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Saving Tons at the Register

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Abstract

Duct losses have a significant effect on the efficiency of delivering space cooling to U.S. homes. This effect is especially dramatic during peak demand periods where half of the cooling equipment's output can be wasted. Improving the efficiency of a duct system can save energy, but can also allow for downsizing of cooling equipment without sacrificing comfort conditions. Comfort, and hence occupant acceptability, is determined not only by steady-state temperatures, but by how long it takes to *pull down* the temperature during cooling start-up, such as when the occupants come home on a hot summer afternoon. Thus the delivered tons of cooling at the register during start-up conditions are critical to customer acceptance of equipment downsizing strategies. We have developed a simulation technique which takes into account such things as weather, heat-transfer (including hot attic conditions), airflow, duct tightness, duct location and insulation, and cooling equipment performance to determine the net tons of cooling delivered to occupied space. Capacity at the register has been developed as an improvement over equipment tonnage as a system sizing measure. We use this concept to demonstrate that improved ducts and better system installation is as important as equipment size, with analysis of pull-down capability as a proxy for comfort. The simulations indicate that an improved system installation including tight ducts can eliminate the need for almost a ton of rated equipment capacity in a typical new 2,000 square foot house in Sacramento, California. Our results have also shown that a good duct system can reduce capacity requirements and still provide equivalent cooling at start-up and at peak conditions.

Introduction and Background

Common residential duct installations are notorious for their poor performance. Poor delivery efficiency has been thoroughly documented and characterized by numerous field tests across the United States. Over one Quad of duct related annual energy waste has been quantified by residential energy researchers and practitioners in the U.S. (Andrews and Modera 1991).

As a result, the "market" for residential ducts is slowly transforming. Energy codes have been modified and home energy ratings have been crafted to encourage improved duct installations. Diagnostic techniques for duct leakage have been developed and standardized. Aerosol technology has been developed and commercialized to facilitate duct sealing. Duct installation protocols have been developed and are now used in builder training programs. Rating systems for duct sealing materials are being improved including research toward longevity characterization (Hammon and Modera 1996; Hammon 1998; Jump, Walker and Modera 1996; Modera et al. 1996; Walker et al. 1998).

Capturing all the Benefits of Improved Duct Systems

This public interest research and industry activity toward improved ducts has generally been driven only by potential savings from direct effects of changes to the ducts themselves. Still to be thoroughly documented are additional potential benefits from HVAC system optimization that are made possible by duct improvements. These benefits include combinations of increased equipment longevity, decreased system first cost, decreased maximum electrical demand, and improved effective capacity; as well as additional energy and operating cost savings. Documenting the potential and devising methods to capture the full benefits of improved residential ducting can accelerate the market transformation for residential HVAC distribution systems.

In addition, previous studies (e.g. Treidler and Modera 1994) have shown that peak electric demand reductions do not automatically accompany energy savings from duct improvements. System optimization including proper re-sizing is necessary to capture full peak demand benefits.

Reduced First Cost From Equipment Down Sizing to Accompany Improved Ducts

Duct improvements alone have a non-trivial first cost. First cost can be a barrier in today's marketplace even with a relatively short pay-back period or a very low life-cycle cost. For example, Jump et al. 1996 found that average duct retrofits cost about $600 for 25 houses in Sacramento, CA. There was a range of $350 to $1000 that depended on ease of access to the duct system because labor costs (that dominate over material costs) increase sharply when ducts are hard to reach. In addition, parts of some duct systems are practically inaccessible (without removing walls, for example) and cannot be retrofitted. Combining the mean cost and energy use reduction of 18%, houses with an annual energy bill of about $600 would have a simple payback in 5 years or less. For houses under construction (when ducts are being installed) the additional cost of correctly installing the ducts and equipment *should* be minimal. However, this requires that installers are properly trained as well as the need for quality assurance/compliance checks. Therefore for a new house most of the additional expense would be in the testing of the installation (for duct leakage, fan flow or system charge). If the duct system is put in the house, rather than the attic, there may be additional costs associated with installing chases/drop ceilings or special joists for the ducts to run through. However these costs are difficult to estimate. This additional cost is offset if a smaller system (in terms of physical duct dimensions as well as A/C capacity) can be installed due to the improved duct system. In this paper we examine this capacity reduction whilst retaining the same occupant comfort - tons at the register and pulldown time.

The Sixty-Four Thousand Ton Question: What is the Right Size for the Air-Conditioning Unit?

If we include both retrofit and new installations, roughly a million tons of residential air conditioning capacity is installed each year in California. This is occurring amid increasing controversy about sizing of equipment and increasing attention being given to the disadvantages of over-sizing (Henderson 1992; Proctor and Albright 1996; Proctor, Katsnelson and Wilson 1995). An interesting aspect of this dialogue is the illumination of the multiple and clearly conflicting sizing paradigms that exist within the HVAC industry. For example, the Air-Conditioning Contractors of America sizing manuals (ACCA 1986)) are intended to optimize size in consideration of all performance parameters (Rutkowski 1996). They advise that slight under sizing of conventional systems is preferable overall.

