THE IMPLICATIONS OF TASK CONDITIONING FOR COMFORT AND ENERGY

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Task conditioning is a new technology responding to a concern for occupant comfort in office buildings. The term "task conditioning" is derived from task lighting, where ambient lighting levels are reduced in non-critical areas, and higher levels are supplied only when and where they are needed. Similarly, in task conditioning local conditioning is supplied directly to the workstation, where and when it is needed.

To date, there has been little research on the performance of task-conditioning systems. This paper provides an overview of task conditioning technology, in the context of increasing the comfort and satisfaction of workstation occupants.

The paper begins with an introduction of the existing system types and installations, and a discussion of the ways in which the primary characteristics of task conditioning are likely to affect comfort and energy. In particular, these systems encourage ventilative cooling, zoning, and temperature stratification. These effects, in turn, may allow increased supply and return air temperatures, with corresponding improvements in chiller performance and increased economizer operation. Tradeoffs abound; for example, local fans may add a large electrical load, but this may be counteracted by some reduction in fan power for the central air supply. A program of laboratory tests of task-conditioning systems is now underway, and this paper briefly summarizes preliminary results. A discussion of the motivation for comfort standards and how comfort standards have been set precedes a discussion of the implications of these systems for current comfort standards.

INTRODUCTION

Fifteen percent of the energy used in the United States is used in commercial buildings (EIA 1988), and a large fraction of this is used in heating, ventilating, and air-conditioning systems (HVAC). However, HVAC is not an end in itself; it is only a means to an end--thermal comfort. In evaluating end-use energy efficiency, it is therefore important to look at both inputs and outputs--at both energy consumption and thermal comfort.

Occupant surveys have found that a thermally comfortable environment is among the most important attributes of an office, but also that this comfort has not been well provided (Harris 1980). A field study of over 300 subjects in 10 California office buildings found that 40% of the workers questioned were unsatisfied with their thermal environment (Schiller et al. 1988). But what exactly is comfort? Thermal comfort has been defined as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE 1981). The concept of thermal comfort can be expanded to include air quality and ventilation effectiveness, as a general indicator of the well being and productivity of workers in buildings. Since individual preferences for thermal conditions vary from hour to hour, day to day, and from person to person, the conventional strategy of uniformly bathing a space in conditioned air may not be the most appropriate HVAC solution to providing comfort. This fact is manifest in the oscillating fans, electric resistance heaters, and diffuser modifications that (management willing) dot the modern office landscape. Task conditioning discussed here incorporates these types of individual control elements in a unified system. In this technology, conditioning is supplied directly to the workstation, allowing the worker to control the airflow (volume, direction, and in some cases temperature), thereby potentially improving both the percentage of people experiencing comfort and the energy efficiency of the system itself.

As a relatively new technology, task conditioning is still in a developmental stage. Little information is available on how people use these systems, the interactive effects between workstations or between local and central systems, or how space conditions are affected on a micro scale. Potential comfort and energy efficiency improvements have not been quantified or even verified. This technology should be studied more closely now, before it becomes widely implemented, so that it can progress in the most efficient direction possible.

This paper presents information obtained in a preliminary study of task conditioning technology, in the context of the requirement for occupant comfort. We will identify what is known and what is not known about the operation of task-conditioning systems. Our intent here is not to present quantitative documentation of the performance of these systems, but rather to discuss how the primary characteristics of task conditioning are likely to affect comfort and energy, and to identify gaps in our understanding of these systems. We will briefly summarize results of our preliminary laboratory experimentation, and discuss our plans for further research into this technology, as well as future research needs in general. To simplify the discussion, we focus on cooling applications and do not address heating applications or perimeter zones.

THE TASK CONDITIONING TECHNOLOGY

The term "task conditioning" is drawn from an analogous concept in lighting. With task lighting, energy is saved by reducing ambient lighting levels in noncritical areas such as hallways and near ceilings. Individual light fixtures, offering higher illuminance under occupant control, are used only when and where they are needed for performing tasks.

Similarly, in task-conditioning systems, conditioning is reduced in noncritical areas, such as circulation areas, coffee rooms, and unoccupied workstations. Individually controlled diffusers are used only when and where they are needed to achieve comfort. The local occupant controls air velocity and direction, and in some cases the air temperature. Thus, the individual units are designed to provide personal comfort, while the central system is controlled to remove the overall space loads. Task-conditioning systems in existing installations vary quite a bit from one another, in terms of the degree of centralization of equipment, the method of system control, and the location and nature of terminal equipment. In fact, the only common element is the provision of local, individually controlled terminal units.

