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Residential New Construction Pilot in NPC Service Territory

Prepared for:
Electric Power Research Institute
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ABSTRACT

From 1994 through 1996, Nevada Power investigated opportunities for improving air conditioning system performance in new residential construction. Data analysis for this investigation was performed by Proctor Engineering Group (PEG) and cosponsored by the Electric Power Research Institute (EPRI) and the Nevada State Energy Office. The investigation involved field testing, monitoring, and metering homes in the Las Vegas area. Two sets of homes were built, the first to standard practice (1995 group), the second to higher duct and AC installation standards (1996 group).

After the standard practice homes were built and field tested, PEG produced estimates of potential savings from a variety of program measures. These estimates were developed with a comprehensive AC/duct simulation model previously used in other such investigations. The simulation used Las Vegas weather and the field measurements from the standard practice homes. Predicted cooling energy savings ranged from 10% for a program design that reduced duct leakage and increased duct insulation to 33% for a program that addressed AC coil air flow, refrigerant charge, duct leakage, and duct insulation. Estimates of peak day kW reduction in the 4 PM to 5 PM hour ranged from 0.27 kW to 0.60 kW per air conditioner for the same mix of program measures listed above.

Higher standard HVAC systems were installed in the 1996 homes. Field testing showed that the primary difference between the 1995 group and 1996 groups was a duct leakage reduction in the 1996 group. The supply duct leakage to outside was reduced from 7% of air handler flow in 1995 to 3% in 1996. Similarly, the return duct leakage from outside was reduced from 6.7% of air handler flow in 1995 to 1.3% of air handler flow in 1996. Duct insulation was also increased from R-4 to R-6 between the two groups. Using a comprehensive duct and AC model, the projected savings for duct leakage reduction and duct insulation was 10%[1].

Electrical consumption data were collected for both groups of homes during the summer of 1996. Proctor Engineering Group (PEG) employed a number of statistical approaches for analyzing the usage data to develop program impact estimates. While all the analysis methods focused on estimating the differences in hourly electricity usage rates between the 1995 and 1996 houses, the methods varied in how they accounted for other factors influencing usage rates. To minimize the risk of misleading results, PEG chose to pursue several alternative statistical modeling techniques in order to "triangulate" an estimate of program impacts. These techniques ranged from simple comparisons of mean usage levels to cross-section time series regression analysis and analysis of covariance models.

The energy savings estimates from the metered data ranged from 6% to 14%, which were comparable to the projections from the comprehensive model. Peak reductions ranged from 0.36 kW in the 4-5 PM hour to over 1 kW in the 8-9 PM hour.

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[1] based on a reduction to 3% total leakage and R-8

EXECUTIVE SUMMARY

Newly constructed homes in Nevada Power 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.

This study tested the energy consumption and peak reduction effects of a pilot program that reduced duct leakage, increased duct insulation, and changed AC installation practice on new residential construction in Las Vegas. Potential savings and peak reductions were projected using a comprehensive duct and AC model. This model projected a 10% energy savings from reduced duct leakage and increased duct insulation[2]. The model also projected 0.33 kW reduction in load at 4-5 PM.

The study consisted of two cohorts, the 1995 cohort built to standard practice and the 1996 cohort built to improved standards. The duct systems in the 1995 cohort were factory built. The 1996 cohort systems were built on site to specific prescriptive and performance criteria. The program was successful in substantially reducing duct leakage and producing a moderate increase in duct insulation. The air conditioner installation practice changes were less than totally effective. The air flow across the indoor coil did not increase to the desired levels, and the on site efficiency tests often showed efficiencies below the expected values for the test conditions.

The energy savings estimates were triangulated through a variety of analytical techniques. The savings estimates from the metered data ranged from 6% to 14%. These are comparable to the projections from the comprehensive model. Peak reductions ranged from 0.36 kW in the 4-5 PM hour to over 1 kW in the 8-9 PM hour.

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[2] based on a reduction to 3% total leakage and R-8

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BACKGROUND

The Las Vegas area is currently the fastest growing market for new residential units in the nation. Nevada Power Company (NPC) and the Electric Power Research Institute (EPRI) 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 Nevada Power Company's service territory. This assessment involved the following:

- detailed field testing of a sample of 30 newly built homes to identify problems with current practice HVAC system installations;
- 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;
- metering and temperature monitoring of 30 new homes built in 1995;
- implementation of higher duct and AC installation standards in matched homes built in 1996; and
- metering and temperature monitoring of the 1996 homes.

Three reports cover this project as follows: Report 1 covering the field investigation and analysis of the homes built in 1994, Report 2 covering the initial analysis of the 1995 cohort, and this Final Report comparing the performance of homes built to standard practice in 1995 and those built to the higher standards in 1996.

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; and
- 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.

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FIELD INVESTIGATION

In 1994, Proctor Engineering Group examined 30 newly built houses in the Las Vegas area with a total of 40 air conditioning systems. The 30 houses came from 17 developments built by 10 general contractors, utilizing 11 HVAC contractors.

In 1995, Nevada Power Company examined 30 newly built houses with a total of 37 air conditioning systems. The 31 houses came from 14 developments built by 9 general contractors.

In 1996, Nevada Power Company worked with the general contractors to select houses that matched those tested in 1995. The houses selected in 1996 were the same plan or model as those selected in 1995, the only difference in the houses was a possible change in orientation. Nevada Power Company examined 21 newly built houses with a total of 26 air conditioning systems. The 21 houses came from 9 developments built by 7 general contractors.

Nevada Power Company worked with the general contractors to get the 1996 houses built to the specifications in “New Construction HVAC Program Implementation Plan for Nevada Power Company” (SOURCE: EPRI, 1995).

This report addresses houses examined in 1995 and 1996.

FIELD DATA COLLECTION PROTOCOL

The field data collection protocol changed between 1995 and 1996. In 1996 duct leakage was measured in two ways, with the flow hood and with a Duct Blaster™ (Duct Blaster™ is a trademark of the Energy Conservatory). In 1995 Nevada Power Company did not have a Duct Blaster™ but acquired one in 1996 to measure the duct leakage prior to drywall installation. This allowed the contractors the option of performing further sealing of the duct system, if needed, while it was still easily accessible. Tables 2-1 and 2-2 summarize the field test procedures for 1995 and 1996, respectively.

Table 2-1
Summary of 1995 Field Test Procedures

Parameter	Tests	Description / Use
Duct Leakage	Blower Door & Flow Hood - exterior leakage for whole system	depressurize house to 50 pa with all registers sealed except the largest least restricted return, measure flow through return grille with flow hood, check pressures in other parts of duct system
	Blower Door & Flow Hood - exterior leakage for return system only[3]	depressurize house to 50 pa with all registers sealed except the largest least restricted return, insert blocking at air handler to isolate the return system from supply, measure flow through return grille with flow hood, check pressures in other parts of duct system
Air Handler Flow	Flow Hood	measure flow rate into return grille(s); calculate air flow as register flow plus return leakage
	Operating Static Pressures	measure static pressures in supply and return plenums; used for adjusting duct leakage results to estimate supply and return leakage fractions when air handler operates; also useful for assessing duct design
AC Charge	Weighing Charge	recover and weigh all refrigerant charge and compare to manufacturers specifications (adjusted for line set length)
AC other	Miscellaneous	collect nameplate information from indoor and outdoor units to determine manufacturers listed capacities and efficiencies
Duct Conduction	Duct System Location	Estimate supply and return duct location (attic, garage, inside, etc.) percentage - 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 ACCA Manual J
Building Airtightness	Blower Door Test	Measure CFM50 of house, also measure pressures developed in key building zones such as attics

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[3] this method excludes cabinet leakage from the return system and attributes it to the supply system

Table 2-2
Summary of 1996 Field Test Procedures

Parameter	Tests	Description / Use
Duct Leakage	Duct Blaster™ - total leakage	pressurize ducts to 25 pa with registers sealed, measure fan flow, check pressures in other parts of duct system (both before and after drywall installation)
	Duct Blaster™ - exterior leakage	repeat above test while blower door pressurizes house to 25 pa, eliminating pressure difference between ducts and house (post testing after drywall is installed)
	Half Nelson - return/supply leakage split	measure pressures in supply and return plenums with air handler on and registers sealed - results used to adjust duct leakage results into supply and return leakage rates
	Blower Door & Flow Hood - exterior leakage for whole system	pressurize house to 50 pa with all registers sealed except the largest least restricted return, measure flow through return grille with flow hood, check pressures in other parts of duct system
Air Handler Flow	Flow Hood	measure flow rate into return grille(s); calculate air flow as register flow plus return leakage
	Operating Static Pressures	measure static pressures in supply and return plenums used for adjusting leakage at test pressure to actual leakage estimate; also useful for assessing duct design
AC Capacity	Enthalpy Change across AC coil	measure wet and dry bulb temperatures in supply and return plenums - when combined with air handler flow rate can calculate actual capacity (under test conditions, which can be adjusted to ARI standard)[4]
AC EER	Wattage Input	use house electric meter to measure watt draw of AC, calculate EER at test conditions by dividing input into capacity
AC Charge	Weighing Charge	observe contractor; 1) evacuate lines and coil, 2) release factory charge and, 3) adjust charge for line set length
AC other	miscellaneous	collect nameplate information from indoor and outdoor units to determine manufacturers listed capacities and efficiencies
Duct Conduction	Duct System Location	Estimate supply and return duct location (attic, garage, inside, etc.) percentage - 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 ACCA Manual J
Building Airtightness	Blower Door Test	Measure CFM50 of house, also measure pressures developed in key building zones such as attics

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[4] Air Conditioning & Refrigeration Institute (ARI) standard rating conditions of 80°F dry bulb and 67°F wet bulb indoors and 95°F dry bulb outdoors.

