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Effects of Occupant Control, System Parameters, and Program Measures On Residential Air Conditioner Peak Loads

Final Report

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Effects of Occupant Control, System Parameters, and Program Measures on Residential Air Conditioner Peak Loads

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ABSTRACT

The diversified demand of residential air conditioners (ACs) is significantly effected by occupant control behavior and system sizing. Consideration of these effects is necessary to properly calculate the impact of program measures and allocate utility demand management resources.

Field monitoring identified four groups of ACs. A significant portion were sized or operated such that they would not benefit directly and proportionally to decreased thermal loads. Some occupants turn the AC off and leave for work. When they return home at the peak hour, they turn the AC on in an overheated house. Initially the AC runs continuously and would do so in spite of most load reduction measures. Other ACs are off during the peak. They make no contribution to the peak and would be unaffected by peak reduction programs.

The characteristics of the four groups at peak are: A) Off. B) Cycling and responsive to decreased load or equipment efficiency improvements. C) Continuously on, but responsive to retrofits. D) Continuously on, unresponsive to load reductions and some efficiency improvements.

Load, occupant control, and AC characteristics of each group are discussed. The effect of load changes and AC efficiency changes on diversified peak are discussed for each group. Examples from field monitoring and aggregate proportions are presented. An integrated model of the effect on peak demand for various program measures is presented based on the proportion of each group type present in the connected load.

Local Area Peak

Local transmission and distribution expenditures are a significant portion of utility infrastructure expense. The majority of demand side management (DSM) attention has been focused on the problem of the system peak. Local planning areas experience a local area peak often driven by residential end users. The local peak of a predominantly residential area differs in important ways from the system peak. The primary differences are:

- The residential peak occurs later, usually 5:00-6:00 PM as residents return home and turn on air-conditioners.
- The residential peak is sharper and has a shorter duration.
- While the residential peak has no large controllable loads, it has a larger component of discretionary usage.
- The air conditioning load causing the residential peak is dominated by external gains. The internal gain is much smaller than in commercial (the lighting load is small).

Figure 1 shows measured load shapes for one utility system and a residential area substation of the same utility during summer peak conditions. (unpublished)