There are three main varieties of task-conditioning systems, at present. The first supplies air to diffusers at desk level, from a fan-powered mixing box mounted underneath the desk. Air is supplied to the mixing box from a flexible duct running either from a low-pressure subfloor air plenum or from vertical chases connecting to a ceiling plenum or duct. The mixing box allows the occupant to control the velocity and temperature of the delivered air by changing the fan speed and adjusting the mixture of cold, primary air and warm, recirculated room air. The second type of system also uses a low-pressure subfloor plenum. In each workstation, a fan mounted within one of the workstation's raised floor panels draws air from the plenum and discharges it through a cluster of circular, rotatable grilles in the panel. The fan speed can be controlled by the occupant using a thumbwheel recessed in one of the grilles. The third type of system does not use local fans. Instead, a central supply fan pressurizes the subfloor plenum, discharging air into the workstation through diffusers. The occupant controls the volume of air delivered by means of a damper.

In all of these types of systems, air can be supplied to the plenum from either a constant- or variable-air-volume central air system. Room air is typically returned at the ceiling, often through lighting systems using heat-removing luminaires. In many cases, room or return air is mixed with primary supply air in the plenum. Most designs have either a minimum air flow stop on the adjustable fans, or a small number of nonadjustable fans to ensure adequate ventilation air.

While only one available system actually includes occupancy sensors, they seem to be an obvious direction for future development. Occupancy sensors offer clear potential for air-conditioning energy savings by turning the local system down or off when the workstation is unoccupied. Minimal air-flow is maintained when the space is unoccupied, and when the space is reoccupied the system remembers its previous settings and returns the space to its previous conditions. The sensors are also used to turn off lights in unoccupied workstations, and may have potential benefits for security and fire safety.

Existing Installations

Task conditioning is far from a common technology, having been employed in only about 50 buildings throughout the world. A detailed discussion of each installation is beyond the scope of this paper, so here we simply summarize a few of the existing installations.

There are roughly a dozen installations in North America. These are mostly small offices, ranging from 700 to 7500 m^2 (7500 - 80,000 ft^2). Two are larger buildings--more than 18,000 m^2 (200,000 ft^2). The largest building has 2000 individual fan units. Most of these systems use low-pressure subfloor plenums and individual fan units. They are evenly split between constant-volume and variable-volume central systems. At least one installation uses a variable-volume central system, with distributed powered mixing boxes in the ceiling to supply a constant volume of variable-temperature air to the floor plenum (Genter 1989). One unique application is a condominium in Kansas City, where floor units are used in residential space (Ellison and Ramsey 1989).

By far, the country with the largest number of installations is South Africa, with approximately 27 buildings featuring task conditioning. More than half of these buildings exceed 5000 m^2 (54,000 ft^2), and the largest is 54,000 m^2 (580,000 ft^2) (J. Zeren, personal communication). Many of these buildings feature fan air terminals and fan coil units integrated in floor panels, fed by electrical and cold-water distribution systems in the plenum. Many of these systems also make use of structural thermal storage. (David 1984; Spoormaker and McMillan 1984)

The largest task-conditioning application in our records is a recent bank building in Hong Kong (about 124,000 m^2, or 1.3 million ft^2). In this building, supply air is ducted to the floor unit, and air is returned both through the light fixtures in the ceiling and through the floor plenum. Decentralized variable-air-volume plants are located on each of the 46 floors. The floor diffusers were designed and tested specially for this building (Tuddenham 1986).

There are several buildings in England, including a 53,000 m^2, (570,000 ft^2) office building in London. This building uses induction units located in the floor and in the desks, bringing primary air from a subfloor plenum. Air is returned at the ceiling, and is then passed between the window glazings to take up some of the envelope loads. (Barker 1985; Barker et al. 1987; David 1984; Waters 1984).

