Analysis of Historical Residential Air-Conditioning Equipment Sizing Using Monitored Data

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Monitored data were analyzed to determine whether residential air conditioners in the Pacific Northwest historically have been sized properly to meet or slightly exceed actual cooling requirements. Oversizing air-conditioning equipment results in a loss of efficiency because of increased cycling and also lowers humidity control. Larger air conditioners are also more expensive to purchase. On the other hand, the penalty of undersizing air-conditioning equipment may be some loss of comfort during extremely hot weather.

The monitored data consist of hourly space-conditioning electrical energy use and internal air temperature data collected during the past 7 years from 75 residences in the Pacific Northwest. These residence are equipped with central air conditioners or heat pumps. The periods with the highest cooling energy use were analyzed for each site. A standard industry sizing methodology (Manual J published by Air Conditioning Contractors of America) was used for each site to determine a sizing estimate. Both the sizing recommendation based on Manual J and peak monitored loads are compared to the capacity of the installed equipment for each site to study how the actual capacities differed from both the estimate of proper sizing and from actual demands.

The characteristics of the maximum cooling loads are analyzed here to determine which conditions put the highest demand on the air conditioner. Specifically, internal air temperature data are used to determine when the highest cooling loads occur, at constant thermostat settings or when the thermostat was set down. This analysis of monitored data also provides insight into the extent occupant comfort may be affected by undersizing air conditioners.

Introduction

Air conditioners are a major source of energy use in the residential sector. Department of Energy (DOE) survey data indicate 33% of all homes have central electric air conditioners which account for 12% of all residential electricity use (DOE 1989a). The same data show residential air-conditioning use has rapidly increased with a growth of 19% from 1984 to 1987. It is postulated that some residential building contractors may tend to oversize air conditioners, perhaps by a large margin, for a number of reasons including as an attempt to ensure occupant comfort. This results in a loss in efficiency, because air conditioners run at highest efficiency when at or near full load. If the air conditioner is operating in part-load conditions, i.e., cycling on and off frequently, the efficiency is significantly lower per unit output and operating costs are therefore higher. Of course, even properly sized equipment will often be in part-load conditions, but oversizing exacerbates this problem.

The penalties of oversizing have been studied by Mclain and Goldberg (1984) using the DOE-2.1A simulation model. Mclain found that the seasonal energy efficiency ratio (SEER) decreased by about 0.2% for each 1% that the air-conditioner was oversized. For example, if air conditioners are oversized by 20% on average, this finding indicates that proper sizing would save 4% of the cooling energy and cost. Sizing considerations for air conditioners are discussed in the next section.

The End-Use Load and Consumer Assessment Program (ELCAP) measured electrical energy consumption and interior temperatures in about 400 residential buildings in the Pacific Northwest. Eighty of the residences have central air-conditioning systems, including heat pumps. The ELCAP data was used to study the maximum cooling energy use and the relationship of cooling loads to equipment capacities. This data offers a wealth of information on air-conditioner operation. The ELCAP study homes were chosen to represent a cross-section of single-family, detached, electrically heated residences in the Pacific Northwest.

The monitored data allows insight into how often cooling equipment is not sized properly and how occupant behavior affects cooling. Unfortunately, no occupant survey data is available on the perceived adequacy of the air conditioners in the ELCAP homes. The ELCAP homes provide an extensive data base for comparing rated cooling capacities of installed equipment to the capacity specified by a standard industry sizing method. This comparison is made in the section titled "Rated Capacities Versus Manual J Design Loads." These results are coupled with the findings in the analysis section to indicate how undersizing, properly sizing, and oversizing equipment translate into meeting occupants' cooling needs.

Sizing Considerations

For all cooling equipment that is purchased and installed, a selection of the equipment capacity must be made. There is not necessarily an ideal size for any given application because tradeoffs between comfort and economics must be considered. This section discusses issues related to selecting equipment capacities.

