PATTERNS OF ELECTRIC WATER HEATER USE AND THE EFFECTS OF WATER HEATER LOAD CONTROL ON CUSTOMERS

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ABSTRACT

How customers use hot water and how water is heated is a significant issue. It is particularly salient since electric utilities are experiencing intense competition from the gas industry for the residential users' energy dollars for water heating. For many utilities, residential water heating is a significant contributor to system peak demands. Thus, the cost of generating the electricity to heat water is often relatively expensive. Further, this coincidence between the water heating peak and system peak often contributes to the need for expensive peaking capacity.

This paper reports on the analysis of the water heater load control experiments conducted as part of the Athens Automation and Control Experiment (AACE). The analysis is based on data from end-use monitoring devices as well as survey data. A total of 36 water heaters were monitored during the winter months of 1986/87. Water heaters were turned off for periods of 2, 3, and 4 hours during the morning and evening peaks.

The winter peak diversified water heater load was approximately 1050 watts and occurred at 7:00 a.m. There was a smaller and broader peak of about 750 watts in the evening. The expected demand reduction from load control ranged from 700 to 920 watts per unit. Because of reliability problems the actual reductions fell in the range of 375 to 500 watts per unit. The highest diversified water heater peak following restoration of control was approximately 2 kW. The effects of control at the system level were no longer apparent two hours after control was restored.

Fewer than 5% of the customers complained to the utility about load control operations. An analysis of hot water consumption suggests that even during the 4-hour morning control action fewer than 14% of the customers experienced less service than they desired. This suggests that most customers can tolerate fairly long control actions on water heaters.

The analysis of hot water consumption also showed that 80% of the customers would have sufficient hot water for an entire day if they had 120 gallon water heaters. This suggests that storage water heating might be a viable alternative to direct control of water heaters.

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INTRODUCTION

How customers use hot water and how water is heated are significant issues. These issues are particularly salient because electric utilities are experiencing intense competition from the gas industry for the residential users' energy dollars for water heating. For many utilities, residential water heating is a major contributor to system peak demands making the cost of generating the electricity to heat water relatively expensive. Further, this coincidence between the water heating peak and system peak often contributes to the need for expensive peaking capacity.

Some utilities with surplus generating capacity and active marketing programs have decided, at least temporarily, to cede the water heating market to the gas utilities because they cannot be price competitive. Other utilities have used direct load control to deal with these problems. Still others are considering programs to downsize the elements in water heaters or to market large capacity water heaters with controls that activate them in the early morning hours when system demands are low. The choice among these alternatives depends upon a variety of factors including the patterns of customer hot water use and equipment reliability.

Historically, utilities have used a variety of direct control strategies for water heaters. These strategies range from turning water heaters off completely for 1 to 6 hours per day to turning them off for 25% to 80% of each hour for periods of several hours.[2] Utilities usually report experimental results in terms of the reduction in demand and the difference between the reduction in energy sales during control periods and the increase in energy sales after control. A 1983 EPRI survey of industry results of water heating control tests reports demand reductions between .39 kW and 1.36 kW for winter control tests and 0.22 kW and 1.2 kW for summer control tests.[3] The increase in energy sales following control were usually somewhat less than the sales would have been during control periods if there had been no control.[4] Information about the impact on customers has primarily been reported in terms of customer complaints because much of the the early monitoring was done only at substations. Only recently has end-use monitoring allowed the systematic study of such impacts.

This study describes the results of the water heater load control experiments from the Athens Automation and Control Experiment (AACE). The AACE is a hardware and software oriented research and development project installed on the Athens Utilities

Board's distribution system in Athens, Tennessee. The Athens Project is a joint effort involving personnel from the Department of Energy's Oak Ridge National Laboratory, members of the Athens Utilities Board, and the Electric Power Research Institute. The purposes of the Athens experiment were to determine: how much energy consumption could be deferred with direct water heater control; the impact of load control actions on the distribution system; if the customer base could be segmented to improve control strategies; if there is a loss of revenues from control; and the extent to which control affects customers. The results will help to make better choices among direct control, downsizing water heater heating elements, and storage water heating.

