Does the Air-Conditioning Engineering Rubric Work in Residences?

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ABSTRACT

Over sizing of residential air-conditioning is the industry and consumer norm. Though long-standing published industry practices and protocols attempt to encourage correct sizing, they have not been effective in preventing the tendency toward dubious margins of "safety". This has adverse consequences for performance and energy use. Conventional compressor-based cooling works best when sizing addresses the performance of the complete system under all--not just extreme--conditions. Alternative cooling systems that do not use compressors are disadvantaged in this oversizing derby because they are capacity limited in most situations.

Attempts to establish that alternative cooling performs well or to optimize the effectiveness of compressor-based systems confront interesting questions: What is the range of expectations of residential occupants? What do climatic design conditions and "exceedence" mean in the residential setting? How do industry sizing techniques interpret the "design temperature" framework? Can consumer desires for instant relief on the hottest day of the year be reconciled with the inherent statistical nature of design conditions, diminishing marginal returns on system capacity and poor part load performance? Success in mass adoption of efficient cooling requires examination of these issues. We explore the questions in the context of non-compressor cooling applications in "transition climates" where summer temperature extremes far exceed design conditions. We argue that design criteria addressing other aspects of performance in addition to meeting the load on "design days" can increase consumer satisfaction, lower costs, and reduce energy consumption.

INTRODUCTION

Attempts to introduce low-energy cooling strategies to the residential market face an obstacle in the prevailing practices for sizing air conditioners. These practices lead to the installation of systems having more compressor capacity than industry recommendations would indicate is best. The capacity constrained nature of most alternative (i.e., not-compressor based) cooling systems does not allow the dubious luxury of oversizing. For compressor-based systems, both overall performance and energy performance are better when systems are not oversized. Proper sizing is encouraged by the air-conditioning engineering design rubric fostered by the Air Conditioning Contractors of America (ACCA) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Unfortunately, for reasons that we discuss, this guidance has failed to eliminate the prevalence of oversizing. Market transformation to low-energy cooling will require some additional strategies.

The intent of the recommended design approach

Load calculation and sizing protocols recommended by air-conditioning industry organizations recognize that it is impractical to design for the simultaneous occurrence of all possible cooling loads, including the most severe weather. Load diversity reduces the actual loads from the worst case. In addition to acknowledging the diminishing marginal benefit for increased capacity, this sensible approach recognizes that the overall system performance is improved when sizing is for less than the highest possible load. Operation is thus optimized under the most prevalent conditions rather than under the rare worst conditions.

The most important way in which load diversity is recognized is the use of a "design temperature" or "design day" that is a hot (but not the hottest) condition typical for the location in which the cooling system is to be installed. The design temperature criterion is characterized by the amount of time that the weather will be hotter than the design temperature, the "trans-design" conditions or "exceedence."[1] The cooling system is sized to achieve the desired indoor conditions under the design load including the design outdoor condition. This engineering rubric tolerates limited excursions from target indoor conditions during trans-design periods. Meeting the load an adequate amount of time becomes the single design criterion.

Taken in isolation, this convention could imply a behavioral model that assumes that people will not complain or demand better performance as long as conditions that are perceived as uncomfortable do not exist for more than a limited number of hours. If meeting this single exceedence criterion were sufficient for market acceptance, then this goal would be relatively easy for alternative cooling strategies to meet. This is because the concept of exceedence offers the flexibility to accept excursions from what ever comfort criteria are established. Further, tolerance for exceedence may be more important to all types of cooling in the unique California transition climate.

A single design criterion is not adequate

The single criterion design strategy depends largely on the assumed tolerance for exceedence to counter the engineer's instinct to meet the load under all circumstances. Though the concept of exceedence is an essential component of a robust design philosophy, it is not up to the task of balancing the factors encouraging ever larger systems. Current prevailing practice relies largely on rules of thumb, being implicitly (and sometimes explicitly) motivated by the desire to assure that homes are designed to have zero exceedence. Characterization of performance for the consumer boils down to "but is it big enough?" or even "bigger is better" (Abrams 1986; Vierra et al. 1995). It is well recognized that the result of this practice is oversizing, leading to poor overall comfort and energy performance of the air-conditioning system (Proctor, Katsnelson and Wilson 1995).

The status quo appears ultimately to be based on conventional wisdom about consumer preferences for instant relief on the hottest day of the year and for absolute guarantees about performance (Vierra et al. 1995). This quest for perfection persists in only one of the many aspects of air-conditioning performance, in spite of the fact that the consumer regularly cost-optimizes and accepts much more frequent and important inconveniences concerning other aspects of their home or their life.

