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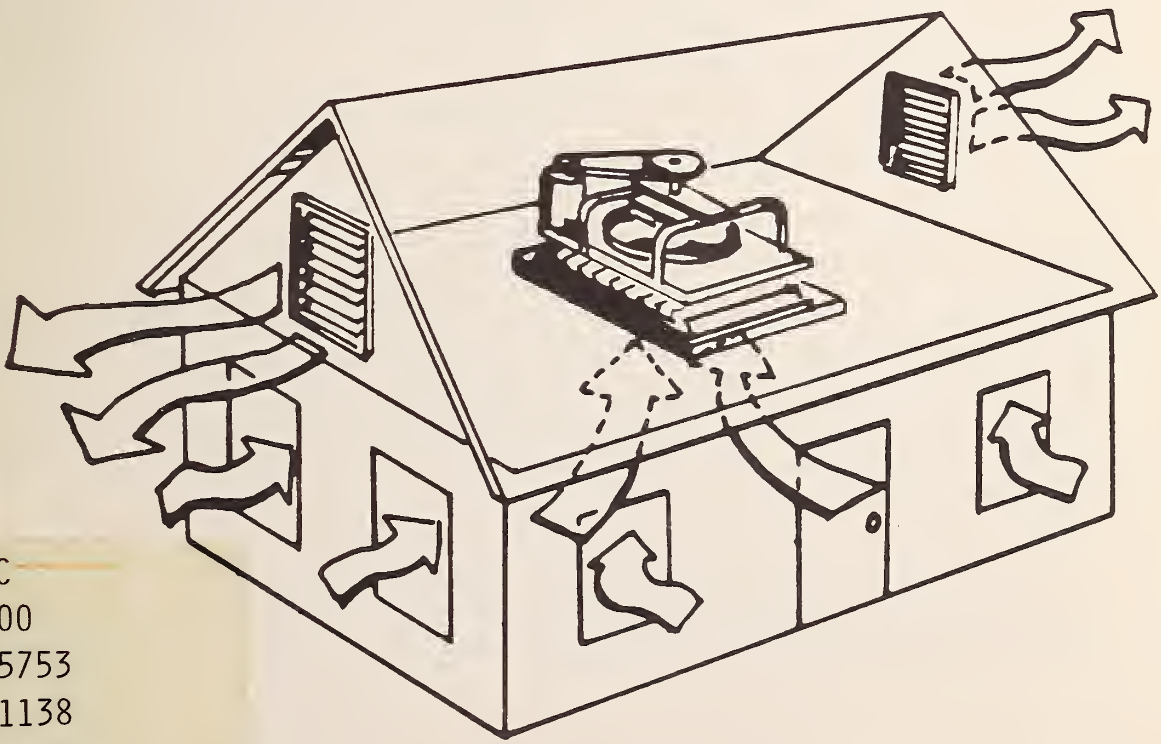
Savings in Electric Cooling Energy By the Use of a Whole-House Fan



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Savings in Electric Cooling Energy By the Use of a Whole-House Fan

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ABSTRACT

Hour-by-hour cooling performances of a typical ranch house, with and without the use of a whole-house fan, were compared for the climate conditions throughout the contiguous United States. The comparative analyses were made by the use of NBSWHF, a modified version of NBSLD, to simulate the complex thermal coupling of whole-house-fan ventilated attic space. The calculations were performed for two operational modes: a cyclic fan mode and a stepwise continuous mode. The calculation predicted a large cooling energy savings as compared to the house without the use of the whole-house fan, without significant deterioration of indoor thermal comfort.

Key Words: building thermal performance; energy calculation; energy conservation; thermal comfort; whole-house ventilation.

ACKNOWLEDGMENT

The work reported in this Technical Note was sponsored by the National Bureau of Standards. Part of the motivation for this analytical study was the extremely beneficial results revealed in a limited field study of the whole-house-fan approach to cooling. That field study was a minor part of a DOE/NBS project sponsored by the U.S. Department of Energy. The authors gratefully acknowledge DOE's interest and support of that project, entitled Attic Ventilation Criteria, which was conducted in Houston, Texas in 1977-78.

CONTENTS

1. INTRODUCTION

During the summer of 1977, NBS engineers conducted extensive tests on attic ventilation in three unoccupied test houses in Houston, Texas[1]. Although this NBS test concluded that the attic fan was ineffective for savings in cooling energy consumption, a limited study conducted on the attic whole-house fan proved to be extremely beneficial.

While an attic fan is usually installed at the gable and draws the outdoor air through gable and soffit ventilation openings, the attic whole-house fan is mounted at the ceiling, and draws outside air through windows and exhausts it through the attic space. The fan would be turned on whenever the outdoor temperature is low enough to provide natural cooling. Since an average whole-house fan would require 400 to 500 watts of electrical energy as contrasted to the 2500 to 3000 required for central air conditioning, it is easy to see that significant electrical energy savings are possible by substituting the use of a whole-house fan for a central air conditioner.

Most of the whole-house fans are designed to ventilate a house at 1/2 to 1 aïr change per minute. If the house temperature is to be maintained at a reasonably comfortable condition, the use of a whole-house fan could be substituted for that of an air conditioner whenever the outdoor temperature is less than about 82°F.

Table 1 shows the number of hours during the year when the outdoor temperature is less than 82° but higher than 65° for ten different cities in the United States. The lower limit of 65° was chosen because it would be unlikely that either natural or whole-house ventilation would be used when the outdoor temperature was that low. Natural ventilation simply by opening windows (but without the fan running) may be sufficient below 72°F. The number of hours shown in Table 1 that occur when the outdoor temperature falls within the 72-82° temperature bin, therefore, represents a potential number of hours when the whole-house fan can be utilized.

The actual number of hours when the whole-house fan is used, however, depends strongly upon the interaction between the building heat transfer and storage characteristics with respect to the cooling potential of the outdoor air. The actual electrical energy savings obtained by the use of the whole-house fan is also dependent upon the manner in which it is operated. The purpose of this study is to evaluate the effectiveness of whole-house ventilation by simulating the detailed building heat transfer process with respect to the mode of operation of a whole-house fan.

The whole-house fan may be activated as soon as the outdoor temperature falls below a set point, and left running continuously not only to maintain the comfort condition but also even to undercool the house. The undercooling is done intentionally to store the coolness to counter the hot daytime condition that follows. Unless carefully monitored, however, this mode of operation may end up wasting a large amount of fan energy.

The wasting of the fan energy may be reduced by reducing the fan speed in accordance with a predetermined control strategy. The fan also may be cycled by an indoor thermostat. This paper addresses several selected modes of whole-house-fan operation. Additional work is needed to identify the energy savings potential of other possible modes of operation.

2. COMPUTER SIMULATION

The National Bureau of Standards Heating and Cooling Load Determination Program, NBSLD, is a comprehensive hourly simulation computer program based on detailed radiant exchange heat balance among the interior surfaces of the building, as well as the transient heat conduction through the various components of the building envelope. Details of this program are given in reference 2. NBSLD was first modified to simulate the detailed heat transfer and thermal storage process of whole-house-fan operation. The modified NBSLD, called NBSWHF, was then validated by comparing its results with the measured results of the Houston test house. The modification is in the attic temperature and heat transfer algorithm to account for precise radiant heat exchange between the underside roof and attic floor surfaces. Also included in NBSWHF are the capabilities to determine Fanger's Predicted Mean Vote (PMV), which is a well-recognized comfort indicator.[3] Figure 1 shows the calculated and measured indoor temperature and cooling load of the Houston test house for the whole-house-fan operating period covering September 27 through October 1 of 1977. Except for the last day, the measured and NBSWHF-calculated cooling loads are in good agreement.