Loads are controlled by sending a signal over the power lines to load control receivers. Upon receiving a signal, the controller causes a relay to open disconnecting the water heater from its power source. If no further control signal is received by the load control receiver, a timer closes the relay after an hour. No signal is required to restart the water heaters unless control is desired for less than an hour. To keep the water heater off for a period of 3 hours, a signal must be sent every hour.

During the experiments reported here, 40 water heaters were monitored. Energy use in watt-hours was measured every five minutes. A total of 288 measurements per water heater were taken each day. Because of data problems, the water heater data for four households were removed from the analysis. The data were filtered subsequent to the data collection. A few large values caused by saturation of the transducers were changed to missing. Measurements of less than 10 watt-hours were set to zero because the appliance monitoring devices sometimes recorded one or two pulses (a pulse was equal to 4.8 watt-hours) in intervals when the water heater was off.

The monitored data were supplemented with surveys of participants. These surveys include information about appliances, demographics, and lifestyle. An energy audit of each participant's dwelling and an audit of the electrical characteristics of the appliances were conducted.

CONTROL AND CUSTOMER CLASSIFICATION SCHEMES

Typically, load control programs attempt to maximize load relief on system peaks. When to control an appliance can be determined by comparing diversified demand curves for individual appliances with the system load shape. The diversified demand of an appliance is the average load for all units of a specific type at a specific time. If 25 of 100 air-conditioners on a feeder are each drawing 4 kW at 4:00 p.m., the diversified demand is 1 kW ((25 X 4)/100).

Figure 1 shows the water heater control periods for the Athens project. The x-axis is the hour of the day. The y-axis is percentage of the daily peak. Percentage of daily peak is calculated by dividing the hourly value by the value for the peak and multiplying by 100. The solid curve is the system load shape. The broken line is the water heating curve. The data for the latter curve were derived originally from data supplied by the Tennessee Valley Authority (TVA). Because the winter system load shape is bi-modal, two-, three- and four-hour experimental control periods were implemented both morning and evening. Morning control was feasible because the system load declines during the mid-morning hours and release of control was not likely to create a new system peak.

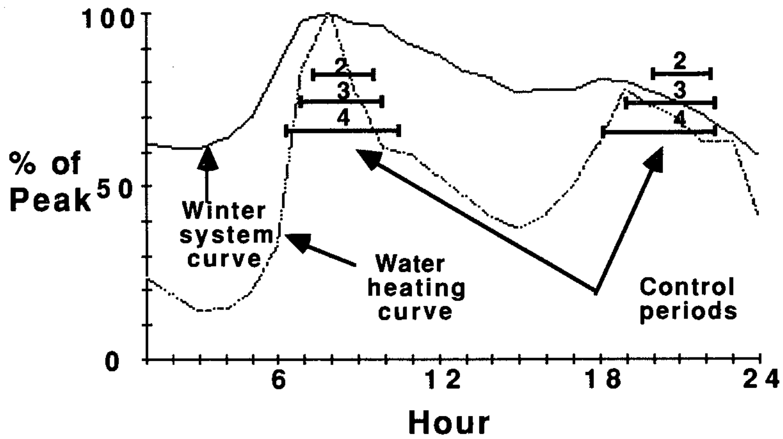

Figure 1. Winter system load shape, water heater diversified load shape, and water heater control periods

Because we were interested in how variations in customer usage patterns might be used to enhance control strategies, we attempted to divide customers into control groups by usage patterns. In the absence of usage data, we reasoned that households with higher expected usage would have water heater load patterns that differed from households that had smaller expected usage. To establish expected usage we used TVA's published guidelines for sizing water heaters. These guidelines relate water heater size to the number of persons in the household, the number of bathrooms in the dwelling, and the presence or absence of a clothes washer and/or a dishwasher. The proportions of households at Athens with these characteristics were estimated based on census data. The design of the system limited us to three water heater groups. Criteria were established for assigning participants to a low, medium, or high expected usage group. Figure 2 shows the classification scheme.

WATER HEATING BEHAVIOR WITHOUT CONTROL

Figure 3 shows the average demand for all water heater customers for non-control days. The diversified demand for water heating for the Athens sample peaks at about 1060 watts at 7:00 a.m. on winter mornings. However, this peak is not unitary. In this sample there is a drop and then a second peak of 980 watts at about 9:00 a.m. Water heater demand then drifts downward until late afternoon when the load begins to climb to a secondary evening peak of approximately 700 watts which lasts from about 7:00 p.m. to 11:00 p.m.

