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Abstract:

Current work is focusing on the performance and durability of unvented-cathedralized attics in hot-humid climates with both tile and asphalt shingle roofing. The advantages for the hot-humid climate are expected to be even greater than for the hot-dry climate.

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ABSTRACT

Beginning in 1996, simulations showed that unvented-cathedralized attics would be advantageous in hot-humid and hot-dry climates, whereby, exterior moisture would be excluded for hot-humid climates, and attic mounted air distribution systems would be inside conditioned space for both climates.

Two test houses were constructed and monitored in Las Vegas with unvented-cathedralized attics. Results showed that the unvented attic houses yielded both cooling and heating energy consumption savings over the conventional 1:150 vented attic house. The 3ºF maximum tile top temperature difference agreed well with the simulated prediction. The maximum measured plywood roof sheathing temperature increase of 21ºF for the unvented attics was less than the temperature variation that would be expected by changing from tile to asphalt shingles of any available color. The maximum measured roof sheathing temperature of 154ºF for the unvented attics was well within acceptable temperature limits. These results set into motion the construction of entire subdivisions with unvented-cathedralized attics. Long-term monitoring was also conducted on ten unvented attic houses compared to conventional vented attic houses; that analysis is on-going.

In summer of 1999, two houses were constructed in Las Vegas and two in Tucson, with cooling systems that were reduced in size compared to traditional sizing methods. These houses were instrumented and monitored. Results showed that sizing the cooling systems at 80% of ACCA Manual J sensible load would provide acceptable cooling system performance.

Current work is focusing on the performance and durability of unvented-cathedralized attics in hot-humid climates with both tile and asphalt shingle roofing. The advantages for the hot-humid climate are expected to be even greater than for the hot-dry climate.

Where We've Been

A residential attic model, contained in the finite element computer program FSEC 3.0, was empirically aligned with measured attic data from three roof research facilities in Florida and Illinois. This model was then used to simulate hourly space conditioning energy use, and roof and attic temperatures, for peak cooling days and annual weather, for Orlando, Florida and Las Vegas, Nevada. Results given in Tables 1 and 2 showed that, when compared to typically vented attics with the air distribution ducts present, unvented-cathedralized attics (i.e. unvented attic with the air barrier and insulation at the sloped roof plane) can be constructed without an associated energy penalty in hot climates (Rudd, Lstiburek 1998). If typical duct leakage is factored in, the energy savings due to unvented-cathedralized attics can be quite large.

Table 1 Summary Of Annual Simulation Results For Las Vegas, Nevada

Las Vegas, Nevada **Simulation Description**	**Annual Cooling Consumption % Difference**	**Annual Heating Consumption % Difference**	**Annual Total Consumption [1] % Difference**	**Annual Total Cost [2] % Difference**
Reference case 1:150 vented attic, R-28 ceiling insulation, ducts in attic, no duct leakage, R-5 duct insulation, R-19 walls, double glazing, black roof shingles				
Ducts in conditioned space	-4.5	-4.0	-4.2	-4.3
Unvented-cathedralized attic	0.3	-6.1	-3.6	-2.2
White tile	-9.0	2.6	-1.9	-4.4
1:300 attic vent area	0.8	-0.8	-0.2	0.2
Duct leakage: 10% return 5% supply	8.3	10.2	9.5	9.1
Duct leakage: 15% return 10% supply	14.3	17.6	16.4	15.6

[1] Consumption based on 10 SEER cooling and electric heat

[2] Cost based on 10 SEER cooling at $.07/kW-h and gas heat (combo water heating system 60% efficiency) at $.02/kW-h

All homes in cooling climates, including those with unvented-cathedralized attics, benefit from tile roofing or a bright white roofing color.

Test Houses At Angel Park Subdivision, Las Vegas, Nevada

Following the favorable indications from simulation results, code variance was obtained and two test houses were constructed in Angel Park with unvented-cathedralized attics. These houses were tested and monitored to evaluate their cooling energy performance compared to a conventional vented attic house.

Short-term monitoring.

Results from short-term testing in the late summer of 1996 showed that the unvented attic houses had cooling energy use savings over the conventional 1:150 vented attic house (Rudd, Lstiburek and Moyer 1997). This was mostly due to the unvented-cathedralized attic which brought the air distribution ducts inside the air and thermal boundary of the building.

