INVESTIGATION OF AIR DISTRIBUTION SYSTEM DEFICIENCIES AND REPAIR BENEFITS IN PHOENIX, ARIZONA

James O. Kolb **Mark P. Ternes**

ABSTRACT

This paper presents information on the extent of air-distribution-system leakage problems found in 96 single-family residential buildings in the service territories of two electric utilities in Phoenix, Ariz., and the air-conditioner electricity savings and electricity demand reductions achieved from system repairs made in a 51-house subsample. Air distribution systems were predominantly located outside the building envelope in attics, so most duct leakage (if present) was to the outdoors.

Duct leakage averaged 249 CFM_{50} for the 96 houses, and repairs reduced duct leakage on average by 88 CFM_{50}, or an average of 30%. A common leakage site for houses with rooftop air-conditioning units was the seal between the unit and the sheet-metal transition piece that connects the main supply and return trunks to the unit.

The average annual air-conditioning energy savings due to duct repairs was 782 kWh, 16% of the 4,890 kWh average annual pre-repair energy use. The simple payback period for the repair work was 2.7 years based on an installation cost of \$140 per house (\$10 for materials and \$130 for labor), and assuming \$70 for travel costs and an electricity cost of \$0.10/kWh. Diversified demand savings to the utility were about 0.23 kW, or 5% to 7% of pre-repair demand. These demand savings can have a value of \$115 to the utility, assuming \$500/kW for demand reduction capacity.

INTRODUCTION

Previous research clearly has established that inefficiencies are associated with residential air distribution systems due to leaks to the outdoors in supply and return ducts, conduction losses, and their interactive effect on building ventilation. Parker et al. (1993) predict that air conditioner performance can be reduced 30% due to duct inefficiencies. Modera (1989) predicts that duct inefficiencies can contribute 1 to 2 kW or more to peak utility demands, although peak savings may not occur for properly sized or undersized air conditioners (Treidler and Modera 1994).

Duct leakage and reductions following repair have been measured in many samples of houses, especially houses located in Florida (Cummings and Tooley 1989) and California (Modera 1993; Jacobson and Proctor 1992; Kinert et al. 1992). Measured data on air-conditioning energy savings and especially demand reductions due to duct repairs are more limited (Vigil 1993; Proctor and Pernik 1992; Cummings et al. 1990). A workshop on residential thermal distribution systems (Nagda 1994) identified the need for reliable field data on energy savings and peak demand reduction as one of 10 priority research needs to improve the state of the art in thermal distribution systems.

A field test of 96 houses selected from the service territories of two utilities in Phoenix, Ariz., was performed to address the following issues: (1) the extent to which duct problems exist in residences on a community-wide basis, (2) the degree to which problems found in typical residences can be repaired, (3) the cooling-season energy savings and demand reductions that coincide with the level of possible repairs, and (4) the economics of performing this efficiency measure from a consumer's and a utility's perspective.

PROJECT DESCRIPTION

The field test design was based on a 96-house sample of single-family, detached houses located in the service territories of the two participating utilities. Between March and June 1993, 96 houses were recruited for the study and instrumented. Houses were recruited on the basis of the following criteria: (1) owner occupied; (2) single, central air-conditioning system—no evaporative or window units; and (3) no plans to move, modify the house envelope or cooling equipment, or significantly change house occupancy.

Duct diagnostics and repairs were performed on all 96 houses. Forty-six houses designated as group 1 received duct diagnostics and repairs during a five-week period in the middle of the 1993 summer, and 50 houses

James O. Kolb and **Mark P. Ternes** are with the Oak Ridge National Laboratory in Oak Ridge, Tenn.

designated as group 2 received duct diagnostics and repairs between October 1993 and March 1994.

Submetered air-conditioning electricity consumption and indoor temperature were monitored in the 96 houses over the 1993 and 1994 summers. Total house and air-conditioner electricity consumption were monitored on a 15-minute basis and indoor temperatures were monitored on a two-hour basis.

Results in this paper are presented for all 96 houses that had duct diagnostics and repairs performed during the field test (groups 1 and 2) and a subgroup of 51 houses (group 3A) composed of those houses that had statistically valid energy-use models from which energy savings and demand reductions could be estimated.

FIELD WORK DESCRIPTION

A local weatherization organization was trained in duct diagnostics and duct repair procedures to perform the field work. The first step was to calculate the duct leakage by the blower door "subtraction" method. A multipoint blower door test protocol that minimized measurement errors was followed to determine the initial ("ducts open") house leakage at 50 Pascals (Pa) of depressurization—or CFM_{50}. A second blower door test was performed with all duct registers sealed from the interior of the house to determine a "ducts-sealed" leakage at 50 Pa of depressurization. Duct leakage was calculated by taking the difference between measurements.