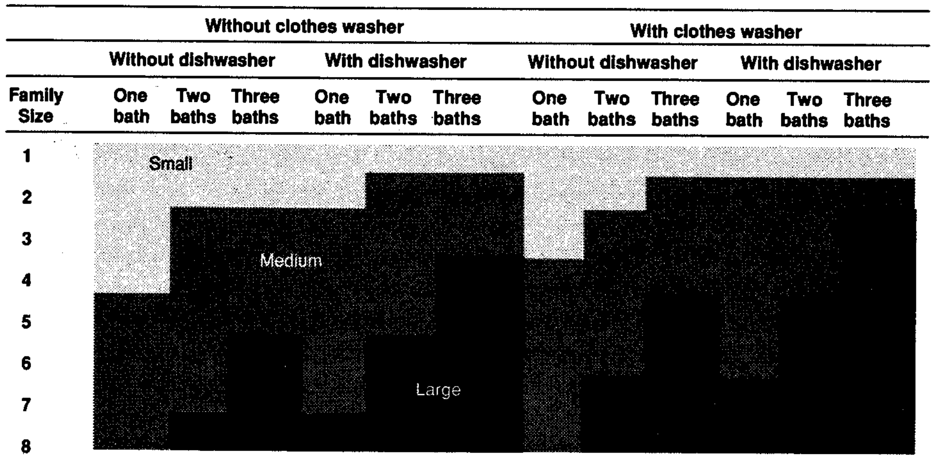

Figure 2. Classification criteria for water heater customers at Athens,Tennessee

Figure 4 shows for non-control days the percentage of water heaters operating for any amount of time during the monitoring interval, the percentage of water heaters which activate, that is, start heating water during the interval, and the percentage of water heaters operating throughout the entire five-minute monitoring interval.

The percentage of units operating peak at 33% around 7:00 a.m. and then drop off until rising to a secondary peak at 9:00 a.m. when about 28% of the units are operating. The number of operating units then declines until about 5:00 p.m. when the percentage of units operating begins to climb reaching about 25%. The percentage of units operating declines to about 7% in the early morning hours.

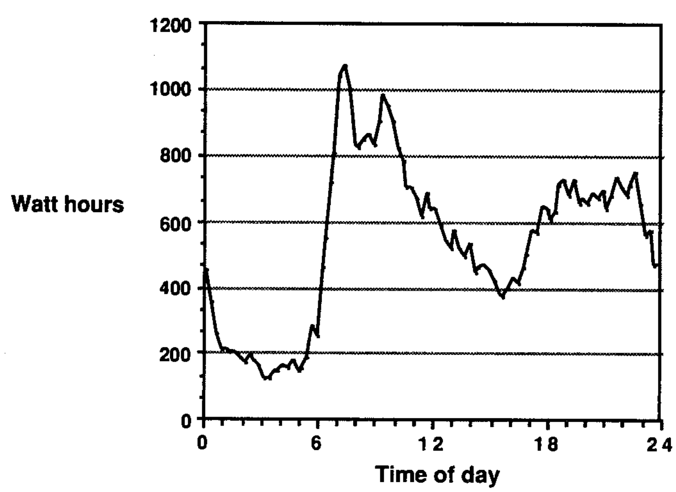

Figure 3. Diversified water heater load for no control days

The percentage of units which are on for each full five-minute monitoring interval tracks the percentage of units running very closely. The percentage of units starting within a five minute interval shows a somewhat surprising characteristic. During the early morning hours the percentage of units activating is fairly stable at about 3%. After the early morning increase, the number of units activating is about 6% and remains fairly constant throughout the day. Thus, consumption does not seem to be directly proportionate to the number of units starting within an interval.

The predominate character of water heater load in a household is a series of short duration events. On the average most water heaters run less than 10 minutes at a time. The longest runtimes are between 6:00 a.m. and noon.

It has already been noted that customers were categorized by expected usage based upon the assumption that there would be differences in the patterns of behavior. Figure 5 shows that there are indeed differences in the patterns. The medium expected usage group peaks at 7:00 a.m., the small expected usage group peaks at around 7:40 a.m., and the large expected usage group peaks at about 8:45 a.m. The different peak times for the different groups explain the bi-modal morning peak.

