95.111

Prepared by:
Proctor Engineering Group, Ltd.
San Rafael, CA 94901
(415) 451-2480

Assessment of HVAC Installations in New Homes

in APS Service Territory

Prepared for:
Arizona Public Service Company

Final Report
April 22, 1996

Contributors:
Michael Blasnik
Tom Downey
John Proctor, P.E.
George Peterson, P.E.

Creators of CheckMe!®

EXECUTIVE SUMMARY

Arizona Public Service Company (APS) contracted with Proctor Engineering Group to investigate opportunities in Arizona Public Service Company's service territory for improving air conditioning system performance in new residential construction. A nested program design was used to provide the highest level of certainty in the results for a fixed budget. This investigation has involved field testing the air conditioning units, duct systems, and building shells of a sample of newly built houses; monitoring the performance of these systems; assessing achievable improvements to the systems; and analyzing the potential energy savings and peak demand reductions from such improvements. The investigation found that newly constructed homes in APS's service territory have substantial deficiencies in their air conditioning systems, similar to those found in studies from other parts of the country (Appendix A contains brief descriptions of related studies). Improvements can be made to provide lower energy usage and reduced demand while improving occupant comfort and satisfaction. These improvements can be accomplished at moderate cost.

The key findings of this study include:

- Duct leakage and existing duct insulation levels reduce overall cooling efficiency. Reasonable improvements can save 16% of the cooling energy for about $140;
- Air conditioners often have insufficient air flow across the indoor coil and are frequently undercharged. Proper installation (following the manufacturers installation instructions) and testing would remedy these problems at a cost of about $70;
- A program which ensures tight, well-insulated ducts and properly installed efficient air conditioners could reduce cooling usage by approximately 42% and diversified peak demand by 1.2 kW. The additional cost is estimated to be $210 per unit;
- With properly installed systems featuring well insulated tight ducts the air conditioners should be resized to take advantage of the lower load. This would lower cost, "lock in" the peak reduction and further reduce the peak demand.

These results are supported by extensive information gathered in this project as well as data from projects in other climates similar to Phoenix. APS has a variety of potentially worthwhile options to pursue for improving cooling efficiency and reducing peak demand. Proper program design, training, and quality assurance are critical issues for actually achieving these improvements.

CONTENTS

TABLES

Table **Page**

FIGURES

Figure **Page**

1
BACKGROUND

The Phoenix Metropolitan area is currently the one of the fastest growing markets for new residential units in the nation. Arizona Public Service Company (APS) contracted with Proctor Engineering Group (PEG) to assess the energy savings and peak demand reductions achievable from a Heating, Ventilating and Air Conditioning (HVAC) efficiency program targeted to new residential construction in Arizona Public Service Company's service territory. This assessment involved the following:

- detailed field testing of a sample of 22 newly built homes (28 HVAC systems) in the Phoenix area to identify problems with current practice HVAC system installations;
- a three level nested monitoring of the 22 homes;
- a determination of achievable improvements to current practice and the costs of those improvements;
- analysis using a calibrated simulation based on field and monitored data to estimate the impacts of potential improvements on energy usage and peak demand, and;
- use of an electronically controlled duct leakage mechanism to assess the impacts of both supply and return system leakage.

This report describes the activities and results from these items.

PRIOR RESEARCH

PEG's prior experience, and the findings of other research projects around the country (see Appendix A), has found that typical air conditioning system installations have numerous problems which adversely impact efficiency, demand, and comfort. The primary problems identified include:

- excessive duct leakage in unconditioned spaces leading to substantial loss of conditioned air, heated return system air, and increased house infiltration;
- insufficient air flow through the indoor coil (many times caused by restrictive duct design which in turn leads to increased duct leakage effects);
- incorrect refrigerant charge;
- excessive air conditioning system sizing.

In prior studies, these problems were found to be common, not unusual, circumstances. Duct leakage has become a significant concern in the recent past. Studies from

California, Florida, Nevada, and the Pacific Northwest have consistently found large efficiency losses due to typical levels of duct leakage and duct conduction losses.

2

FIELD INVESTIGATION

Trade practices and housing styles vary throughout the country and so do the relative frequency and severity of different air conditioner installation problems. In addition, other problems or savings opportunities may be as or more important in APS's service territory than those listed in Appendix A. A field investigation of newly constructed houses in APS's service territory was needed to characterize the local problems and opportunities.

SAMPLE

This study utilized a three-level nested sample of 22 homes containing 28 air conditioning systems. The sample group included base-line (as-constructed) homes and enhanced homes (homes repaired to achieve reduced duct leakage).

The breakdown of the sample is shown in Table 2-1:

Table 2-1
Sample Design

Sampling Level	Baseline Homes	Enhanced Homes
Level 1 Field measurements and AC Submetering 28 systems, 22 homes	6- two-system homes 10-one-system homes 22 systems total 16 homes total	6-one-system homes 6 systems total 6 homes total
Level 2 Subset of Level 1 Temperature monitoring 18 systems, 15 homes	3- two-system homes 6- one-system homes 12 systems total 9 homes total	6- one-system homes 6 systems total 6 homes total
Level 3 Subset of Level 2 Intensive monitoring 6 systems, 5 homes	1- two-system home 1- one-system home 3 systems total 2 homes total	3- one-system homes 3 systems total 3 homes total

The only difference between the enhanced homes and the baseline homes was the amount of duct leakage. The average supply duct leakage of the baseline homes was

9% of air handler flow, while the enhanced homes were sealed by PEG to 3% of air handler flow. The average baseline return duct leakage was 5% while the enhanced homes were sealed to 3% of flow.

Both baseline and enhanced homes were subject to the same level of field testing as listed in
Table 2-2.

Nine of the houses were unoccupied when tested, but were ready for occupancy (i.e., fully drywalled with operating central air conditioning systems) and the remainder were occupied and less than one year old (the majority of occupied houses had just recently been moved into). APS arranged scheduling and provided contacts with local builders and/or homeowners. The 22 houses came from 19 developments built by 11 general contractors. They are believed to be representative of typical new construction in the area.

FIELD DATA COLLECTION PROTOCOL

PEG designed the field investigation to examine a wide variety of potential HVAC problem areas and to collect information needed to assess summer design cooling loads and overall building shell thermal integrity. The field procedures included many recently developed state-of-the-art diagnostic tests (particularly for assessing the duct systems). The field testing protocol is summarized in Table 2-2.

Table 2-2
Summary of Field Test/Data Collection Procedures

Parameter	Tests	Description / Use
Duct Leakage	Duct Blaster™[1] - total leakage	pressurize ducts to 25 pa with the Duct Blaster™ mounted at the air handler, registers sealed, measure fan flow, check pressures in other parts of duct system
	Duct Blaster™ - exterior leakage	repeat above test while blower door pressurizes house to 25 pa, eliminating pressure difference between ducts and house
	Duct Blaster™ - supply only exterior leakage	repeat above test after the return system has been separated from the supply system by installing a blockage at the air handler blower compartment
	Pressure Pan - leakage location indicator	measure pressures at individual registers with blower door pressurizing house to 50 pa
Air Handler Flow	Operating Static Pressures	measure static pressures in supply and return plenums - used for reference point when measuring air flow with Duct Blaster™, also used to determine system flow resistance.
	Duct Blaster™ - air flow test procedure	duplicate the supply side pressures after blocking the return and installing the Duct Blaster™ at the air handler
AC Charge	Weighing of refrigerant	use recovery equipment to recover and weigh the refrigerant charge in the system and compare to the factory nameplate rating and actual refrigerant line set lengths
AC Input	Wattage Input	use house electric meter to measure actual electric input for a one time test of input for both the outdoor condensing unit and air handler
AC other	Miscellaneous	collect nameplate information from indoor and outdoor units, assess potential outdoor unit radiant gain in afternoon
Duct Conduction	Duct system diameters and lengths	measure individual duct run lengths, record diameter and draw a diagram of the duct system layout
	Duct System Location	record percentage of supply and return ducts in various locations (attic, garage, inside, etc.) - used to estimate ambient conditions around ducts for modeling conduction and leakage
Design Cooling Load	Building Dimensions, materials, R-values, shading/exposures,	calculate design cooling loads & proper AC size using enhanced ACCA Manual J[2]
Building Airtightness	Blower Door Test	measure CFM50 of house, also measure pressures developed in key building zones such as attics

IMPLEMENTATION

Specially trained field technicians were needed to perform the field work within the project's time and budget constraints. PEG contracted with Conservation Services Group (CSG) to perform the work. CSG technicians had been previously trained by

[1] Duct Blaster™ is a trade mark of the Energy Conservatory.

[2] The Manual J program used in this project used blower door measured leakage rate to estimate Air Changes per Hour (ACH) rather than based on visual observations of the building shell (standard ACCA practice).

PEG and were experienced with PEG procedures. All technicians were trained in data collection by PEG's field manager to ensure quality.

The two person teams required an average of half a day per house. Scheduling began at the end of June, 1995 and all field work was completed promptly by mid-July.

PEG's field manager reviewed all data, daily. The data was entered into spreadsheets along with supplementary information from published air conditioner manufacturer ratings. The raw data were further analyzed for quality and calculations were performed to derive the system parameters of interest.

FINDINGS - GENERAL CHARACTERISTICS

The typical house in the study was a slab-on-grade home with 3 bedrooms, about 2100 square feet of living space, a volume of about 19,500 cubic feet, gas heat (10 of the single system houses were equipped with heat pumps), double glazed windows, and R-30 attic insulation with a tile roof. Thirteen of the houses had tinted glass to help lower the cooling load and six of the houses were equipped with external shade screens. There were 18 one story and 4 two story houses. Six of the houses had two AC systems but only two of the two story houses had two systems, the remaining four two system houses were one story houses. All of the single AC houses had the air handler located in the attic (one had a roof mounted package unit). The attic location exacerbates the impacts of return system leakage and increases conductive heat gains.

The houses were tight, with an average air leakage of 1959 Cubic Feet per Minute at 50 Pascals pressure (CFM50) measured with a blower door. This level of air tightness lowers the cooling and heating load of the house and saves energy. However, when the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standard 62-1989 is applied to modeled ventilation over three quarters of the houses do not meet the minimum infiltration criteria. ASHRAE standard 62-1989 specifies that residential structures must have 0.35 natural Air Changes per Hour (ACH) or 15 CFM per person whichever is greater. The average natural ACH of the homes in the project was 0.29. The number of units that do not meet the ASHRAE standard (with the windows closed[3]) based on blower door measurements and the Lawrence Berkeley Laboratory (LBL) infiltration model[4], is shown in Table 2-3.

[3]The ASHRAE standard assumes that adequate ventilation can be accomplished by opening windows. Since the lowest ventilation rates will occur when the indoor to outdoor temperature difference is small, opening windows for ventilation may be a viable option.

[4] Calculated using specific wind speeds published in the 1993 ASHRAE Fundamentals and bin weather data published in the Air Conditioning Contractors of America (ACCA) Manual J Seventh Edition Table A4-1. Based on an indoor temperature of 70°F in winter and 75°F in summer.

Table 2-3
Modeled Infiltration Failing to Meet ASHRAE Standard

	.35 ACH	15 CFM/person[5]
Failing to Meet Standard	18	6
% Failing to Meet Standard	82%	27%

FINDINGS - DUCT CHARACTERISTICS

The supply systems commonly consisted of a rigid metal supply plenum with 10″ and 12″ diameter helix core flex duct take offs that were commonly reduced at rigid sheet metal wyes to 6″ and 8″ diameter runs to the individual registers. The average supply system had about 110 linear feet of supply duct with an average surface area of 250 square foot, most of which was located in the attic (23 of the 28 system inspected had 100% of the supply duct system located in the attic).

Most of the return systems consisted of helix core flex duct connected directly to the air handler without a return system plenum. The average return system consisted of a 13 foot run of 18″ flex duct with an average surface area of 58 square foot, all located in the attic. Five systems used platform returns either with a grille mounted directly on the platform or a ducted return run connected to the platform.

All twenty eight of the systems examined had the typical R-4 insulation value that is common with flex duct systems. Most supply plenums were wrapped with one inch foil-scrim-kraft faced fiberglass duct wrap. The return system platform plenums had no insulation even though three of them were located in garages.

FINDINGS - DUCT LEAKAGE

Detailed duct leakage measurements were used to quantify the magnitude and impact of the existing leakage problems and the opportunities for improvement. Duct leakage can be measured in several different ways (Proctor et al, 1994). All duct leakage measurements were performed with the Duct Blaster™ mounted at the air handler blower compartment opening[6]. Three measures of duct leakage are summarized in this

[5] Occupancy estimated as number of bedrooms plus one.

[6] This is accomplished by mounting the Duct Blaster™ to a piece of cardboard that has been cut to fit the opening of the air handlers blower compartment door, removing the blower compartment door and using duct tape to temporarily attach the cardboard to the air handler in place of the blower compartment door. Appendix C describes this technique.

report: Total leakage, leakage to outside, and normal operating leakage split between supply and return.

