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VENTILATION COOLING OF RESIDENTIAL BUILDINGS*

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SOLAR BUILDINGS RESEARCH AND DEVELOPMENT PROGRAM
CONTEXT STATEMENT

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In keeping with the national energy policy goal of fostering an adequate supply of energy at a reasonable cost, the United States Department of Energy (DOE) supports a variety of programs to promote a balanced and mixed energy resource system. The mission of the DOE Solar Buildings Research and Development Program is to support this goal, by providing for the development of solar technology alternatives for the buildings sector. It is the goal of the program to establish a proven technology base to allow industry to develop solar products and designs for buildings which are economically competitive and can contribute significantly to building energy supplies nationally. Toward this end, the program sponsors research activities related to increasing the efficiency, reducing the cost, and improving the long-term durability of passive and active solar systems for building water and space heating, cooling, and daylighting applications. These activities are conducted in four major areas: Advanced Passive Solar Materials Research, Collector Technology Research, Cooling Systems Research, and Systems Analysis and Applications Research.

Advanced Passive Solar Materials Research. This activity area includes work on new aperture materials for controlling solar heat gains, and for enhancing the use of daylight for building interior lighting purposes. It also encompasses work on low-cost thermal storage materials that have high thermal storage capacity and can be integrated with conventional building elements, and work on materials and methods to transport thermal energy efficiently between any building exterior surface and the building interior by nonmechanical means.

Collector Technology Research. This activity area encompasses work on advanced low-to-medium temperature (up to 180° F useful operating temperature) flat plate collectors for water and space heating applications, and medium-to-high temperature (up to 400° F useful operating temperature) evacuated tube/concentrating collectors for space heating and cooling applications. The focus is on design innovations using new materials and fabrication techniques.

Cooling Systems Research. This activity area involves research on high performance dehumidifiers and chillers that can operate efficiently with the variable thermal outputs and delivery temperatures associated with solar collectors. It also includes work on advanced passive cooling techniques.

Systems Analysis and Applications Research. This activity area encompasses experimental testing, analysis, and evaluation of solar heating, cooling, and daylighting systems for residential and nonresidential buildings. This involves system integration studies, the development of design and analysis tools, and the establishment of overall cost, performance, and durability targets for various technology or system options.

This report is an account of research conducted in the systems analysis and applications research area. It evaluates the energy savings potentials of passive and hybrid ventilation cooling of residential buildings.

Ventilation Cooling of Residential Buildings

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ABSTRACT

The effectiveness of ventilating residential buildings with unconditioned outdoor air as an adjunct to, or replacement for, conventional vapor-compression air conditioning has been examined. The work reported was based on total energy analyses of a prototypical residential building in 24 locations throughout the continental United States. The energy analyses assumed fan-forced ventilation and examined the relative merits of various control strategies and various configurations of thermal mass within the building. Where possible, the results of these studies are extrapolated to conditions of natural ventilation. The primary conclusions are that (1) ventilation has the potential to substantially reduce cooling energy use in the residential sector, (2) levels of thermal mass above those typically found in new construction enhance the effectiveness of ventilation and reduce peak energy use, and (3) to realize a significant fraction of the benefits of ventilation over conventional air-conditioning technology, effective means must be developed for exchanging heat with the external environment without allowing intrusion of moisture-laden air.

INTRODUCTION

The purpose of the study reported here is to investigate the effectiveness of ventilation with unconditioned outdoor air as an adjunct to, or replacement for, conventional vapor-compression air conditioning in residential buildings. The results are presented by comparing the auxiliary cooling energy required to maintain a given comfort level (as defined by interior dry-bulb temperature) for several ventilation systems and building configurations. The energy requirements presented herein are based on sensible thermal load calculations and, therefore, do not correspond to building boundary energy--that is, the effects of latent loads and of primary fuel utilization efficiencies associated with the generation, transmission and on-site energy conversion equipment are not included in the analysis. The building energy analyses were performed using a developmental version of the public domain computer program BLAST 3.0. (BLAST--Building Loads Analysis and System Thermodynamics--is trademarked by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.) A prototypical residential building was analyzed in a variety of locations for which TMY weather data are available. (Typical Meteorological Year (TMY) weather tapes and documentation can be obtained from the National Oceanic and Atmospheric Administration, Asheville, North Carolina.) Both integrated annual auxiliary cooling loads and hourly peak auxiliary cooling loads are reported.

This study is motivated by two observations. First, past energy analyses (Place et al. 1983; Sullivan et al. 1981; CCB/Cumali Associates 1980) of the performance of residential buildings utilizing direct solar gain have clearly demonstrated that the cooling implications of passive heating strategies are nonnegligible. These studies also indicated that the levels of thermal mass typically found in passive heating systems are important in mitigating the increases in cooling load resulting from the heating system design. This suggests the need for a more integrated design process for passive systems where heating and cooling are addressed simultaneously.

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The second observation motivating this work is that among the passive and hybrid cooling technologies, only forced ventilation and evaporative cooling have a sufficiently developed technology base to support widespread use in the near-term. While other cooling options have been designed, constructed, and in a few cases, analyzed and/or tested, their thermal behavior has not been modeled or characterized in a manner that permits reliable prediction of thermal performance in different climates. Therefore, it is ventilation and evaporative strategies that will have near-term impacts on the consumption of nonrenewable energy resources for cooling. For this reason, it is important to examine ventilation (and evaporation) to quantify their effectiveness and better define their limitations. Moreover, in order to provide a sound basis for more widespread use of ventilation cooling, energy performance must be characterized to allow the designer to select the most appropriate system parameters for any particular design project. Therefore, a secondary purpose of this project is to extract salient results from the thermal analyses that are not specific to the building or the climates considered herein.

Past studies of ventilation cooling (Berkeley Solar Group 1980; Kusuda and Bean 1981) have had limited scopes relative to the climates, the ventilation system configurations, or the building parameters examined. Historically, considerable effort has been devoted to studying natural ventilation (see references cited by Chandra et al. 1982) with a heavy emphasis on architectural considerations relating to optimization of natural ventilation rates; this research typically has not attempted to quantify the energy implications of ventilation. More recent research (Chandra and Kerestecioglu 1982) has examined both the air exchange and heat removal rates for natural ventilation systems but to date has not led to conclusive results in either area. Because the current understanding of ventilation and its impacts on human comfort and energy use are highly qualitative, there is no well-defined or reliable design procedure for ventilated buildings. While a few design and end-use strategies are common practice (for example, whole-house fans and operable windows), little is known about the actual energy benefits or about the potential benefits of more aggressive ventilation strategies. The work reported here attempts to provide broad answers to the energy questions and a framework for defining future research needs.

This study encompasses two major aspects of ventilation as a passive or hybrid cooling system. First, the effects of varying ventilation system design parameters on auxiliary cooling energy requirements are examined. The parameters included are (1) air exchange rate, (2) control strategy, and (3) control settings. The second consideration is how the building design influences the effectiveness of the ventilation system. This portion of the study focuses on the coupling between ventilation air and the building construction materials, with comparisons between designs which include various amounts of thermal mass, and different degrees of coupling between the internal mass and the ventilation air. The study focuses on structural cooling rather than occupant cooling. That is, the effects of ventilation induced air motion on occupant comfort are not examined here. Substantial additional energy benefits over and above those reported here, may be attributable to ventilation cooling of buildings if these comfort issues are accounted for.

The second section describes the methodology used in the analyses and the assumptions on which they are based. The third section describes and interprets the results of the study and, finally, the fourth section summarizes the conclusions.

METHODOLOGY

Prototype Building Description

A detailed description of the architecture, occupancy, internal loads, and building materials of the residential prototype is presented in Andersson et al.(1983) and Carroll et al.(n.d.); salient features of the design are repeated below. Table 1 summarizes (1) the thermal properties of the building envelope, (2) the internal loads, and (3) the auxiliary heating and cooling system control. This building has been used for a variety of other parametric studies (Place et al. n.d.; Andersson et al. 1983; CCB/Cumali Associates 1983; Sullivan et al. 1981).

While it is impossible to define a "typical" residence in the United States, the structure analyzed here is representative of a broad range of designs. The building is rectangular and asymmetric, with dimensions of 49 ft (14.9 m) by 24 ft (7.3 m) and has a modest glazing area of 176 ft^2(16.4m^2)--15% of the 1176 ft^2 (109m^2) floor area. The building is oriented on an east-west axis, and the glazing is unevenly distributed over the four exposures; 132 ft^2 (12.3 m^2) of glazing appears on the south facade, while the remainder is allocated to the north side of the structure to provide a throughflow path for ventilation air. Double glazing is assumed throughout, and the south-facing windows are shaded by a 3.5 ft (1.07 m) roof overhang. A floor plan for the building is shown in figure 1.

The base building contains a substantial amount of thermal mass in a bare, externally insulated, 4 in (10.2 cm) thick concrete floor slab and 4 in (10.2 cm) thick concrete partition walls defining a three-zone configuration, as shown in figure 2a. The partition walls within each zone are assumed to be standard stud wall constructions. Insulation levels in the external opaque walls and ceiling are taken to be consistent with recommendations that resulted from Building Energy Performance Standards studies. As shown in the cross-sectional elevation of the thermal model in figure 2b, an attic space is assumed as a fourth (unconditioned) thermal zone.

The building is assumed to be occupied and to have typical levels of internal equipment and lighting loads. The auxiliary heating and cooling equipment is controlled entirely by air temperature thermostats and is assumed to have sufficient capacity to meet the loads in the structure for all hours of the year. Since the three occupied zones in the structure are thermally coupled only through conduction (not convection), the heating and cooling systems are controlled separately for each zone; the cooling thermostat is set at 78°F (25.6°C) for the entire simulation period, while the heating thermostat is at 68°F (20.0°C) during the daytime hours and set back to 60°F (15.6°C) from 11:00 p.m. to 8:00 a.m.

The base building is architecturally identical for all climates investigated in this study. As described in the results section, the base building description was modified for some simulations to examine the effects of varying the coupling of ventilation air to the structural mass. To evaluate the effectiveness of thermal mass in mitigating cooling loads in the presence of ventilating strategies, three separate building modifications were employed:

1. For the base building, the exposed area of concrete floor slab was systematically reduced by incrementally covering the slab with carpet.

2. The concrete partition walls were systematically reduced in area and replaced with more conventional 2 in (5.1 cm) by 4 in (10.2 cm) stud walls faced with 0.50 in (1.27 cm) gypboard.

3. For the structure with gypboard partition walls, the insulated concrete floor slab was systematically reduced in area and replaced with a vented crawlspace under an insulated wood floor.

As noted above, a more complete description of the building is given in Andersson et al.(1983) and Carroll et al.(n.d.).

Energy Analyzing Technique

The prototypical building was analyzed to determine its energy performance using a developmental version of the public domain program BLAST-3.0 (Hittle 1979). For the study reported here, several features of the program are especially important.