Tile top temperatures were hardly effected by the unvented attic. The 3°F maximum tile top temperature difference agreed well with the simulated prediction. The maximum measured plywood roof sheathing temperature increase of 17°F for the unvented attics was less than the temperature variation expected by changing from tile to asphalt shingles of any available color. During the test period, the maximum measured roof sheathing temperature of 126 °F for the unvented attics was well within an acceptable temperature performance range of wood-based roof sheathing (< 180°F). Subsequent long-term monitoring through mid-summer (described below) found the maximum roof sheathing temperature for both attics to be higher.

Table 2 Summary Of Annual Simulation Results For Orlando, Florida

Orlando, Florida **Simulation Description**	**Annual Cooling Consumption % Difference**	**Annual Heating Consumption % Difference**	**Annual Total Consumption [1] % Difference**	**Annual Total Cost [2] % Difference**
Reference case 1:300 vented attic, R-19 ceiling insulation, ducts in attic, no duct leakage, R-5 duct insulation, R-11 walls, single glazing, black roof shingles				
Ducts in conditioned space	-2.2	-4.1	-2.8	-2.5
Unvented-cathedralized attic	1.1	-8.7	-2.2	-0.6
White tile	-10.2	3.5	-1.9	-5.6
1:150 attic vent area	-1.3	-0.8	-0.6	-0.9
Duct leakage: 10% return 5% supply	14.4	18.4	15.7	15.1
Duct leakage: 15% return 10% supply	22.8	32.0	25.9	24.4

[1] Consumption based on 10 SEER cooling and electric heat

[2] Cost based on 10 SEER cooling at $.08/kW-h and gas heat (combo water heating system 60% efficiency) at $.02/kW-h

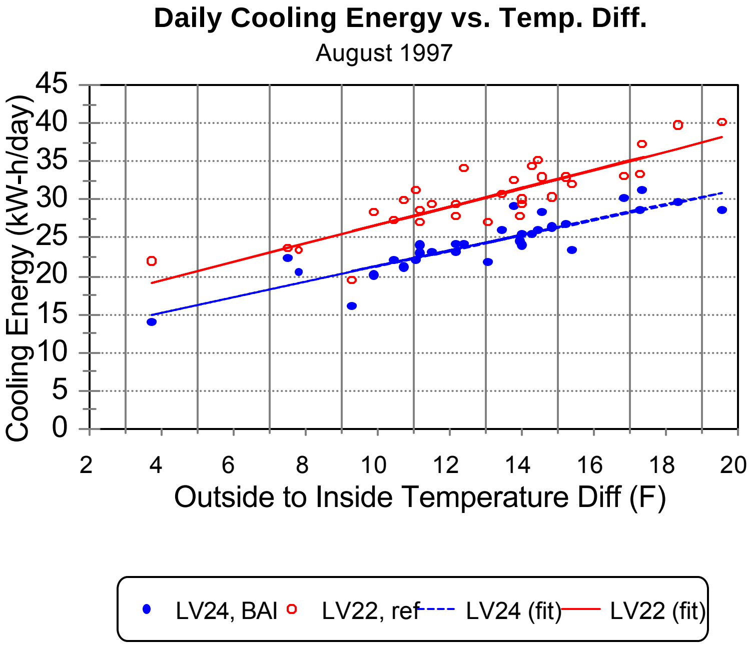

Figure 1 Regression of cooling energy consumption verus inside to outside temperature difference for the vented attic (LV22) and unvented attic houses

Long-term monitoring.

One of the two unvented attic houses (Angel Park Lot 24) and the conventional vented attic house (Angel Park Lot 22) were monitored between July 1997 and March 1998. Both houses had medium colored tile roofs. Analysis of the cooling season data showed an average of 5% savings for the unvented attic house. This is illustrated in Figure 1. Relatively low duct leakage in the vented attic house contributed to the somewhat lower-than-expected savings. Figure 2 shows the average temperatures for each hour of the month of August 1997. Notably, there was a difference of about 35°F in the temperature of the spaces where the air distribution system was located. Maximum roof sheathing temperature reached 154°F for the unvented-cathedralized attic and 133°F for the vented attic.