During the testing, the technicians noted that most of the duct systems had obvious and easily eliminated leakage at the plenums, boot connections, and air handler. For example it was common to find large leaks at the joint between the supply plenum and the takeoffs or starter collars. They also noted that most connections in the duct system may be subject to future failure because they were made with duct tape. One of the HVAC contractors used mastic on some of the joints on the systems they installed. The application of mastic was spotty and tended to only be installed where it could easily been seen (i.e. a common spot for mastic application was at the return grille can while the duct connections in the attic were sealed with duct tape). The systems tested were as tight as they will ever be. They can be expected to leak more over time due to tape failure and disturbances (i.e., disconnections and tears) caused by service personnel working in the attics.

The total duct leakage test establishes the total amount of leakage out of the ducts when all the registers are sealed and the ducts are pressurized to the test pressure (25 Pascals). This test measures both leakage to inside and outside the house. Total duct leakage is a fast and accurate test method that is easily applied to new construction even before the drywall is installed. The average total leakage rate was 310 CFM25. The distribution of total duct leakage is shown in Figure 2-1.

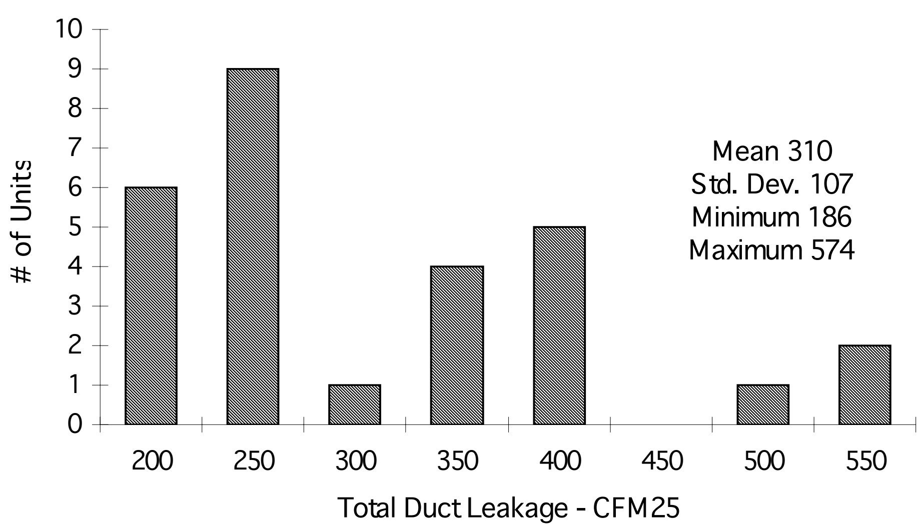


Figure 2-1
Total Duct Leakage

The three leakiest duct systems all had major return system leakage. Two of these systems had platform return plenums located in the garage while the third had a partially disconnected return duct at the air handler in the attic.

Duct leakage to (and from) the exterior is a better measure of duct leakage problems than the total leakage measurement, but involves more difficult and time-consuming tests. In this study, exterior duct leakage was measured using a blower door and a Duct Blaster™ pressurizing both the building and the ducts simultaneously. Having the house and the ducts at the same pressure reduces the duct leakage to inside to a minimum and thus measures the duct leakage to the exterior. The distribution of exterior duct leakage is shown in Figure 2-2.

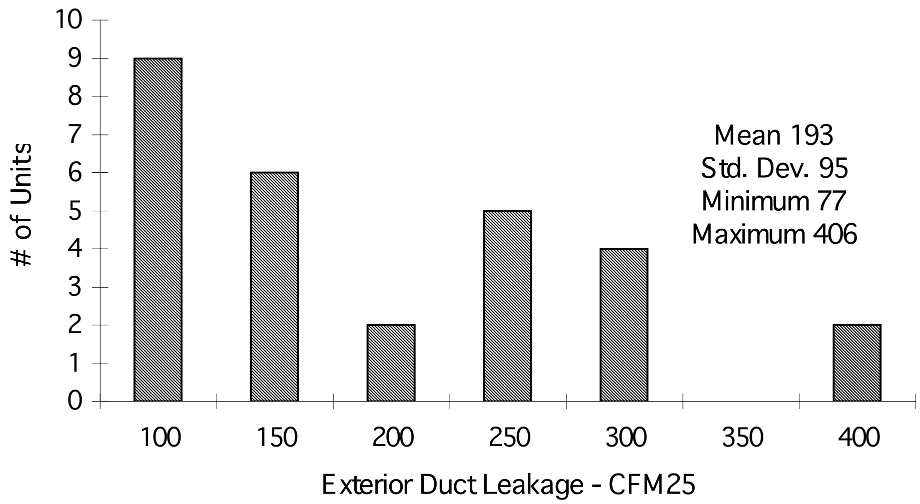


Figure 2-2
Duct Leakage to the Exterior

The two systems with the highest duct leakage to outside are two of the systems with the highest leakage in Figure 2-1. One of the systems has a platform return plenum in the garage and the other has the partially disconnected return duct at the air handler in the attic.

The average duct leakage to outside was 193 CFM25 (272 CFM50). This is similar to that seen in recent studies of newly constructed houses. Recent studies performed by PEG found duct leakage to outside in newly constructed homes of 253 CFM50 in Nevada and 292 CFM50 in Southern California.

Both the duct leakage to outside test and the total duct leakage test are useful in estimating the size of the holes in the duct system. The key quantities that effect energy usage however are the leakage in the supply and return systems under operating conditions (as a percentage of the air flow through the indoor coil). These key duct leakage quantities were determined in the following manner:

Field Investigation

1. A blockage was installed at the air handler blower compartment opening to the return system, isolating the supply system. The supply leakage to the exterior was then tested[7] as previously described.
2. The return system leakage was calculated as the difference between the total system leakage to outside and the supply system leakage to outside.
3. The operating leakage for each side was estimated by adjusting the leakage rate to the average pressure in that side of the duct system[8].
4. The operating leakage estimates were divided by the total operating air flow through the indoor coil.

The operating duct leakage split between supply and return is summarized in Figure 2-3. The flow rates averaged 110 CFM for supply leakage and 68 CFM for return leakage, representing about 9 percent of the air handler flow on the supply side and 5 percent of the air flow on the return side.

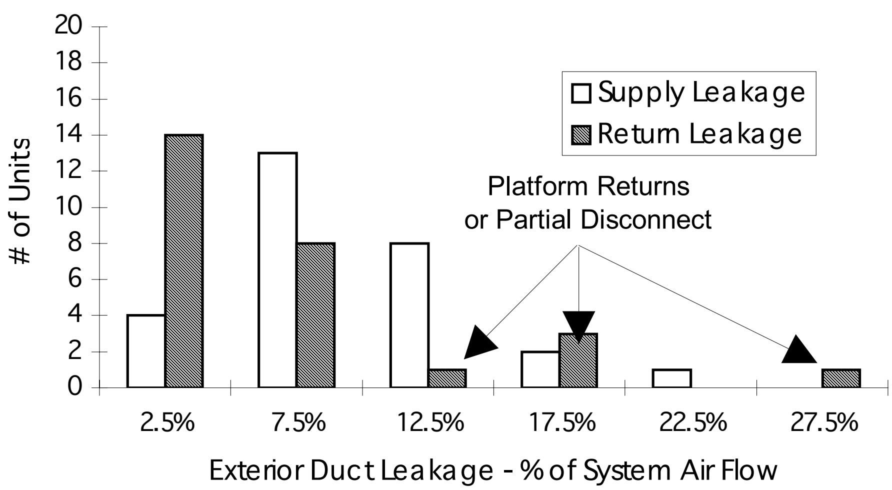


Figure 2-3
Supply and Return Leakage as a Percentage of Flow

Leaky return systems were concentrated in four of the systems with platform returns and the system with the partially disconnected return duct. Return leakage to outside on those units was more than 3 times that of the other return systems. The low return system leakage rates for systems not employing platform returns is attributed to the fact

[7] This testing procedure attributes the portion of air handler blower compartment leakage other than through the door to the supply system.

[8] The flow exponent was assumed to be 0.65. The leakage at operating conditions therefore was calculated as Test Flow * (operating pressure/test pressure)^.65 (See Appendix C for further explanation of the flow exponent)

that the systems consisted of short duct runs with only two joints which were sealed with duct tape that hadn't failed yet.

Duct Leakage Repair

Six of the duct systems tested in this study were randomly selected to receive duct sealing. This duct sealing was undertaken to determine the level of tightness that could be accomplished on systems in the Phoenix housing stock. It should be noted that this sealing took place on a retrofit basis after the system was installed. Sealing the system at the time of installation will result in lower leakage rates (all joints will be accessible for sealing) and be less labor intensive (very little additional time will be required of the installer to properly seal the system).

On average the duct sealing work performed required less than 4 person hours of labor and $50 of materials. The labor requirements were high because the repairs took place in attics and most repairs required the removal of duct tape or panduit strapping on the outer vapor barrier of the duct to access the inner liner where the sealing needed to take place. Another time consuming task was the removal of the individual registers for sealing around the boot to drywall connection. The labor requirements for the duct installation contractor will be much lower as the only additional labor required will be the application of mastic instead of tape. The results of the duct sealing work is shown in Table 2-4.

Table 2-4
Average Duct Sealing Reductions

	Pre Test	Post Test
Duct Leakage to Outside (25pa)	170	77
Supply Leakage Fraction	7.96%	3.07%
Return Leakage Fraction	13.53%	3.25%

FINDINGS - AIR CONDITIONING SYSTEMS

The houses had a wide variety of air conditioning system makes and models. Air conditioners serving an entire house were typically three and one half to four tons while houses with two systems usually had one large system for the main living area (typically three and one half to four tons) and a smaller unit for cooling the bedroom areas (typically two and one half tons). The typical air conditioner was a split system with the air handler located in the attic (only one of the systems was a rooftop mounted package system). The systems examined all had properly sized indoor air handlers/coils for the size of the outdoor unit (with the exception of one of the two system houses where the contractor had mistakenly connected a three ton outdoor unit to the four ton indoor coil and air handler and connected the four ton outdoor unit to the three ton indoor coil and air handler). Only two of the air conditioners had "upsized" indoor coils (both coils were rated one ton larger than the outdoor unit, contractors often do this to get an increased SEER rating). Rated SEER values ranged from 10 to 12 while rated EERs ranged from 8.7 to 10.9 and averaged 9.9. Twenty six of the systems had orifice type refrigerant metering expansion devices (mostly capillary tubes) and the remaining two systems had thermostatic expansion valves (TXV's).

Air Handler Flow Rate

The proper operation of an air conditioning system depends upon providing the correct air flow rate through the indoor coil -- usually listed by the manufacturer as 400 CFM per ton of nominal capacity. Low air flow has been a common problem found in other studies of air conditioner performance (Proctor, 1991; Neal, 1990). In addition to potentially shortening equipment life, incorrect air flow renders most standard tests for proper refrigerant charge invalid. In a hot/dry climate such as Phoenix, where sensible cooling is the major portion of the air conditioners job, the Air Conditioning Contractors of America (ACCA) recommends higher air flows.

All systems were tested for air flow with a clean filter in place and operating at the cooling mode blower speed. The Duct Blaster™ air flow test method was used because of its reliability. The procedure (detailed in Appendix C) involves these steps:

1. The supply system static pressures are measured in two duct locations while the system is running at steady state. The static pressures are measured using a static pressure probe and a digital manometer.
2. The return system is blocked at the air handler blower compartment.
3. The Duct Blaster™ is installed in the air handler blower compartment opening. All air flow through the air handler fan must then come through the Duct Blaster™ which is a combination fan and flow measurement device.
4. The supply system static pressures measured in step 1 are duplicated by turning the air handler fan on and adjusting the speed of the Duct Blaster™ fan.
5. The measured flow rate duplicates the operating flow rate of the system.

Figure 2-4 shows the distribution of measured flow rates compared to manufacturers' specifications. The average measured flow rate was 344 CFM per ton, fourteen percent below the target value of 400. More than half of the units were below 350 CFM/ton (often used as a level requiring corrective action). It should be noted that these units have the highest air flow they will ever experience. As the units get older, the blower and indoor coil will become dirty and the air flow will decrease.

