Non-Compressor Cooling Alternatives for Reducing Residential Peak Load

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ABSTRACT

Until the advent of air conditioning in the middle of this century, most homeowners in temperate climates kept their houses cool by opening windows at night and closing them in the daytime. The *Alternatives to Compressor Cooling Project* is a multi-disciplinary project with the goal of reducing residential peak loads and improving indoor air quality by reintroducing ventilation cooling to modern houses. To accomplish this goal, the project applies building designs that minimize cooling load, integrated mechanical systems that provide ventilation cooling as well as heating and air conditioning, and user friendly controls that provide optimal control of ventilation.

Three builder-ready house designs were completed that merge marketable features with design elements that improve summer performance. Off-the-shelf ventilation cooling hardware was identified and integrated with the house designs. An advanced thermostat was developed and evaluated. Advanced controls and ventilation cooling systems were field tested in several California houses.

Computer simulations were completed to identify California climates where ventilation cooling alone, and systems with down-sized compressors can be applied. Simulations show 43% of California's geography can be cooled solely with ventilation-based cooling systems if homes are constructed to specific standards.

Current efforts are underway to complete development of an integrated ventilation cooling and heating system that provides improved air quality, a variable speed blower to reduce fan energy use and improve comfort, and further improve control functions and user intelligibility. The advanced control, integrated ventilation-cooling-heating system, and marketable house designs are to be made available to merchant and custom builders.

Introduction

For the past decade, electricity demand growth in the west has outpaced new generation additions; California is projected to experience an electricity capacity deficit of 2757 MW in 2003 (CEC 1997). Though only 7.4% of residential energy use is for cooling (CEC 1998), cooling represents 58% of total residential energy demand (CEC 1989), or 28% of the of the total peak demand, equivalent to 15,000 MW (Keese 2000). Since residential air conditioners are responsible for a significant portion of the peak demand spike, reduction of air conditioner demand should be a high priority.

Compressor-based cooling has become the standard in California's rapidly expanding residential developments, even in mild coastal areas. Poor load factors are likely to disproportionately increase the cost of service to residential utility customers due to the high cost of on-peak generation, the necessity to expand transmission/distribution capacity, and the comparative difficulty in providing service to the residential market. Moderately improved house designs integrated with properly controlled ventilation cooling can provide superior comfort and air quality, while eliminating air conditioners in coastal climates and significantly reducing air conditioner size in all climates.

The Alternatives to Compressor Cooling Project was launched in 1993 by the California Institute for Energy Efficiency to explore the science behind ventilation cooling; identify and resolve health, safety, and building/occupant interaction issues; quantify its potential; develop the technology required for market implementation; and explore avenues of technology transfer. Numerous reports and papers document the progress of the project. Initial work reviewed comfort and health issues (Arens et al 1995). Subsequent efforts explored the interaction of thermal mass and nighttime ventilation (Givoni 1996), cooling system engineering practices (Brown et al 1996), behavioral issues (Lutzenhiser and Hackett 1994), simulated performance (Huang 1999), field testing (Freitag 1998), and building/system design issues (Loisos and Ubbelohde 1996, Loisos and Springer 1998, Loisos & Springer 1999). Current project efforts, supported by California's Public Interest Energy Research Program, are focused on efforts to commercialize ventilation cooling technology. This paper describes key project results, project activities, and goals for market introduction of ventilation cooling systems. Focusing on more recent activities, this paper is necessarily a review of the immense body of work that was completed to investigate and develop residential ventilation cooling,. Greater detail on project work can be obtained from the references.

The project is now in its fifth phase; major accomplishments for the previous four phases included the following:

- Phases I and II: Completed the technical and sociological research necessary to develop a house and mechanical design approach, characterize performance, and identify market and institutional barriers to the adoption of alternative cooling strategies. The characteristics of a prototype house were also developed.
- Phase III: Advanced a prototype house design for the Southern California market to a marketable level. Developed concepts and preliminary functional specifications for an advanced control, and field-tested existing control hardware. Developed a market transformation program, including the institution of the Pacific Coast Builders' Conference Gold Nugget Award category for the "Summer Comfort" house.
- Phase IV: Developed a prototype house design for the Northern California market. Completed and field tested a working prototype of the advanced control. Completed a specialized DOE-2 model for predicting performance and optimizing design parameters.