Individual duct pressures were then measured with the house depressurized to 50 Pa to indicate locations of the highest leakage, and the dominant duct leakage—supply or return—was identified by measuring the pressure difference between the inside and outside of the house with the air-conditioning fan on. Repairs at leaking joints and penetrations primarily were made using mastic and fiberglass tape, with the goal of reducing duct leakage to 150 CFM_{50}. Duct leaks were repaired starting with the largest and most significant supply or return leaks, as indicated by the duct pressure tests and also by the visual examination of the duct system using a "smoke" source.

A final "ducts open" measurement of house leakage was made after duct repairs were completed to determine the reduction in duct leakage. Additional field information obtained during the repair visits included material costs, time to perform the repairs, and photographs of problems.

SAMPLE GROUP CHARACTERISTICS

The predominant type of house in the field test was a one-floor, nonbasement design—only 7% of houses in groups 1 and 2 and 10% of group 3A houses had more than one floor. The average conditioned area of houses in groups 1 and 2 was 1,614 ft^2, with a maximum of 2,800 ft^2 and a minimum of 792 ft^2. The average conditioned area of the group 3A houses was 1,663 ft^2, only 3% higher than for groups 1 and 2. Houses in groups 1 and 2 had an average age of 15 years, with construction occurring between 1950 and 1990 in all cases. The average house age for group 3A was somewhat lower, at 13 years, but the period of construction remained the same.

A majority (73%) of the air conditioners in group 1 and 2 houses were rooftop-mounted units. The average age was 12 years for rooftop-mounted units and 9 years for nonrooftop units. Heat pumps were the most prevalent type of air-conditioning unit (49%), and gas-package units were the least prevalent type of unit (9%). Air conditioner characteristics of group 3A houses were similar to those of group 1 and 2 houses.

Air distribution systems were predominantly located outside the building envelope in attics. Therefore, most duct leakage (if present) was to the outdoors. Sheet metal was the dominant material used to construct supply and return ducts in both groups 1 and 2 and group 3A houses. Flexible ducts were the only other material used for supply and return ducts, mostly for connections between rooftop-mounted air conditioners and trunks in attics. The use of house framing and construction (such as interior closets) for ducts or plenums was not a prevalent practice in the houses studied.

DUCT LEAKAGE MEASUREMENTS

The average duct leakage for the 96 houses in groups 1 and 2 was 249 CFM_{50} (Table 1). Two-thirds of the houses had duct leakage between 100 CFM_{50} and 300 CFM_{50} (Figure 1). Only 7% had relatively tight systems (< 100 CFM_{50}) and only 11% had extremely leaky systems (> 400 CFM_{50}). Total house leakage averaged 1,717 CFM_{50}, of which 15% was attributed to duct leakage.

The average duct leakage reduction in the 96 houses due to repairs performed under this field test was 88 CFM_{50}, or 35% of the pre-repair rate. An average percent reduction of 30%, as indicated in Table 1, is calculated by averaging the percentage reductions achieved in individual houses. Results for group 3A houses were similar to those for the overall sample, as demonstrated in Table 1.

Duct leakage reductions were limited to < 50 CFM_{50} in half the houses, as shown in Figure 2. Sixteen of these houses had no leakage reduction—little or no repair

TABLE 1 **Average Duct Leakage Results**

	Groups 1 & 2	Group 3A
Number of houses in group	96	51
Number of houses with no leakage reduction	16	8
Average duct leakage (CFM_{50})	249	244
Average leakage reduction (CFM_{50})	88	100
Average percentage leakage reduction[a]	30%	34%

[a]Calculated by averaging the percentage reductions achieved in individual houses.

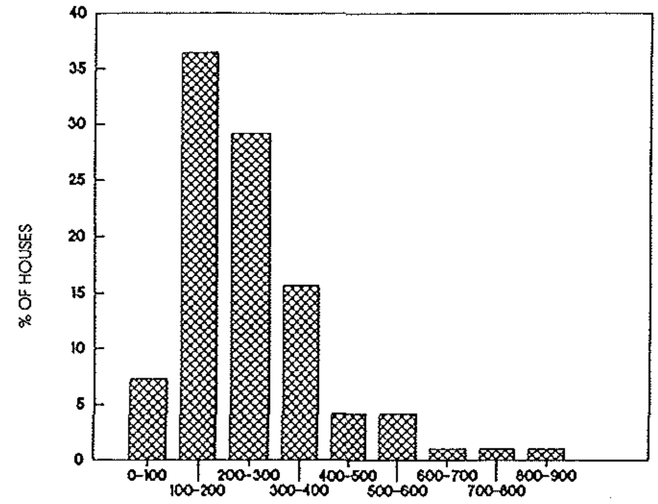

Figure 1 Distribution of duct leakage for group 1 & 2 houses.