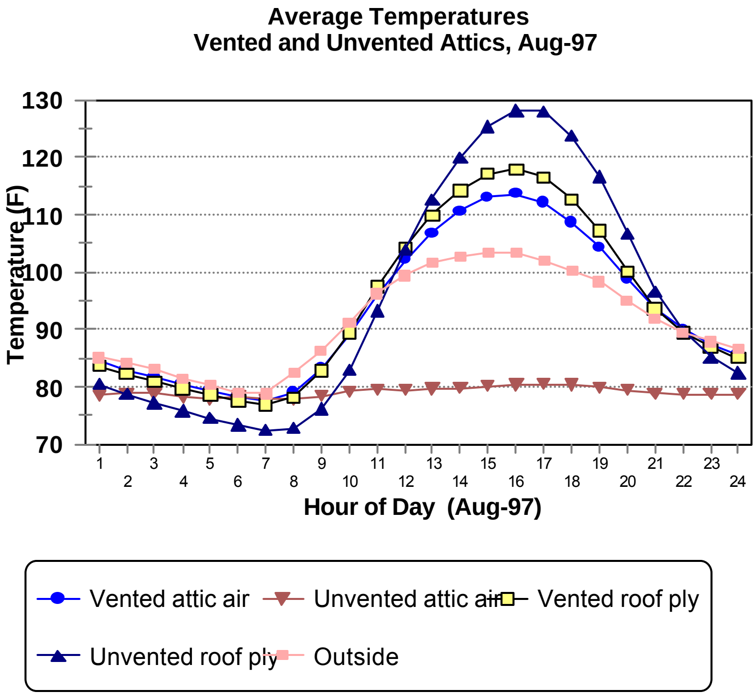

Figure 2 Average hourly temperatures for the month of August; shows the large difference in temperature where the air distribution systems are located

Analysis of the heating season data showed heating energy consumption savings of over 50% for the unvented attic house. This information is shown in Table 3 and Figure 3. In addition to the benefits of the unvented-cathedralized attic, part of these savings were also due to the higher performing low-e windows. The exact effect of the windows is unknown since the use of window coverings varied with the occupants. We have found that most window coverings in the Las Vegas climate are kept closed during summer, somewhat limiting the benefit of high performance windows, but use varies in winter. Although we know that getting the duct system inside conditioned space, and not venting solar gains

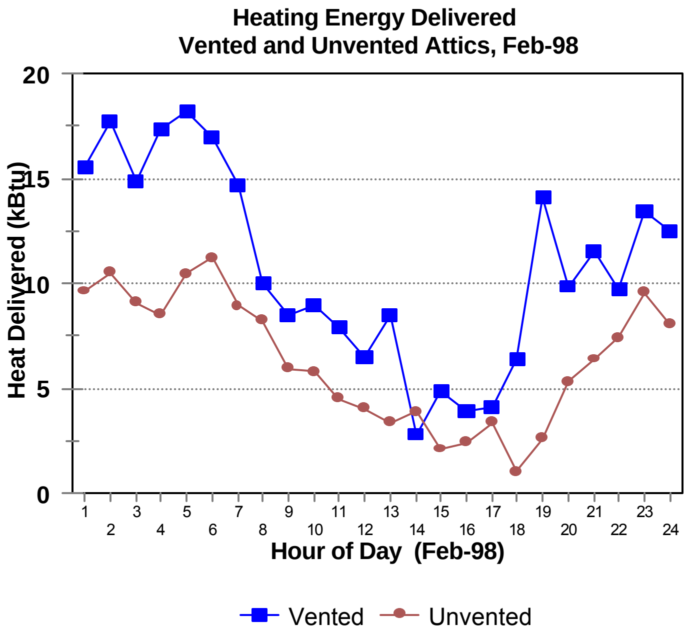

Figure 3 Hourly average heating energy delivered, measured at the air handler unit, for the month of February

conducted through the roof had a beneficial affect, the exact portion of the 50% heating energy savings that can be attributed to the unvented attic is unknown given the confounding influence of the higher performance windows and varied window covering usage.

Table 3 Summary of measured heating data for unvented and vented attic houses in Las Vegas 7-28 February 1998

	Avg Outside Temp. (F)	Avg Inside Temp. (F)	Avg Temp. Diff. (F)	Cooling On-time (h)	Heating On-time (h)	Heating Delivered (kW-h)	Heating Delivered (kW-h/day)	Normalized Heating Delivered (kW-h/day-F)	% Diff.
Vented Attic	50.0	70.9	-20.9	0	84.8	1618	76	3.55	
Unvented Attic	50.0	76.9	-26.8	0	63.6	951	45	1.63	-54%

Figure 4 is a high/low/mean plot of the temperature of the bottom of the roof sheathing of the unvented attic. The lowest monthly average outdoor air temperature in Las Vegas is 44°F. Typical wintertime indoor conditions of 70°F and maximum 40% relative humidity yield a dewpoint temperature of 45°F. At night, the sheathing temperature briefly approached the maximum expected indoor air dewpoint temperature of 45°F, then sharply rose during the day. Moisture measurements were made of the roof sheathing during the winter and all readings were below 6% moisture content. These results indicate that the unvented-cathedralized attic system can be safely applied without wintertime roof sheathing moisture problems in locations where the monthly average outdoor air temperature exceeds 45°F.