Goals for Phase V include developing a hot climate house; an integrated heating, ventilation, and cooling system; and improved controls to provide variable speed heating, ventilation, and ventilation cooling. Phase V project efforts will result in a mechanical system that is fully developed, tested, documented, and ready for market.

House Designs

For ventilation cooling to work effectively, heat gain must be minimized and sufficient thermal mass must be incorporated to absorb heat during the day and reject it during the night when the house is ventilated. In July 1995 the project conducted a design charette with architects and builders to develop a house design that meet these requirements while retaining marketable qualities. The charette resulted in four conceptual house plans, the best of which was refined into working drawings (Loisos & Ubbelohde 1996). This prototype house was intended to address market pressures faced by the merchant housing industry while at the same time offering superior summer performance over a house built to California energy standards.

The house was originally designed under the premise that it would only be applied in transition climates[1] and would not require the use of compressor cooling. Later in the project the ground rules were changed to allow down-sized compressor cooling systems in order to expand the range of applicability and decrease potential market barriers.

The initial two-story 2369 ft² house design was suited to the Southern California market. In later project phases two additional house designs, a 1998 ft² one-story plan and a 1744 ft² one-story plan, were developed to meet market and climate demands for all areas of California. Design packages for these houses were developed, including architectural, structural, and mechanical drawings and specifications sufficiently complete for building permit submittal.

Since residential development site maps are seldom optimized for solar orientation, the houses were designed to perform well in any orientation. All houses are of wood frame slab-on-grade construction. Envelope features that distinguish the houses from standard construction include improved wall and ceiling insulation, slab perimeter insulation, high performance windows, extended window overhangs, and tight construction[2]. Thermal mass, critical to the performance of the ventilation cooling system, was enhanced by covering 50% of the slab with tile, and by applying ¾" gypboard to interior walls. This combination of tight construction, good insulation, limited solar gain, and high thermal mass were included in the designs with the intention of improving comfort by providing relatively constant and uniform indoor air and mean radiant temperatures.

The current phase (Phase V) of the project calls for two houses to be constructed using one or more of the plans developed under the project, or at least built to similar specifications. Test houses will be located in transition and hot inland climates, and will be monitored to verify energy and demand savings.

[1] "Transition climate" is roughly delineated as the area between the coast and the central valley or southern desert where the climates are alternately affected by cooler marine or warmer inland influences.

[2] 'Tight" construction is defined by the Energy Star program as having a Standard Leakage Area of 3.8 or less.

Human Issues Related to Ventilation Cooling

Health Considerations

Several options were reviewed for integrating ventilation cooling with other heating and cooling system components. Since the success of ventilation cooling hinges on the temperature of the air used for ventilation, both direct and indirect evaporative cooling were considered early in the project as means of reducing ventilation air temperature. Comfort and health effects of elevated relative humidity were examined, with the conclusion that relative humidities of 70 or even 80% may provide acceptable comfort in dry climates. However, allergy inducing dust mite species, which can tolerate humidities down to 50%, probably dictate the upper limit (Arens et al 1995). Lower air temperatures in the vicinity of cool floors also act to increase relative humidity, particularly in summer months (Wilcox 1997). To reduce dust mite exposure, the project abandoned direct evaporative cooling but continued to evaluate indirect evaporative cooling as an option to precool ventilation air.

Health considerations also prompted the decision to apply systems that pressurize rather than depressurize occupied spaces. Whole house exhaust fans are popular in many regions for augmenting natural nighttime convective cooling. While whole house fans efficiently move large volumes of air, the air admitted through windows is not filtered and can introduce pollen and other allergens. In loosely constructed homes depressurization can also introduce fiberglass particles from attics into the living space. These considerations prompted the project team to concentrate on systems that pressurize indoor spaces with filtered air.

The need for mechanical ventilation in tightly constructed houses has been widely recognized and has been debated at length in committee meetings on ASHRAE Standard 62.2P (Best 2000). A recent study states that exposure to airborne toxins is most likely to occur inside homes, offices, or automobiles (Ott and Roberts 1998). These authors also indicated that 16% of the total exposure of the U.S. population to benzene, a known causative agent of leukemia, is from home sources such as gasoline stored in attached garages and from car exhaust. Since benzene levels in outdoor air peak during the day, the ideal time to ventilate is during the night. Thus, optimal schedules for providing cooling and improving air quality coincide.