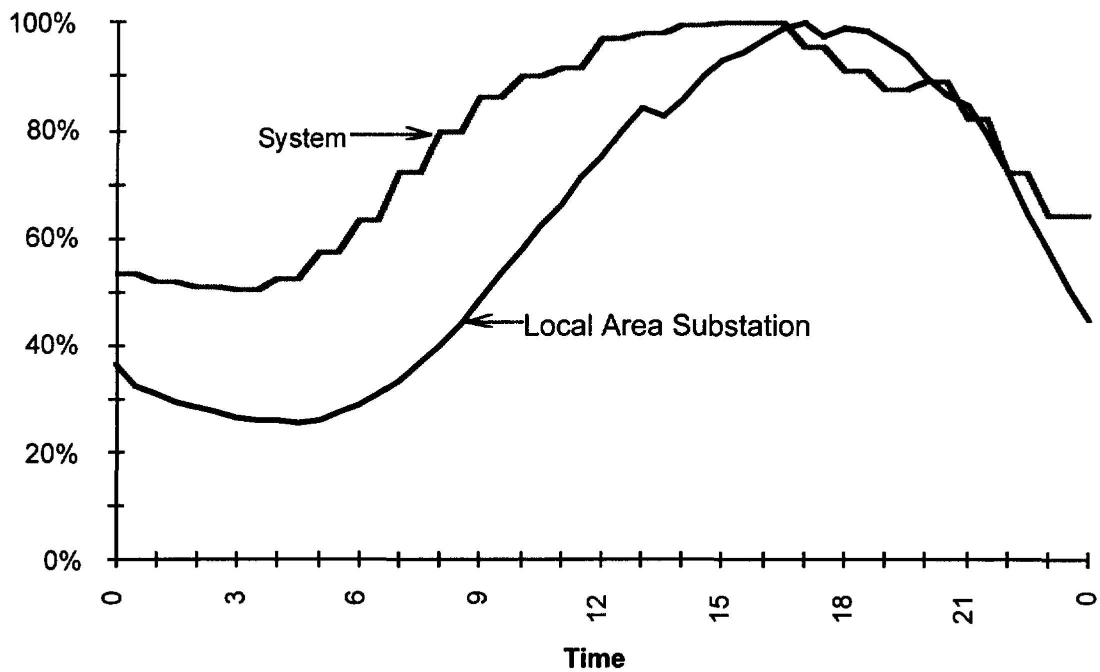


Figure 1 Local Area Peak Load Shape

An estimated 42.4% of the local peak was due to residential central AC, and any DSM program designed to address the local peak problem must focus on this end use.[1] The occupant's thermostat control adjustment behavior and system sizing strongly effect the peak load. (McGarity et al. 1987; Parker et al. 1996; Reddy and Claridge 1993) Not all measures that reduce AC load will reduce AC peak equally.

This analysis first looks at an air conditioner load pattern generated by a constant thermostat setting. Then the effect of thermostat adjustment and system sizing on AC load are studied. These results are used to predict the benefit of various potential energy efficiency improvements . Finally field data is analyzed to determine the frequency of the operating modes in real locations.

Model of Operating Modes

Constant Thermostat Setting.

An air conditioner with a constant thermostat setting will behave as shown in Figure 2. That is:

- Until it is sufficiently warm outside, the air conditioner is off.
- After the outside temperature exceeds a threshold, the AC cycles to maintain the setpoint. As the duty cycle and power draw increase, the diversified peak demand rises with temperature.

[1] A residential AC contribution to peak of 90% has been reported for Texas. (Zanikau et al. 1992)

- At the temperature labeled "onset of continuous operation", (OCO), the house cooling load is exactly matched with the capacity of the unit.
- Above the OCO, the unit runs continuously and the space temperature exceeds the setpoint. When running continuously the total input rises slowly due to increased power draw at higher condenser temperatures, and the house setpoint temperature is exceeded.

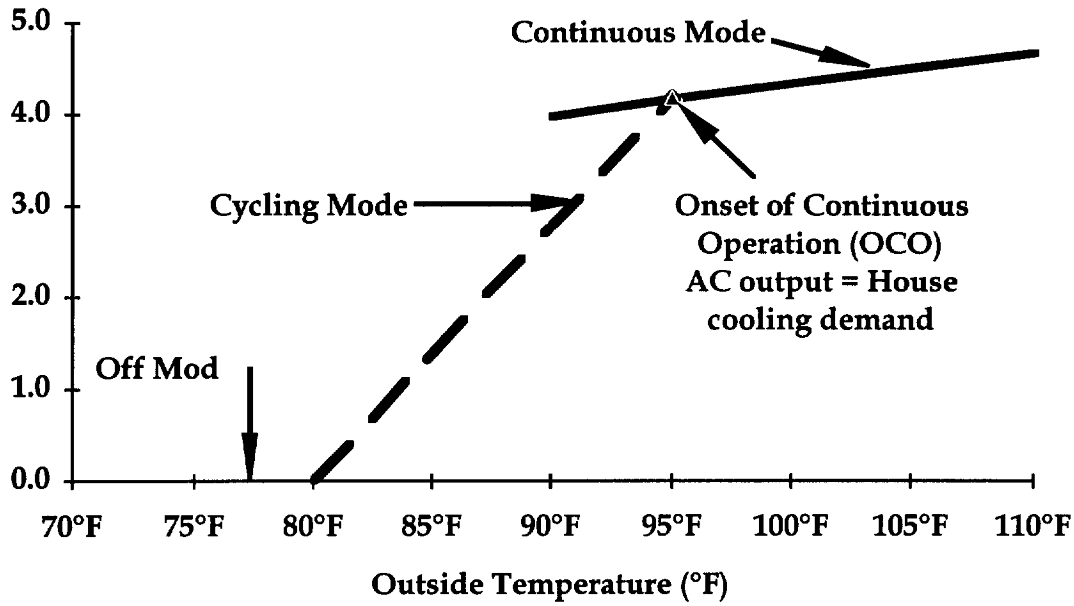


Figure 2 AC Operating Modes with Constant Thermostat Setting

Residential Air-Conditioner Operation.