The weakness of the single criterion design approach is related to the limitations of the associated simplistic behavioral model. In fact, peoples' satisfaction with the thermal performance of their dwelling places has many dimensions that are not reflected by the load carrying capacity of the cooling system. Also, exceedence can be an ambiguous measure of performance, with large excursions from desired conditions on the hottest days not distinguishable from milder variations from the norm that would be characteristic of a thermally superior house. In the end, it may be that the weakness of the single criterion approach embodied in the engineering design rubric is best illustrated by its failure to supplant the current practice.

Characteristics of alternative cooling systems

Alternative cooling systems use the natural cooling potential of the air (ventilation), water (evaporative cooling), and ground to maintain indoor comfort. Several references (Abrams 1986; Cook 1989; Feustel, de Almeida and Blumstein 1992; Huang and Zhang 1995) document the capabilities of ventilative, indirect/direct evaporative, hybrid, and other technologies. Since these systems require electricity only for air or water transport, they generally use only a fraction of the energy needed for mechanical cooling. However, whereas a compressor-based refrigeration cycle can provide some measure of heat extraction at all hours, the cooling capacities of low-energy cooling systems are dependent on ambient air conditions. Capacity can be small or nonexistent under certain conditions, and in particular during peak cooling periods. Thus, alternative systems cannot--in the conventional sense--be oversized to handle trans-design conditions. Also, the operation of alternative systems generally requires some planning ahead (e.g. precooling during nightime hours); with recovery from errors in planning being relatively slow. Compressor-based systems can quickly begin to react to a period of inoperation by providing a supply of cold air from registers.

These limitations of alternative cooling systems are mitigated because these systems are necessarily coupled with building designs that minimize heat gain and increase thermal stability. One can expect such integrated systems to have improved comfort under any conditions because of reduced temperature variations within the house, decreased radiant heat exchange between occupants and warm ceilings/walls or windows, and fewer localized discomfort scenarios such as direct beam sunlight in the summer. These house/cooling systems also have the advantage of failing gracefully in that the indoor conditions will likely be better than those of a conventional house when controls fail to operate the cooling system optimally, the cooling system fails or is intentionally left off while occupants are away, or the capacity of the system is exceeded by extreme weather conditions. Unfortunately, none of these advantages is reflected in a single criterion focused on meeting the cooling load.

Compressor-based system optimization

Correctly sized compressor-based systems provide better overall performance than oversized systems that could conceivably handle trans-design conditions. Theoretical analysis, measured data, and field experience all confirm that compressor-based systems are more efficient when right sized, avoiding cycling losses. Less cycling also improves air mixing and produces more consistent temperatures. In addition, proper moisture removal is insured, though this can be less of a concern in dry climates (Henderson 1992; Lucas 1992; Neal and O'Neal 1992; Proctor, Katsnelson and Wilson 1995; Reddy and Claridge 1993).

The first cost penalty for oversizing is of importance as are the apparent maintenance cost and equipment life penalties associated with more frequent cycling (Abrams 1986). First-cost issues become clear when cost-optimizing a conventional system including the ductwork distribution system. In this case, putting first-cost resources into improved ductwork instead of extra compressor capacity will also improve overall performance and comfort (Modera 1996; Treidler et al. 1996)

Interestingly, the introduction to the ACCA load calculation manual indicates that slight undersizing is overall preferable to oversizing, stressing a need to explain the trade-off, including a minor comfort loss, to the house owner (ACCA 1986). Other industry guidance provided with load calculations provides a mixed message about the preferred amount of under or over sizing and the appropriateness of margins of safety (Lucas 1992).

THE EXISTING SIZING RUBRIC

The existing sizing rubric is an interplay of comfort criteria and exceedence allowance corresponding to the weather conditions chosen as design conditions. It forms part of the basis for load calculations recommended by ACCA and ASHRAE.

Comfort criteria

The ACCA residential air-conditioning load calculations recommend the use of 24° **C** (75° **F**) and 50 to 55% relative humidity as inside design conditions, with the caveat that the owner, builder or codes can specify otherwise (ACCA 1986). This is with the assumption that uneven loads in the residential setting will cause temperature variations of plus or minus 1.5° **C** (3° **F**) in various parts of the house (Hunt, 1995). The resulting band is remarkably similar to the width of the ASHRAE comfort zone under the typical office example conditions, but approximately 0.5° **C** (1° **F**) lower overall. There is an optional plus or minus 2.5° **C** (4.5° **F**) range that can be specified which allows a 10% derating of the load.