THERMAL COMFORT AND COMFORT STANDARDS

People vary in their thermal preferences. In private offices, each with its own thermostat, each occupant can select the proper setpoint, and the system will automatically control for varying loads. However, many of today's office buildings have modular, open-plan work areas. In open-plan offices there is typically only one thermostat controlling a large area, and this can cause problems such as "thermostat wars." A common alternative is to fix the setpoint at some optimum temperature and to lock the thermostat cover.

But is there such an "optimum" temperature? A great deal of research has gone into what an optimum temperature should be, and it has been specified in comfort standards. ASHRAE Standard

55-1981 (ASHRAE 1981) is the standard in use in the United States today.[1] The current version, published in 1981, is now under revision. This standard is sometimes used as a basis for litigation, and is referenced in the building codes of several states. Several other countries also use the ASHRAE standard, and the other widely used comfort standard (ISO 1984) is substantially similar in its requirements.

The acceptable temperature ranges in the comfort standard are 20.0 to 23.6°C (60.0 to 74.5°F) in the winter, and 22.8 to 26.1°C (73.0 to 79.0°F) in the summer. This range is referred to as the ASHRAE Comfort Zone, and assumes typical clothing (summer and winter), moderate humidity, air velocity, and radiant temperature, and sedentary activity. In addition to this comfort zone, the standard specifies limits on several other environmental variables, such as air movement, humidity, temperature oscillations and drifts, vertical temperature differences, radiant asymmetry, and floor temperatures.

Standards are based on experiments with human subjects. In most such experiments, seated subjects wearing a standardized outfit are exposed to different combinations of conditions in a controlled environment, and are questioned about their thermal comfort. From this, one can estimate the percentage of people who will feel uncomfortable in a given environment (see, for example, Rohles and Nevins 1971). The standards must then also specify an acceptable percentage of people uncomfortable. In the ASHRAE comfort standard, that level was set at 20% through a consensus process. Even if one wanted to try to provide comfort to everyone, however, the minimum fraction unsatisfied achievable in the laboratory is 5%, with 20% a more realistic minimum in actual workplace environments (Schiller et al. 1988). While this is due in part to variability among people in metabolic rate, surface area, and other thermal parameters, part of the explanation is simply their variability in subjective factors such as thermal comfort. You can't satisfy everyone with one set of environmental conditions.

TASK CONDITIONING IMPLICATIONS FOR COMFORT

Comfort standards specify uniform conditions throughout the working environment in part because these are the conditions that conventional systems provide. A typical centralized HVAC system in an office building is designed to supply conditioned air from an evenly-spaced array of ceiling diffusers. Air is introduced into the room at a low temperature and is mixed through entrainment with room air to create a uniform environment in the room.

But the modern climate-controlled building is a relatively new development, and localized and individually controlled conditioning predominated in earlier times. Consider, for example, the hearth: people have used localized heating for centuries. Electric resistance heaters, oscillating fans, and operable windows in the office are all forms of individually controlled task conditioning. An important distinction between these examples and the newly developed task-conditioning systems, however, is the fact that task conditioning is a *system*--a systematic and centrally coordinated response to the need for localized and individually controlled conditions.

Task conditioning provides comfort in a different way than conventional systems. Since comfort standards are closely related to the types of systems traditionally used to provide comfort, these new task-conditioning systems may permit new ways of defining and using comfort standards. Some of the particular ways that task conditioning may affect comfort are by allowing individual control, and by permitting temperatures to vary due to zoning, localized cooling, and stratification.

Individual Control

The analysis of individually controlled systems involves a psychological and sociological study of behavior, and little research has gone into how occupants actually respond to task conditioning in

[1] *For brevity, the terms "standard" and "comfort standard" will be used throughout this paper to refer to ASHRAE Standard 55-1981.*

offices. Given control over the system, occupants can be expected to control conditions in such a way that they are comfortable. Even in offices that have no provision for individual control, occupants have been known to cover diffusers or even alter existing control systems to make their environment more comfortable. Although occupants often may not understand the dynamics of their control actions and the subsequent system responses, the use of temperature control panels and air outlets in automobiles suggests that people can take control of their own comfort.