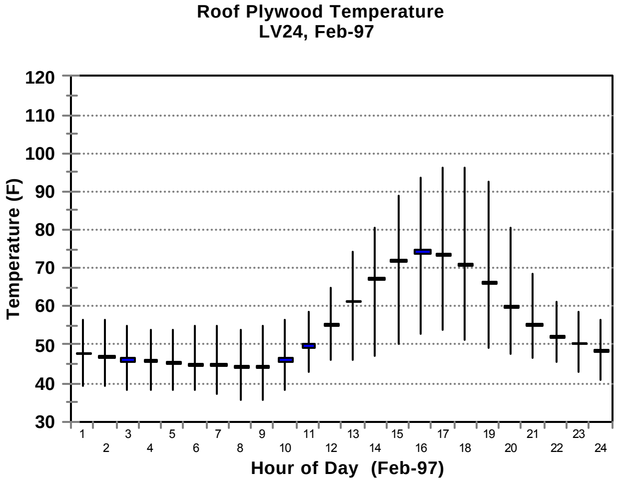

Figure 4 High/low/mean plot of the temperature at the bottom of roof sheathing temperature for the unvented attic for the month of February, the sheathing had low moisture content

Scale Up For Production Housing

The favorable testing and monitoring results set into motion construction of entire subdivisions of unvented-cathedralized attic homes constructed to the Building Science Consortium (BSC) Building America Initiative (BAI) specifications. Subdivisions already completed are Cypress Pointe and Four Seasons in Las Vegas. Ten of these houses were tested and instrumented for long-term monitoring compared to conventional vented attic houses. The data have been collected and are being analyzed. Other subdivisions are currently under construction, including: Crown Ridge, Arbor View and Stallion Mountain in Las Vegas, and Bluffs Retreat and Spanish Trails in Tucson.

Right-sizing the cooling systems

Typically cooling systems are oversized. Much of this is based on rule-of-thumb, tradition, and compensation for “unknowns” such as infiltration and air distribution system gains through leakage and conduction. A major disadvantage of oversizing cooling systems is the lack of humidity control in humid climates. In dry climates, the cooling system will operate less efficiently, and shorter air circulation periods will increase temperature variations and decrease comfort.

The BSC Building America program seeks to extract unnecessary first cost out of oversized cooling systems to pay for building improvements that will reduce total energy consumption and increase comfort. In the Southwestern U.S. market, these improvements generally include: 1) unvented attic; 2) high performance glazing with spectrally selective low-e coating; 3) superior building airtightness and thermal insulation; and 4) mechanical ventilation system. In some cases, these improvements can also allow further economies with the heating system, like combination space and domestic hot water heating systems.

Due to cautious mechanical design, most of the Building America houses with unvented-cathedralized attics have had cooling systems that were oversized. In addition to higher first cost, the high airflow blower units have an electrical energy consumption penalty. In some cases, the high air flow has created thermal comfort challenges for the central-fan-integrated supply ventilation system.

Reduced-size Cooling Systems at Arbor View, Las Vegas, Nevada

In the summer of 1999, two houses were constructed at the Arbor View subdivision in Las Vegas, Nevada having cooling systems that were significantly reduced in size compared to the traditional sizing method. The cooling systems were sized using ACCA Manual J procedures, then cut further to approximately 80% of the Manual J sensible load. The indoor and outdoor units were correctly matched and the proper refrigerant charge was verified. These houses were instrumented to determine whether the smaller cooling systems would meet the load and maintain comfort. Several different analyses showed that one house (Arbor View Lot 6 Plan 2260) was working well, while the other (Arbor View Lot 7 Plan 1787) was probably too small even though it maintained comfort conditions. The cooling tons were reduced from the typical 4 to 3 for Lot 6, and from the typical 3.5 to 2.5 for Lot 7. Using manufacturer performance data, the actual installed systems were 84% of Manual J sensible sizing for Lot 6, and 76% for Lot 7. In terms of total capacity, Lot 6 was at 97% of Manual J total load; Lot 7 was at 81%.