Load control strategies could make use of these patterns to more effectively shift the load. Early peaking households could be controlled in the early hours of the morning and be released at about mid-morning. Late peaking households could be controlled from just before mid-morning until about noon. This would permit the shifting of significant amounts of load from early morning to around noon.

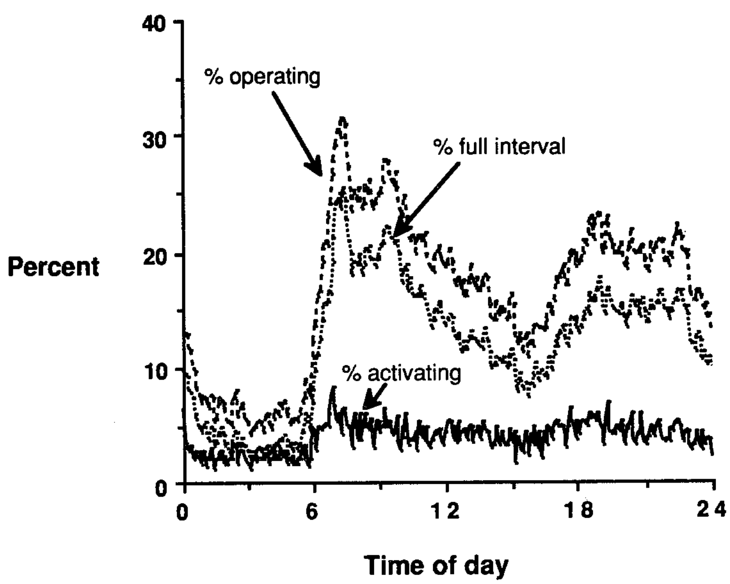

Figure 4. Percentages of units starting, running for a 5 minute monitoring interval, and running less than monitoring interval

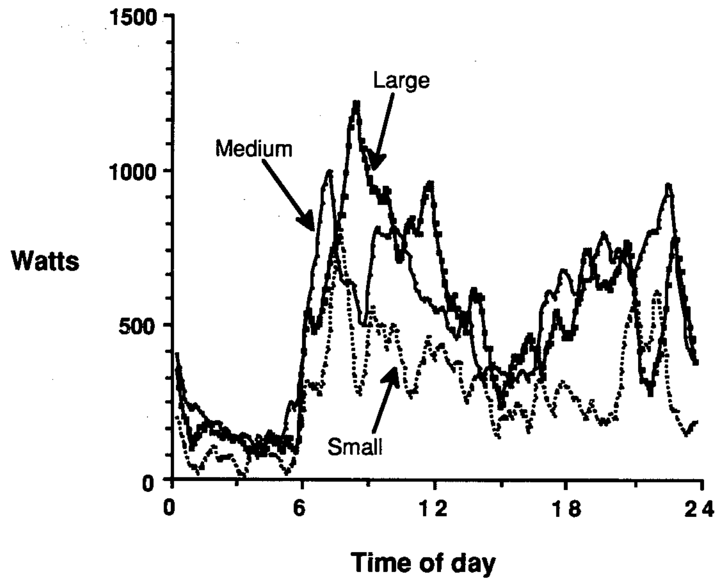

Figure 5. Diversified water heater demand for customers classified as having small, medium and large expected usage

WATER HEATER LOADS UNDER CONTROL

Figure 6 is a plot of the diversified water heater load with and without control. The control action shown here is the four-hour morning control action from 6:30 a.m. to 10:30 a.m. The diversified load during control was expected to go to zero. However, there is some demand during the control period which is attributed to load control receivers which did not release load when the signal was sent or which timed out early. These problems were intermittent and were not confined to specific load control receivers. Although it has not been widely reported in the literature, we believe this is a common problem with load control hardware. The graph also shows the peak when control was released after four hours. In this case, the diversified load reached almost 2 kW per unit.

Figure 7 compares the water heater demand on non-control days with the demand on control days. Each column represents one of the six control periods. The height of the column represents the average demand per water heater for that control period on a non-control day. Depending on the control period, the expected demand reduction (undeferred plus deferred) is between 700 and 920 watts per unit. This is the load that may be potentially deferred, assuming the load control units operate with 100% reliability.