Market Issues

To have a significant impact on the reduction of California's peak load, non-compressor cooling systems must be attractive to the merchant housing industry, which is notoriously resistant to change and highly sensitive to marketing image and costs. Cooling systems that are conspicuous in appearance, provide a different quality of comfort, have unique maintenance requirements, or require specialized contractor training are not likely to succeed in this environment. Further, products must be readily available through conventional sources.

These market acceptability issues led the project team to reject direct and indirect evaporative cooling as near-term options, even though they are suited to the California climate. Though they may rarely be used, small (1½-2 ton) air conditioners provided with the systems lend the appearance of conventional cooling and the security of knowing that cooling capacity, sized using conventional methods, is available to meet extreme loads.

Comfort and Sociological Issues

Sociological research by project participants was challenged by the difficulty of identifying "normal" or "universal" human behaviors with respect to comfort and people's use of controls. Outside controlled environmental chambers, people exhibit considerable individual and situational variability in perceptions of comfort. People adapt to changing environmental circumstances and acclimatize to hotter or cooler temperatures over time. However, people tend to adapt to, and become accustomed to, mechanically-cooled conditions. Alternatives must provide – and must be marketed as providing – better cooling than conventional systems (Lutzenhiser et al. 1994).

People are used to believing they have control over their indoor environment. When cooling is dependent on outdoor air temperature, a sense of control is challenging to provide. A benchmark idea, conceived by the project team, was to allow the home occupant to select the desired *minimum* morning indoor temperature to produce a predicted *maximum* afternoon indoor temperature. Incorporating this capability into thermostat settings addresses this need for control.

Selection of Cooling Systems

Fan Options

Two options for integrating a ventilation fan into the cooling system were considered which both share supply ductwork with the heating system. The first option uses the furnace (or heating system) fan to provide ventilation. A single motor-operated damper provides switching between return air and outside air. The same damper allows relief air to purge hot air from the attic. This design option requires that the furnace fan have separate speeds for heating, ventilation cooling, and compressor cooling, and requires that the furnace or cooling coil accommodate the high air flow used for ventilation.

The second option uses a separate fan that is isolated from the furnace and return air ducting by barometric dampers. Air is relieved from the house through a damper between the house and the attic. This system approach only requires that the ductwork be sized to accommodate high ventilation air flow rates; the furnace and cooling coil size can be sized for their respective air flows. However, the separate fan design has the disadvantage of requiring more dampers, with the potential of damper failure and/or increased damper leakage. Also, the second fan adds cost and complication.

A manufacturer of a damper similar to that shown in Figure 1 was identified, justifying the abandonment of the separate fan design approach. This damper is marketed, with a control system, as a residential economizer.

Direct and Indirect Evaporative Precooling

Evaporative coolers are common in certain areas of California. Lower air temperatures delivered by these systems, especially at night when wet bulb temperatures are lower, suggest they hold promise for ventilation cooling. However, systems that add moisture to the indoor environment were eliminated from consideration pending further research on health effects and adaptability to humidity.

Indirect evaporative cooling can be used to achieve lower ventilation supply air temperatures without adding moisture. Performance analysis verified that indirect cooling would significantly extend the climate range of compressorless houses. Several factors, including lack of a manufactured product, space requirements, visual impact, and installation and maintenance issues discouraged application of this technology to systems intended for the immediate market.

Integrated Air Handling Unit Development

Opportunities for Improved Heating and Cooling Delivery Systems

The current phase of the project includes development of an integrated heating, ventilation and cooling unit (HVC). Installation problems observed with residential economizers pointed to the need for a product that minimizes the necessity for field fabrication and wiring, simplifies installation, and optimizes performance.

There appears to be growing builder interest in combined hydronic systems that use the water heater as a heat source for space conditioning (Best 1998). These systems eliminate furnace gas piping, venting, and combustion air ducting. Energy and cost saving opportunities and market barriers have been thoroughly studied (Thorne 1998).