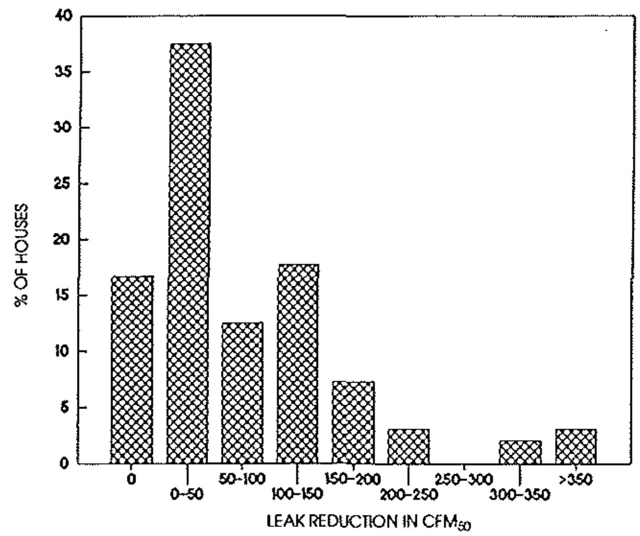

Figure 2 Distribution of duct leakage reduction for group 1 & 2 houses.

work was performed in these houses because they had low duct leakage (< 100 CFM_{50}) and hence no repairable deficiencies, or they had leaks in ducts located in cathedral ceilings and other inaccessible locations that could not be repaired. The average duct leakage reduction in houses in which repairs actually were performed was 106 CFM_{50}, with an average percent reduction of 36%.

Figure 3 shows that small reductions (< 75 CFM_{50}) generally were achieved in houses with initial duct leakage of less than 150 CFM_{50}, with greater reductions obtained in houses with leakier systems. Results varied widely though. One factor contributing to the observed scatter was the presence of leaky ducts in cathedral ceilings and other inaccessible locations that were difficult, if not impossible, to repair. Houses with such systems are identified separately in Figure 3, showing that reduc-

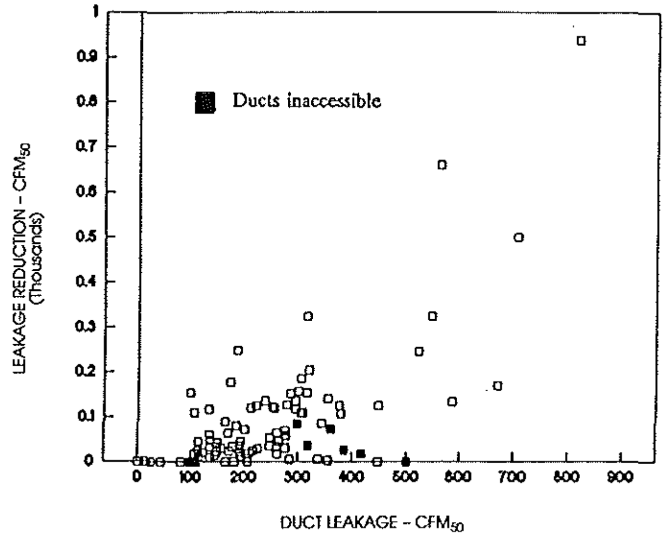

Figure 3 Variation in duct leakage reduction with initial duct leakage for group 1 & 2 houses. Leakage reduction exceeds initial leakage in a few houses because differences in large numbers are used to calculate leakage reduction with the "subtraction" method, and enthusiastic field personnel sealed some obvious house leakage sites in a few houses.

tions for such houses were less than those for the sample as a whole.

A common leakage site repaired in the field test houses was the seal between the rooftop-mounted air conditioner and the metal transition piece that connects the main supply and return trunks to the unit (Figure 4). This seal was repaired in 48 of the 70 houses with rooftop-mounted units. This seal develops a leak when the air conditioner moves away from the metal transition piece because the air conditioner is not rigidly attached to roof mounts. Several screws installed in the angle bar mounting bracket can readily prevent this movement. Failure of this seal can be a significant source of duct leakage because the fan-induced pressure differences are greatest at the transition piece than at any other duct location and because leaks at the rooftop unit seal can both lose conditioned supply air and draw hot ambient air into the return. This seal routinely became one of the first duct locations to inspect and repair because of the frequency of problems. Sealing this leakage site first also made subsequent diagnostic measurements more meaningful because a significant source of supply and return leakage was eliminated.