Evidence indicates that provision for individual control may be a benefit, whether or not the occupants actually make use of it (Hedge, in press; Paciuk 1989; Schiller et al. 1988; Tuddenham 1986). These studies found that people prefer to have control, but that they do not always make full use of that control. One study found that by providing experimental subjects with control over their environment, "the optimum level of satisfaction is increased substantially and a given level of satisfaction can be extended to a much wider range of environmental conditions" (Jones 1988). One recent survey of task-conditioning systems found that almost a third of the occupants never adjusted their local systems, and less than 10% adjusted it daily. Their satisfaction, however, improved (Hedge, in press). These findings suggest that the mere sense of control can increase one's sense of comfort, whether or not the controls are actually used to change physical conditions.

When conditions are allowed to vary over time and space, and occupants control the conditions in which they work, it becomes possible in principle to make a larger percentage of the population comfortable, and to offer a broader menu of conditions from which to pick. Comfort standards currently specify the most *neutral* conditions possible, and with task conditioning they could be formulated to allow this broader menu of *preferred* conditions.

Zoning

If task-defined zones can be controlled and conditioned separately, as in task conditioning, it is possible to maintain work areas within specified comfort conditions, while allowing unoccupied or temporarily occupied areas to be maintained within more relaxed environmental criteria. These unoccupied areas might be circulation areas or areas that are seldom used, such as hallways, coffee rooms, restrooms, or the areas between cubicles. One way of achieving this in an open-plan office is to condition the work areas directly, while allowing the ambient temperature in the rest of the areas to "float." Measurements in our laboratory indicate that differences of up to 2.5°C (4.5°F) between adjacent workstation are possible (laboratory results are described in more detail in Bauman et al. in press).

The ASHRAE comfort standard applies to spaces that are occupied for 15 minutes or more at a time. It is quite possible that transitory spaces would not have to be as heavily conditioned as workspaces, but to our knowledge, little research has gone into studying the extent to which the comfort zone might be expanded for this effect. Comfort may also be affected by moving quickly from one condition to another. A comfort standard requiring geographically and temporally uniform conditions within the entire room would not allow this type of differential zoning. The current revision of the ASHRAE standard may relax its definition of the "occupied" zone to apply specifically to where the occupants are actually located in the zone. More research is needed into the different comfort requirements for various office activities and within distinct areas within office buildings.

Localized Cooling

By providing localized cooling, task conditioning provides the opportunity for task-based zoning. Since the air is delivered very close to the occupant, its temperature and velocity will be very important. The delivered air can (in fact, must) be at a higher temperature than with a conventional system. This can be done either by mixing cold supply air with room or return air, or by supplying warmer air, allowing equipment and lighting loads to be removed after the air has already locally cooled the occupant.

To some extent, temperature and velocity can be traded off to provide ventilative cooling. With task-conditioning systems, it may be possible to maintain comfort with supply air at an even higher temperature if it has a higher velocity, cooling the occupant directly by air movement over the skin. There is obviously a limit to this tradeoff where the air velocities required at high temperatures become unpleasant or inconvenient. Since this limiting velocity may vary between people, a properly designed diffuser must be adjustable, as in the task-conditioning systems. Conventional ceiling systems do not allow for individual adjustment, and must unilaterally avoid high room air velocities. In studies of task-conditioning systems, several researchers have found that draft was not a problem (Hanzawa et al. 1989; Hedge, in press; Wyon 1988), although one researcher surveyed a building in which subfloor ventilation was perceived as a source of draft, causing discomfort (Huber et al. 1988).

The ASHRAE comfort standard allows temperature to be traded off for velocity, but it limits velocity in the occupied zone to a specified maximum of 0.15 m/s (30 fpm) in winter and up to 0.8 m/s (160 fpm) in summer. The upcoming revision of the comfort standard may reduce these velocity limits even further. Measurements in our laboratory with one task-conditioning system have shown that mixing occurs rapidly. Velocities measured within the jet of air were as high as 0.8 m/s (160 fpm) at chair level. But the velocities attenuate quickly with lateral distance from the diffuser, and outside of the jet of air, velocities were always below about 0.2 m/s (40 fpm). The temperature also changed rapidly: outside the air jet, about 0.6 m (2 ft) from the diffuser, the air was 2°C (3.6°F) warmer. These indicate that the placement and design of the diffuser are important parameters if ventilative cooling is to be encouraged. If velocity limits are further reduced in the comfort standard, task conditioning terminal units could not be located near the occupants--defeating the purpose of localized conditioning.