Builders have industry-recommended methods for sizing air conditioners, and building codes can also provide sizing constraints. However, builders may significantly oversize cooling equipment to cover uncertainties and ensure occupant comfort. Any discussion of sizing must consider comfort issues. In the hot dry climate studied, comfort is assumed to be defined by the ability of the equipment to maintain the temperature set by the occupant. Some occupants may prefer oversized equipment to ensure that the house remains comfortable at all times and can be quickly cooled down. If homeowners were fully informed of the sizing options, most would likely tolerate some level of discomfort for limited periods of time to save money.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Air Conditioning Contractors of America (ACCA) recommend the use of certain "design" conditions for equipment sizing (ASHRAE 1979; ACCA 1986). A climate-specific 2.5% outdoor air temperature value is commonly used for "design" conditions. This means that, on average, the outdoor air temperature will exceed this design temperature for only 2.5% of the hours from June through September (roughly 73 hours). The equipment should be able to maintain a recommended internal temperature of 75°F (23.9°C) for all hours at or below the design temperature. Comfort cooling must include both sensible (temperature reduction) cooling and latent (moisture removal) cooling. For the predominantly arid climates in this study, sensible cooling is the principal concern.

The ACCA load calculation methodology, Manual J (ACCA 1986), advises that "cooling only" equipment should be sized within 100% to 115% of the total calculated sensible load at design conditions. However, the discussion in the Introduction of Manual J warns about the loss of efficiency caused by oversizing and even suggests slightly undersizing the equipment:

> When equipment is oversized, efficiency is reduced, operating costs increase, and control over space conditions is lessened. Optimum efficiency and control occur when the equipment operates under full load. Since full load conditions occur only a few hours per year, properly sized equipment operates at over capacity and reduced efficiency most of the time. Oversizing the equipment aggravates this situation even more.
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> Slightly undersized equipment will provide comfort and efficiency most of the time, but space conditions will drift when extremes in weather occur. Overall, this is preferable to oversizing the equipment, but the increase in energy efficiency at the cost of a minor loss of comfort must be explained to the owner.

The BSR/ASHRAE Proposed Standard 90.2P (ASHRAE 1990) directs that equipment should be sized within 100% to 125% of the calculated sensible load. ASHRAE states in the *Cooling and Heating Load Calculation Manual* (ASHRAE 1979) that the lack of a safety factor in the calculation technique "...requires that the designer introduce any margin of safety by a positive action, rather than rely on an assumed hidden margin." Conversely, the Air-Conditioning and Refrigeration Institute (ARI) warns utilities about the efficiency losses due to oversizing in a guide for utilities that are planning incentive programs (ARI 1990). ARI recommends that contractors be required to use an approved load calculation procedure and proper unit sizing to qualify for rebates for high-efficiency equipment.

Heat pump sizing is more complex than air-conditioning sizing as consideration of both heating and cooling loads must be given. Manual J allows oversizing heat pumps by up to 25% if overall operating costs decrease. The Electric Power Research Institute's (EPRI) *Heat Pump Manual* (1985) recommends oversizing cooling capacity by 25% to 35% for colder climates.

The cooling capacity affects how rapidly the internal temperature can be decreased when a set down of the thermostat occurs. A thermostat set-down may impose severe demands on the cooling equipment. ASHRAE (1979) notes that: "Additional capacity may be required for intermittently cooled or heated buildings to bring the temperature...to the design indoor temperature within a specified time." The analysis of monitored data examines how often the peak cooling load results from a set down of the thermostat.

In summary, decisions about air-conditioning equipment sizing are bounded by unacceptably low capacity for cooling if undersized, and higher purchase price, operating costs, and potential loss of humidity control if oversized. (Humidity control is a function of operation time, which is reduced when oversizing occurs). The industry sizing calculation techniques are the best sizing methods available, but these techniques may often not be used by builders selecting air conditioners, as is examined later. Also, occupant preference is a factor in sizing; internal temperature and humidity levels that are adequate depend on the desires and needs of the occupants.

Analysis of Monitored Data

The ELCAP data included in this work were collected from August 1984 through August 1991. A monitoring device was installed in each of the houses with data sent via telephone line to a computer at PNL. Monitored instantaneous power levels were integrated over hourly periods to obtain the energy consumption drawn by the cooling equipment over the entire hour. One temperature sensor was installed in the main conditioned living area of each house. Data accuracy from each site has been checked both by manual and automated verification procedures.

On-site inspections at each of the ELCAP residences allowed inspectors to determine many of the actual, rated power input and output capacities of the cooling equipment. The inspectors were instructed to obtain the condensing unit designations from air conditioners and heat pumps. Unfortunately, they were only able to obtain this information for 60 of the 75 sites. When designation numbers were obtained, ARI Unitary Directories from 1958 to 1985 were used to look up cooling capacities and power input ratings for the equipment at standard ARI rating conditions.