In order to predict the effect of various technologies designed to reduce central AC load, a model of operation on peak must be utilized. Based on previous experience with submetered units, air conditioners at peak are modeled as falling into four operating modes:

A Continuous Off - The AC is not running at all during peak.
B Cycling - The AC is cycling to maintain the setpoint temperature.
C Could Cycle - Currently the AC operates continuously at peak, but would cycle if load reduction or capacity improvement retrofits were performed.
D Continuous On - The AC is currently operating continuously and even with retrofitting would still do so.

As shown in Figure 3, these modes closely parallel the behavior of a single unit illustrated in Figure 2. Continuous operation can and does occur in the lower temperature ranges because of occupant control, such as a sharp drop in setpoint.

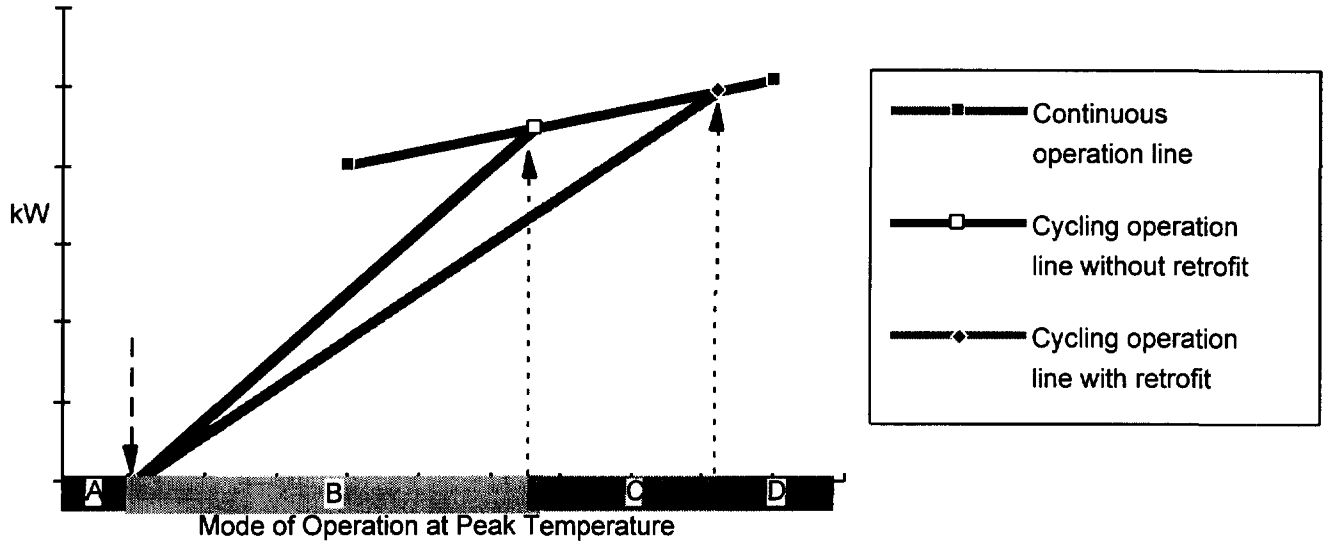


Figure 3 Air Conditioner Modes of Operation at Peak Temperature

Thermostat Control Factor

The operating mode at peak is strongly influenced by occupant thermostat operation and AC sizing. Of these the occupant thermostat control is the most important. Previous studies have shown that occupants utilized a variety of thermostat control strategies (Parker et al. 1996; Proctor, 1991). They are:

- Constant off
- Constant thermostat setting
- Daily set up/set down
- Manual off/on

Constant Off. With constant off control, the AC is off on the peak day.