The ACCA procedures explicitly assume steady-state cooling. There is no direct provision for the often observed programmable thermostat or manual control of the system, much less pull-down of a hot house on a summer afternoon (Berkeley Solar Group et al. 1995; Lutzenhiser et al. 1994; Parker, Mazzara, and Sherwin 1996; Wilcox 1996). Nevertheless, the ACCA sizing procedures remain the best accepted by industry experts and most likely to result in a well-sized system (Hammon and Modera 1996). This situation may be due to the lack of consideration of load diversity, leading to an overestimation of loads that balances out the lack of provision for transient operation (Abrams 1986, Brown et al. 1996). Still, some experts assert that even the ACCA sizing method over-sizes in some climates (Neal and O'Neal 1992; Proctor and Albright 1996).

The dominant sizing paradigm in current use is “bigger is better” (Abrams 1986; Vieira et al. 1995), or perhaps “but is it big enough?” (Brown et al. 1996). Field studies are confirming that, on average, residential HVAC equipment is severely over-sized (Lucas 1992; Proctor, Katsnelson and Wilson 1995; Reddy et al. 1992). One explanation is that poor duct performance, while not explicitly recognized, is accounted for by extreme over-sizing. Sub-optimal system design and lack of commissioning (e.g., refrigerant charging) are additional problems that over-sizing may be attempting to cover up. Or perhaps desired performance characteristics like temperature and humidity control, decreased operating cost, or decreased maintenance are just not accounted for in many common sizing methods.

Performance Characteristics Valued by Users and the Building Industry.

Some insights into the sizing confusion can be found in studies that try to discern the expectations of residential occupants. In the hot-humid Florida climate, a desire for good performance in extreme weather has been found to be a major driver of over sizing (Parker 1996; Vieira et al. 1995). Accommodating large numbers of guests or the “party” scenario can also affect consumer expectations about cooling systems performance (Hall, Hungerford, and Hackett 1994; Chandra 1996).

In discussions about the viability of re-sizing strategies, building industry input often boils down to a key question: “...if we down size the air-conditioner, will it still be able to pull the house temperature down quickly when the owner returns to a dormant house on a hot summer afternoon?” (Raymer 1998). This leads to a good hypothesis to test through modeling and eventually field tests, and to a set of several corresponding questions:

Given the well documented poor performance of new distribution systems, do existing designs actually pull the house temperature down quickly?

In particular, what happens when a poor duct system and the air handler are in the attic and the system is activated after being dormant on a hot summer afternoon? There is a wide range of quality and performance for duct installations, with delivery efficiency typically ranging from 50-90% (Jump et al. 1996). How well do the worst systems perform this task? What about the average or the best?

How much over sizing is necessary to make up for poor duct performance?

How do typical levels of over sizing compare with the increased equipment capacity needed to make up for poor duct installation performance in the pull-down scenario? What are the corresponding capacity losses associated with incorrect refrigerant charge or other commissioning issues? Could experience with poor pull-down performance be a major driver for over sizing?

Which is more effective in increasing pull-down ability: improving the ducts or increasing the size of the AC unit? Which costs less?

Are improved ducts competitive with or more desirable than increased equipment size in increasing pull-down ability? If so, can improved duct installations be sold in lieu of larger equipment?

A New Performance Paradigm: Capacity at the Registers

Current performance and sizing paradigms usually look at the capacity of the air conditioning equipment itself. The pull-down scenario and other occupant performance expectations help to illustrate the obvious, that a more important parameter is the cooling capacity actually delivered to the conditioned space. Or, expressed more simply, the capacity at the registers or tons at the register.

This new paradigm has several advantages. It is capable of capturing the effects of most of the important problems with the system, including factors related to duct layout and actual airflow across the coil, refrigerant charge, duct insulation, and duct leakage. Increasing the capacity at the register obviously requires that these problems be addressed, as opposed to ignored in favor of just having a big compressor unit. Can users become skeptical of systems sold by compressor unit size? – Asking instead how much cooling comes out of the registers. This study works toward developing this concept, while examining the optimization of system performance for the important pull-down operational scenario.

The capacity at the registers, rather than the capacity on the nameplate of the equipment, is the key performance issue for house occupants. This is most vividly seen in the effect of the capacity at the registers on the pulldown time. In this case, occupants are sensitive to the speed at which a house is made comfortable after being allowed to heat up during the day. The factors that change the equipment nameplate capacity into capacity at the registers are:

Capacity of AC unit. Field tests and manufacturers' tabulated data (Proctor 1997, 1998a and 1998b, Neal and Conlin 1988) show that the output capacity of an AC unit is less than the nameplate capacity for most operating conditions. It is also a function of airflow over the coil, matching of condenser and evaporator sections and the ambient weather conditions. Additional capacity reductions occur due to poor system charging.