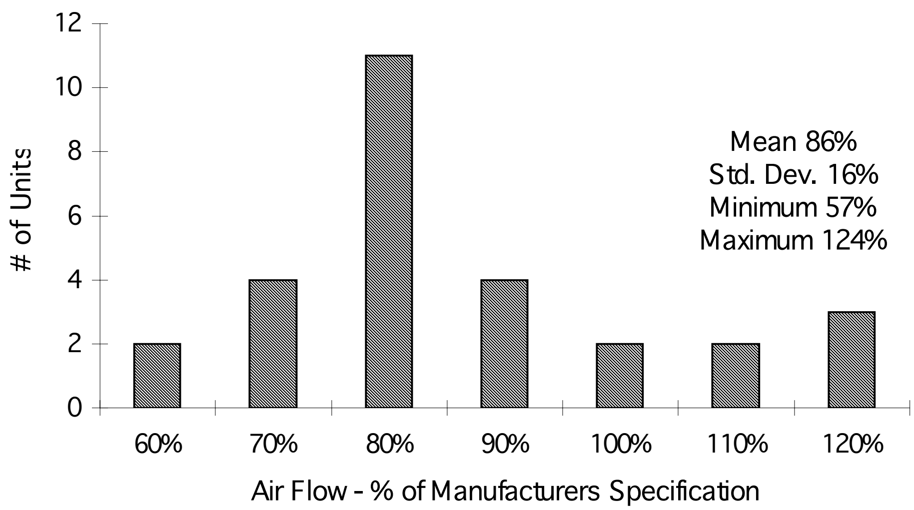
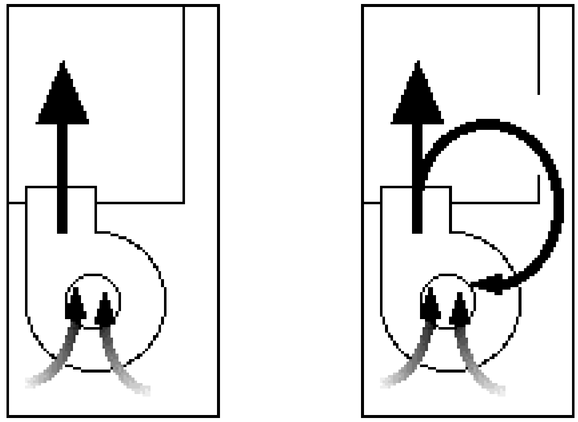


Figure 2-4
Air Handler Flow

The potential causes of the low air flow were investigated. Information on the air handler and condensing unit manufacturer and model numbers were used to determine the operating characteristics of the system (e.g. air flow rate at various external static pressures). All of the systems examined had an air handler that was capable of delivering the necessary CFM for the size of the condensing unit if the external static pressure of the duct system was low enough. The external static pressure is made up of the evaporator coil, the filter, and the ductwork. In many cases the measured static pressure due to the duct work alone was high enough that adequate flow could not occur. With the filter and coil in place the air flow is decreased even further.

An additional cause of low air flow was discovered on the heat pumps. These systems had an average air flow 9% less than air conditioners with gas heat. Further examination of these systems found it was common practice for the heat pump to be installed without back-up electric heat strips. The cabinet opening provided by the manufacturer for the heat strip element insertion was left open which resulted in recirculation of the air in the supply plenum back into the air handler blower compartment. This problem is illustrated in Figure 2-5.



Furnace or Heat Pump with all panels in place

Heat Pump with panel missing

Figure 2-5
Air Handler Flow Bypass - Heat Pumps

Checking Refrigerant Charge

Manufacturers of residential air conditioning systems recommend various methodologies for determining proper system charge. The most common non-invasive method for air conditioners with fixed metering devices (cap tube or fixed orifice) is evaporator superheat. For systems with TXVs the subcooling method is suggested. The most accurate (but also the most time consuming) method is recovery and weighing of the refrigerant.

In order for either of the superheat or subcooling methods to be accurate two critical items must be determined to be correct prior to their use:

- Air flow through the indoor coil must be within +/- 50 CFM of the manufacturers suggested flow (400 CFM per ton/wet coil).
- For superheat (which is the method that would need to be used on the majority of the systems) the indoor and outdoor temperatures must be within a specified range.

Based on PEG's past experience with new construction testing it was anticipated that a large portion of the systems would not have adequate air flow through the indoor coil. (64% of the units in this study had air flow less than 350 CFM per ton). It was also anticipated that indoor wet bulb temperature in relationship to the outdoor dry bulb temperatures would be outside the specified range to check superheat**.** For these reasons, the refrigerant was recovered and weighed to assess charge. Although this is the most time consuming of the methods available it is also the most accurate.

The field technicians used a step by step procedure to lead them through recovery of the refrigerant. Precautions were taken to ensure that no contaminates would be introduced to the system and that all refrigerant would be recovered. The key points of the procedure include:

- The use of a vacuum pump and micron gauge to evacuate the service manifold line sets and recovery cylinder prior to recovery of the refrigerant (to keep from introducing non-condensables into the refrigerant)
- The use of a recovery device to evacuate the air conditioner to a minimum vacuum of 15″ Hg to ensure that all refrigerant has been recovered from the system.
- The use of a precision scale to weigh the cylinder before and after recovery.

Refrigerant Charge

Incorrect refrigerant charge is a common problem with air conditioning systems. It is a common expectation that newly installed systems would be properly charged. Unfortunately, new systems appear to suffer from incorrect charge as often as older systems (SOURCE: Hamerlund et al, 1990, Blasnik et al, 1995).

Most installation technicians are under demanding time constraints when installing systems. In order to cut the amount of time necessary to install a system, many technicians rely on shortcuts, rules of thumb and guesswork rather than adhering to the manufacturers installation instructions.

Most air conditioners come from the factory charged with enough refrigerant to accommodate a twenty five foot line set. If the installed line set is less than or more than twenty five feet the charge must be adjusted to compensate for the difference (if the line set is less than twenty five foot charge must be removed or if more than twenty five foot, charge must be added). Most installation technicians consider weighing in the correct charge too time consuming and rely on refrigerant system pressures to indicate if the charge is correct.

There are many rules of thumb for assessing the charge in air conditioners. One of the most common methods used is looking at the refrigerant gauge pressures to see if they are in the "correct" range for the presumed indoor and outdoor conditions. The correct range is often interpreted as: low side pressure is near 70 to 80 psi or condenser saturation temperature approximately 20°F hotter than ambient. If the pressure/temperature is in the "correct" range the system is assumed to be charged properly.

This is one of the first studies of new construction that has weighed the refrigerant charge of the air conditioners. Previous studies of new construction completed by PEG used superheat or subcooling in conjunction with measured kW input and system capacity to determine if the air conditioner's charge was correct. Most studies have found air conditioners to be overcharged and undercharged at about the same rate. Previous PEG studies found roughly one quarter to one third of the systems overcharged and one quarter to one third undercharged.

Twenty seven of the twenty eight units in the project were tested for refrigerant charge. The one rooftop package unit was not tested because there was no stable level space for the refrigerant scale. This system is not included in the summary. The results of the charge assessment are summarized in Table 2-5

Table 2-5
Air Conditioner Refrigerant Charge

Charge	# of Units	% of Units
Within 5% of Correct Charge	5	18%
Undercharged	21	78%
Overcharged	1	4%

Recovering and weighing of the refrigerant indicated that only five of the twenty seven units tested were correctly charged. Figure 2-6 displays the distribution of refrigerant charge.

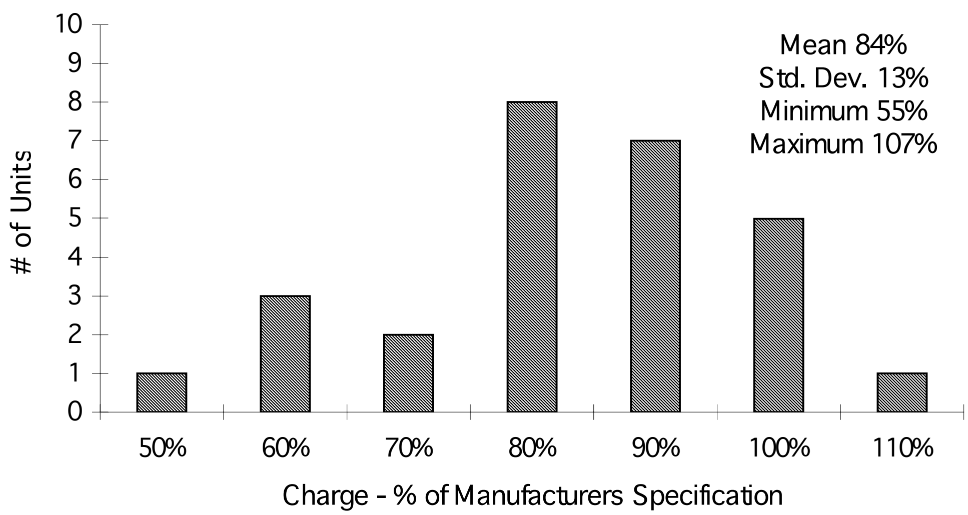


Figure 2-6
Charge as a % of Manufacturers Specification

Field Investigation

A number of possibilities exist for the predominance of undercharged systems. The most likely is that the system is installed and the charge in the outdoor unit (correct for a 25 foot line set) is released into the system. This results in the unit being low on charge by the amount necessitated by the line set length beyond 25 feet. Sixteen of the systems tested had refrigerant line sets with less than 10 foot of deviation from the manufacturers allowed for 25 foot (these systems require less than one half pound of charge adjustment). The average percentage of correct charge for these units was 89%. The average percentage of correct charge for those systems requiring more than 7 ounces of charge adjustment was 77%.

Another possibility for the high occurrence of undercharged systems could be due to inadequate evacuation of the systems by the installation technician. Incomplete evacuation would result in the technician reading pressures that are inflated by the air left in the system and drawing conclusions based on the corresponding saturation temperatures.

Installation technicians frequently do not properly evacuate the refrigerant line sets and indoor coil prior to releasing the refrigerant from the outdoor unit. PEG has yet to observe an installation technician use a micron gauge in evacuation. A common error is the use a compound gauge to determine vacuum. If the technician had a properly calibrated gauge, and if the vacuum pump was able to pull the system down to 29" Hg.(neither scenario is very likely), the vacuum would only be 25,400 microns. Most manufacturers recommend a vacuum of 1000 microns. Ensuring that this depth of depressurization with a compound gauge is impossible (the technician would have to confirm that the compound gauge read 0.039" Hg). Additional information concerning compound and micron gauges is contained in Appendix E.

The effect of incorrect charge is shown in Figure 2-7. Incorrect charge reduces both capacity and efficiency. As little as 10% undercharge will reduce capacity as much as 14% (for 82 degrees F outside temperature).

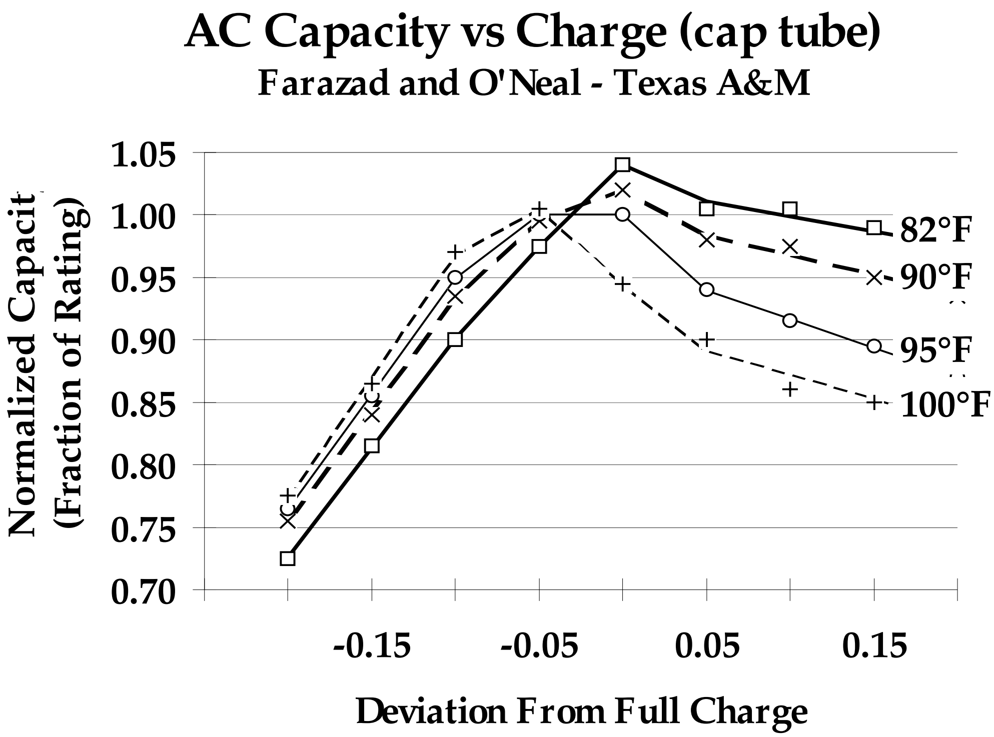


Figure 2-7
Capacity vs. Charge

A dramatic example of the affect of incorrect charge and air flow was encountered during the course of this study. One of the participant houses complained several times to the general contractor that their system was not cooling the house. Eventually the contractor came out and told the homeowner that their attic was not properly insulated (the insulation contractor only added one inch of cellulose when they were sent back). Approximately two months after the customer moved into the house the compressor failed on the air conditioner. Testing performed by PEG indicated the system only had slightly more than 60% of the manufacturers recommended charge and the air flow was less than three quarters that recommended by the manufacturer.

Air Conditioner Sizing

The Air Conditioning Contractors of America (ACCA) Manual J is a standard reference for estimating the design load for residential air conditioning systems. The enhanced Manual J calculations performed on the houses in this study found cooling loads at design conditions ranging from 17,500 to 50,400 Btu/hr with an average of 30,251 Btu/hr. Slightly less than half of the design load came from heat gains through windows and glass doors. The next highest contributor to the gain was attic and wall conduction, with the remainder of the gains nearly evenly dispersed between infiltration, duct conduction, and internal gains.

