control during cool and cloudy periods, the AC setpoint must be set lower, thus wasting considerable energy over the entire season. To correct this problem, a new control approach is proposed; that is, controlling the AC system with a humidistat, but also limiting room temperature (on the downside) to prevent a “runaway” AC system. A more detailed discussion is found at the end of these recommendations.

Dehumidifier on a Timer. Dehumidifier on a timer is an effective means for controlling indoor RH. The length of dehumidifier operation depends upon the size of the house, the temperature of the house (produced by solar radiation exposure), and the infiltration rate. Based on engineering judgment, the authors suggest the following dehumidifier run time per 1000 square feet of house floor area for the various infiltration rates (based on a 40-pint per day unit); 1.5 hours per day for 0.05 ach, 2.5 hours per day for 0.15 ach, 3.5 hours per day for 0.30 ach, and 4.5 hours per day for 0.45 ach.

Dehumidifier on a Humidistat. Dehumidifier controlled by a humidistat can be an effective means for controlling indoor RH. There are some challenges related to humidistat performance. First, setting the control dial to the desired level (say 62%) is difficult because of lack of resolution or accuracy. Second, humidistat deadbands are often large, which means that the units may remain OFF or remain ON for longer than desired periods. Third, humidistat control drifts, with the result that indoor RH may drift higher or lower by as much as five percentage points, for no apparent reason.

Space Heating with a Humidistat. This approach was generally quite effective. For unknown reasons, the humidistats seemed to perform somewhat better when controlling a heating system. The problem of large energy use during cooler months, identified in the Phase I project when heating to a fixed 89^{o}F, was eliminated by the humidistat control. When cooler (and lower dew point temperature) weather occurred, the humidistat invariably detected lower indoor RH (produced by the lower outdoor dew point temperatures) and therefore shut the heating system OFF. Furthermore, during very hot and sunny weather, the humidistat also shut the heating system OFF when the house temperature reached the 88^{o}F to 90^{o}F range (this was observed in House 2 when the heating system did not come ON for an entire week in August). Therefore, space heating controlled by a humidistat is a good option when heating is provided by a heat pump, and may be a good option for gas heat depending upon the fuel cost.

A New RH Control Strategy is Proposed; Combined Humidistat/Thermostat Control of the AC System

A new control strategy is proposed as a variation on “AC at 80^{o}F from 9 PM - noon (or 9 PM to 7 AM)”. Two major problems were identified with the “AC at 80^{o}F from 9 PM – noon” approach. First, during cool and cloudy weather, the AC system does not run long enough to control RH. Second, during hot and sunny weather, the AC system runs much longer than required to achieve RH control.

To resolve both of these problems, we propose controlling the AC system by means of a humidistat, but disabling the AC system during the peak hours of noon to 9 PM. In this manner, the AC system will run when it needs to run and will shut down when it is not required.

Humidistat control, however, introduces an additional control problem. That is, that the AC system may not, under some circumstances, be able to meet the humidistat setpoint, and then the AC would stay ON continuously for days and weeks at a time. In order to solve this problem, a thermostat would be installed in series with the humidistat, shutting OFF the AC system if the room temperature drops below a set level, such as 77^{o}F.

The low temperature limit provided by the thermostat (set in “cooling” mode) is critical. Without the thermostat, this approach would be the same as one occasionally observed in the field today, to control the AC system with a humidistat alone. The problem with using only a humidistat (without the thermostat in series) is that houses have been badly damaged by moisture condensation and mold growth when the humidistat could not be satisfied. This can happen in several ways.

- If the humidistat is set too low, such as 40%, then the AC system may never satisfy that setpoint, and the house would overcool. As the house cools below the outdoor dew point temperature, moisture begins to condense inside wall cavities, electrical chases and boxes, and wherever high moisture content air from outdoors migrates. Note that the more the AC system is oversized, the more risky this control strategy becomes.
- If the humidistat control indications (on the turn dial) are not accurate, then the AC could stay ON indefinitely. For example, if the humidistat were set to 60%, but the control point was actually 45%, then the AC might never meet that control point.
- If the humidistat has a large deadband, the AC could stay ON indefinitely. Consider an example of a house the authors are aware of, but that is not within this study. The humidistat was set to 50% on the dial. Testing found that the humidistat turned the AC system ON at

47%, but because it had an 8 percentage point deadband, room RH would need to fall to 39% before it would shut the AC system OFF. Because the AC unit could not achieve that RH level of 39%, the AC stayed on for weeks, producing average indoor temperatures below 60^{o}F, and moisture and mold damage.

With this new control approach, the dangerous situation described above is avoided because the thermostat would prevent the residence from cooling below the thermostat setting (e.g., 77^{o}F or whatever setting is selected).

The AC unit would then be controlled by a humidistat set at say 60% (or 58% in a house with high infiltration), and enabled to operate from 9 PM to noon (15 hours). A thermostat, set to say 77^{o}F (in the cooling mode), would be installed in series with the humidistat. If the room temperature then dropped below 77^{o}F, then the thermostat would shut the AC system OFF. During the period noon to 9 PM, the thermostat (assuming it was programmable) would be set to the thermostat's highest setting (e.g., 88^{o}F) so the AC system would remain OFF during the utility's peak.

Previously we had indicated setting humidistats to 62% for good RH control. However, that assumes that the system is available for operation 24 hours per day. Since, we are proposing shutting OFF the AC system for 9 hours each day, the RH level must be lower (at say 58% or 60%) during the 15 hours of possible AC operation in order to keep indoor RH within acceptable control during the 9 hours that the residence is "floating". In a house with low infiltration rates, a setting of 60% would likely achieve our RH control objectives. In a house with high infiltration rates, a setting of 58% might be necessary to achieve our RH control objectives.

The humidistat would then be the primary controller, cycling the system ON and OFF in response to room RH. The thermostat, as the secondary controller, would prevent the system from running excessively in case the humidistat could not be satisfied.

This approach of controlling the AC with a humidistat, and with a thermostat in series, has several advantages.

- Overall, RH control will be better insured, but unnecessary energy use will be eliminated.
    - On hot and sunny days, the AC run time will be decreased, saving energy.
    - On cooler and cloudy days, the AC run time will be increased.
- Because of the thermostat override (limiting temperature to say 77^{o}F on the downside), the problem of a runaway AC system is eliminated.
- Because the system is disabled during the peak demand period, the utility sees a demand "valley" instead of a demand "peak".

Note that this approach is similar (essentially a mirror image) to that used with the humidistat control of the space heating system, which was used in three houses. With the space heating approach, the heating system was turned ON when the room RH rose above the setpoint of 62%. A thermostat, wired in series with the humidistat, was set to 88^{o}F or higher as a precaution in case the humidistat controller fails and "tries" to keep the heating system ON continuously. One difference is that with this proposed humidistat control of the AC system, the system is disabled during the 9-hour peak period from noon to 9 PM.

There are some important control issues that need to be considered.

- It is important that the programmable thermostat have battery backup so that the program is not lost and the time clock of the thermostat does not drift.
- If the thermostat program is lost, then the protection provided by the thermostat (to prevent a runaway AC system) would be gone. The results of a runaway AC system (running nonstop) are important to keep in mind. It can result in extended periods of low indoor temperatures (such as 55^{o}F to 65^{o}F, depending upon the degree of AC system oversizing), and this in turn (after a few weeks) would result in major condensation and mold problems throughout the house.
- If the thermostat clock drifts, then the AC system may run during the utility's peak period of 12 – 9 PM.
- Keep in mind that this approach still has a runaway AC vulnerability because sometimes programmable thermostats lose their program even with a battery in place. This can occur because the battery fails, a lightning strike, or for other reasons. A second layer of protection can be provided by installing a second non-programmable thermostat in series with the humidistat, this one set at 77^{o}F (in cooling mode) all of the time. Even if the programmable thermostat failed, the second non-programmable thermostat would still prevent cooling to below 77^{o}F.
- It is important that the humidistat performs adequately. Initial experience based on testing at House 1, 2, and 3 indicates that the better humidistats that are now available can provide reasonable control, but issues remain.
    - RH drifts from the apparent humidistat setpoint, and the reason for this drift is unknown.
    - Deadbands are still large (12 to 23 percentage points for many units). The large deadband can lead to excessive swings in indoor RH.
    - It is difficult to set the humidistat to 60% (or other desired setting) because the control dial is often not particularly accurate and deadbands are often quite large.
- The thermostat must be set to the "cooling" mode, so it will shut the system OFF if the temperature falls below the setpoint. If set to the "heating" mode, then the thermostat will shut the AC system OFF whenever the room temperature is above 77^{o}F, which would be most of the time.