Constant Thermostat Setting. With this strategy, the thermostat is set at one temperature and very rarely adjusted. When the air conditioner is controlled by a constant thermostat setting in the range 75°F to 85 °F, a large percentage of the cooling hours are characterized by the unit cycling on and off. This minimizes continuous operation of the air conditioner. This strategy may be more prevalent in retirement areas because residents are home during the day. Research in California and in the Southern US indicate that less than 50% of the air conditioners are controlled in this manner. (BSG 1990; Parker et al. 1996; Proctor 1991; Reed 1991)

Daily Set-up/Set-down. This strategy consists of a consistent daily pattern of setting the thermostat up at one specific time during the day and down at another specific time, with only occasional minor adjustments of the thermostat. This pattern is common for homes in which the occupants work away from home during the day and return in the evening. It can be produced by manual adjustment or by an automatic thermostat. After the AC has been off, the house is warm, and it takes the AC a period of time to reduce the interior temperature sufficiently for cycling to begin. During the cool down period the unit may operate continuously at any outdoor temperature. This pattern appears to be a major contributor to the local area peak. A study by a utility in the Southeast has shown that it is exacerbated by programmable thermostats. (Parker 1998) It is likely that this control strategy is more prevalent in bedroom communities.

Off/On. With off/on control the thermostat is manually switched on when the occupant wants it cooler and off when s/he considers it cool enough. This is accomplished with the off-cool switch on the thermostat or by adjusting the set point of the thermostat up/down. This behavior makes peak reduction by modifications to the system difficult since use is not necessarily related to ambient temperature. The AC unit may operate continuously at any temperature under the off/on control pattern. Research in Fresno, CA indicates that approximately 30% of the air conditioners in that city are controlled in this manner. (Proctor, 1991)

Interaction of Thermostat Control and AC Sizing to Produce Operating Mode

The operating mode is determined by a complex interaction of load, customer thermostat control and effective air conditioner sizing. Effective air conditioner sizing is simply the ratio of the actual capacity to the actual load seen by the air conditioner. The effective AC sizing can be more or less than the calculated sizing ratio based on estimated design load and published capacity. The reasons for the difference are many, including AC condition (air flow and refrigerant charge) and air distribution system losses.

Each category contains a variety of customer households.

A- Off Operation. This category includes central air conditioner that are not operating at peak. This category includes households where:

- House occupants are not home during peak and they keep the AC off
- House occupants do not use air conditioning. They are saving money or do not like air-conditioning.
- The house has more than one AC, this unit is not used.
- The AC unit is broken.
- Occupants turn up the thermostat setting shortly before the peak occurs.

B- Cycling Operation. Category B ACs are cycling to meet the cooling load at peak. This category contains three predominant groups based on thermostat operation and effective sizing:

- Constant thermostat setting with an AC system that is effectively oversized for the load.
- Off/On or Set-up/down thermostat operation with a thermostat adjustment to a lower temperature significantly before the peak period and an oversized AC system that is able to satisfy the thermostat before the peak occurs.
- Off/On or Set-up/down thermostat operation with a thermostat adjustment to a higher temperature before the peak period.

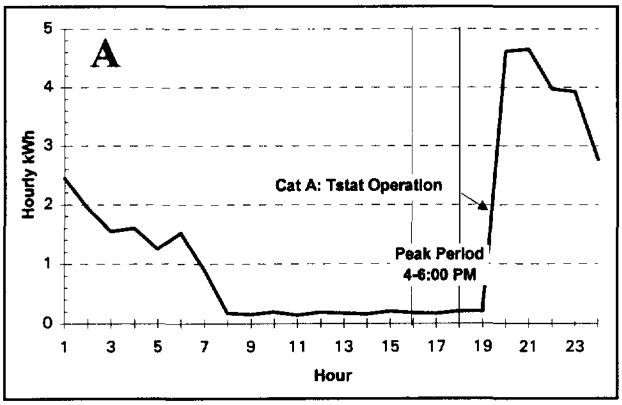
C- Could Cycle. Air-conditioners in Category C run continuously during the peak, however, with sufficient load reduction, they would cycle during the peak. The reduction of the duty cycle from