The ASHRAE standard for "thermal environmental conditions for human occupancy" is somewhat more robust, defining comfort criteria for widely differing situations with varying activity levels and clothing levels (ASHRAE 1992; 1995). The standard's criteria for acceptability is worth noting. The stated purpose of the standard is to "specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space" (ASHRAE 1992, 3). This includes both overall ambient thermal conditions and other factors related to non-uniformity of the thermal environment.

Exceedence as embodied by design weather conditions

The exceedence aspect of the design rubric is embedded in design weather data. The recent addendum 55a-1995 to ASHRAE Standard 55-1992 explains in its section on compliance that: "Design weather data are statistically based and established to acknowledge certain percentages of exceedence (i.e., 1% design, four month summer basis, 29 hours of exceedence). This recognizes the impracticality of providing an HVAC (Heating, Ventilating, and Air-Conditioning) system which can meet all loads under all weather conditions that could be encountered in its lifetime. Thus, in practice, the requirements of the standard cannot be expected to be met during a number of hours equivalent to the design weather data exceedence percentage or during excursions from the design conditions" (ASHRAE 1995, 3).

The tolerance for exceedence has historically been implicit in the design weather data published by ASHRAE, with the variety of exceedence levels provided to "...enable the engineer to match the risk level desired for the problem at hand" (ASHRAE 1993, 24.1). However, the connection with the comfort criteria was only recently explicitly established with the addition of the addendum 55a-1995 explanation.

It is important to remember that a system will only incur excursions from desired comfort conditions corresponding to the specified exceedence level if all other design loads occur concurrently with severe weather. In practice, this simultaneous loading is unlikely to occur (Abrams 1986). This load diversity represents an inherent margin of safety built into the rubric.

Current interpretations and issues in the residential setting

The ACCA procedures list design temperatures for a single exceedence level (2.5%, 4 month summer basis, 73 hours) for their manual cooling load calculations (ACCA 1986). There is no explanation or description of any options with respect to choice of exceedence level for cooling calculations. A brief explanation of the concept of exceedence, including the impracticality and inefficiency of designing for record low temperatures, is provided in the section on heating load calculations.

Also of interest is the assumption that the air-conditioning system will be operated on a 24-hour per day basis with the thermostat always set at the indoor design temperature. Certainly, the provision of extra "pull-down" capability to allow perfect performance with the cooling equivalent of "set-back" would lead to undesirable oversizing. However, at face value, the lack of this capability would appear to be at odds with energy or load management strategies and emerging residential time-of-use rate structures which would dictate that air-conditioning be left off when the house is not occupied (i.e., when occupants are all at work during the day). Consideration of the safety margin represented by load diversity helps to explain this apparent paradox.

Prevalence of use of existing guidelines. The ACCA design guidelines enjoy limited use for conventional compressor systems, with more than one study finding a prevalence of oversized air conditioners (Lucas 1992; Proctor, Katsnelson and Wilson 1995; Vierra et al. 1995).[2] At the same time, deficiencies in installation and duct work typically reduce system performance and impact comfort. Thus, the current conventional residential cooling market does not provide a robust test for the rubric. For alternative systems, it must be noted that the ACCA manual indicates that it should not be used to estimate loads for residential structures with unusual or atypical design features, specifically including passive solar homes.

Unique issues in residential applications. Typical design calculations, oriented toward the commercial office building, assume a definable occupancy pattern, uniform or at least well-mixed indoor conditions, and consistent occupant requirements for comfort. Such assumptions are suspect when used in designing air-conditioning systems for residences where the occupancy is erratic, comfort requirements fluctuate due to different clothing and activity levels, and where temperatures may vary substantially from room to room due to different solar exposure, poor air mixing, and stratification in a two story house.

Practitioner perspectives

There is skepticism and distrust of the rubric among those who will eventually have to help implement low-energy cooling. In one 1994 planning exercise for the development of compressorless house designs in California climates,[3] a short-lived consensus was that a 9 hour exceedence criteria (0.1% annual basis) should be used. A representative opinion was that only one afternoon per year of exceedence from the indoor design comfort conditions was acceptable. Given uncertainty in the design and analysis, this is approaching a zero tolerance for exceedence.

Apparently alternatively cooled houses face a double standard. As previously noted, the ACCA recommendation for conventional systems uses a 73 hour exceedence level (2.5%, four month summer basis). In shifting to an annual basis, ASHRAE is abandoning the 9 hour (0.1%) criteria in favor of design weather data for 36 hours (0.4%), 88 hours (1.0 %), and 175 hours (2.0%) exceedence. The previously noted diversity effects are again relevant here. The higher level of scrutiny for low-energy systems may not acknowledge that the exceedence periods will almost always be reduced by the non-concurrence of the internal and solar loads.