1. Heating and cooling loads are calculated on an hourly basis.

2. Solar gains through windows and on opaque surfaces are calculated in considerable detail, accounting separately for beam, diffuse, and ground-reflected radiation.

3. The dynamic effects of structural mass on the thermal storage capacity of the building are accounted for by the response factors used in the calculation of conductive heat transfer.

4. The thermal load calculation allows the interior air temperature to float between user-defined thermostat setpoints; the control strategies are user-defined and -scheduled so that thermostat setbacks can be reliably simulated.

5. The program utilizes the iterative thermal balance technique developed by Walton (1980) to calculate building loads; this methodology allows simultaneous simulation of adjacent zones, while properly accounting for the dynamic effects of thermal storage in conductive heat transfer through the constructions defining the individual zones. (As implemented in BLAST 3.0, the coupling is limited to conduction and forced convection. Although the solution technique is suitable for natural convective coupling, no suitable interzone convective mass flow/heat exchange algorithms currently exist.)

Several validating exercises have been carried out using BLAST (Bauman, Andersson et al. 1983; Judkoff et al. 1983). In all cases, agreement between BLAST predictions and experimental data have been excellent. Of particular importance to the work reported here, the validations reported in Bauman et al. (1983) include emphasis on solar gains, thermal mass, and forced ventilation cooling.

The results presented in the section are the total energy requirements (summed for the three occupied zones) for the building, as calculated in the loads section of the program. This portion of the program accounts only for sensible loads and does not account for the performance characteristics of the on-site energy conversion systems. These issues are normally accounted for in the mechanical system and central energy plant portions of the program, which were not used in this study because of their orientation toward nonresidential building equipment. The total energy requirements reported here must, therefore, be dealt with carefully to avoid misinterpretation; actual energy requirements of the building boundary will be larger by amounts that are climate-dependent. Since the goals of this study are (1) to examine the sensitivity of the auxiliary load to specific ventilation system and building design parameters and (2) to explore the potentials for ventilation cooling, the effects of latent loads and system inefficiency generally can be neglected--i.e., the variation of auxiliary energy requirements with the design parameters for the ventilation system and building are of prime interest, rather than the absolute magnitudes of the energy requirements. It is further noted that the temperature of the air transferred to the occupied space by the ventilation cooling system is increased so that its relative humidity within the space is less than or equal to the relative humidity outside. Therefore, if the ventilation system is not allowed to operate when (1) the ambient humidity is above the comfort level and (2) the air conditioner is operating, then neither the comfort conditions nor the latent loads will be aggravated by the ventilation system. As described below, the ventilation system utilized in this study includes a humidistat control option, and relevant sensitivities have been examined.

The energy analyses used weather data from 24 locations from the original Typical Meteorological Year (TMY) data base to drive the BLAST simulations. The locations are identified in figure 3. The hourly TMY weather data are aggregates of statistically selected "typical" months from the long-term SOLMET data base.

Ventilation System Description

The energy analyses assume the existence of an auxiliary cooling system and a controlled, fan-forced ventilation system.* This configuration provides a basis for quantifying the effectiveness of ventilation in terms of auxiliary energy savings. Other bases for quantification can, of course, be envisaged; for example, the auxiliary system could be removed in the analyses, and a comparison of the comfort levels realized under different ventilation strategies could be performed. Given the current understanding of comfort and existing analytical capabilities, this would necessarily lead to more subjective conclusions. In addition, the conclusions would be more closely coupled to the specific building configurations studied and, therefore, less amenable to generalizations.

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*The ventilation system is assumed to operate in parallel with (uncontrolled outside air penetration due to) infiltration. In effect, this corresponds to the assumption that the ventilation system does not substantially affect the air pressure in the building. In general, the infiltration rates are much smaller than the natural ventilation rates of interest and would not have noticeable energy impacts in relation to those resulting from the (controlled) ventilation strategy.

As noted above, the analyses assumed a fan-forced ventilation system rather than pressure- (wind-) driven or buoyancy-driven (stack effect) natural ventilation. Currently, there are not adequately defensible and general algorithms describing natural rates of ventilation for common passive systems, and control strategies for many natural ventilation systems (such as opening of windows) are based on the behavior of the occupants. Therefore, results obtained using currently accepted approximations would necessarily be applicable only to the specific systems of natural ventilation to which the algorithms applied; again, the results could not be generalized. For this reason, this study attempts to present the results for fan-driven ventilation in a way that allows extrapolation to specific natural ventilation systems if the anticipated ventilation rates and control strategies are given.

The version of BLAST used in this study served as a test bed for the development of the ventilation cooling model subsequently implemented in BLAST-3.0. The model used here consists of representations of four ventilation system components for each user-defined zone of the structure.

1. A fan, with a user-specified capacity.

2. A thermostat controller that activates the fan when the exterior temperature is below both a user-specified upper limit and the zone air temperature. The cooler also deactivates the fan when the zone air temperature reaches a user-specified lower limit, thereby preventing overcooling of the occupied space.

3. A clock timer controller with a user-defined hourly schedule for fan capacity. The clock timer is used in conjunction with the thermostat controller described above, which overrides the schedule to prevent (1) overcooling and (2) fan operation when the exterior-interior temperature differential obviates ventilation cooling.

4. A humidistat switch that overrides all other controls and prevents fan operation when the exterior relative humidity is above a user-specified maximum.

The fan controllers permit selection of one of three ventilation system control strategies:

1. Prompt Control - The thermostat controller adjusts the fan on-time for each hour in order to bring in sufficient outdoor air, when conditions permit, to maintain the occupied space at a user-defined thermostat setting. This strategy is representative of common residential ventilation systems.

2. Anticipatory Control - The clock timer permits scheduled flushing of the building with outdoor air to precool the structure. This strategy is most appropriate for nonresidential structures where, during unoccupied periods, controlled ventilation for maintaining indoor air quality is unnecessary, and comfort conditions relating to both temperature and humidity can be relaxed.

3. Mixed control - The prompt and anticipatory strategies are combined. In this case, the thermostat controller for prompt ventilation is separated from the thermostat override for the scheduled ventilation so that, for example, the building can be promptly ventilated into the comfort range during the daytime and precooled to a point below the bottom of the comfort range at night.

The control strategies, control parameters, and fan size can be changed on a seasonal basis. At the conclusion of the simulation, the integrated fan on-time is reported for each zone and each control period. It is noted here that the ventilation system simulation does not account for the work done on the air by the fan, which results in a small increase in the air temperature across the fan (typically about 0.5°C)

RESULTS

Baseline Energy Use

The energy performance of the base-case building was simulated in the 24 climates identified in the section above. Conventional air conditioning was assumed, and no cooling-load avoidance strategies (other than window shading by the roof overhang) were included in the simulations. Furthermore, no deliberate cooling-load rejection techniques, such as controlled ventilation, were employed, though the effects of uncontrolled penetration of outside air in the form of infiltration were included. The results of this baseline study are summarized in table 2, which shows the total annual heating and cooling energy requirement (thermal loads) and, as indicators of climatic severity, the heating and cooling degree-days calculated from the TMY weather data that drove the BLAST simulations.

It is noted that the heating energy requirements shown in table 2 are realistic in that they do not neglect load reduction strategies that the occupants would typically employ (e.g., night setback). The cooling energy requirements, however, do not include (1) latent effects, which would increase energy requirements relative to the tabulated values, or (2) occupant intervention to avoid or reduce cooling loads. The latter strategies could include natural ventilation through operable windows or solar gain control strategies such as operation of window blinds or curtains. It is interesting to note that for about one-half of the climates studied, the inherent energy problem, even in a residential building, is cooling, and that heating is the dominant problem in only 8 of the 24 climates. The fact that cooling is not considered a more important issue in the residential sector is attributable largely to the relatively common occurrence of simple and highly effective passive strategies--most notably ventilation.

Three climates were selected for detailed study of the effectiveness of ventilation cooling. Albuquerque, NM, Washington, DC, and Madison, WI, were chosen to represent, respectively, climates where cooling energy requirements dominate, both heating and cooling requirements are significant, and heating is the dominant energy issue. For each location, the extent to which ventilation can reduce auxiliary cooling energy requirements has been examined for a variety of different assumptions regarding (1) ventilation system and control and (2) building design as it relates to location and amount of thermal storage mass. The results of these individual studies are summarized in the subsections below.

Thermostat Control

The total monthly heating and cooling energy requirements for the unventilated baseline building are shown in figure 4a for the Albuquerque, Washington, and Madison climates. The curves through the points are intended only to provide visual organization. The somewhat anomalous appearance of the February and March heating data relative to the line reflects the different number of days in the months. No corrections have been made for the variable length of months, since its effect should be less than 3% during the cooling season, the focus of this study. It is interesting to note that while there is a factor of 5.4 variation in heating requirements among these climates, the cooling variation is only a factor of 2.6.

Shown in figure 4b is the average daily outdoor dry-bulb temperature swing for the three climates; these temperature data were taken from the TMY weather tapes used in the energy analysis. Disregarding, for the present, the outdoor humidity, the figure clearly demonstrates the potential for ventilation cooling. In Madison, the average daily high temperature for the entire cooling season is less than the 78°F (25.6°C) cooling thermostat setting. In both Washington and Albuquerque, the average high temperature is also below the cooling thermostat setting except during July--and even then the average low temperature is still near 70°F (21.1°C). It is tempting to predict that if humidity effects can be ignored (or suppressed) and if thermal mass is provided in the two warmer climates to allow use of nighttime precooling of the structure, then cooling energy requirements can be largely eliminated by ventilation in all three climates. The results shown later clearly demonstrate that in reality this cannot be accomplished--presumably because the average day analysis is not sufficiently indicative of overall performance. However, the potential benefits of ventilation and the importance of thermal mass are obvious.

In performing the studies of ventilation, it was necessary to define a period of the year during which the various ventilation control strategies would be employed. During the heating season, the ventilation thermostat was set at 78°F (25.6°C), which prevented overheating. During the cooling season, however, the goal was to obtain lower indoor temperatures when outdoor conditions were favorable. The point at which the changeover to the summer operating mode took place is important because of the potential for either (1) overestimating the cooling benefits of ventilation while aggravating the heating problem or (2) underestimating the benefits of ventilation during the cooling season. The changeover point was determined by engineering judgment; it was found that when those months accounting for 85-90% of the cooling load were defined as the cooling season, there was little, if any, aggravation of heating problems, and well over 90% of the potential cooling benefits of ventilation were realized. For the three climates of immediate interest, the cooling season is defined in table 3.

