VENTILATIVE COOLING IN SOUTHERN RESIDENCES: A PARAMETRIC ANALYSIS

P.W. Fairey,III **A.A. Kerestecioglu** *ASHRAE Associate Member* **S. Chandra** *ASHRAE Member*

ABSTRACT

The Florida Solar Energy Center has developed a building energy analysis program that models in detail the combined, transient thermal and mass transfer in buildings. The program, called MADTARP (Moisture Adsorption and Desorption and Thermal Analysis Research Program), is a derivative of the TARP program developed at NBS by George Walton.

A number of parametric computer analyses have been performed with MADTARP using various building cooling strategies and climate conditions. Results indicate a potential for significant prediction errors if moisture adsorption/desorption effects in buildings are ignored. This is especially true for buildings intermittently ventilated in humid climates.

The paper discusses the modeling assumptions and presents a detailed parametric analysis of ventilative cooling in southeastern climates.

INTRODUCTION

The natural ventilation of buildings to provide for human comfort (people cooling) in summertime without air conditioning can be an effective strategy in climates with no heating loads and strong, steady, and predictable wind patterns. Much traditional, subtropical and tropical island architecture takes advantage of this strategy.

In the continential U.S., however, natural ventilation can best be used for cooling the building structure rather than cooling people. People cooling requires relatively rapid air motion across the skin (100-300 fpm), thus, people cooling is best provided by powered oscillating or ceiling fans. Winter heating requirements calling for limited window areas and low nighttime summer windspeeds combine to cause room air velocities to be relatively low (20-30 fpm (0.1-0.3 m/s)) in naturally ventilated suburban buildings. Therefore, the air speeds needed (120-150 fpm (0.61-0.76 m/s)) to provide comfort at elevated air temperature (82-83 F (27.78-28.83°C)) may be reliably obtained only through the use of fans. Natural ventilation for building cooling, however, may be effectively used in all U.S. climates to reduce energy consumption.

For the purposes of this study, human comfort at temperatures above 78 F (25.56°C) was achieved through the use of fans, in which case, parasitic fan power was accounted for in the results. Other than this, all ventilative cooling is assumed to be purely passive. In other words, we assumed a constant ventilation airflow rate and parametrically varied it and assumed zero fan power to provide the airflow.

Philip Fairey is principal research scientist; A. Kerestecioglu is a research engineer; S. Chandra is director, Research and Development Division, Florida Solar Energy Center, Cape Canaveral, Florida.

Three generic 1500 ft^2 (139 m^2) residential buildings (typical frame, FB, energy-conserving frame, FC, and heavy mass called block passive, BP) have been examined in the study. The building floor plan is shown in Figure 1, and a summary of the building characteristics for the three buildings is given in Table 1. Detailed building descriptions may be found in Fairey et al. (1985).

Only one mechanical cooling system has been used in the study. It was chosen to be as close to "typical" of newly installed air-conditioning systems as possible. The base equipment from which the performance criteria were developed was a two-ton external condensing unit coupled with an 850 cfm (0.4 m^3/s) internal evaporator unit. The rated SEER of the system under ARI standard test conditions is 8.0 with an attendant sensible heat fraction (SHF) of 0.76. The capacitance of this system was varied according to building type, but the performance characteristics remained identical. The choice of an alternative mechanical cooling system would alter the results presented here, and no attempt has been made in this study to examine these effects.

Two strategies have been employed for the control of natural ventilation in this study: temperature control and enthalpy control. For temperature controlled natural ventilation it was assumed that the residences would be ventilated if the ambient temperature was greater than 69 F (20.56°C) and less than the air-conditioning thermostat setting.

Enthalpy control is similar in that the residence is vented only when the ambient conditions fall between both temperature **and** enthalpy bounds. The temperature bounds for enthalpy control were constant for all runs at 69 F (20.56°C) and 85 F (29.44°C). The upper enthalpy bound, however, is based on the thermostat setting and is equal to the enthalpy associated with the set-point temperature that corresponds to 60% relative humidity. Table 2 gives the upper enthalpy bounds associated with each thermostat setting examined. The lower enthalpy bound is zero.

Two modeling approaches have been used in this study to predict air-conditioning performance and cooling loads. One model includes moisture adsorption and desorption (MAD) at interior building surfaces and furnishings, while the second model neglects these factors. Both models use TARP (Walton 1983) as the basic thermal performance modeling tool. MADTARP has been developed from TARP over the last two years by the Florida Solar Energy Center. It was developed specifically to examine MAD phenomena in buildings (see Fairey et al. 1985). The MAD algorithms used by MADTARP are covered by Kerestecioglu et al. (1985), and complete details and modeling techniques are covered in Kerestecioglu (1985).

In the development of MADTARP, emphasis was given to the MAD calculations and mechanical cooling unit interfaces. The thermal simulator of the original TARP has not been changed. Therefore, the heat of MAD has not been explicitly accounted for in the TARP thermal balance. This is likely to underestimate the savings potential of ventilative cooling and overestimate the effects of MAD.

RESULTS

A number of sensitivity studies have been performed during the course of the analysis. The sensitivity of cooling load to MAD, ventilation air change rate, generic building type, and interior surface heat transfer coefficient has been studied in two cities: Orlando, Florida, a distinctly hot, humid climate, and Atlanta, Georgia, a more temperate "borderline" climate. At the conclusion of the sensitivity analysis the three building types were examined in 14 cities at two thermostat temperatures: 78 F (25.56°C) and 82 F (27.78°C). The two ventilation control strategies (temperature and enthalpy) were examined for each of the three building types to develop potential ventilative cooling savings contours for the southeastern U.S.

MAD Versus NOMAD

A set of analyses with no moisture adsorption and desorption (NOMAD) by the building materials has been accomplished to determine the effect of MAD on residual building moisture loads after ventilation periods. By residual moisture load, we mean the moisture load caused by material MAD and not predicted in the NOMAD analysis. The analyses examined the sensitivity of the cooling load to changes in the effective MAD capacity of the building. The MAD capacity of a building can be represented as a function of the effective MAD thickness and the effective MAD surface area (see Kerestecioglu et al. 1985). To examine MAD effects in buildings, the effective MAD surface area was varied while the effective MAD thickness was held constant. To simplify computer analysis, a parameter called the Effective Surface Area Multipler (ESAM) was derived by dividing the effective MAD surface area by the actual heat-transfer surface area of the building. Thus, an ESAM of zero means that no MAD material is available within the building.