FINDINGS - GENERAL CHARACTERISTICS

The typical house in the study was a slab-on-grade home with 3 bedrooms, about 1875 square feet of living space, gas heat, double glazed windows, and R-30 attic insulation with a tile roof. Few south or west facing windows had any architectural shading. Twenty-three of the twenty-six systems had 100% of the duct system located in the attic. The attic location exacerbates the impacts of return system leakage and increases conductive heat gains. Three systems serving the lower floor of two story buildings had the duct system located between floors. Houses with two systems usually had both return grilles located in one central location, commonly the upstairs hallway.

The houses were fairly tight, with an average air leakage of 1714 CFM50 (Cubic Feet per Minute at 50 Pascals) in 1995 and 1795 CFM50 in 1996. This level of air tightness lowers the cooling and heating load of the house and saves energy.

FINDINGS - DUCT CONSTRUCTION

1995 Houses. The duct systems in the 1995 houses commonly consisted of a rigid metal return plenum, duct board supply plenum and connecting (triangular) boxes with R-4 insulated round flex duct branches to the individual rooms. Most of the systems tested were "bag" systems which are used by the majority of Las Vegas contractors. Bag systems are factory built to the specifications of the contractor. The system is assembled at the factory including the main branch and individual runs. The installers simply put the system in place and make plenum connections. The system was duct taped on the inner liner at the time of factory assembly. Duct or aluminum tape was used at field connections.

1996 Houses. The duct systems in the 1996 houses consisted of a insulated rigid metal return plenum and duct board or sheet metal supply plenum and R-6 flex duct runs[5]. The branches of the duct system were upgraded to insulated sheet metal wyes in place of the duct board triangular boxes. Insulated sheet metal elbows were used to transition between the duct run and the boot at the register. Both of these changes were made to help reduce the operating static pressure and increase air flow. All duct systems were assembled on site at the house and were sealed with mastic at all joints. The transition from the air handler to the plenums were sealed with mastic and the air handler seams were sealed with aluminum tape.

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). Total leakage and leakage to the exterior at a specific test pressure are both measurable and helpful specifications. However, normal operating leakage, split between supply and return, must be estimated to calculate the energy and peak effect of duct leakage.

The total duct leakage test establishes the leakage from the ducts when all the registers are sealed and the ducts are pressurized to 25 pascals. Total duct leakage is a fast and accurate test method that is easily applied to new construction even before the drywall is installed. In 1996, total duct leakage was tested using a Duct Blaster™. The standard established in EPRI TR-105310 is 75 CFM25. The average measured

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[5] Builders were concerned that R-8 insulated ducts would not fit within the confines of the existing structure without altering trusses.

total leakage rate for the 1996 cohort was 81 CFM25. The distribution of total duct leakage is shown in Figure 2-1.

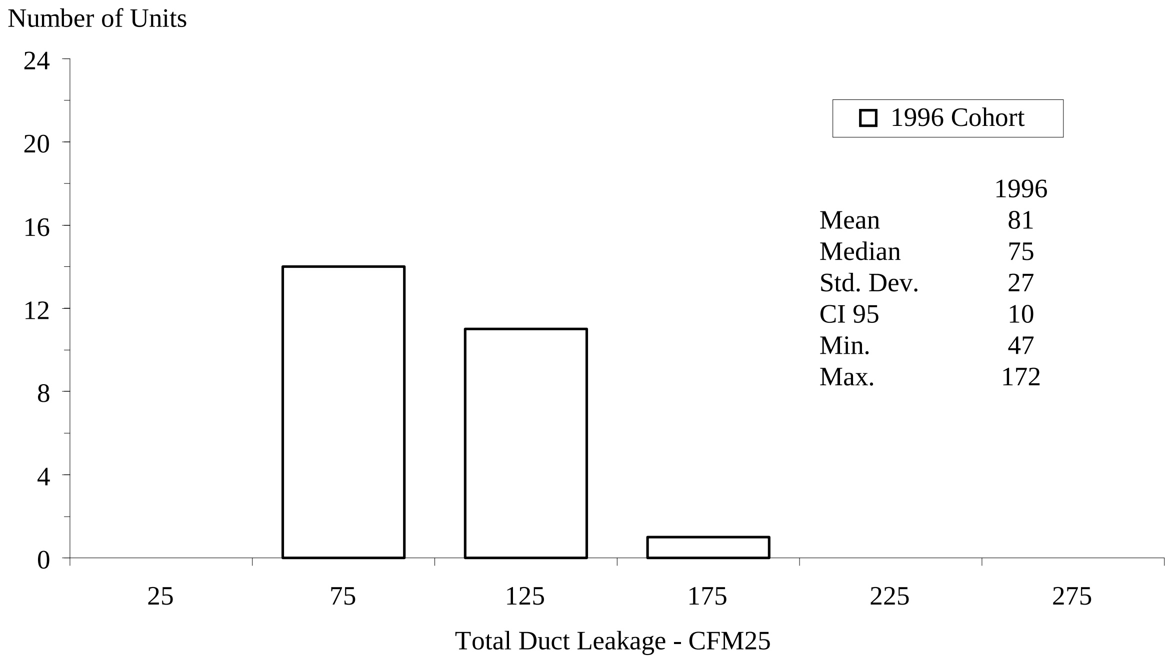
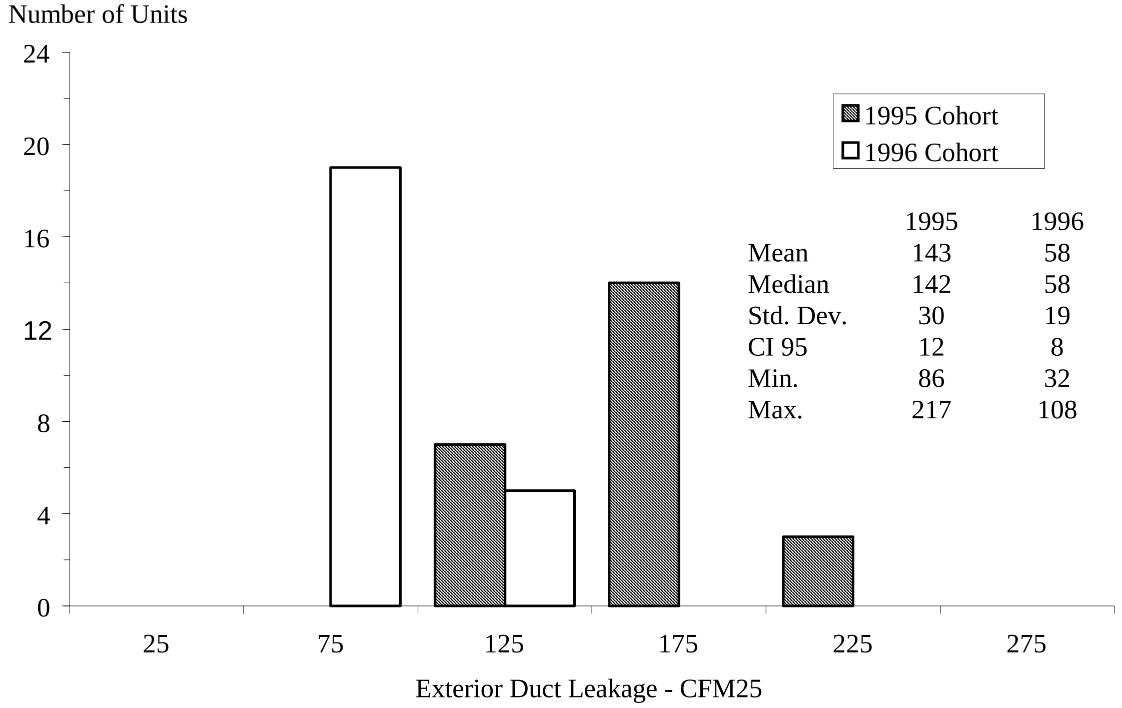


Figure 2-1
Total Duct Leakage

The first house completed of the 1996 cohort had the highest duct leakage of the group (172 CFM25). This house was sealed using a butyl backed aluminum tape rather than mastic. With the first house eliminated the mean leakage of the sample is 77 CFM25 and the median 75 CFM25.

