Effects of Air Conditioner Sizing on Energy Consumption and Peak Demand in a Hot-Dry Climate

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ABSTRACT

Oversizing of air conditioners is a common practice that reduces comfort and energy efficiency; the practice also results in higher first costs and exacerbates the effects of residential air conditioning on utility peak demand. At a subdivision in a hot dry climate (Redding, CA), a production homebuilder completed several houses at their standard practice equipment sizing of 155 to 185% of the total calculated Manual J load and subsequently built the remainder of the development with equipment resized to 135 to 150% of the total calculated Manual J load. Thirteen of these houses (7 in the standard practice sizing category; 6 in the resized category) were monitored for air conditioner runtime, interior temperature, and electricity consumption of the outdoor condenser unit. Data was collected for three months, covering the end of summer and start of the swing season. This study found that in comparison to the standard practice group, the resized group had longer average and maximum runtimes, consumed the same amount of energy, and if implemented on a large scale would reduce the electric utility's peak demand.

Introduction

Background on Air Conditioning Sizing and Energy Savings

Oversizing of residential cooling systems is common among builders and HVAC contractors; it results in greater first cost and reduced energy efficiency and comfort due to short cycling. In humid climates, the short cycling results in reduced latent capacity. Mechanical contractors often oversize units in order to reduce time spent on load calculations, to lower their potential for callbacks, and to allow for extraordinarily low thermostat set points (Vieira 1995).

Short-cycling decreases capacity and increases energy consumption due to start-up losses that occur at the beginning of each cycle. The power input to the air conditioning system rises to near its steady-state level within a few seconds, yet the cooling output rises to its steady-state level over the course of a few minutes. The Seasonal Energy Efficiency Ratio (SEER) rating accounts for this effect via the cycling loss coefficient (C_D), which is determined experimentally (ARI 2006). For single-speed systems, SEER is calculated as:

$$\text{SEER} = \text{EER}_{82} * (1 - C_D / 2)$$

where EER_{82} is the steady-state energy efficiency ratio at an outdoor temperature of 82°F. Decreasing the value of C_D therefore increases the SEER rating. Due to increased SEER standards and market competition, equipment manufacturers have an incentive to reduce the value of C_D, and have successfully done so. The SEER procedure allows for a default value (in lieu of testing) for C_D of 0.25; most modern equipment has C_D in the range of 0.05 to 0.10 (Sonne 2006, Sachs 2006).

Previous studies have found differing results in energy savings due to reductions in capacity. A study of 308 homes in Florida (James 1997) found an energy savings of 5.6% associated with reducing system capacity from 150% to 120% of design loads. In contrast, a more recent analysis of four houses in Florida (Sonne 2006) found that the savings potential is dependent on location of the duct system. They found that the savings was 2 to 3% in systems with ducts located within conditioned space and negligible in systems with ducts in unconditioned attics. Sonne et al. postulated that the difference between their findings and previous findings may be due to technology improvements aimed at reducing the value of C_D.

Experimental Overview

Building Science Corporation (BSC) worked with a production homebuilder on a development in Redding, California. The project was partially underway when BSC became involved. The initial sixteen houses were built according to the homebuilder's standard methods in this region, which were substantially more energy efficient than the average new house in the region. The only major change BSC recommended was upgrading the space conditioning systems to high-efficiency furnaces and properly sized air conditioning systems.

As part of the builder's standard practice, a third-party consultant specified 4-ton air conditioners for the two smaller house plans and 5-ton air conditioners for the 2 larger house plans. For these houses, the evaporator coil sizes were matched to the condenser units. BSC reviewed the Manual J sizing calculations and found that the air conditioners were oversized due to assuming typical amounts of duct leakage; these houses were specified and tested to confirm low duct leakage. The builder and HVAC contractor therefore reduced the size of the air conditioners; the two smaller plans received 3.5-ton condensers, and two larger plans received 4-ton condensers. Due to a miscommunication between the builder and contractor, all of the houses in the resized group received 4-ton evaporator coils and air handler units. Oversizing the air handler and evaporator coil with respect to the condenser is standard practice for some HVAC contractors in dry climates and results in higher evaporator coil temperatures and therefore higher efficiency; however in this case it would have been desirable to install all systems under uniform matching or mismatching criteria.

In the remainder of this paper the houses built with the original size condensers will be considered the standard practice (S) group, and the houses built with the resized condensers will be considered the resized (R) group. Within the seven houses in the standard practice group, four houses were unoccupied model homes (M), and three others were occupied (O). All six of the resized group houses were occupied (O). Labels were applied to each house to uniquely identify them: SM1 through SM4, SO1 through SO3, and RO1 through RO6 (see Table 1).

House Characteristics

The houses in this study were newly-constructed, slab-on-grade homes. The four house plans in the community are all single-family, single story, and range from about 2100 to 2900 square feet of conditioned floor area. The enclosure insulation consists of R-38 (°F-hr-ft^2/Btu) blown fiberglass at the ceiling plane and R-15 netted & blown fiberglass plus 1" of EPS sheathing (R-4) for the walls. The windows are double-pane low-e with an overall U-value of 0.33 Btu/hr-ft^2-°F and a solar heat gain coefficient (SHGC) of 0.22.

The air handlers and duct systems were located in the vented attics. The duct system was entirely flex duct with R-6 insulation. The duct sizes were not changed when the air conditioners were resized, as they were not oversized for the lower airflow.