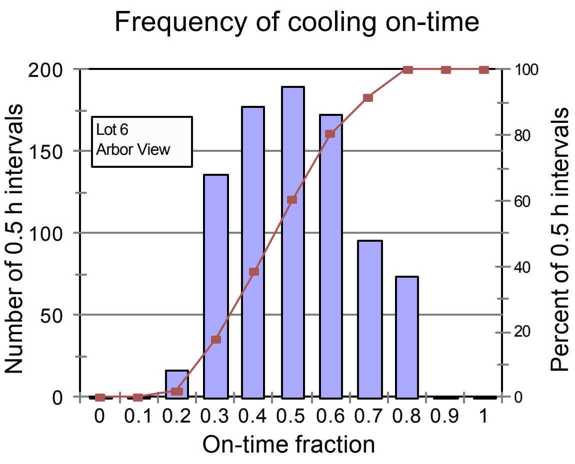

Figure 5 Frequency of cooling on-time fraction over one-half hour intervals for Lot 6

Figure 5 is a histogram showing the frequency of cooling system on-time over 30 minute periods. All of the measured on-time fractions for Lot 6 were below 0.8, meaning that the system never ran continuously for 30 minutes to meet the cooling load. For Lot 7, 94% of the on-time fractions were below 0.8, and 4% were between 0.9 and 1.0. Had the cooling system for Lot 7 been closer to the intended 80% of Manual J, performance would have been improved.

Figures 6 shows a scatter and regression plot of cooling on-time fraction versus outside to inside temperature differential. At a 30 F temperature difference, the cooling on-time fraction was about 0.7 for Lot 6, and 0.9 for Lot 7.

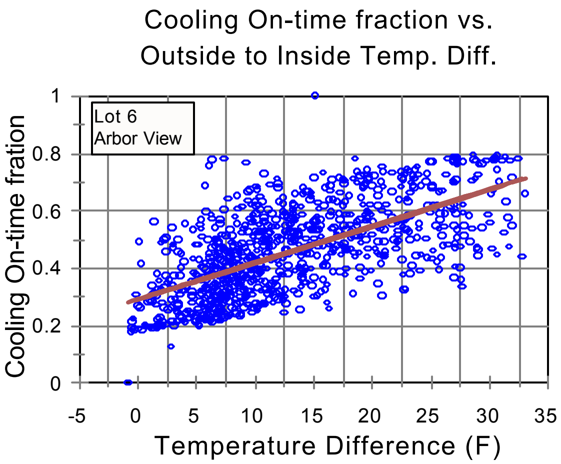

Figure 6 Regression of cooling on-time fraction versus inside to outside temperature difference for Lot 6

Paralleling the analysis presented by Proctor (1998), Figure 7 shows a scatter plot of the relative sensible load (RSL) versus the mean outside temperature. Over the testing period, there were 10 one-half hour periods where the outside air temperature exceeded the design temperature of 106^{o}F. The RSL is the ratio of the measured delivered sensible capacity to the estimated design load (EDL). In Figure 7, the EDL is equal to the sensible capacity from manufactures data for the specified and installed equipment. The manufacturers data was selected at indoor conditions of 80 F drybulb and 67 F wetbulb temperature, and at 95 F outdoor drybulb temperature. For Lot 6, the RSL exceeded 67% of the EDL 19% of the time. That occurred 35% of the time for Lot 7.

To determine whether the smaller cooling systems could maintain comfortable room temperatures throughout the house, seven thermocouples were distributed in each house. Figure 8 illustrates the temperature variation between rooms for the house at Lot 6. The average local variation ranged from -0.7 to +1.4 degrees from the house average. The Great Room was consistently warmer than the other locations. During testing, a supply register with low airflow was identified in this area. For the house at Lot 7, the average local temperature variation ranged from -1.6 to 0.0 degrees from the house average.