Half of the homes did not meet the standard for duct leakage, but were considerably improved over the 1995 cohort (as seen in the following data) and the 1994 cohort which had a total duct leakage of 235 CFM25.

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 in both 1995 and 1996 using a blower door and flow hood. This reduces the duct leakage to inside to a minimum and thus measures the duct leakage to the exterior. The distributions of exterior duct leakage for comparable 1995 and 1996 sites are shown in Figure 2-2.



	1995	1996
Mean	143	58
Median	142	58
Std. Dev.	30	19
CI 95	12	8
Min.	86	32
Max.	217	108

Figure 2-2
Duct Leakage to the Exterior [6]

The 1996 protocols and implementation resulted in a substantial reduction in duct leakage compared to the 1995 and 1994 cohorts. The average leakage to the exterior was lowered from 143 CFM25 in 1995 to 58 CFM25 in 1996.

Both leakage to outside and total duct leakage supply useful information. The key quantities however are the leakage in the supply and return under operating conditions (as a percentage of the air flow through the indoor coil). These key quantities were estimated in this study in a three step process:

1) Exterior leakage at test pressure was allocated to the supply and return (based on a total and a return only test in 1995, and from the half Nelson test and duct locations in 1996).
2) The operating leakages for supply and return were estimated based on the operating[7] pressures.
3) The operating leakage estimates were divided by the flow through the coil.

Figure 2-3 provides a comparison of the operating supply duct leakage for comparable 1995 and 1996 sites. The supply leakage averaged 83 CFM in 1995 and 37 CFM in 1996, representing about 7 percent and 3 percent of the air handler flow respectively.

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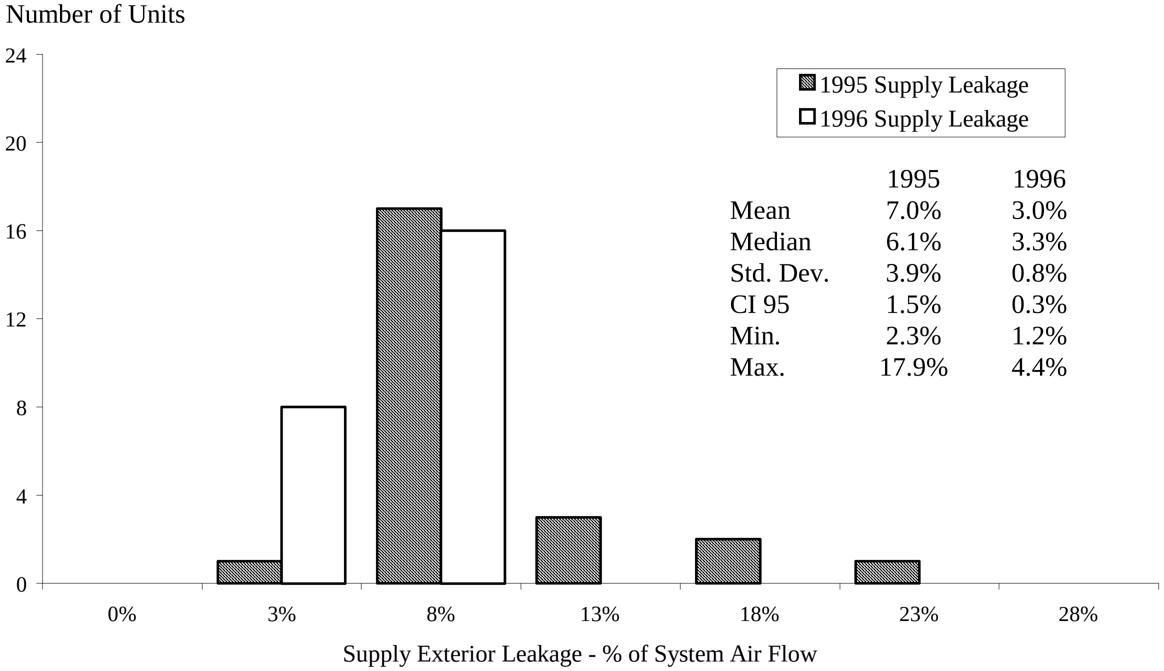
[6] The first two houses of 1996 did not receive the blower door/flow hood duct leakage testing. These two houses and their matches are not included in Figure 2-2.

[7] 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

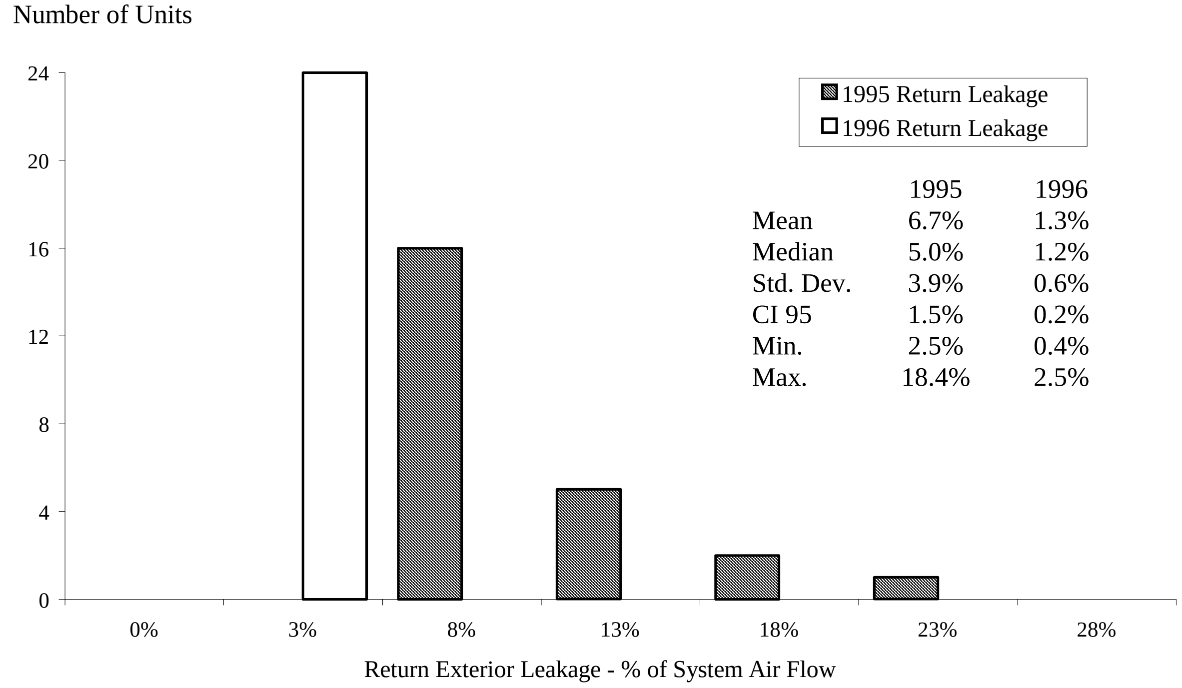


	1995	1996
Mean	7.0%	3.0%
Median	6.1%	3.3%
Std. Dev.	3.9%	0.8%
CI 95	1.5%	0.3%
Min.	2.3%	1.2%
Max.	17.9%	4.4%

Figure 2-3
Supply Leakage as a Percentage of Flow

Supply leakage has the greatest effect of all the duct variables on energy consumption. The average supply duct leakage was reduced from 7 percent in 1995 to 3 percent in 1996.

Figure 2-4 provides a comparison of the operating return duct leakage. The flow rates for return leakage averaged 78 CFM in 1995 and 16 CFM in 1996, representing about 7 percent and 1 percent of the air handler flow respectively.



	1995	1996
Mean	6.7%	1.3%
Median	5.0%	1.2%
Std. Dev.	3.9%	0.6%
CI 95	1.5%	0.2%
Min.	2.5%	0.4%
Max.	18.4%	2.5%

Figure 2-4
Return Leakage as a Percentage of Flow

Improvements in return duct integrity were very impressive. The average return leakage dropped from almost 7 percent to near 1 percent. The leakiest return in 1996 was equal to the tightest return in 1995.