Air leakage reductions from repairing this seal can be significant. An average reduction of 68 CFM_{50} was measured in 17 houses in which this leakage site was the only duct repair performed (see Table 3).[1] In houses with rooftop-mounted air conditioners and that received other return-side duct repairs, greater duct leakage reductions

[1]The houses in group 3A that received only rooftop seal repairs had an average leakage reduction of 35 CFM_{50}.

Figure 4 *Leak at the rooftop-mounted air conditioner seal before repair.*

TABLE 2 Summary of Duct Leakage Measurements for Group 1 & 2 Houses

	Number of Houses	Average Duct Leakage (CFM_{50})	Average Duct Leakage Reduction (CFM_{50})	Average Duct Leakage Reduction[a] (%)
Rooftop unit sealed	48	254	87	36%
Rooftop unit not sealed	22	240	75	21%
No rooftop unit	26	248	101	27%

[a]Calculated by averaging the percent reductions achieved in individual houses.

TABLE 3 Summary of Duct Leakage Measurements for Various Types of Repairs

	Number of Houses[a]	Average Duct Leakage (CFM_{50})	Average Duct Leakage Reduction (CFM_{50})	Average Duct Leakage Reduction[b] (%)
		Supply Repairs Only		
Rooftop unit sealed	6	366	166	53%
Rooftop unit not sealed	2	360	345	68%
No rooftop unit	3	187	92	52%
		Return Repairs Only		
Rooftop unit sealed	22	245	79	33%
Rooftop unit not sealed	8	236	57	22%
No rooftop unit	10	263	141	32%
		Only Rooftop Seal Repairs		
Rooftop unit sealed	17	237	68	29%
		Supply and Return Repairs		
Rooftop unit sealed	3	193	91	69%
Rooftop unit not sealed	7	331	73	22%
No rooftop unit	5	363	165	38%
		No Repairs		
Rooftop unit not sealed	5	70	0	0%
No rooftop unit	7	160	0	0%

[a]Data for one house without a rooftop unit is inadvertently not included in the table.
[b]Calculated by averaging the percent reductions achieved in individual houses.

were measured in the houses that had the transition piece seal repaired than those houses that did not, although differences were only on the order of 20 CFM_{50} (79 CFM_{50} compared to 57 CFM_{50}). A similar comparison of houses receiving supply-side repairs or both supply- and return-side repairs can be misleading because of the small sample sizes involved.

Average duct leakages and reductions were nearly identical for houses with rooftop units (70 houses) compared to houses without rooftop units (26 houses), as shown in Table 2. Table 3 shows that repairs were performed more often to return ducts than supply ducts. No clear, statistically valid pattern as to the leakage reductions that could be expected from return and/or supply repairs emerges from this table, however. For example, in houses with rooftop-mounted air conditioners, greater reductions were obtained in houses receiving just supply repairs than in houses receiving both supply and return repairs.

There was no indication that duct leakage increased with house age (Table 4). In fact, the five oldest houses (built in the 1950s) had the lowest average duct leakage of 99 CFM_{50}. This may be attributed to the fact that the oldest homes had predominantly sheet-metal ducts rather than ductboard or flexible ducts.

DISCUSSION OF DUCT LEAKAGE RESULTS

Duct leakage is lower on average for the sample of Phoenix-area houses than has been reported in other studies of duct leakage. Kinert et al. (1992) reported an average duct leakage of 374 CFM_{50} in a large sample of California homes, and Davis and Robinson (1993) reported an average duct leakage of 621 CFM_{50} in a study of 18 Arkansas homes.

TABLE 4 **Average Duct Leakage and Leakage Reduction Results for House Ages in Groups 1 & 2**

	House Age - Years				
	1 - 4	5 - 14	15 - 24	25 - 34	35 - 44
Number of houses[a]	7	37	35	9	5
Average duct leakage (CFM_{50})	209	303	252	224	99
Average duct leakage reduction (CFM_{50})	88	134	65	76	69

[a]The ages of three houses were not known.