Using the simplest control strategy, ventilation of the attic and of the occupied space have been studied; the results are summarized in table 4 and figure 5, respectively. The summer control strategy consisted of a differential thermostat that vents the individual zones down to 68°F (20.0°C) whenever ambient dry-bulb temperatures are favorable; no ambient humidity constraints were imposed. The size of the ventilation fan was assumed to be adequate to provide an air exchange rate of 100 air changes per hour (ACH); when the ambient temperature was less than 68°F (20.0°C), the fan controller throttled the total air change during that hour to prevent the zonal air temperature from falling below the 68°F heating thermostat setting. The fan controller did not distinguish between flow rate throttling or on/off operation. No attempt was made to precool the massive structure at night. The ventilation fan used in these preliminary studies was deliberately oversized to ensure that the maximum benefits of ventilation would be realized. As discussed later, significantly smaller ventilation rates would provide essentially the same cooling load reductions so no special significance should be given to the 100 ACH assumption. It is noted that recommendations associated with commercially available "whole-house" fans typically recommend fan sizes of about 60 ACH. The results presented in table 4 and figure 5 do not include any fan energy; the results, therefore, correspond to a maximally effective natural ventilation system.

As shown in table 4, ventilation of the attic alone had little effect on the total cooling energy requirements of the occupied space. In comparison to the unventilated building, reductions in auxiliary cooling for the season amounted to 6.5%, 4.0%, and 2.5% in Albuquerque, Washington, and Madison, respectively. This is seemingly inconsistent with experience--summer attic temperatures can be very high and it is tempting to expect ventilation to substantially reduce heat gains to the occupied space through the ceiling. The implication of the results is that either ceiling heat gains are a relatively minor contributor to total cooling load or the dominant mode of heat transfer to the upper surface of the ceiling insulation is radiation from the roof. In the latter case, attic air temperature would have second order effects on ceiling heat gains. While this issue was not pursued further in this study, it is surmised that the latter explanation--that radiation is the dominant heat-transfer mechanism in the attic during the summer--explains the counterintuitive nature of the result. This is further supported by results by Fairey (1982), who found that in the Cape Canaveral climate, metallic foil radiation barriers in the attic immediately above the ceiling insulation significantly decreased the net conductance of the roof-ceiling construction.

Direct ventilation of the occupied space was shown to be very effective in reducing cooling energy requirements, as shown in figure 5. This figure shows the total monthly cooling load without ventilation (as in figure 4) and the residual cooling load that cannot be removed by the simple ventilation strategy examined here. Total cooling energy requirements were reduced by 72.8%, 76.8%, and 81.6%, respectively, in Albuquerque, Washington, and Madison. It is noted once more that no humidity criteria are assumed in these results, so actual savings should be expected to be somewhat smaller; the curves in figure 5 represent the upper and lower limits of effectiveness of either natural ventilation or whole-house fans. Actual performance will depend heavily on the occupants' comfort requirements. It is further noted that if the expected degradations in effectiveness of ventilation (attributable to failure of direct ventilation to meet comfort criteria relating to humidity levels) can be circumvented by concepts for indirect ventilation cooling, then the upper limit of effectiveness as shown in figure 5 is a realistic performance goal.

The results described above assume a ventilation control thermostat setting of 68°F (20.0°C). Figure 6 shows the sensitivity of the residual cooling load to the thermostat setting. In order to obtain the results for settings below 68°F (20.0°C) where simultaneous heating and cooling would occur, the heating system was turned off for the summer months. As shown by comparing the residual loads at 60°F (15.6°C) and 68°F (20.0°C), substantial additional benefits (20, 15, and 30%, in Albuquerque, Washington, and Madison, respectively) are achievable with a control strategy that is more aggressive than the 68°F (20.0°C) setting assumed in figure 5. Most of the additional benefit is attributable to nighttime precooling of the thermal mass in the baseline building.

Scheduled Control

To determine the effectiveness of precooling the thermal mass at night, a second control strategy was examined. In this case, ventilation was allowed only during the nighttime hours, the only air exchange between the interior and exterior of the building during the day being the uncontrolled infiltration. During the nighttime hours (11:00 p.m. to 7:00 a.m.) the ventilation rate is again determined by a differential thermostat that prevents overcooling. As before, a ventilation capacity of 100 ACH was assumed for each zone in the occupied space.

The effectiveness of this strategy is determined by the thermostat setting and schedule. The residual cooling load as a function of the thermostat setting for ventilation is shown in figure 7. Not surprisingly, and as evidenced by comparison of figures 6 and 7, precooling alone is considerably less effective than direct ventilation. For the same thermostat setting, the precooling strategy leaves about twice as large a residual cooling load as the 24-hour thermostat control strategy. It is noted here that the slope of the curves in figure 7 is determined not only by the effectiveness of precooling thermal mass but also by the climate. The leveling off of the curves at lower temperatures does not reflect an inherent limitation of the thermal mass precooling strategy; rather it reflects the fact that ambient temperatures this low are not often available during the summer months to provide precooling.

Notwithstanding the fact that pure thermostat control is more effective, figure 7 shows that nighttime precooling substantially reduces cooling energy requirements. More specifically, for consistency within these analyses, one must assume that ventilation to 68°F (20.0°C) (the heating thermostat setting during the winter months) is acceptable during the daytime, and that at night, interior temperatures down to 60°F (15.6°C) are acceptable (consistent with the wintertime setback). If an aggressive ventilation strategy is assumed, then the two strategies are combined, thereby venting to the daytime heating thermostat setting during the occupied hours and to the heating setback temperature at night. Table 5 shows the effect of this combined strategy on reducing the residual cooling energy requirements in the three climates of interest here.

As shown in table 5, scheduled precooling of the massive structure provides reductions in auxiliary cooling energy requirements for the total cooling season of 20.1%, 20.3%, and 24.4% for Albuquerque, Washington, and Madison, respectively; these reductions are over and above those resulting from the simple thermostat control. One concludes that precooling is advantageous and its benefits will be largest in cooler climates and/or buildings with longer cooling seasons where lower outside temperatures will be more common.

The combined control strategy was used in all of the remaining studies reported in this paper; daytime and nighttime ventilation thermostat settings of 68°F (20.0°C) and 60°F (15.6°C), respectively, are assumed.

Ventilation Rate

All the results presented above assume a ventilation rate capability of 100 ACH. The controls have allowed throttling of the hourly air-change rate to prevent overcooling of the occupied space. Figure 8 shows the sensitivity of the residual cooling season energy requirement to the ventilation fan size. As shown, there is little benefit in ventilation rates larger than about 15 ACH--substantiating the earlier assumption that a fan size of 100 ACH would provide essentially all the energy benefits that one could hope to achieve through ventilation. The typical commercial recommendation for whole-house fan sizing (60 ACH) is probably quite realistic, in that forced ventilation systems must be sized to produce adequate ventilation even if working against disadvantageous local breezes.

Natural-ventilation data relating to air change rates are relatively rare. Recent experimental work by the Florida Solar Energy Center (Chandra 1983) has provided enough information to allow figure 8 to be used for preliminary estimates of the energy savings achievable with natural ventilation strategies. For a particular residential scale building, researchers have used tracer-gas dilution techniques to measure air change as a function of local wind speed. While the errors on these very difficult measurements are as yet unquantified, the results are very encouraging. The natural ventilation rates were measured to be approximately 19, 23, and 30 ACH at local wind speeds of 6, 7, and 10 miles per hour (2.7, 3.1 and 4.5 m/s). For the climates examined here, local wind speed data (U.S. Dept. of Commerce 1979) are summarized in table 6. While these wind speeds and directions are averages and as noted earlier, averages can be misleading, they are encouraging. Average wind speeds appear high enough and directions consistent enough throughout the cooling season to provide effective natural ventilation. If air change rates of the magnitude measured by FSEC can be obtained consistently by paying appropriate attention to local wind conditions during the building design process, then most benefits of ventilation can be realized without the use of fans. Similarly, unless one can assure rates of ventilation substantially in excess of those obtainable with operable windows (e.g., 3 to 5 ACH), designs for natural ventilation will not provide much energy benefit without substantially compromising comfort requirements.

Humidistat Control

The results presented to this point have assumed that ventilation is controlled only by a dry-bulb temperature-sensing differential thermostat; no humidity control has been assumed beyond the presence of rain (100% relative humidity) precluding ventilation. In order to evaluate the extent to which high outdoor humidity will degrade the effectiveness of ventilation, an ambient humidity sensing device was added to the control algorithm. Ambient humidity above the humidistat settings prevents ventilation. With all other control parameters as before, and with ventilation capacity of 100 ACH, the sensitivity of the residual cooling load to the humidistat setting is shown in figure 9.

Realistic upper limits to the humidistat setting would be about 80%. At this point, little degradation in the effectiveness of the ventilation system is observed in the relatively dry Albuquerque climate. For Madison, degradation of performance is larger, but ventilation still provides significant reductions in cooling energy requirements. However, in the more humid Washington climate, even at this relatively high humidistat setting, well over 50% of the cooling load reduction capabilities of the ventilation system are lost. Similar results would be expected for a large fraction of the eastern seaboard and the southern part of the United States--the regions where cooling is most important. In these areas, unless one is willing to substantially compromise traditionally accepted comfort requirements, simple whole-house natural or forced ventilation does not provide a viable alternative to conventional vapor compression air conditioners.

The conclusion stated above points to two areas that warrant future study. First, there are those who question the traditional statements of comfort requirements for overheated conditions. The extent to which the radiant environment and air motion can mitigate the deleterious effects of simultaneously high dry-bulb and wet-bulb temperature warrants further study. Second, investigation is required into concepts for indirect ventilation systems, which isolate the occupant from direct contact with the ventilation air. Concepts combining the heat exchange process and thermal storage would be especially advantageous. For example, the use of hollow core concrete in the floor slab and/or partition walls with ventilation air limited to the cores might provide a substantial fraction of the potential benefits of ventilation without the attendant loss in comfort.

Thermal Mass

All the results discussed above refer to the baseline building, which has substantial amounts of thermal mass in the 1176 ft^2 (109 m^2), 4 in (10.2 cm) thick floor slab and the 432 ft^2 (40.1 m^2) of 4 in (10.2 cm) thick interior partition walls separating the three occupied thermal zones in the building. The ceiling and inside surfaces of the exterior walls are 0.5 in (1.27 cm) gypsum board. In questioning the extent to which the thermal mass influences performance, three issues are important. First, the concrete thickness must be large enough to provide adequate storage but not so thick that interior portions of the mass are not participating in the diurnal charge/discharge cycle. Second, the exposed area of the thermal mass will affect storage capacity, and finally, the coupling of the mass to the adjacent air will affect the heat-transfer rate to and from the mass. Each of these issues has been examined.

Assuming the same ventilation parameters as in the previous result but with no humidistat control, the thickness of the interior concrete partition walls was systematically varied from 0.5 in (1.27 cm) to 10 in (25.4 cm). The residual cooling load as a function of partition wall thickness is shown in figure 10. As shown, concrete thicknesses beyond about 10 cm (4 in) are not effective in reducing residual cooling loads; since both surfaces of the partition walls are exposed, the implication is that the diurnal charging/discharging cycle affects only about 5 cm (2 in) of concrete.