FINDINGS - AIR CONDITIONING SYSTEMS

The houses had a wide variety of air conditioning system makes and models. The capacity of single air conditioners serving an entire house averaged slightly over four tons. The combined AC capacity for two system houses averaged about five and a half tons. In the two system homes a large system serves the main portion of the house and a smaller system serves the bedrooms. About 25 percent of the units were package systems. Rated EERs ranged from 8.7 to 9.8 and averaged 9.3. Rated SEER values ranged from 10.0 to 10.5 and averaged 10.3

Air Handler Flow Rate. The proper operation of an air conditioning system depends upon providing the correct air flow rate across the indoor coil. EPRI TR-105310 set 400 CFM per nominal ton (the wet coil flow suggested by the manufacturers) as the minimum standard. Low air flow has been a common problem found in other studies of air conditioner performance (Proctor, 1991; Neal, 1990). In a hot/dry climate such as Las Vegas, where sensible cooling is almost the exclusive goal of air conditioning, ACCA Manual S recommends higher air flows. For a sensible load ratio of .9, they recommend a temperature drop of 17 °F which translates to 577 CFM per ton at design.

Air flow rate through the return grill was measured (all systems had a single return grill) using a flow hood. Return grill flow was added to the estimated return leakage flow (very low in the 1996 cohort).

The 1995 cohort had an average flow rate of 361 CFM per ton measured with a wet coil, ten percent below the standard. Thirteen of the units were below 350 CFM/ton (often used as a level requiring corrective action).

The 1996 cohort had an average flow rate of 348 CFM per ton adjusted to wet coil conditions[8], thirteen percent below the standard. Sixteen of the units were below 350 CFM/ton.

Figure 2-5 compares the distribution of wet coil air flows between the two cohorts.

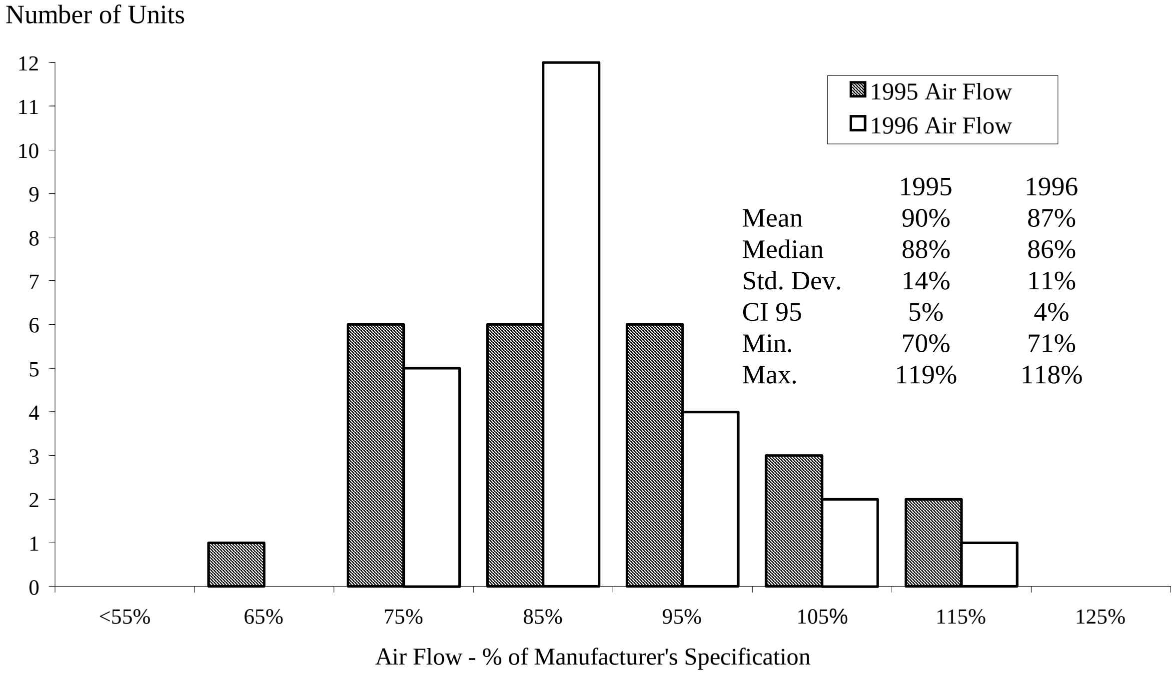


Figure 2-5
Air Handler Flow

Air flow on the 1996 units is still below the standards in EPRI TR-105310. The standards state, "The measured CFM/ton must be at least 400 CFM/ton (wet coil)."

One potential cause of low air flow on these units is use of a reduced blower speed. One of two units visited by the author were set on less than maximum blower speed (and had low air flow).

In 1996, the ducts were designed to ACCA Manual D. The designs were based on a duct external static pressure of .5 inches water column. The coil adds another .2 to .38 inches to be overcome by the blower. With this additional static pressure the specifications show many of the blowers on these units are not able to deliver 400+ CFM/ton.

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[8] The air flow was measured with a dry coil in 1996. This gives a higher air flow since a dry coil is less restrictive than a wet coil. The dry coil air flow averaged 387 CFM per ton. Wet coil air flows are approximately 90% of dry coil flows (348 CFM in this case).

It is likely that the coil air flows will equal or exceed 400 CFM/ton if the duct sizing procedures in EPRI TR-105310 are followed:

1) System air flow requirements shall be determined as outlined in Section 5 of ACCA Manual D. (the 1996 cohort was designed to this criteria)
2) All systems shall have at least one supply run for each 4,000 Btu/hr of rated capacity of the cooling equipment installed. (52% of the 1996 cohort did not meet this criteria)
3) All systems shall have at least one return duct run, equipped with a filter grille for every 30,000 Butcher of rated capacity of the cooling equipment installed. (81% of the 1996 cohort did not meet this criteria)
4) Duct systems shall be sized to minimize design static pressures and afford adequate sizing to overcome additional static pressure caused by installer deviation from the design specifications. To ensure the system is adequate to allow for these deviations the total design static pressure calculated in Section 5 of ACCA Manual D shall be reduced by 20% before the selection of the duct system is completed (thus lowering available static pressure on both the supply and return side by 20%).

The last three specifications are all methods of ensuring that the duct static pressure does not exceed the capacity of the fan.

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).

In 1995, refrigerant was recovered and weighed to determine the level of correct charge. When the charge specified by the manufacturer was compared to the amount recovered, it was determined that fifty-nine percent of the systems contained less than ninety percent of the correct charge (10% was allowed for measurement error). Five percent of the units contained more than 110% of correct charge and the remaining 35% were within +/- ten percent of correct charge.

In 1996 Nevada Power Company personnel were on-site for unit start up. The start up procedure included; line set measurement, evacuation to 300 microns, 5 minute leakage test, and charge adjustment to correct for refrigerant line length. The total refrigerant charge was not recovered and weighed, but this procedure is presumed to obtain correct refrigerant charge.

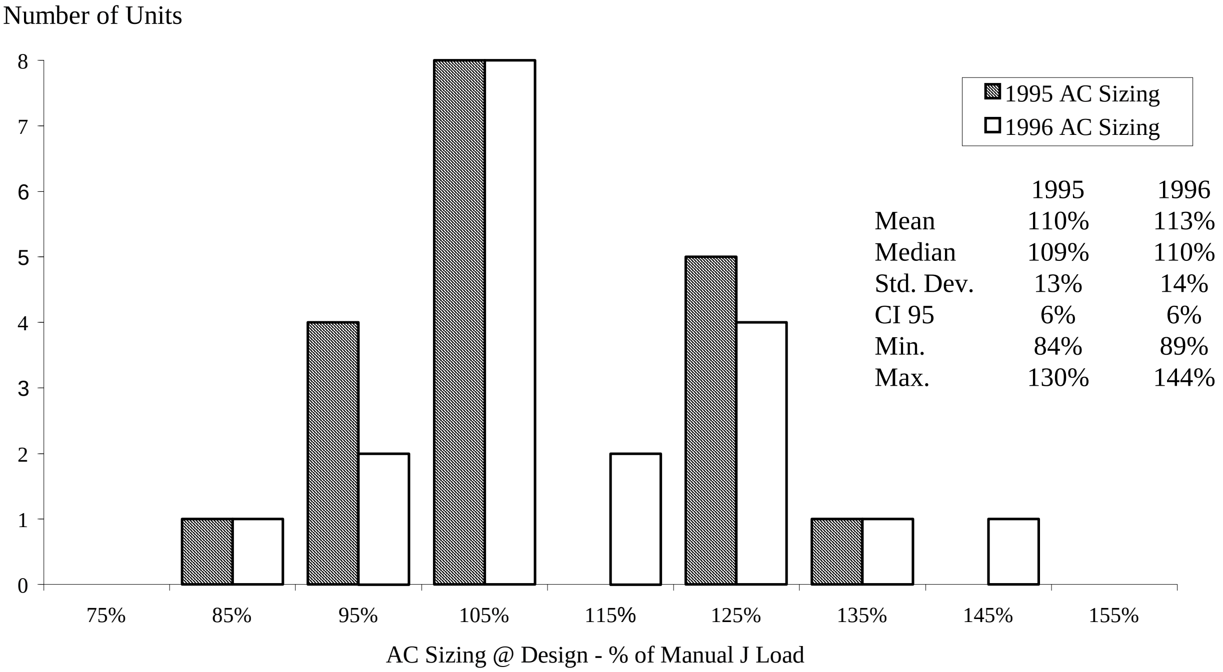
A significant number of the air conditioners did not show the expected capacity or efficiency when tested in the field. The two most common reasons for low performance are air flow and charge. The field capacity data are the source of a lingering concern that charge may still not be correct on some of these units. One unit visited by the author was brought up to expected performance by the addition of 12 oz. of refrigerant.