Stratification

In a room with little air motion, air becomes thermally stratified, producing warmer temperatures at higher points in the room. A conventional ceiling-based system is designed to supply cooler, conditioned air from above; by design, the supply air and the warmer portions of the room air mix rapidly, so that relatively uniform temperatures result throughout the space. Floor-supplied rooms may or may not experience stratification. Under low-flow conditions, floor-based task conditioning can resemble displacement ventilation. This technique, becoming popular in the Scandinavian countries, supplies air at low velocities from the floor, and relies upon stratification in the slowly rising air for energy conservation and pollutant removal effects (Sandberg and Blomqvist 1989). As the air is warmed by the room loads, it slowly rises, taking heat and pollutants with it, and uniformly flushing the room.

According to the ASHRAE standard, a temperature differential exceeding 3°C (5°F) between ankle and head heights causes discomfort. Sandberg and Blomqvist (1989) found that in displacement ventilation, the temperature distribution was quite dependent upon the heat load and volume of supplied air, and these parameters are expected to be important in task conditioning as well. In our laboratory tests, we found that at low flow rates of 43 L/s (90 cfm) per local unit and relatively high heat loads, this task-conditioning system behaved similarly to displacement ventilation systems. About 3.5°C (6.3°F) of stratification from floor to ceiling was observed, and the ASHRAE stratification limit of 3°C (5°F) from ankle to head height was sometimes exceeded. At the more common higher flow rates of about 85 L/s (180 cfm) per unit, however, stratification was essentially eliminated. It will be important to characterize the temperature and velocity distributions produced in actual spaces conditioned by task-conditioning systems under different conditions to accurately assess the effects on comfort.

TASK CONDITIONING IMPLICATIONS FOR ENERGY CONSUMPTION

While task conditioning has been developed to respond to comfort concerns, it will also have energy use implications. These implications have not been studied directly, and it is difficult at this time to predict precisely what they will be, since they are in large part influenced by occupant behavior and air flows in the space, neither of which is well understood or easily quantified. We have reviewed existing literature (Heinemeier et al. 1990), and identified several important energy-affecting characteristics of task conditioning. This section will discuss what the energy effects are most likely to be, what we know now, and what we will need to find out in order to comment on the energy implications more concretely.

Chiller Energy

Since task-conditioning systems supply conditioned air much closer to the occupant than conventional systems, and can provide ventilative cooling, the supply air temperature can be increased. An increased supply temperature can correspond to an increased evaporator temperature and therefore to an increased chiller coefficient of performance (COP). One study found that for a centrifugal chiller, the COP could be increased by approximately 3.1% for every 1°C (1.7% for every 1°F) the evaporator temperature was raised (Usibelli et al. 1985). For example, if the supply temperature can be raised from 13°C (55°F) to 18°C (65°F), (with a corresponding increase in the evaporator temperature,) the COP can be increased by more than 18%.

In conventional systems, the return temperature is typically close to the occupied space temperature. In task conditioning, however, only the area immediately surrounding the occupant must be within the comfort zone. The conditioned zone is therefore only part of the volume of the room, and the return temperature can also be higher.

Both increased supply and return temperatures have a potential for energy savings with the "free" outside cooling available using an economizer cycle. With an air-side economizer, when the outside air temperature drops below that of the return air, 100% outside air can be used to reduce the amount of energy required to cool the air down to the supply air temperature. If the return temperature can be increased, the result will be a greater number of hours with reduced mechanical cooling. When the outside air temperature drops further, to below that of the supply air setpoint, cooling can be achieved without running the chiller by mixing outside air with the return air in varying quantities to achieve the desired supply temperature. Therefore, if the supply setpoint can be increased, this "free" cooling would be possible for a larger number of hours throughout the day or season. This suggests that the greatest increase in economizer energy savings would be achieved in mild climates, where the amount of time the economizer is operated could be increased the most.

Fan Energy

Increased return and supply air temperatures made possible with task conditioning will also have an effect on energy consumption of the central fans, although in some cases it will be a counteracting effect. If localized cooling allows the supply temperature to increase while the return temperature remains the same as in a conventional system, the temperature differential will be reduced. This will require a higher airflow rate to remove room loads, with a corresponding increase in fan energy. The relative magnitudes of chiller savings and increased fan consumption would determine whether the net energy use will be higher or lower. This tradeoff is a common consideration in VAV systems (see, for example, Norford 1986). If, on the other hand, stratification allows the return air temperature to increase while the supply temperature remains the same, the temperature differential will be raised, reducing the required airflow rate. Since a small reduction in flow rate can result in a large reduction in fan power, significant energy savings could be achieved (Usibelli et al. 1985). Lower first costs could also be achieved by downsizing the central fan and ductwork, offsetting increased costs for the task components. If both the supply and return temperatures are increased, resulting in the same temperature differential as in a conventional system, the fan power will not be altered.