The model numbers obtained in the inspections did not always allow the equipment ratings to be determined exactly from the ARI Directories but rather often only determined a possible range. This was because the power input and capacity for equipment often varied with the coil unit as well as the condensing units, and only the condensing unit was known. Furthermore, the ratings for any given condensing unit model can change from year to year and only an estimated range of years was available for when each house was built and the cooling equipment was purchased, such as 1975 through 1978.

This section uses the monitored electrical data to examine the highest cooling energy consumption rates to infer the adequacy of cooling equipment sizing for the ELCAP sites.

Data Processing. Of the 80 sites with central cooling equipment, 5 were eliminated from this analysis because of lack of data. Due to monitoring limitations, 62 of the 75 remaining sites did not have separate air-conditioner end-uses; instead space heating, ventilation, and air-conditioning (HVAC) were monitored together. Many of these sites had heat pumps, which may be in heating mode during cold periods in the cooling season. Because the inclusion of heating energy data in the analysis would produce erroneous results, steps were taken to ensure that only cooling data were considered. This was a simple procedure because the periods of interest were those where cooling demands were highest, i.e., during the warmest times of year. To this end, only data from June 16 through September 9 and from 1 p.m. through 8 p.m. were included (which is referred to as "summer afternoon"). These data filtering procedures were selected to focus on cooling periods while attempting to eliminate heating periods.

Several sites experienced a few abnormally high power values in the summer period that were not in the normal range for the cooling equipment at those sites. Further examination of the days with these high values using internal and outdoor temperature data and HVAC data indicated hours which were likely heating instead of cooling; these hours were eliminated from the analysis. These sites may have had other, unknown devices in addition to the known heating or cooling equipment on the monitored circuit, such as fans, contributing to the unexplained high power levels.

Analysis of Peak Cooling Energy Consumption. Visual inspection was used to determine from the monitored data whether energy consumption indicated the cooling equipment operated for hour-long periods at or near the equipment power draw. Summer afternoon energy consumption per hour for each site was plotted with the hours sorted such that the data were in ascending order, from lowest to highest hourly energy consumption. A significant set of hours with near constant energy consumption at the highest levels monitored indicates that the equipment is likely running continuously for these hours. The plots of the cooling energy consumption were examined along with the available ARI rated power input information to estimate the number of sites where the cooling equipment was running continuously for a significant number of hours. These plots for each site are shown in the appendix of a recently published report (Lucas 1992).

A few examples help illustrate the process of determining capacity-limited sites. Figures 1 and 2 illustrate examples of the sorted cooling energy consumption plots. Figure 1 shows a site where the air conditioner can be seen to run continuously for full hours and Figure 2 shows a site where the air conditioner never runs continuously for full hours. In these figures, the y-axis shows the monitored energy consumption per hour while the x-axis shows the number of hourly data points. Data from June 16 through September 9, from 1 p.m. through 8 p.m. were used to focus on periods where cooling loads are normally highest. Only energy consumption rates above 500 kWh/hr (i.e., 500 average watts) were graphed to focus on hours with significant mechanical cooling.

Figure 1 can be seen to be a site that has cooling equipment running continuously for a significant number of hours. The cooling consumption per hour in Figure 1 flattens out from about 4000 to 4400 kWh/hr, with about 200 hours at this level. The two dashed lines at 4400 and 5200 kWh/hr show the range of possible power input ratings for all air-conditioning units in the ARI directories with this site's condensing unit. This site's maximum energy consumption per hour is at or near the lower level for the power input ratings.