3. TEST HOUSES

Using this validated NBSWHF computer program, the simulation studies were conducted for the Hastings Ranch House (a three-bedroom house with 1,176 ft^2 floor area), which embodies current energy conservation designs and is more energy efficient than conventional houses.[4/] The computer model of the house was, however, modified in accordance with the prevailing local building practices and moved around to the ten cities listed in Table 1. The essential features of the house are:

<u>Floor</u>:

- ° 4-inch concrete slab-on-grade over 1" rigid foam insulation for California, Arizona, and Texas houses.
- ° Wooden floor with R-7 insulation over crawl space for the Atlanta and Portland houses.
- ° Basement floor for the Washington, Minneapolis, and Chicago houses.

<u>Roof</u>:

- ° 22.6° pitched roof with 1-1/2 ft overhang over the walls.
- ° R-19 attic floor insulation, except for the Minneapolis house, which had R-22 attic floor insulation.

Walls:

- R-11 insulation with aluminum siding, except for the house in California, which had stucco walls.

Windows:

- Double-glazed windows for Minneapolis, Chicago, Portland, and Washington.

Other data used such as window characteristics, air leakage data, and internal heat source data were made consistent with those used in the DoE's Building Energy Performance Standards (BEPS). Details for the BEPS residential building data are given in reference 4. The building had 15% of floor area as the glazing area, which was evenly distributed among all four walls. This assumption was intended to model current practice, in which windows are not preferentially oriented. An internal load of 15.5 kWh/day was distributed in accordance with a typical household lighting, cooking, appliance-use schedule, as well as the occupancy pattern. As to the air leakage data, it was assumed that the infiltration under standard design condition is 0.6 air change per hour. The hourly air change values, however, were adjusted with respect to actual wind speed and indoor/outdoor temperature difference using the Achenbach and Coblentz relationship.[5/]

4. CALCULATED COOLING ENERGY CONSUMPTION

Tables 2 and 3 show the results of the NBSWHF calculations in terms of annual cooling load comparison between the houses with and without the whole-house fan, determined for the ten cities using ASHRAE TRY weather data tapes.[6/]

The ASHRAE TRY weather data tapes contain hourly coincident values of outdoor temperature, humidity, wind speed, wind direction, and cloud cover. In NBSWHF the cloud cover data were converted into hourly solar radiation data by the Kimura/Stephenson method.[7/]

The whole-house fan may be operated in many different ways with regard to starting/stopping, setting of the fan speed, and continuous vs cycling, etc.

In this study, the operation of the whole-house fan was simulated in two different modes. In mode #1, the hourly total volume of the outside air introduced into the house was precisely regulated to satisfy the net sensible cooling requirements of the house for a 78°F room temperature set point. This was done in the following sequences:

(1) The hourly sensible cooling requirement without whole-house fan for a given thermostat setting was first determined by a rigorous building heat transfer calculation on an hourly basis.

(2) If the coincident outdoor temperature DB was below the indoor thermostat setting 78° and yet higher than 70°F, the necessary volume of outdoor air to satisfy that cooling requirement was then calculated by the following relation:

$$cfm = \frac{\text{Sensible Cooling Requirement}}{1.08\ (78 - DB)} .$$

(3) The calculation for that hour was then repeated to determine the room and attic temperature under the condition when the air conditioner was off and the whole-house fan would introduce the volume of air determined in step 2 on the basis that the room air was exhausted through the attic space. In order for a given whole-house fan to deliver exactly the right volume of air as determined by the equation in step 2, however, it is intrinsically assumed that the fan is cycled. In other words, the total running time of the fan was assumed proportional to the required cfm as specified in step (2) divided by the full-load capacity of the fan (to deliver an equivalent of 1 air change per minute of the house air.).

The second, iterative calculation showed that the whole-house fan was indeed able to maintain the room temperature at the set value within 1°F.

(4) The energy consumption of the fan was determined by multiplying the standard power rating (in this example 450 watts) by the fan running time. If the calculated air delivery rate exceeded the rated air delivery rate of the fan, the rated fan air delivery rate was used.

Table 2 also lists the total number of hours of the whole-house fan operation, estimated fan energy consumption, and estimated electrical energy savings on air conditioning (based upon the seasonal COP of 2.5) as a result of the whole-house-fan use, as well as the net seasonal electrical energy savings obtainable by the use of the whole-house fan.

In typical applications, however, the whole-house fan is not cycled by the room thermostat as simulated in the mode #1 calculation. It is operated continuously with full capacity of one air change per minute as long as the outdoor temperature is above 78°F but below 82°F, with the room air conditioner turned off. This mode of operation, designated as mode 2, was simulated using NBSWHF. The whole-house fan in the mode #2 analysis is also assumed to operate at half capacity (i.e., 0.5 air change per minute) when the outdoor temperature is below 78°F but above 72°F. When the outdoor temperature was below 72°F it was also assumed that the fan was stopped and the house was cooled with natural ventilation of 6 air changes per hour, or one-tenth of the standard whole-house-fan rate. The indoor temperature will be very close to the outdoor temperature when the whole-house fan is introducing the outdoor air with a rate of one air change per minute, which would create a breeze of 100 200 ft per minute. The breeze makes the occupant comfortable under higher temperatures than 80°F, as shown in Figure 2, which depicts the Fanger comfort index. The PMV stands for the "Predicted Mean Vote" and represents the average thermal sensation of people representing many social strata and age groups on the combined effect of temperature, humidity, mean radiant temperature, and air speed across the body. The scale for the PMV is as follows:

3 hot
2 warm
1 slightly warm
0 neutral
-1 slightly cool
-2 cool
-3 cold.

The physiological fundamentals of PMV with respect to thermal environment, effect of sex, race, age, food and other factors are given in reference 3. Figure 2 shows also that the full-capacity whole-house-fan breeze (100~200 fpm) would make the occupant feel too cool if the room temperature were below 80°F. This is the reason that the fan capacity was assumed to be cut down to a half of full capacity. Furthermore, it was assumed that the natural ventilation without fan could provide approximately 6 air changes per hour of outdoor air circulation and is good enough to provide a comfortable condition when the outdoor temperature is below 72°F but above 65°F.

Table 3 shows the result of the mode #2 calculations for the same houses used in the mode #1 simulation. A marked increase in the electric energy savings is mostly due to the fact that the number of hours when the fan is on (WHF hours) to replace the air conditioner is larger than in the mode #1 operation. The increase of the cooling kWh savings was, however, somewhat offset by the increased fan energy consumption. The fan power in this case was estimated by examining typical commercial whole-house fan ratings and was assumed to be 450 watts at full capacity and 130 watts at half capacity. It appears that the electrical power consumption varies with 1.7 power of air delivery rate while the theoretical fan brake horse power should vary with the cubic power of the air delivery rate, in accordance with the fan law. The deviation from the fan law is due to the reduction in the electrical motor efficiency as its rpm is reduced.

Figures 3 through 12 show the daily cooling kWh plotted versus daily average outdoor temperature for the ten cities used in the analysis. For this analysis, the whole-house-fan was operated in mode #2. Most of the figures show the marked decrease of the daily cooling kWh when the whole-house-fan was utilized, except for Phoenix and Fresno, where the cooling kWh savings are somewhat smaller than in the other cities. This is because the percentage of possible whole-house fan hours during the summer in these two cities is considerably smaller than in the other cities, as shown in Table 1 and Figure 24. The two straight lines shown in these figures are least-squares-fit representations of the calculated daily total cooling kWh points.

Figures 13 through 22 show the hourly frequency of calculated PMV's for the houses with and without the use of whole-house ventilation. These hourly frequency profiles under shaded histogram represent the house without whole-house fan, while the unshaded histograms represent the house with whole-house fan. The house with a whole-house fan operated under mode 2 tends to show many hours with higher PMVs. The PMVs in these calculations, however, were calculated on the basis of a predetermined set of occupancy responses to the hot environments as follows:

1) The occupant wears typical business suit (clo = 1.0). The room air motion is zero.