The 97.5% design conditions for Phoenix are 107°F dry bulb -- 71°F wet bulb outdoors (about 56 grains of moisture per pound of air or 17% Relative Humidity) and 75°F dry bulb indoors. The capacity of the installed equipment at design conditions was estimated from manufacturers' data corrected to 107°F outside and 75°F inside. The distribution of installed capacity vs. design load is shown in Figure 2-8.

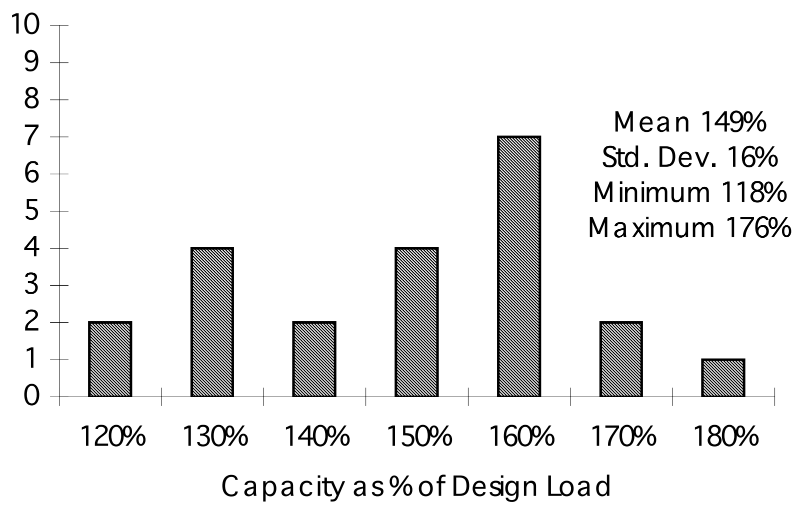


Figure 2-8
Installed Capacity vs. Design Load

The average design capacity of the equipment installed <u>per house</u> is 44,736 Btu/hr. This capacity represents an average 48% oversizing when compared to the calculated design loads.

Two system houses were not sized any closer to design than single system houses. The average two system house had a Manual J calculated heat gain of 42,455 and was equipped with air conditioners with a total design capacity of 63,729 (50% oversize). The average single system house had a Manual J calculated heat gain of 25,675 and was equipped with an air conditioner with a design capacity of 37,614 (47% oversize).

Not only are these units oversized compared to Manual J, Manual J overestimates the actual cooling load. These issues are detailed in Appendix D.

Table 2-6
Sizing Comparisons

	Single System Homes	Two System Homes	All Homes
Rated Capacity @ ARI Std Conditions	46,600	78,950	55,423 Btu/hr
Modeled Capacity @ 107°F out 75/62°F in	37,614	63,729	44,736 Btu/hr
Manual J Estimated Load	25,675	42,455	30,251 Btu/hr
% of Manual J Estimated Load	47%	50%	48%

SUMMARY OF FIELD FINDINGS

New homes in this sample were extremely air tight with up to 82% that may not meet ASHRAE ventilation standards with the windows closed. The measured supply duct leakage averaged 9% of the air handler flow. Return leakage was very similar at slightly over 8%. Significant problems were found with low flow across the inside coil and incorrect charge. These findings are consistent with similar investigations (See Appendix A). Table 2-7 summarizes the key results from the field investigation.

Table 2-7
Summary of Field Findings

	Shell	**Ducts**		**Air Conditioner**			
	Leakage	Operating Leakage (% of flow)		AC Sizing (% Over)	Air Flow	Charge	
	CFM50	Supply	Return		CFM/ton		
Unit Mean		9%	8%		345	Correct	18%
House Mean	1959			148%		Under	78%
Std Deviation	804	4%	8%	16%	65	Over	4%
Median	1634	8%	5%	147%	329		
Minimum	956	3%	0%	118%	229		
Maximum	3554	21%	34%	176%	497		

3
PERFORMANCE MONITORING

To help establish an accurate estimate of the annual energy usage and peak kW of the air conditioners, all twenty eight systems received some level of monitoring over an eight week period. The monitored data gathered was used to fine tune the comprehensive model described in Section 4. The levels of monitoring were:

- Level 1
  average kW usage of the air handler and condensing unit
- Level 2
  air handler and condensing unit average kW plus five critical temperatures
- Level 3
  air handler and condensing unit average kW plus eight temperatures, cycle length, and condensate flow (one unit was equipped with motorized dampers that opened known size duct leaks according to a test schedule)

LEVEL 1 MONITORING

APS supplied the average kW metering for both the air handler and the outdoor condensing unit for all systems. End use meters produced by Process Systems Inc. (PSI) were used for this purpose. The meter consists of a microprocessor attached to the end use load (air handler and condensing unit) with a current transducer in the circuit breaker panel. The electric load was measured several times a second and recorded as an average over fifteen minutes. The readings were stored until the PSI meter called the APS central computer at a preprogrammed time (usually in the early morning hours) using the customers phone line. The kW information was recorded at 15 minute intervals over the eight week monitoring period.

LEVEL 2 MONITORING

Twelve systems were monitored with customized ACR Systems Inc. Smart Reader 6 (SR6) data loggers. The customized SR6 is capable of recording temperature data from one internal channel and four external channels and AC electrical current data from two external channels. The temperature sensors were 36 gauge type T thermocouples. The AC electrical current data was gathered with the use of an Amprobe adjustable range current probe. The data points gathered with the SR6 are summarized in Table 3-1.

Table 3-1
Level 2 Sensor Locations

SR6 Input (Analog)	Location	Parameter
AC Electrical Current	Power wire @ fan motor	Air handler current
Temperature #1 (internal)	Attic (by air handler)	Duct location temperature
Temperature #2	Outdoors	Outdoor ambient temperature
Temperature #3	Supply plenum	Temperature of air exiting coil
Temperature #4	Return plenum	Temperature of air entering air handler
Temperature #5	Return grille	Temperature of air entering the return duct

LEVEL 3 MONITORING

Six systems were monitored with Campbell Scientific CR10 measurement and control modules. The CR10 is compact, rugged, fully programmable datalogger/controller. The CR10 has the flexibility to perform many data acquisition and control functions and is capable of being downloaded or reprogrammed via modem. PEG used the CR10 to gather data on the operating parameters of six air conditioners and to control one of the air conditioners that was equipped with mechanically controlled duct leakage openings. Three types of measurement devices were used in conjunction with the CR10. The temperature probes were 36 gauge type T thermocouples. The electrical current was sensed with a 50 amp split core current transducer. The reference temperature for the thermocouples was provided by a thermistor. condensate flow from the indoor coil was measured with the use of a tipping bucket gauge attached to the termination of the condensate drain. The data points gathered with the CR10s are summarized in Table 3-2.

Table 3-2
Level 3 Sensor Locations

CR10 Input	Location	Parameter
Temperature #1 (Analog)	Return plenum	Temperature of air entering air handler
Temperature #2 (Analog)	Supply plenum	Temperature of air exiting coil
Temperature #3 (Analog)	Attic	Duct/AH location temperature
Temperature #4 (Analog)	Return grille	Temperature of air entering the return duct
Temperature #5 (Analog)	Supply register	Temperature of air leaving a main supply duct
Temperature #6 (Analog)	Outdoors	Outdoor ambient temperature
Temperature #7 (Analog)	Secondary duct location	Temperature of second duct location
Temperature #8 (Analog)	Indoors	Temperature by thermostat
Temperature #9 (Analog)	CR10 Reference	Temperature at CR10 terminal strip
Temperature #10 (Analog)	Evaporator Coil	Saturation temperature of coil
Temperature #11 (Analog)	Suction line at AH	Temperature of suction line
AC Current (Pulse)	Power wire @ Compressor	Air conditioner status
Tipping Bucket Gauge (Pulse)	Condensate drain	Condensate flow

4

ACHIEVABLE IMPROVEMENTS AND THEIR COSTS

Once the nature and extent of the problems were defined in the field investigation, PEG staff investigated the realistically achievable improvements that could be made to the duct and air conditioning systems and the associated costs. Improvements examined include: sealing the ducts, using better insulated ducts, properly installing and testing the air conditioner, and increasing the peak EER of the air conditioner by two points.

- The incremental cost of contractors installing properly sealed duct systems is estimated at $75 per system, $30 for materials (mastic and ties) and $45 for 1 hour of extra labor. Based on prior experience with systems in California, Florida, and North Carolina, PEG estimates that new construction duct leakage of less than 3% is achievable[9].
- Based on previous PEG research, the average composition of the duct systems seen in this sampling of homes and consultation with local wholesalers the estimated extra cost for doubling the duct system insulation level to R-8 at about $65 per house.
- PEG estimates that properly installing and testing an air conditioner (including proper evacuation, proper charge, checking capacity and EER) requires an extra 1.5 hours per system at an incremental cost of about $70.
- Using a properly sized air conditioner (about one ton reduction after system improvements) will save $100 per air conditioner.
- The incremental cost of an air conditioner with a two point higher peak EER[10] is estimated at $350 per system based on price quotes from 5 manufacturers.

The benefits of these potential improvements were assessed through detailed modeling of air conditioner and duct performance.

[9]Researchers and practitioners have a variety of opinions on the proper specification. Some argue for a more stringent standard based on the potential gains from a well sealed distribution system. Some argue for a less stringent standard based on the level of success they have had while using contractors with little training and little or no follow up.

[10] Peak EER and SEER are not equivalent. Peak load reductions are not assured by increasing SEER. (SOURCE: Proctor, et al, 1994)

5

MODELING IMPACTS ON USAGE & PEAK DEMAND

The field investigation and monitoring results found opportunities for potentially significant improvements in system efficiency. Assessing the impacts of the identified problems and their solutions on energy usage and peak demand requires an analysis which models the air conditioner, duct system, and building shell and incorporates the interactions between them. For example, when a leaky return draws air from the attic it raises the temperature at the inlet to the indoor coil resulting in an increase in air conditioner capacity. PEG has adapted the Palmiter Duct Model (SOURCE: Palmiter and Bond, 1991) and created an AC model based on field data, laboratory data, ASHRAE models, and DOE2 models. The AC and duct models are combined into a comprehensive model that incorporates many of the complex interactions in the systems studied. The model calculates system efficiencies, losses, loads, energy usage, and demand based on a typical weather year (TMY) in Phoenix.

A realistic analysis of peak demand impact also requires characterizing the effect of occupant behavior patterns on actual cooling demand. PEG has developed a model which utilizes submetered air conditioner data to characterize the interactions between occupant behavior patterns/cooling load and effective capacity. This peak model (Model P) significantly improves upon most existing peak models which usually model peak from one general residential AC demand curve.

AIR CONDITIONER PERFORMANCE MODELING

Air conditioner performance can be characterized at given conditions by system capacity and EER. These two quantities can be used to calculate the power draw and, along with air handler flow rate, the temperature drop across the indoor coil. System capacity is modeled as a function of outdoor temperature, return plenum temperature, return humidity, air handler flow rate, and charge. The model is tuned to the Phoenix climate and monitored data from these houses. EER is modeled as a function of outdoor temperature, return plenum temperature and charge. The air conditioner model return plenum temperature is calculated from the duct system model.

For both capacity and EER, each factor effecting performance is represented as a multiplicative adjustment to the rated value. The adjustment factors are based on available published data and studies by PEG.

DUCT EFFICIENCY MODELING

The impact of duct leakage and conduction on effective system efficiency and building loads is complex. Duct leakage can cause four types of efficiency losses:

- the supply air that leaks to the exterior is a direct efficiency loss;
- the return air coming from outside and spaces warmer than outside (e.g. the attic) adds to building loads;
- the supply and return flows increase the air leakage rate of the building shell depending upon the relative size of the flows and the building's natural infiltration rate;
- when the air handler is off, the duct leaks still add to the building shell leakage rate.

Each of these effects is accounted for in the duct efficiency model. The model inputs include the supply and return leak fractions, the temperature of the air surrounding the return ducts, and the natural air leakage rate of the building shell (based on the blower door test and a limited implementation of the LBL infiltration model).

Conductive heat gain into the ducts is modeled as a function of duct area, R-values, the temperature of the air around the ducts (which depends on outdoor temperature and duct location), and the temperature of the air in the ducts (which depends on the air conditioner capacity, duct air flow, AC on time, and duct leakage rate). Duct conduction losses are dependent on the duty cycle of the air conditioner and as such are dependent on the relationship between the load, capacity, and duct size.

The leakage and conduction models interact in terms of calculating return plenum and average supply duct temperatures and in avoiding any "double-counting" (e.g., the efficiency loss due to conductive gains into the portion of supply air which leaks out of the ducts is not included).

ENERGY USAGE MODELING

All of the duct-related losses are expressed in terms of percentage efficiency losses to the air conditioning system. The effective capacity of the air conditioner is calculated as the system capacity at given conditions adjusted for duct efficiency losses. The building shell load is calculated based on the empirical relationship between time of day, outdoor temperature, and actual cooling delivered at the intensively monitored sites . The effective capacity and the building shell load are used to calculate the duty cycle, which is used to calculate the cycle on time, and hourly energy usage through an iterative process. These calculations are performed for each cooling hour in the Phoenix TMY to arrive at an annual energy usage rate.