All of the test houses were tested for enclosure leakage and duct leakage by a third party tester as part of the builder's normal quality assurance program. Enclosure leakage results ranged from 1.7 to 2.3 square inches per 100 square feet surface area leakage ratio. For these houses, these measurements were equivalent to 2.9 to 4.3 ACH 50. The average was 3.3 ACH 50, and there was little difference between the average air leakage of the standard practice and resized houses (2.0 and 1.9 square inches per 100 square feet surface area, respectively).

Duct leakage was tested after the houses were finished using a duct pressurization test. Results were compared in terms of leakage normalized by nominal air handler flow. Results varied from 3.5% to 5.7% of nominal flow, with an average of 4.3%. There was little difference between the standard practice and resized houses (averages of 4.4% and 4.3%, respectively).

Manual J Calculations

A cooling load calculation was performed for each house in the study using a commercial software tool based on ACCA Manual J version 8 (ACCA 2003). The ASHRAE 0.4% design condition of 106°F for Redding, CA (ASHRAE 2005) was used for the outdoor temperature, along with an indoor temperature of 75°F, and appropriate values for the envelope attributes and internal loads. Table 1 below contains the results of these calculations along with the nominal size of the condenser unit, estimated air conditioning system capacity at design conditions, and the ratio of installed capacity to calculated design load. The system capacity had to be estimated, as a third-party evaporator coil was used (per the contractor's standard practice) and extended performance ratings were not available for the combination of condenser and evaporator coil. The estimate was made by assuming that the installed evaporator coil had the same performance characteristics as the condenser manufacturer's evaporator coil of the same nominal capacity, which allowed use of the condenser manufacturer's published extended performance ratings.

The seven standard practice houses have installed capacities from 155% to 184% of their calculated total design loads, and the six resized houses have installed capacities from 135% to 152% of their calculated design loads. All of the condensers and furnaces were made by the same manufacturer, and the evaporator coils were made by a second manufacturer.

Table 1: Manual J Cooling Load and Estimated System Capacity in Monitored Houses

House	Plan	CFA (sf)	Orientation	Installed AC Size (Condenser/Evaporator, nominal tons)	Estimated AC Capacity at 105 °F (kBtu/hr)	Manual J Load (kBtu/h)			Capacity/Load Ratio
					total	sensible	latent	total	
SM1	1	2077	N	4/4	44	26.5	1.0	27.5	1.60
SM2	2	2301	N	4/4	44	27.4	1.0	28.4	1.55
SM3	3	2666	N	5/5	56	30.1	0.8	30.9	1.81
SM4	4	2923	N	5/5	56	29.8	0.7	30.5	1.84
SO1	1	2077	E	4/4	44	24.8	1.0	25.8	1.71
SO2	3	2666	SW	5/5	56	30.3	0.8	31.1	1.80
SO3	4	2923	SE	5/5	56	31.1	0.7	31.8	1.76
RO1	3	2666	W	4/4	44	28.7	0.8	29.5	1.49
RO2	3	2821	SE	4/4	44	31.8	0.8	32.6	1.35
RO3	3	2666	NW	4/4	44	30.7	0.8	31.5	1.40
RO4	2	2301	SW	3.5/4	39	26.5	1.0	27.5	1.42
RO5	4	2923	W	4/4	44	28.2	0.7	28.9	1.52
RO6	1	2077	N	3.5/4	39	26.5	1.0	27.5	1.42

CFA = Conditioned Floor Area

Data Collection

Data collected by the monitoring equipment included outdoor temperature and relative humidity in one location in the community, indoor temperature at three locations in each house, relative humidity at one location in ten of the houses, and condenser runtime and condenser energy consumption in each house.

The outdoor temperature sensor was mounted out of the direct sun under the north-facing eave of one of the houses. This sensor recorded the outdoor temperature every 15 minutes. Comparison of the recorded data with data from a nearby airport indicates that the sensor experienced indirect solar heating from the roof deck. The temperatures recorded by this sensor are similar to the airport data at night, yet peak 0 to 8°F higher during the day; the magnitude of the difference correlates with the solar declination.

Temperature was recorded hourly at three locations in each house: at the thermostat, in the master bedroom, and in a second bedroom or den on the opposite side of the house from the master bedroom. In ten of the thirteen houses relative humidity was recorded in at least one of these locations as well.

Transitions in operation state of the condenser unit were recorded, giving run time and length. A separate meter recorded total condenser electricity consumption in 30-day periods.

During installation of the monitoring equipment, one-time measurements of the airflow, power draw, and external static pressure (ESP) across each air handler were made. Airflow was measured at each of the two returns in each house with an air handler/return filter flowmeter and a digital manometer. Power draw of the air handler was measured with a portable power meter. External static pressure was measured with a handheld digital manometer.