For a monitored townhouse in Cocoa, Florida excellent agreement of the model with the measured data was obtained at an ESAM value of 0.52 (see Kerestecioglu et al. 1985). To determine the sensitivity of the cooling load to this parameter, the three buildings were examined in Orlando and Atlanta for a range of ESAM values. The resulting annual cooling loads were then normalized as follows:

$$NCL = CL^x/CL^o$$

where NCL is the normalized cooling load at the given ESAM value, CL^x is the annual cooling load at the given ESAM value, and CL^o is the annual cooling load at an ESAM value of zero. Thus, all loads are expressed as a function of the predicted cooling load when no effective MAD material exists in the building.

Figure 2 gives the results of the analyses. The unvented buildings have only a small sensitivity (<7% change over entire range) to changes in ESAM value. However, for ventilated buildings (15 ach) the cooling load is highly sensitive to ESAM. In fact, it is most sensitive near the ESAM value in best agreement with the monitored townhouse.

The townhouse, however, was unoccupied and contained only limited furnishings. A typical residence would contain far more MAD materials (e.g., linens, furniture, clothing, etc.). To account for this, the ESAM value used in the remainder of the analysis presented here was increased slightly to a value of 0.75. Obviously, the auxiliary cooling loads of ventilated buildings are highly sensitive to the effective building moisture capacity, and they should be interpreted in view of the results given in Figure 2.

Note the relative positioning of the different building types and climates in Figure 2. Generally, the Orlando climate exhibits a lower NCL in the unvented buildings and a higher NCL in the vented buildings. The heavy mass building has the lowest NCL of the unvented buildings. In fact, in Orlando the NCL for the unvented massive building is very close to unity for all ESAM values. In both climates the most sensitive unvented building is the typical frame building, and the most sensitive vented building is the energy-conserving frame building. By far the most pronounced result, however, is that regardless of building type or climate the auxiliary cooling loads for temperature-controlled, ventilated buildings are significantly underestimated if MAD is not considered in the analysis model.

Results from the analysis illustrate the importance of modeling MAD if ventilative cooling is considered. NOMAD ventilative cooling models predict large potential savings for residential buildings in the Southeast. Recent studies performed using NOMAD models predict similar savings (Kammerud et al. 1984; Kusuda 1981; Neeper and McFarland 1982). Results of the MAD analysis at ESAM values of 0.75, however, show a significant reduction in predicted energy savings. Figure 3 illustrates the energy-saving potential of temperature-controlled natural ventilation for the three house types in the two climates. For typical frame houses, the NOMAD model overpredicts ventilative cooling savings by 125.7% in Orlando and 64.6% in Atlanta. As the thermal integrity and capacity of the building is improved, the error in predicted savings is reduced. But even in the heavy mass building the NOMAD model overpredicts temperature-controlled ventilation savings by 38.6% in Orlando and 16.3% in Atlanta.

Ventilation Air Change Rate

The cooling load of the three buildings was also examined as a function of the ventilation air change rate (VACH). The natural VACH of a building is dependent on a number of factors: the building site windspeed and direction; the external geometry of the building and its adjacent surroundings; the window type, size, location, and geometry; and the internal wall partition layout of the building. Each of these factors may have an overriding influence on the natural VACH of a given building. For typical buildings located in suburban environments, Chandra et al. (1983) have concluded that one may expect average natural VACH between 10 and 20 air changes per hour under typical wind conditions. For higher-than-average windspeeds or for buildings specifically designed to take maximum advantage of natural ventilation, VACH may be raised to 30 to 60 ach. For the interested reader, a detailed discussion of natural ventilation in residential buildings is given by Chandra et al. (1983).

Since the building VACH is highly dependent on a variety of factors and may vary significantly from time to time in any given building, the residual cooling load of the three buildings was examined for a range of 0 to 60 ach in both climates. The resulting cooling loads were then normalized to the cooling load of the unvented building so that both building type and climate could be directly compared.

Figure 4 presents the results of the analysis. A number of interesting phenomena are apparent from the results. First, the percent cooling-load savings (1-NCL) resulting from natural ventilation increases with the thermal integrity and capacity of the building. Regardless of climate, the typical frame building exhibits less savings than the energy conserving frame building, and the heavy mass building significantly outperforms both frame buildings. In addition, both frame buildings reach their optimum savings potential for low values at VACH, showing almost no thermal carry-over effect of ventilation cooling into air-conditioning periods. The heavy mass building, on the other hand, continues to improve in performance, albeit only slightly, through the entire analysis range. Although it is not shown in the figure, the actual load savings move in the same direction as the percent savings, with the better buildings yeilding greater load savings even though their base (unvented) loads are lower.

All three buildings exhibit a significant climate dependence. As expected, the cooler, dryer climate of Atlanta offers a significant ventilation cooling advantage over Orlando. However, due to length of the cooling season, total load savings is greater in the harsher climate. At 15 VACH the heavy mass building yields ventilation savings of 34% in Orlando and 51% in Atlanta, but the corresponding total load savings are 5.22 MBtu (5.51 GJ) for Orlando and 4.29 MBtu (4.53 GJ) for Atlanta. Thus, greater actual load (and dollar) savings are achieved in Orlando even though greater percentage savings are attained in Atlanta.

The results indicate that optimum ventilation savings may be attained at a relatively low VACH. The additional benefits obtained by increasing vent rates from 15 to 30 VACH are negligible for the frame building and marginal for the heavy mass building. Further increases to 60 VACH appear unwarranted, but model validation and further analyses are necessary before establishing design guidelines.

Enhancement of Convective Heat Removal

Previous research has shown that the convective heat-transfer coefficient (h_c) at interior surfaces increases with increasing room air velocity (see Chandra and Kerestecioglu 1984; Faultersack 1983). Most building energy analysis programs do not account for this fact. For the purpose of this study h_c has been varied by introducing a user-specified h_c multiplier (h_cM) into the computer code. The h_c value normally used by the program is then modified by this multiplier at each time step before the room energy balance is performed. The h_cM may be specified to apply during periods of ventilation, during periods of no ventilation, or both. For the ventilation sensitivity analysis presented, h_c is enhanced only during ventilation periods or when the thermostat setting is above 78 F (25.56°C) and ceiling fans are operated.

MADTARP allows room interior h_c to be specified in two ways--detailed and simple. The detailed model was used here. In the detailed model h_c is calculated based on the surface and air temperatures according to the natural convection coefficient algorithms of ASHRAE. After h_c is calculated it is simply multiplied by h_cM to determine the final h_c values used in the room thermal balance. In the simple model h_c values are constant over time but are different for different heat flow directions (up, down or horizontal). Some analysis was also done using the simple model. This increased the absolute magnitude of the cooling loads by up to 10%, but the curves for NCL (e.g., Figures 4,5,6) remained unchanged.