PEAK DEMAND MODELING (MODEL P)

The diversified demand of air conditioning systems during system peak involves more than simply modeling performance and efficiency during peak conditions. Occupant behavior patterns can have a large influence on actual demand during peak. Some households (Group A) have no air conditioning use during peak. These homes may be unoccupied at that time or the occupants have the air conditioner switched off. Other households may have the air conditioner running continuously (Group D). This is the case because often occupants have adjusted the thermostat down. Another group of households (Group B) have their air conditioners cycling on and off based on thermostatic control. Some households may effectively have a constant thermostat setting in the period of interest but the effective capacity of their air conditioning system is less than the load. These households (Group C) have air conditioners running continuously, but some achievable reduction in load or increase in effective capacity would result in them cycling. The proportion of households in each of these categories must be estimated to arrive at reasonable estimates of diversified peak demand.

PEG estimated the proportion of households in each of the above customer groups at 5 PM on peak weekdays based on the submetered new homes in this test. PEG classified each customer-peak hour into one of the four groups. The diversified demand is calculated as the weighted sum of the demands of the four groups. Group A households have no demand at peak. Group D households' demand equals their modeled connected load.

SUMMARY OF MODEL INPUTS

The cooling model requires information on numerous aspects of the air conditioner, the duct system and its surroundings, and the building shell. Table 5-1 describes the inputs and the sources used in this project.

Table 5-1
Model Inputs & Data Sources

Category	Model Input	Source / Assumption
Temperatures	Outdoor Temperature	TMY for Phoenix
	Indoor Temperature	Assumed at 78°F
	Temperature surrounding ducts	weighted average of outdoor and attic temperatures based on field-estimated location breakdown for supply and return as well as monitored temperatures
	Temperature of infiltrating air	Combination of TMY and attic temperature data
Duct System	Supply & return leakage fractions	based on Duct Blaster™ tests, air flow test, and operating pressure measurements
	Duct leakage % of shell leakage	based on Duct Blaster™ test and blower door test
	Duct Area (square feet.)	on site measurements
	Duct R-Value	R-4 based on insulation thickness
Air Conditioner	Rated capacity & EER	from nameplate information and published values
	Air Handler Flow	from field tests using Duct Blaster™ and duct leakage
	Charge	weighed charge extracted from (and replaced in) unit
Building Shell	Cooling load	Monitored AC capacity corrected for distribution losses and Manual J calculations
	Airtightness (CFM50)	from blower door test

MODELING RESULTS - BASELINE CONDITIONS

When applied to the systems tested in the field investigation, the energy and demand models predict an average annual cooling energy consumption of 3729 kWh with 3.67 kW of diversified demand at 5 PM (4809 kWh and 3.63 kW if severely undercharged systems are included). Duct-related efficiency losses are high and air conditioner installation problems are severe (including less than 80% charge on 6 units in the sample). Some of these installation problems are self correcting (resulting in compressor failure). The summary tables are produced without these severely undercharged units.

The estimated impacts and costs of potential improvements to new residential construction in Phoenix (excluding severely undercharged units) are summarized in Tables 5-2 and 5-3. Table 5-2 shows the savings and peak reduction potential without resizing the air conditioners and Table 5-3 shows the same information if the air conditioners are resized to 15% over Manual J. This results in actual oversizing well over 15%, particularly on homes with properly installed air conditioners and sealed/insulated ducts.

Table 5-2
Estimated Program Impacts & Costs (without resizing)
Severe undercharge excluded

Program Design Elements	Direct Cost	Savings			
		kWh	%	kW	%
Baseline - Systems as found	0	3729		3.67	
A. Restrict Duct Leakage to 3% of system air flow	$75	417	11%	0.50	14%
B. Duct Lkg to 3% & R-8 Duct Insulation	$140	581	16%	0.64	17%
C. Correct AC charge and air flow rate	$70	1143	31%	0.77	21%
D. Duct Lkg to 3%, Charge, Air flow	$145	1458	39%	1.12	31%
E. Duct Lkg to 3%, R-8, Chg/flow	$210	1571	42%	1.22	33%
F. EER 2 higher, Chg/flow	$420	1795	48%	1.32	36%
G. All of the above	$560	2152	58%	1.69	46%

Table 5-3
Estimated Program Impacts & Costs (units resized to Manual J +15%)
Severe undercharge excluded

Program Design Elements	Direct Cost	Savings kWh	%	kW	%
Baseline - Systems as found	0	3729		3.67	
A. Restrict Duct Leakage to 3% of system air flow	$75	522	14%	0.65	18%
B. Duct Lkg to 3% & R-8 Duct Insulation	$140	728	20%	0.82	22%
C. Correct AC charge and air flow rate	$70	1242	33%	0.96	26%
D. Duct Lkg to 3%, Charge, Air flow	$145	1536	41%	1.29	35%
E. Duct Lkg to 3%, R-8, Chg/flow	$210	1675	45%	1.42	39%
F. EER 2 higher, Chg/flow	$420	1887	51%	1.48	40%
G. All of the above	$560	2246	60%	1.85	51%

These tables show that there are a number of potentially attractive options for reducing cooling usage and peak demands at reasonable incremental costs.

MODEL VERIFICATION

Usage data were available for 22 sites (28 air conditioners). To validate the model, the 16 sites with single ACs were selected and time periods with complete usage data for all sites were sought. Seventeen days between August 26, 1995 and September 12, 1995 were suitable for analysis. The airport weather data for the period was used to drive the model for each site. Actual outdoor temperatures varied from 77 to 110 F, providing a good range of conditions for testing the model.

The total modeled cooling usage for the period averaged 713 kWh per site. The actual metered average consumption was 712 kWh. This is a surprisingly high level of agreement. The site-by-site correlation was generally weak, which was to be expected given variations in occupant behavior and thermostat settings.

The comprehensive model used in this study is unique in modeling many of the interactions between ducts, air conditioner, and building shell. Many of the interactions have been tested and improved based on the monitored houses in this study. At the same time this model, like all models, is based on simplifications of the systems and their interactions. The savings from air flow and charge correction is currently being explored in laboratory tests by PEG.

6
CONCLUSIONS AND RECOMMENDATIONS

Newly constructed homes in Arizona Public Service Company Company's service territory have substantial deficiencies in their cooling systems, similar to those found in studies from other parts of the country. Moderate cost improvements can be achieved to lower energy usage and demand while improving occupant comfort and satisfaction.

CONCLUSIONS

- Duct leakage and existing duct insulation levels reduce overall cooling efficiency. Reasonable improvements can save 16% of the cooling energy for about $140;
- Air conditioners often have insufficient air flow across the indoor coil and are frequently undercharged. Proper installation (following the manufacturers installation instructions) and testing would remedy these problems at a cost of about $70;
- A program which ensures tight, well-insulated ducts and properly installed air conditioners could reduce cooling usage by approximately 42% and diversified peak demand by 1.2 kW. The additional cost is estimated to be $210 per unit;
- Air conditioners can be installed with lower connected load (via lower capacity) if the systems are operating properly. Resizing the air conditioner is also a more certain change in peak than relying on the effect of duct tightness (or other program elements) alone.

APS has a variety of potentially worthwhile options for improving cooling efficiency and reducing peak demand. Proper program design, training, and quality assurance are critical issues for actually achieving these improvements.

RECOMMENDATIONS

1) Program implementation should include quality assurance procedures to ensure savings actually occur. These quality assurance procedures should include performance testing and feedback to technicians.
2) Duct systems should be designed and installed in accordance with ACCA Manual D.
3) Ducts should be sealed with mastic and tested to ensure that total leakage does not exceed 3% of fan flow when tested at 25 pascals.
4) Ducts outside conditioned space should be insulated to R-8 or better.

5) Air conditioners and heat pumps should be installed in complete compliance with manufacturer's instructions.
6) In order to ensure peak reduction, improvements on system installation and design should be accompanied with reductions in air conditioner capacity.
7) If air conditioner capacity is reduced, it is recommended that the duct systems remain the same size to reduce static pressures and improve air flow.
8) If recommendation #7 is followed, it is essential that duct insulation be increased.
9) Air handler manufacturers should be enlisted to work with utilities toward the common goal of building tighter air handling units, which are the cause of significant distribution system leaks and are outside the influence of the local installer;

The following additional research is recommended:

- New construction air conditioner installation practices in Phoenix should be observed. The results would allow refinement of program specifications.
- A sample of homes should be built to these specifications. On these units, equipment performance and customer satisfaction should be monitored.

REFERENCES

Blasnik, M., J. Proctor, T. Downey, J. Sundal, and G. Peterson, 1995a. “Assessment of HVAC Installations in New Homes in Southern California Edison’s Service Territory”. Proctor Engineering Group, San Rafael, CA.

Blasnik, M., J. Proctor, T. Downey, J. Sundal, and G. Peterson, 1995b. “Assessment of HVAC Installations in New Homes in Nevada Power Company’s Service Territory”. Proctor Engineering Group, San Rafael, CA.

Blasnik, M., T. Downey, J. Proctor, and G. Peterson, 1996. “Assessment of HVAC Installations in New Homes in APS Service Territory”. Proctor Engineering Group, San Rafael, CA..

Cavalli, J. and J. Wyatt, 1993. "Interpreting Impact Evaluation Results to Defer Local T&D Investment". 1993 International Energy Program Evalution Conference, Chicago, IL.

Cummings, J., J. Tooley Jr., N. Moyer and R. Dunsmore. 1990. “Impact of Duct Leakage on Infiltration Rates and Pressure Differences in Florida Homes.” Proceedings from the ACEEE 1990 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington, D.C.

Cummings, J., R. K. Vieira, J. K. Sonne, and J. Klongerbo. 1994. "Residential Air Conditioning Sizing Methodology Draft Final Report". Submitted to Department of Community Affairs, Florida Energy Office, Tallahassee, FL.

Farzad, M. and D. O’Neal. 1988. “An Evaluation of Improper Refrigerant Charge of a Split-system Air Conditioner with Capillary Tube Expansion - Final Report”, Energy Systems Laboratory, Texas A&M University, ESL/CON/88-1.

Gammage, R.B . et al. 1986. "Parameters Affecting Air Infiltration and Airtightness in Thirty-one East Tennessee Homes". *Measured Air Leakage of Buildings*, pp. 61-69. Trechsel/Lagus, editors, ASTM STP940.

Hammerlund, J., J. Proctor, G. Kast and T. Ward. 1990. "Enhancing the Performance of HVAC and Distribution Systems in Residential New Construction." Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington, D.C.

Jacob, M. and A. Zebedee, 1994. "The Day the Engineers Were Right: Confirming the Peak Demand Reductions of FPC's Air Conditioner Duct Test and Repair Program". Proceedings from the 1994 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington D.C.

Jacobson, R., J. Proctor and A. Polak. 1992. “PG&E Appliance Doctor Pre-Production Test.” Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington, D.C.

Jump, D. A., and M. Modera. 1994 “Energy Impacts of Attic Duct Retrofits in Sacramento Houses.” 1993 . Proceedings from the 1994 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington D.C.

Kinert, R.C., D Engle, J. Proctor, R. Pernick. 1992. “The PG&E Model Energy Communities Program: Offsetting Localized T & D Expenditures With Targeted DSM”. Proceedings from the 1992 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington D.C.

Neal, L. 1990. "Field Experiences with Central Air Conditioners and Heat Pumps", AEC North Carolina Alternative Energy Corporation.

Neal, L. and D. O'Neal. 1992. "The Impact of Residential Air Conditioner Charging and Sizing on Peak Electrical Demand." Proceedings from the 1992 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington D.C.

O'Neal, D., C. Ramsey and M. Farzad. 1989. "An Evaluation of the Effects of Refrigerant Charge on a Residential Central Air Conditioner with Orifice Expansion". Energy Systems Laboratory, Texas A&M University, ESL89-06.

Orans, R. and C. Woo, and J. Swisher. 1991. "Targeting DSM for T&D Benefits: A Case Study of PG&E's Delta District". Electric Power Research Institute, Palo Alto, CA.

Palmiter, L. and T. Bond, 1991. "Interaction of Mechanical Systems and Natural Infiltration". Proceedings from the AIVC Conference on Air Movement and Ventilation Control within Buildings.

Palmiter, L. and P. Francisco, 1994. "Measured Efficiency of Forced-Air Distribution Systems in 24 Homes". Proceedings from the 1994 ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington D.C.

Parker, D.S. 1989. "Thermal Performance Monitoring Results From the Residential Standards Demonstration Program." *Energy Buildings*, pp 231-248.

Proctor, J., B. Davids, F. Jablonski, and G. Peterson. 1990. "Pacific Gas and Electric Heat Pump Efficiency and Super Weatherization Pilot Project: Field Technical Report". Pacific Gas and Electric Company, San Francisco, CA.

Proctor, J. 1991. "Pacific Gas and Electric Appliance Doctor Pilot Project: Final Report." Pacific Gas and Electric Company, San Francisco, CA.