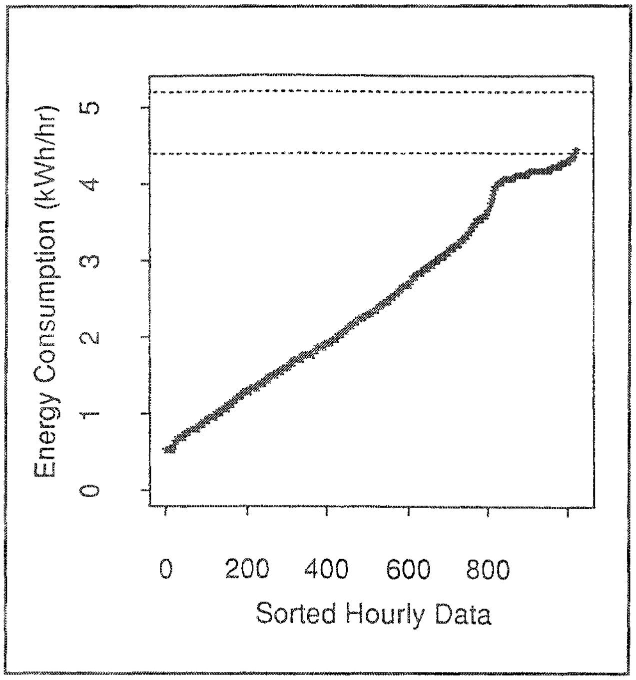

Figure 1. Cooling Power for a Site with Many Hours at Full Capacity. The dotted lines show the possible range of rated power input for the air conditioner.

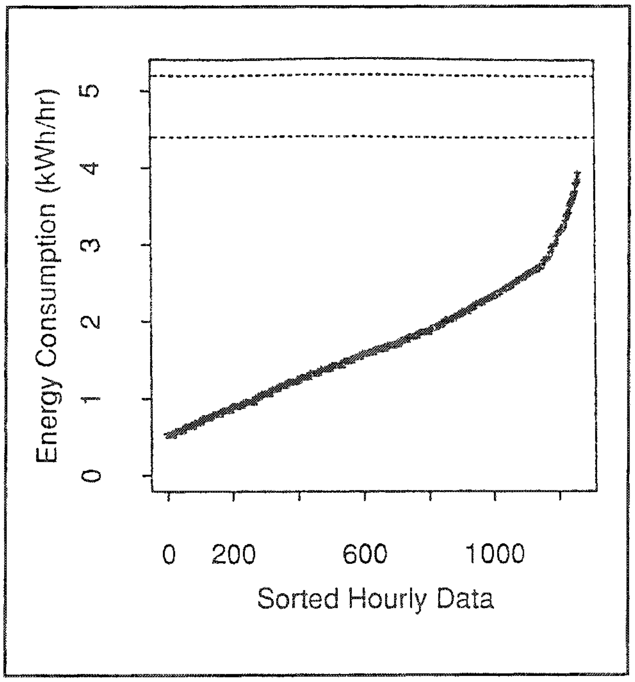

Figure 2. Cooling Power for a Site that Never Reaches Full Capacity. The dotted lines show the possible range of rated power input for the air conditioner.

Even though the equipment for the site in Figure 1 is occasionally running continuously for full hours at a time, the air conditioner at this site is not undersized according to Manual J sizing assumptions. This is because the air conditioner appears to have run continuously (i.e., at or above 4000 kWh/hr) for about only 1.3% of all June through September hours. The design calculation techniques essentially allow up to 2.5% of these summer hours to have continuous air conditioner operation. Note that this finding applies for the assumptions used in the sizing methodology; only the occupants can give an opinion about how adequate the cooling capacity actually is.

Figure 2 shows a site with an air conditioner that is oversized. The sorted energy consumption rates for the site in Figure 2 clearly never reach the possible range of rated power input for the air conditioner at the site. Also, the curve shows no signs of leveling out at the highest levels, which would indicate continuous operation over full hours. Note that the condenser units are from the same manufacturer and are the same model in the two sites shown in Figures 1 and 2. The Manual J sizing calculations indicate that the Figure 1 site has a design load about twice as large as that for the site in Figure 2. The monitored data bears out that the cooling equipment at the Figure 1 site does have larger cooling loads.

One caveat must be mentioned about the use of the sorted cooling data. The power input to cooling equipment is not constant, it changes with outdoor temperature and indoor wet or dry bulb temperature changes. Thus the curve in Figure 1 does not completely flatten out when full capacity is reached, but rather many hours occur in the range of 4000 to 4400 kWh/hr. The ARI rating is for 95°F (35°C) outside air temperature; many of the ELCAP sites experience higher temperatures. Therefore, some sites had maximum hourly energy consumption rates that exceeded the highest possible power input rating from the ARI directories.

Based on visual inspection of the sorted power data for each site, 13 of the 75 sites (17%) were judged by the author to have a significant number of hours of continuous cooling; these sites will be referred to as being "capacity-limited". A cutoff hourly energy consumption level above which the equipment was considered to be operating continuously was selected for each site based on visual inspection of the sorted power plots. The percentage of summer afternoon hours above the cutoff was determined for each of the 13 sites. This percentage ranged from 5% to 70% with a mean of 19%, well above the 2.5% allowed for in the design methodologies. Note again, however, that only afternoon hours, from mid-June to early September, were included to eliminate possible hours with heating instead of cooling. The overall average percentage of time of continuous equipment operation when all hours in June through September are included should be much lower for these sites.