Three values of h_cM are examined here. An h_cM value of 1.5 is used to represent the effects of enhanced room air circulation due to ceiling fan use. Another FSEC study (Chandra et al. 1983) has shown that reasonable use of ceiling fans will enhance boundary layer air velocities, resulting in heat-transfer coefficients approximately 1.5 times the natural convection value. Natural ventilation at high VACH rates (50-80 ach) will produce similar effects.

Under certain specific circumstances h_c may be significantly enhanced through the "wall jet" effect. The term "wall jet" refers to a phenomenon by which an incoming air jet attaches itself to an interior surface. This causes significantly higher-than-normal local surface velocities and heat-transfer coefficients. An upper h_cM value of 3.0 was used in this study to indicate the upper limiting potential of such phenomena in buildings expressly designed to take advantage of wall jets. The remaining value of $h_cM = 2.0$ was chosen as an intermediate point for the analysis.

Figures 5 and 6 depict the change in normalized cooling load as a function of VACH as h_cM is increased from the normal base ($h_cM = 1.0$) to the three enhanced values. Data are presented for the energy conserving frame and heavy mass buildings in Orlando (Figure 5) and Atlanta (Figure 6). The frame buildings show less sensitivity to changes in heat-transfer coefficient, indicating once again that ventilation cooling of frame buildings is not significantly improved by either high VACH or enhanced convective heat transfer at interior surfaces.

The massive buildings show a greater sensitivity to h_c enhancement. It may be noted in Figures 5 and 6 that the greatest margin of benefit of h_c enhancement occurs at the lower h_cM values. The change in cooling savings when going from $h_cM = 1.0$ to $h_cM = 1.5$ is greater than the change in savings when going from $h_cM = 2.0$ to $h_cM = 3.0$, regardless of building type. This indicates that h_cM values approximating 1.5 are approaching the value at which the advantages of further enhancement of convective heat transfer are negligable unless material conductivity is increased as well.

At any rate, enhancement of h_c leads to only limited improvement in ventilative cooling savings. Comparison of Figures 5 and 6 illustrates the relative sensitivity of the buildings to climate. Note that, as expected, the differences caused by the relative climates are much more pronounced than are the changes caused by variation of VACH or h_cM. Careful comparison of Figures 5 and 6 also reveals the fact that the spread between the cooling loads in the frame and massive building is also increased in Atlanta as compared to Orlando. This is in part caused by the fact that ventilation induces a greater residual moisture load in Orlando than it does in Atlanta (see Figure 2).

Effects of Ventilation Control Strategy

For temperature-controlled ventilation, room relative humidity increases with ventilation savings. Worst month average room relative humidity exceeds 85% in Orlando and 80% in Atlanta (see Figure 7) for all of the ventilated buildings. These high humidities result mainly from venting, but preliminary FSEC research indicates that if the room thermostat is more accurately modeled, the resulting room RH will be lower by 5% to 10%. Even then room humidities can be unacceptably high. In order to examine the potential of ventilation cooling without unreasonable room relative humidity increases, an enthalpy-controlled ventilation analysis was performed.

Under enthalpy control the building is not vented during the most humid ambient conditions and room relative humidity remains much lower. Enthalpy-controlled ventilation is often used in commercial buildings but, to our knowledge, a comprehensive analysis of enthalpy-controlled ventilation has not been performed for residential buildings. Table 2 defines the control bounds used for enthalpy control in this analysis.

Less annual savings are attained through enthalpy-controlled ventilation than temperature controlled ventilation. This is to be expected, since far fewer hours of ventilation potential exist under enthalpy control, especially if a room enthalpy of 32.2 Btu/lb (57.2 kJ/kg) is desired (i.e., 78 F (25.56°C) at 60%). However, a significant reduction in room relative humidity is observed under enthalpy control, and it may, therefore, be more descriptive of what real people are prone to attempt in residences.

Figure 7 depicts the results of the analysis in the form of a bar chart. Note that the control strategy causes large shifts in predicted peak-month room relative humidity regardless of building type or climate. The highest peak month room relative humidities consistently occur in the heavy mass building, and the lowest occur in the typical frame building. This is due to the fact that the thermal nature of the energy-conserving and massive buildings is such that less air-conditioner run time is required in these buildings, particularly at off-peak conditions. As a result, less moisture is removed and indoor relative humidity rises even though the infiltration rate is lower in the two energy-efficient buildings.

Enthalpy-controlled ventilation greatly reduces the cooling-load savings (1-NCL) as compared to temperature-controlled ventilation. This fact is especially apparent in the heavy mass buildings where, in Atlanta, the cooling-load savings drop from 51% to 28.5%. Thus, although room relative humidity may be kept reasonable through enthalpy-controlled ventilation, cooling load savings are significantly less.

An additional clue to understanding the large differences between enthalpy and temperature control is found in the ventilation air changes the buildings undergo in each mode. Table 3 presents the total air changes the buildings experience in each mode over the primary cooling season. The difference in climate conditions is quite clear in Table 3. For temperature-controlled ventilation there is only a small difference between the total ventilation air changes in the two climates. For enthalpy control, however, the difference is quite large. This illustrates the fact, that even though the temperature regimes may be similar, the air moisture content is significantly higher in Orlando than in Atlanta.

Effects of Thermostat Setting

For a building, the greatest potential cooling-load savings come from increases in the thermostat setting. After considering parasitic fan power, cooling-load savings of 7% to 13% per degree increase in thermostat setting are achievable in most buildings. Thus, savings of 28%-52% are achievable through the use of ceiling fans and a thermostat increase from 78 F (25.56°C) to 82 F (27.78°C). Note that peak month room RH does not increase significantly when the thermostat is raised. A less than 1% rise in room RH is seen in both climates between the set-points of 78 F (25.56°C) and 82 F (27.78°C). Moisture content of the zone rises but the temperature rises at an equivalent rate; as a result, no significant increase in room RH is seen with thermostat changes.

Table 4 presents the cooling energy savings possible from ceiling fans before and after accounting for fan parasitic power consumption. The results are based on the unvented house and an increase in the thermostat settings from 78 F (25.56°C) to 82 F (27.78°C). The h_c was multiplied by a factor of 1.5 for the 82 F (27.78°C) runs to account for the increased surface airspeeds created by the fans.

The effects of house type are again significant -- effectiveness increases with the thermal integrity and capacity of the house. The change in the normalized cooling load for the FB and BP house types are shown in Figure 8 for Orlando and Atlanta.