The average duct leakage of 249 CFM_{50} for the 96 group 1 and 2 houses is much less than these reported values but is more consistent with the 285 CFM_{50} reported by Vigil (1993) for 82 North Carolina homes. In fact, duct leakage exceeded 400 CFM_{50} in only 11% of the 96 houses. Proctor and Pernik (1992) reported that three studies showed 80% to 98% of 226 homes in California had duct leakage greater than 150 CFM_{50}. In the Phoenix field test, 74% of the houses had duct leakage greater than 150 CFM_{50}. The average percentage leakage reduction of 30% for the group 1 and 2 houses also is significantly lower than the 60% to 70% range reported by Cummings et al. (1990) as being typical for duct repairs in Florida and the 58% to 74% reported by Vigil (1993), Davis and Robinson (1993), and Kinert et al. (1992). However, the average duct leakage after repair of 161 CFM_{50} in the Phoenix test houses compares favorably with the range of 118 to 161 CFM_{50} reported in these other studies.

One reason for these observations is that a high percentage of the field test houses had sheet-metal ductwork, such that duct leaks generally were not large leaks caused by failures at joints in ductwork (the exception was leaks at joints between metal transition pieces of rooftop units and connecting flexible ducts). Houses used in other duct leakage and repair studies often had air distribution systems made of ductboard and flexible duct, which can be leaky and less durable over time than sheet-metal ducts. The observation that the oldest field test houses, with predominantly sheet-metal ducts, had lower-than-average duct leakage supports this hypothesis.

An additional explanation is the absence in the Phoenix test homes of return plenums and other duct systems built from drywall and the house structure itself. These systems can have leaky characteristics and have been found to be significant sources of duct problems in other studies.

It is possible that the ability of the field technicians to diagnose and make repairs was not at the highest level of expertise because it was a new process for them to apply, and there was no local source of quality assurance to evaluate their work as it progressed. However, with the exception of houses with inaccessible ducts and houses with low (< 150 CFM_{50}) duct leakage, leakage reductions were significantly greater than 30%, especially for houses with duct leakage greater than 300 CFM_{50}.

AIR-CONDITIONING ENERGY SAVINGS

Analysis of energy savings and electric demand reductions from duct repairs was based on the performance of houses that had stable occupancy and house envelope and cooling equipment conditions. A 1993 pre-repair period of June 1 to July 15 and a 1994 post-repair period of May 26 to July 15 were used for all the houses because these pre- and post-repair periods had similar ambient temperatures. The humidity conditions were slightly different. The post-repair period occurred during the "monsoon" season, which could make the calculated savings less than what actually occurred.

No control group is available with this selection of pre- and post-repair periods to normalize effects of other weather variables and other factors. Analysis continues using different dates that allow group 2 to serve as the control for group 1 in the summer of 1993 and vice versa in 1994, as originally planned in the experimental design.

Analysis Method

Energy use and savings analyses were performed with daily average data (15-minute electricity data and 2-hour outdoor-indoor temperature difference data aggregated to daily totals or averages). These data were then used to develop regression equations for pre- and post-repair electricity use.

The primary model used for the regression analysis assumed that the daily electricity use of the central air conditioner was linearly related to the daily average temperature difference between the inside and outside of the house:

$$\text{kWh} = a + (b \cdot \Delta T) \tag{1}$$

where

kWh = daily electricity use of the air conditioner,
ΔT = daily average outdoor minus indoor temperature,
a = intercept coefficient (determined by regression), and
b = slope coefficient (determined by regression).

This model has been successfully used by one of the authors and other researchers to analyze the energy savings of duct repairs and other efficiency measures affecting air-conditioning energy use (Ternes and Wilkes 1993; Proctor and Pernick 1992; Cummings et al. 1990). Parker (1994) has successfully used a multiple linear regression model that includes a solar irradiance term, but previous use of such a model by one of the authors often resulted in the estimation of negative coefficients for the solar term, which are physically confounding (implying that sunnier days require less air-conditioning electricity use).

Linear regression techniques were used to estimate the parameters *a* and *b* for the pre- and post-repair periods for each house using the pre- and post-repair daily data. The daily average temperature difference was the sum of hourly outdoor-indoor temperature differences divided by 24.

Pre- and post-repair normalized air-conditioning electricity uses for each house were calculated using the pre- and post-repair regression values for *a* and *b* for each house, a standard indoor temperature of 78°F, and typical meteorological year (TMY) outdoor temperatures for Phoenix (used to represent historical weather conditions).

Daily electricity-use values were estimated using average daily temperature differences (calculated using the standard indoor temperature and TMY outdoor temperatures for the summer) and the values of *a* and *b* for each house. Only temperature differences between April 26 and October 15 were used to eliminate periods during the remainder of the year when positive temperature differences occurred but no air conditioning was required. The daily electricity uses were summed for the period of analysis to obtain an estimate of the normalized annual electricity use for each house. The post-repair annual electricity use was subtracted from the pre-repair annual electricity use to obtain the estimated normalized annual electricity savings.