It is noted that the residual cooling load increases rather rapidly below about 2 in (5 cm) and has an anomalous behavior as it approaches zero. This increase in residual thermal energy requirements, of course, is expected. However, below about 2 in (5 cm), figure 10 may not accurately represent the relationship between load and concrete thickness. This is due to the inability of the response factors used in programs such as BLAST to adequately represent the thermal storage effects when the response time of the construction is comparable to the one-hour time step used in the program. (Under these conditions, although thermal storage effects may not be fully accounted for by the response factors, thermal resistance is properly represented.) This is an area that warrants additional study--experimental data and/or analysis is needed to determine the limits of applicability of existing response factor techniques for calculating thermal conduction in building materials. In addition, for materials with rapid response times and large capacities, algorithms for improved energy analysis are needed.

Figure 11 shows the relationship between the exposed area of 4 in (10.2 cm) concrete partition walls and residual cooling load for the ventilated building. The figure was generated by systematically replacing concrete wall sections with uninsulated frame walls with 0.5 in (1.27 cm) gypsum board on each surface. It is noted that the exposed 4 in (10.2 cm) thick concrete slab is present in the building. As shown, the frame partition walls substantially degrade performance, presumably because a night strategy of ventilation precooling was being used. Again, we note that thermal storage in the gypsum board may not be fully accounted for in the figure. However, one concludes that in comparison to nonmassive partition walls, cooling load reductions of about 38%, 47%, and 50% are attributable to the concrete walls in Albuquerque, Washington, and Madison, respectively.

It is further indicated by figure 11 that additional thermal mass would not be very beneficial in this building in these climates. This implies that the ventilation system coupled with thermal mass is meeting essentially all of the cooling energy requirements whenever external conditions are favorable. The remaining cooling load is simply not removable by ventilation with diurnal storage strategies. This conclusion would not hold for a building with a different internal load profile, different level of thermal integrity, or different amount of internal solar gain (i.e., different shading configuration, glazing area, or, perhaps, glazing distribution).

The results presented thus far assume that the thermal mass is coupled to an average room air temperature through the standard convection coefficients documented by ASHRAE (1981) and shown in table 7. Although there is substantial evidence (Bauman, Gadgil et al. 1983) that these values are not representative of buildings, there are no acceptable alternatives at present. In order to investigate the sensitivity of the effectiveness of the ventilation strategy to the strength of the convective coupling, the floor was systematically carpeted to provide a degree of isolation between the thermal storage mass and the room air. The carpet was assumed to have a thermal resistance of 1.5, resulting in an effective coupling to the floor of .35 BTU/hr-ft^2 °F (1.96 W/m^2 °C) and .13 BTU/hr-ft^2 °F (0.75 W/m^2 °C) for heat flow upwards and downwards, respectively. It is noted that for vertical walls, variations in the convection coefficients by factors of 2 have been commonly observed in both experiments and analyses (Altmayer et al. 1983). Addition of the carpet to the floor in this study provides a similar change in the convective coupling strength.

For these simulations, the concrete partition walls were replaced by the frame wall construction described earlier. The results are shown in figure 12 for the Madison and Washington climates. As could be expected, since the building is not overmassed, there is a linear relationship between the carpet area and residual cooling energy requirement. The sensitivity of the residual cooling load to the "effective" convection coefficient is obviously quite large--addition of the carpet to the entire floor slab increased the residual cooling load by about 70%.

Finally, the effect of the thermal mass in the floor slab has been investigated by systematically replacing sections of the concrete floor space with a vented crawlspace beneath an insulated (R-10) wood floor; interior partitions were again assumed to be frame walls. The results are shown in figure 13. The linear relationship between residual cooling load and floor slab area is consistent with the discussion of figure 11--that is, removing the concrete partitions led to an "undermassed" building for which each unit of thermal mass contributes equally to cooling load reduction. The slope of the lines in figure 13 combines two effects--the diurnal thermal storage effect and the ground-coupling effect. Though the slab is assumed to be insulated (R-10) from the ground temperature, there is a relatively small but constant heat flow to the ground, which, when integrated over the cooling season, is significant. The vented crawlspace largely decouples the floor surface from the ground heat sink.

Summary

Table 8 summarizes the salient results of this study for the 24 climates. The table shows the inherent, nonvented cooling load, the residual cooling loads for both the massive baseline building and the building with stud wall partitions and an exposed floor slab, and the peak cooling loads for each of the configurations. The ventilation strategy used in all climates was identical to that used in the previous studies, that is, the combined control strategy with night precooling, no humidistat, and a ventilation rate capability of 100 ACH. In comparison to an unventilated building, ventilation reduces total cooling energy requirements by about 90% in the cooler climates, 75% in moderate climates such as Nashville, and from 30% to 60% in the most severe cooling climates. Also, as shown, the mass is most effective in the cooler climates where the reduction in total cooling energy requirements and peak load are typically 40%-50% and 20%-50%, respectively. In the warmer climates, the mass has somewhat less effect, reducing total cooling energy requirements and peakloads by 10%-20% and 5%-10%, respectively.

CONCLUSIONS

The study reported here has clearly demonstrated that ventilation can substantially reduce cooling loads in most U.S. climates. The extent to which these reductions are currently being realized through simple natural ventilation strategies and whole-house fan utilization is unknown; one would guess, however, that the effects are large. However, one would also guess that substantial additional savings in both energy consumption and peak loads are available through more aggressive control strategies, more effective use of thermal mass, and development of indirect ventilation strategies.

Several issues requiring further research were raised by this study:

1. Standard techniques for calculating the dynamic response of building constructions are probably in error when calculating the thermal storage effects of standard nonmassive constructions, though thermal resistances are properly dealt with.

2. The dynamic variations in surface convection coefficients are important in determining the performance of thermally massive constructions. There is a strong need to better understand these variations so that the energy performance of buildings can be characterized in a way that is accurate and useful to the designer.

3. There is a strong need to develop and evaluate concepts for indirect ventilation systems where outdoor air is not introduced into the occupied space.

4. There is a strong need to better understand comfort conditions under overheated conditions. In particular, it is important to determine the extent to which the cooler radiant environment characteristic of thermally massive constructions during the cooling season, and the air motion characteristic of ventilated buildings, can mitigate higher air temperatures and humidity levels.

5. Natural ventilation rates for buildings must be characterized in a meaningful way. In the meantime, forced ventilation is the only reliable approach to ensuring that the benefits of ventilation are achieved.

In spite of the uncertainties attendant to the research issues identified above, it is believed that the systematics observed in this study are correct. Specific conclusions then are:

1. Ventilation is potentially a highly effective passive or hybrid cooling option.

2. The advantages of thermally massive construction are large if the mass is deliberately excited, for example, by night precooling strategies. Whether the mass is effective under more conventional circumstances has not been investigated in this study.

3. Natural ventilation can produce adequate air-exchange rates under average conditions to ensure that the majority of the benefits of ventilation are realized.

Finally, one can surmise that the benefits of ventilation and thermal mass would be even larger in commercial buildings. In those situations where internal loads are higher than in a residence, the cooling season will be longer, extending into months where ambient temperatures are lower, thereby increasing the potentials of ventilation. Furthermore, in buildings not occupied at night, precooling to lower temperatures is possible. These more aggressive ventilation strategies would be more effective than implied by this study, since lower resource temperatures are available at the beginning and end of the longer cooling season.

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TABLE 1

Prototype Building Description	
Floor Area	109 m^2 (1176 ft^2)
Total Glazing Area	16.4 m^2 (176 ft^2)
Number of Glazing Panes	2
Windows	
Position of Top	1.98 m (6.15 ft) above floor
Position of Bottom	0.76 m (2.5 ft) above floor
South Overhang	
Length	1.07 m (3.5 ft)
Position	2.44 m (8 ft) above floor
Exterior Wall Construction	1.27 cm (0.5") gypboard on frame
Partition Wall Construction	10.2 cm (4") solid concrete
Floor Construction	10.2 cm (4") concrete slab
Ceiling Construction	1.27 cm (0.5") gypboard on frame
Envelope Conductances	
Ceiling	0.166 $W^\circ C^{-1} m^{-2}$ (0.0293 $Btu\text{-}hr^{-1} {}^\circ F^{-1} ft^{-2}$)
Walls	0.270 $W^\circ C^{-1} m^{-2}$ (0.0476 $Btu\text{-}hr^{-1} {}^\circ F^{-1} ft^{-2}$)
Floor	0.485 $W^\circ C^{-1} m^{-2}$ (0.0856 $Btu\text{-}hr^{-1} {}^\circ F^{-1} ft^{-2}$)
Windows	0.31 $W^\circ C^{-1} m^{-2}$ (0.55 $Btu\text{-}hr^{-1} {}^\circ F^{-1} ft^{-2}$)
Thermostat Settings	
Heating - Daytime	21.1°C (78°F)
Nighttime	15.6°C (60°F)
Cooling	25.6°C (78°F)
Average Infiltration Rate	0.6 air changes per hour
Internal Load	15.6 $kwh\text{-}day^{-1}$ (53,100 $Btu\text{-}day^{-1}$)
Thermal Zones	
Unconditioned	Attic
Conditioned	North, South and East
Percent Solar Radiation	
Absorbed by:	
Furniture	25%
Carpet and Slab	60%
Walls and Ceiling	15%

TABLE 2

Baseline Annual Energy Requirements

Location	Cooling Degree Days (25.6°C) (78.1°F)	Annual Cooling Energy Requirement (KWh)	Heating Degree Days (18.3°C) (64.9°F)	Annual Heating Energy Requirement (KWh)
Phoenix, AZ	952	12240	951	109
Miami, FL	348	11363	147	0
Brownsville, TX	417	10175	443	115
El Paso, TX	398	11691	1571	551
Fresno, CA	377	7966	1762	992
Fort Worth, TX	410	7614	1468	1300
Lake Charles, LA	265	7276	944	602
Albuquerque, NM	179	6232	2641	1793
Charleston, NC	182	5679	1337	995
Cape Hatteras, NC	92	5204	1522	1706
Nashville, TN	174	4809	2079	2857
Dodge City, KS	217	4730	3058	5418
Columbia, MO	141	4205	2924	5868
Washington, DC	122	3752	2780	4707
Medford, OR	127	3495	3064	3477
Ely, NV	49	2678	4491	5135
New York, NY	38	2488	2826	6085
Madison, WI	51	2405	4207	9714
Bismark, ND	68	2355	5101	13046
Boston, MA	57	2186	3304	7599
Great Falls, MT	63	2119	4282	9267
Santa Maria, CA	17	2041	2056	108
Seattle, WA	11	1052	3073	4926
Caribou, ME	9	1009	5321	13273

TABLE 3

Cooling Season Definitions

Location	Total Annual Cooling Load (Unventilated) KWh	Cooling Season	Cooling Season Cooling Load (Unventilated) Kwh
Albuquerque	6243	1 May to 30 September	5657
Washington	3752	1 June to 30 September	3400
Madison	2403	1 June to 31 August	2022

TABLE 4

Attic Ventilation

	Cooling Energy Requirement (KWh)					
Month	Albuquerque		Washington		Madison	
	Unvented	Vented Attic	Unvented	Vented Attic	Unvented	Vented Attic
May	810	759				
June	1274	1219	794	763	568	550
July	1525	1447	1088	1044	844	830
August	1297	1227	986	953	604	585
September	835	713	535	509		
Cooling Season Total	5739	5365	3402	3267	2016	1965
Cooling Load Reduction	6.5%		4.0%		2.5%	

TABLE 5

Nighttime Precooling Benefits

	Seasonal Cooling Energy Requirement (KWh)		
	Daytime/Nighttime* Ventilation Thermostat Setting**		Precooling Benefit
Location	20.0°C/20.0°C (68°F/68°F)	20.0°C/15.6°C (68°F/60°F)	
Albuquerque	1155	923	20.1%
Washington	607	484	20.3%
Madison	264	199	24.4%

*Daytime: 8:00 a.m. to 10:00 p.m.
Nighttime: 11:00 p.m. to 7:00 a.m.