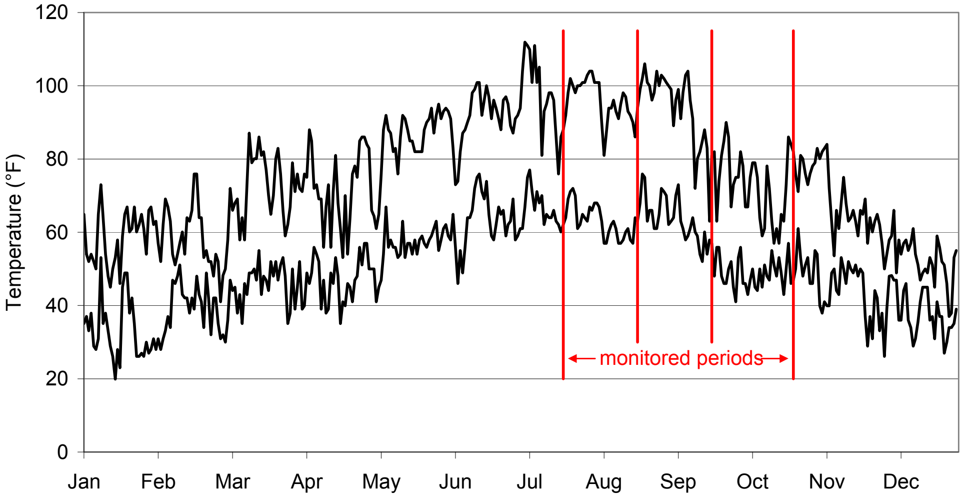
At the conclusion of the field monitoring, a homeowner survey was administered, covering aspects such as thermostat set points, number of occupants, occupancy patterns, and unusual electrical loads.

Monitored Period

Due to the construction schedule, the monitoring period included only half of the cooling season. Installation of the monitoring equipment was completed on two separate dates. Monitoring began in the first ten houses (SM1 to SM4, SO1 to SO3, and RO1 to RO3) on 7/20/07 and in the remaining three houses (RO4 to RO6) on 8/1/07. Monitoring lasted three months, well past the end of the cooling period in this location.

Figure 1 shows the daily high and low outdoor temperature for all of 2007 as recorded by a weather station at the Redding Municipal Airport. The three one-month long monitored periods are indicated on the graph. The monitored period did not include the hottest recorded temperatures this summer, which was 112°F on 7/4/07. The hottest temperature during the monitored period was 106°F on 8/23/07. The 0.4% recorded temperature for this summer was 104°F. For comparison, the ASHRAE extreme annual design condition is 111°F and the 0.4% design condition is 106°F. The monitored period included only 2 hours above the design condition of 106°F, but had 60 hours above 100°F.

Figure 1: Redding Municipal Airport Daily High and Low Temperatures for 2007

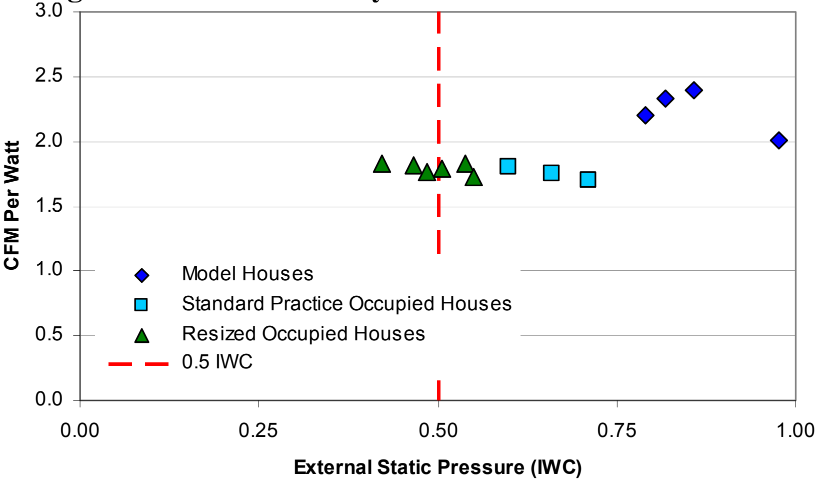


Results

Air Handler Efficiency

The air handler (AHU) efficiency was calculated in terms of CFM per watt, and plotted against the external static pressure (ESP) in Figure 2.

Figure 2: AHU Efficiency vs. External Static Pressure



The model houses were built on an accelerated schedule and therefore had different AHUs than the remaining houses. The model homes had variable-speed AHUs, with measured air-moving efficiencies of 2.0 to 2.4 CFM/watt at ESP of 0.8 to 1.0 inches of water column (IWC) (199 to 249 Pa). The higher ESP in the models was due to dirty air filters (the models were the first houses built and were operating with their original filters) and slightly higher airflow (due to the variable-speed AHUs). The occupied houses had single-speed AHUs, with an average efficiency of 1.8 CFM/watt at ESP of 0.4 to 0.7 IWC (100 to 174 Pa), similar to other field studies showing average power draws of 1.7-2.0 CFM/watt at ESP of 0.38 to 0.55 IWC (95 to 137 Pa) (Proctor and Parker 2000). Previous work including a survey of manufacturers' data at 0.5 IWC (125 Pa) of ESP showed a median of 2.2 CFM/watt (CEC 2006).

All of the standard practice units showed external static pressures higher than the manufacturer's recommendation of 0.5 IWC (125 Pa). The median of the occupied standard practice homes was 0.66 IWC (164 Pa). The median of the model homes was 0.84 IWC (209 Pa). This is consistent with measurements by CEC (2006), showing a median cooling speed ESP of 0.80 IWC (199 Pa) in a survey of 60 installed furnace systems. A significant portion of the pressure drop in the houses in the current study was due to the MERV-13 filters used at the return grilles. While the pressure drop across the filters was not measured directly, the median return pressure (as measured between the filter and the blower) in the standard occupied houses was 0.38 IWC (95 Pa), significantly above the 0.15 IWC (37 Pa) that would normally be expected. The filters are specified as having a pressure drop of 0.28 IWC (70 Pa) at 500 ft/min face velocity when first installed; with the measured flow volume and face area resulting in 250 to 350 ft/min face velocity and assuming the pressure drop is linearly related to the airflow, the estimated pressure drop across the filters would be 0.14 to 0.19 IWC (35 to 47 Pa). The pressure drop would increase as the filters became dirty. It is notable that the resized houses had lower ESP, in the range of the manufacturer's recommendation, due to the fact that the sizes of the ductwork, return grills, and return filters were not reduced when the air conditioning system was resized.