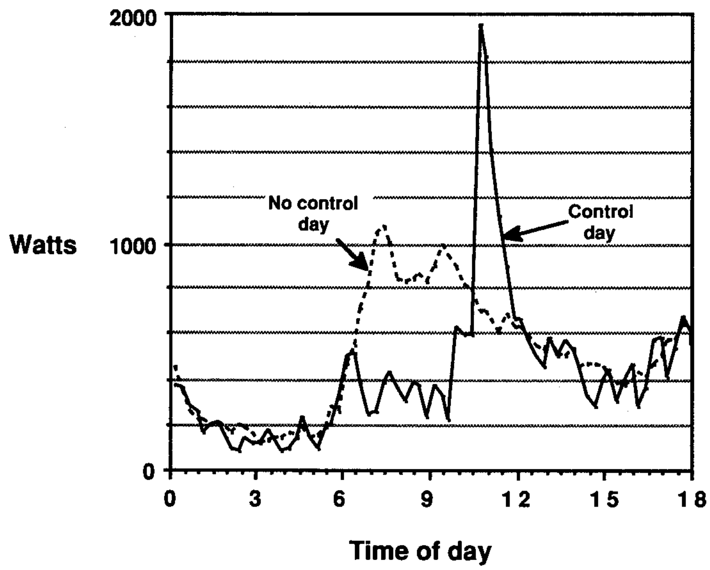

Figure 6. Diversified water heater load with and without control

The dark segment at the bottom of the column represents the average deferred demand during the control period. This actual deferred demand ranged from about 375 to 500 watts per unit depending on the control period. The average deferred demand was obtained by subtracting the average demand for a control day from the average demand for a non-control day.

The light segment at the top represents average demand that went undeferred on control days. Because the load control receivers frequently failed to operate, there is about 50% less reduction in demand in each control period than was expected.

Load control causes a coincidence of load. If it occurs at the wrong time, this coincidence of load may result in a new system peak defeating the purpose of load control. Thus, we are interested in the magnitude of the peak after the load is controlled. We are also interested in how long the effects of control remain in the system. In order to investigate the length of time the effects of coincidence remain in the system, the difference in average energy use for control and no control days was calculated. The graph of these differences, plotted from the end of a four-hour control period, is shown in Figure 8. The effects of control are largely dissipated when the difference in diversified demand reaches zero and begins to oscillate about zero. The maximum difference between the average diversified load without control and the diversified load just after control is released is about 1550 watts. The graph shows that the effects of coincidence for a four-hour load control action are largely dissipated in about an hour and fifteen minutes. Similar analyses show that for a three-hour control action the diversity is reestablished in about the same amount of time and that for a two-hour action the diversity is reestablished in slightly less time.

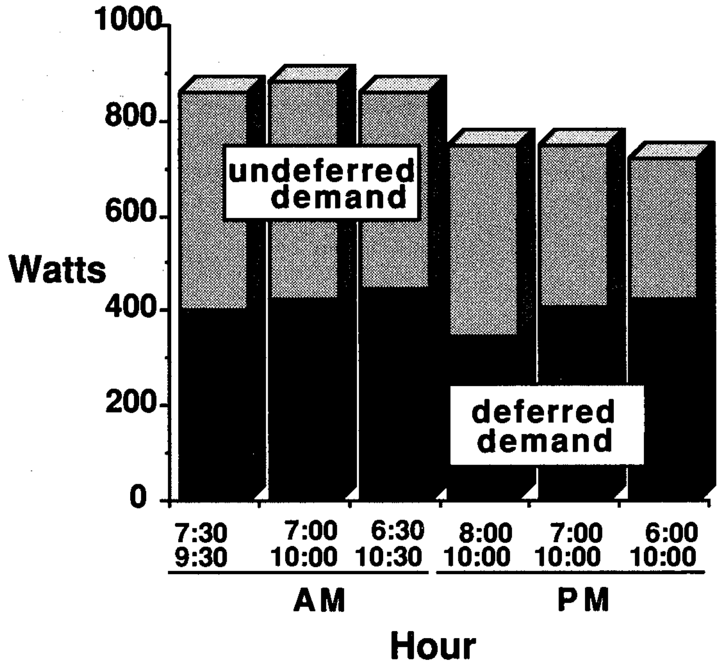

Figure 7. Average deferred water heater demand per water heater compared to deferred demand

Finally, one of the rationales for load control is that demand can be deferred without a substantial reduction in energy sales. For each of the morning control actions, the average total energy used was calculated from the beginning of the control action to 7-1/2 hours after control was released. Table I shows the results of these calculations as well as the calculation for non-control days. These data show that energy supplied by the utility was reduced by approximately 1 kW for each of the three control actions.