Recommendations to Homeowners for Vacant Home RH Control

Determining the best energy conservative method for controlling indoor relative humidity in Florida homes depends upon the options available to the homeowner, the type and state of building construction, and the extent to which the structure is exposed to the sun. Several methods have been identified to control humidity; AC system operation, dehumidifier operation, or space heating system operation. The way these systems are used to control RH will vary depending upon the style of residence.

- A typical single-family home (or duplex) without heavy tree shading will heat up to 84 to 88 degrees throughout most of the summer. Because of this heat, which drives down relative humidity, the typical home will require the least amount of intervention by the AC system, a dehumidifier, or the heating system.

- A single-family home (or duplex) with heavy shading may be 3 to 5 degrees cooler, and require longer operation of the AC system, dehumidifier, or heating system.
- A dwelling unit located in an apartment or condominium building (especially if surrounded by other conditioned units) will often require lower temperature settings or longer system operation.

The various recommended vacant home RH control approaches are summarized in Tables 1, 2, and 3. Be sure to read the accompanying text to gain a more complete understanding of the various approaches.

Table 1. Five vacant-home indoor humidity control approaches for single-family Florida homes with considerable sun exposure. (T means thermostat temperature setting; RH means humidistat setting).

	Controller	Setting	Length
AC (3-7 AM)	Programmable thermostat	T = 71F	4 hours [5]
AC (9PM-7AM)	Programmable thermostat	T = 80F	10 hours [5]
AC	Humidistat and thermostat	RH = 58%; T = 79F (T-stat in cooling mode) [1]	System cycles based on weather (OFF noon to 9 PM)
Dehumidifier	On-board or external humidistat	RH = 58% [2]	System cycles based on weather
Dehumidifier	Timer	RH below 50% [3]	5 hours per 1000 ft^2 [5]
Heating System	Humidistat and thermostat	RH = 58%; T = 89F (T-stat in heating mode) [4]	System cycles based on weather

[1] humidistat and thermostat (set to cooling at 79F) will operate in series so that the RH must be above 58% and the room temperature must be above 78F for the AC system to operate.
[2] note that accurately setting to the on-board humidistat to 58% may be difficult because of lack of resolution on RH scale and also humidistat accuracy. External humidistats have control accuracy limitations as well.
[3] selecting at 50% RH or below on the on-board humidistat allows the dehumidifier to run for extended periods (during the 5 hour operation period), but also allows disables the dehumidifier during periods of cooler/drier outdoor weather.
[4] humidistat and thermostat (set to heating at 89F) will operate in series so that the RH must be above 58% and the room temperature must be below 90F for the heating system to operate.
[5] if the house and duct system are tested and found to be fairly tight, then length of time can be reduced by up to 50% compared to the listed length in Table 1.

Typical homes. Following is a discussion of vacant home RH control approaches based on the assumption that the single-family home is substantially exposed to the sun (no heavy shading).

1) Air conditioning from 3 to 7 AM at 71 degrees is an efficient way to maintain a vacant home to help prevent mildew. This requires a programmable thermostat. If airtightness testing of your home and AC duct system shows low natural air infiltration (little air leakage to the outside) and no significant leaks in the a/c duct system, then it may be possible to reduce AC run time at 71 degrees to just 2 hours per day from 3-5 AM Program the thermostat to 88 degrees for all other hours. If you have not had your a/c ducts checked, call 1 800 DIAL FPL to schedule a Duct Test.

2) Air conditioning from 9 PM to 7 AM at 80 degrees is neither as effective nor as efficient as 71 degrees for 2 to 4 hours, but it can effectively control indoor RH in most sun-exposed single-family homes. It may be possible to raise the thermostat setting to 82 degrees if testing has found that both the house and a/c duct system are reasonably tight. Program the thermostat to 88 degrees for all other hours. If you have not had your house and a/c duct tightness checked, call 1 800 DIAL FPL to schedule a Test.

3) Running the air conditioning system with humidistat control (and thermostat override) may be the most

effective and energy efficient way to control indoor RH. Set the humidistat to 58% relative humidity, and set the thermostat to 79 degrees (in cooling control mode). The humidistat and thermostat must be installed in series, so both have to be active for the AC to operate. In other words, the room RH would have to be above 58% and the room temperature would have to be above 79 degrees for the AC system to turn on. If the thermostat is programmable, set it to cool at 79 degrees from 9 PM until noon and at 88 degrees from noon and 9 PM (the AC will then remain off from noon to 9 PM). The AC will run more efficiently at night, and it will also shut off when the relative humidity target is met. Replace the batteries in the programmable thermostat every year before leaving the home vacant.

4) Using a dehumidifier set at about 58% relative humidity may be the most energy efficient way to control humidity in vacant homes. Note that the house may warm considerably above the normal unconditioned house temperature, because the dehumidifier gives off considerable heat. If the house would normally reach 88 degrees, then it might warm to 93 degrees with an active dehumidifier. Note that accurate setting of the on-board humidistat is difficult, and may require some trial and error to get it to cycle at approximately 58% RH. An out-board humidistat may also be used, but some of the same accuracy issues apply as well. Placing the dehumidifier in a bathroom shower stall or other space with a drain provides a measure of safety against water spillage. Operation of one or more floor fans may be useful in distributing the warm and dry air.

5) As an alternative to running the dehumidifier at a specific humidity setting, you can plug the dehumidifier and one or more floor fans into a timer rated for power of both appliances and turn them on starting at midnight for 5 hours per day for each 1000 square feet of floor space. In a 2000 sq. ft. home, for example, the run time for one 40-pint dehumidifier would be 10 hours per day. Or run two dehumidifiers for 5 hours. In homes that have been tested and are tight, the dehumidifier operation time may be reduced by 50%. Remember to place the dehumidifier so the moisture removed can go into a bathroom or kitchen drain.

6) Customers who have a heat pump with a humidistat could also effectively control humidity by setting the AC system to "heat" (thermostat setting of 89 degrees) and the humidistat to 60%. A temperature of 89 degrees in the house will keep indoor RH below 65% all of the time, simply because warm air produces lower relative humidity. With the humidistat and thermostat connected in series, the house will heat up to 89 degrees, except that during the spring and fall when outdoor dew point temperatures decline, the indoor RH will fall below 60% and shut off the heating system. This saves considerable energy during spring and fall periods. Heating should not be used to control humidity with ordinary electric resistance or gas heaters because it could be too costly in the cooler months.

Shaded homes. Control of relative humidity is more difficult in heavily shaded homes (due to vegetation), or in homes with cool roofs, large overhangs, and little window exposure to the sun. Table 2 presents slightly modified control strategies based on the fact that the home receives less heat from the sun. Note that the AC system operating temperature (9 PM to 7 AM) is reduced to 79F and the dehumidifier run time is increased.

Table 2. Five vacant-home indoor humidity control approaches for single-family Florida homes with limited sun exposure. (T means thermostat temperature setting; RH means humidistat setting).