In order to estimate fan power consumption, a destribution of fan wattage based on an assumed living pattern was chosen for a 24-hour cycle. Table 5 gives the location and wattage (at full speed) of the fans used in the analysis along with the hourly total fan wattage over the day. For each MADTARP run a "BIN" analysis program was used to determine the number of hours when the indoor dry bulb fell in the ranges 78-79, 79-80, 80-81 and 81-82 F for each hour of the day. Four-speed fans were assumed and variation in fan speed was accounted for by adjusting the full wattage of the fans by fan-speed multipliers. The multipliers were 0.25, 0.5, 0.75 and 1.0 for the indoor dry bulb ranges of 78-79, 79-80, 80-81 and 81-82 F, respectively. The total fan energy was determined as:

$$\text{Fan energy (Btu)} = \sum_{i=1}^{24} \sum_{j=1}^{4} NOH_{i,j} * FW_i * MUL_j \times 3.413$$

where

j = Indoor dry bulb range
- 1 = 78-79 F
- 2 = 79-80 F
- 3 = 80-81 F
- 4 = 81-82 F

i = Hour of day

$NOH_{i,j}$ = Number of hours in the j^{th} indoor dry bulb range and i^{th} hour of the day.

FW_i = Fan wattage (in watts) at hour i (see Table 5)

MUL_j = Fan speed multiplier for the j^{th} indoor dry bulb range

The quantity (1+(1/COP)) * FAN ENERGY (as calculated above) was added to the cooling load calculated by MADTARP. The COP above refers to the air conditioner seasonal operating COP as calculated by MADTARP. In this way, both the fan electricity consumption and the air-conditioning energy consumption needed to remove the heat produced by the fan are accounted for.

VENTILATION COOLING POTENTIAL IN THE SOUTHEAST

Each of the three house types has been examined in 14 climates. Many of the climates may be classified as hot, humid climates, but some are not and are included in order to understand trends at the edges of the hot, humid climate zone. Figure 9 gives the results of the analysis in the form of percent cooling load savings contours for the southeastern U.S. Each of the cities used in the analysis is indicated on the figure.

The high sensitivity of cooling load savings to building type is readily apparent in the figure with the less thermally efficient building showing far less percentage savings than the efficient houses. The heavy mass building shows a much greater ability to effectively use ventilation cooling than the frame buildings. Nonetheless, predicted savings are lower than previous predictions (Neeper and McFarland 1982) for massive residences. This is probably because other ventilation studies have not attempted to model the effects of MAD.

The climatic influence of the Blue Ridge Mountain chain is quite pronounced in Figure 9 causing a deep dip far into the south. This results in Atlanta having a ventilation cooling potential equivalent to Baltimore and St. Louis. Additionally, Tallahassee and the west coast of Florida have savings equivalent to the coast of North and South Carolina. Dallas and Jacksonville stand out as particularly poor ventilation cooling climates, and there is a distinct difference in the ventilation cooling potential between the east and west coasts of the Florida peninsula.

The potential of the combined use of ventilative cooling and ceiling fans has also been studied for Orlando and Atlanta. The parasitic power of the fans was calculated as described earlier. Both detailed and simple h_c models were used and they produced nearly identical percent savings. The results from the detailed h_c model are presented here. For 80 F (26.67°C) an h_c multiplier (h_cM) of 1.15 was used and for 82 F (27.78°C) an h_cM of 1.5 was used. Both temperature and enthalpy ventilation strategies were analyzed.

Figure 10 presents the results as bar graphs. The savings are calculated as compared to the unvented house's cooling load at 78 F (25.56°C) for each house type.

Note the dramatic savings possible at 82 F (27.784°C). Even more impressive are the larger savings numbers for the better houses. The effect of climate is also significant. Enthalpy ventilation is nearly as effective as temperature ventilation in Atlanta but not in Orlando.

So far, all results have been presented for annual cooling loads. However, for closed buildings, MADTARP predicts cooling loads (albeit small) even in January in Orlando. In order to examine the efficacy of ventilative cooling during only the summer months, results were obtained for Atlanta and Orlando for the months of June-August and April-October, respectively.

These results are also presented in Figure 10 as the shaded region. The results are again very dependent on building type and climate. Enthalpy venting causes a significant reduction in savings for the frame base buildings at 78 F (25.56°C), but at the higher setpoints of 82 F (27.78°C) the reductions in savings become far less significant. Both enthalpy and temperature venting may save substantial amounts of summertime cooling energy, especially when combined with ceiling fan use. It must be noted that most of the increased savings at 80 F (26.67°C) and 82 F (27.78°C) are due to increases in thermostat settings and the use of ceiling fans for people cooling. The percent savings from only ventilation is well illustrated by the 78 F (25.56°C) bar graphs.

To reiterate the humidity penalty of temperature-based ventilation, the average July indoor RH levels are indicated by the numerals within each bar. Enthalpy ventilation saves less but results in more acceptable indoor humidities. However, in Atlanta at a setpoint of 82 F (27.78°C), indoor RH is about the same for enthalpy and temperature venting.

CONCLUSION

A number of ventilation cooling parameters have been examined by this study. Some parameters appear to have a significant impact on predicted cooling loads. Of these, the most important for the building energy analyst is the modeling of MAD. Without the capability of examining the dynamic MAD performance of residences there is a very high likelihood that large errors in ventilation cooling performance predictions will be made. The error is much more significant in "typical" buildings than in energy-conserving buildings, but the error exists in both. Accounting for MAD results in predicted ventilation cooling-load savings that are significantly lower than previous predictions in all the climates studied.

A major conclusion of the study is that ventilation cooling energy savings are significantly dependent on building type. As the thermal integrity of the building is improved, the building baseload goes down but the total energy savings from ventilation increases. Massive houses saved more than frame houses.

The use of ceiling and/or oscillating fans to induce air motion has good energy savings potential if thermostat settings are raised accordingly. Cooling-load savings of about 30% were achieved in Orlando and Atlanta by increasing the thermostat setting from 78 F (25.56°C) to 82 F (27.78°C) in the typical frame building. Higher (40%-50%) savings are achieved in the energy conserving and heavy mass buildings. When increased thermostat settings are coupled with ventilation, dramatic savings (50%-90% depending on building type and climate) are possible as compared to the unvented home at a thermostat setting of 78 F (25.56°C).

The strategy chosen to control the ventilation of buildings plays a large role in the achievable savings as well as the resultant room relative humidity levels. If upper limits on room humidities are desired, enthalpy-controlled ventilation may be employed. This will significantly reduce the residual latent cooling loads associated with temperature-controlled ventilation but at a penalty in ventilation cooling savings. For the most humid climates (e.g., Orlando) there will be little or no ventilation during the midsummer months if the house is to be maintained at 78 F (25.56°C). Nonetheless, enthalpy-controlled ventilation may provide a closer approximation of how people ventilate their buildings than does temperature-controlled ventilation. In Atlanta, if 82 F (27.78°C) is maintained there are only negligible differences in temperature and enthalpy ventilation. A large difference still exists in very humid climates like Orlando.