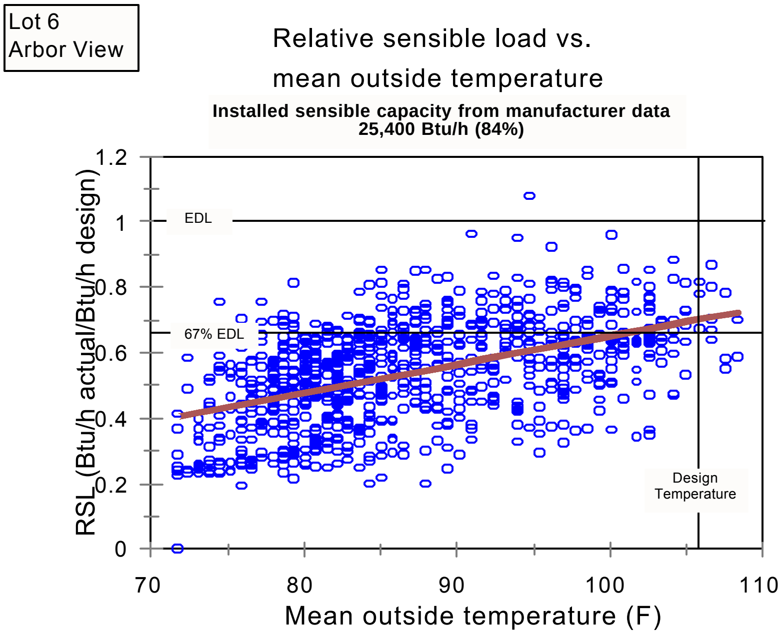

Figure 7 Relative sensible load (RSL) versus mean outside air temperature for installed equipment at Lot 6

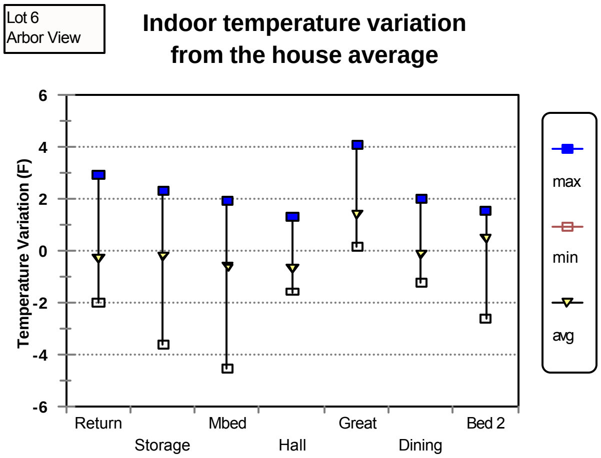

Figure 8 High/low/mean plot showing temperature variation from the house average for six rooms and the central return for Lot 6

Reduced-size Cooling Systems at Bluffs Retreat, Tucson, Arizona

In late summer 1999, the same process was completed for two houses constructed at Bluffs Retreat subdivision in Tucson, Arizona. Both houses were built to the BSC Building America specification with unvented-cathedralized attics. The installed cooling systems had total cooling capacities of 73% and 82% of Manual J for Lots 580 and 581, respectively. The sensible cooling capacities were 64% and 71%, respectively. Cooling system operation and indoor and outdoor temperatures were monitored to determine whether the smaller cooling systems would meet the load and maintain comfort, and how hard they were working to do that.

Analysis showed that while the cooling systems for both houses met the load and maintained indoor temperature control (see Figures 11 and 12), they both had many hours with cooling system runtime fractions of 1.0. For Lot 580, out of 696 total hours analyzed, 74 hours, or 11%, were at a runtime fraction of 1.0. For Lot 581, out of 960 total hours analyzed between, 184 hours, or 19%, were at a runtime fraction of 1.0.

A scatter and regression plot of cooling system on-time fraction versus mean outside temperature is shown in Figure 9. At the 0.4% design temperature for Tucson of 104°F (ASHRAE 1977), the cooling system on-time fraction was 0.83 for Lot 580, and 0.88 for Lot 581. Figure 10 shows an expected trend of increased cooling system use in the afternoon hours.

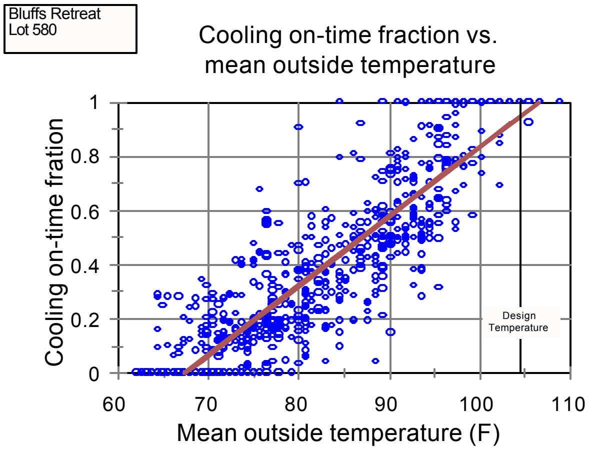

Figure 9 Regression of cooling system on-time fraction versus mean outside temperature for Lot 580

The two Tucson houses tested in this study, sized between 73% and 82% of the ACCA Manual J total capacity, and between 64% and 71% of Manual J sensible, have shown the lower limits of acceptable sizing of cooling capacity. The actual rated capacities of the BSC Building America houses should be installed at a more conservative 80% of Manual J sensible.