	Controller	Setting	Length
AC (3-7 AM)	Programmable thermostat	T = 71F	4 hours [5]
AC (9PM-7AM)	Programmable thermostat	T = 79F	10 hours [5]
AC	Humidistat and thermostat	RH = 58%; T = 78F (T-stat in cooling mode) [1]	System cycles based on weather (OFF noon to 9 PM)

Dehumidifier	On-board or external humidistat	RH = 58% [2]	System cycles based on weather
Dehumidifier	Timer	RH below 50% [3]	6 hours per 1000 ft^2 [5]
Heating System	Humidistat and thermostat	RH = 58%; T = 89F (T-stat in heating mode) [4]	System cycles based on weather

[1] humidistat and thermostat (set to cooling at 78F) will operate in series so that the RH must be above 58% and the room temperature must be above 77F for the AC system to operate.
[2] note that accurately setting to the on-board humidistat to 58% may be difficult because of lack of resolution on RH scale and also humidistat accuracy. External humidistats have control accuracy limitations as well.
[3] selecting at 50% RH or below on the on-board humidistat allows the dehumidifier to run for extended periods (during the 6 hour operation period), but also allows disables the dehumidifier during periods of cooler/drier outdoor weather.
[4] humidistat and thermostat (set to heating at 89F) will operate in series so that the RH must be above 58% and the room temperature must be below 90F for the heating system to operate.
[5] if the house and duct system are tested and found to be fairly tight, then length of time can be reduced by up to 50% compared to the listed length in Table 2.

Embedded homes. Control of relative humidity is particularly difficult in apartment and condominium buildings, especially those embedded into a larger, multi-story building. Referring to Table 3, one can see that several of the AC system thermostat control points have been lowered. Dehumidifier run time has been increased. The dehumidifier timer could, for example, be set to turn on from 8 AM to 11 AM and from 10 PM to 1AM. Again, if the unit has been tested and found to be fairly airtight, then system run times could be reduced by up to 50%. Remember to place the dehumidifier so the moisture removed can go into a bathroom or kitchen drain.

Table 3. Five vacant-home indoor humidity control approaches for embedded condo and apartment units. (T means thermostat temperature setting; RH means humidistat setting).

	Controller	Setting	Length
AC (3-7 AM)	Programmable thermostat	T = 70F	4 hours [5]
AC (9PM-7AM)	Programmable thermostat	T = 75F	10 hours [5]
AC	Humidistat and thermostat	RH = 58%; T = 76F (T-stat in cooling mode) [1]	System cycles based on weather (OFF noon to 9 PM)
Dehumidifier	On-board or external humidistat	RH = 58% [2]	System cycles based on weather
Dehumidifier	Timer	RH below 50% [3]	6 hours per 1000 ft^2 [5]
Heating System	Humidistat and thermostat	RH = 58%; T = 89F (T-stat in heating mode) [4]	System cycles based on weather

[1] humidistat and thermostat (set to cooling at 76F) will operate in series so that the RH must be above 58% and the room temperature must be above 75F for the AC system to operate.
[2] note that accurately setting to the on-board humidistat to 58% may be difficult because of lack of resolution on RH scale and also humidistat accuracy. External humidistats have control accuracy limitations as well.
[3] selecting at 50% RH or below on the on-board humidistat allows the dehumidifier to run for extended periods (during the 6 hour operation period), but also allows disables the dehumidifier during periods of cooler/drier outdoor weather.
[4] humidistat and thermostat (set to heating at 89F) will operate in series so that the RH must be above 58% and the room temperature must be below 90F for the heating system to operate.
[5] if the house and duct system are tested and found to be fairly tight, then length of time can be reduced by up to 50% compared to the listed length in Table 3.