2) When the occupant feels warm as the indoor temperature increases (PMV = 2.0), he starts shedding his clothes until the clo value becomes 0.5 or the equivalent of light summer clothing.

3) If the PMV value is still higher than 2.0 at clo = 0.5, the PMV is recalculated with increased air speeds at steps of 0.1 m/s until 0.5 m/s is reached.

In figures 13 through 22, the PMV values in the abscissa are shown to represent these three conditions. Although these figures clearly indicate that the use of whole-house fans would shift the comfort profile toward "warm," a majority of occupants would be comfortable even during the hottest period of the season by wearing light clothes and staying in the breezy areas in the house. The same figures also indicate that the whole-house fan would make the occupant feel cool in many hours during the year unless he wears heavy clothes and stays in non-breezy areas.

The higher PMV values shown in Figures 13 through 22, especially for the whole-house fan calculation, could therefore be reduced by as much as 1.0, if they were evaluated at 0.5 clo and at 0.5 m/s (or approximately 100 fpm) instead of zero. In other words, a thermal comfort level of about 1.0 (slightly warm condition) could be maintained throughout the summer for all of the whole-house-fan houses in the United States.

In order to compare the cooling kWh effectiveness of the whole-house fan at indoor thermostat settings other than 78°F, figure 23 is prepared for the Washington, D.C. ranch house. This figure was obtained for the mode #1 condition so that the effectiveness of the whole-house fan could be compared at identical indoor conditions. It is shown also that the relative amount of cooling kWh saving becomes greater as the indoor cooling thermostat is set at a higher temperature. The implication of this particular figure is that an equal or greater amount of cooling kWh savings can be obtained simply by increasing the cooling thermostat setting without even using a whole-house fan. For example, the annual cooling kWh reduction by whole-house fan at 78°F for the Washington D.C. ranch house is from 2500 kWh to 1900 kWh, or 600 kWh. Figure 23 shows that the same kWh savings can be obtained by simply turning the thermostat from 78° to 82°F. The comfort aspect at 82°F can be made similar to that of 78°F by using ceiling fan or similar room circulating fan as long as the room humidity level is not excessive.

This point merits attention for economic considerations, since the cost of purchasing and installing a whole-house fan is not trivial.

5. CONCLUSIONS

A large amount of net cooling energy savings -- as much as 56 percent -- is possible by replacing the air conditioner with a whole-house fan, without causing undue thermal discomfort.

Cooling energy savings by the use of a whole-house fan appear to be less effective in desert climates such as Phoenix and Fresno, than in other cities. It is generally true that the cooling kWh savings become greater as the number of potential hours for whole-house ventilation increases, as shown in Figure 23.

More studies are needed to develop the sensitivities of major parameters and the effectiveness of whole-house cooling -- such as house thermal mass, indoor thermostat setting, and size of the whole-house fan. Also to be included in the future studies are economic analyses as well as the indoor relative humidity problems (when the outdoor air humidity level is high).

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Table 1. Number of Hours During the Year When Temperature Falls Within Various Temperature Bins

Locations	Temperature Bins* col 1 65-71	col 2 72-77	col 3 78-82	col 4 above 82	col 5 above 72	Percent Possible whole-house-fan hours (col 2 + col 3) / col 5 x 100
Atlanta, GA	1878	1217	663	439	2319	81%
Burbank, CA	1967	528	67	53	648	92%
Chicago, IL	1102	717	330	275	1322	79%
Fresno, CA	1087	745	526	1195	2466	52%
Ft. Worth, TX	1117	1378	934	1422	3754	62%
Houston, TX	1374	1808	1160	1244	4212	70%
Minneapolis, MN	906	704	389	452	1545	71%
Phoenix, AR	1157	900	718	2422	4040	40%
Portland, OR	755	345	192	138	675	78%
Washington, DC	1110	1008	601	722	2331	69%

* The bin data were generated from ASHRAE TRY (Test Reference Year) weather data tapes.

Table 2. Annual Cooling Requirement of Hastings Ranch House With and Without the Use of Whole-House Fan (WHF)

Control Mode #1 (Whole-house fan cycled by room thermostat)

Locations	Annual Cooling kWh Without WHF	Annual Cooling kWh With WHF	WHF Hours of Operation	Cooling Savings kWh	Estimated* Fan Power Consumption kWh	Net Savings Electric Energy kWh	Net Savings Electric Energy %
Atlanta, GA	3098	2056	288	1042	130	912	29.4
Burbank, CA	1870	1444	107	426	48	378	20.2
Chicago, IL	1725	1189	173	536	78	548	26.6
Fresno, CA	2845	2342	182	503	82	421	14.8
Ft. Worth TX	3894	2992	275	902	124	778	20.0
Houston, TX	4394	3172	361	1222	162	1068	24.1
Minneapolis, MN	1853	1332	162	521	73	448	24.2
Phoenix, AR	4580	4078	182	502	82	420	9.2
Portland, OR	1347	1025	90	322	41	281	20.9
Washington, DC	2567	1859	201	708	90	618	24.1

* Assumed fan size 450 watt

Table 3. Annual Cooling Requirement of Hastings Ranch House With and Without the Use of Whole-house Fan

Control Mode #2 (stepwise fan speed control)*

Locations	Annual Cooling kWh Without WHF	Annual Cooling kWh With WHF	WHF Hours of Operation	Cooling Savings kWh	Estimated* Fan Power Consumption kWh	Net Savings Electric Energy kWh	Net Savings Electric Energy %
Atlanta, GA	3098	879	1880	2219	469	1750	56.4
Burbank, CA	1870	961	595	909	124	785	42.0
Chicago, IL	1725	629	1047	1096	249	847	49.1
Fresno, CA	2845	1722	1271	1123	341	782	27.5
Ft. Worth, TX	3894	2037	2312	1857	613	1244	31.9
Houston, TX	4394	1834	2968	2560	775	1785	40.6
Minneapolis, MN	1853	755	1093	1098	274	824	44.5
Phoenix, AR	4580	3356	1618	1224	449	775	16.9
Portland, OR	1347	655	537	692	135	554	41.3
Washington, DC	2567	1094	1609	1473	412	1061	41.3

* DB>82 air conditioner with no whole-house fan 0.6 AC/hr
82>DB>78 no air conditioner with whole-house fan 60 AC/hr
78>DB>72 no air conditioner with whole-house fan 30 AC/hr