Occupant Thermostat Behavior

There was substantial variation in occupancy and occupant behavior among both the model and occupied homes. The model homes were unoccupied, but had all of the interior lights on during the day. Among the occupied houses, both occupancy and thermostat behavior varied widely. The number of occupants varied between 1 and 5 people per house, with a median of 3. Thermostat behavior was quite varied. All of the houses had programmable thermostats installed by the builder; however none of the occupants appeared to use the programmable feature.

Previous studies (Parker 1996) have identified four categories of thermostat operation by the occupants: constant off, constant setpoint, daily set up/set down, and manual on/off. All of these behaviors were observed in the collection of occupied houses in this study.

Only one house showed an example of the constant off category. The occupants in one house (SO1) turned off their air conditioner for a total of 22 days from 7/20 to 9/19, resulting in significantly lower energy consumption than their neighbors but at the expense of peak indoor temperatures of 90°F.

The four model houses and five of the occupied houses had constant thermostat settings, with relatively infrequent adjustments to the setpoint. The model houses were locked at a single temperature and were not changed. These houses showed a strong relationship between air conditioner hourly runtime and indoor-outdoor temperature difference (see Figure 3). In the occupied houses, the correlation between air conditioner hourly runtime and indoor-outdoor temperature difference was not as strong, due to varied interior loads and occupant behavior (see Figure 4).

Two of the occupied houses had daily setup/setback schedules. Both of the houses appeared to do so manually, as the schedule varied somewhat from day to day. One of the houses set up the thermostat at night and back in the morning. The second set up the thermostat at night and back in the late afternoon.

One of the occupied houses was operated as a manual on/off system. This resulted in wide swings in temperature, long runtimes, and weak correlation between air conditioner hourly runtime and indoor-outdoor temperature difference (see Figure 5).

Figure 3: Correlation of SM1 Runtime Fraction to Indoor-Outdoor Temperature Difference

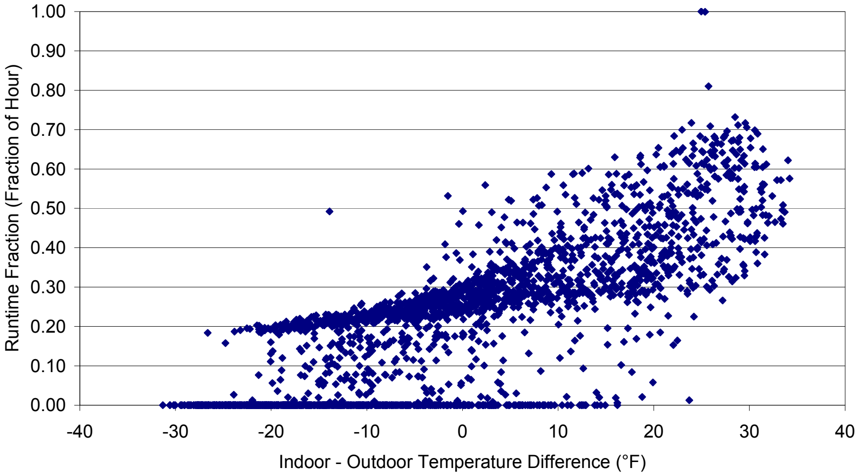


Figure 4: Correlation of SO2 Runtime Fraction to Indoor-Outdoor Temperature Difference

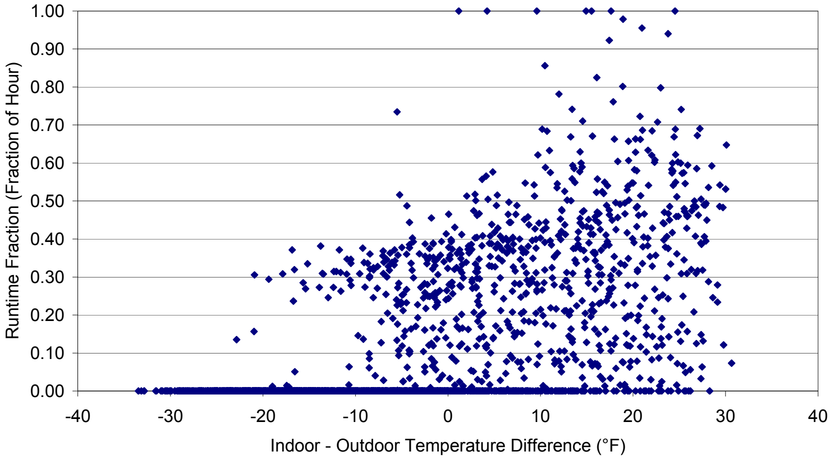
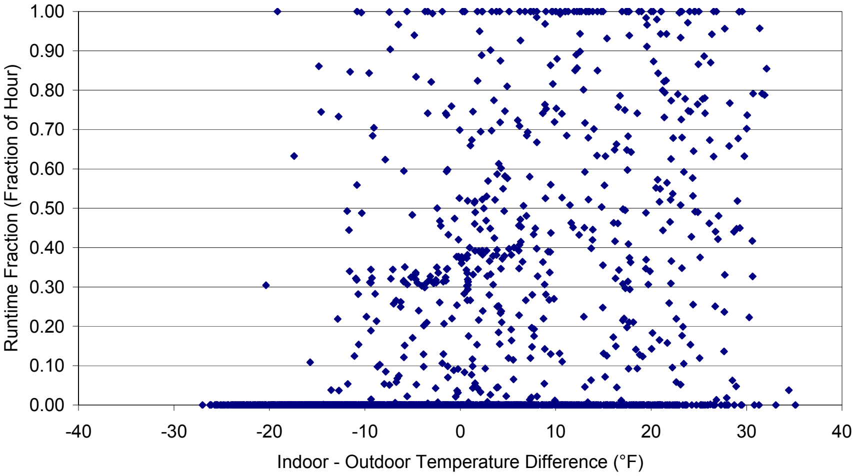