Proctor, J. and R. Pernick. 1992. "Getting it Right the Second Time: Measured Savings and Peak Reduction from Duct and Appliance Repair." Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings American Council for an Energy Efficient Economy, Washington, D.C.

Proctor, J. 1993. "Estimating Peak Reduction from Submetered Data." 1993 International Energy Program Evalution Conference, Chicago, IL.

Proctor, J., M. Blasnik, B. Davis, T. Downey, M. Modera, G. Nelson and J. Tooley. 1993. "Diagnosing Ducts: Finding the Energy Culprits". Sept/Oct 1993 *Home Energy* pp 26-31.

Proctor, J., Z. Katsnelson, G. Peterson, and A. Edminster. 1994. "Investigation of Peak Electric Load Impacts of High SEER Residential HVAC Units". Pacific Gas and Electric Company, San Francisco, CA.

Rice, C. 1991. "The ORNL Modulating Heat Pump Design Tool – User's Guide". Prepared for the U. S. Department of Energy.

Tooley, J. Jr. and N. Moyer. 1989. "Mechanical Air Distribution and Interacting Relationships". Proceedings from Symposium on Improving Building Systems in Hot and Humid Climates, pp. A24-31. Texas A&M University, College Station, TX.

GLOSSARY

97.5% Design - ASHRAE published values for outdoor design temperature that will be exceeded on average 73 hours of the summer months (June through September).

ACCA Manual J - Residential heating and cooling load estimation methodology published by the Air Conditioning Contractors of America.

Air Changes per Hour (ACH) - The number of times that air in the house is replaced with outdoor air in one hour.

Air Handler - The fan and cabinet assembly that moves air across a heat exchanger and through a duct system.

Blower Door - A large variable speed fan fitted with flow and pressure measuring devices. It is mounted in a doorway to measure the leakage of a structure.

Capacity - The amount of heat added to (heating) or removed from (cooling) a structure by the heating or cooling equipment.

Capillary Tube - A refrigerant metering device that utilizes fixed diameter and length of tubing to control the flow of refrigerant.

CFM50 - A measurement of the house air leakage based on the air flow necessary to maintain a 50 pascal pressure differential between the house and outside.

Charge - The quantity of refrigerant in a system.

Connected Load - The amount of power draw when the unit is running continuously.

Design Cooling Load - The heat gain of a structure at the ASHRAE 97.5% design outdoor temperature and 75°F dry bulb 62°F wet bulb indoors (expressed in Btu/hr).

Diversified Peak Demand - The amount of power draw realized by the utility during their peak period for a particular end use for the customers that have that end use.

Dry Bulb Temperature - The temperature measured using a common thermometer.

Duct Blaster™ - Similar to a small blower door, this device is used to test the leakage of a duct system.

Duct Leakage (Exterior) - The leakage of the duct system to outside the structure.

Duct Leakage (Total) - The leakage of the duct system including unintentional leakage to inside and outside the structure.

Duty Cycle - The percentage of time that an end use is on during a specified period.

EER - The Energy Efficiency Ratio. The capacity of an air conditioner (in Btu/hr) divided by the electrical input (in watt hours).

Effective Capacity - A rating of the systems true operating capacity adjusted for duct losses experienced.

Evacuation - The removal of gases from a closed refrigerant system until the pressure is below atmospheric pressure.

Evaporator - The heat exchanger (coil) in a refrigerant system that removes heat thus boiling the refrigerant.

Flow Hood - A calibrated air flow measurement device.

Group A - The group of customers shown through Model P to have their air conditioners off during peak.

Group B - The group of customers shown through Model P to have their air conditioners cycling on and off during peak due to thermostatic control.

Group C - The group of customers shown through Model P to have their air conditioners running continuously during peak, but could be in Group B if some reduction of load or increase of effective capacity were implemented.

Group D - The group of customers shown through Model P to have their air conditioners running continuously during peak.

Half -Nelson - A methodology used to estimate the ratio between total supply leakage and total return leakage based on pressure measurements with all registers blocked.

HVAC - Heating, Ventilating and Air Conditioning.

Indoor Coil - The evaporator coil, located at the air handler, on an air conditioning system.

Latent Capacity - The amount of moisture removed by a cooling appliance.

Micron Gauge - A calibrated instrument used to measure vacuum in a closed refrigerant system.

Model P - A model that examines occupant behavior patterns to make adjustments to peak effects of various DSM options.

N factor - The infiltration/leakage coefficent. A conversion factor from blower door measured leakage(CFM 50) to modeled average infiltration rates, This factor is derived from a simplification of the LBL model.

Overcharge - The condition of an air conditioning system that has more refrigerant than is specified by the manufacturer .

Package Unit - An air conditioning system with all major components located in one cabinet.

Pascal - A small metric unit of pressure. One pascal is 0.000145 PSI.

Pressure Pan - A shallow pan placed over a supply or return grill with a blower door operating. The pressure measured at the pan is a qualitative indication of duct system leakage.

Return System - The portion of the duct system used to return air from a structure to the air handler.

Saturation - The temperature/pressure at which both the refrigerant liquid and vapor are present in equilibrium

SEER - The Seasonal Energy Efficiency Ratio, a comparative measure of an air conditioners efficiency, much like EER but rated at a much cooler outdoor temperature.

Sensible Capacity - The amount of heat added to or removed from a structure measured by dry bulb temperature.

Split System - An air conditioning system that has the condenser remotely located from the evaporator.

Static Pressure - A measure of pressure that is equally exerted in all directions within a given point of the duct system.

Subcooling - The difference in temperature between liquid refrigerant and saturated refrigerant at the same pressure.

Superheat - The difference in temperature between refrigerant vapor and saturated refrigerant at the same pressure.

Supply System - The portion of the duct system used to deliver conditioned air from the air handler to individual rooms.

Hourly Temperature Bins - The number of hours during the season that the outdoor temperature falls within the specified range.

Thermostatic Expansion Valve (TXV) - A refrigerant metering device that adjusts the flow of refrigerant to maintain a constant superheat at the exit of the evaporator coil.

Ton of Cooling - The amount of heat required to melt a ton of ice at 32°F in one hour (12,000 Btu/hr).

Unconditioned Space - The part of a structure that is not intentionally heated or cooled by the heating or cooling equipment.

Undercharge - The condition of an air conditioning system that has less refrigerant than is specified by the manufacturer.

Weighing in Charge - A method of charging refrigerant systems by using a scale.

Wet Bulb Temperature - The temperature measured by a thermometer covered with a wet wick with air blowing across it. The measured temperature is lower than the dry bulb temperature and is a measure of moisture in the air.

APPENDIX A: SUMMARY OF RELATED STUDIES

A number of previous studies have been conducted on duct systems and air conditioners in both new construction and retrofit applications. These studies were completed by Cummings et al., Hammerlund et al., Jacobson et al., Jump and Modera, Neal, Proctor et al. (1990) and Proctor (1991). Five of these studies included field monitoring of energy usage (Cummings et al., Jacobson et al., Jump and Modera, Proctor et al. (1990) and Proctor (1991). All but one of these studies examined impacts of retrofit improvements to the air conditioners and/or duct systems on previously constructed houses, while Hammerlund et al. dealt solely with newly constructed homes.

BLASNIK ET AL Assessment of HVAC Installations in New Homes in Southern California Edison's Service Territory.

In a study of newly constructed residences in the Coachella Valley region of Southern California 10 houses with central air conditioners were examined for installation practices and system performance. Each residence was tested for problems in two major areas; duct leakage to the exterior and air flow through the indoor coil (system charge could not be assessed due to the lack of power to the air conditioners).

Ten houses from two local contractor were selected for testing in two subdivisions. One of the subdivisions were all one story houses while the other contained all two story houses. Even though the residences examined were newly constructed and all had received a utility financial incentive for installation of energy efficient air conditioners, significant deficiencies were found in all air conditioning systems.

The predominate problem found was duct leakage to the exterior. Testing indicated that the one story houses had a much higher duct leakage rate than the two story houses. The measured average duct leakage to the exterior was 441 CFM50 and 144 CFM50 respectively. The primary difference was found to be the extensive use of building cavity and platform return plenums on the single story houses. The measured supply duct leakage when corrected to the system operating pressures represents an average of 9.5% of the air handler flow on the one story houses and 4.1% of the air handler flow on the two story houses. Return leakage was more than twice as large, averaging 20.8% and 11.6% in the two types of houses respectively.

Low air flow through the indoor coil was also found to be a problem in these residences. The average airflow through the indoor coil (including return system leakage) was 319 CFM per ton. This is about 20% below the manufacturers recommendation of 400 CFM per ton. Examination of the duct systems indicated that the main cause of low air flow was attributed to undersized return duct systems.

With interactive effects taken into account, the average energy savings opportunities for cooling the residences by decreasing duct leakage, improving duct system R-value and insuring properly operating air conditioning systems was estimated at 44%

BLASNIK ET AL Assessment of HVAC Installations in New Homes in Nevada Power Company's Service Territory.

In a comprehensive study of newly constructed residences in Las Vegas 30 houses containing 40 central air conditioning systems were examined for installation practices and system performance. The houses represented 17 developments built by 10 general contractors, utilizing 11 HVAC contractors. Each residence was examined for problems in five major areas; duct leakage to the exterior, air flow through the indoor coil, refrigerant charge, air conditioner sizing and building shell leakage.

The average measured duct leakage to the exterior was 253 CFM50 (about 17% of the measured building shell leakage). The average duct leakage adjusted to the operating pressures of the duct system was 99 CFM of supply leakage and 103 CFM of return leakage, representing approximately 9% of the total system flow for both the supply and return side of the system.

Low air flow through the indoor coil was also found to be a problem in these residences. The average airflow through the indoor coil (including return system leakage) was 345 CFM per ton. This is about 14% below the manufacturers recommendation of 400 CFM per ton. Half of the systems tested had airflow below 350 CFM per ton (often used as a level requiring corrective action). Examination of the duct systems indicated that the main cause of low air flow was due to inadequate duct system sizing and the extensive use of flex ducting. The only HVAC contractor that used rigid metal ducting rather than flex duct was one of only two contractors that had correct air flow on all of their systems examined (the other contractor with correct air flow on all systems examined used air handlers that were oversized by one ton over the condensing unit which resulted in adequate air flow but excessive system static pressure which increased the operating duct leakage).

Thirty seven systems were checked for refrigerant charge. Even though all systems had just recently been installed only 21% were correctly charged. Of the remaining systems, 29% were undercharged and 50% were overcharged. Air conditioner sizing was also examined. The rated capacity of the air conditioners at design conditions for Las Vegas was compared to the Manual J calculated cooling load of each house. The average house was found to have air conditioning capacity that was oversized by 33% when compared to the calculated design loads.

With interactive effects taken into account, the average energy savings opportunities for cooling the residences by decreasing duct leakage, improving duct system R-value and insuring properly operating air conditioning systems was estimated at 47%

CUMMINGS ET AL.

In a comprehensive study of 91 "typical" Florida houses Cummings et al. (1990) studied the energy effects of duct leakage. Blower door tests were performed on 63 houses to determine the impact of duct leakage on infiltration rates in the house. Duct repairs were made on 25 houses and 24 of these houses had their cooling energy usage monitored before and after the duct repairs.

Tracer gas testing found that infiltration rates for the houses were four times greater when the air handler was operating than when it was off. The average Air Changes per Hour (ACH) for the 91 houses was 0.21 with the air handler off and it increased to 0.93 when the air handler was turned on. Tracer gas testing found that the Return Leakage Fraction (RLF) averaged 10%. Thirty percent of the houses tested had an RLF of greater than 10%, with the majority of the leakage coming from unconditioned attic space.

The blower door testing performed on 63 houses indicated that on average 11.7% of the total house leakage area was located in the duct system. While the duct system accounted for less than 1% of the volume of the houses, it was determined to cause 71% of the total house infiltration when the air handler was on.

In the 25 houses that received duct sealing work, it was found that on average 16% of the blower door measured house leakage area was attributable to duct leakage. Blower door testing indicated that the retrofit duct repairs reduced the average duct leakage by 68%. Tracer gas testing determined that the return leakage fraction for these homes were reduced from an average of 16.7% to an average of 4.5%. Measured cooling energy usage showed that 22% of the cooling energy usage was attributable to the duct leakage and an 18% reduction in cooling energy usage was realized after duct repairs were performed.

HAMMERLUND ET AL.

In an extensive study of newly constructed residences in the Los Angeles area 66 apartments and 12 houses with ducted heat pump systems were examined for installation practices and system performance[11]. Each residence was tested for problems in three major areas; duct leakage to the exterior, air flow through the indoor coil and refrigerant charge.

[11] None of the houses tested were over two years old.

Even though the residences examined were newly constructed and most had received a utility financial incentive for installation of energy efficient heat pumps, significant deficiencies were found in all three areas.

The predominate problem in single family residences was duct leakage. The blower door testing performed on these houses indicated that the vast majority of the homes had excessive duct leakage over what could be reasonably achieved. Over 85% of the houses had supply leakage in excess of 50 CFM_{50} and 90% of the return systems had duct leakage in excess of 50 CFM_{50}. This duct leakage resulted in an increased cooling load of approximately 30%.