The weather for the data collection period compares well with design condition assumptions. During the data collection period of the middle and late 1980s, summer outdoor air temperatures around the Pacific Northwest equal or exceed design temperatures close to the 2.5% of the time. Four out of five National Weather Service stations had temperatures at or above the design outdoor air temperature 2 to 3% of the summer periods; the fifth, Seattle, exceeded its design temperature 4.2% of the time.

Further examination was done to determine the effects of equipment capacity limitations. Internal temperature data were used to determine if the temperature was higher when the air conditioner was running continuously for full hours than the temperature at normal cooling conditions. The 13 capacity-limited sites had a higher average summer afternoon temperature when any air conditioning was occurring than the other sites 79.3°F (26.3°C) to 77.0°F (25.0°C). The statistical hypothesis that the capacity-limited sites have a higher average temperature when cooling is true at a 0.05 level of significance. Compared to the other sites, the 13 sites also had a higher temperature increase from the mean of all cooling hours to the mean of peak cooling hours, 0.7°F (0.4°C) to 0.4°F (0.2°C), though the difference across the two groups is not statistically confirmed at the 0.05 level. These findings indicate the occupants in the capacity-limited sites may suffer because of the limitations of the cooling equipment.

Characteristics of Peak Cooling Loads. This section reports on how occupant behavior affects the cooling energy consumption, i.e., what are the thermostat setpoints when the peak cooling occurs for each site. At issue here is whether or not the highest cooling energy consumption is commonly caused by a set down of the thermostat, perhaps when occupants return from work or school in the afternoon. Naturally, a set down can put more severe demands on the air conditioner because it must lower instead of just maintain the internal temperature. Thermostat set downs are of interest not just for sizing considerations, but because they may cause higher utility peak loads for the cooling season.

The internal temperature change from one hour before the peak hour to the peak hour was determined. The 13 capacity-limited sites were not included here as occupants of these sites have less ability to influence the temperature. For all summer days when cooling occurred, the average set down was 1.1°F (0.6°C) and average temperature decreases greater than 2°F (1.1°C) occurred at 17% of the sites, which indicates that most occupants do not frequently make major changes to thermostat settings for cooling.

Occupant behavior related to the frequency of using air conditioning to maintain comfort was studied. Figure 3 shows, for all sites, the percent of hours that cooling power was above 500 kWh/hr in the summer afternoon hours and the average internal temperature for the same time periods. The circled points show 12 of the 13 sites considered to have inadequate capacities (the 13th did not have temperature data). This figure illustrates the wide range of behavior exhibited by occupants in cooling their homes. The sites in the two right-hand quadrants are frequently cooling, but have different setpoints. The sites in the lower left quadrant are likely in mild climates that require little cooling, while the sites in the upper left quadrant are "sufferers" who use the air conditioner infrequently despite high internal temperatures. This wide array of behavior is consistent with DOE national survey