Executive Summary Figures

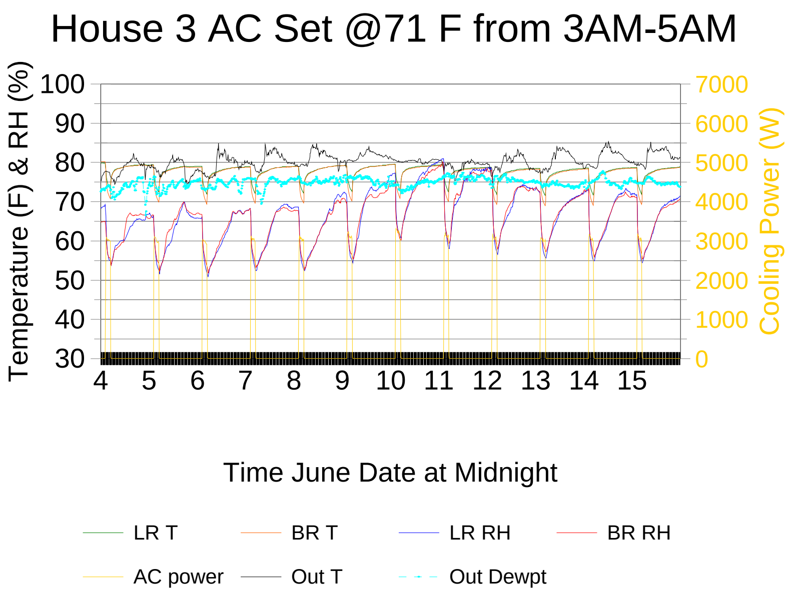

Figure ES-1

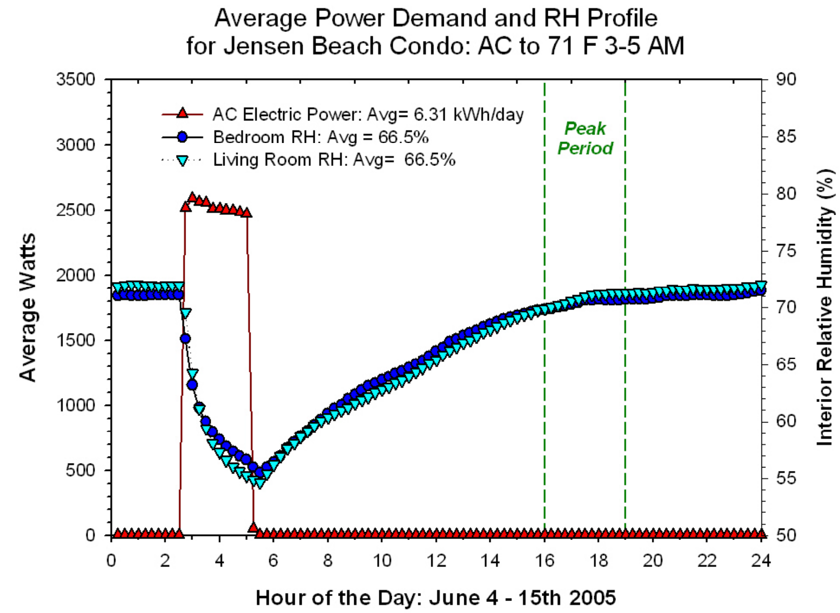

Figure ES-2

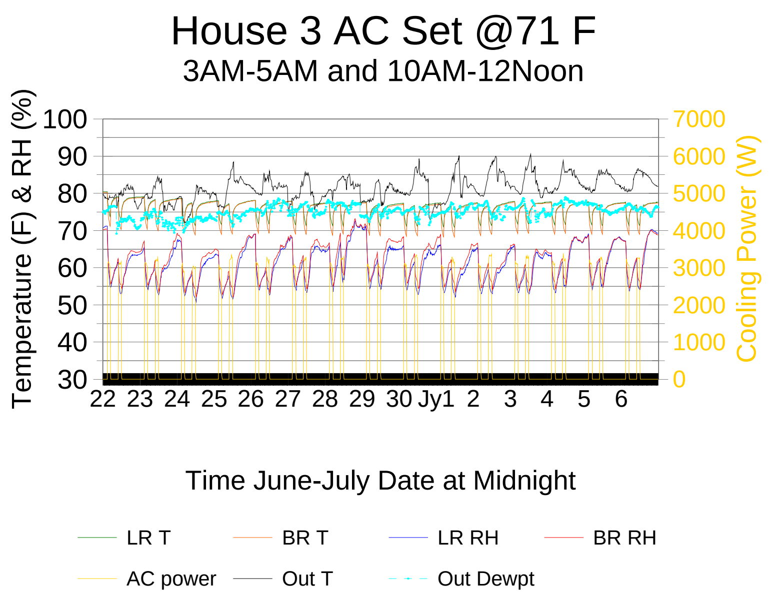

Figure ES-3

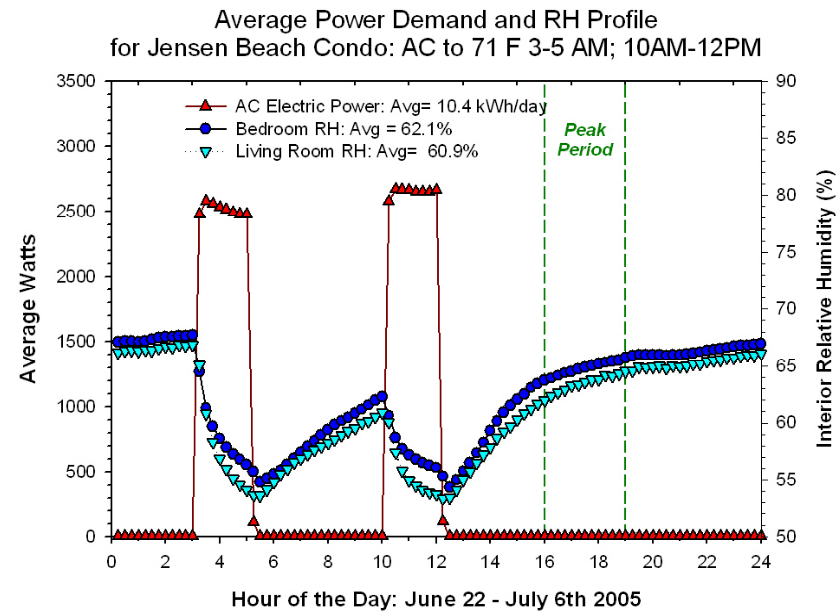

Figure ES-4

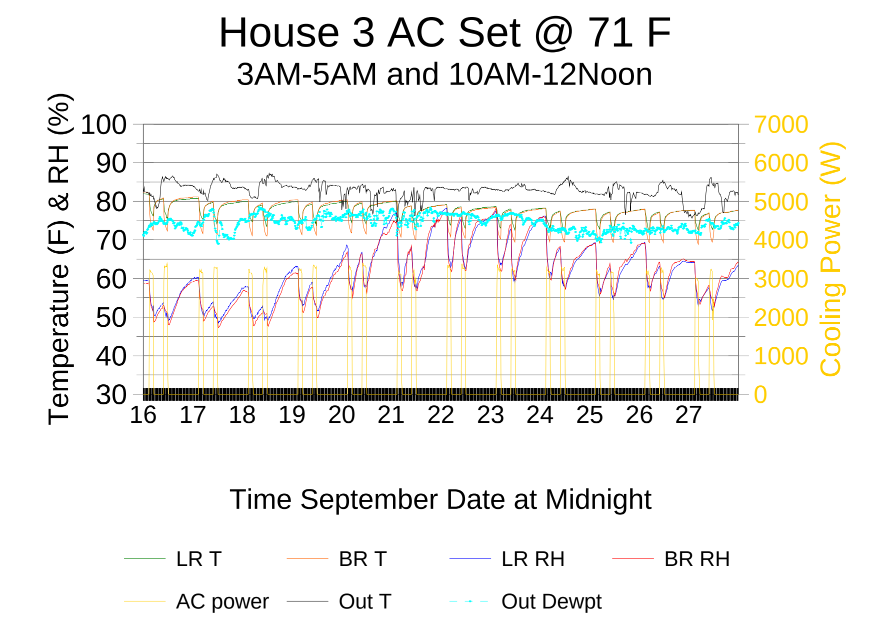