Table I A comparison of energy consumption (watt-hours) during and after control actions on control and no control days

Control Action	Energy on control day	Energy on no control day	Difference
7:30-9:30	5,120	6,040	-920
7:00-10:00	5,618	6,852	-1,234
6:30-10:30	6,630	7,554	-1,194

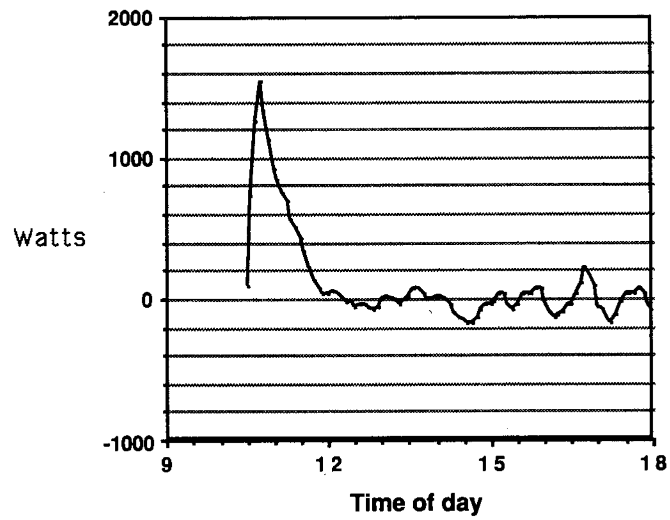

Figure 8. A plot of the difference in diversified load on a control and no control day after a four hour control action

CUSTOMER HOT WATER USE AND LOAD CONTROL ACTIONS

An important issue in direct load control is whether the customer experiences deprivation of service. Most studies have determined the effects of direct control by tracking customer complaints. The Athens Utility Board did receive some complaints from customers, but these represented fewer than 5% of the customers under control. A more direct method of ascertaining the impact of load control on customers is to examine the amount of hot water used by the customers. This can be estimated by calculating the amount of water heated based on the amount of electricity used and comparing that with the effective size of the tank. The calculation of the amount of hot water is:

$$m = \frac{E}{Cp\Delta T}, \text{ where:}$$

m = pounds of water

E = the diversified energy use of the water heater,

ΔT = the temperature difference between the inlet temperature and the temperature after heating in °F;

Cp = the specific heat of water = $\frac{(1\,\text{Btu/lb})}{°\text{F}}$.

For conversion of units, 1 watt-hour = 3.415 Btu. Pounds of water were multiplied by 8.3 to get gallons of water per household.

This calculation requires both the inlet temperature and the actual temperature of the tank. Neither of these values was known directly. However, the temperature of the water at the Athens supply tank was available. For the period of interest, the water temperature at the supply tank was approximately 50° F. The movement of the water through underground pipes and the location of water heaters in heated and unheated spaces made it unlikely that water at the inlet was the same as the system temperature. The amount of the variation was unclear. Nonetheless, the system temperature provided a useful guide. In lieu of a measurement of the temperature in the tank, we assumed that the water would be heated to 140° F. This was consistent with the setpoints recorded by the installers. Thus, the estimates were based on the assumptions of a 90° temperature rise. Thermal losses also have been ignored.

On non-control days the household with the largest consumption was estimated to use approximately 146 gallons of water. Half of the households used less than 45 gallons of hot water per day; 90% used less than 100 gallons of hot water per day.

Figure 9 is a series of graphs that display the percentage of water in a tank used during a control period and the cumulative percentage of households at that percentage level. The columns of graphs differentiate the morning and evening control periods. The rows of graphs differentiate the control actions. The percentage of tank can exceed 100% if the tank size is smaller than the amount of "hot" water used.

According to water heater manufacturers, the householder will begin to experience a decline in water temperature once 60% of the water in a tank has been used. The rectangular area shown where consumption exceeds 60% of the tank size is the area of insufficient service. The intersection of the cumulative use curve with the area of insufficient service gives the percentage of customers that experience insufficient service. This percentage of customers is represented by the solid dark area in each graph.