Duct leakage. Any air leaking out of the supply ducts does not reach the conditioned space and is lost capacity. Air leaking into return ducts from hot attics (or garages) is an extra load for the equipment to meet that is subtracted from the equipment capacity. Duct leaks occur most often at the connections - plenums, branches and register boots. Field measurements of duct leakage (Jump et al. 1996, Cummings et al. 1990, Downey and Proctor 1994, Modera and Wilcox 1995 and Olsen et al. 1993) show that there is a wide range of possible duct leakage values.

Duct insulation. In addition to duct leakage, ducts lose energy by conduction through the walls of the duct. Adding insulation tends to reduce these conduction losses. Conduction losses also depend on the exposed duct area outside the conditioned space.

Duct layout. The location of the ducts determines where the leaks go to and the surrounding temperature for condition and return leakage losses. Ducts inside conditioned space have all their losses to conditioned spaces and therefore deliver all the equipment output to conditioned space. Ducts in attics have the supply leak losses condition the attic air, not the air in the house, and the high temperatures in attics lead to large conduction and return leak losses. The duct layout also includes the number of connections (more connections tend to increase leakage) and the position of registers relative to the equipment. A system with registers mounted near the equipment will have short duct runs requiring few connections (reducing leakage potential) and resulting in a smaller surface area that reduces conduction losses. In most Sunbelt climates (including California) the trend in new construction is to use a slab foundation that results in duct systems being installed in attics (with equipment occasionally in garages). Data from the Residential Energy Consumption Survey (Energy Information Administration 1993) confirm that new houses are increasingly built on slabs, particularly in cooling climates. Trends in construction and their impact on duct location were discussed in detail by Andrews and Modera 1991 who also concluded that the majority of new duct systems will be installed in attics in cooling climates.

Airflow rate. Very few duct systems are designed to ensure that the ducts minimize flow resistance so that the equipment has the correct flow across the heat exchanger. Field tests (e.g., Proctor 1997, Jump et al. 1996) show that a typical system has about 85% of the recommended system flow, with many systems (about a third) critically flow restricted to the point where manufacturers' information states that systems may suffer physical damage. Additional field tests in Florida (Parker et al. 1997) show that 85% of fan flow is not an unduly harsh performance penalty because these Florida results showed that systems had about 300 cfm/ton or approximately 75% of recommended flow.

Refrigerant Charge. Refrigerant charge has a significant impact on AC performance as shown in field and laboratory tests (Rodriguez et al. 1995, Blasnik et al. 1996 and Treidler and Modera 1994). In most cases, systems are undercharged, with a corresponding decrease in system capacity.

Modeling Forced Air Distribution Systems

To estimate the impact of these factors on the capacity at the registers a simulation tool (called REGCAP) has been developed. The REGCAP model was developed because existing models either have too many simplifying assumptions (e.g., proposed ASHRAE Standard 152P, ASHRAE 1998), or do not adequately model the ventilation, thermal and moisture performance of the ducts and the spaces containing ducts. REGCAP models the thermal behavior of the ducts and also the equipment. The thermal, moisture and ventilation models were developed from existing models outlined previously by Wilson and Walker 1991 and 1992. The attic ventilation and thermal model has been discussed in Forest and Walker 1993a and 1993b and Walker 1993. These models of ventilation and heat transfer, excluding the ducts, have been verified with extensive field measurements. The air flow modeling for REGCAP combines the ventilation models for the house and attic with duct register and leakage flows using mass balance of air flowing in and out of the house, attic and duct system. The thermal modeling uses a lumped heat capacity approach so that transient effects are included. The ventilation and thermal models interact because the house and attic ventilation rates are dependent on house and attic air temperatures and the energy transferred by the duct system depends on the attic and house temperatures.

The equipment model for REGCAP uses manufacturers' performance data that shows capacity changes with outside weather conditions, flow rate across the evaporator coil, and the return air conditions. Some simple regressions have been used to interpolate between specific performance figures in the manufacturers' tabulated data. Additional information regarding air conditioner performance changes due to incorrect system charge and system air flow have been adapted from laboratory data (Rodriguez et al. 1995). Using these correlations, the output from the airflow and thermal models are used together with weather data to determine the air conditioner performance. The temperature change across the cooling coil is determined from the mass flow rate through the coil (the system fan flow) and the calculated capacity of the equipment. Due to the limited data available and the possible changes in equipment performance for specific A/C units we have made these equipment performance algorithms as simple as possible and assumed that the various effects combine independently. Given the information available we could not justify a more complex approach that could look at the interactions of various effects to see if they are truly independent. That research is beyond the scope of this paper and may be examined in future investigations.