Low air flow through the indoor coil and incorrect charge were also found to be a problem in these residences. Only 30% of the houses tested had air flow within the manufacturers specifications for proper air flow. This low air flow made the checking of charge by manufacturers recommended procedures impossible on all but five of the houses. Of those five houses one was undercharged and the remaining four were overcharged.

The duct leakage to the exterior of the building was considerably lower on the multifamily residences tested. This was due to both shorter duct runs and lower operating pressures typical of multifamily residences. However, low air flow through the indoor coil proved to be a more serious problem in the multifamily residences tested. Less than 15% of the units tested had the correct air flow through the indoor coil. Two thirds of the heat pumps in the multifamily residences were incorrectly charged with 61% being overcharged and 8% being undercharged.

With interactive effects taken into account, the average energy savings opportunities for cooling single family residences was 38% and multifamily residences had average cooling savings opportunities of 18%.

JACOBSON ET AL.

This study of 250 single family residences evaluated the potential for implementing the lessons learned in previous Appliance Doctor™ studies to full scale production programs. The retrofit program focused on the problem areas of duct leakage to the exterior, low air flow through the indoor coil, and incorrect refrigerant charge.

The project was split into two groups of air conditioned homes; randomly selected customers and high bill complaint/high AC usage customers. Thirty of the houses were monitored pre and post retrofit to evaluate the impact of the retrofit measures.

The study design was comprised of contracting, marketing, training, diagnosis and repair, and quality assurance components.

Contracting was structured in a fixed cost performance contract with two local HVAC contractors. Job completion was based on successful completion of set criteria and payment was made after each job successfully passed a technical review process. The fixed fee contracting structure proved to work well as long as the technical process review happened in a timely fashion.

Marketing was targeted to customers that were projected to have high seasonal cooling usage based on billing history data. A "seasonal swing" algorithm was created to indicate those customers with high seasonal cooling usage. Customers were offered services at a fraction of the cost they would normally incur for the repairs and their total end cost for the service was dependent on the services received. All customers received duct sealing but, not all customers needed air flow or charge repair so the end cost to the customer was prorated based on the services received. The straight forward direct mailing piece that was mailed out resulted in all 250 slots for the project being filled within two days. A customer survey showed that customer satisfaction was high (rated 4.4 on a scale of 5) and over half of the customers felt their system was operating more efficiently and would result in lowered energy costs.

The crew configuration that worked best was a two person duct sealing crew equipped with a blower door and other diagnostic tools followed by an HVAC specialist to service the air conditioner. The testing of the systems indicated significant problems with duct system leakage.

Eighty seven percent of the high bill complaint customers had duct leakage in excess of 150 CFM_{50} while 80% of the randomly selected had duct leakage in excess of 150 CFM_{50}. Low air flow through the indoor coil was determined to be a problem on 50% of the high bill complaint customers and 29% of the random customers. Problems with undercharged units were nearly equal (36% of the high bill complaint customers and 41% of the random customers). No overcharged units were detected in the random group while 27% of the high bill complaint group had overcharged units.

Submetering showed a cooling energy savings of 16% for the high bill complaint customers (21.5% if undercharged units are excluded) and 9% for the random customers. High usage customers proved to have a higher occurrence of problems with their systems and realized a greater benefit from the services provided. The "seasonal swing" methodology proved to be reliable at indicating customers likely to benefit from the program.

Quality assurance and training played an important role in the project and proved to be successful in providing a means for insuring quality work from HVAC technicians. The testing protocol, technical process review and prompt feedback continually improved technician performance and understanding of the program. Technical process review and feedback were a crucial control feature of the project that were required to be delivered in a timely fashion.

JUMP AND MODERA

This study examined the combined energy effect of duct leakage retrofit repair and the application of additional duct insulation on thirty houses with attic located duct systems. The energy effects were monitored on a total of 5 houses during the summer season and 6 winter season houses. The 6 winter season houses were all equipped with electric heating systems. Short term (~ 2 week) monitoring took place for both pre and post retrofit periods.

The extensive diagnostic testing included duct leakage testing, system air flow measurement, and measurement of normal operating static pressures within the duct systems. The monitoring included temperatures throughout the duct system, attic, and outside, as well as power consumption of all significant HVAC system components.

Testing found that supply and return leakage areas were nearly equal. However the return system leakage reduction averaged 73% while the supply system leakage reduction was only reduced by 56%. The greater success in sealing the return system was attributed to the leakage being concentrated in a few sites. Overall, approximately 64% of the duct leakage was eliminated and this sealing work reduced the house leakage area by approximately 14%. Increasing the duct R-value to an R-6 on both the plenums and the individual duct runs reduced conduction losses by an average of 33%.

NEAL

Neal performed an investigation into measured system performance on ten central air conditioning systems in North Carolina. The study was designed to compare the actual performance of the equipment to the manufacturers rated performance.

This study found that on average the air conditioners were performing at 70% of rated efficiency. Four of the ten units did not have proper of air flow through the indoor coil and five of the ten were incorrectly charged. It was noted that all of the units examined had at least one efficiency or service life problem.

PROCTOR ET AL. (1990)

Pacific Gas & Electric Company sponsored an investigation of heat pump operating efficiency for high bill complaint customers in the winter of 1989. This study was designed to identify major problems existing with heat pump installations and to design a system to correct those deficiencies. The study focused on the problem areas of low air flow through the indoor coil, incorrect refrigerant charge, excessive use of back-up heat strips, other control problems, shell leakage, and duct system leakage.

The study examined 51 heat pumps in 49 houses. Each of the houses was visited by a heat pump technician that used a set procedure to diagnose and repair problems with the heat pump. To quantify problems with the duct system and the building shell each of the houses was inspected with the use of a blower door. Three of the retrofitted houses were chosen for pre and post retrofit short term monitoring.

Technician visits identified at least one major problem in over 90% of the houses tested. Seventy three percent of these houses had received a recent visit by professional HVAC service personnel that had not found nor solved the problems identified in the study. Table A-1 lists the major problems found at the sites.

Table A-1
Problems Identified by House

Problems	**Number of Houses with Problem**	**Problem Solvable Through Program**
Diffuse Duct Leakage > 150 CFM_{50}[12]	33	25
Low Air Flow	24	19[13]
Incorrect Charge[14]	16	16
Disconnected Ducts	16	14
Refrigerant Leaks	10	10
Recirculation Through Outdoor Coil	9	0
Auxiliary Heat on First Stage	3	3
House Leakier Than 0.75 ACH	15	15

Savings projections indicated that duct leakage repair was the best option for lowering the customers high seasonal energy usage, followed by refrigerant charge correction, sealing of shell leakage sites , installation of auxiliary strip heat cut-outs , and correction of low air flow.

[12] Duct leakage was measured after all disconnected ducts had been repaired.

[13] Low air flow on these units were caused by restrictive duct design. Modification of the duct system through adding runs or increasing duct sizing was outside the scope of this program.

[14] The methodology used for checking charge in this study did not indicate units that were overcharged. Additionally only units that could be brought to correct air flow were tested for charge.

PROCTOR (1991)

A comprehensive study was commissioned by Pacific Gas & Electric Company during the summer of 1990 on 15 houses in Fresno, California to determine the potential energy and peak reduction savings of a program for residential air conditioners. During the study all houses were monitored for energy usage for a period preceding repairs and after repairs. The majority of the customers selected were high bill complaint customers.

All 15 of the houses had at least one major problem with the air conditioner or the duct system. Ninety percent of the homes had duct leakage in excess of 150 CFM_{50}. Duct leakage accounted for 14.7% of the total building shell leakage area. The average cooling load increase due to the duct leakage was 25%. The average retrofit duct leakage reduction achievable was 60%, with a corresponding monitored cooling energy savings of 18%.

Sixty seven percent of the systems had low air flow through the indoor coil. Cleaning resulted in an average increase in air flow of 16% . Fifty six percent of the air conditioners had an improper level of refrigerant charge.

All of the houses in the study experienced at least a 10% reduction in monitored cooling energy usage and a number of the houses experienced savings in excess of 30%.

DUCT SEALING PEAK EFFECT STUDIES

Valid estimation of peak day electrical usage for residential air conditioners and their duct systems are intrinsically difficult due to the fact that the evaluator is trying to predict an event that occurs rarely and is usually outside the measured data set. Additionally peak usage of air conditioners is driven by numerous variables (i.e. occupant behavior, outdoor temperature, relative humidity, time of day, sky cover, etc.).

Proctor (1993) examined six analytical models using submetered data from the Appliance Doctor™ Pre-Production Project to analyze the strengths and weaknesses of the models at estimating peak reduction. All six models showed consistent results that peak reduction occurred in the early evening hours (local residential distribution peak) when duct systems were sealed. Peak reduction in the early afternoon hours (system peak) could not be proven due to the small size of the sample.

Cavalli and Wyatt (1993) examined a sampling of 240 submetered air conditioners from the PG&E Model Energy Communities Project. This study was designed to determine if there was any peak effect attributable to: 1) duct sealing on residential air conditioners and 2) early replacement of air conditioners that were oversized (as determined by ACCA Manual J) and had low rated EER's (this group also received duct repairs).

The results showed negligible peak operating impact from duct sealing of 0.04 kW. Replacement of air conditioners with correctly sized more efficient air conditioners was shown to be effective at reducing the peak operating impact by approximately 1.4 kW. The authors indicate the results of their analysis is limited by the fact that the data was from a cool summer where the maximum temperature never reached 100°F.

Jacob and Zebedee (1994) examined the peak impact of duct sealing using metered data from the Florida Power Corporations duct sealing program. The analysis showed an estimated average peak demand savings of 0.5 kW.

These three studies show that there is no absolute agreement on peak reduction attributable to duct sealing alone. Together however, they support the point that duct sealing combined with sizing reductions will reduce peak.

APPENDIX B:
COMBINED MODEL AND DATA SOURCES

The combined model presented in this report is composed of three primary sub-models: a duct loss model, an air conditioner performance model, and a residential air conditioner peak load model.

A schematic of these three models is shown in Figure B-1

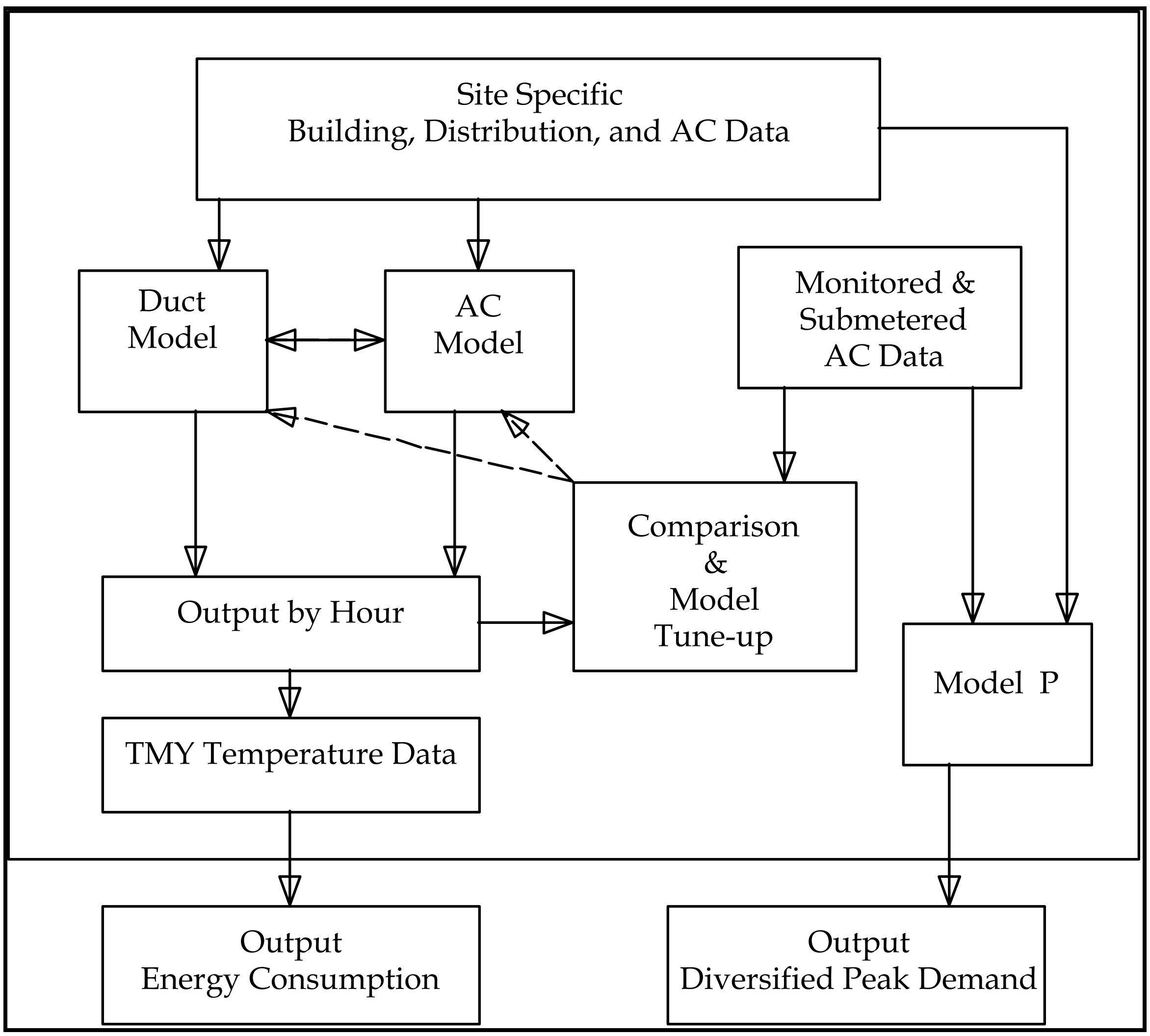


Figure B-1
Combined Model Schematic

DUCT LOSS MODEL

The duct loss model includes the impacts of direct leakage losses, induced building infiltration losses, and conductive losses. The model characterizes these losses as a loss of effective system capacity. The duct model also calculates return plenum temperatures and average supply air temperatures based on leakage, duct location, conduction rates, buffer space temperature, and indoor and supply plenum temperatures.