The large number of local fans will also have an effect on energy consumption. One large fan tends to be more energy efficient than several smaller fans (Jordan 1989). In a task-conditioning system the central supply fan can be downsized, due to the reduced static pressure requirement. But the combined load of the many task fans, possibly with lower efficiencies, may outweigh this effect. On the other hand, an argument in favor of smaller individual fans is that they are operated individually, and at any time a significant number may be turned off (especially if occupancy sensors are used). This mode of operation could have efficiency advantages over operating one large central fan at partial load with inlet vane control. The advantages would not be so clear, however, when each individual work-station requires only a small amount of airflow, if the small fans have part-load inefficiencies. To accurately determine the relative merits of different fan sizes for a task-conditioning system, patterns of operation should be investigated, and the part-load characteristics of the task fans should be evaluated and compared with those of large supply fans.

We measured the power consumed by one local fan from a floor-based task-conditioning system, along with its corresponding air delivery. The lowest power setting was approximately 20 W, and it went up to approximately 42 W, with the corresponding flow rates increasing roughly linearly to a maximum of about 95 L/s (200 cfm). On the average, U.S. installations have one such fan for about 11 m^2 (120 ft^2) of floor area. This corresponds to a connected load of about 3.8 W/m^2 (0.35 W/ft^2). As an interesting comparison, offices typically have a connected lighting load on the order of 10-20 W/m^2, (1-2 W/ft^2), about three to six times as high. But these specific floor-based fans are somewhat inconvenient to turn off, and may be left on 24 hours a day, so their annual energy consumption is likely to be significant.

CONCLUSIONS

The large economic value of increased productivity (and its suggested relationship to thermal comfort), compared with the relatively low cost of energy, tends to suggest a shift in focus from making energy-efficient buildings to increasing comfort. However, task conditioning is one of many strategies that illustrate that a tradeoff is not necessarily required. A system optimized for maximum occupant comfort might be operated differently than a system optimized for maximum energy efficiency, but with appropriate system design, it may be possible to increase both comfort and efficiency at the same time. According to one investigator, "From my observation, buildings that use the least energy provide the maximum productivity. The secret to both is proper controls and a well-engineered system" (Dorgan 1988). And, conversely, out-of-control buildings will be both uncomfortable and energy-inefficient.

Task conditioning does not mesh well with the traditional way of standardizing comfort, however. Task-conditioning systems create temperature variations from the floor to the ceiling, and from one space to the next, which may not be allowed by current comfort standards. Additionally, the high velocities and air temperatures associated with ventilative cooling are not well accounted for in the standards. These effects may however, have the potential to save energy.

Since task conditioning really provides comfort in a different way than traditional systems, and since it has the potential to provide greater comfort with less energy consumption, potential changes in the comfort standards should be investigated. In particular, future standards could more clearly define the occupied zone to be only the zone where someone is currently working. This would make it easier to justify occupancy sensors and differential zoning. Perhaps different comfort zones could be defined for different parts of the office building, for different tasks, or for temporarily unoccupied areas. The standard could also state that the building should be *able to provide* conditions in the comfort zone upon demand, and would not necessarily be required to provide them at all times. For example, higher velocities, which may be preferable to some people at some times, would be allowed so long as those who find them uncomfortable can avoid them.

Few buildings in the United States have installed these localized and individually controlled systems to date, and little is known about their actual performance. However, they may become more common in the future, so it is important to understand how they affect energy consumption and thermal comfort. We are now in the early stages of a project in which we will investigate this technology through laboratory testing of different models, field studies of occupants and conditions in actual installations, energy simulation, and review of energy codes and comfort standards. We are interested in the experiences others in the buildings community have had with this technology, and solicit their input.

ACKNOWLEDGMENTS

The work described in this report was funded by a grant from the Universitywide Energy Research Group of the University of California.

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