The general data requirements for REGCAP are:
DUCTS: size, location, leakage, insulation
EQUIPMENT: manufacturers performance data, refrigerant charge, and evaporator airflow
ENVELOPE: leakage, thermal properties

CLIMATE: Temperature, windspeed and direction, humidity ratio, solar radiation

The REGCAP output includes:
DUCTS: air and energy flows at the registers, losses to unconditioned space
EQUIPMENT: operating condition capacity and efficiency
ENVELOPE: Thermal losses and ventilation flows

Because REGCAP includes transient terms in the thermal model it can be used for non-steady state analyses, such as the pull-down experiments discussed in this paper. In addition it has the capability to do complete seasonal duct system analyses using the appropriate weather data. Note that REGCAP does not have a sophisticated thermal model for estimating house loads. A simple overall hear transfer coefficient based on exterior surface area and typical thermal properties of walls and windows was used together with a simple estimate of solar loads based on the measured solar radiation in the weather data file. These are coupled in a lumped heat capacity analysis to account for the thermal mass of the house. A simple house load model is sufficient for these simulations because we are concentrating on duct system performance rather than building envelope performance. In addition, without specific house and site information a more complex house thermal model was not justifiable.

Simulations

For this initial study, the input data parameters were selected to focus on key questions. The following list examines key input parameters and gives the limited range of values that we used for the simulations in this paper:

Weather. REGCAP uses a design day and "hot day" (highest peak temperature for Sacramento from the TMY data base, NCDC 1980). The design day has a peak temperature of 36°C (97°F) and this temperature is steady from 2:00 p.m. to 5:00 p.m. The design day has relatively low humidity, with the humidity ratio being about 0.005 to 0.007 for most of the day (the corresponding relative humidities are in the range of 10% to 30%). The hot day has a peak temperature of 41°C (106°F), with temperatures greater than 39°C (102°F) for four hours. This hot day is also more humid, with humidity ratios of about 0.01 during system operation (corresponding to about 22% RH). With these humidity levels, the supply plenum air temperatures are above the dewpoint and therefore REGCAP was not required to simulate moisture transfer processes and latent equipment loads. Future versions of the simulation tool will have the ability to track moisture. The solar radiation is about the same for both days with peaks of direct normal of about 3200W/m^2 (12kBtu/hour/ft^2). The air-conditioner is off from midnight to 3:00 p.m. to find initial conditions for the house and attic. Then at 3:00 p.m., the air handler is turned on. The TMY data is linearly interpolated to provide 15 minute data to increase the time resolution of the simulations.
Refrigerant Charge. Three levels were used: proper charge, typical charge (85% Proctor 1997 and Blasnik et al. 1996) and 70% charge (worst case found in field tests by Proctor 1998b)
Airflow across coil. Two flows were tested: 425 cfm/ton (manufacturers design specification for the unit for which we have data) and 345 cfm/ton. Field tests (Proctor 1997 and Blasnik et al. 1996) have shown that most systems have about this flow across the coil.
Duct Leakage. four cases:

1. poor - 30% of fan flow for both supplies and 30% for returns - this is from the average of the worst 25% of houses surveyed in California by Jump et al. 1996.
2. typical - 11% of fan flow leakage for both supplies and returns from field surveys by Modera and Wilcox 1995 and Walker et al. 1997, for new construction in California (This is also the default to be used in proposed changes to California T24 Energy Code (CEC 1998)).
3. good - 3% of fan flow leakage for both supplies and returns. This is a leakage level that can be achieved using current duct sealing technology if the ducts and equipment cabinet are in unconditioned space.
4. best - zero leakage. To realistically achieve this using existing duct systems requires bringing ducts and equipment inside the conditioned space.

Air handler and duct location. Two cases: 1. Ducts and air handler in attic, and 2. Ducts and air handler all inside the conditioned space. These represent the two extremes, where we have maximum duct losses in the attic and minimum duct losses if they are in the conditioned space.

Equipment Capacity. The rated capacity was calculated for the simulated house using ACCA Manuals J and S. These ACCA calculations indicated that a rated capacity of three tons would be required. It was assumed that a correctly design system would have this capacity (this corresponds to the RESIZED and BEST systems simulated). However, this is not typical of residential installations, so the rated capacity was also estimated based on surveys of HVAC contractors (Vieira et al. 1996) with one ton for each 46 m^2 (500 ft^2) of floor area. A survey of 19 houses by the authors found that California houses average about 375 ft^2 floor area per ton and a survey of 22 houses in Arizona by Proctor 1997 averaged 450 ft^2/ton. This indicates that we have not chosen overly severe system oversizing for these simulations.

Other input parameters are fixed for every simulation:

Duct Insulation. RSI 0.7 (R-4) as found in new CA construction (Walker et al. 1997).

Duct Surface Area. From proposed ASHRAE standard 152P (ASHRAE 1998) defaults. These defaults are based on measured duct surface areas in California houses (e.g., Jump et al. 1996). For a 184 m^2 (2000 ft^2) home with two returns, the defaults are: 50 m^2 (540 ft^2) for supplies, 20 m^2 (215 ft^2) for returns. The supply and return ducts are 200 mm (8 inches) and 400 mm (16 inches) in diameter respectively. **Attic Leakage.** Uses the typical code specification of 1/300 as the ratio of open vent area to ceiling/attic floor area.