As mentioned earlier, in the calculation of MAD the heat of phase change was not accounted for in the thermal processor. A newer version of the program (MADTARP 2.0) that will account for the heat of phase change of MAD is currently under development. For a closed building the effect of the heat of phase change is insignificant. However, for ventilated buildings it may be very important, and in fact, may increase the energy savings from building ventilation.

REFERENCES

Chandra, S.; Fairey, P.; and Houston, M. 1983. "A handbook for designing ventilated buildings." Final Report to U.S. DOE, FSEC-CR-93-83.

Chandra, S.; and Kerestecioglu. A.A. 1984. "Heat transfer in naturally ventilated rooms: data from full-scale measurements." ASHRAE Transactions, Vol. 90, Part 1, pp. 211-223.

Fairey, P.; Kerestecioglu, A.; Vieira, R; Swami, M.; and Chandra, S. 1985. "Latent and sensible load distributions in energy efficient and passively cooled residences," FSEC-CR-125-85.

Faultersack, J.H. 1983. "Interior heat transfer in a passively cooled roof pond building." MS Thesis, Trinity University.

Kammerud, R.; Ceballos, E.; Curtis, B.; Place, W.; Andersson, B. 1984. "Ventilation cooling of residential buildings." ASHRAE Transactions, Vol. 90, Part 1.

Kerestecioglu, A.A. 1985. "The detailed mathematical prediction of simultaneous heat and mass transfer in cavities." Ph.D. Dissertation, Florida Institute of Technology.

Kerestecioglu, A.A.; Fairey, P.; and Chandra, S. 1985. "Algorithms to predict detailed moisture effects in buildings." Proceedings of ASHRAE/DOE/BTECC Thermal Performance of the Exterior Envelopes of Buildings III.
mber 1985.

Kusuda, T. 1981. "Savings in electric cooling energy by the use of a whole house fan." NBS Technical Note 1138.

Neeper, D.; and McFarland, R. 1982. "Some potential benefits of fundamental research for the passive solar heating and cooling of buildings." Los Alamos National Lab, LA-9425-MS.

Walton, G. 1983. TARP Reference Manual, NBSIR, 83-2655, National Bureau of Standards.

ACKNOWLEDGMENTS

This research has been partially funded by the U.S. Department of Energy, San Francisco Operations Office. We thank the DOE program managers, Mr. Marvin Gorelick and Ms. Janet Neville for their support. In addition, a part of this research has been funded by the Gas Research Institute, and the authors are grateful for the patience of Doug Kosar, the GRI monitor. Mr. Muthusamy Swami is also to be acknowledged for his assistance in the preparation of this paper.

TABLE 1
Summary of Building Characteristics

Characteristic	Frame Basecase (FB)	Frame Conserving (FC)	Block Passive (BP)
Windows	A=224 ft^2 SC=0.45 EWN SC=0.87 S +2 ft overhang	A=140 ft^2 on N/S only SC=0.87S; .2N +2 ft overhang	same as FC
Roof/Attic	5/12 pitch a= 0.8 e = 0.9 R-19 clg. insul.	same as FB + attic radiant barrier	same as FC
Walls	R-11 in 16 inch centers a = 0.75 e = 0.9	R-19 for all walls + a=0.1 & e=0.5 on EWN walls (simulates radiant barrier system [RBS])	Block + ext. insulation R-11 on S & R-6 on EWN a=0.1 & e=0.5 on EWN (RBS) + all internal partitions 8 in concrete block
Infiltration (@ design)	0.75 ach	0.5 ach	same as FC
Sensible internal loads (Btu/day)	50,807	44,620	same as FC
Duct location	Attic space	Cond. space	Cond. space

TABLE 2
Bounds for Enthalpy Controlled Ventilation

Room		Ambient Control Bounds			
T_{stat} (F)	RH (%)	T_{low} (F)	T_{high} (F)	h_{low} (Btu/lb)	h_{high} (Btu/lb)
78	60%	69	85	0	32.2
80	60%	69	85	0	33.6
82	60%	69	85	0	35.1

TABLE 3
Total Ventilation Air Changes by Month for Enthalpy and Temperature Controlled Natural Ventilation, 78 F Setpoint

Month	Orlando		Atlanta	
	Temperature	Enthalpy	Temperature	Enthalpy
June	4875	75	4620	3570
July	4305	0	5625	615
August	4605	0	6090	1305
September	6285	30	4695	4260
TOTAL	20,070	105	21,030	9750

TABLE 4
Ceiling Fan Cooling Energy Savings in Unvented Houses. Percent savings per F setup of thermostat. thermostat setup. Gross savings and net savings after including fan energy.

House Type	Atlanta		Orlando	
	Gross	Net	Gross	Net
Frame Base, FB	10.6%	8.7%	9.4%	7.5%
Frame Conseervng, FC	14.7%	11.3%	12.2%	9.4%
Block Passive, BP	16.6%	12.9%	12.9%	10.1%

TABLE 5
Fan Wattage and Schedules

Location	Fan size	Assumed Watts at Full Speed
Bedroom 1	36"	60
Bedroom 2	36"	60
Master Bedroom	48"	70
Kitchen	36"	60
Dining Room	36"	60
Living Room	52"	80

Fan Wattage Over the Day

Hour of Day	Total House Fan Power Watts @ Full Speed
1	190
2	190
3	190
4	190
5	190
6	190
7	190
8	190
9	250
10	200
11	140
12	80
13	80
14	80
15	80
16	80
17	140
18	140
19	200
20	80
21	80
22	200
23	190
24	190