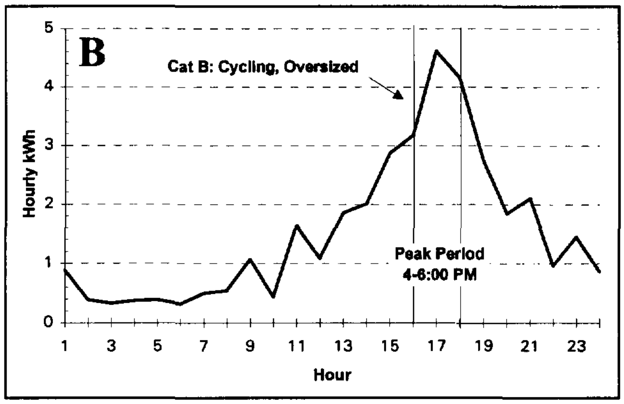
100% would reduce the diversified peak load. Category C contains at least two groups based on thermostat operation and effective sizing:

- Constant thermostat setting with an AC system that is now correctly sized (Onset of Continuous Operation occurs at design conditions) or effectively undersized but would be oversized if the cooling load were reduced or the effective cooling capacity were increased.
- Off/On or Set-up/down thermostat operation with a thermostat adjustment to a lower temperature somewhat before the peak period. This is combined with a unit that would be oversized if the cooling load were reduced or the effective capacity increased.

D- Continuous On. Category D air conditioners run continuously during the peak and, even with standard load reductions or efficiency improvements, would continue to run continuously at peak. An estimated 20% of customers are in this group. The AC duty cycle of these customers will be 100% both before and after retrofits. Category D is expected to contain two groups based on thermostat operation and equipment sizing:

- Constant thermostat setting with an AC system that is significantly undersized or a house with excessive heat gains, e.g. large return duct leaks in the attic.
- Off/On or Set-up/down thermostat operation with the thermostat set point reduction occurring near the peak period. In this case, the AC operates to pull down the house temperature during the peak. Even with standard load reductions or efficiency improvements cycling would not occur until after the peak. These units could have almost any effective sizing. Sizing will only effect the length of the pull down period. This group is considered a major contributor to peak in bedroom communities. This operation and the higher heat gain from late afternoon sunlight are probably the major contributors to the shape and timing of the local area peak.





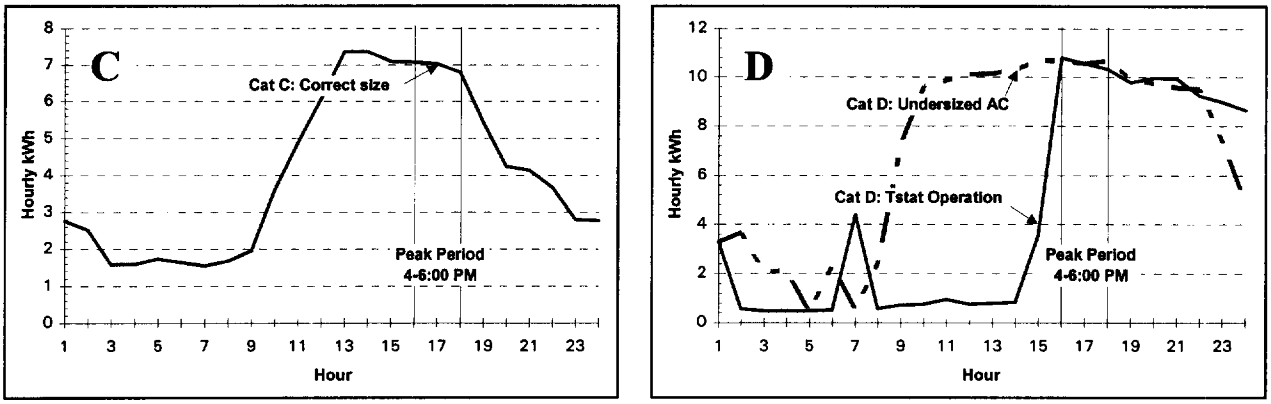


Figure 4 Examples of Operating Modes

Frequency of Operating Modes.