Because some houses had inadequate days of indoor temperature data, a second model was used in which the daily electricity use of the central air conditioner was assumed to be linearly related to the daily average outdoor temperature. Results from this "outdoor temperature" model were used only when there were no results available for the "temperature difference" model. The

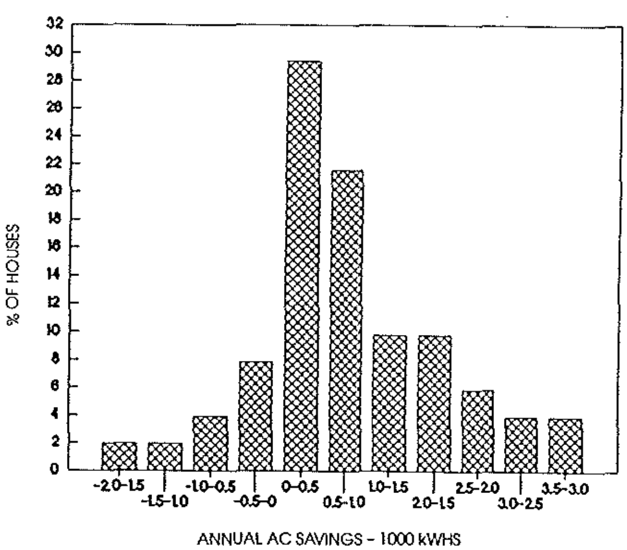

Figure 5 *Distribution of air conditioning energy savings for group 3A houses.*

temperature difference model was assumed to be the more reliable basis for estimating normalized air-conditioning electricity energy use.

Valid energy savings and demand reductions could not be estimated for 13 of the 96 houses because of attrition from moves, air-conditioning equipment changes, or changes in house occupancy, house characteristics, or conditioned space. Regression models were determined to be not statistically valid for an additional 32 houses because 20 or more days of data were not available for both the pre- and post-repair periods, or the coefficient of determination of the regression (R^2) was less than 0.7. The selection of an R^2 cutoff of 0.7 was arbitrary but consistent with that used by researchers in the analysis of retrofit savings using billing data (Fels and Reynolds 1990).

Air-Conditioning Energy Savings Results

The distribution of annual air-conditioning energy savings for group 3A is shown in Figure 5. Although most houses had positive energy savings, 16% had negative energy savings, a result often observed in field studies of retrofit measures. About 50% of the houses had energy savings in the 0- to 1,000-kWh range. The average energy savings of the houses was 782 kWh (see Table 5), or 16% of the pre-repair air-conditioning energy use of 4,890 kWh. The average ratio of post- to pre-repair energy use of 0.85 indicates a 15% savings for the group, which is consistent with the previous result. These savings are consistent with the 13% to 18% savings reported by Vigil (1993), Cummings et al. (1990), and Proctor and Pernick (1992).

The standard error and standard deviation of the mean energy savings listed in Table 5 indicate significant variance in individual energy savings results. However, a "t" statistic of 5.26 indicates that the mean value of the savings is greater than zero with a significance level of less than 0.0001.

The relationship between energy savings and duct leakage reduction is shown in Figure 6. Energy savings are positive for most of the 51 houses, although no dependency of savings on achieved leakage reduction is evident. Significant but widely varying energy savings result at all leakage reduction levels, even at zero leakage

TABLE 5 **Air Conditioning Energy Use and Savings for Group 3A Houses**

Variable	Mean	Max.	Min.	Std. Error	Std. Deviation
Pre-retrofit energy use (kWh)	4890	9086	2126	184	1317
Post-retrofit energy use (kWh)	4108	7264	1677	204	1456
Energy savings (kWh)	782	3394	−1934	149	1063
Post/pre energy use	0.85	1.38	0.38	0.03	0.21