Several observations can be made by comparing these graphs. First, consumption during the morning control periods is greater than consumption during the evening control periods. Secondly, a maximum of 13% of the customers experience insufficient service (solid dark area) during the four-hour morning control period. Less than 7% experience insufficient service in either of the other two morning control periods. No customers experienced insufficiency of service during the two- and three-hour control periods in the evening. Less than 5% experienced insufficient service during the four-hour evening control period. At least some users experienced some deficiency during the four-hour control periods. These percentages are consistent with the fact that the Athens Utility Board received fewer than 5% complaints from customers under water heater control.

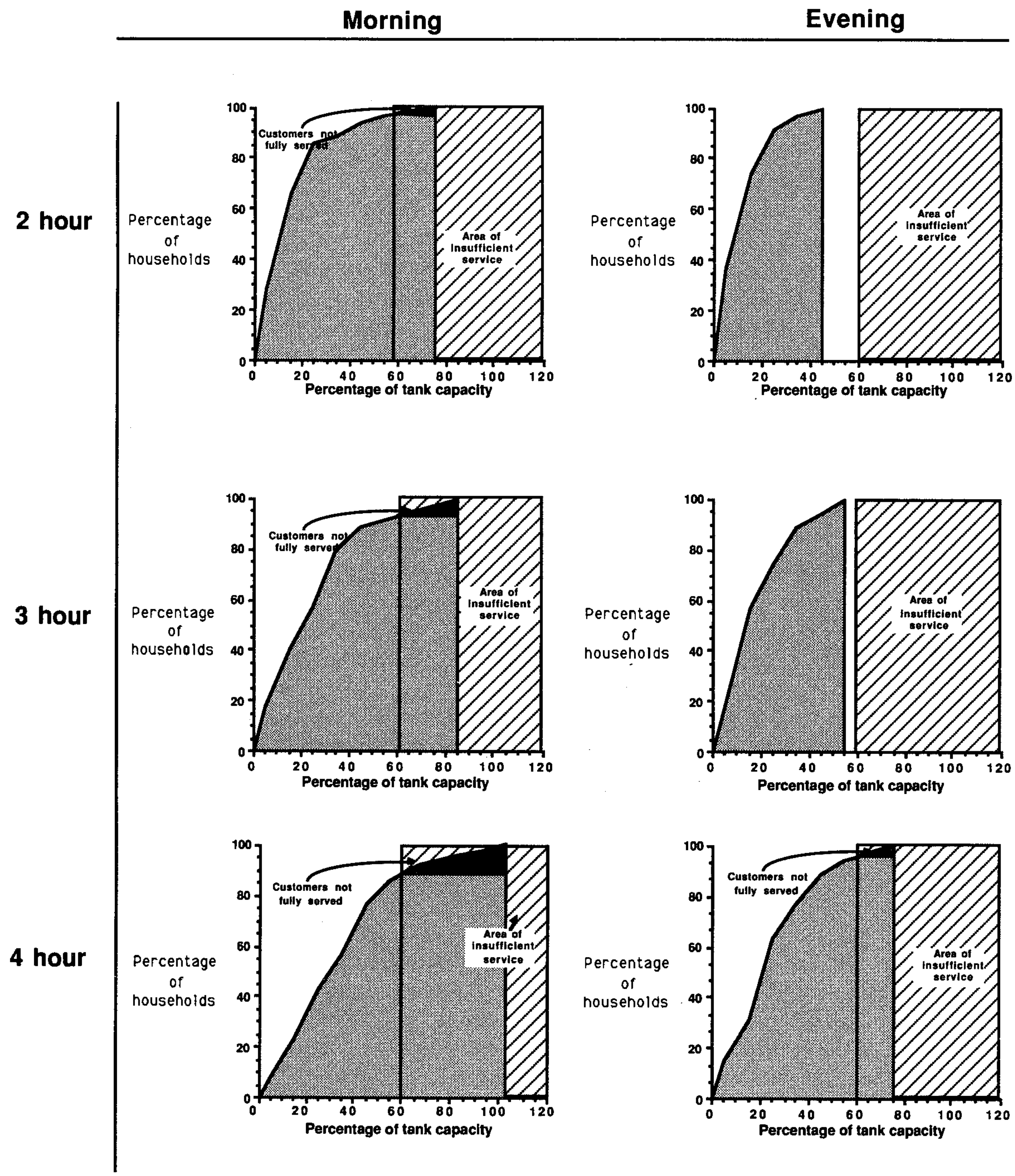

Figure 9. Customers experiencing deficient service as a result of water heater load control actions