An opportunity also exists to use available equipment to providing varying air volumes. Electronically commutated motors are used in single-speed residential equipment because they allow a wide variety of speed settings. They operate very efficiently at low speeds, drawing as little as 50 Watts without losing more than 13% of their high speed efficiency. This feature makes them highly suitable for providing fresh air ventilation to meet indoor air quality needs. Variable speed capability also enhances the performance of heating and ventilation cooling, while providing quiet operation. The authors tested a hydronic heating system using a variable speed blower motor at one of the PG&E ACT² residential sites[1]. The system had extraordinarily low fan energy use, maintained the temperature setpoint extremely well, and was quiet.

Component Integration

The HVC integrates fan, damper, heating and cooling coils, and control components. Four options for combining these components were evaluated:

1. Standard size heating and cooling coils at the return side of blower; separate filters for return and outside air
2. Standard size coils at supply side of blower with barometric damper to provide ventilation air bypass
3. Oversize coils at supply side of blower with no bypass
4. Integrated heating-cooling coil at return side of blower

Criteria used to select the optimal configuration included ease of filter replacement and other maintenance, cabinet size, coil and blower performance, and cost. The fourth option, shown in Figure 1 best met these criteria. Combining heating and cooling coils into a single coil retained performance goals and mitigated cost increases for the oversized coil. Alternating heating (water) and cooling (refrigerant) tubes in the 4-row coil share the same

[1] Pacific Gas & Electric Company Advanced Customer Technology Test, Rocklin site

fins. The coil was placed at the blower inlet to improve fan performance by decreasing turbulence and minimizing "system effect" pressure losses. The low air velocity at air conditioning fan speeds minimizes the risk of water droplets leaving the face of the coil. This configuration also results in the most compact design of the four options.

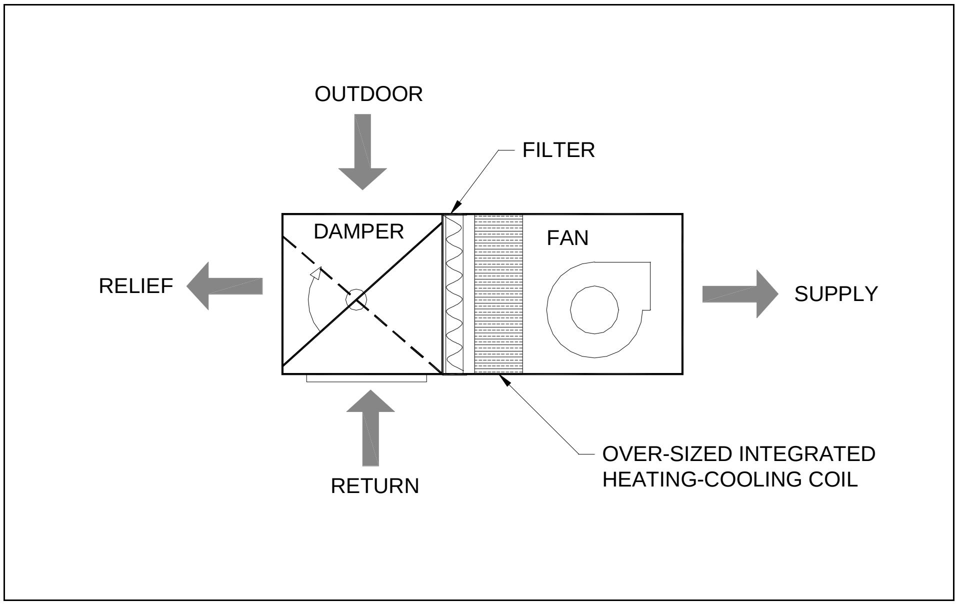

Figure 1. Oversized Integrated Coil in Return

The damper shown in Fig. 1 is typically installed in an attic space. During a vent cycle it draws in outside air from a roof vent. Relief air from the pressurized house is discharged into the attic space, thus ventilating the attic with cooler air.

Fabrication and Testing

The design shown in Figure 1 has been fabricated and is scheduled for laboratory and field testing in 2000 and 2001. The damper has been tested independently for durability, pressure drop, and leakage. Air handler tests will be completed to develop blower curves, coil performance, energy use, and temperature control characteristics.

Control Development & Field Testing

Prior Technology

The project adopted a residential economizer that has been in production for more than five years. Controls marketed with the damper consist of a differential thermostat that starts the fan and opens the outside air damper when outside air is cooler than inside air, and a low limit control that shuts the fan off and closes the damper when the indoor air temperature is below the setting. The low limit control is separate from the heating/cooling thermostat.