72>DB natural ventilation, no air conditioner and no whole-house fan, 6 AC/hr

when DB = outdoor temperature

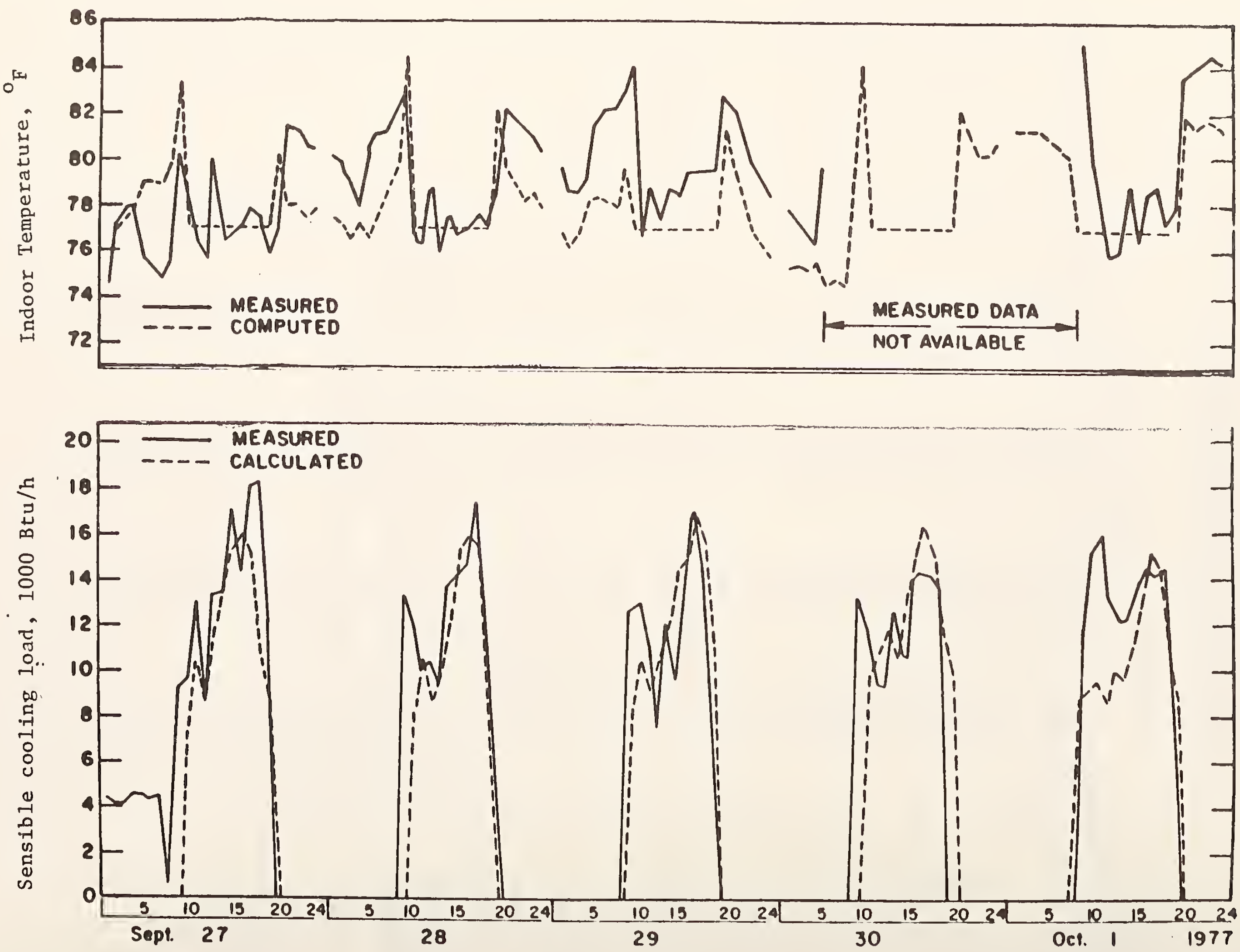

Figure 1. Comparison of measured and calculated temperature and cooling load in the NBS Houston test house under whole-house-fan operation.

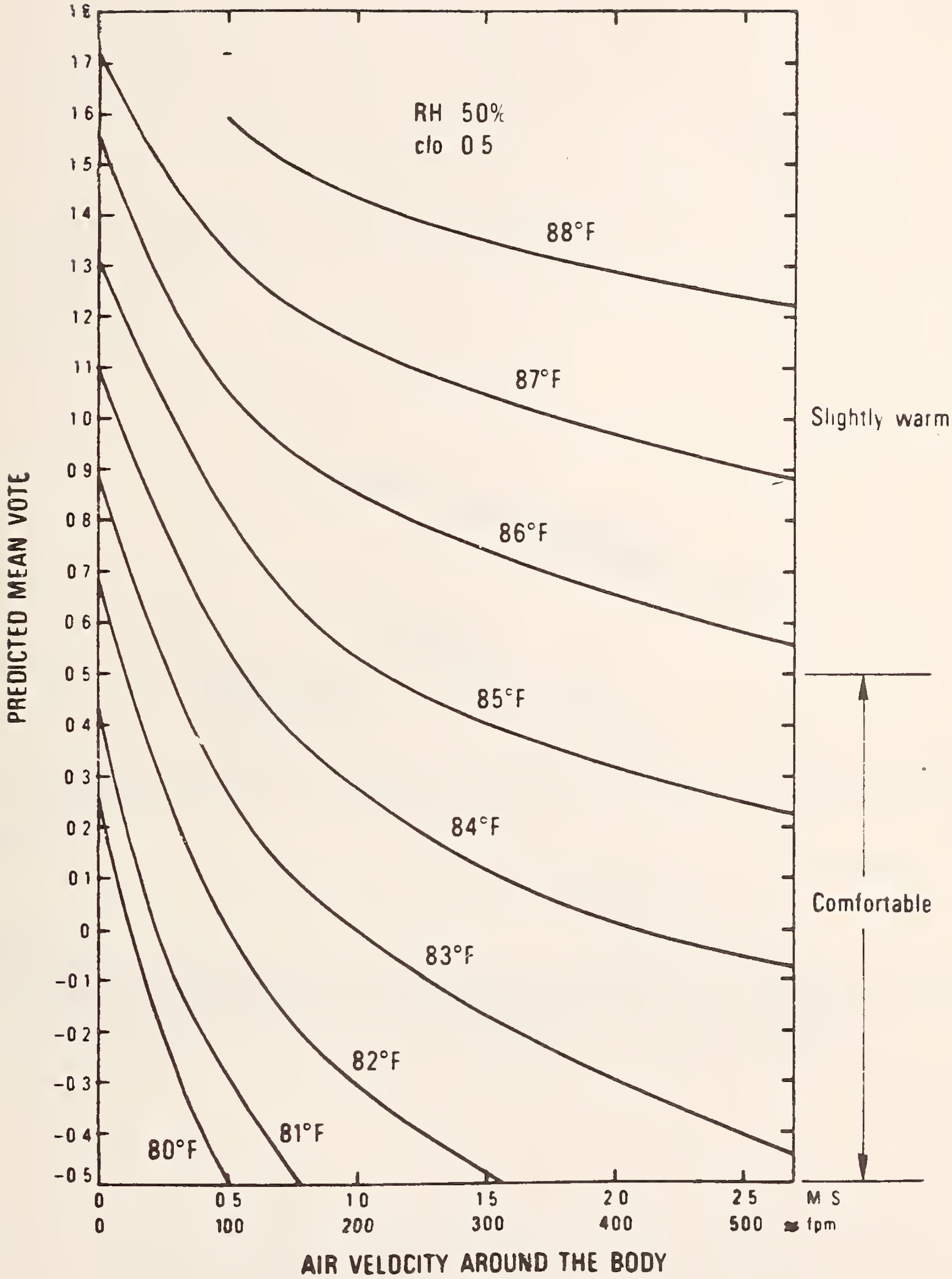

Figure 2. Fanger's comfort index with respect to air speed around the body.