The single criterion is also difficult to use in conventional marketing. Consider an air-conditioning contractor describing the performance of the new air-conditioning unit that they are bidding on. Assume for the moment that they rigorously applied ACCA manuals in sizing the system. To describe the sizing rationale, the contractor would have to inform the customer that the system that they are offering may not work (well) for many afternoons per year. Or that the system may not even work (well) on the day of the bid (if you believe that many air conditioner sales happen on the hottest days of the year). Can the diversity considerations be adequately explained in this context? A small marketing problem to say the least!

THE "TRANSITION CLIMATE" CONTEXT

The research that prompted this discussion is focused on development of alternatively cooled houses for the "transition climates" of California. The question of the frequency and severity of exceedence conditions is particularly germane to the unique characteristics of this region. "Transition climates" is a loosely-defined term applied to locations 10 to 30 miles inland where the climate is alternately dominated by the cooler coastal air or the warmer drier continental air of the Central Valley in the north and the desert regions in the south. This interplay of coastal and inland influences results in a wider range of conditions. Whereas the coastal areas are generally mild, and the inland area have uniformly high daytime and low nighttime temperatures, the transition climate is more episodic.

One way to examine this climate variability is to compare ASHRAE design temperatures at the different exceedence levels. At the higher levels, (i.e., more hours above the design temperature) temperatures in the transition climate are as much as 4.5° **C** (8° **F**) below those of Central Valley locations. At the lower exceedence levels , the temperatures in the transition climate are only 2° **C** (4° **F**) below those of the Central Valley. The impact of this on house design practices is that the tighter the exceedence criteria, the more cooling design conditions in the transition climate will resemble those in the hotter inland areas (Huang and Zhang 1995).

More severe "exceedence" conditions test the rubric

Perhaps the most distinguishing feature of California transition climates is that the weather extremes exceed the design conditions by an unusually large amount, exacerbating any breakdown in the crucial behavioral model. The several afternoons that exceed the design conditions are not just a little hotter, but often are "heat storms" that are known in Southern California as "Santa Anas". Thus, the California transition climate presents a particularly vexing test of the exceedence rubric and associated implied behavioral model.

The paradox of the California transition climate. The very large and growing, but very infrequent residential air-conditioning load in the transition climate exemplifies "the load from hell" for the electric supply infrastructure (Lovins 1992, 6). This load has been characterized as a 100-200 hour per year phenomenon in parts of California . The cost of maintaining system capacity to serve this load is much greater than the revenue currently obtained from it. So, from the economic perspective, alternatives to compressors are very desirable in the transition climate. But 100-200 hours is uncomfortably close to the hours of exceedence for the looser ASHRAE criteria . It would seem that the transition climate load invalidates the behavioral model implied by the single criterion approach, with consumers purchasing air conditioners (and demanding compressor cooled houses) solely to deal with what are the trans-design or "acceptable" exceedence conditions. Should the California transition climate be considered the best climate for implementing alternative cooling systems or the worst?

Theories about adaptation to climate. The rubric and model may not be rigorously tested in other cooling climates because of adaptation effects that are only beginning to be studied. However, adaptation may not fully apply to the trans-design conditions in the California transition climates. Periods of severe weather do not sneak up on California occupants slowly like a sweltering Florida or blazing Arizona summer. They manifest themselves in "heat storms" which hit in a few periods of 3-5 days over the summer where temperatures can be 5° **C**

to 10° C (9° F to 18° F) hotter than an average summer day. If an adaptive response takes more than one day, it will not help in most of California.

Unlike full-on physiological heat acclimatization which can take up to a month, it has been speculated that comfort "adaptation" derives from expectations based on some weighted running mean of the previous weeks' weather (de Dear 1996). Residents may be less tolerant of the trans-design conditions in the California transition climate than they would where trans-design conditions are just incrementally hotter than the day before. Interviews with residents of California transition climate areas also suggest the opposite possibility: that the relatively short durations of "heat storms" make them tolerable. Because high heat is likely soon to be succeeded by cooler weather, these conditions may be understood as temporary inconveniences, rather than permanent afflictions (Hall, Hungerford and Hackett 1994).

FINDING MORE COMPLETE PERFORMANCE CRITERIA

The mass adoption of alternative or optimized compressor-based systems will depend heavily on assertions that can be accepted by residential consumers concerning performance. Any efforts to foster low-energy systems will initially confront a buying public with the pre-conceived notion that a compressor-based air-conditioning device with a large enough capacity is necessary and sufficient for summer comfort, as well as the apparent double standard for low-energy cooling. The remaining discussion recognizes that the development and acceptance of low-energy systems must take place in the context of "mass production" of efficient cooling, with more complete performance criteria needed to hold up against "but is it big enough?"