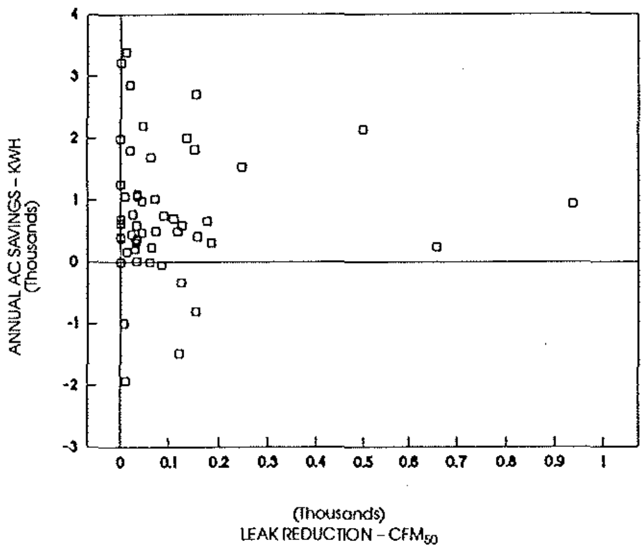

Figure 6 *Variation in air-conditioning energy savings with leakage reduction for group 3A houses.*

reduction. The same pattern of energy savings measured in houses with no measured leakage reduction makes the savings observed in houses with leakage reduction somewhat questionable. Future analysis should shed more light on this.

Several explanations are offered for these observations. The wide variation in energy savings and houses with negative savings may be due to models that do not include all the variables impacting energy use. Variance can exist in the measured leakage reductions because the "subtraction" method, which requires finding the difference between large numbers, was used in their calculation. Finally, different leaks can affect energy use differently (depending on whether they are supply or return leaks, where the return leaks draw from, etc.), although their leakage rate is the same.

Average energy savings were higher in houses without rooftop-mounted air conditioners than in houses with such units (1,251 vs. 530 kWh, as shown in Table 6). The air leakage reductions achieved in these two groups were about the same, further indicating that savings are

TABLE 6 **Average Energy Savings for Selected Subgroups of Group 3A Houses**

	Number of Houses	Average Energy Savings (kWh)	Standard Error (kWh)	Significance Level[a]
All Houses				
Rooftop unit sealed	23	526	244	0.04
Rooftop unit not sealed	10	530	112	0.0001
No rooftop unit	18	1251	251	0.0001
Rooftop Seal Repairs Only				
Rooftop unit sealed	8	689	353	0.09

[a]Probability of a mean value less than zero.

not well correlated to leakage reduction. One reason the group of houses without rooftop units had such high average savings is that the group included three houses with supply and return repairs that had average energy savings of 1,433 kWh.

The energy savings associated with repairing the seal of rooftop-mounted units remain questionable. Houses in which this leakage site was the only duct repair performed had an average energy savings of 689 kWh, 14% of the "pre-repair" energy use. However, no difference in savings was observed between houses with rooftop-mounted units that had the seal repaired and those that did not (526 kWh vs. 530 kWh).

AIR-CONDITIONING DEMAND SAVINGS

The goal of this analysis was to determine the effective change in the air-conditioning electricity demand averaged over all 51 houses (or diversified demand savings) during the highest temperatures of the year. The diversified demand was selected as the primary variable of interest in this analysis because electric utilities see the combined effect of demands from individual customers as opposed to the individual demand behavior of those customers.

The pre- and post-repair periods were the same as those used for the energy-savings analysis. Maximum outdoor temperatures reached 113°F during the pre-repair period in 1993 and 117°F during the post-repair period in 1994. Therefore, both periods contained adequate temperatures above 100°F to develop regression models of diversified demand vs. outdoor temperature.

Again, no control group is available with these repair periods to adjust the change observed in the diversified demand of the repair group. Analysis continues using different dates such that control groups can be included. Also, analysis continues examining individual house demands to complement the diversified analysis method.

Analysis Method

The following regression model of diversified air-conditioning demand as a function of outdoor temperature was developed to allow extrapolation of diversified demand to outdoor temperatures higher than the maximum outdoor temperatures of 113°F and 117°F experienced during the pre-and post-repair periods, respectively:

$$kW_t = a + (b \cdot T_{t-90}) \qquad (2)$$

where

kW_t = diversified air-conditioner demand of all 51 houses at a particular 60-minute increment (t),

T_{t-90} = outdoor temperature 90 minutes earlier than t,

a = intercept coefficient (determined by regression), and

b = slope coefficient (determined by regression).

Diversified demand over a 60-minute time interval, as compared with shorter time intervals, was selected to improve the regression model results by reducing the scatter in the demand data. Regressions of diversified air-conditioning demand vs. outdoor temperature were improved significantly by assigning the average demand calculated for a specific time interval to the outdoor temperature 90 minutes earlier. This time lag effect is caused by the thermal mass of the building, which stores heat from outside the building before releasing it to the inside and causing demand for air conditioning.