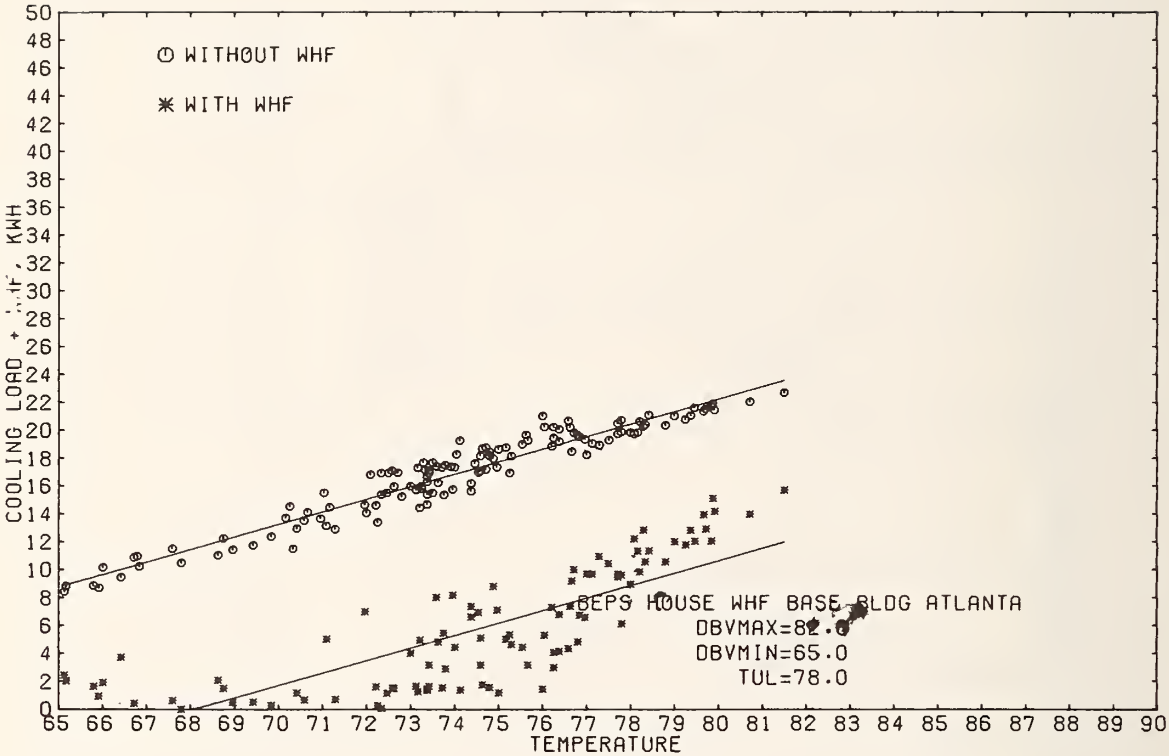

Figure 3. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Atlanta, GA with and without the use of whole-house fan (WHF).

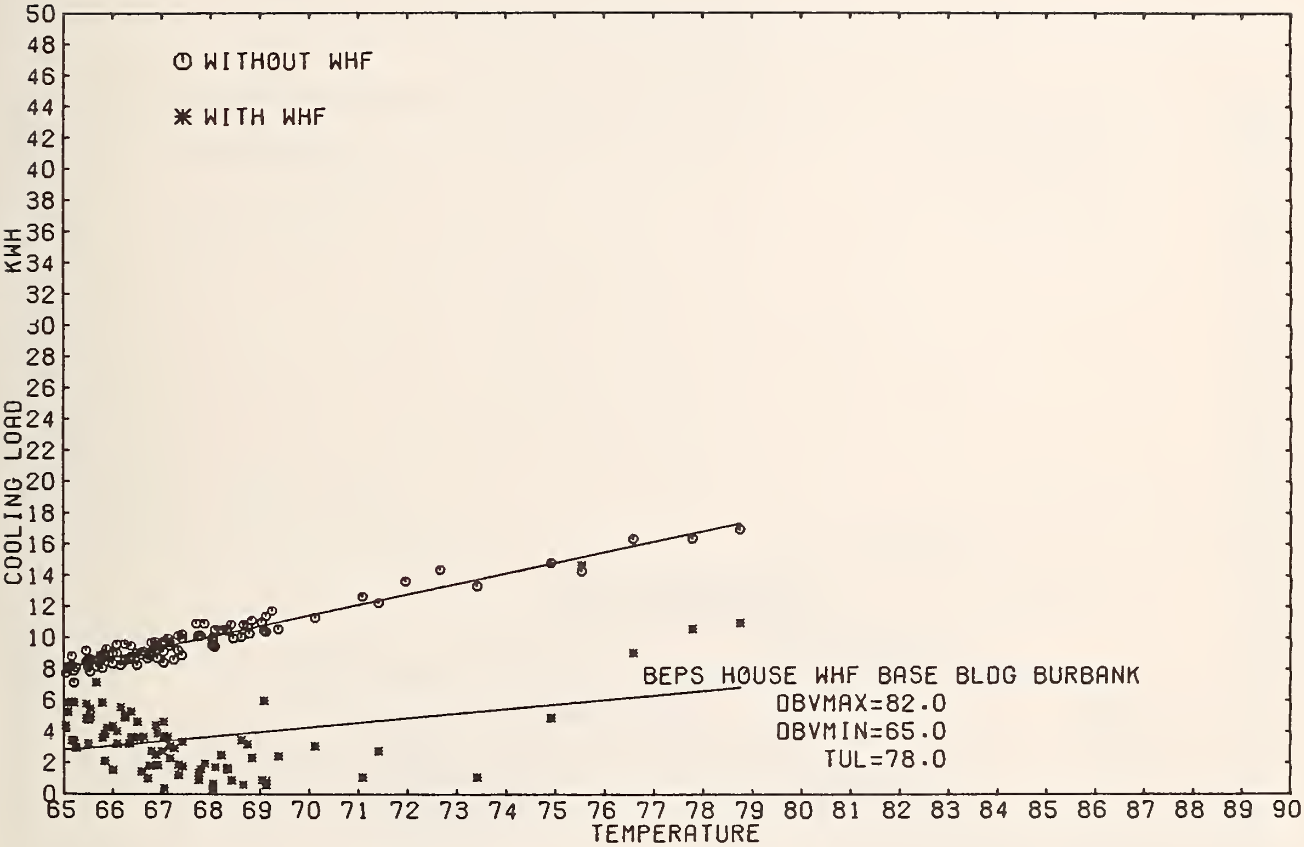

Figure 4. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Burbank, CA with and without the use of whole-house fan (WHF).