Figure ES-5

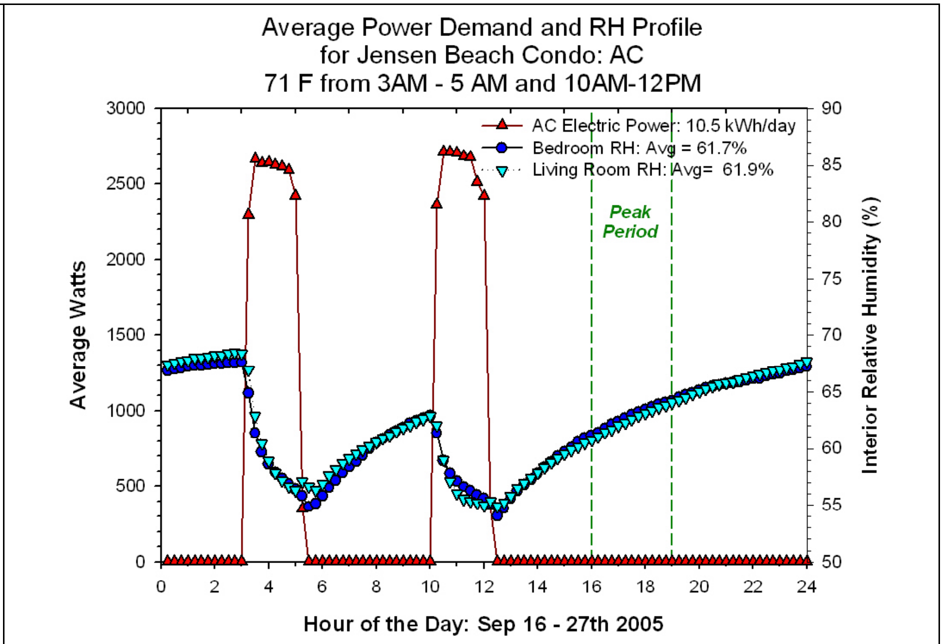

Figure ES-6

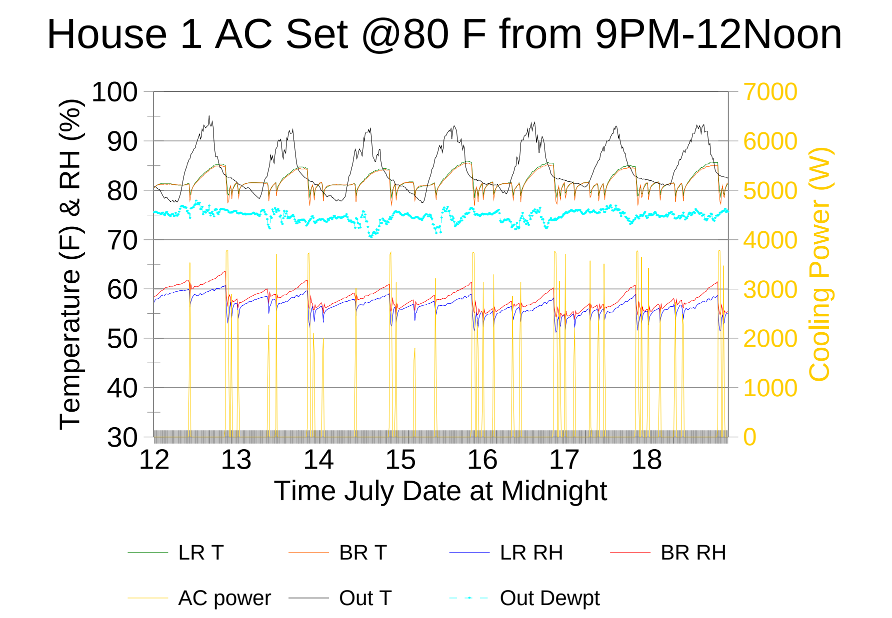

Figure ES-7

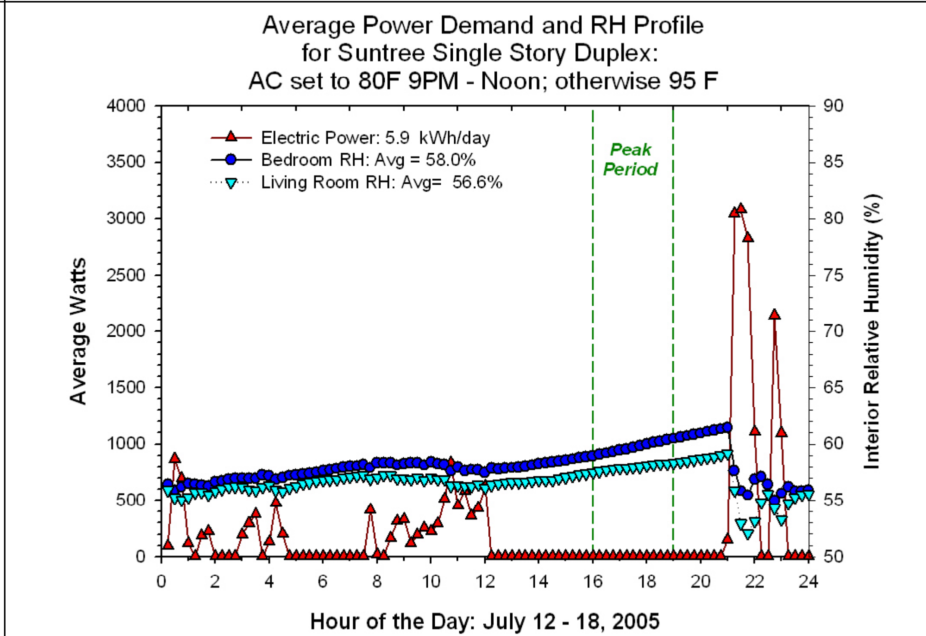

Figure ES-8

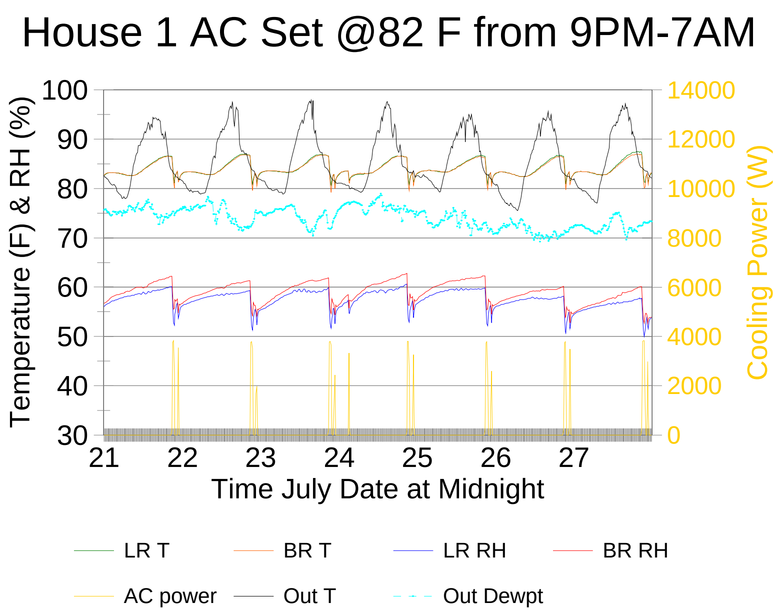

Figure ES-9

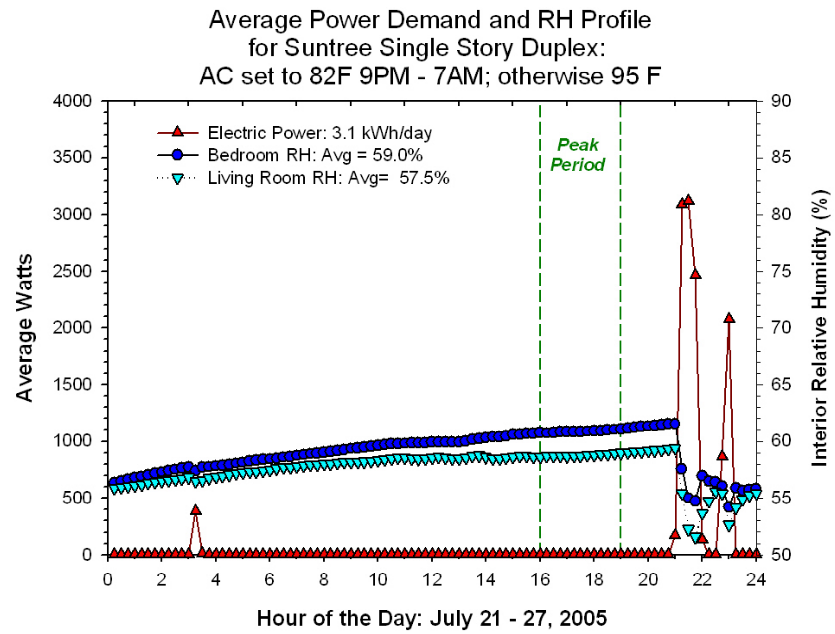