**Maximum Ventilation rate: 100 ACH

TABLE 6

Cooling Season Wind Data

Month	Albuquerque		Washington		Madison	
	Average Speed (m/s)*	Prevailing Direction	Average Speed (m/s)*	Prevailing Direction	Average Speed (m/s)*	Prevailing Direction
May	4.5	South				
June	4.5	Southeast	4.0	South	4.5	Southwest
July	4.0	Southeast	4.0	Southwest	3.6	South
August	3.6	Southeast	4.0	South	3.6	Southwest
September	4.0	Southeast	4.0	South		

$*MPH = \frac{3600(m/s)}{1609.3}$

TABLE 7

Convection Coefficients

Surface	Heat Flow Direction	Convection Coefficient (W/m^2°C)
Partition Walls	Horizontal	3.08
Floor	Vertically Upward	4.04
Floor	Vertically Downward	0.94

TABLE 8

Location		Cooling Season	Energy Requirements									
City	State		Unvented/Massive		Vented/Massive		Vented/Nonmassive		Due to Ventilation (%)	Due to Mass (%)	Due to Ventilation (%)	Due to Mass (%)
			Total (KWh)	Peak KW	Total (KWh)	Peak KW	Total (KWh)	Peak KW				
Phoenix	AZ	1 Apr to 31 Oct	11378	6.15	7844	6.15	8429	6.44	31.1	6.9	0.0	4.5
Miami	FL	1 Feb to 31 Dec	10941	4.07	5156	3.78	5919	4.11	52.9	12.9	7.2	8.1
Brownsville	TX	1 Mar to 30 Nov	9809	4.38	5547	4.34	6242	4.58	43.5	11.1	0.9	5.1
El Paso	TX	1 Apr to 31 Oct	8470	4.79	3534	4.39	4326	4.78	58.1	18.3	8.2	8.5
Fort Worth	TX	1 May to 30 Sep	7215	5.12	4159	5.12	4542	5.43	42.4	11.0	0.1	5.8
Fresno	CA	1 May to 31 Oct	6970	7.55	2243	4.94	3040	5.61	67.8	26.2	34.7	12.0
Lake Charles	LA	1 Apr to 31 Oct	6875	4.35	2991	4.16	3574	4.54	56.5	16.3	4.3	8.3
Charleston	SC	1 May to 31 Oct	5229	8.33	1613	3.81	*	4.22	69.2	*	54.3	9.7
Nashville	TN	1 May to 31 Oct	4712	4.19	1104	3.34	1728	3.92	76.4	36.1	20.3	14.8
Dodge City	KS	1 May to 31 Oct	4617	5.23	1244	4.71	1799	5.17	73.1	30.8	9.9	8.8
Cape Hatters	NC	1 Jun to 30 Sep	4306	3.16	1620	3.76	1923	3.98	82.1	37.6	0.0	5.6
Columbia	MO	1 Jun to 30 Sep	4094	8.51	974	4.50	1393	4.92	76.2	30.1	47.2	8.6
Medford	OR	1 Jun to 30 Sep	3246	4.37	366	2.39	652	3.11	88.7	43.9	45.3	23.1
Ely	NV	1 Jun to 30 Sep	2519	4.44	184	2.21	339	3.04	92.7	45.8	50.3	27.3
New York	NY	1 Jun to 30 Sep	2370	3.69	227	2.69	339	3.47	90.4	43.1	27.2	22.6
Bismark	ND	1 Jun to 31 Aug	2296	4.08	282	2.95	445	3.64	86.9	36.5	27.8	19.1
Boston	MA	1 Jun to 30 Sep	2059	7.69	245	2.82	447	3.75	88.1	45.3	63.4	24.8
Great Falls	MT	1 Jun to 30 Sep	2034	4.07	233	2.18	392	3.11	88.6	40.6	46.4	29.9
Santa Maria	CA	1 Jul to 31 Oct	1260	4.43	33	1.88	59	3.70	97.4	43.2	57.5	29.1
Seattle	WA	1 May to 30 Sep	1047	3.50	37	1.21	72	2.02	96.4	48.1	65.3	40.0
Caribou	ME	1 Jun to 31 Aug	930	7.80	21	0.97	50	2.10	99.0	58.4	88.6	57.7

*Data not available.