Addressing the mass market and the long-term

Low-energy cooling must succeed in an environment including both a production building industry with speculative or semi-custom construction and a "housing as investment" scenario with frequent turnover or resale. For a speculatively built house, there is little flexibility to implement thermally sound houses or cooling system "options" according to the preference of individual buyers. For the increasingly more common semi-custom scenario, the critical decisions determining cooling capacity for a non-compressor house come earlier in the construction process than they would for a compressor cooled house. In either scenario, understanding buyer expectations is crucial.

What are the critical issues in achieving savings persistence throughout the life cycle of an alternatively cooled house? In a resale scenario, how does the original buyer (efficiency enthusiast or not) market their alternatively cooled house to a general market without suffering an economic loss? One study suggests that under some circumstances this may be an easier problem with "older" homes, regardless of the climate, not being "obligated " to have air-conditioning (Hall, Hungerford and Hackett 1994).

What is the range of expectations of residential occupants?

The body of knowledge regarding occupant expectations of residential cooling is shallow, but provides some insights into the issues. Most notably, the single criterion "meeting the load" engineering approach is not supported by the literature.

Observed operational practices. The series of papers in the "Culture, Comfort and Cooling" Special Issue of Energy and Buildings offered a number of surprising findings from empirical studies of air-conditioning use and other sorts of cooling behavior (Kempton and Lutzenhiser 1992). A key finding involves variability in cooling behavior and understanding of the appropriate use of cooling equipment. In several samples from utility-sponsored studies, for example, most users of room air conditioners were found to leave the temperature control at the coldest setting, switching the units off and on manually even though equipped with thermostatic controls (e.g., Kempton, Feuermann and McGarity 1992). A fairly wide variety of cooling strategies were reported, even in hot California climates, including non-use of air-conditioning when the equipment was available and energy costs were zero (Lutzenhiser 1992).

In more recent research, examination of a large number of central air-conditioning load shapes in single-family residences (Lutzenhiser et al. 1994) shows very low levels of air-conditioning use in a semi-transitional hot-dry California climate, as well as distinct "automatic," and "manual" control strategies. Also, a recent California Energy Commission study of building standard compliance found thermostat settings averaging 26.5° **C** (80° **F**) at 5 pm, with a standard deviation of 1° **C** (2° **F**). Settings were recorded only when an air-conditioner is on (Berkeley Solar Group et al. 1995; Wilcox 1996). These data suggest that California thermostat settings may be higher than assumed in the ACCA design procedure, near the upper boundary of the ASHRAE comfort zone example for typical offices.

Studies in low-income housing in the hot-humid Florida climate (Parker, Mazzara and Sherwin 1996) and in the Pacific Northwest (Lucas 1992) found similar variability in control strategies. Average thermostat settings of 25° **C** were observed in both studies. Variability in preference for cooling space temperatures is noted by the Florida study as having important implications for sizing, and by inference, for alternative cooling strategies. A study of sizing practices in the same climate includes evidence that preference by some for lower temperatures or simply acknowledgment of variability in preference is a significant driver for oversizing (Vierra et al. 1995).

Expectations for special events or guests. The divide between the "public" and "private" use of the home is relevant to consumer acceptance of alternative designs. What may be considered tolerable for the family might be potentially uncomfortable for guests, particularly a large number of guests (Hall, Hungerford and Hackett 1994). A high-performance demonstration house project in the more severe Florida climate took this issue seriously enough to designate accommodation of the party scenario as a primary purpose for a second stage of cooling capacity (Chandra 1996).

Expectations on the hottest day of the year. At face value, the rubric assumes that target indoor conditions will not be achieved under trans-design conditions. But what do homeowners expect? Experience in the hot-humid Florida climate suggests that homeowner complaints about hot weather performance are a major driver of oversizing (Parker 1996; Vierra et al. 1995). On the other hand, results from field studies in California suggest that slightly elevated indoor temperatures that are understood to be "temporary," are likely to be understood as acceptable and may not even be noticed--rather, they are simply part of summer living in warm climates (Hall, Hungerford and Hackett 1994; Lutzenhiser et al. 1994). Expectation derives from experience. In this regard, it is important for the success of alternative designs that consumers be able to experience their performance under hot conditions, and that peoples' accounts of living in such houses be available to prospective buyers.

System responsiveness. It has been suggested that response times are important in office occupant satisfaction. In advocating operable windows for offices and better control systems, one author (Leaman 1993) argues that faster response by the building or air-conditioning system to the occupants "request" will allow a wider tolerance of conditions. It is further argued that this is why people tolerate a wider range of conditions at home. But, alternative systems are not immediately responsive. They require planning ahead. Also, operable windows do not directly help under design or trans-design conditions.