In order to be assured of the rated performance, it is necessary that the refrigeration systems be carefully installed, including weighing in the refrigerant, allowing for the actual line set length, and commissioning the installed system by evaluating actual performance. This includes a series of measurements and calculations to obtain the proper superheat, temperature drop, and air flow. Air flow of between 400-450 ft^3/min per ton of cooling is highly desirable in arid climates where moisture removal is generally undesirable and lower flow rates reduce sensible capacity.

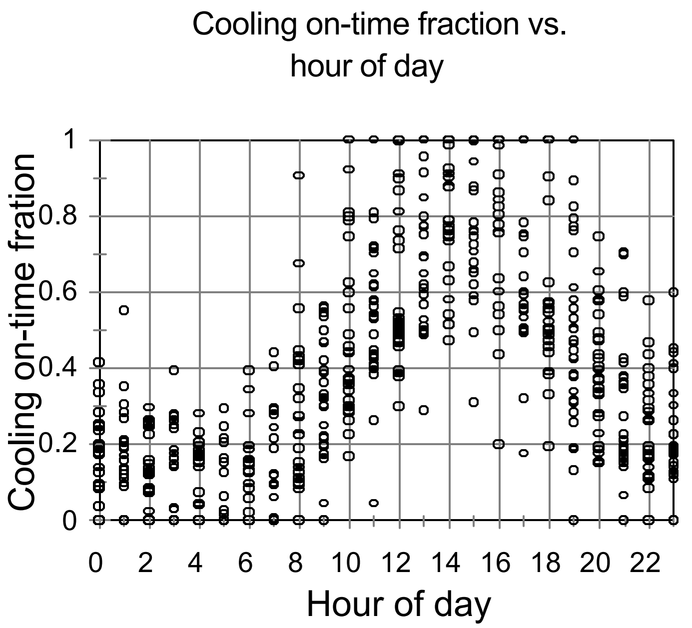

Figure 10 Scatter plot of cooling system on-time fraction versus hour of day for Lot 580 (expected trend of increased use in afternoon)