Figure ES-10

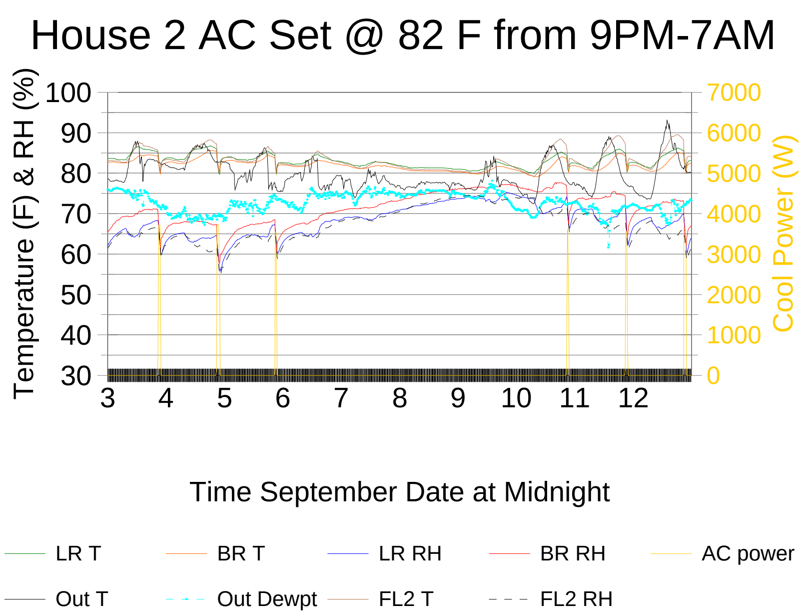

Figure ES-11

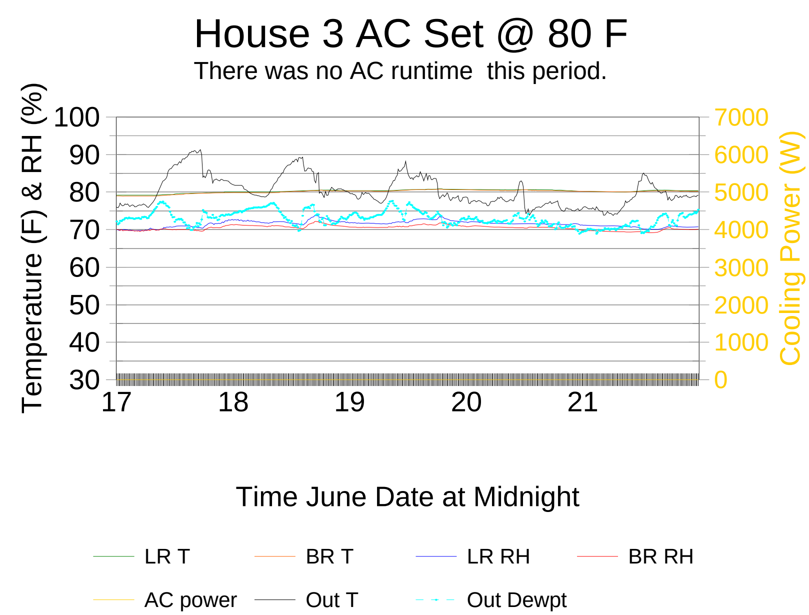

Figure ES-12

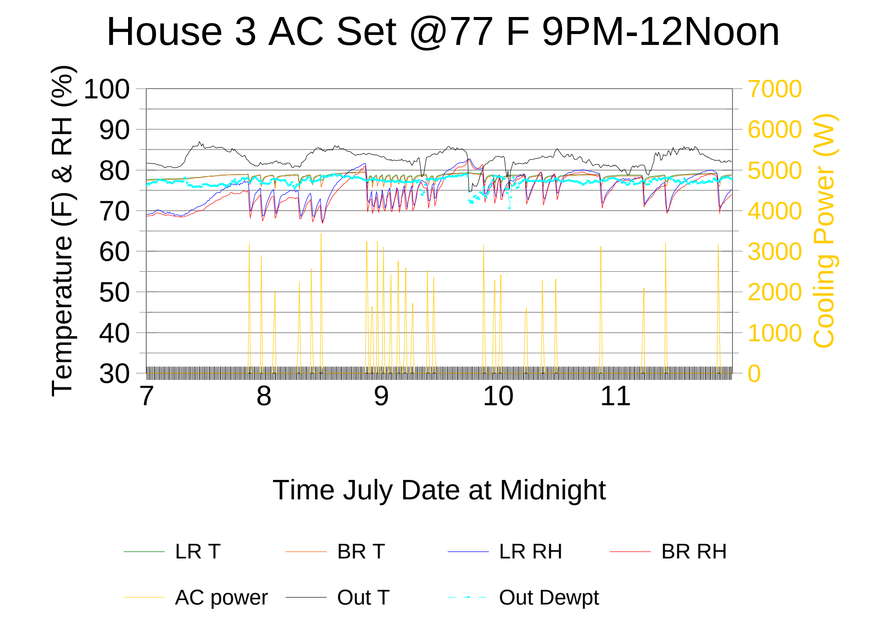

Figure ES-13

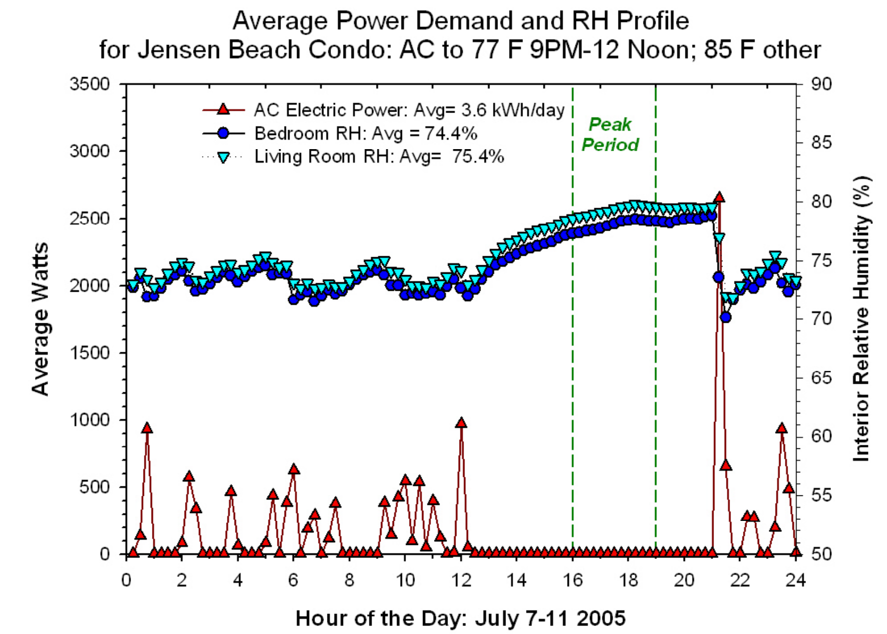

Figure ES-14