A related issue is expectations regarding "pull-down", or the ability to cool a "dormant" house upon returning home. Though no literature provides insight into this scenario, it can be speculated that occupants would value a thermally superior house that stayed relatively cool when "dormant" at least as much as the ability to obtain rapid cooling of a house that became much too warm.

Does risk analysis apply to air-conditioning and comfort? As previously noted the concept of risk assessment is explicitly mentioned in industry handbooks when discussing issues related to design and sizing. Consumers regularly cost-optimize other scenarios where perfect gratification or performance is impractical or prohibitively expensive. Choosing a high insurance deductible and choosing not to install one bathroom or one phone line for every person living in a house are common examples of management of risk or inconvenience. Assuming a rational or consistent consumer (admittedly an heroic assumption when risk perception is involved), it would seem illuminating to consider the risk of "not meeting the load" relative to broken appliances, power outages, tardy garbage collectors, freeway or street noise, condensation on windows, and other risks of failure or partial disabling of all or part of the home.

Challenges to the subjective comfort model. Just as occupant behavior seems to be highly variable--even flexible--so too is comfort definition. Kempton, Reynolds, Fels and Hull (1992) have reported, for example, very little increase in occupant discomfort when their central air-conditioning units were turned off as part of a remote load control program for up to half of the time on the hottest summer days. Work in Japan (Fujii and Lutzenhiser 1992) and Thailand (Busch 1992) provides some support for a cultural theory of comfort in which the relative meanings of climate, comfort, and acceptable cooling conditions can be seen to vary across cultures and circumstances within cultures. Controversial positions have been taken on the issue of the cultural malleability of comfort.[4]

Toward a robust characterization of summer house performance

The single criterion approach has failed to produce consistent performance for conventional cooling systems. Emphasis on the tolerance for exceedence that is inherent in this approach does not appear to be adequate, by itself, to divert the focus from "but is it big enough?" However, the design philosophy outlined in the introduction to ACCA load calculation manual could form a basis for a more robust characterization, if expanded or extended to alternatively cooled houses (ACCA 1986).

These industry procedures already "...optimize the pertinent matrix of performance parameters -- temperature control, humidity control, air motion, ventilation, op-cost, installed cost, temperature excursions, demand kW, etc." (Rutkowski 1996). The guidance to the user of the manual recognizes both an increase in operating costs and a loss of control over space conditions with oversizing and concludes that, overall, slight undersizing of conventional systems is preferable. Perhaps most important, the guidance broaches the subject of discussing these trade-offs with the owner/occupant. Sadly, it is clear with respect to such consumer education that "...this effort could be neutralized by the efforts of an impostor -- home owners usually talk to more than one contractor" (Rutkowski 1996).

For conventional systems, lower noise and temperature uniformity throughout the house can be added to the list of advantages for properly sized and designed systems. The introduction of additional criteria of performance, desirable for conventional cooling systems, is the key for alternative cooling systems. There are many advantages to non-compressor designs which emphasize the ability of the house itself, rather than the cooling system to provide comfort. Dwellings are naturally cooler when occupants return home from work. Indoor temperature swings are fewer and milder, less radical excursions from comfort are experienced during severe weather, and the systems can be quieter. One common thread in many of these attributes surrounds the tendency of the thermally superior house to fail gracefully, and not completely depend on the reliability and rigor of control of the compressor-based system.

Without well developed complementary criteria that embody these advantages, the single criterion of "meeting the load" gravitates toward the extreme of "bigger is better," despite the tolerance for exceedence in the classic implementation. The crucial step in moving away from the single criterion approach appears to involve the creating and fostering of an effective characterization of the additional attributes. One key to acceptance may involve allowing potential purchasers to experience the alternatives, thus reinforcing the message of assertions about alternative parameters of performance. This "bootstrapping" will be one important facet of market transformation for low-energy cooling.

A case study in developing alternatives to compressor cooling in California

The California Institute for Energy Efficiency "Alternatives to Compressor Cooling (in California Transition Climates)"project has as a central goal the creation of designs for low-energy alternatively cooled houses suitable for the production building industry. For this effort, there is an obvious need to emphasize the attributes of the house itself in creating desirable conditions, while working with the tolerance for exceedence embodied in the design rubric.

Strategic use of thermal mass and solar shading are among the approaches used to increase the inherent ability to maintain comfort before the application of alternative cooling strategies. These attributes will be qualitatively emphasized by various means such as relating the experience of the house to that of an Italian palazzo, with the inherent associations with an oasis of comfort in the Mediterranean summer (Loisos 1996). In addition, improved acoustics and improved fire protection will be emphasized as attributes that can accompany the thermal improvements for the house.