DISCUSSION AND CONCLUSIONS

The paper describes the analysis of the winter water heater data from the end-use monitoring units gathered as part of the Athens Automation and Control Experiment. The winter diversified water heater load shape is bi-modal. The largest demand, approximately 1050 watts, occurs at 7:00 a.m. A smaller and broader peak of around 750 watts occurs in the evening. No more than 35% of the units operate at one time. The number of units starting in any five-minute interval is fairly constant throughout the day and is in the range of 3% to 6%.

The Athens customers were classified according to expected usage. Expected usage was determined on the basis of the number of persons in the household, the number of bathrooms, and the presence or absence of a clothes washer and/or dishwasher. There was a distinct variation in the daily load shape associated with expected usage class. This variation in load shape by class explains the bifurcation of the early morning water heater peak load. These variations provide an opportunity to develop alternatives to current load control shedding strategies.

The effects of six different water heater load control strategies were extensively investigated. The expected demand reduction ranged between 700 and 920 watts per unit depending on the control strategy and the time of day. Because the load control receivers did not function reliably, the actual reduction range was between 375 and 500 watts per unit. The highest diversified payback demand at restoration was approximately 2kW. This was about four times the expected load at that hour. The main effect of load control was largely dissipated within an hour and fifteen minutes after the control ended.

The data in this paper provide significant insight into hot water use. Eighty percent of the households use less than 80 gallons of hot water per day. Further, water is heated many times each day for short periods. The average runtime for water heaters reached a maximum eight minutes during the morning peak but was less than five minutes for most of the waking hours.

A comparison of estimates of hot water used with the hot water available in the water heater tank suggests that few households experienced a shortage of hot water as a result of the control actions. Fewer than 5% of the load control customers complained to the Athens Utility Board about the lack of hot water. The calculated values are consistent with this pattern of complaints.

Direct load control does reduce load and the cost of installing load control per kW is below that of peaking generation. However, the experience with the Athens project suggests that even after many years of industry experience with direct load control, there are still significant reliability problems and the utility will lose some energy revenues. There are some alternatives to direct load control.

One alternative is to replace the standard 4 kW heating elements in water heater tanks with smaller elements, for example, 2.5 kW. Recent verbal reports about a Missouri experiment suggest that this might significantly reduce peak water heating load. The rationale for the large elements was that they were needed for rapid recovery so that electric water heaters would be competitive with gas heaters. Our use data suggest that with a sufficiently large tank, downsizing the element will not lead to deficiency of service problems. Some preliminary investigation suggests that downsizing is effective if there are needle peaks but much less effective if the peak is fairly broad. Thus, downsizing might have different effects on the morning and evening peak for utilities like Athens.

Another alternative is storage water heating. The consumption data presented here clearly imply that storage water heating is a viable alternative. Approximately 80% of Athens' customers would manage nicely with a 120-gallon storage water heater. Storage water heating is attractive because it reduces daytime load and it can be used to build nighttime load. This may be particularly attractive to utilities with low power factors who would like to increase nighttime baseload.

To make storage water heating more effective, new control circuitry may need to be designed. The circuits should be designed so that the clocks could be synchronized frequently by the utility and the on and off times set remotely. It is not clear that separate metering is essential. Customers could be given a water heating credit on their bill. Such an approach might make electric water heating competitive with gas water heating.

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[2] **IEEE Bibliography on Load Management**, 85JH7337-9-PWR, Piscataway, N.J. IEEE, 1985. B. F. Hastings, "Ten Years of Operating Experience with a Remote Controlled Water Heater Load Management System at Detroit Edison," **IEEE Transactions on Power Apparatus and Systems,** Vol. Pas-99, No. 4, July/Aug., 1980. W. E. Mekolites, R. M. Murphy, and J. L. Laine, "AEP Water Heater Load Management Test," Proceedings of the American Power Conference, Vol. 43, 1981.

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