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 Manual J calculations performed on the houses in this study found cooling loads at design conditions ranging from 26,000 to 53,000 Btu/hr with an average of slightly over 38,000 Btu/hr. About half of the design load came from heat gains through windows and glass doors. The remainder of the gains were nearly evenly dispersed between infiltration, attic conduction, wall conduction, duct conduction, and internal gains.

Nevada Power personnel estimated the design loads for these homes using Manual J. They calculated the loads based on worst case orientation, .2 ACH infiltration, and used a RSM multiplier of 1.1[9].

The 97.5% design conditions for Las Vegas are 106°F dry bulb -- 65°F wet bulb outdoors (about 27 grains of moisture per pound of air) and 75°F dry bulb indoors. With the extremely low outdoor humidity it is no surprise that the latent load will be near zero. The capacity of the installed equipment at design conditions was estimated from manufacturers' data for a dry coil corrected to 106°F outside and 75°F inside. The average design capacity of the equipment installed per house in 1995 was 41,700 Btu/hr and increased to 42,700 Btu/hr in 1996. Four systems were installed with half ton larger units in 1996. This capacity represents an average oversizing (beyond Manual J) of ten percent in 1995 and thirteen percent in 1996. This percentage of oversizing is less than PEG has found in previous work.

Figure 2-6 compares the capacity adjusted to design conditions to Manual J design load.



	1995	1996
Mean	110%	113%
Median	109%	110%
Std. Dev.	13%	14%
CI 95	6%	6%
Min.	84%	89%
Max.	130%	144%

Figure 2-6
AC Sizing Compared to Manual J

The air conditioners installed on new homes in Las Vegas are closer to Manual J loads than those Proctor Engineering Group have studied elsewhere. Studies of homes in Las Vegas and in Phoenix have shown that the actual sensible load for many new homes is 67% of the Manual J[10] estimate (SOURCE: Blasnik et al, 1996). For this reason, air conditioners sized to 85% of Manual J is not a large concern. For peak reduction and energy savings it may be possible to reduce the size of air conditioners below Manual J estimates.

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[9] RSM multipliers are intended to adjust Manual J results to ARI conditions. It is common practice to use this multiplier for all cases, however, it is not necessary when the equipment is selected from the manufacturers performance data at the same conditions as were used for load calculations.

[10] Calculated without the RSM multiplier

SUMMARY OF FIELD FINDINGS

Table 2-3 summarizes the key results from the field investigation.

Table 2-3
Summary of Field Findings

	Shell		Ducts				Air Conditioner			
	Leakage		Operating Leakage to Outside (% of Flow)				Rated Capacity		Air Flow	
	1995 CFM50	1996 CFM50	1995 Supply	1995 Return	1996 Supply	1996 Return	1995 Btu/hr	1996 Btu/hr	1995 $\frac{\text{CFM}}{\text{Ton}}$	1996 $\frac{\text{CFM}}{\text{Ton}}$
Unit Mean			7.0%	6.7%	3.0%	1.3%	42171	43232	361	348
House Mean	1714	1795					51794	53111		
Std. Dev.	484	383	3.9%	3.9%	0.8%	0.6%	11401	11088	52	43
CI 95	217	172	1.5%	1.5%	0.3%	0.2%	4469	4346	21	17
Median	1580	1807	6.1%	5.0%	3.3%	1.2%	46000	46200	354	343
Minimum	1100	1149	2.3%	2.5%	1.2%	0.4%	22600	24000	279	283
Maximum	2803	2424	17.9%	18.4%	4.4%	2.5%	58500	58500	474	471

3

ANALYSIS

Homes in the 1996 cohort were built to higher standards for duct leakage, duct insulation, and initial charge installation (designed to reduce incidents of incorrect charge and charge contamination with air and moisture). The presence of lower duct leakage and higher levels of insulation were confirmed (see Field Results Section)

Each home in the 1996 cohort was matched to a home with the same floor plan by the same builder (the 1995 cohort).

To help estimate the annual energy usage and peak kW of the air conditioners, homes had temperature data recorded at five minute intervals in the supply and return plenums. Time of use recording electrical meters were installed on forty nine homes and the average watt draw over each five minute period was recorded and used in the analysis.

PEG employed a number of statistical approaches for analyzing the electricity usage data to develop impact estimates. While all of the analysis methods focused on estimating the differences in hourly electricity usage rates between the 1996 and 1995 houses, the methods varied in how they accounted for other factors influencing usage rates. Some of the key factors considered in the analyses included weather variables (outdoor temperature and enthalpy), estimated house cooling loads from Manual J calculations, time of day, and the site matching approach used in the project design. PEG anticipated that the analysis would be challenging due to a combination of the modest number of occupied houses with data, the large impact of behavior on cooling usage, and the high collinearity caused by the diurnal patterns of temperature, cooling loads, occupancy patterns, and other electrical end-uses. To minimize the risk of misleading results, PEG chose to pursue several alternative statistical modeling techniques in order to “triangulate” an estimate of program impacts. These techniques ranged from simple comparisons of mean usage levels to cross-section time series regression analysis and analysis of covariance models.

Proctor Engineering Group first prepared the data for analysis. Temperature, weather, and electric use were put into a consistent format, cleaned, combined, and synchronized.

The usage data were first cleaned to eliminate data from periods when the houses were unoccupied or zero usage was recorded for a whole hour. Next, anomalous usage patterns were identified from time series plots of usage rates. Three houses (1 from 1995 and 2 from 1996) had usage patterns which were much different from the other sites and may have been due to intermittent occupancy or data collection problems. These sites were flagged as potentially problematic for analysis purposes.

The analysis then began with the simplest comparison of the average usage levels for the two groups of houses. This comparison showed that the 1996 houses had an average usage rate of 2.42 kW while the 1995 houses averaged 3.22 kW[11]. The difference of 0.8 kW indicates a 25% reduction in usage. However, if the three sites with anomalous usage are removed, the savings drop to 0.53 kW (2.79 vs. 3.31) equal to 15.9% of usage. Still, this comparison does not account for the general construction characteristics of the houses or potential variations in the pattern of missing data (e.g., which days are represented in which groups).

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[11] whole house kW

PEG explored a number of techniques for controlling for these potential confounding factors. The most direct statistical approach involved an analysis of covariance model with Julian day and year built as categorical variables and the Manual J estimate of building load as a continuous covariate. This analysis yielded an estimate of 0.48 kW (14.5%) savings. However, this approach does not consider the impacts of weather on usage levels or savings and does not differentiate between cooling savings and potential differences in baseload end-uses.

PEG examined the relationship between usage levels and weather variables (outdoor temperature and enthalpy). Temperature proved to be a better predictor than enthalpy (not unexpected for the Las Vegas climate). Thermal mass effects make lagged temperature variables important to the model specification. PEG found that nearly all of the temperature effects could be captured by a single weighted lagged temperature variable based on the outdoor temperatures of the prior three hours (with greatest weight to the earliest temperature). This temperature variable was used for further model development.

PEG explored a number of regression model specifications which accounted for the temperature dependence of usage levels and savings. Because the temperature sensitivity of each house is expected to be related to the building shell cooling load (as estimated by Manual J), interaction variables of outdoor temperature (i.e., the 3 hour weighted lagged outdoor temperature) and Manual J load were examined. This interaction variable had considerably more explanatory power than the uninteracted temperature variable. An ordinary least squares model using this interacted variable with a slope offset for houses built in 1996 yielded an estimate of 9.1% electricity savings. This estimate is generally consistent with the 8.2% estimated savings from distribution efficiency differences predicted from a simplified duct model run using the same weather data and house specific duct insulation and leakage information.