The basic model including leakage and infiltration effects is the work of Palmiter (SOURCE: Palmiter and Bond, 1991). Proctor Engineering Group has added the effects of conduction and energy recovery (when supply leakage is mitigated by nearby return leaks and other recovery mechanisms) into that model.

AIR CONDITIONER MODEL

The model calculates changes in capacity and efficiency due to:

- Ou tdoor temperature
- Refrigerant charge (capacity and efficiency generally peak at proper charge, but the effect is dependent on other variables)
- Return plenum wet bulb temperature
- Return plenum dry bulb temperature
- Air flow through the indoor coil

The model also calculates the supply plenum air temperature based on the return plenum temperature, system capacity, and air flow rate.

The model draws on a variety of sources including:

- Campbell Scientific and ACR monitored data.
- ASHRAE calculation procedures (SOURCE: ASHRAE Fundamentals 1993: Chapter 23, Duct Design, HVAC 2 Toolkit {DOE-2 algorithms and subroutines}).
- Laboratory tests of air conditioners with charge varied from 20% below to 20% above proper charge (SOURCE: Farazad and O'Neal, 1988 and 1989) These tests were conducted with outdoor coil inlet air temperatures from 82¡F to 100¡F.
- Laboratory tests on the high temperature performance of air conditioners. Charge varied from 30% undercharged to 40% overcharged; outdoor coil inlet air temperatures ranged from 95¡F to 120¡F (EPRI & Texas A&M University, 1995 - in process)
- Simulation runs by Proctor Engineering Group for higher outdoor temperatures and lower indoor wet bulb conditions with MODCON, the air conditioner simulation program of Oak Ridge National Laboratory (SOURCE: Rice, 1991).
- Data gathered from major manufacturers on performance of air conditioners .

MODELED COOLING LOADS

Building shell loads for the combined energy consumption model were based on temperature and capacity data from sites monitored with Campbell Scientific and ACR data acquisition systems. The calculated building shell load was set equal to the measured capacity adjusted for duct losses according to the equation below:

$$\text{Shell Load} = \text{Measured Capacity} \times (1 - \text{Duct Losses})$$

PEAK LOAD MODEL (MODEL P)

Model P includes all the impacts both known and unknown that effect occupant behavior to produce a given duty cycle at peak. These effects are nested in the empirical base for Model P - submetered air conditioner data from peak hours. The output from Model P is the diversified demand of the residential air conditioners under varying scenarios.

Model P divides residential air conditioners into four groups. Group A consists of air conditioners that are not operating on peak. On peak, Group B and C air conditioners cycled (Group B) or potentially cycled (Group C) by the thermostat. Group D air conditioners run constantly on peak and would do so even if substantial improvements were made in the effective capacity of the system. The breakdown of groups used in this study is shown in Figure B-2.

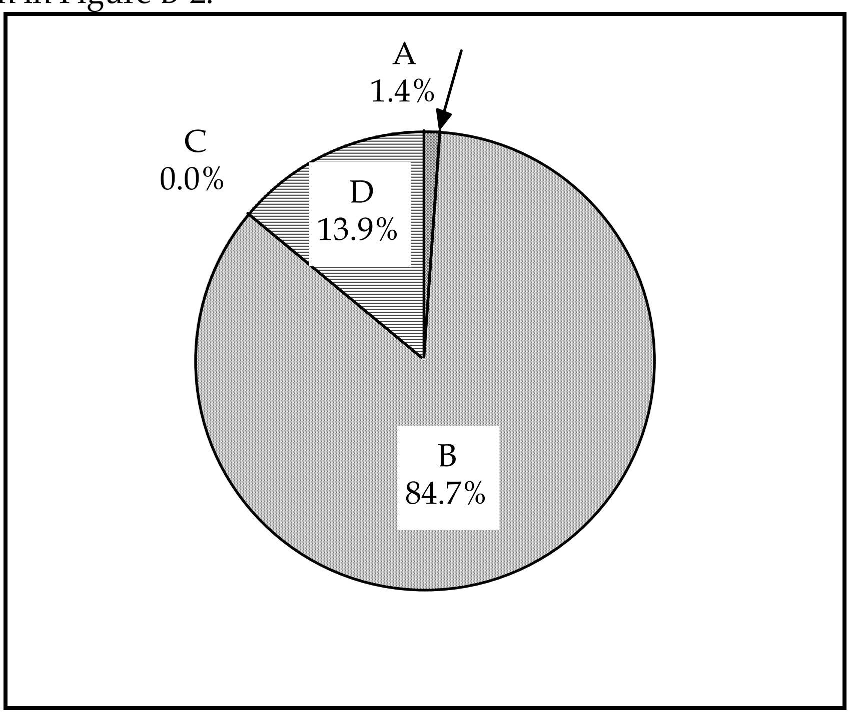


Figure B-2
Incidence of Model P Classes

The output from Model P is the diversified demand of the residential air conditioners under varying scenarios. The diversified demand is calculated as the weighted sum of the demands of the four groups (weighted by their occurrence in the submetered data.) The demand of the four groups are:

- Group A air conditioners have no demand at peak
- Group B and C air conditioners have a peak demand that is dependent on the ratio of the cooling load to the effective capacity of the unit (duty cycle). Under different scenarios, the duty cycle will change.
- Group D demand equals their connected load. The connected load (which is dependent on outdoor temperature, return plenum temperature, refrigerant charge, and indoor coil air flow) is an output from the combined air conditioning and duct model.

Model P was developed by Proctor Engineering Group in order to improve predictions of peak effects from alternative technological options. The data used to build Model P for this study came from APS submetering:

- Arizona Public Service supplied average kW metering in 15 minute intervals for both the air handlers and the outdoor condensing units for 27 AC units at 22 sites. End use meters produced by Process Systems Inc. were attached to the loads by current transducers at the circuit breaker panels.

The five hottest monitored weekdays were analyzed for peak load. A total of 72 site-days were analyzed for 5:00 PM operations.

APPENDIX D:
SIZING AND APPARENT LOAD

VERIFICATION OF MANUAL J LOAD ESTIMATES

Manual J has long been a standard calculation method for determining design cooling loads. Nevertheless some contractors are reluctant to accept that equipment sized strictly to Manual J loads will meet the needs of their customers under design (and hotter) conditions. Proctor Engineering Group used the recorded temperature drop and measured flow data from a number of units to calculate the actual sensible capacity delivered by the air conditioner under severe conditions. The analyzed units had the following characteristics:

- The thermostat was not reset during the day of the analysis
- The analysis days had peak temperatures of 106°F.
- The minimum return temperatures were 75°F or lower (thermostat setting of less than 75°F)

All but one of the analyzed units showed a common feature, they were cycling throughout the Design days. Figure 1 displays the return plenum temperatures for Unit #35.

Return Plenum Temperature

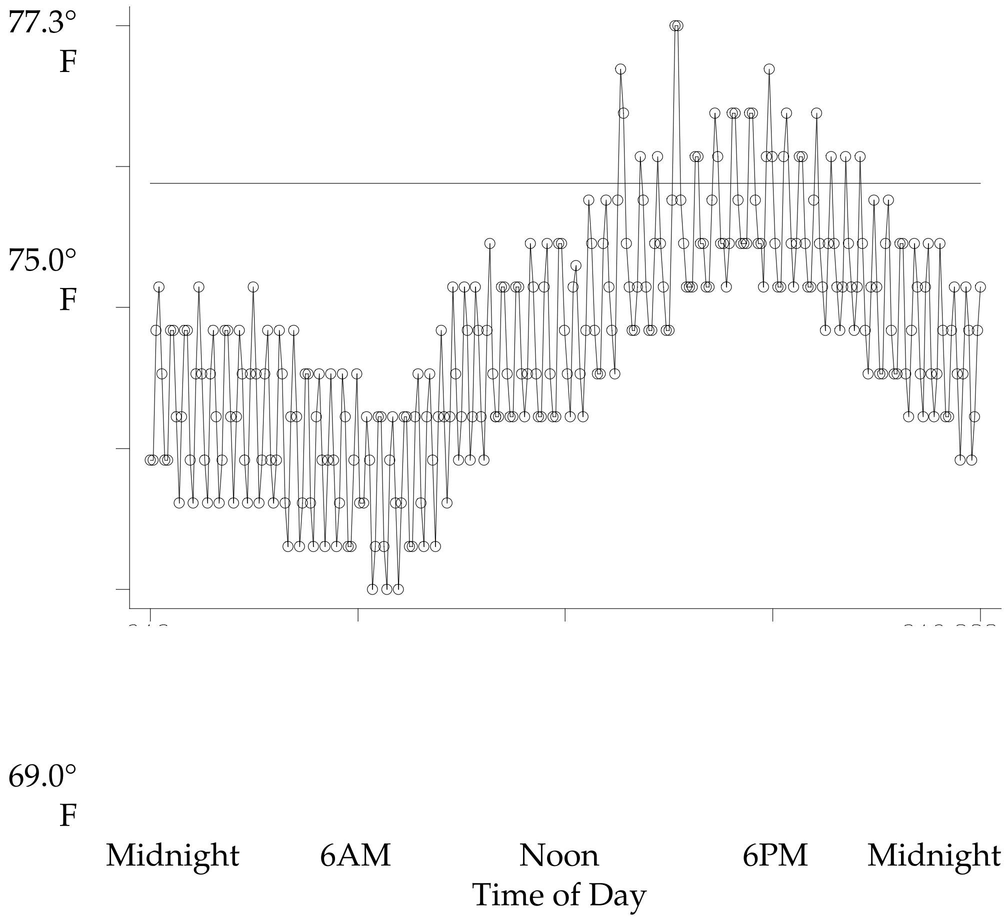


Figure 1
Typical Return Plenum Temperatures on a Design Day

The relationship between Manual J estimated load and the actual load is shown in Figure 2.

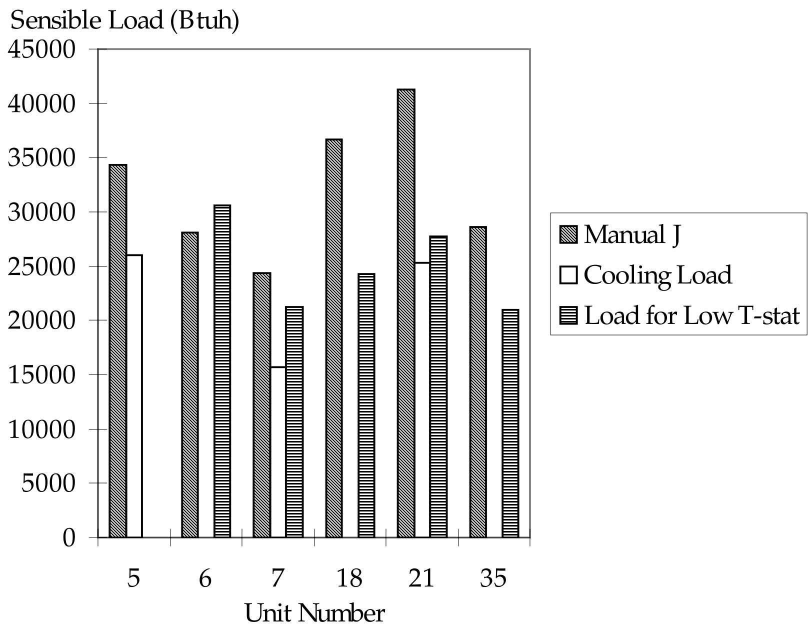


Figure 2
Design Day Maximum Load vs. Manual J Estimated Design Load

For 83% of the units the actual load was substantially less than the Manual J. The average maximum sensible load in a design day was 67% of Manual J for houses with thermostat settings near 75°F.

Unit #6 had a sensible load in excess of Manual J. The problem causing the excess sensible load in this house is not known, but it is more than a low thermostat setting. This unit points out an important factor about the practice of oversizing air conditioners, when an air conditioner is oversized, the oversizing hides problems that otherwise would get attention and be solved.