Figure 5: Correlation of RO4 Runtime Fraction to Indoor-Outdoor Temperature Difference



Air Conditioner Capacity and Runtime

A major objective of the monitoring was to determine the effect of resizing on the run lengths and runtime fractions of the air conditioners. The HVAC contractor was concerned that the resized air conditioners would not be "large enough." Two metrics were used to address this concern. The first metric was how long the air conditioner ran during the hottest day of the monitored period, and the second was how long the longest runtime of the entire monitored period was, and what caused it to be this long.

A summary of the air conditioner operation during the hottest day in the monitored period is presented in Table 2. The hottest day occurred on 8/1/07, with the on-site temperature measurement reaching 109°F. The data show that the standard practice groups have maximum hourly runtime fractions in the range of 0.49 to 0.76, and the resized group has higher maximum hourly run fractions in the range of 0.74 to 1.00.

Throughout the monitored period SM3 showed unusually short runtimes of 6 to 8 minutes. It was determined that the thermostat was causing this phenomenon, although it was still able to maintain the desired setpoint.

Table 2: Results of Air Conditioner Operation on Hottest Day in Monitoring Period

House	Longest Run Length (minutes)	Highest Hourly Run Fraction (fraction of hour)
SM1	42	0.70
SM2	49	0.82
SM3	8	0.49
SM4	42	0.70
SO1	44	0.73
SO2	44	0.73
SO3	65	1.00
RO1	216*	1.00
RO2	88	1.00
RO3	54	0.90
RO4	109*	1.00
RO5	74	1.00
RO6	59	0.98

* These long runtimes were due to changes in the thermostat set point

A summary of longest runs, and what caused those runs, is presented in Table 3. The cause of the long runs could be estimated based on the interior temperature response and occupancy of the houses. The rate of temperature reduction with the air conditioner active is the same at a given (constant) cooling load and outdoor temperature. Therefore, if indoor temperature response is different than usual under the same outdoor conditions, it is likely that there is a cooling load that is out of the ordinary. For the unoccupied models, this was usually an open door or window (due to prospective homebuyers wandering through the model). In the occupied houses, the load could be cooking, showering, open doors or windows, or other occupant behavior.

Table 3: Summary of Longest Air Conditioner Runs

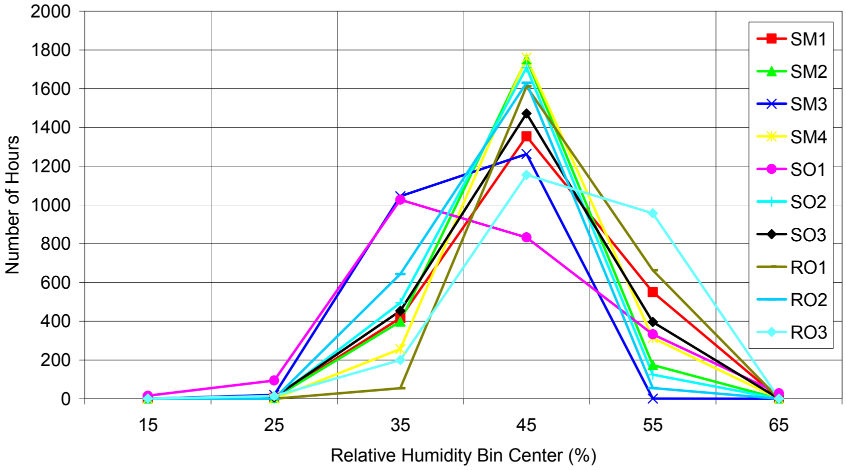
House	Date	Longest Run Length (minutes)	Apparent Cause
SM1	9/2	110	Open door or window
SM2	8/31	78	Open door or window
SM3	9/19	27	Change in setpoint
SM4	8/31	62	Open door or window
SO1	8/22	165	Change in setpoint
SO2	8/27	170	Change in setpoint
SO3	7/24	198	Change in setpoint
RO1	7/23	342	Change in setpoint
RO2	7/27	314	Change in setpoint
RO3	7/22	134	Cooking or open door or window
RO4	9/1	224	Change in setpoint
RO5	9/2	100	Change in setpoint
RO6	8/3	215	Open door or window

The data show that changes in set point are the most common cause of long runs, with non-envelope loads such as cooking or open doors or windows a close second. These non-envelope loads were not measured and therefore are suppositions based on a comparison of the rate of decrease in the indoor temperature upon air conditioner activation with the "normal" rate of decrease at the same outdoor conditions. The resized group does have longer maximum runs but variation due to individual occupant behavior is more pronounced than variation between sizing groups. Long runs most often happen when the enclosure load is highest and capacity is lowest (during peak outdoor temperatures) but drastic thermostat changes were observed even at night, which resulted in occasional long runtimes with minimal enclosure loads.