In the approach under consideration, house designs including different alternative cooling system options will be rated according to the outside conditions[5] under which they can meet the classic comfort criteria.[6] It will then be up to the builder/owner to judge the value of the other attributes of the house in a "trade-off" with the "capacity" criterion, with the trade-off manifesting itself in the choice of acceptable exceedence level.

As an example, a "38° **C** (100° **F**) capable" house could be built in Concord (29 hours per year of exceedence) by those who do not place much value in the additional house attributes. The same house could be built in Fairfield (73 hours of exceedence at 99° **F**) by the average builder/owner, or in Rocklin (175 hours of exceedence at 99° **F**) by the builder/owner who fully appreciated the value of the alternate parameters to balance the need to "meet the load".

CONCLUSIONS

The tolerance for exceedence in the engineering rubric is a necessary component of a robust design approach to challenging the dysfunctional status quo in air-conditioning design. Unfortunately, it falls short of this goal by itself. Sensibly allowing for limited excursions from subjective comfort parameters, as encouraged by industry fostered procedures, has not been successful in subduing the prevailing practices that lead to "but is it big enough?". This is because the other equally important attributes of a house/cooling system are not recognized as the other side of the "trade-off" that is implicit in the industry fostered approach.

Key to the widespread adoption of more effective cooling systems is recognizing and developing effective information about thermal stability and uniformity, less severe excursions under extreme conditions or other failure modes, lowered noise, and improved moisture control. These criteria must balance the capacity criterion to produce improved occupant satisfaction and better system performance for both alternative and optimized conventional cooling systems.

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ENDNOTES

1) ASHRAE publishes design weather data corresponding to exceedence levels of 29 hours (1%), 73 hours (2.5%), and 146 hours (5%) per four month summer period (ASHRAE 1993). An additional ASHRAE publication provides data for California, Nevada, Arizona, and Hawaii with an annual basis and exceedence levels of 9 hours (0.1%), 44 hours (0.5%), and 175 (2.0%) per year (ASHRAE 1982).

2) The definition of "use" of the guideline is important. There is some evidence that contractors will report use of the guideline when they have implemented the guideline calculation procedures, but then purposely oversized through the addition of a "safety" factor.

3) See the "case study" later in this paper.

4) See the spirited exchange between Prins (1992) and a panel of social scientists and energy analysts.

5) The goal is to establish a single (dry-bulb) temperature rating for the house designs as a simple indicator of the capabilities of the house. This can work only in regions which have similar nightly minimums and similar humidity characteristics (fortunately all of California except monsoon influenced regions like the Imperial and Coachella Valleys). The approach includes establishing an equivalence between design "heat storm" sequences used to model the performance of the houses and simple design temperatures available on a city-by-city basis.

6) Plans are for performance criteria to be based around ASHRAE Standard 55, with consideration of: room-to-room variations around the design point, appropriate metabolic rate and clothing levels, and a maximum 1°**C** (2°**F**) upward adjustment for air movement.

REFERENCES

Abrams, D.W. 1986. *Low-Energy Cooling* New York: Van Nostrand-Reinhold.

ACCA. 1986. *Manual J - Load Calculation for Residential Winter and Summer Air Conditioning*. Washington D.C.: Air Conditioning Contractors of America (H. Rutkowski, Technical Director).

ASHRAE. 1982. *Climatic Data for Region X., ASHRAE Publication SPCDX.*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers (Golden Gate and Southern California Chapters).

ASHRAE. 1992. *ANSI/ASHRAE 55-1992, Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers (Standards Project Committee 55-1981R).

ASHRAE. 1993. *ASHRAE Handbook, Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers (R. A. Parsons, Editor).

ASHRAE. 1995. *ANSI/ASHRAE 55a-1995 Addendum to Thermal Environmental Conditions for Human Occupancy.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers (Standards Project Committee 55-1981R).

Berkeley Solar Group, Recom Technologies, C. Miles, M. Modera, and Taber Chaitin. 1995. *Energy Characteristics, Code Compliance and Occupancy of California 1993 Title 24 Houses, 1993 Residential Filed Data Project.* Sacramento: California Energy Commission and California DSM Measurement Advisory Committee.

Busch, J. F. 1992. "A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand". *Energy and Buildings* 18(3-4):235-250.

Chandra, S. (Florida Solar Energy Center). 1996. Personnal communication to author. May 24.

Cook, J., ed. 1989. *Passive Cooling*. Cambridge: MIT Press.

de Dear, R. (Macquarie University, Sydney). 1996. Personal communication to author. January 21.