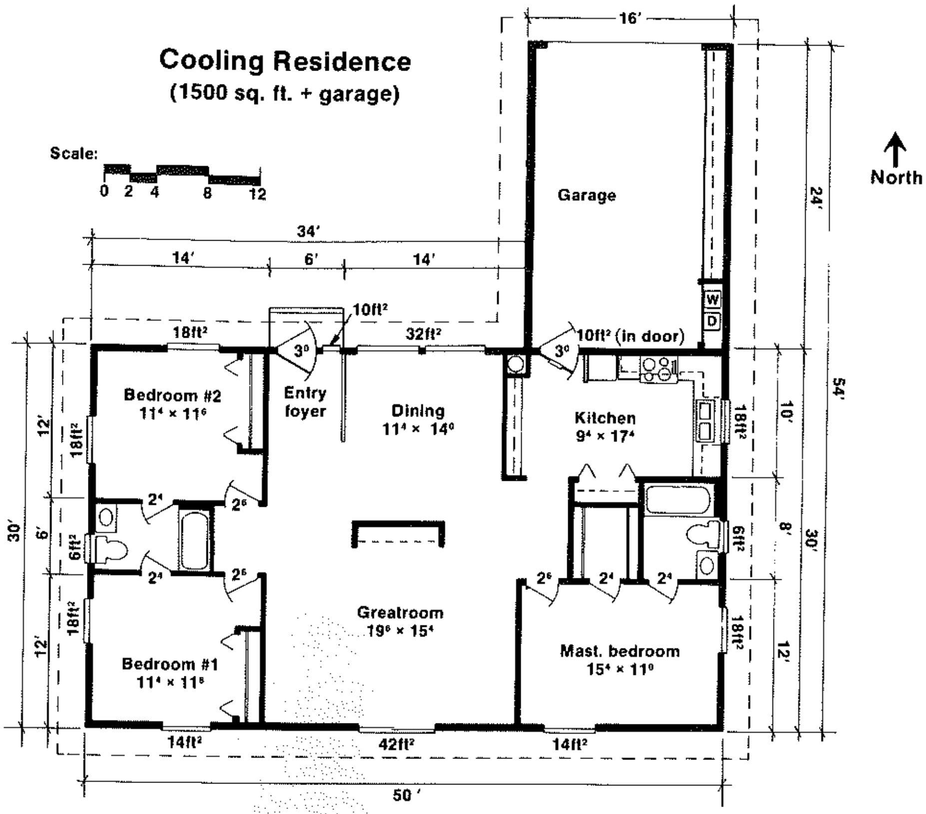


Figure 1. Floor plan of residences used in MADTARP analysis

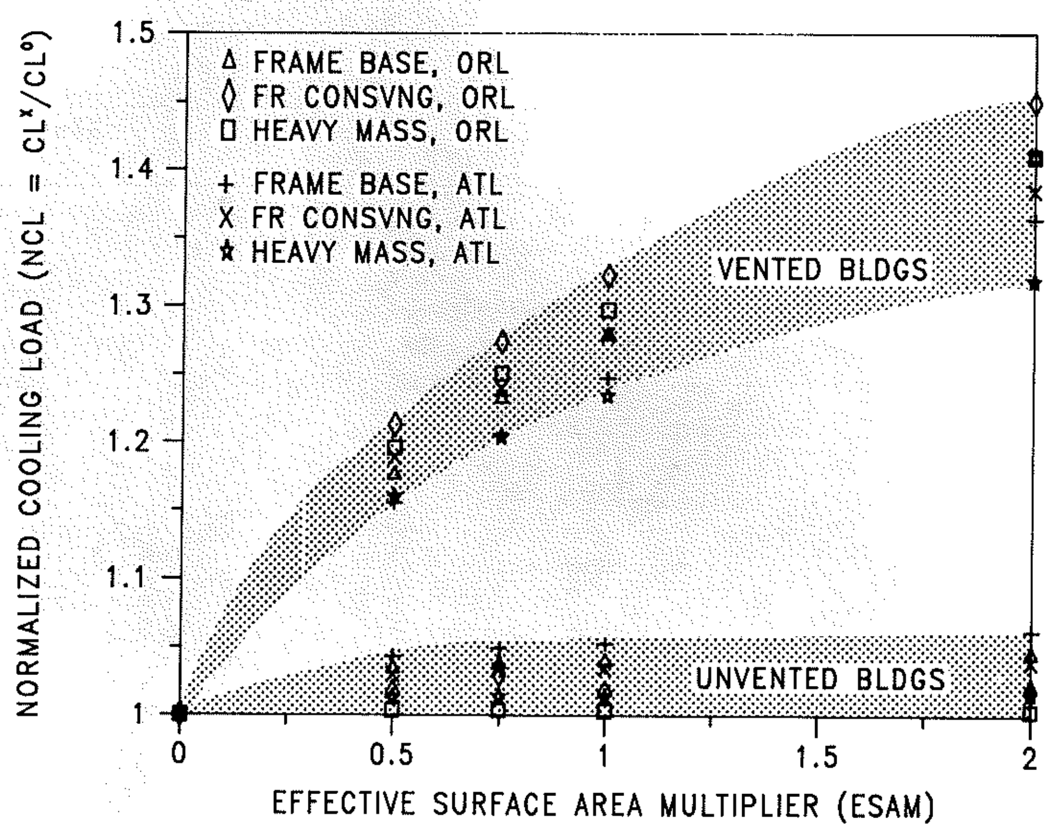


Figure 2. Effects of ESAM variation for vented and unvented buildings in Orlando and Atlanta. The predicted NOMAD load is the base

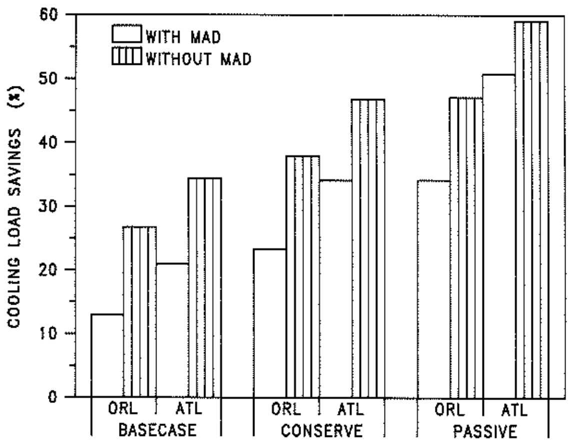


Figure 3. Predicted ventilation cooling load savings for three building types in Orlando and Atlanta for MAD and NOMAD analysis. Vented at 15 VACH if 69 F < ambient < 78 F

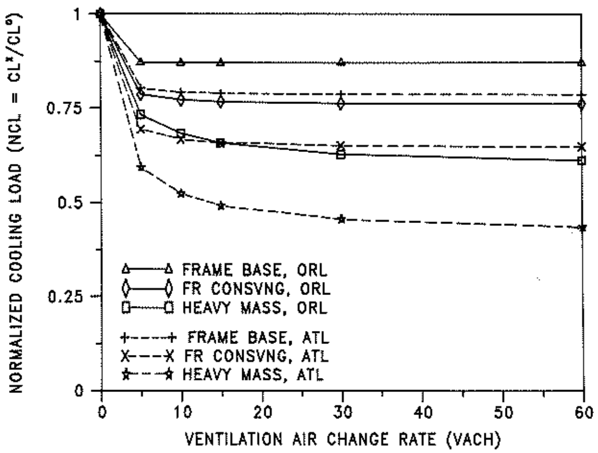


Figure 4. Effects of increasing VACH for three building types in Orlando and Atlanta. Vented if 69 F < ambient < 78 F