House. The house is 184 m^2 (2000 ft^2), single story, slab on grade, with RSI 2.25 (R-13) walls and RSI 5.25 (R-30) ceiling. It has an SLA (@4Pa) of 3.8 cm^2/m^2 (This is the California T24 Energy Code (CEC 1988) default - based on many tests (123 California houses - "corrected" for removal of duct leakage)). 35% of the envelope leakage is to the attic, 5% at floor level, and 15% in each wall. The thermal mass of the house was estimated from the mass of building materials (wood, drywall, etc.) and their specific heats using a lumped heat capacity approach.

Table 1 contains a list of the simulations performed for this paper. These simulations were chosen to answer questions about how sensitive the capacity at the register is to the key parameters that could be controlled in the construction/system installation process: system charge, air handler flow, duct leakage and system location. In addition, the nameplate installed capacity was changed to see if a good duct system with a smaller AC unit could give the same net performance as a larger ac unit with a poor duct system. Each case in Table 1 was run twice - for both design day and hottest day conditions.

Table 1. List of REGCAP Simulations

	System Charge	Air Handler Flow	Duct Leakage Fraction	Duct and equipment Location	Rated Capacity

	[%]	[CFM/Ton]	[%]		[Tons]
BASE	85	345	11	Attic	4
POOR	70	345	30	Attic	4
BEST	100	425	3	Attic	4
BEST RESIZED	100	425	3	Attic	3
INTERIOR DUCTS	85	345	0	House	4
INTERIOR DUCTS RESIZED	85	345	0	House	3
IDEAL	100	425	0	House	3
IDEAL OVERSIZED	100	425	0	House	4

The base case is typical of new construction in California. The poor system represents what is often found at the worst end of the spectrum in existing homes. The best system is what could reasonably be installed in new California houses using existing technologies and careful duct and AC system installation to manufacturers' specifications. The best resized system looks at the possibility of reducing the equipment capacity using the best duct system. Interior ducts examines the gains to be had if duct systems are moved out of the attic. The resized interior ducts will determine if a smaller piece of equipment can deliver the same capacity as a bigger piece of equipment with a poor duct system. Lastly, the ideal system is an interior duct system that has been installed as well as possible (the other interior systems were installed with typical charge and air flow specifications). An additional simulation was done with no cooling system for comparison purposes.

Note that the resized capacity systems did not have a resized duct system. In some cases it should be possible to install a smaller duct system - thus reducing conduction losses to the attic. However, for this study the duct surface areas remained the same for simplicity.

Simulation Results

Three key results are examined:

1. Initial delivered capacity at the registers with hot house, attic and duct system.
2. Pulldown time for interior to reach 24°C (75°F).
3. Final delivered capacity at the registers with cool house (possibly attic) and duct system. The final capacity is determined when the system has cooled the house to 24°C (75°F).

To illustrate the temperatures used to calculate the tons at the register and the pulldown time, Figures 1 through 4 show the temperatures for some of the simulation results. Figure 1 shows the temperatures in the house and attic when there is no air conditioning. This simulation can be used as a reference for comparing the other simulations. The figure shows that at the 3:00 p.m. (15:00 hours) starting point for the systems to cool the house, the house air was at 39°C (102°F). Figure 1 also shows the peak attic temperature to be 57°C (135°F) at about 1:00 p.m. (13:00 hours) which coincides with the peak solar gain for the roof. The peak house temperature of about 41°C (106°F) occurs later in the day.

During the afternoon the interior temperature rises above the outdoor temperature. This suggests that an energy-efficient strategy for the homeowner would be to use a whole-house fan (or a residential economizer) until the indoor temperature dropped to outdoor temperature. Because these systems are not commonly used, we have not considered this option. Note also that in the evening the house is warmer than both the attic or outside due to its thermal mass.

Figure 2 is the simulation result for the Base Case system. The ducts are in the attic and so the supply temperature is close to the attic temperature until the system turns on. The supply temperature is about 7°C (13°F) below room temperature and comparing the room temperature to Figure 1 shows how this cools the house air. In addition, the duct losses to the attic tend to cool the attic. This is seen at the end of the simulation, where the attic temperature is about 5°C (9°F) cooler than in Figure 1.

Figure 3 is for a poor system. Compared to Figure 2, the supply temperature is not as cool and the resulting room temperature is not reduced as much. When the system starts, there is very little cooling done to the house because the supply air temperature is nearly the same as the house temperature. This is because the low capacity due to low charge and fan flow is completely taken up by return leaks from the hot attic and conduction losses.