These operating modes affect the potential peak reduction that can be obtained by any retrofit designed to reduce residential air conditioner peak loads. The percentages of the total number of AC units in each mode are used to calculate potential reduction. The frequency of the various modes of operation are determined by analyzing a submetered sample of representative houses on peak days. Submetering must be at the hourly or finer level. Figure 4 was derived from hourly data. The days must be peak days as some people change AC operation at higher temperatures, i.e. people only use the AC during the hottest weather or may stop setting it up because of the long cool down time.

The statistical base for frequency estimates comes from analyzed submetered data. Population demographics is expected to strongly influence the frequency distribution. A retirement community will probably have more constant thermostat settings than a bedroom community where people are not home during the day.

The estimates shown in Table 1 are used based on the following datasets. The "Number" represents the number of peak day AC operation successfully classified after dropouts for poor or incomplete data quality.

- The Fresno, CA estimate is based on 100 units. (unpublished)
- Coachella Valley, CA: twenty houses had hourly submetered AC usage data, and the 17 hottest weekdays of 1992 were analyzed for operating mode. (Proctor, Blasnik & Downey 1995)
- Nevada Power Company (NPC) Sample #1: Data for 40 primary ACs for customers participating in a load management program were analyzed on 6 hot days in 1992. Secondary ACs were not metered which would reduce category A in particular. (Blasnik et al. 1995; internal PEG datasets)
- Nevada Power Company (NPC) Sample #2: Data for 78 primary and secondary ACs for customers participating in a load management program were analyzed on 5 hot days in 1994. Load management days were excluded. (ibid.)
- EPRI: Data for 136 ACs located near 18 different weather stations in hot climates were analyzed. (ibid.) Customers were not participating in a program. The data was analyzed for both a 4:00 and 6:00 PM residential peak. After two hours of temperature draw down, a significant number of category D units were Cs in the 6:00PM period.
- Arizona Public Service Company (APS): Data for 28 primary and secondary ACs from 22 newly constructed homes were analyzed on 5 hot days in 1995. (Blasnik et al. 1996)

Table 1 Frequency of Operating Modes

Operating Mode	Fresno, CA	Coachella Valley, CA	NPC #1	NPC #2	EPRI 4:00 PM	EPRI 6:00 PM	APS
A	20%	18%	2%	18%	19%	21%	1%
B	44%	60%	68%	52%	47%	50%	85%
C	16%	6%	4%	3%	5%	12%	0%
D	20%	16%	26%	27%	28%	17%	14%
Number	100	340	236	269	406	406	72

Residential Air Conditioner Peak Savings Analysis

Five strategies are analyzed and the potential for peak reduction (kW) and annual energy consumption reduction (kWh) are discussed herein. Other retrofit strategies may be analyzed similarly.

- High efficiency AC replacement
- Downsized AC replacement
- AC unit repair
- Load reduction

High efficiency AC replacement. This strategy involves the replacement of an existing central air conditioner with the same size higher efficiency (at peak) unit. The higher efficiency unit produces the same cooling capacity at a reduced kW by incorporating such features as a larger condenser, a more efficient compressor, etc. With the same capacity the AC will have the same run times as before. The lower kW draw will result in a proportional reduction in annual energy use. No peak reduction will occur with category A (Off) operating mode. All other operating modes will have a peak reduction proportional to the lower kW draw.

Downsized AC replacement. This strategy involves the replacement of an existing oversized central air conditioner with a properly sized unit of the same efficiency. Oversizing can occur because the original equipment capacity exceeds the cooling load for the building, or shell and distribution measures can be implemented which reduce the effective load and make the unit oversized. Downsizing an air conditioner (with no other changes) reduces the electrical load when the unit is operating. The unit will run longer at lower kW draw. The net peak reduction is small since the only improvement is due to the reduction in cycling losses (longer on times produce improved efficiency). James et al. (1997) found efficiency degradations of 3.7% and 9.3% for systems 20% and 50% oversized respectively. Category C & D will have peak reductions equal to the reduced unit kW.