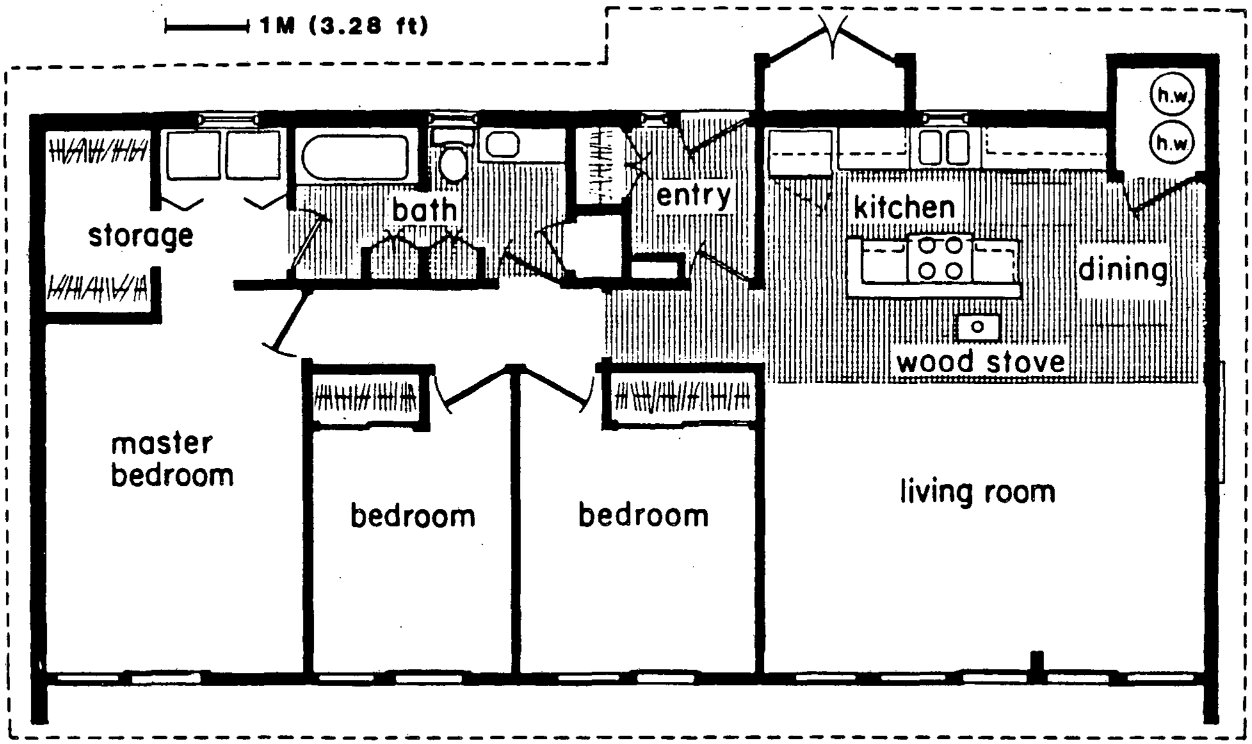


Figure 1. Floor plan of prototype residence

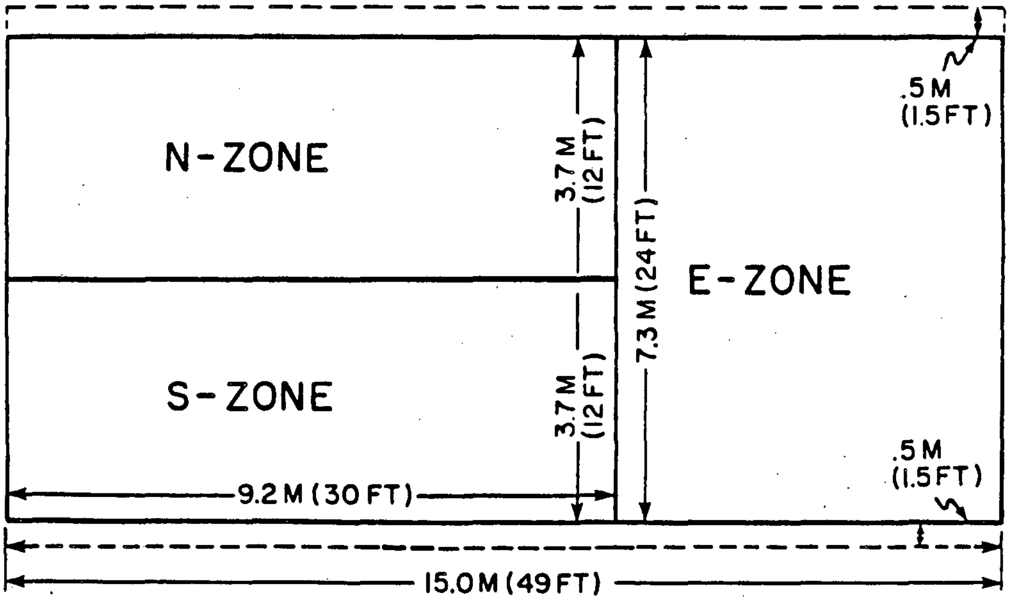


Figure 2a: Thermal zones for BLAST simulation

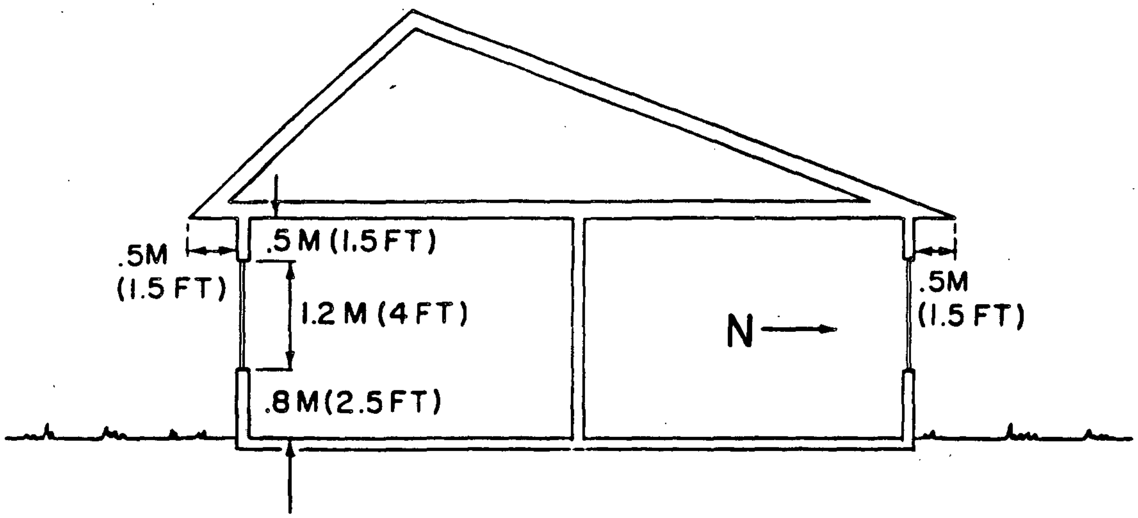


Figure 2b: Thermal zones for BLAST simulation

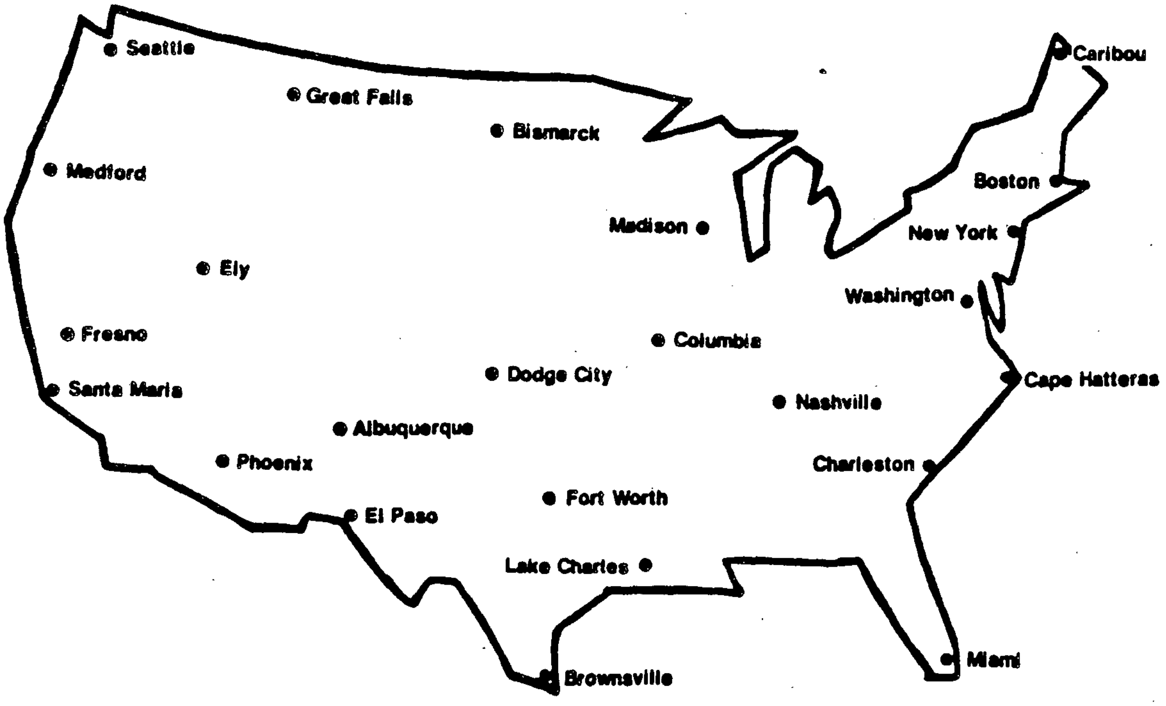
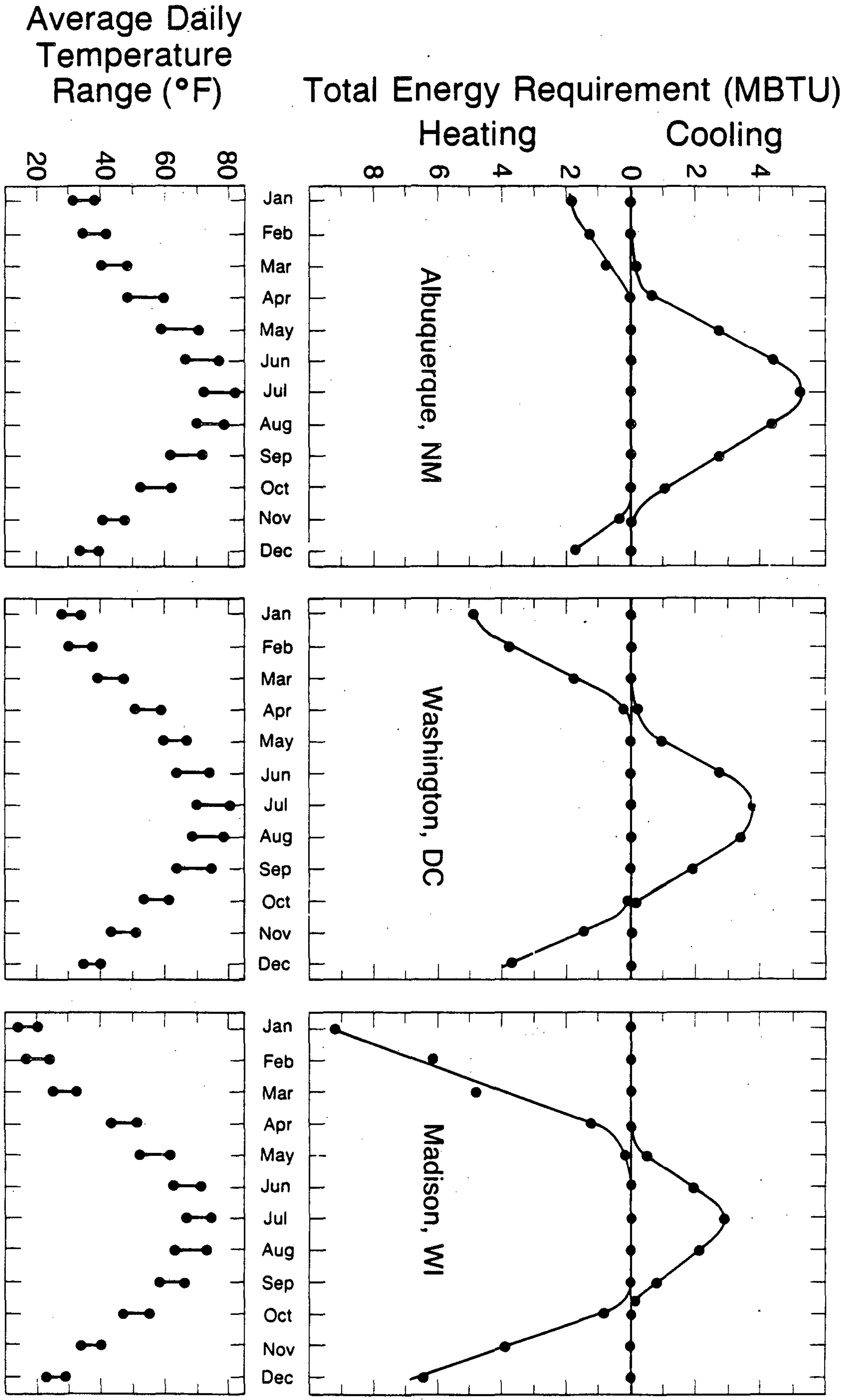
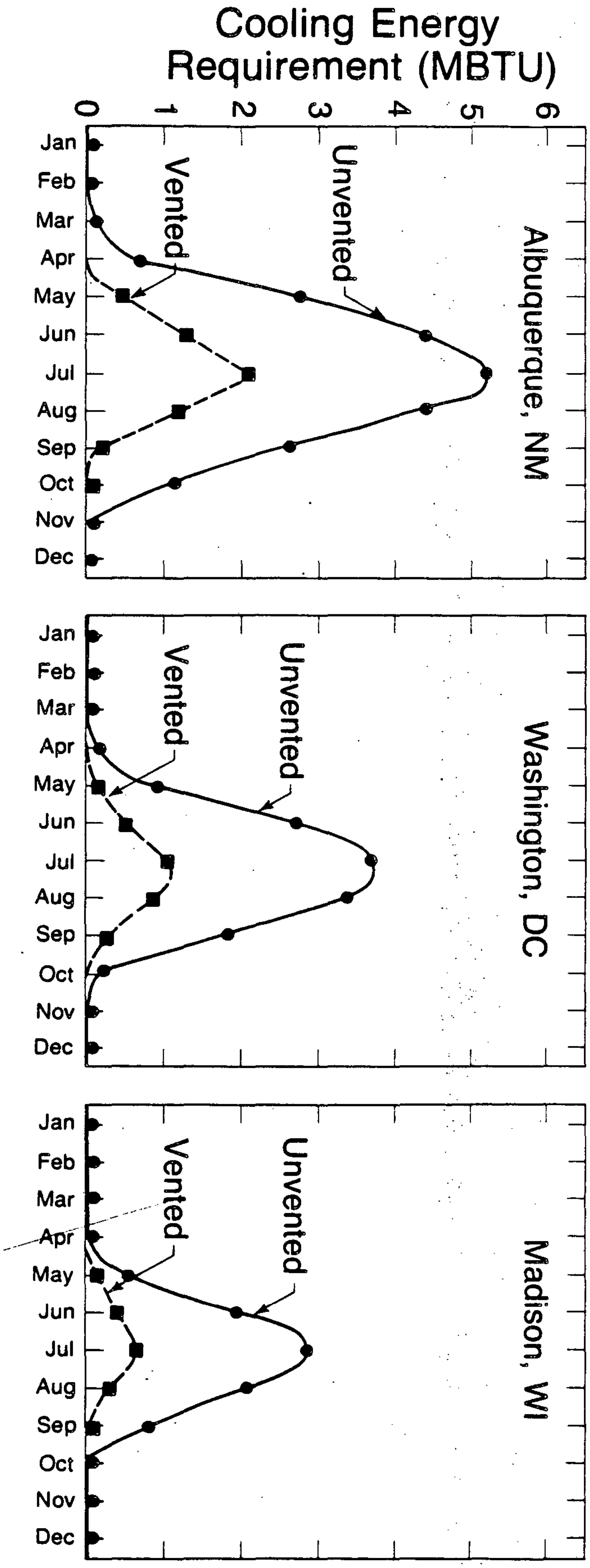