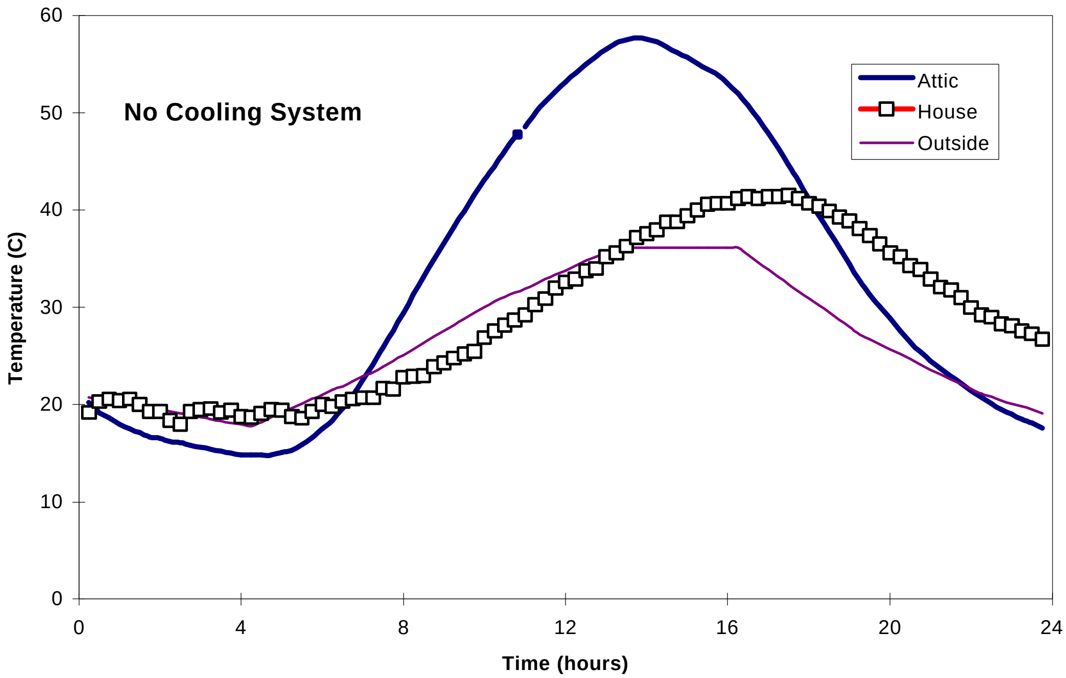

Figure 1. Simulation results for a Sacramento design day with no cooling system.

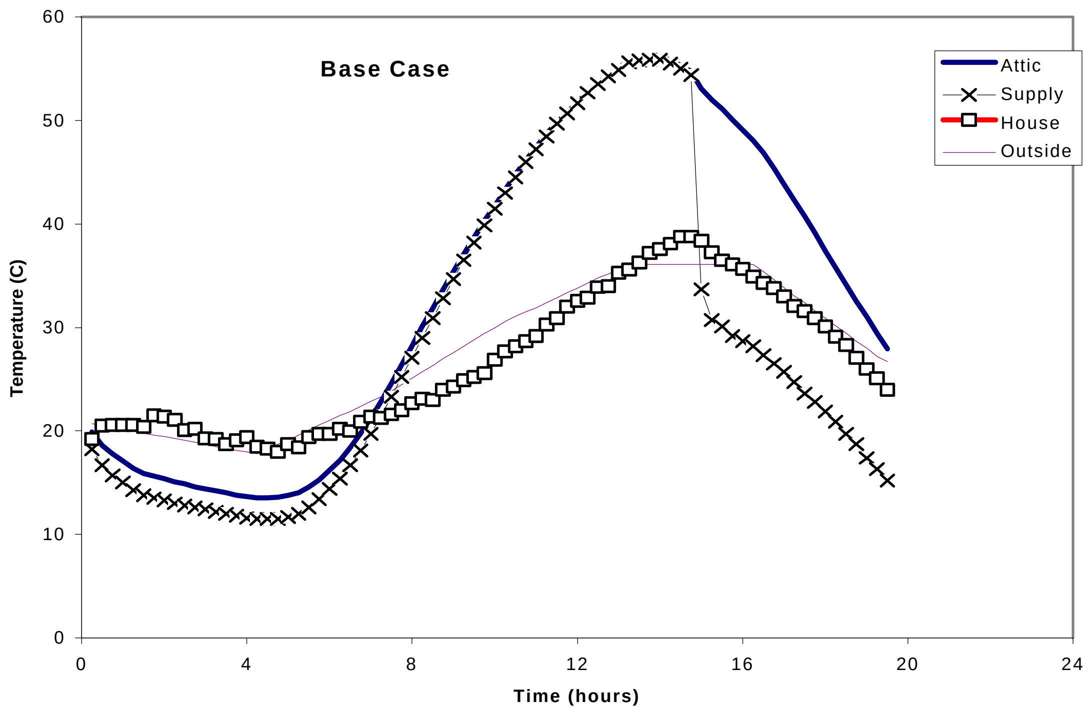

Figure 2. Simulation results for the base case system for a Sacramento Design day.