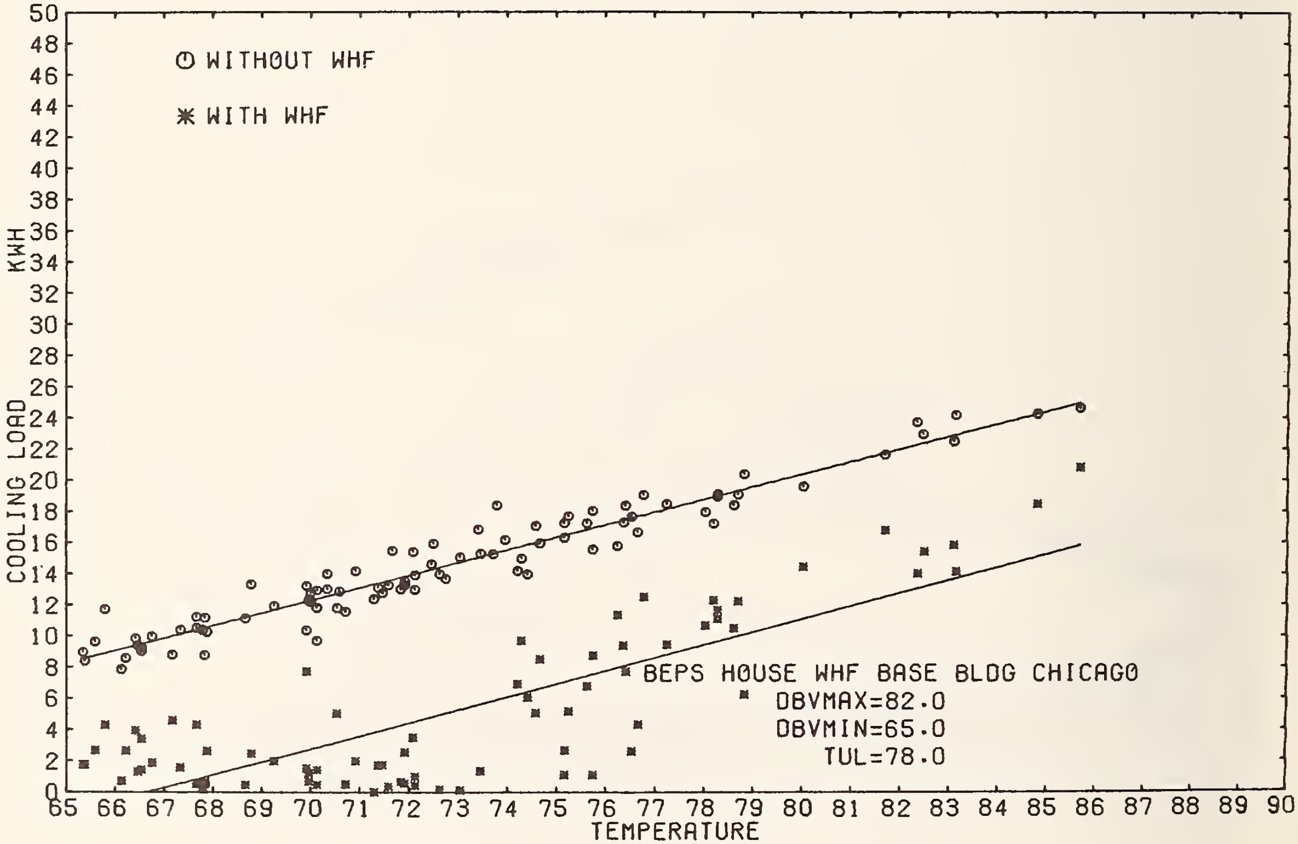

Figure 5. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Chicago, IL with and without the use of whole-house fan (WHF).

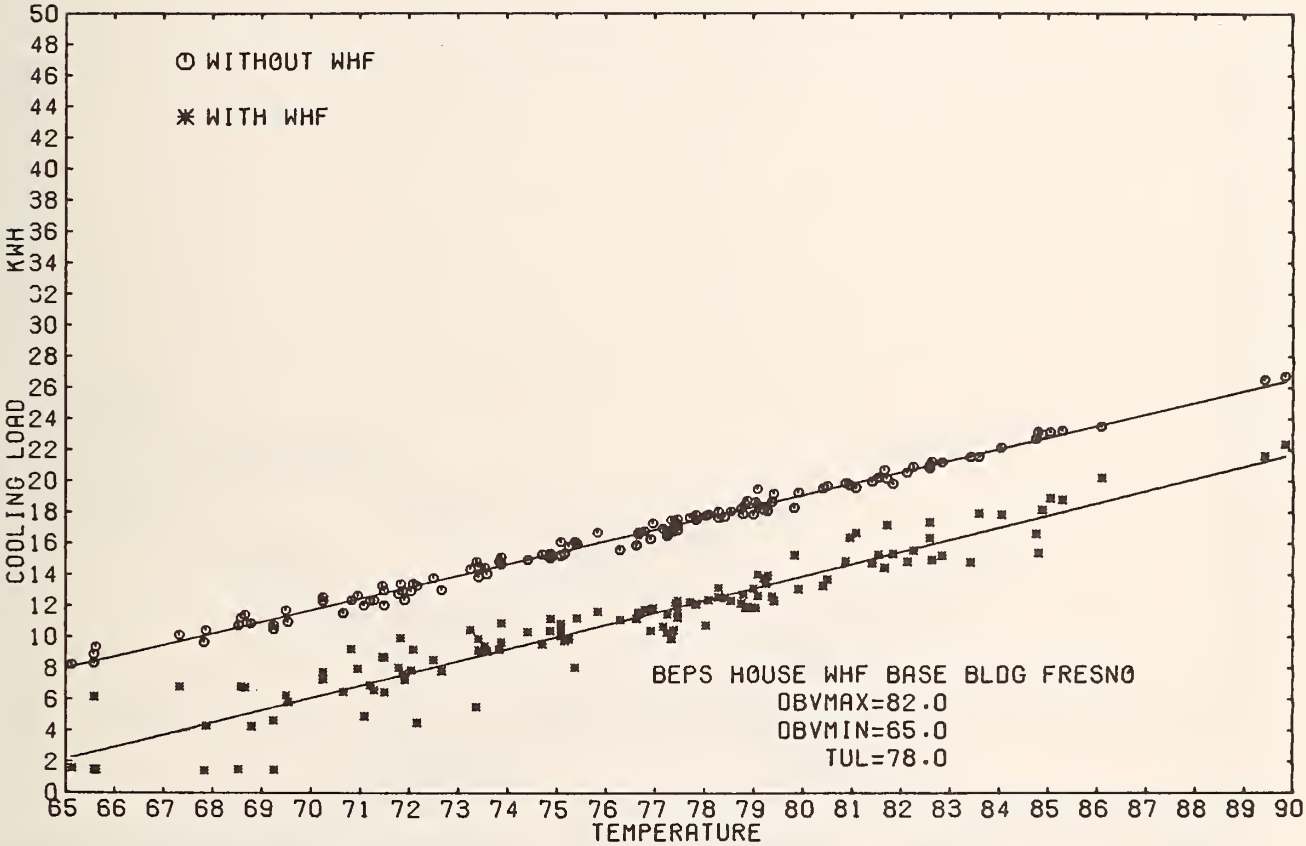

Figure 6. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Fresno, CA with and without the use of whole-house fan (WHF).

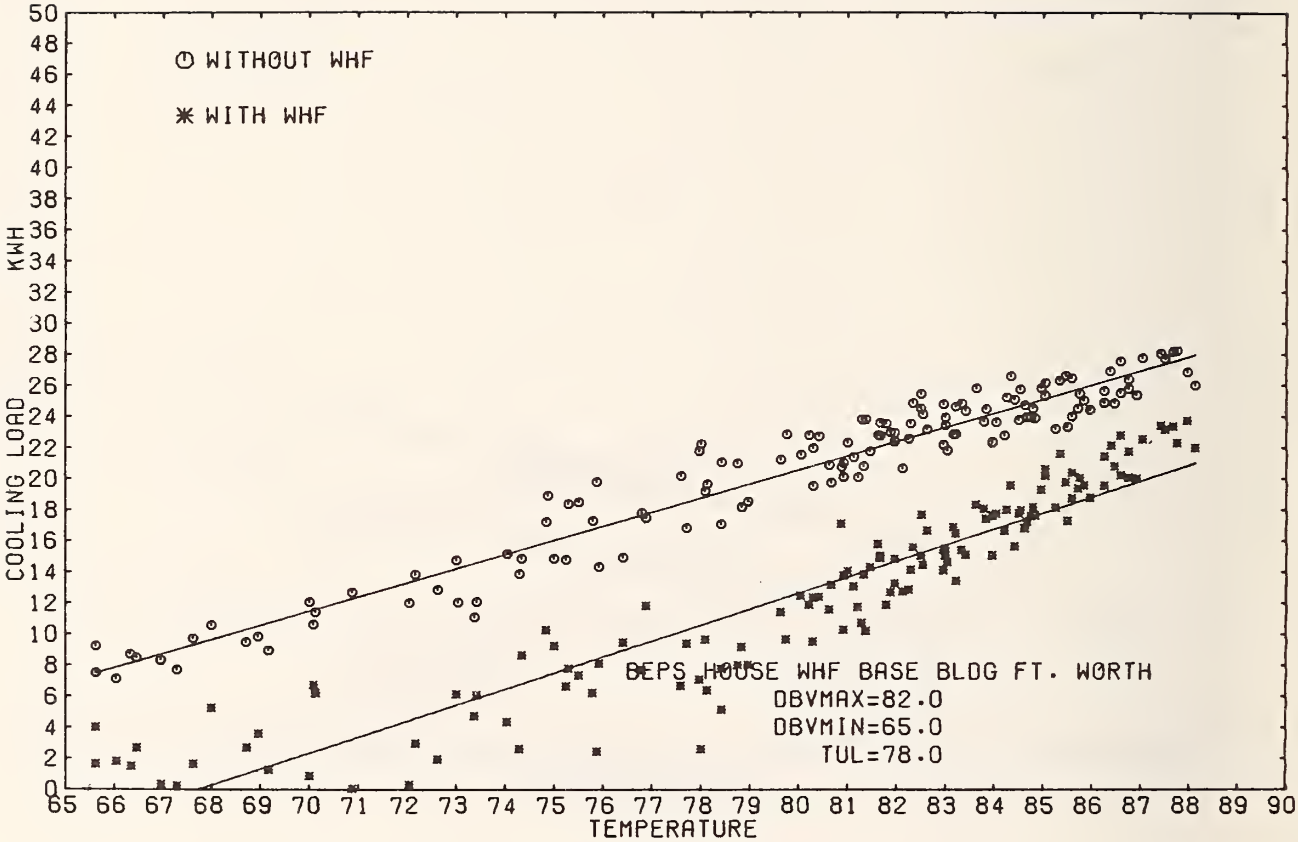

Figure 7. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Ft. Worth, TX with and without the use of whole-house fan (WHF).