24 Locations Analyzed

Figure 3: Locations analyzed



XBL 836-2706

Figure 4: Temperature range and total energy requirement



XBL 836-2705

Figure 5: Cooling energy requirement

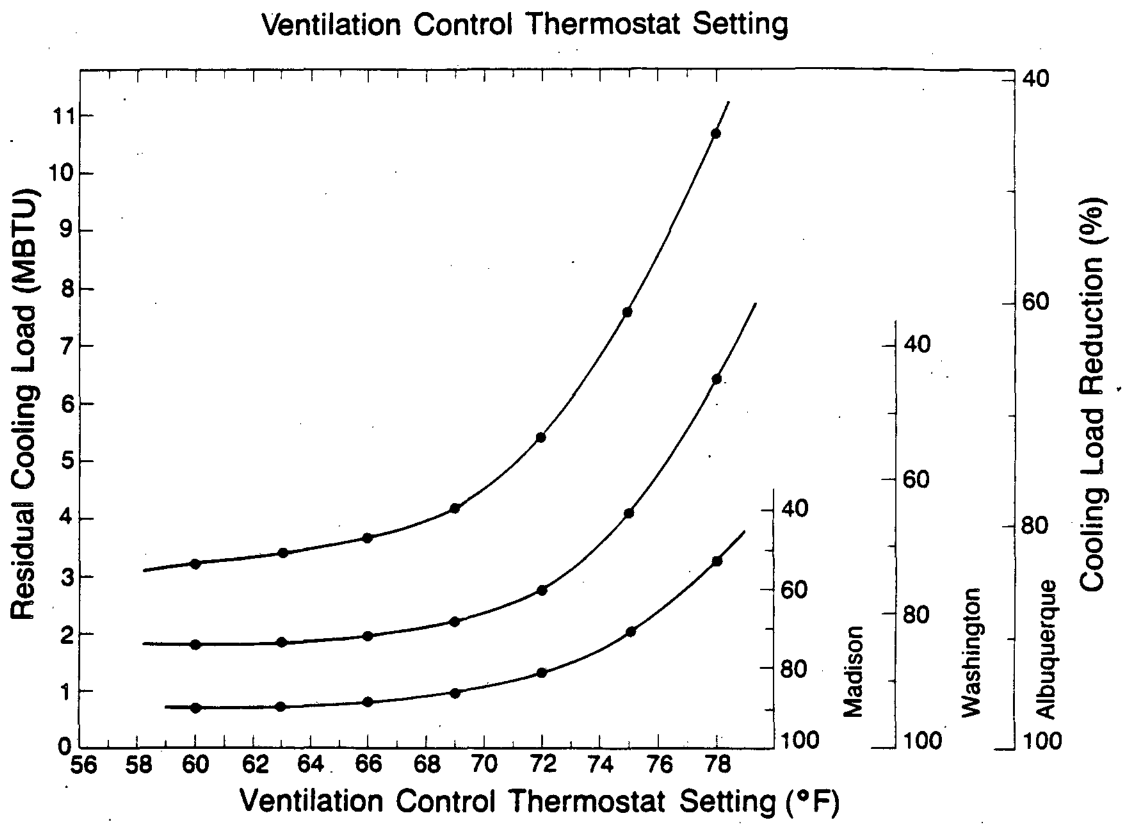


Figure 6. Ventilation control thermostat setting

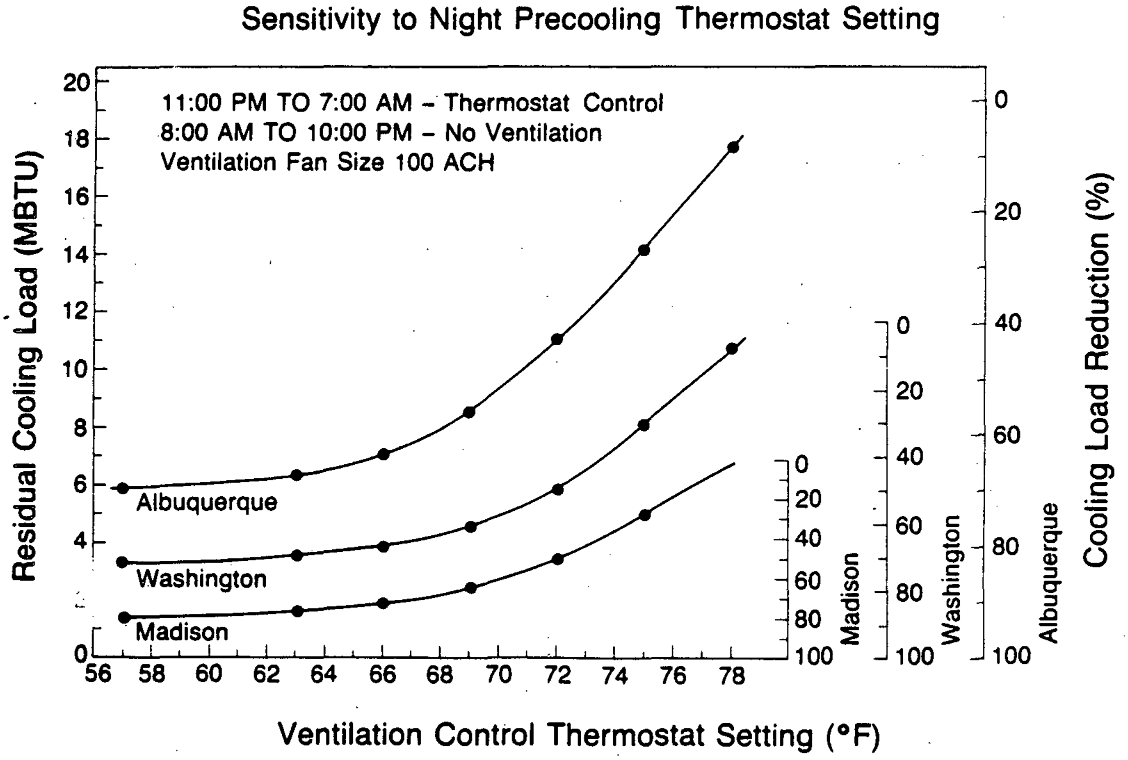


Figure 7. Ventilation control thermostat setting

XBL 836-2707

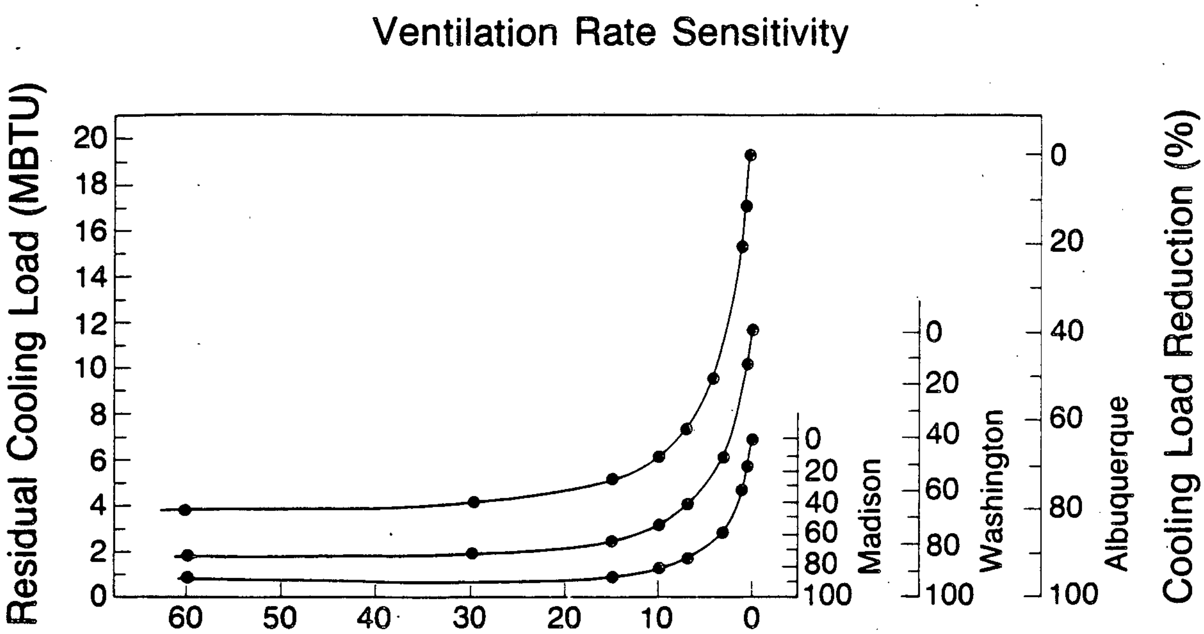


Figure 8. Ventilation fan size (ACH) XBL 836-2704

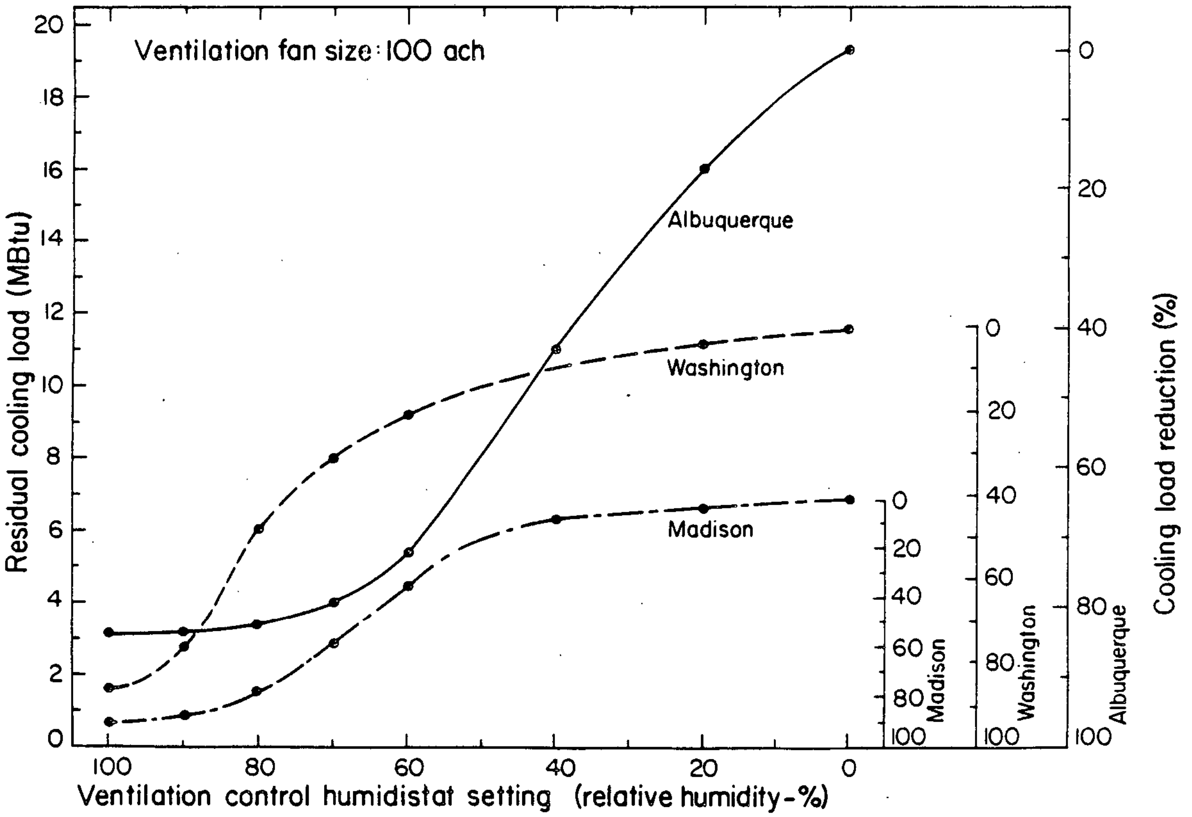


Figure 9. Ventilation control humidistat setting (relative humidity - %)