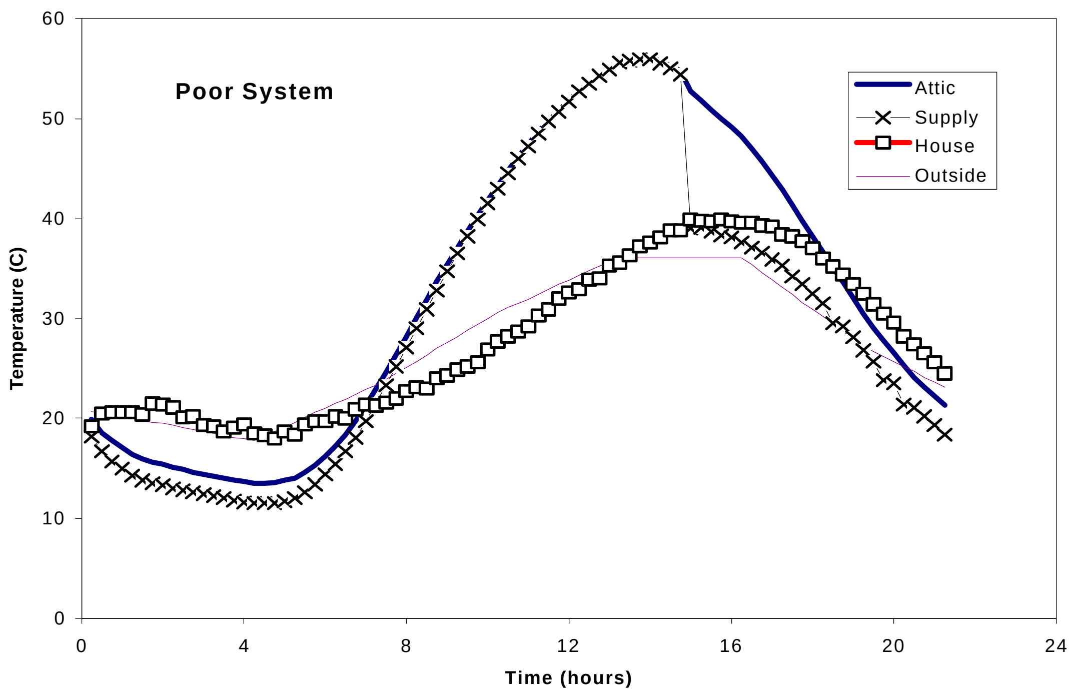

Figure 3. Simulation results for a poor system on a Sacramento design day.

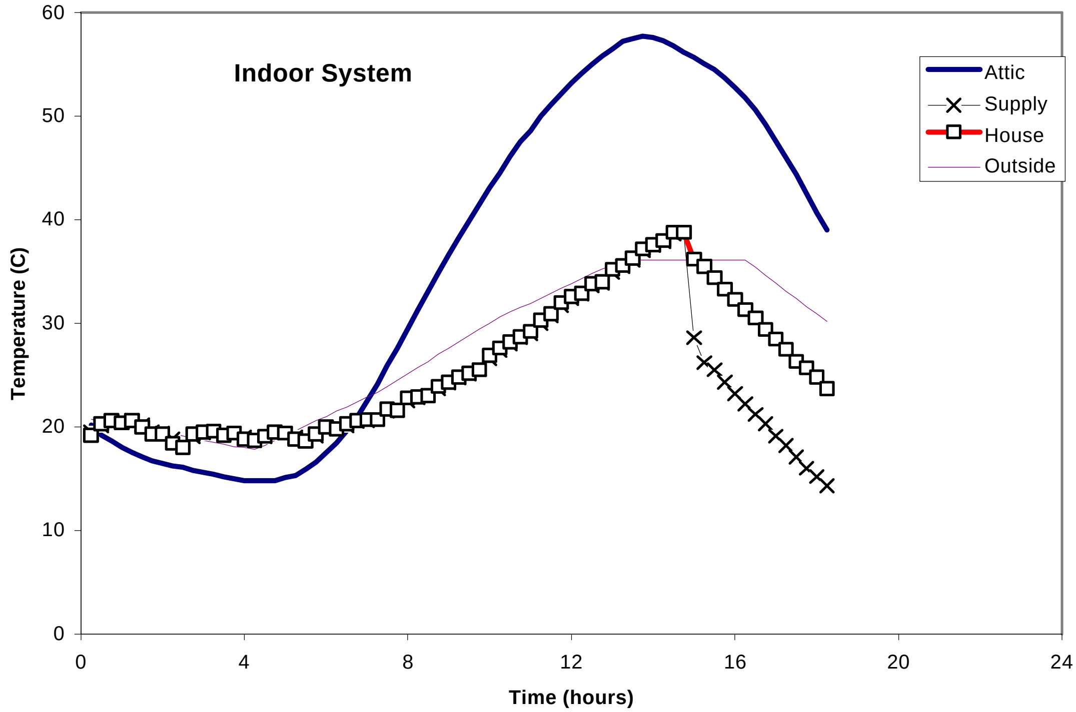

Figure 4. Simulation results for an indoor cooling system on a Sacramento design day.

Figure 4 shows the simulation results for an indoor system. In this case, the system starts at the indoor temperature rather than the attic temperature so that the initial cooling of the conditioned space is greater. Because this system's losses are less than for the attic systems, the delivered capacity continues to be greater than for the equivalent attic system after the initial cooling. In addition to cooling the house faster, the indoor system does not cool the attic and so the attic temperatures are almost the same as for the no cooling system case in Figure 1.