Interviews conducted with owners of houses equipped with these systems revealed that owners did not understand how the systems functioned or how to operate them (in several cases improperly installed dampers made systems less than effective). To address this problem, substantial project time was devoted to developing a control that communicates the concepts of ventilation cooling to the user and encourages proper use, consistent with the particular comfort demands of the subject(s).

Field Tests

Field tests were conducted on four houses equipped with the residential economizer described above. The houses were built to current California energy standards. Follow-up tests were completed on two of the houses, replacing standard controls with the advanced controls described below. Field test participants were interviewed before and after installation of the advanced controls. Both sets of homeowners indicated they would surely install the controls and ventilation systems were they to build new homes. Monitoring results showed that the systems were effective at reducing indoor temperatures and air conditioner operating hours, even though the houses were not optimally designed for ventilation cooling (Frietag 1998, Loisos & Springer 2000). Indoor temperatures below 78ºF were maintained on days with maximum outdoor temperatures exceeding 95ºF. Additional testing with houses designed to project standards is planned in Phase V.

Advanced Control Development

The same manufacturer that produces the damper previously described manufactures a programmable wall display unit. This unit utilizes a "soft key" design that allows the labels of thermostat buttons to be redefined, depending upon the settings being implemented. These controls also used embedded control programs that can be readily modified to suit a variety of applications.

The project team developed a functional specification for the control, and a user interface mockup was developed in Java script and placed on an internet web page[1] for review and evaluation. User interface screens, as well as complete control algorithms for operating ventilation cooling, heating, and compressor cooling functions, were programmed into the controller. Both single speed and variable speed blower versions have been developed.

Ventilation Cooling Control User Interface

The user interface, with the "cooling mode" screen displayed, is shown in Figure 2. Screen icons display indoor and outdoor temperatures, and fan status (the squiggly arrow indicates that the house is being ventilated). The window icon indicates when it is appropriate to open windows[2]. The "Set" button allows selection of long term temperature settings (see Figure 3). Pressing the up/down buttons to the right of the screen accesses short-term (override) temperature settings. Pressing the "Fan" button manually operates the fan to either recirculate air or ventilate the house. The "Help" button accesses context-sensitive help information.

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[1] http://www.davisenergy.com/acc

[2] Field tests of houses with existing mechanical ventilation systems showed more cooling effect was obtained when windows were opened.

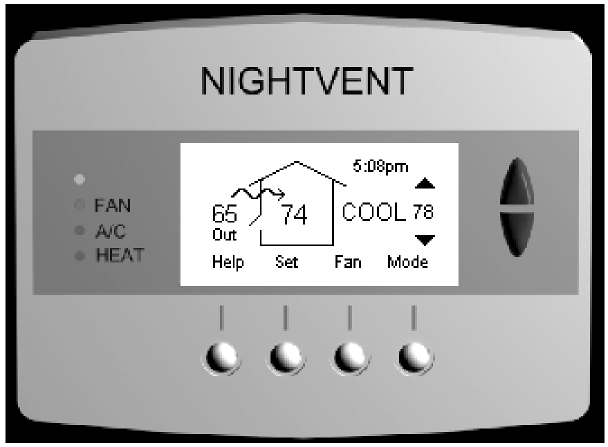

Figure 2. User Interface with Cooling Mode Screen Displayed

Figure 3 shows the screen used to make "long-term" temperature settings in cooling mode (appears after pressing "Set" button). This screen is designed to aid the user in understanding the consequences of ventilation cooling temperature settings. The "Lo" setting (adjusted using "Set Low") is used to select the vent cooling low limit temperature, or the lowest indoor temperature that can be comfortably tolerated at night. The "Hi" setting (adjusted using "Set Hi") defines the operating point for the air conditioner, or the maximum preferred temperature if no air conditioner is installed. The shaded segment of the temperature bar predicts the full range of temperatures the user can expect, and is based on computations of predicted indoor temperatures. If the low limit setting is raised, the shaded bar moves to the right until it intersects the "Hi" setting, and the message "A/C will run" is displayed. This strategy introduces an element of game playing to the process of setting temperatures that may induce the user to avoid the use of the air conditioner.