XBL 8110-1398

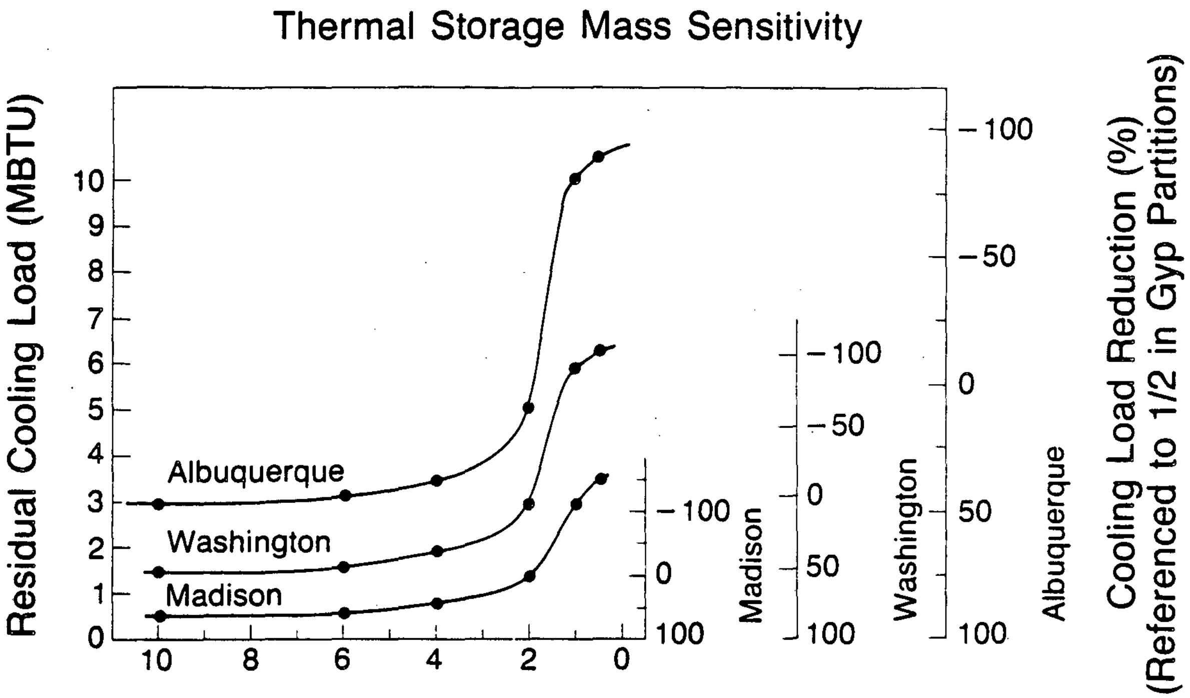


Figure 10. Concrete partition wall thickness (in)

XBL 836-2703

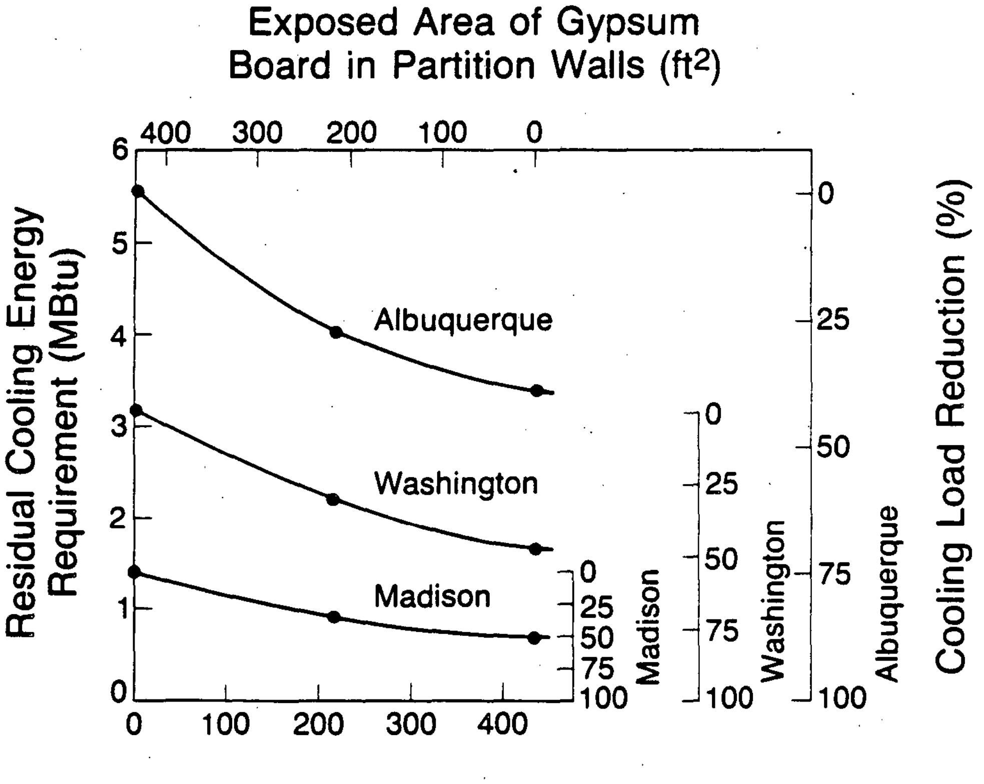


Figure 11. Exposed area of concrete in partition walls (ft^2)

XBL 836-2726

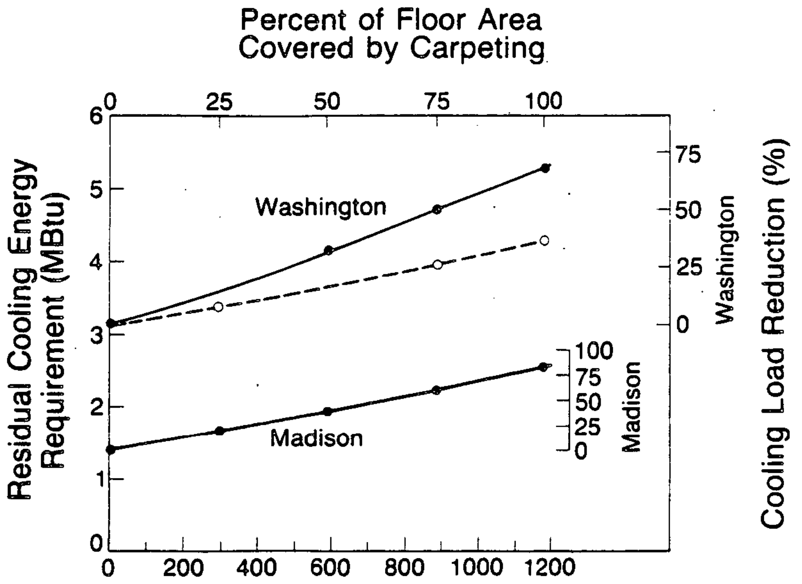


Figure 12. Carpeted floor area (ft^2) XBL 836-2725

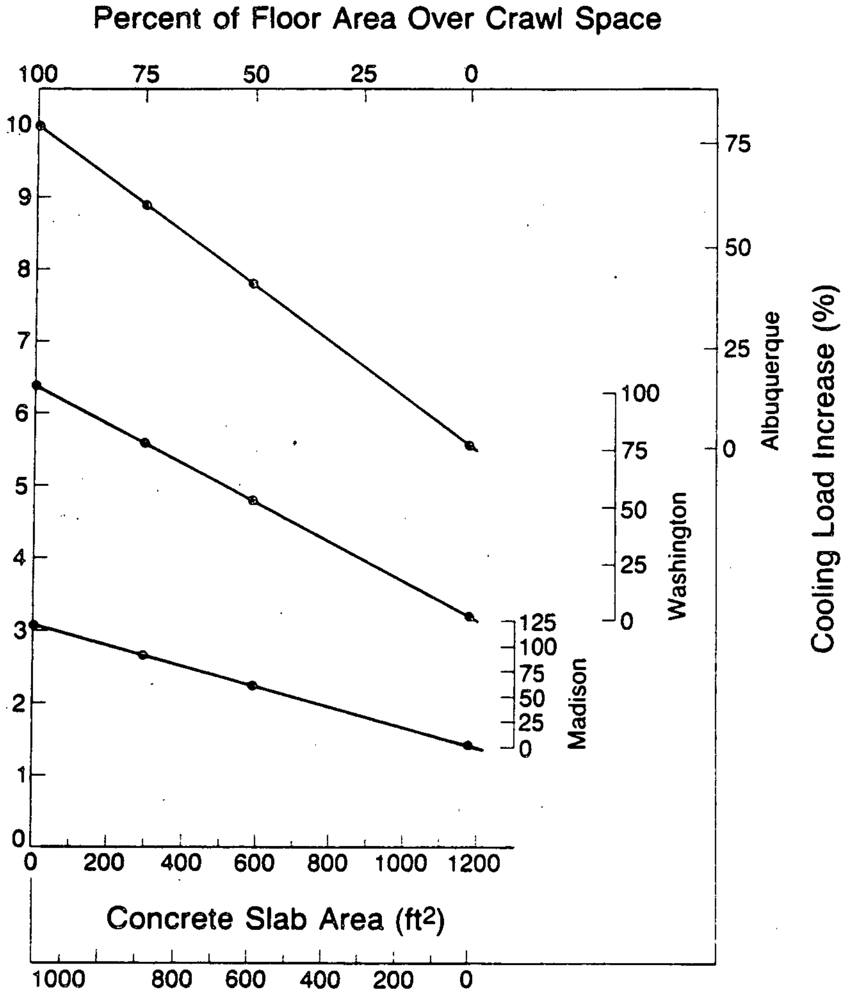


Figure 13. Floor area over crawlspace (ft^4) XBL 836-2724

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