Regressions were performed for both the pre- and post-repair periods to derive best-fit equations for the variation of air-conditioning electricity demand with outdoor temperature. Only days with daily average temperatures greater than 100°F were used in the analysis to improve the regression model results for the highest demands, which occur at the highest outdoor temperatures. Average air-conditioner demands for all houses were calculated for each time interval and then assigned to appropriate outdoor temperatures for the specific time intervals.

Pre- and post-repair demands at several outdoor temperatures (105°F to 120°F) were estimated using the regression curves.

Results of Demand Analysis

The diversified demand savings for the group 3A houses ranged from 0.22 to 0.24 kW at outdoor temperatures ranging from 105°F to 120°F, respectively (Table 7). These demand savings represent 5% to 7% reductions from pre-repair diversified demands of 3.05 to 4.54 kW at 105°F and 120°F, respectively. Because these demand reductions occur at 4 p.m. to 5 p.m. during the cooling season, they would contribute significantly to reductions in the utility system's peak demand, which is driven by residential air conditioning.

Measured demand savings from the field test implies that, in general, the air conditioners installed in the field test houses are now oversized. If most units were still undersized, they would operate continuously at peak hours before and after duct sealing with no demand reduction realized.

TABLE 7 **Air-Conditioning Diversified Demands for Group 3A Houses**

	Outdoor Temperature			
	105°F	110°F	115°F	120°F
Pre-repair demand (kW)	3.05	3.55	4.05	4.54
Demand reduction (kW)	0.22	0.23	0.23	0.24
Demand reduction (%)	7.3%	6.4%	5.8%	5.3%

ECONOMIC VALUE OF MEASURED BENEFITS

Direct costs for performing diagnosis and repairs of ducts averaged $10 for materials and $130 for labor based on 6.5 person-hours at a $20-per-hour labor rate. Travel costs were estimated to be $70 per house, assuming one hour of travel time and 100 miles. These travel costs for the Phoenix metro area are exceptionally high because of the large geographic area. The total cost of $210 is consistent with costs reported by Cummings et al. (1990) and Vigil (1993) of $200 and $380, respectively.

Average annual energy savings of 782 kWh would be worth $78.20 using the electricity rate of $0.10/kWh that applies to residential customers of the utilities participating in the study. The average direct cost of $210 for duct diagnosis and repair would have an attractive 2.7-year simple payback from a consumer's point of view.

Diversified demand savings of 0.23 kW per residential customer would be worth $115 per residential customer using $500/kW for demand reduction capacity (Duncan 1994).

CONCLUSIONS AND RECOMMENDATIONS

Typical houses in Phoenix have air-distribution-system-related problems that lead to increased energy use and diversified electric demand. Duct leakage averaged 249 CFM_{50} for the 96 houses, and repairs reduced duct leakage, on average, by 88 CFM_{50}, or an average of 30%. The average annual air-conditioning energy savings due to duct repairs for a 51-house subsample was 782 kWh, 16% of the 4,890-kWh average annual pre-repair energy use. Diversified demand savings to the utility were about 0.23 kW, or 5% to 7% of pre-repair demand.

There appears to be sufficient financial gain from consumer and/or utility perspectives to justify repairs of these systems, although not all houses have problems. The average energy savings of 782 kWh has a simple payback period of 2.7 years based on an installation cost of $140 per house ($10 for materials and $130 for labor), and assuming $70 for travel costs and an electricity cost of $0.10/kWh. The demand savings of 0.23 kW can have a value of $115 to the utility, assuming $500/kW for demand reduction capacity.

The seal at rooftop-mounted air conditioners is a frequent and significant duct leakage site for the types of houses and systems found in Phoenix. Problems with the seal can be easily observed and cost-effectively repaired because few or no diagnoses are required. The Arizona Heat Pump Council and utilities in this area should consider transferring this finding to local air-conditioning contractors, possibly through annual training programs conducted by the Council. The problem should be described; the impact on the air-conditioning system, comfort, and electricity consumption should be discussed; and techniques to repair the seal should be reported.

Duct leakages and reductions measured in this and other studies must be used cautiously when applying them to different housing stocks. Differences in duct construction, regional installation practices and designs, and the selection process used to select houses in the reported studies must be factored into the decision of the applicability of these data from other studies. Pilot tests are needed to verify leakages and reductions before proceeding with full-scale programs.

An improved method of installing and repairing ducts located in cathedral ceilings is needed that can be performed routinely by repair personnel and is cost effective. Cutting the drywall/plaster ceiling to gain access to the duct and patching the hole is not an optimum approach because it is expensive (especially if repainting is involved) and requires skills that typical repair personnel do not have. This approach is not likely to be satisfactory to customers unless conditions are restored to their original condition.

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