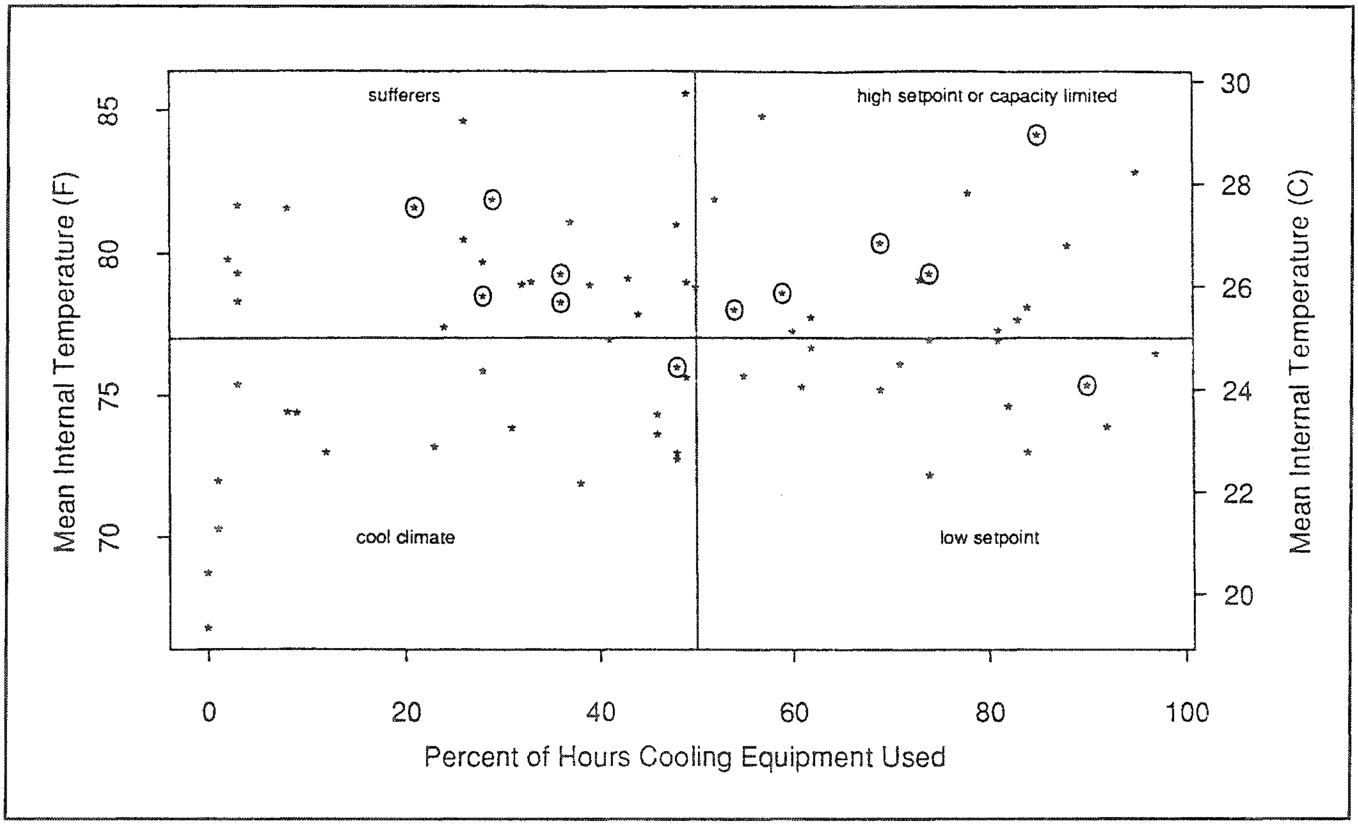

Figure 3. Mean Summer Afternoon Internal Temperature Versus Percent of Hours Cooling. Sites thought to have inadequate capacity have circles around the asterisks.

data (DOE 1989b) which shows that, during the summer, 34.9% of occupants reported turning on the air conditioning only a few times, 23.5% reported turning on the air conditioning quite a bit, and 32.4% reported having the air conditioning on all the time.

Rated Capacities Versus Manual J Design Loads

The rated capacities, or possible range of capacities, for the installed cooling equipment were determined from the ARI directories for 60 of the ELCAP sites. These were compared to the design loads calculated with the Manual J procedure for the same sites. The goal here is to compare how cooling equipment has historically been selected relative to proper sizing techniques.

Introduction. Information needed for Manual J sizing calculations was obtained from the inspections; however, this information was not always complete. For many sites, assumptions had to be made about foundation insulation, exterior shading, and other input into the Manual J methodology. A 20% increase to the design load was applied in the Manual J calculations to account for losses due to ducts assumed to be located externally; this adjustment is included in the 100% design load. The report, *Heat Loss Characteristic of the Residential Sample* (Conner et al. 1990), further discusses the uncertainties about ELCAP sites' construction details due to incomplete information on the buildings.

Note that the set of testing conditions for determining the capacities in the ARI Unitary Directory are somewhat different from the design conditions used by Manual J and ASHRAE. (When actually selecting equipment, manufacturer's performance data should be used.) The ARI capacities are based on a 95°F (35°C) outdoor design temperature, an 80°F (26.7°C) internal temperature and an indoor wet-bulb temperature of 67°F (19.4°C). The sizing techniques use the ASHRAE outdoor design temperature for the local climate and assume a 75°F (23.9°C) internal temperature and a wet-bulb temperature of 64°F (17.8°C). The ARI Directory gives no information about the split between sensible and latent capacity. The latent capacity is a less significant consideration in the Pacific Northwest than for many other parts of the nation as the hotter, inland regions (where most of houses studied in this paper are located) are very dry. In fact, most Pacific Northwest climates do not have any latent heat gain from outside air at design conditions (ACCA 1986).