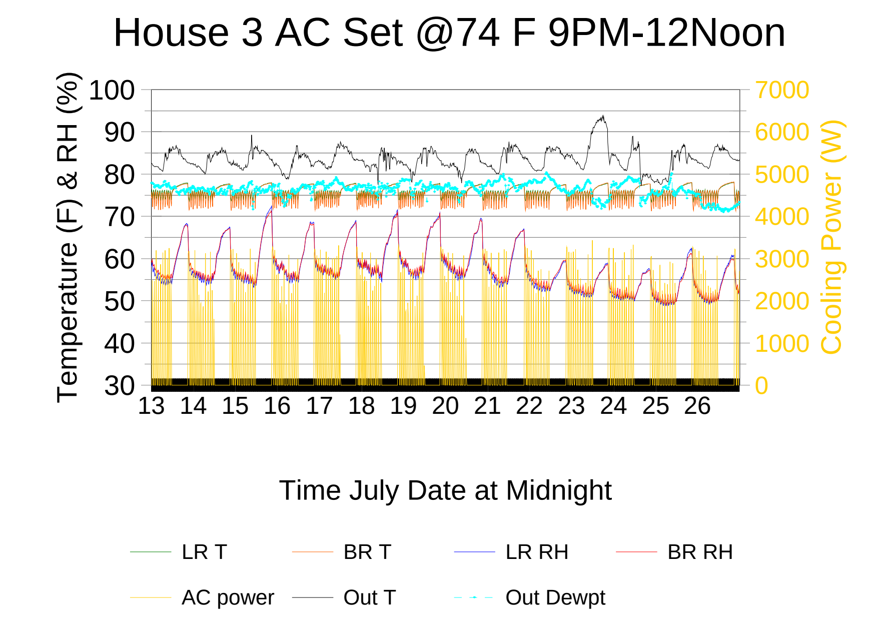

Figure ES-15

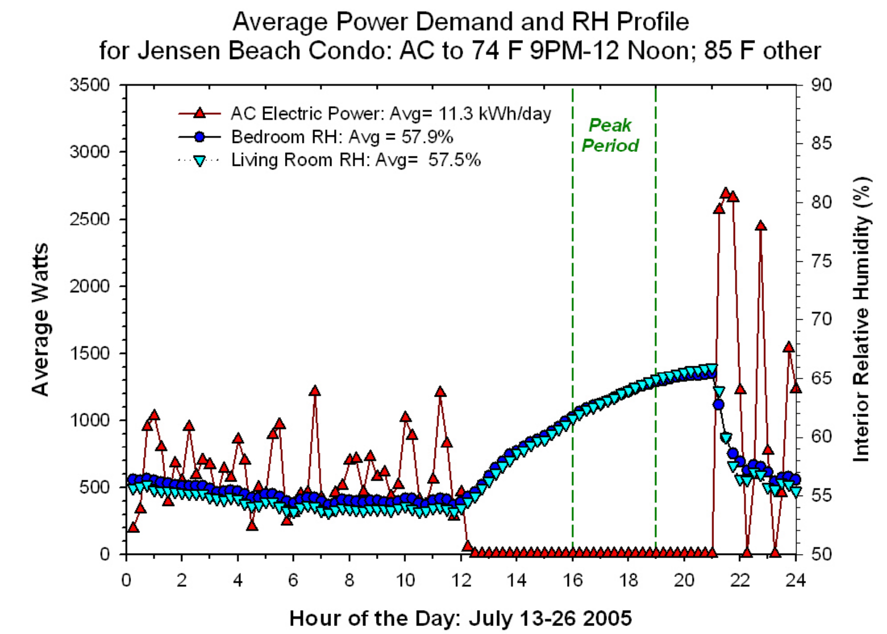

Figure ES-16

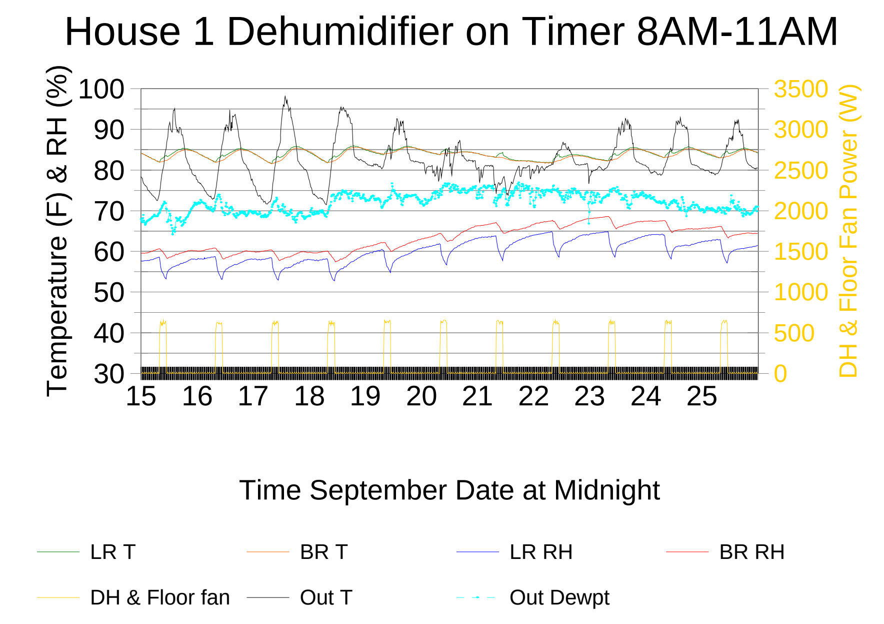

Figure ES-17

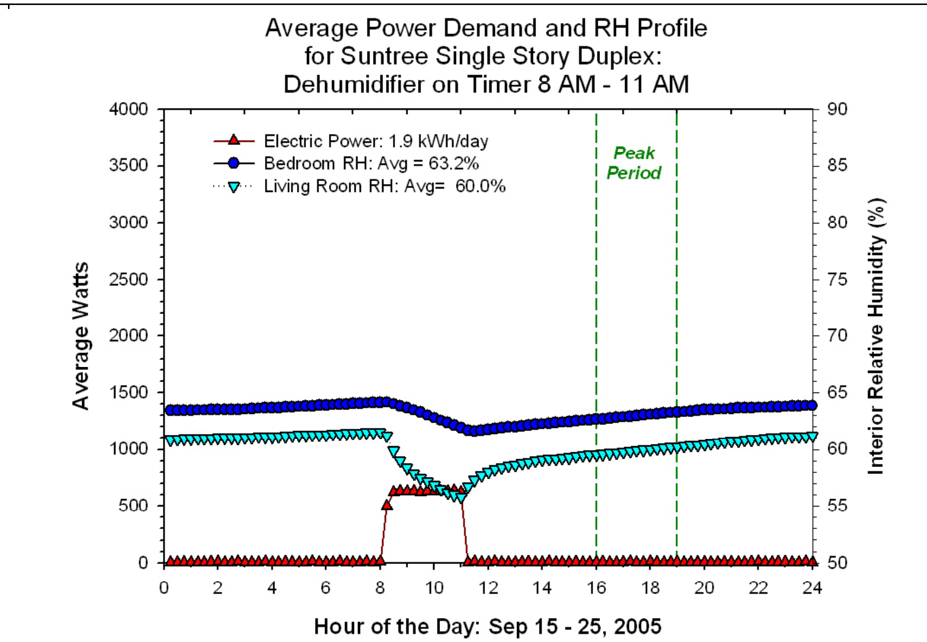

Figure ES-18

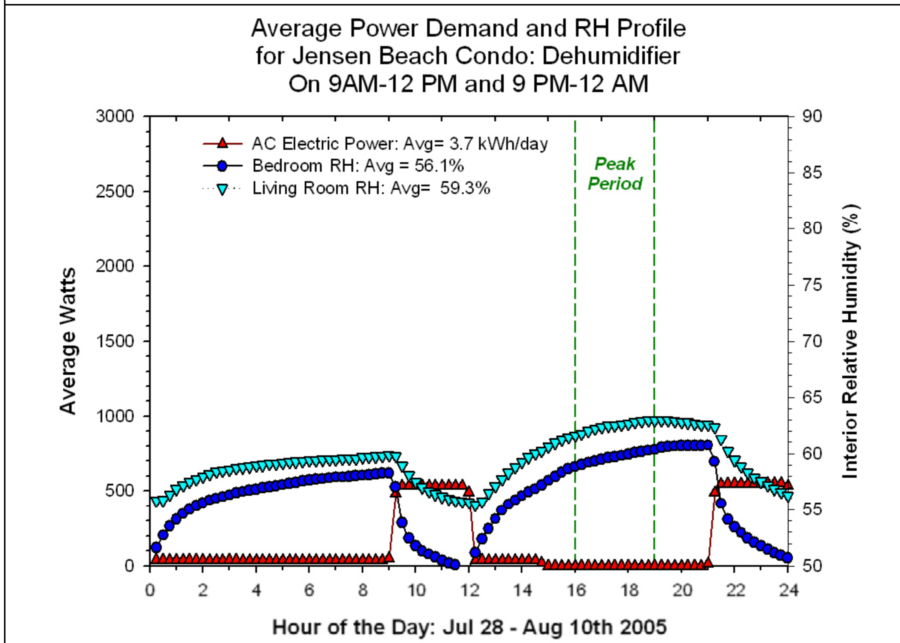

Figure ES-19