Indoor Relative Humidity

Relative humidity was measured at the thermostat in at least one location in ten of the thirteen houses. The measurements show that no houses had a significant number of hours over 60% relative humidity and all had median relative humidity of between 40% and 50%. Figure 6 shows the distribution of hourly measurements for the ten houses with relative humidity sensors. Seven of the ten houses had very similar behavior, with relative humidity most often in the 40% to 50% range and very few hours outside of the 30% to 60% range. SM3, SO1, and SO2 show behavior atypical of the remaining seven houses. SM3 had lower median and average relative humidity. SM3 had short, frequent runtimes (discussed later) so it is possible that the evaporator coil stayed cold enough between runs to effectively dehumidify the space; however coil temperature was not measured and so only speculation is possible. The occupants of SO1 turned off their air conditioner for several days, resulting in high temperatures and correspondingly low relative humidity for a large number of hours. Finally, SO2 shows a higher number of hours in the 50% to 60% range than the other houses. Analysis of time-series data shows uniformly higher relative humidity than other houses in either the standard or resized group; therefore it is more likely due to occupant behavior (cooking, bathing, plants, etc) than differences in the air conditioning system. Overall, there is no clear difference in the humidity levels between the standard and resized groups.

Figure 6: Distribution of Relative Humidity Hourly Measurements



Condenser Energy Consumption

The monitoring period was broken into three 1-month-long periods: July 20 to August 19, August 20 to September 19, and September 20 to October 19. Air conditioner electricity consumption data for the houses are shown in Table 4. Because three houses (SO4 to SO6) were not monitored for all of the July 20 to August 19 period, daily average consumption was calculated as a comparable metric.

Table 4: Daily Average Condenser Electricity Consumption

House	Daily Average AC Consumption (kWh), Period Ending:		
	8/20/07	9/20/07	10/20/07
SM1	16.9	24.8	7.7
SM2	17.7	13.4	1.5
SM3	25.4	25.9	4.6
SM4	21.8	15.6	1.2
SO1	10.6	8.8	1.0
SO2	17.7	17.8	1.4
SO3	21.9	18.4	1.2
RO1	24.4	18.8	2.1
RO2	18.8	16.6	1.3
RO3	22.5	16.5	1.6
RO4	18.5	15.7	0.0
RO5	14.6	15.2	0.9
RO6	20.7	20.6	2.4

After eliminating the four model houses and one standard practice occupied house (SO1) due to unusual occupancy habits, only two houses (SO2 and SO3) provided useful data for a basis of comparison in the standard practice group. The occupants of these two houses had normally expected behavior, with occasional but not drastic adjustments to the set point.

Table 5 below shows the average and standard deviation of the electricity consumption of the standard practice comparison basis group (SO2 and SO3) and the resized group (RO1 through RO6). The difference between the two groups is statistically insignificant. Given the large variation in energy consumption due to occupant behavior, a much larger sample group would be needed before the uncertainty would be smaller than the difference between the averages.

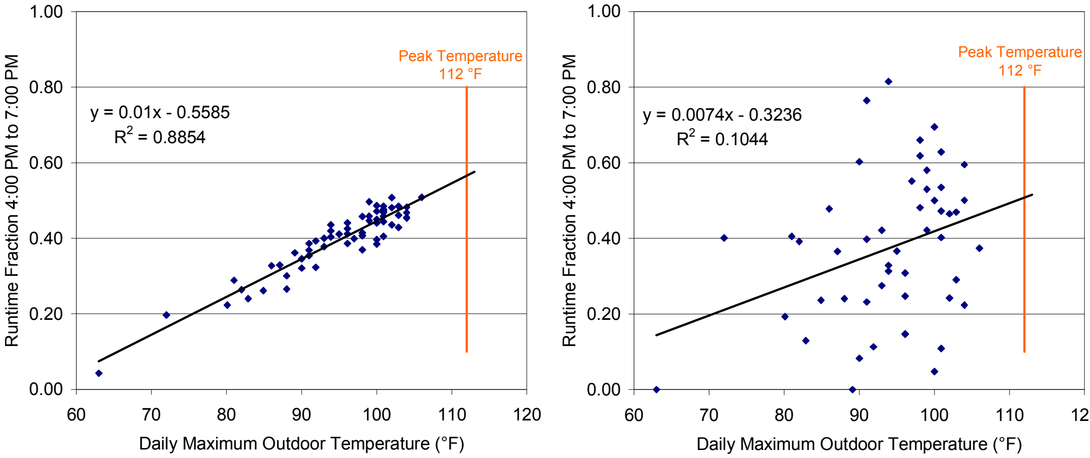
Table 5: Comparison of Condenser Energy Consumption in Standard Practice and Resized Groups