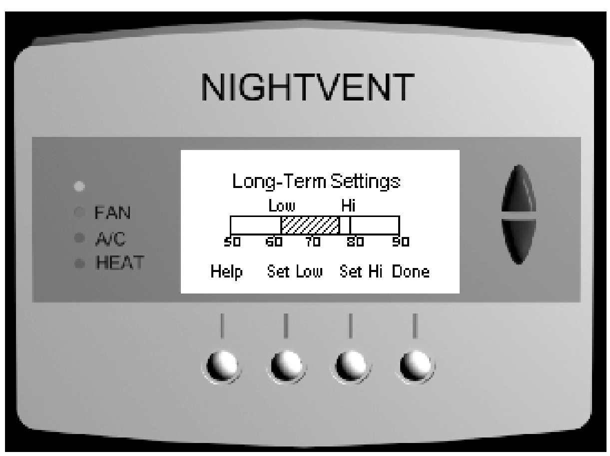

Figure 3. User Interface with "Long-Term" Cooling Settings Displayed

Statistical analysis of monitoring data was used to develop the predictive algorithms that define the range of the comfort bar, which is reset on a daily basis. Algorithm parameters are modified by actual temperature measurements obtained by the control during operation, to correct for unique thermal behavior of the houses in which the controls are installed.

Additional user screens are provided for displaying current operating mode and temperature, for setting heating temperatures and schedules, adjusting clock settings, and other functions A vacation mode provides automatic heating/cooling changeover while minimizing heating and air conditioning operation.

User interface and control algorithm improvements are continuing. Personal interviews, responses to the web page user interface mockup, and laboratory and field test evaluations will be used to produce final refinements. Because the control hardware is already in production, vent cooling controls can be marketed immediately following software refinements.

Performance Analysis

Analysis Objectives and Methods

DOE-2 computer simulations of night ventilation cooling systems were completed to determine the potential for application of night ventilation cooling in the various California climates. Objectives of this Phase IV analysis did not include determination of energy savings and peak load reduction, which are to be determined in Phase V using both DOE-2 modeling and field tests. However, DOE-2 analysis was completed to evaluate the performance of the Southern California prototype relative to standard designs, without ventilation cooling. Energy and demand savings for the prototype houses with new ventilation control algorithms in place will be determined in the current project phase (Phase V).

The DOE-2 model used for the climate analysis incorporated a custom function for simulating slab and ground heat transfers that was based on a two-dimensional finite difference model. Rather than full year weather data, five day hot weather sequences for 171 California locations were developed to correspond to 2% design conditions (Zhang and Huang 1999).

Analyses were completed using the Southern California prototype house (Loisos and Ubbelohde 1996). This two-story house was analyzed by dividing it into eight thermal zones to at least partially model temperature variations between the living spaces, attic, and garage. Five operational modes were evaluated, including (1) no ventilation, (2) natural ventilation through windows, (3) ducted mechanical ventilation of 1500 cfm, (4) mode 3 with an indirect evaporative cooler, and (5) mode 3 with a 1½ ton air conditioner. As modeled, vent cooling controls effectively vented the house down to a 65ºF indoor low limit temperature. For the indirect evaporative cooling cases, ventilation air temperatures were computed using a 60% approach to wet bulb temperature (from outdoor dry bulb temperature).

Analysis Results

Using 78ºF maximum indoor temperature as a comfort criterion, comfort was maintained by ventilation systems in 43% of the locations analyzed without using air conditioning or indirect evaporative cooling. In general these locations include Northern and Southern California coastal climates, Northern California inland bay climates, and mountain regions. Indirect evaporative cooling extends non-compressor systems into Northern

California valleys and about 10 miles inland in Southern California. A 1½ ton air conditioner with vent cooling will maintain comfort in all locations except the upper central valley and the Southern California deserts. A computer-generated map was developed to provide a visual representation of the cooling potential for the five ventilation cooling and combined ventilation/air conditioning modes (Huang 1999).

Annual cost savings for the prototype house equipped with conventional air conditioning (and no ventilation cooling) compared to the same house built to California standards ranged from 16 to 53%. Peak demand for the prototype house only exceeds 2 kW in 7 of the 171 climates analyzed, all located in the Southern desert. The expected result is substantially reduced peak load, higher summer fan energy use due to longer fan run times, and lower winter fan energy use due to variable speed operation.

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