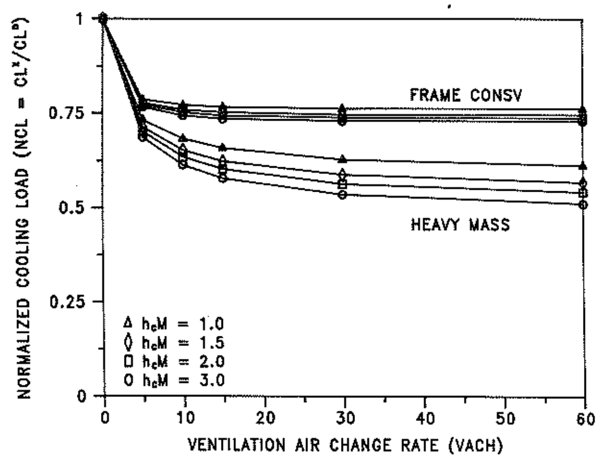


Figure 5. Effects of VACH variation in two building types for h_cM values in Orlando, FL

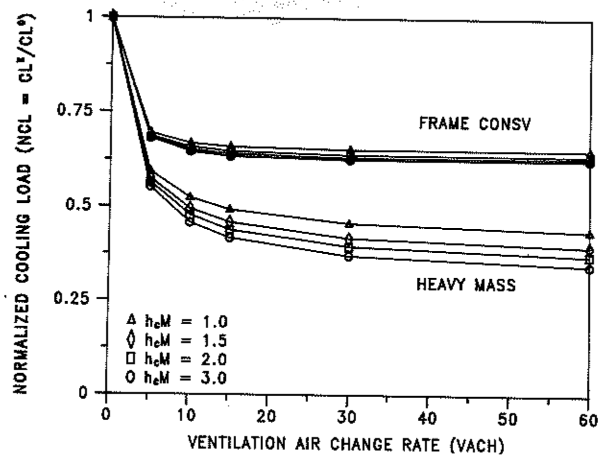


Figure 6. *Effects of VACH variation in two building types for four h_cM values in Atlanta, GA*

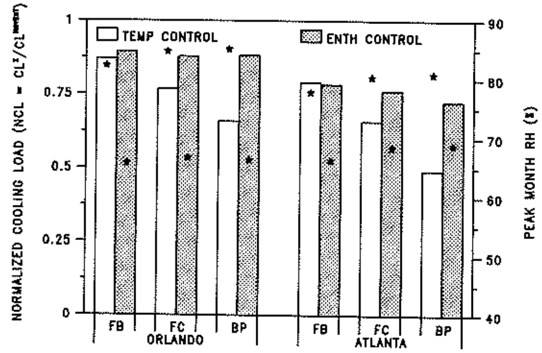


Figure 7. *Effects of vent control strategies on residual cooling load and peak month room relative humidity for three building types in Orlando and Atlanta*

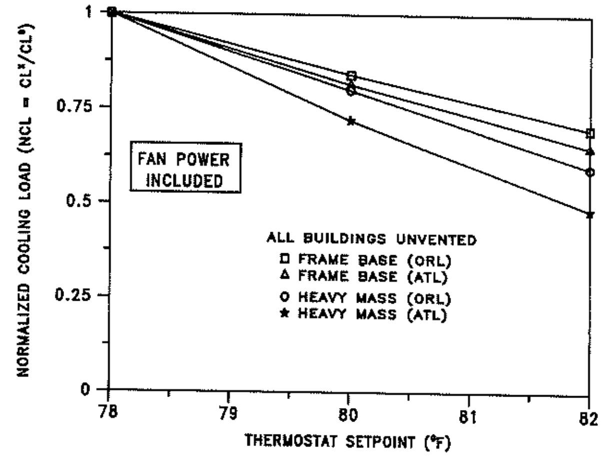
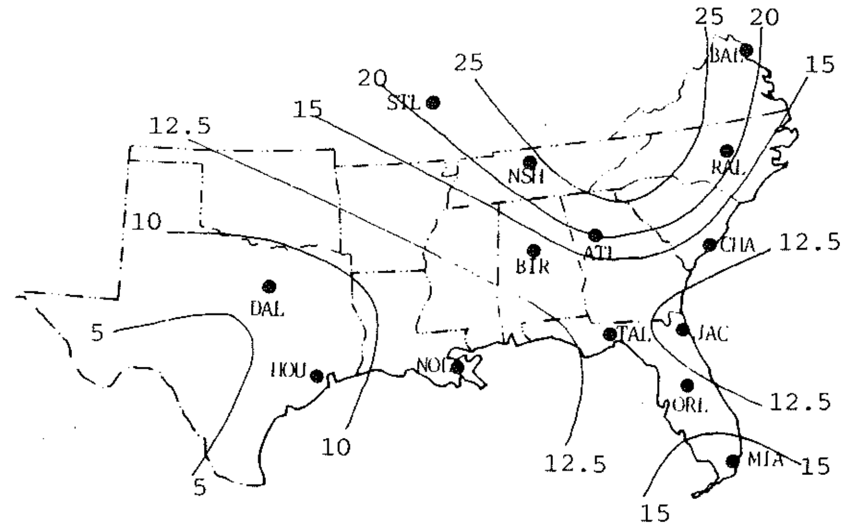
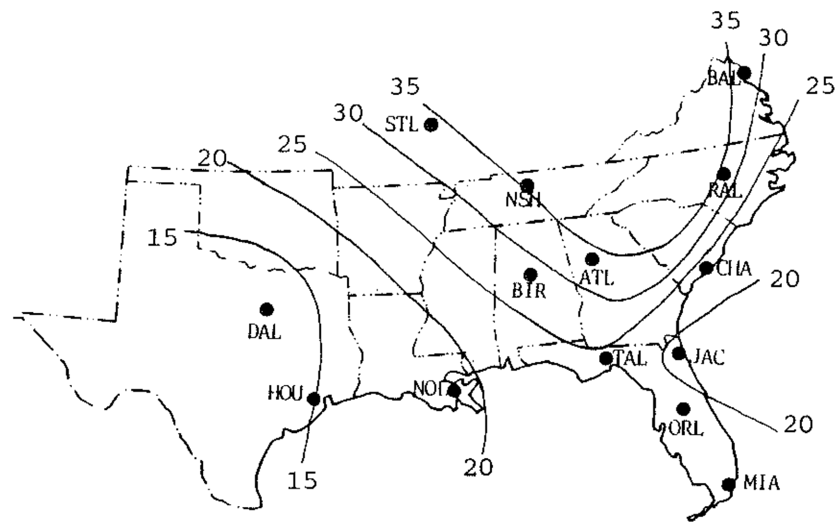