AC unit repair. Unit repair that improves efficiency will result in decreased annual usage. Unit repair may increase or decrease the kW draw. For example, when the charge on an undercharged unit is corrected, both the capacity and power draw increase. The cooling capacity increases faster than the power draw so the efficiency increases, annual usage is reduced, but peak power draw is increased. If the unit operates continuously at peak (D), the units contribution to the peak will increase. If the unit is cycling at peak (B), its increased capacity will reduce the duty cycle and the average contribution to peak will decrease.

Load reduction. The cooling load can be reduced by increasing the thermal integrity of the building shell or reducing gains in the duct system. The primary shell strategies are attic insulation, wall insulation, roof coatings, and radiant barriers. Duct insulation and duct leakage repair are primary measures applicable to the distribution system. Duct leakage adds to air conditioning load by loss of conditioned air to outside the thermal envelope and by drawing in hot air from the attic or outside. The effect of these items on peak demand is highly interactive with the occupants control of the air conditioning system. In a significant number of cases, the implementation of shell and distribution measures by themselves will not appreciably affect peak demand. In cases where the house is unconditioned during the day and the AC is turned on in the evening, it will run continuously for a cool down period. This cool down period may extend throughout the time of area peak load, (D). With moderate load reduction the cool down period will be shorter, but the AC will still run continuously during the peak period. Only dramatic load reductions will allow cycling for this group. Reducing the cooling load will reduce the diversified electrical load for air conditioners that cycle at peak, category B. The peak reduction will be proportional to the load reduction. Category C are those AC units that currently run continuously at peak but would cycle if the load were reduced. The load reduction would first go to reducing the cool down period, then to reducing the duty cycle. The peak kW load reduction is proportional to the duty cycle reductions only.

Estimating Residential Air Conditioner Peak Load Reduction Potential

A model of peak reduction, Model P, has been developed to improve the predictions of peak reduction from central AC measures. (Proctor, Blasnik & Downey 1995) In the model the expected peak reduction of each strategy (measure or group of measures) is analyzed separately for each operating mode. The predicted savings by mode are multiplied by the frequency of occurrence of that mode to derive an estimate for the average effect. Naturally it is important to include all modes, even those with no effect. to obtain a valid prediction. This model accounts for customer behavior, design, and installation effects that are lost in simpler models.

$$\Delta \text{Peak kW} = \Sigma_i (F_i \times \Delta kW_i)$$

Where:

ΔPeak kW	Overall peak reduction
i	Mode$_i$ A, B, C or D
F_i	Frequency of Mode$_i$ in percent
ΔkW_i	kW reduction for Mode$_i$

Table :

Table 2 Peak Reduction by Operating Mode

Retrofit	Operating Mode Const Off **A**	 Cycling **B**	 Could Cycle **C**	 Const On **D**
High Efficiency AC Replacement	None	Good	Good	Good
Downsized AC Replacement	None	Small	Good	Good
AC Unit Repairs	None	Moderate	Varies	Varies
Load Reduction	None	Good	Moderate	None

Conclusions & Summary

Whether or not a reduction of the cooling load or improvement of AC system efficiency will translate into a corresponding reduction in peak depends on several interacting factors. The building load, distribution system gain, AC sizing, and operation of the thermostat interact to produce four operating modes — labeled A, B, C, &D. The effect of these operating modes is to lessen the diversified peak reduction from retrofit programs. For all retrofit options category A customers, constant off, will achieve no peak reduction. The high efficiency AC replacement is the only retrofit that will achieve significant peak reduction for all three (B, C, and D) operating modes. Building shell and distribution system measures will achieve their full potential peak reduction on Category B customers and will achieve no peak reduction on Category D customers except when very high load reductions are achieved.

Based on this analysis, a comprehensive strategy for maximum reduction of local peak loads from residential central ACs is a combination of cooling load reduction and AC replacement with a downsized high efficiency unit. Load reduction alone could have disappointing results. If air conditioners are going to be replaced, load reduction measures installed in conjunction with the new AC will allow for a smaller AC which will cost less, hard-wire the peak reduction, and give better humidity control in humid climates.

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