PEG explored a variety of related model specifications involving temperatures and Manual J load estimates and found savings estimates varying from 6% to 12% in most cases. All of the models exhibited some problems with heteroscedasticity and model specification. The statistical uncertainty of these savings estimates was typically ±100% (at 90% confidence) when robust standard errors were calculated which properly reflected the panel data set structure.

In an effort to reduce the potential impact of confounding factors on savings estimates, PEG identified a subset of the data from houses in matched pairs where both houses had reasonable usage patterns (excluding the three sites with anomalous patterns and their matches) and data were available from both houses of the pair in the same hour. This screening created a data set of 18 sites (9 pairs) with a total of 4608 matching hours of data. This reduced data set provides for balance between the two groups in terms of Manual J load estimates (identical for each pair) and temperature/weather effects (only the same hours are used within each pair), reducing the potential for bias from these factors. A simple comparison of usage levels indicates that 1996 houses used 0.52 kW less on average (2.79 vs. 3.31) equal to 15.9% of usage (these figures coincidentally equal those previously cited for all data but the three anomalous houses). Because different house pairs had differing numbers of hours of data, PEG performed a weighted analysis to give each pair (not hour) equal weight. This analysis indicated average savings from the 9 matched pairs of 0.38 kW (vs. 2.89 vs. 3.27), equal to 11.6% of usage.

PEG further examined the matched pair data set using regression analysis. A cross-sectional time-series analysis of the matched sites using just the weighted lagged temperature variable (with a slope offset for 1996 houses) found savings ranging from 7.6% to 11.4% depending upon estimation approach. Savings ranged from 9.1% to 14.1% when using the Manual J interacted temperature variable. These models had about three times the estimated precision of the ordinary regression models fit to the larger data set, but still exhibited some problems.

PEG explored a number of additional model specification and estimation approaches and found savings estimates in the same general range. No single statistical model emerged as provided "the" answer, but the relatively consistent range of results using a number of data screens, model specifications, and estimation approaches leads PEG to conclude that average savings were likely to be in the range 6% to 14%. These figures are consistent with expectations given the differences in duct insulation and tightness measured in the houses.

DEMAND SAVINGS AND LOAD PROFILES

PEG examined the matched pair data set to estimate peak demand savings and load profiles. The average difference in demand for the 188 matched hours ending 5 PM was 0.36 kW (4.37 vs. 4.73) , equal to 7.7% of demand. The difference in demand between the groups is relatively small during this peak and grows rapidly over the following hours and reaches a maximum of 1.42 kW for the hour ending at 9 PM. Figure 3-1 shows the hourly load profile of the savings (difference in matched pair kW), averaged over all matched pair hours..

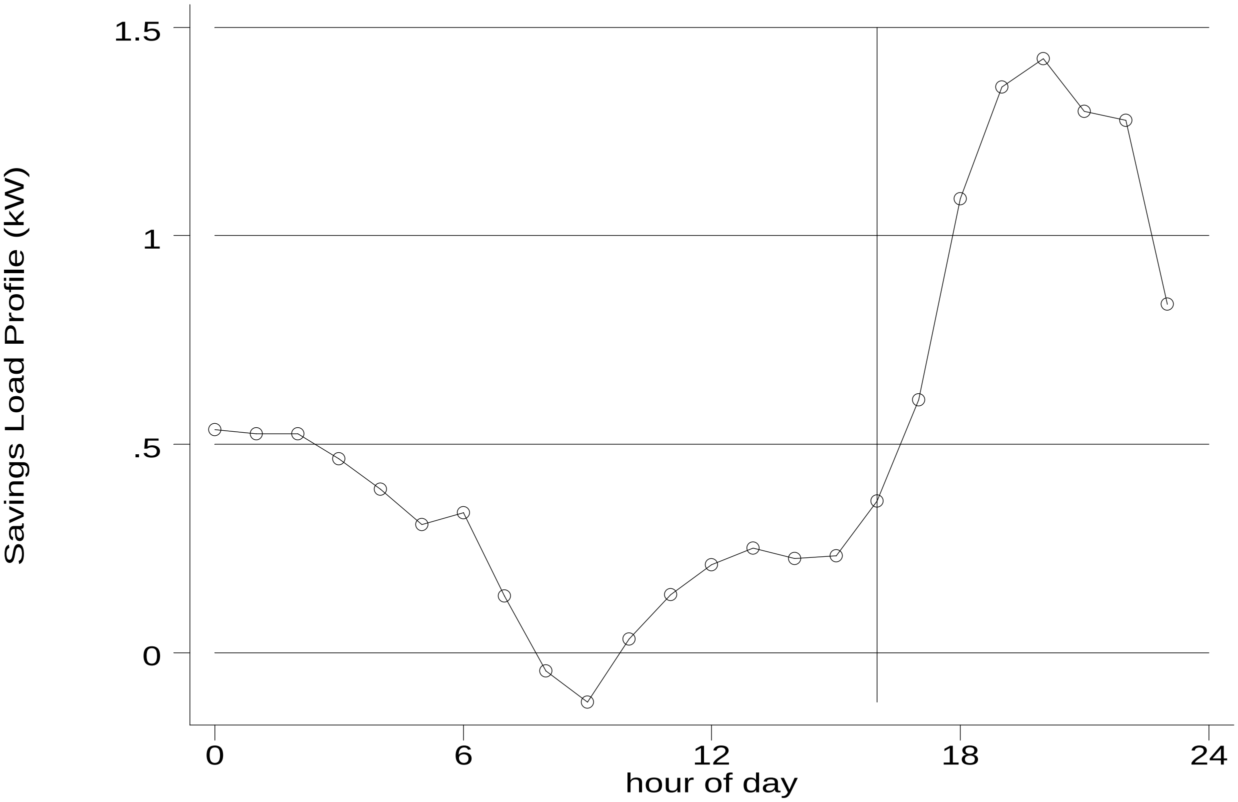
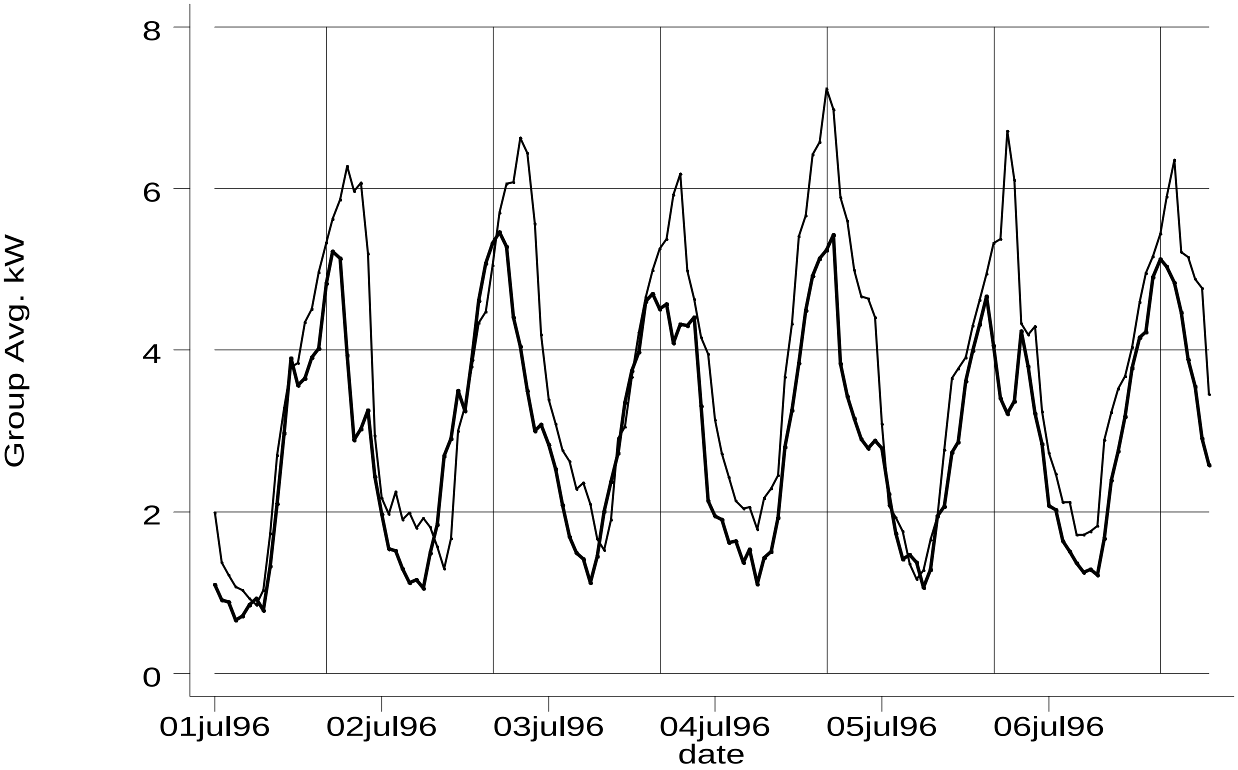


Figure 3-1
KW Reduction Matched Pairs

This relationship is similar to the relationship found in a 1991 study of peak reduction due to duct sealing in Fresno California (SOURCE: Proctor, 1993). In that study, the duct systems in existing homes were repaired to reduce duct leakage. The peak reduction developed from submetered data in that study showed peak reductions of 24% at 8 PM.