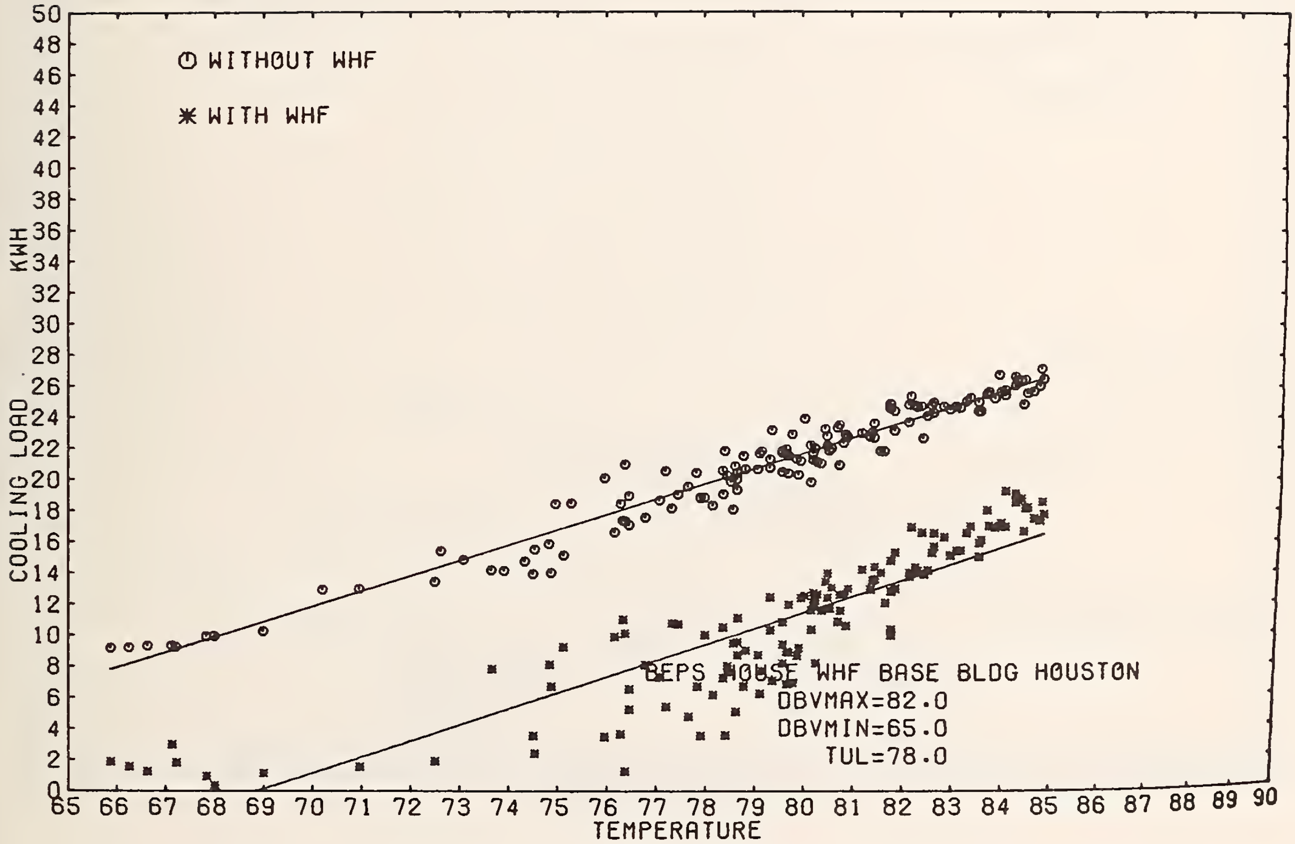

Figure 8. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Houston, TX with and without the use the whole-house fan (WHF).

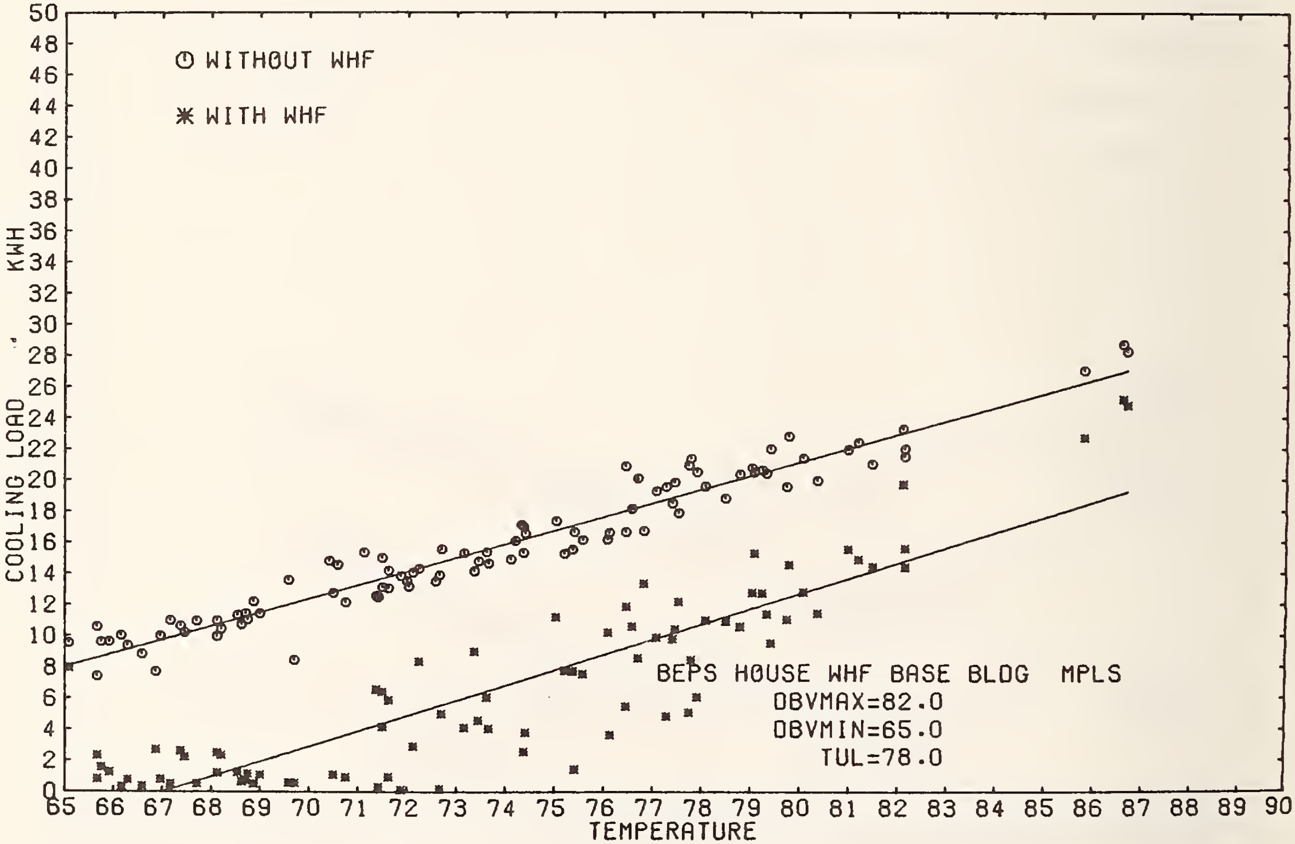

Figure 9. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Minneapolis, MN with and without the use of whole-house fan (WHF).