Group	Quantity	Daily Average AC Consumption		
		8/20/07	9/20/07	10/20/07
Standard Practice (SO2 & SO3)	Average	19.8	18.1	1.3
	Standard Deviation	3.0	0.4	0.1
Resized (RO1 to RO6)	Average	19.9	17.2	1.4
	Standard Deviation	3.5	2.1	0.9

Peak Demand

As the utility's peak demand for this summer occurred prior to completion of these houses, measured data during peak demand are not available. However assuming cycling losses are low, delivered cooling at a given temperature is nearly proportional to runtime. Therefore, runtime during near-peak conditions can be extrapolated to peak conditions. Figure 7 below shows the runtime fraction during the peak demand period each day (4:00 PM to 7:00 PM) versus the daily maximum temperature for that day (which typically occurs earlier than the peak demand), for SM3 and RO4, the houses with the best and worst correlation, respectively. This data includes only the first two months of monitoring (7/20/07 through 9/19/07), as the third month had little cooling in any of the houses.

Figure 7: Run Fraction during Peak Period Each Day, Best (SM3) and Worst (RO4) Correlations



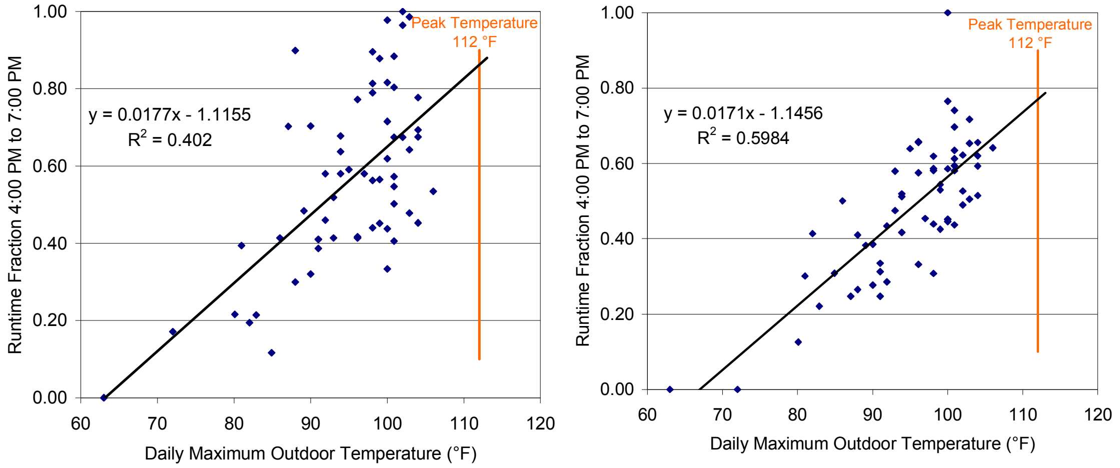
SM3 is a model home, with no occupants and a constant set point. In contrast, RO4 is an occupied home with an occupant that used the thermostat as a manual on/off switch for the air conditioner. The difference between the two is a rather extreme illustration of the variability that occupant behavior introduces into the cooling electric demand. Fortunately, over a large sample of the population this variability decreases and the utility's total load becomes more predictable.

Using a linear curve-fit to the data, an estimate can be made for the runtime fraction under peak conditions of a large population of similar homes. Table 6 contains the curve-fit data, coefficient of determination, and estimated average runtime fraction under peak conditions for all of the monitored houses. The data shows that, under averaged occupant behavior (i.e. conforming to the curve-fit line), none of the houses in any of the groups would run continuously for the entire peak period; estimated runtime fractions are actually quite low for most of the houses, in the range of 0.46 to 0.71. However, three of the six resized houses (RO1, RO2, and RO6) show average runtime fractions sufficiently high that actual occupant behavior would cause a portion of a population of these houses to run continuously during peak conditions. Figure 8 shows the extrapolation of two of these houses (RO1 and RO2) to peak temperatures.

Table 6: Extrapolation of Runtime Fraction to Peak Conditions

	Curve Fit: y = mx + b			Estimated Runtime Fraction at Peak
	m	b	R^2	
SM1	0.0116	-0.59	0.57	0.71
SM2	0.0109	-0.62	0.60	0.60
SM3	0.0100	-0.56	0.89	0.56
SM4	0.0116	-0.75	0.59	0.54
SO1	0.0171	-1.36	0.35	0.55
SO2	0.0091	-0.56	0.27	0.46
SO3	0.0137	-0.93	0.48	0.61
RO1	0.0177	-1.12	0.40	0.87
RO2	0.0171	-1.15	0.60	0.77
RO3	0.0130	-0.79	0.58	0.66
RO4	0.0074	-0.32	0.10	0.51
RO5	0.0123	-0.80	0.62	0.57
RO6	0.0134	-0.76	0.57	0.74

Figure 8: Houses with High Likelihood of Running Continuously During Peak Conditions



Peak demand savings due to resizing air conditioners depends on whether or not the air conditioner was cycling during peak demand prior to resizing. For the houses with air conditioners that are cycling during peak conditions, the average power draw during peak will be the power draw while running times the runtime fraction. A marginal decrease in capacity will result in a marginal increase in runtime fraction, a marginal decrease in power draw while running, and little impact on peak power demand. Only power draw due to cycling losses will be reduced. On the other hand, for the houses with air conditioners running continuously during peak conditions, the runtime fraction cannot be increased and therefore the average power will be the same as the power draw while running. In this case, a marginal decrease in capacity will not be offset by an increase in runtime fraction; therefore any decrease in capacity will result in a direct reduction of peak demand. Therefore, houses with air conditioning equipment sized such that they run continuously during peak load conditions provide the majority of the potential peak demand savings due to marginal decreases in air conditioner capacity. For air conditioning systems that cycle under peak load conditions, large decreases in capacity are needed in order to significantly affect peak load.