Perhaps the most direct evidence of energy and demand impacts is provided by a load profile of the average usage rates for each group. Figure 3-2 shows this load profile for the first week in July 1996. The newer houses clearly have considerably lower maximum demand levels, but peak impacts are more modest (the 4 to 5 PM hour of each day is indicated with a vertical line). The 1995 houses appear to peak later and more sharply than the 1996 houses.



Fine line = 1995 Cohort Bold Line = 1996 Cohort

Figure 3-2
House Load Profiles Week 1 July, 1996

4

RESULTS

OVERALL RESULTS

Triangulation of estimates from the metered data puts the 1996 savings at 6% to 14% (likely near the center of that range). These figures are consistent with expectations given the differences in duct insulation and tightness measured in the houses.

RESULTS ON MATCHED PAIRS

Five pairs of homes had comparable conditions and sufficient electrical data for a simple regression analysis of energy savings. This analysis is detailed in Appendix B. The results for these homes is contained in Table 4-1.

Table 4-1.
Results of Analysis of Matched Pairs

Matched Pair	House Number	System Number	Avg. kW during cycling	Savings Estimate
A	1	5	2.58	10%
	31	41	2.31	
	Little Change in Air Flow or Duct Leakage			
B	17	21	2.58	3%
	46	53	2.50	
	Little Change in Air Flow or Duct Leakage			
C	10	33	3.60	23%
	40	60	2.77	
	50% reduction in Duct Leakage and 5% increase in Air Flow			
D	8	18	2.45	21%
	38	62	1.94	
	40% reduction in Duct Leakage and 2% decrease in Air Flow			
E	11	35	2.26	9%
	41	63	2.05	
	50% reduction in Duct Leakage and 6% increase in Air Flow			

IDENTIFIED POTENTIAL

The 1995 program update reported the potential savings for the 1995 cohort based on the comprehensive simulation model. Table 4-2 details this information.

Table 4-2
Model Estimates 1995 Homes
Without Resizing

		Savings			
		Energy		Peak Demand (hour ending 5 PM)	
Program Design	Direct Cost	savings	%kWh ±95% CI	reduction	%kW ±95% CI
Baseline - Systems as Found	$0	3878		3.97	
A. Restrict Duct Lkg 3%	$95	241	6% ±1.3%	0.16	4%
B. Duct Lkg 3%, R-8 Duct Insul.	$235	407	10% ±1.8%	0.27	7%
C. Correct AC Charge & Flow	$68	986	25% ±9.9%	0.35	9%
D. Charge, Flow, Duct Lkg 3%	$163	1178	30% ±10.2%	0.50	13%
E. Charge, Flow, Duct 3%, R-8	$303	1293	33% ±10.2%	0.60	15%

COMPARISON - MEASURED RESULTS VERSUS POTENTIAL

The primary difference between homes in the 1995 and 1996 cohorts was the reduction in duct leakage. The projected savings for duct leakage reduction and duct insulation (R-8) was 10%. The triangulated savings estimates (6% to 14%) were comparable.

5

CONCLUSIONS AND RECOMMENDATIONS

Newly constructed homes in Nevada Power 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.

This study tested the energy consumption and peak reduction effects of a pilot program that reduced duct leakage, increased duct insulation, and changed AC installation practice on new residential construction in Las Vegas.

The study consisted of two cohorts, the 1995 cohort built to standard practice and the 1996 cohort built to improved standards. The duct systems in the 1995 cohort were factory built. The 1996 cohort systems were built on site to specific proscriptive and performance criteria. The program was successful in substantially reducing duct leakage and producing a moderate increase in duct insulation. The air conditioner installation practice changes were less than totally effective. The air flow across the indoor coil did not increase to the desired levels, and the on site efficiency tests often showed efficiencies below the expected values for the test conditions.

CONCLUSIONS

- Detailed analysis of initial data shows that energy savings from duct sealing and insulation are within the range projected in the 1995 report;
- Additional work is needed to obtain proper air flow across the indoor coils.
- Additional work is needed to determine the cause of low field measured efficiency in some of these units.

There are 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

Any efforts to transform the new construction market should address the following in a resource effective manner:

1) Contractor level quality assurance should be implemented. 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) 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.

If greater certainty concerning energy consumption and peak impacts is desired, the following additional research would be indicated:

- The cohorts in this study be followed through a complete summer with the homes occupied, any problems with data acquisition equipment in these homes solved, and customer satisfaction measured for both cohorts.
- A third cohort be built with ducts designed for proper air flow, equipment resized to match the reduced load, and independent verification of proper charging.
- An alternative to a third cohort would be to resolve of any remaining AC efficiency problems in the 1996 cohort that are evident in field efficiency testing.

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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 and retrofit applications. These studies were completed by Blasnik et al. (1995a), Blasnik et al. (1995b), Blasnik et al. (1996), Cummings et al., Hammerlund et al., Jacobson et al., Jump and Modera, Neal, Proctor et al. (1990) and Proctor (1991). Six of these studies included field monitoring of energy usage (Blasnik et al. (1996), Cummings et al., Jacobson et al., Jump and Modera, Proctor et al. (1990) and Proctor (1991). These studies examined impacts of improvements to the air conditioners and/or duct systems on new and/or existing homes.

BLASNIK ET AL. (1995A)

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. (1995B)

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[12]. Each residence was tested for problems in three major areas; duct leakage to the exterior, air flow through the indoor coil and refrigerant charge.

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.

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

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}[13]	33	25
Low Air Flow	24	19[14]
Incorrect Charge[15]	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.

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.

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

[14] 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.

[15] 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.

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.

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APPENDIX B: ALTERNATIVE ANALYSIS

As an additional check on the validity of the savings estimates derived from metered data, an alternative evaluation was performed by a different analyst. In that analysis, five pairs of homes had sufficient electrical data for a simple regression analysis of energy savings..

The results for these homes are contained in Table B-1.

Table B-1.
Results of Analysis of Matched Pairs

Matched Pair	House Number	System Number	Avg. kW during cycling	Savings Estimate
A	1	5	2.58	10%
	31	41	2.31	
	Little Change in Air Flow or Duct Leakage			
B	17	21	2.58	3%
	46	53	2.50	
	Little Change in Air Flow or Duct Leakage			
C	10	33	3.60	23%
	40	60	2.77	
	50% reduction in Duct Leakage and 5% increase in Air Flow			
D	8	18	2.45	21%
	38	62	1.94	
	40% reduction in Duct Leakage and 2% decrease in Air Flow			
E	11	35	2.26	9%
	41	63	2.05	
	50% reduction in Duct Leakage and 6% increase in Air Flow			

APPENDIX C: CHANGES IN DUCT LEAKAGE TEST PROCEDURE

Duct leakage was tested using the Duct Blaster™ and Blower Door test procedure in EPRI TR-105309 (1994), and using the Flow Hood and Blower Door procedure in 1995 and 1996. The resulant 1994 and 1995 measurements are shown in Table C-1.

Table C-1
Duct Leakage Test Method Comparison (1994 vs. 1995)
(leakage as percent of air flow across the coil)

	Mean	Std. Dev.	Min	Max
1994 Duct Supply Leakage	9%	5%	2%	24%
1995 Duct Supply Leakage	6%	3%	1%	18%
1994 Duct Return Leakage	9%	7%	2%	39%
1995 Duct Return Leakage	3%	2%	1%	9%

The changes in test procedure reduced the estimated leakage fractions by 1/3 (note that even the maximum leakage measurements in 1995 [18% and 9%] were smaller than the 1994 measurements [24% and 39%]). It is doubtful that the population of builders reduced their duct leakage by that much in one year without intervention.