Despite using different assumptions, the ARI rated capacities are comparable to the Manual J design loads because of offsetting effects. Cooling capacity decreases with increasing outdoor temperature and increases with increasing indoor temperature. The higher ARI internal temperature assumption of 80°F (26.7°C), which gives a higher sensible capacity, is somewhat offset by generally lower outdoor design temperatures in the Pacific Northwest. Even if the ARI capacities are considered too high because of the high internal temperature assumption, the low latent loads of the Pacific Northwest make the sensible capacities of any given cooling unit higher than they would be for more humid climates, making a high capacity estimate more reasonable.

Findings. The ratio of actual equipment capacities to design loads calculated with Manual J for the 60 sites where equipment information was available are shown in Figure 4. The bars represent the range of possible ratios for each site because often only a range of capacities, not the exact capacity, was known. The bars are sorted from lowest to highest ratio. Dotted horizontal lines are shown at 100% of the design load, and at 115% and 125%, the recommended limits of oversizing discussed in the section on sizing considerations. Asterisks are shown above the 13 sites that were identified from the monitored data as operating at full capacity for significant periods.

About half the sites have cooling equipment that is oversized above the 125% limit ASHRAE recommends and about two-thirds of the sites are above the 115% oversizing limit of ACCA. About 10 sites have cooling capacities below the design cooling load and are undersized. The mean sizing ratio using the low end of the range of possible capacities for each site is 1.39; and 36 sites have ratios below this mean sizing ratio while 24 have ratios above. The mean ratio using the high end of the range of possible capacities for each site is 1.48. Even using the low end of each equipment's possible capacity range, the hypothesis that the sample mean for the ELCAP sites are sized above the 125% oversizing limit is true at a 0.01 level of significance. Note that air conditioners were oversized 1% more than heat pumps on average.

Clearly, there are occupant-controlled factors affecting cooling loads such as internal heat gain levels, cooling setpoint, and solar heat gains that cannot be known in any design calculation. However, Figure 4 shows that the Manual J technique is usually a good indicator of what cooling capacity is needed to prevent the equipment from running at full capacity for long and frequent periods. Most of the 13 sites that were identified as having capacity limitation problems have low capacity to design load ratios. Statistically, the hypothesis that the mean ratios for the capacity-limited sites is below the mean ratios for the other sites is accepted at the 0.01 level of significance.

Interestingly, the four sites with the lowest ratio were all identified as operating at full capacity for significant periods. However, four sites had equipment that appear to be excessively oversized based on the Manual J calculations but yet were determined to have capacity limitations. Dealers may have doubts about sizing calculations and greatly oversize equipment to try to guarantee occupant comfort at all times to insure they receive no complaints. An issue not examined here is that maintenance problems such as improper refrigerant charging may result in equipment that does not adequately cool even though the equipment capacity should be sufficient.

Conclusions

The ELCAP hourly energy data base allowed insight into how adequately cooling equipment is sized to meet the needs of occupants. Clearly, proper sizing techniques have not always been used. Proper sizing of cooling equipment is important for both economic and comfort reasons. Note that these results are only for the Pacific Northwest and are historical in nature because the cooling equipment was installed in the 1960s, 1970s, and early 1980s. Key findings are summarized below.

- Monitored cooling energy data revealed that 13 out of 75 sites (17%) appeared to operate frequently at full cooling capacity during the summer.
- When cooling occurred during summer afternoon hours, internal air temperatures were an average of 2.3°F (4.1°C) higher for these capacity-limited sites relative to other sites. This indicates that occupants with undersized equipment do suffer a loss of comfort.