Conclusions

The resized equipment is sufficient to meet the loads in the houses. Both the resized and standard practice systems can have excessive runtimes when set points are changed, particularly if the change is large or happens during periods of high outdoor temperature. The resized group has longer average and maximum runs. For maximum runs, variation due to individual occupant behavior is more pronounced than variation between sizing groups.

The results of this study agree with a recent study (Sonne 2006) finding only a small difference in cooling energy use would be expected between resized systems and systems oversized within normal ranges (50-100% oversized). The houses in the current study had ducts in unconditioned attics, which would tend to reduce any energy savings gained by sizing closer to the actual load due to longer runtime and the resulting increase in duct leakage and heat gain. Differences in monthly energy consumption between the groups are statistically insignificant, in large part due to varying occupant behavior.

Of the standard practice group, only one house (SM3) had cycle times short enough to cause concern in terms of short-cycling inefficiencies and equipment durability; this was due to a malfunctioning thermostat and not the equipment sizing.

In a large sample of houses with air conditioning equipment sized similar to the standard practice group (155% to 180% of Manual J), virtually none would be expected to run continuously during peak electrical demand; therefore modest reductions in size are of marginal value as they save only the cycling losses (reductions in instantaneous power draw would be offset by longer runtimes). In a large sample of houses with air conditioning equipment sized similar to the resized group (135 % to 150% of Manual J), a fraction of the houses will run continuously during peak electric demand, therefore reducing peak demand by the reduction in electricity draw of the system (instantaneous power draw is reduced and runtime is still 100%). Houses with air conditioning equipment sized even closer to Manual J will increase both the fraction of houses running continuously and the peak demand savings of each house, therefore more significantly reducing peak demand. However, houses sized closer to Manual J will also experience longer average and maximum runtimes; when designing systems at this level care should be taken to properly locate and size supply and return registers to minimize noise and comfort issues associated with air conditioner operation. Previous research (Proctor 1998) has demonstrated that actual house loads in hot-dry climates were on the order of 67% of ACCA Manual J calculated loads; reducing equipment size closer to 100% of calculated load or lower has been shown to provide acceptable results in this and other studies (Rudd 2000).

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References

Air Conditioning Contractors of America (ACCA). 2003. *Manual J Residential Load Calculations, 8th Edition.* Arlington, Va.: Air Conditioning Contractors of America.

Air-Conditioning and Refrigeration Institute (ARI). 2006. *Standard for Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment.* Arlington, Va.: Air-Conditioning and Refrigeration Institute

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). 2005. *2005 ASHRAE Handbook—Fundamentals.* Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

California Energy Commission (CEC). 2006. *2008 California Building Energy Efficiency Standards: Fan Watt Draw and Air Flow.* Sacramento, Calif.: California Energy Commission.

James, P., J.E. Cummings, J. Sonne, R. Vieira, and J. Klongerbo. 1997. "The Effect of Residential Equipment Capacity on Energy Use, Demand, and Run-Time." In *ASHRAE Transactions*, Vol 103, Pt. 2. Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Parker, D., S. Barkaszi, J. Sherwin, and C.S. Richardson. 1996. "Central Air Conditioner Usage Patterns in Low-Income Housing in a Hot and Humid Climate: Influence on Energy Use and Peak Demand." In *1996 ACEEE Summer Study on Energy Efficiency in Buildings—Proceedings*, 8:147-160. Washington, D.C.: American Council for an Energy Efficient Economy.

Proctor, John. 1998. "Monitored In-Situ Performance of Residential Air-Conditioning Systems." In *ASHRAE Transactions*, 104(1B): 1833-1840. Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Proctor, J., and D. Parker. 2000. "Hidden Power Drains: Trends in Residential Heating and Cooling Fan Watt Power Demand." In *2000 ACEEE Summer Study on Energy Efficiency in Buildings—Proceedings*. Washington, D.C.: American Council for an Energy Efficient Economy.

Rudd, A., J. Lstiburek, and K. Ueno. 2000. "Unvented-Cathedralized Attics: Where We've Been and Where We're Going" 2000. In *ACEEE Summer Study on Energy Efficiency in Buildings—Proceedings*. Washington, D.C.: American Council for an Energy Efficient Economy.

Sachs, H., H. Henderson, D. Shirley, S. Nadel, D. Jaynes. 2006. "Can SEER Be Saved?" In *2006 ACEEE Summer Study on Energy Efficiency in Buildings—Proceedings*. Washington, D.C.: American Council for an Energy Efficient Economy, Washington, D.C.

Sonne, J., D. Parker, and D. Shirey III. 2006. *Measured Impacts of Proper Air Conditioner Sizing in Four Florida Case Study Homes.* Final Report FSEC-CR-1641-06. Cocoa, Fla.: Florida Solar Energy Center.

Vieira, R.K., J. Klongerbo, J.K. Sonne and J.E. Cummings. 1995. "Florida Residential Air Conditioning Sizing Survey Results," In *ASHRAE Transactions* V.101, Part 2. Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.