Table 2 summarizes the tons at the register and pulldown time results for all the simulations. The increased loads of the hottest day reduce the delivered capacities and increase the pulldown time. As expected, the interior systems and the non-leaky attic system (*BEST*) have the fastest pulldown and greatest tons at the register. For the hottest day simulations, the *POOR* system heats the house when it is first turned on because the supply air temperature is hotter than the house air - hence the negative initial delivered capacity. This result is mainly due to the low system capacity (caused by poor charge, low air flow and high outside temperatures) and the return leaks heating up the return air.

Analysis Of Simulation Results

The simulation results in Table 2 show that the *BEST* system with a smaller A/C unit (rated at three tons rather than four tons) can provide almost the same performance as the *BASE* system. The pulldown time is longer by a single time period (15 minutes) for the *BEST RESIZED* system. Moving the ducts inside allows a smaller capacity system (*IDEAL*) to have faster pulldown and more tons at the register than the *BASE* system. In addition, the *IDEAL* system has greater initial tons at the register than the *BEST* system in the attic that has 25% more nameplate capacity.

Table 2. Tons at the register and pulldown time simulation results							
			Design Day			Hot Day	
	Rated Capacity, Tons	Initial Tons at the register	Pulldown time, Minutes	Final Tons at the register	Initial Tons at the register	Pulldown time, Minutes	Final Tons at the register
BASE	4	0.83	270	1.55	0.58	315	1.51
POOR	4	0.09	390	0.68	-0.05	435	0.68
BEST	4	1.56	195	2.33	1.24	240	2.30
BEST RESIZED	3	0.80	285	1.59	0.58	330	1.59
INTERIOR DUCTS	4	1.68	195	2.08	1.66	240	2.02
INTERIOR RESIZED	3	1.20	285	1.35	1.18	345	1.33
IDEAL	3	1.41	240	1.72	1.41	300	1.66
IDEAL OVERSIZED	4	2.06	135	2.73	2.07	180	2.62

The results show that improved and resized systems were not penalized relative to the *BASE* case. The *BEST* attic and interior systems pulldown twice as fast as the *POOR* system and more than an hour faster than in the *BASE* system. The *INTERIOR RESIZED* system has a longer pulldown time than expected because the capacity is lower by not having complete system charge. The *IDEAL* system is the same but with complete system charge. This difference shows that the maintenance and correct installation of the A/C unit is as important as duct losses when estimating delivered capacity and pulldown time.

Ranking systems by tons at the register when the system first comes on shows that the resized systems have better or comparable performance to the base case. The improved systems with the same capacity as the base case have about double the tons at the register initially. This initial improvement is reduced at the end of the pulldown period, but it is still about 25%. Also note that the poor system has almost no initial delivered capacity. It is amusing to note that a very poor system under peak loads initially ***heats*** the house (negative tons at the register) and cools the attic until the attic temperature drops enough to allow cooling of the house.

Normalizing the tons at the register by the rated capacity (three or four tons) of the equipment illustrates the relative efficiencies of each system. The *BEST* and *BEST RESIZED* systems have better final results than the *INTERIOR* and *INTERIOR RESIZED* systems because they have the correct system charge and airflow across the coil which makes the equipment output closer to the nominal rating. This comparison also illustrates that the rating conditions used by manufacturers do not give a reliable estimate of the capacity near peak conditions. Even for an ideal distribution system, the unit can only deliver about half its rated capacity at peak conditions.

Conclusions

The simulation results show that improved ducts and system installation can allow the use of a smaller nameplate capacity air conditioner (almost one ton less in our case, and at least one ton in more demanding situations) without reducing the cooling delivered to the house (tons at the register) or the pulldown time. If system nameplate capacity is unchanged, either improving duct systems (to have little leakage) and correctly installing the equipment, or moving the ducts inside results in significant pulldown performance improvements. In these cases pulldown times were reduced by more than an hour and initial tons at the register were approximately doubled.

The results also show that without knowing about the quality of installation or location of the air conditioning system, the nominal capacity of the A/C unit is not a good indicator of system performance and is never a good indicator for pulldown purposes. Thus proper sizing of cooling equipment to meet peak loads cannot be done using nameplate ratings, but requires using manufacturers performance data at more realistic conditions.

Our results for low quality systems suggest that residential economizers would likely improve both for comfort and energy efficiency, because of the long period of start-up time during which the indoor temperature is above the outdoor temperature. In most cases, however, the resources would be better spent on improving the distribution system efficiency rather than installing an economizer.

Field studies are planned to validate the concepts embodied in this report and verify improved performance of redesigned systems. Future simulation work will look at some other possible duct system scenarios (e.g., the effect of reflective roofs, radiant barriers in the attic or additional attic venting), the effect of climate (Florida vs. California), comparison to existing steady state models (ASHRAE 1998) and longer term simulations to examine performance over a season.

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