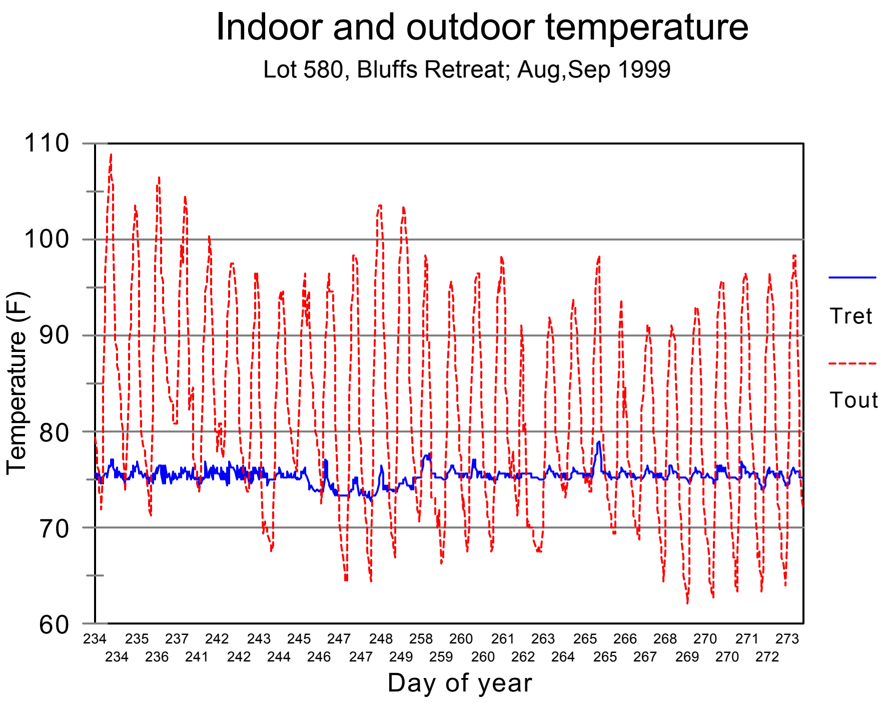

Figure 11 Indoor and outdoor temperature during the study for Lot 580

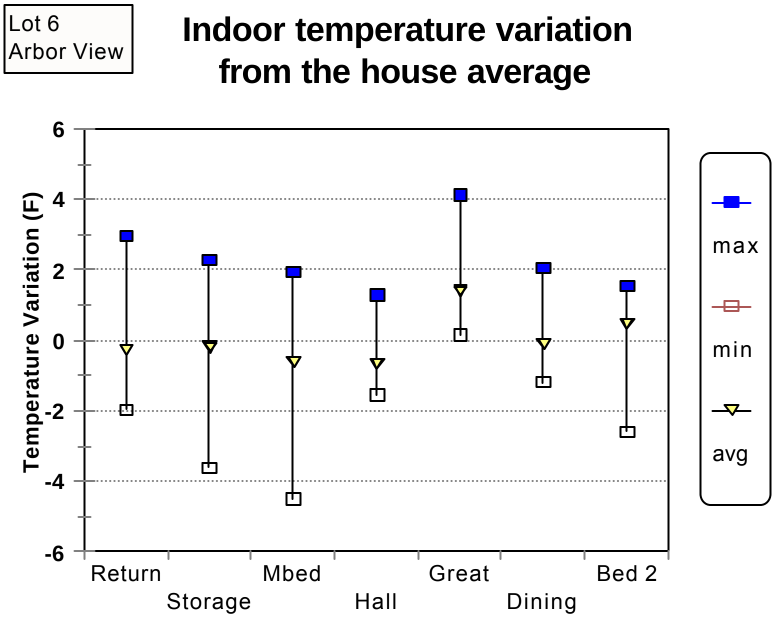

Figure 12 High/low/mean plot showing temperature variation from the house average for six rooms and the central return for Lot 6

Recovery from thermostat setup

Some discussion, and testing, has centered around the issue of recovery time from a thermostat setup. Upon leaving the house, some homeowners are accustomed to setting up the thermostat cooling setpoint, or even turning the cooling system off, then setting it back to normal when they return. Most HVAC contractors recommend maintaining a steady setpoint (set it and forget it), or they recommend a setup or setback of not more than 4°F. Service and warranty managers have expressed that if their customers don't see the temperature move within 30 minutes they will get a call. They realistically expect full recovery from a 4°F setup in not more than 90 minutes.

The BSC Building America team believes that recovery time should not be an important metric when determining system size. While oversized systems can recover faster from changes in thermostat setting, oversized cooling systems cause humidity control problems in humid climates, and will operate less efficiently most of the time due to shorter cycling. It is believed that superior comfort control can be achieved for the same or less operating cost, by taking the excess first cost out of oversized cooling systems and applying that resource to building envelope or system improvements while leaving the cooling setpoint continuously at a comfortable setting. A controlled experiment may be designed and implemented to validate this strategy.

Where We’re Going

Houses constructed in the hot-humid climate can benefit the most from unvented-cathedralized construction. Ventilation is one of the most effective ways to deal with humidity problems in heating climates, but ventilation can be one of the major causes of humidity problems in southern humid climates (Lstiburek 1993; ASHRAE 1997). Damaging moisture related problems in hot-humid climates are caused by humid outdoor air coming into contact with surfaces made cold by cooling system operation. In Florida, for example, it is not uncommon to have an outdoor air dewpoint temperature of 75°F, and a vented attic air dewpoint of 85°F. When an attic surface temperature is lower than the attic air dewpoint, or attic air is drawn into walls by mechanically induced pressure differentials, condensation will occur and mold may result. Leaks in return air ducts can also draw in attic air, greatly reducing system efficiency. In the hot-humid climate, the best solution for eliminating attic related moisture problems is to keep outside moisture out of the attic by not venting the attic to outdoors.

While unvented-cathedralized attics in custom homes and retrofits are not uncommon, two test houses will be completed by May 2000 by a large production builder in Jacksonville, Florida. These houses will be used to evaluate the performance and cost impacts of unvented-cathedralized attics for production builders in hot-humid locations. One house has a conventional vented attic, and to isolate the effect of the unvented-cathedralized attic in the Building America house, both houses have the air distribution system inside conditioned space. The Building America house also has a central-fan-integrated supply mechanical ventilation system with a stand-alone dehumidifier and fan recycling control for year-around improvement in indoor air quality.

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