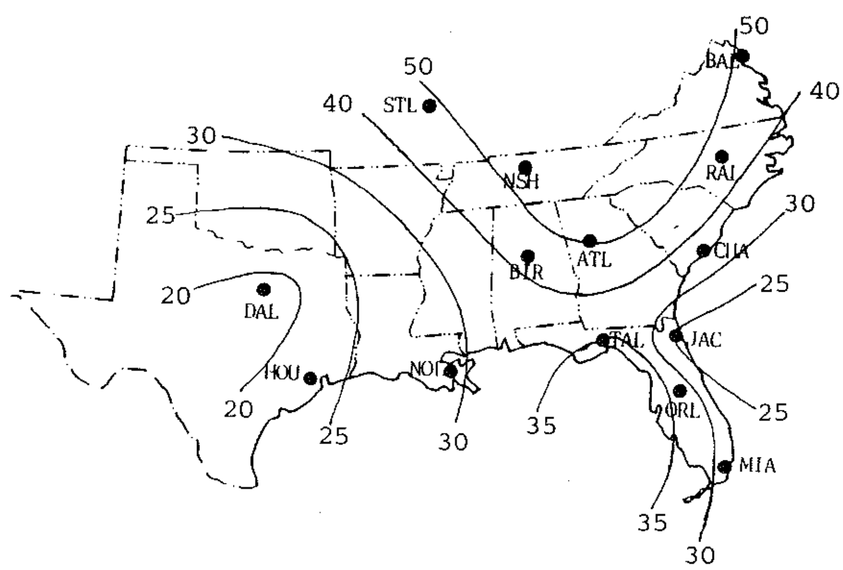
Figure 8. *Reductions in cooling load in Orlando and Atlanta through the use of ceiling fans and higher thermostat setpoints after accounting for parasitic fan power*



(a) Typical frame house (FB)



(b) Energy conserving frame house (FC)



(c) Heavy mass house (BP)

Figure 9. Predicted ventilation cooling load savings (%) for three house types in the Southeast. (Thermostat = 78 F; vented at 15 air changes per hour if 69 F < ambient < 78 F)

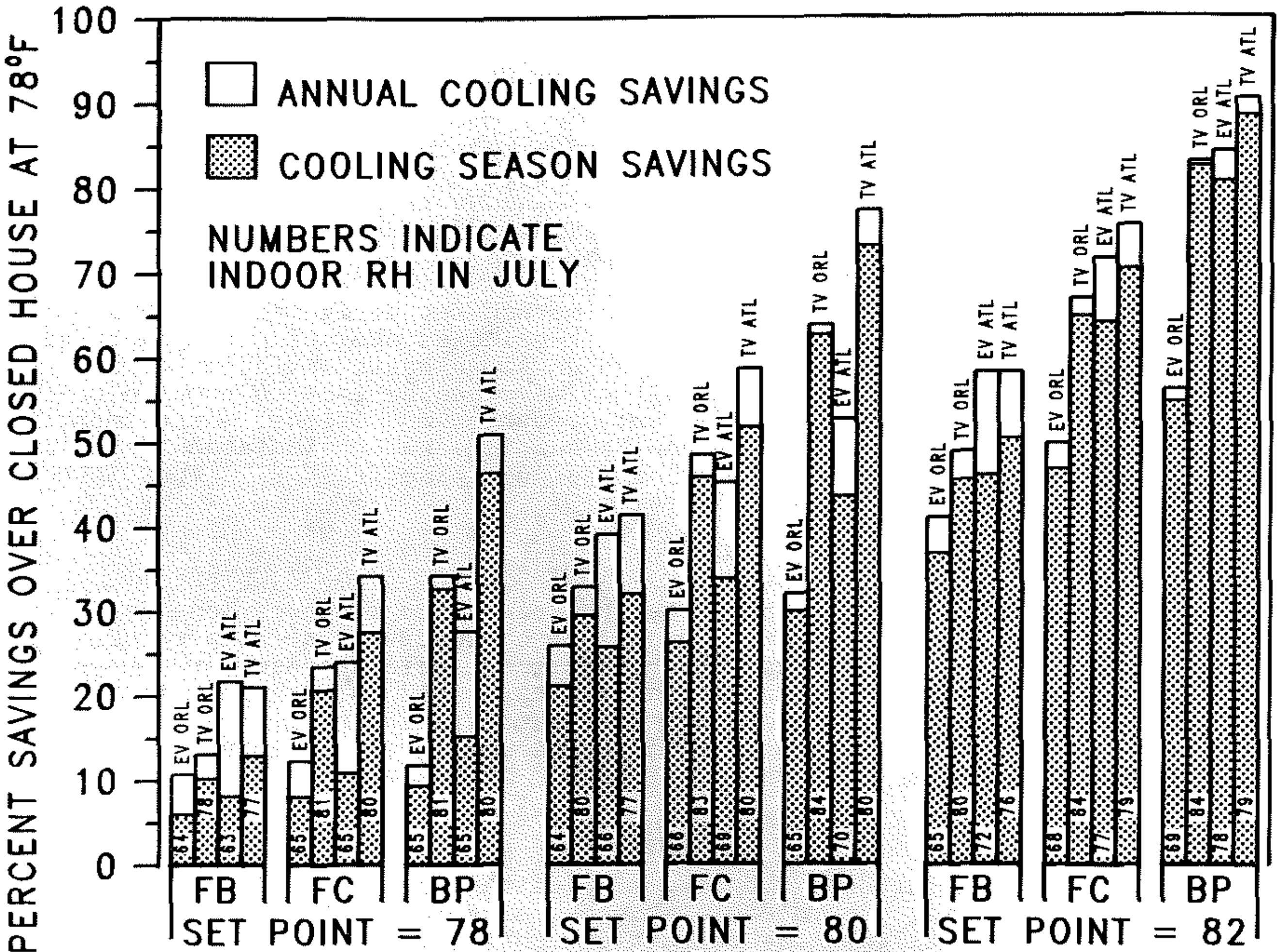


Figure 10. Cooling energy savings from ventilation and ceiling fans for enthalpy (EV) and temperature venting (TV) strategies. July indoor RH maintained is also indicated. Three different house types (FB = frame base, FC = frame conserving, BP = heavy mass) analyzed in two climates. Cooling season is April - October in Orlando and June - August in Atlanta