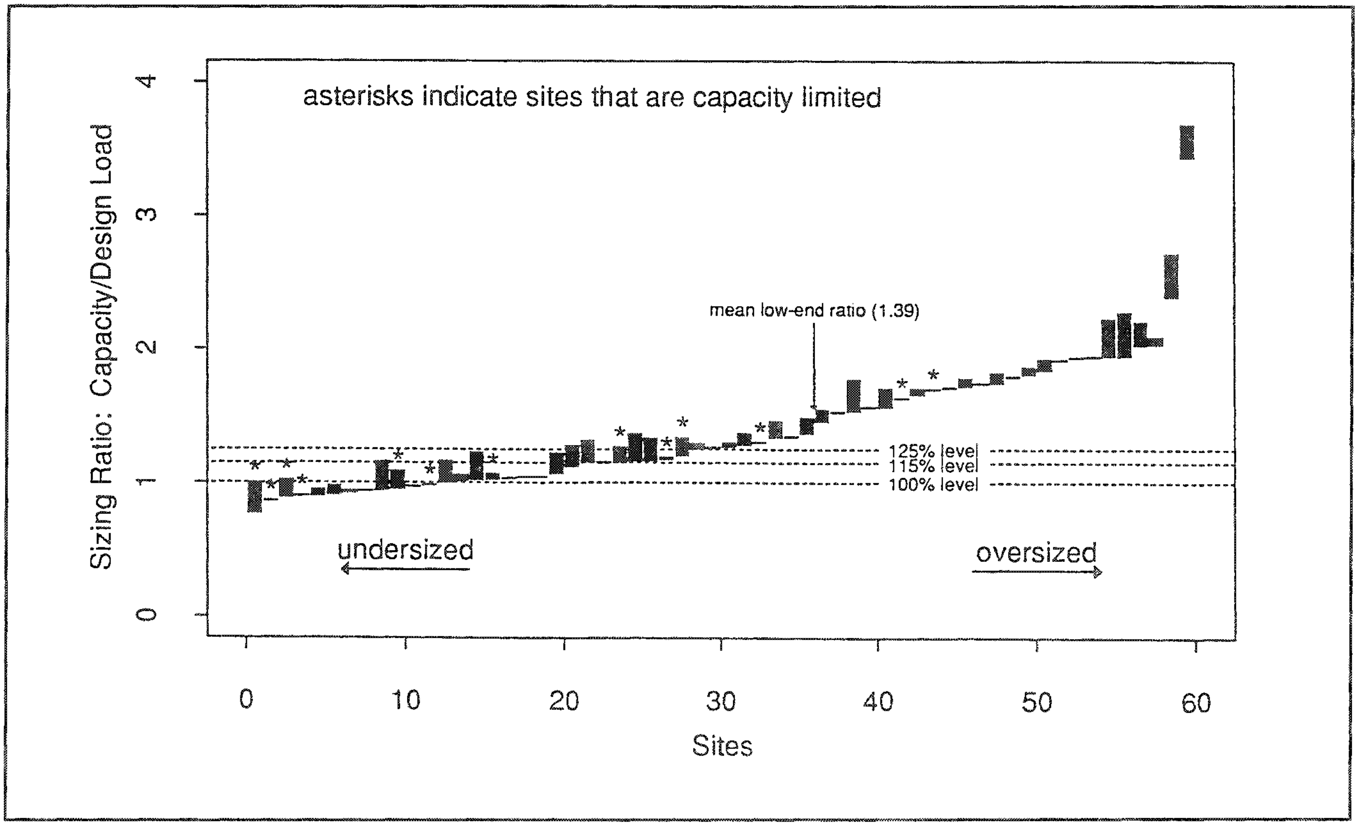

Figure 4. Ratios of Cooling Capacities to Design Cooling Loads for 60 Sites. Each bar is one site; the bars show the possible range given the uncertainty about actual capacities.

- In sixty Pacific Northwest homes, cooling equipment are 39% to 48% oversized, on average. About half the sites have cooling equipment oversized beyond the industry-recommended 25% limit and about one-sixth have undersized equipment.

- The cooling equipment of most of the 13 sites that operated frequently at full cooling capacity were undersized or properly sized. However, 4 of these 13 appear to be oversized.

- The ELCAP data indicates a reasonable average downsizing of 20% is available from existing cooling capacities. Previous research shows downsizing by 20% would save 4% of the cooling energy and cost. By applying this potential to residential central electric air-conditioning expenditures on a national basis (DOE 1989a), an annual savings of about 285 million dollars may be achievable. In addition, capital costs would be reduced.

- The actual average cooling capacity for 60 Pacific Northwest homes was 2.56 to 2.71 tons (9001 to 9528 watts), while the average Manual J design load was 1.96 tons (6891 watts).

- The mean internal air temperature was 77.4°F (25.2°C) for all sites when cooling occurred in summer afternoon hours. This is above the 75°F (23.9°C) temperature assumed for sizing calculation purposes.

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