The Duct Blaster™ and Blower Door procedure is regarded as the superior procedure because it better controls the test pressures in the ducts. The lower leakage estimates from the 1995 homes reduce the estimated total duct loss and the estimated savings due to distribution efficiency improvements. Through interactions, these lower estimates of distribution loss are also responsible for the lower savings estimates from proper air conditioner installation.

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APPENDIX D: MODEL UPDATES AND RESULTS FROM PRIOR YEARS

DIFFERENCES ASSOCIATED WITH CHANGES IN THE COMPREHENSIVE MODEL

Since EPRI Report TR-105309, substantial improvements have been made in the comprehensive model. These changes include:

- Hourly simulation in place of bin analysis
- Upgrade of attic temperature model based on monitored attic temperature data
- Upgrade of return grille temperature based on monitored return grille data
- Upgrade of charge and air flow effect model based on laboratory testing of air conditioners at high temperatures (work at Texas A&M University)

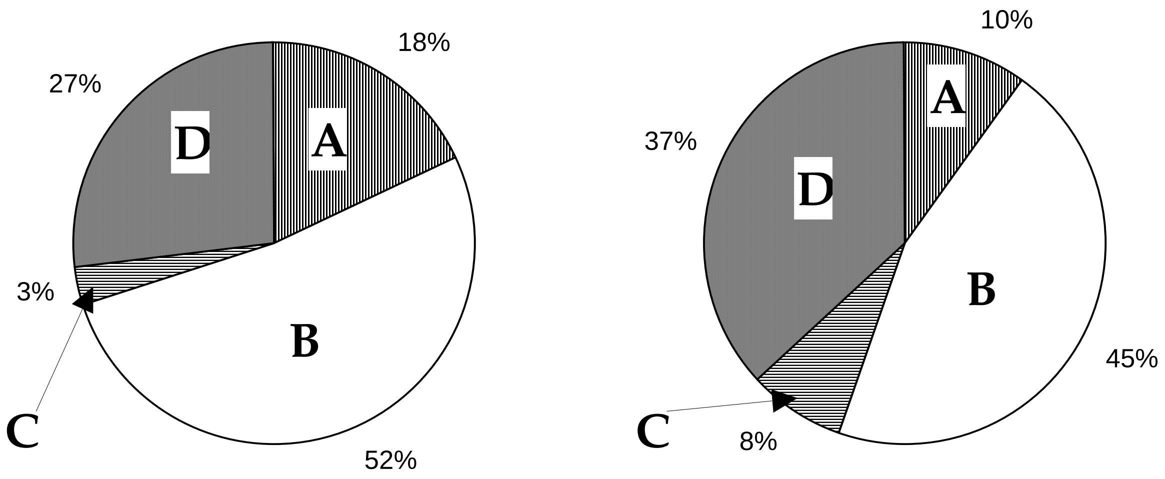
These changes have reduced the estimated savings potential from duct improvements and increased the estimated savings potential from improvements in air conditioner installation practices.

CHANGES IN PEAK DEMAND MODEL

Analysis of peak demand impact requires characterizing the effect of occupant behavior patterns on actual cooling demand. PEG has developed Model P which utilizes air conditioner load data to characterize the interactions between occupant behavior patterns/cooling load and effective capacity. Four groups are determined:

Group A	no air conditioning use during peak
Group B	air conditioners cycling on and off due to thermostatic control
Group C	air conditioners running continuously, but some achievable reduction in load or increase in effective capacity would result in cycling
Group D	air conditioners running continuously due to behavior or other factor beyond load and effective capacity

PEG used the disaggregated summer 1995 load data from homes built in 1994 (EPRI TR-105309 homes) to estimate the proportion of homes in each group. EPRI TR-105309 estimates of Model P groups were based on the then available data (load data from customers in a load management program). The 1995 data are a significant improvement. The initial and updated proportion of households in each category are shown in Figure D-1.



Customer Mix - EPRI TR-105309 **Customer Mix - Update**

Figure D-1
Model P Classes from Initial and 1994 New Construction Samples

COMPREHENSIVE MODEL RESULTS ON 1994 SITES

Proctor Engineering Group applied version 2.3 of the comprehensive duct and air conditioner model to the data collected on the 1994 and 1995 systems. The results for the homes built in 1994 are shown in Tables D-1 and D-2.

Table D-1
Model Estimates 1994 Homes
Without Resizing

		Savings			
		Energy		Peak Demand	
Program Design	Direct Cost	kWh	% ±95% CI	kW	%
Baseline - Systems as Found	$0	3017		3.56	
A. Restrict Duct Lkg to 3% of Coil Flow	$95	290	10% ±2.4%	0.22	6%
B. Duct Lkg 3%, R-8 Duct Insul.	$235	421	14% ±3.1%	0.33	9%
C. Correct AC Charge & Flow	$68	770	26% ±6.2%	0.38	11%
D. Charge, Flow, Duct Lkg 3%	$163	1020	34% ±7.2%	0.58	16%
E. Charge, Flow, Duct 3%, R-8	$303	1109	37% ±7.5%	0.66	18%
F. EER 2 higher, Charge, Flow	$418	1356	45% ±7.2%	1.06	30%
G. All of the Above	$653	1631	54% ±8.4%	1.26	36%

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Changes in Peak Demand Model

Table D-2
Model Estimates 1994 Homes
Units Resized to 115% of Manual J

		Savings			
		Energy		Peak Demand	
Program Design	Direct Cost	kWh	% ±95% CI	kW	%
Baseline - Systems as Found	$0	3017		3.56	
A. Restrict Duct Lkg to 3%	$95	343	11% ±2.7%	0.51	14%
B. Duct Lkg 3%, R-8 Duct Insul.	$235	491	16% ±3.4%	0.63	18%
C. Correct AC Charge & Flow	$68	821	27% ±6.3%	0.69	19%
D. Charge, Flow, Duct Lkg 3%	$163	1060	35% ±7.2%	0.88	25%
E. Charge, Flow, Duct 3%, R-8	$303	1159	38% ±7.5%	0.96	27%
F. EER 2 higher, Charge, Flow	$418	1401	46% ±7.2%	1.31	37%
G. All of the Above	$653	1674	55% ±8.4%	1.53	43%

Note on Tables D-1 and D-2:

1) Unit of evaluation is AC system. Average number of AC systems per house in 1994 sample is 1.33 (selection of single vs. multiple AC homes was not random).

2) Correcting charge and correcting air flow both improve the efficiency and capacity of the air conditioner. These changes are highly interactive with the duct efficiency. Taken alone, correcting charge produces twice as much savings as correcting air flow.

COMPREHENSIVE MODEL RESULTS ON 1995 SITES

Proctor Engineering Group applied version 2.3 of the comprehensive duct and air conditioner model to the data collected on the 1995 systems. The results are shown in Tables D-3 and D-4.

Table D-3
Model Estimates 1995 Homes
Without Resizing

		Savings			
Program Design	Direct Cost	Energy		Peak Demand	
		savings	%kWh ±95% CI	%kW	
Baseline - Systems as Found	$0	3878		3.97	
A. Restrict Duct Lkg 3%	$95	241	6% ±1.3%	0.16	4%
B. Duct Lkg 3%, R-8 Duct Insul.	$235	407	10% ±1.8%	0.27	7%
C. Correct AC Charge & Flow	$68	986	25% ±9.9%	0.35	9%
D. Charge, Flow, Duct Lkg 3%	$163	1178	30% ±10.2%	0.50	13%
E. Charge, Flow, Duct 3%, R-8	$303	1293	33% ±10.2%	0.60	15%
F. EER 2 higher, Charge, Flow	$418	1685	43% ±10.0%	1.09	28%
G. All of the Above	$653	1936	50% ±10.3%	1.30	33%

Table D-4
Model Estimates 1995 Homes
Units Resized to 115% of Manual J

		Savings			
		Energy		Peak Demand	
Program Design	Direct Cost	savings	%kWh ±95% CI	kW	%kW
Baseline - Systems as Found	$0	3878		3.97	
A. Restrict Duct Lkg to 3%	$95	286	7% ±1.4%	0.24	6%
B. Duct Lkg 3%, R-8 Duct Insul.	$235	454	12% ±1.9%	0.36	9%
C. Correct AC Charge & Flow	$68	1020	26% ±9.9%	0.45	11%
D. Charge, Flow, Duct Lkg 3%	$163	1209	31% ±10.1%	0.60	15%
E. Charge, Flow, Duct 3%, R-8	$303	1326	34% ±10.3%	0.69	18%
F. EER 2 higher, Charge, Flow	$418	1710	44% ±9.9%	1.17	30%
G. All of the Above	$653	1960	51% ±10.3%	1.38	35%

Notes for Tables D-3 and D-4:

1) Unit of evaluation is AC system.