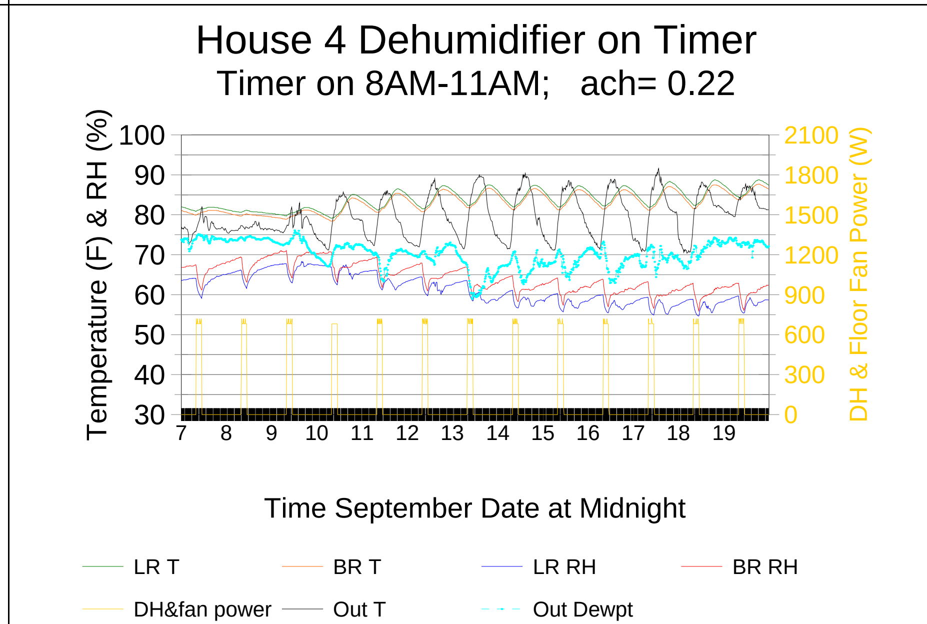

Figure ES-20

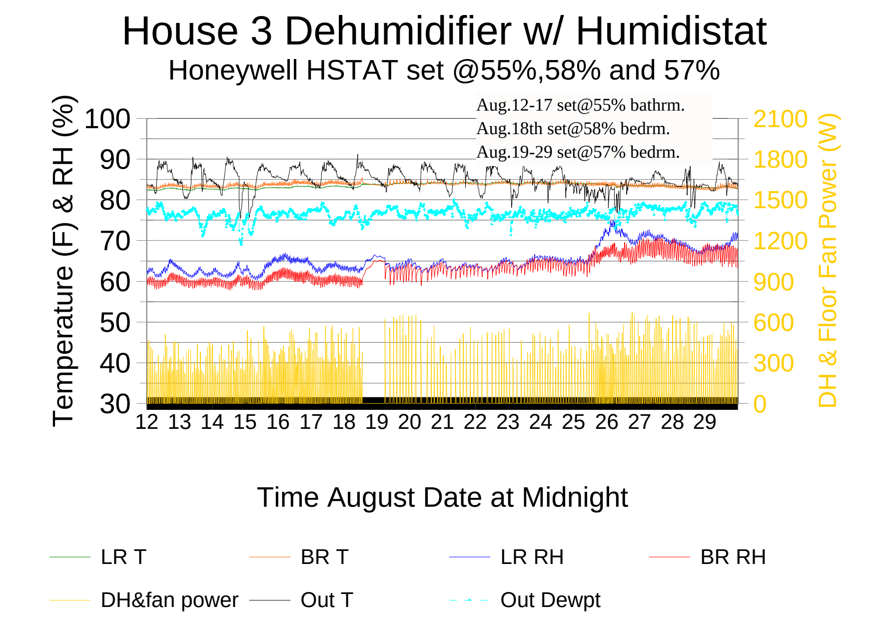

Figure ES-21

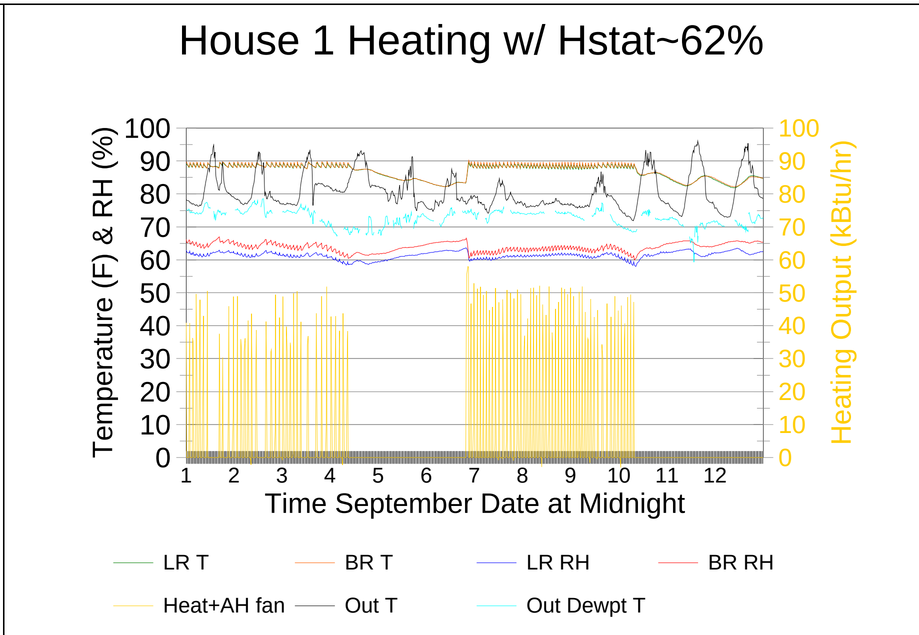

Figure ES-22

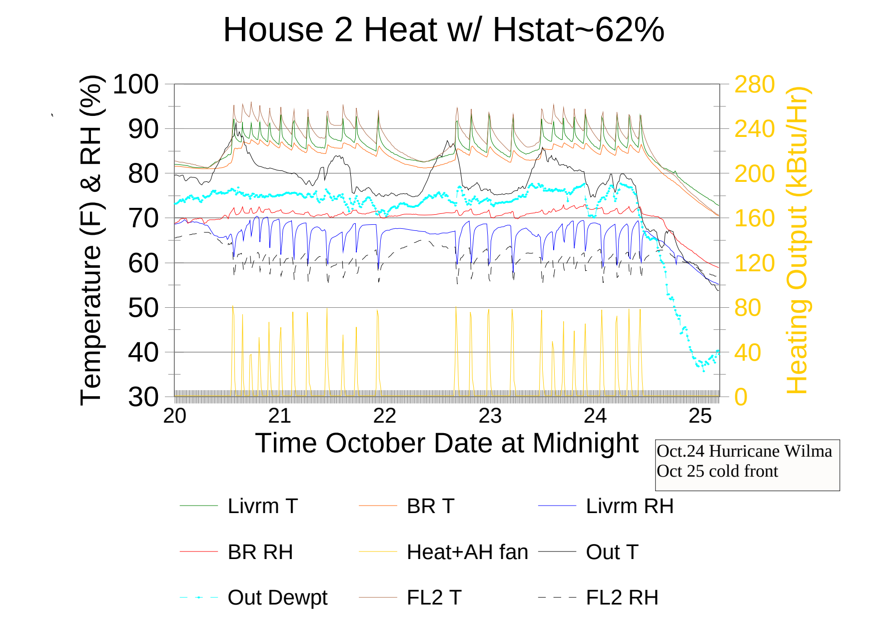

Figure ES-23

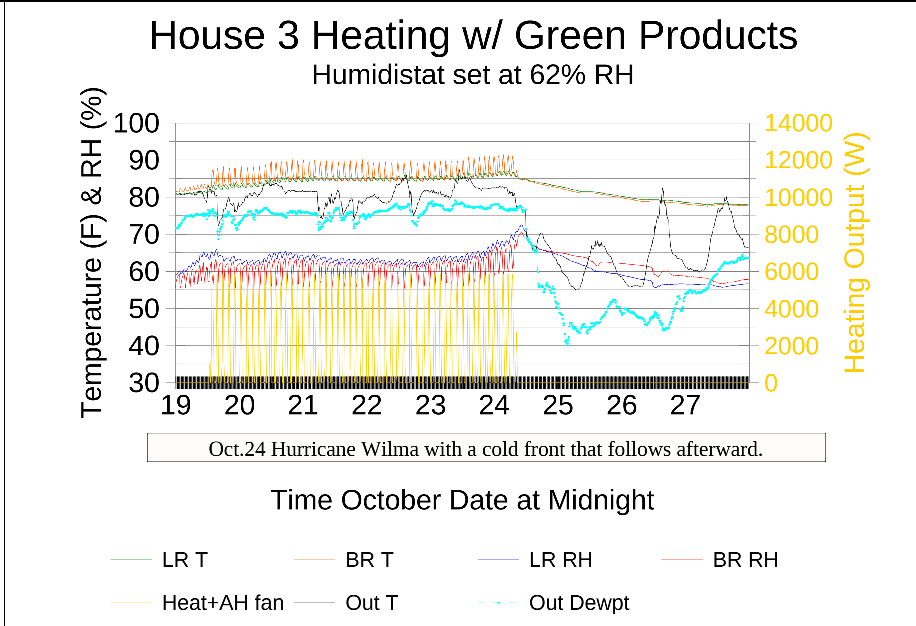

Figure ES-24