Feustel, F., A. de Almeida, and C. Blumstein. 1992. "Alternatives to compressor cooling in residences". *Energy and Buildings* 18(3-4):269-286.

Fujii, H. and L. Lutzenhiser. 1992. "Japanese residential air-conditioning: natural cooling and intelligent systems". *Energy and Buildings* 18(3-4):221-234.

Hall, D. R., D. G. Hungerford, and B. Hackett. 1994. "Barriers to Non-Compressor Cooling: Air Conditioners in Social Context". *In Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings,* 1:59-63. Washington D.C.: American Council for an Energy-Efficient Economy.

Henderson, H. 1992. "Simulating Combined Thermostat, Air Conditioner, and Buildings Performance in a House." *Transactions of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers,* 98(1):370-386.

Huang, Y.J., and H. Zhang. 1995. *Analysis of Climatic Conditions and Preliminary Assessment of Alternative Cooling Strategies for Houses in California Transition Climate Zones.* LBL-36177. Lawrence Berkeley National Laboratory

Hunt, M. (Davis, Calif.; instructor of a class on using ACCA manuals). 1995. Personal communication to author . October 12.

Kempton, W., D. Feurermann and A. E. McGarity. 1992. "'I always turn it on super': user decisions about when and how to operate room air conditioners." *Energy and Buildings,* 18(3-4):177-192.

Kempton, W. and L. Lutzenhiser. 1992. "Introduction to Special Issue on Social and Cultural Aspects of Cooling" *Energy and Buildings.* 18(3-4):171-176.

Kempton, W., C. Reynolds, M. Fels, and D. Hull. 1992. "Utility control of residential cooling: resident perceived effects and potential program improvements." *Energy and Buildings,* 18(3-4):201-220.

Leaman, A.. 1993. "Designing for Manageability." *Building Services* , March 1993.

Loisos, G. (Oakland, Calif.). 1996. Personal communication to author. May 23.

Lovins, A. 1992. *Air Conditioning Comfort: Behavioral and Cultural Issues.* SIP I. Boulder, Colo.: E Source, Inc.

Lucas, R. 1992. "Analysis of Historical Residential Air-Conditioning Equipment Sizing Using Monitored Data." *In Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings,* 2:157-165. Washington D.C.: American Council for an Energy-Efficient Economy.

Lutzenhiser, L. 1992. "A question of control: alternative patterns of room air conditioner use" *Energy and Buildings,* 18(3-4):193-200.

Lutzenhiser, L., B. Hackett, D. Hall and D. Hungerford. 1994. *Alternative Cooling Technologies for California: Social Barriers, Opportunities and Design Issues.* UER-289. Berkeley: University of California Energy Institute (late Universitywide Energy Research Group).

Modera, M. (Lawrence Berkeley National Laboratory). 1996. Personal communication to author.

Neal, L and D O'Neal. 1992. "The Impact of Air-Conditioner Charging and Sizing on Peak Demand." *In Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings,* 2:189-200. Washington DC.: American Council for an Energy-Efficient Economy.

Parker , D. (Florida Solar Energy Center). 1996. Personal communication to author. April 2.

Parker, D. M. Mazzara, and J. Sherwin. 1996. "Monitored Energy Use Patterns in Low-Income Housing in a Hot and Humid Climate (Draft)". *Submitted for publication in Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings,.* Washington DC.: American Council for an Energy-Efficient Economy.

Prins, G., 1992. "On condis and coolth (with comments)." *Energy and Buildings,* 18(3-4):251-268.

Proctor , J., Z. Katsnelson and B. Wilson. 1995. "Bigger is Not Better: Sizing Air Conditioners Properly." *Home Energy,* 12(3): 19-26.

Reddy, T.A. and D.E. Claridge. 1993. "Effect of Air Conditioner Oversizing and Control on Electric Peak Loads in Residences" *Energy,* 11:1139-1152.

Rutkowski, H. (HTR Engineering, Dover, Ohio; author of ACCA Manual J). 1996. Personal communication to author. April 23.

Treidler, B. M. Modera, R. Lucas, J. Miller. 1996. "Impact of Residential Duct Insulation on HVAC Energy Use and Life-Cycle Costs to Consumers." *Transactions of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers,* 102(1).

Vierra, R.K., D.S. Parker, J. F. Klongerbo, J.K. Stone, J. Cummings. 1995. *How Contractors Really Size Air Conditioning Systems.* FSEC-PF-289-95. Florida Solar Energy Center. (submitted for publication in Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Washington DC.: American Council for an Energy-Efficient Economy).

Wilcox, B. (Berkeley Solar Group). 1996. Personal communication to author.