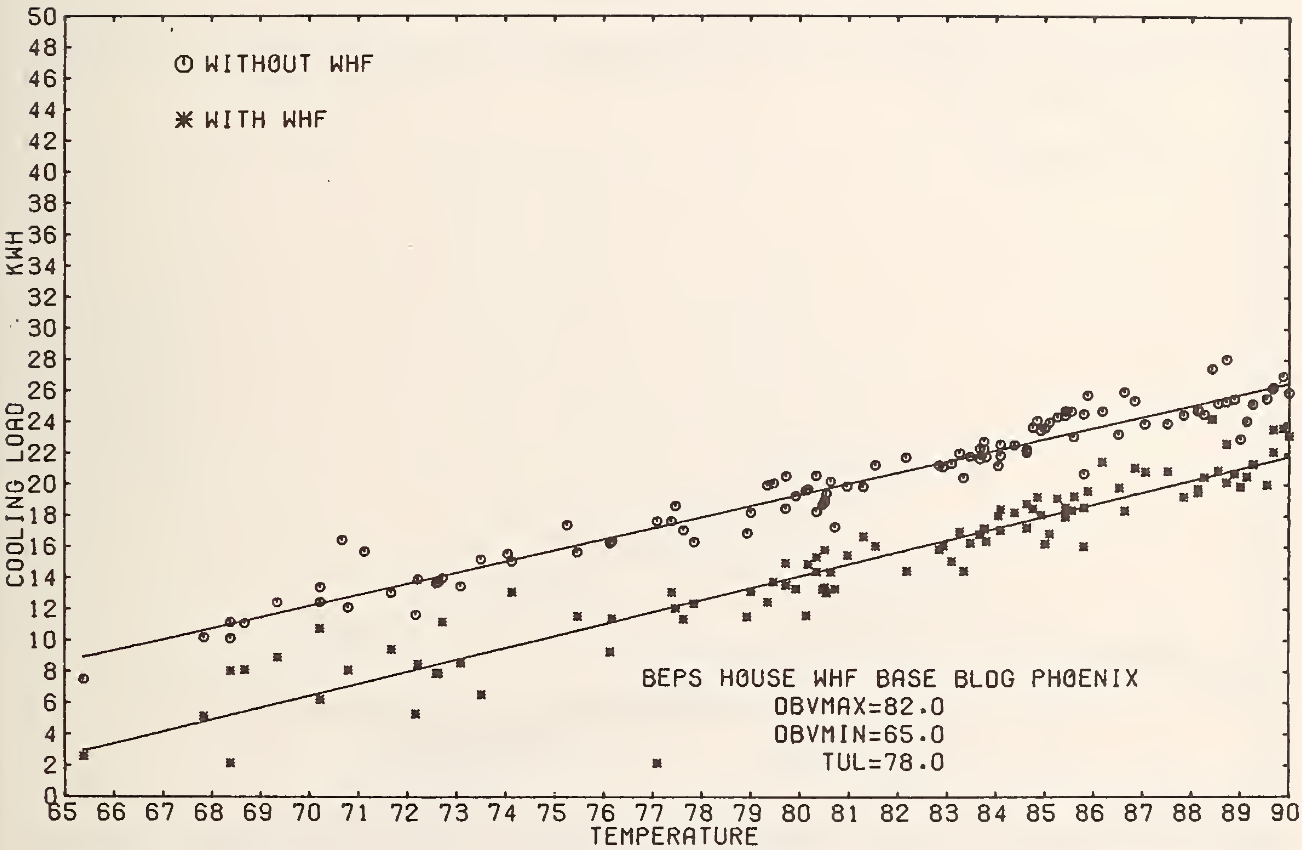

Figure 10. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Phoenix, AZ with and without the use of whole-house fan (WHF).

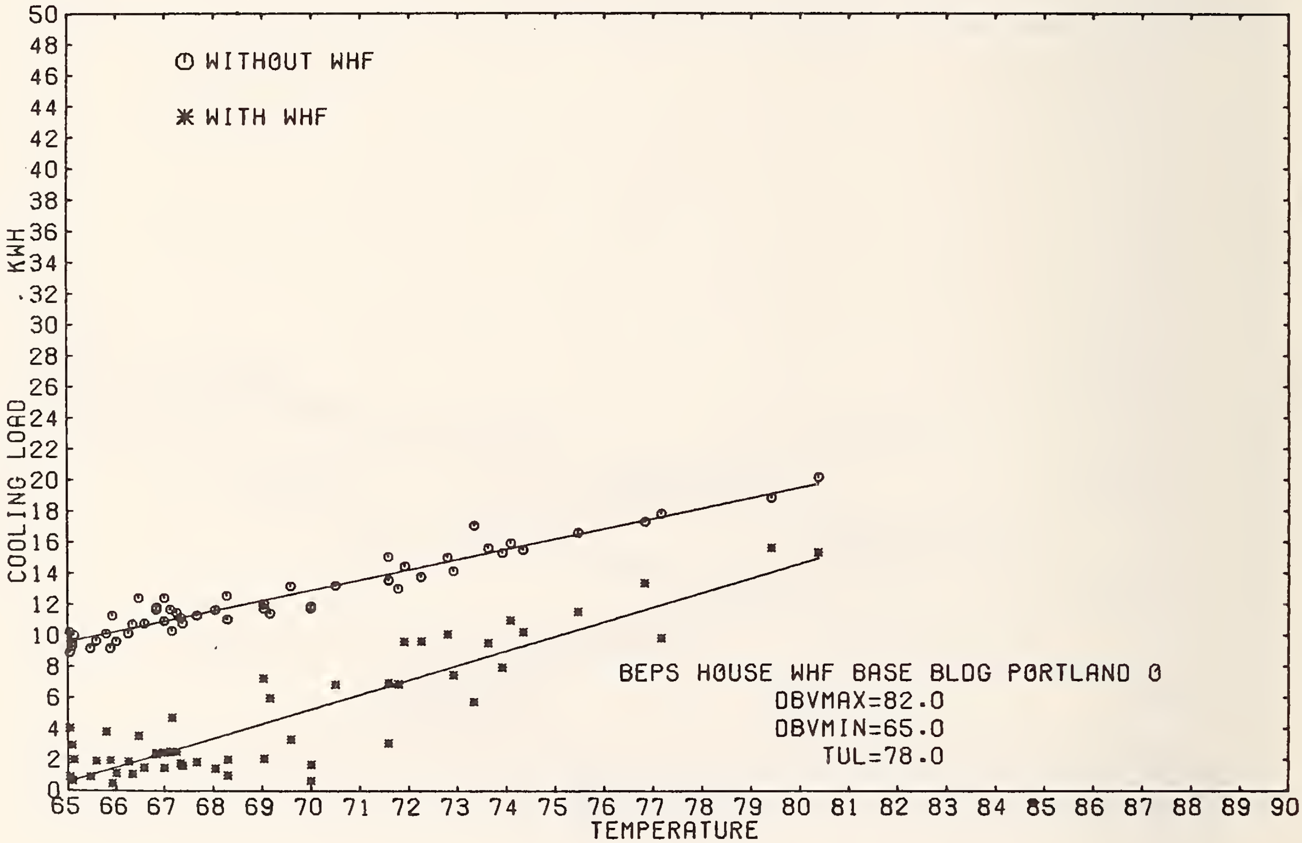

Figure 11. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Portland, OR with and without the use of whole-house fan (WHF).

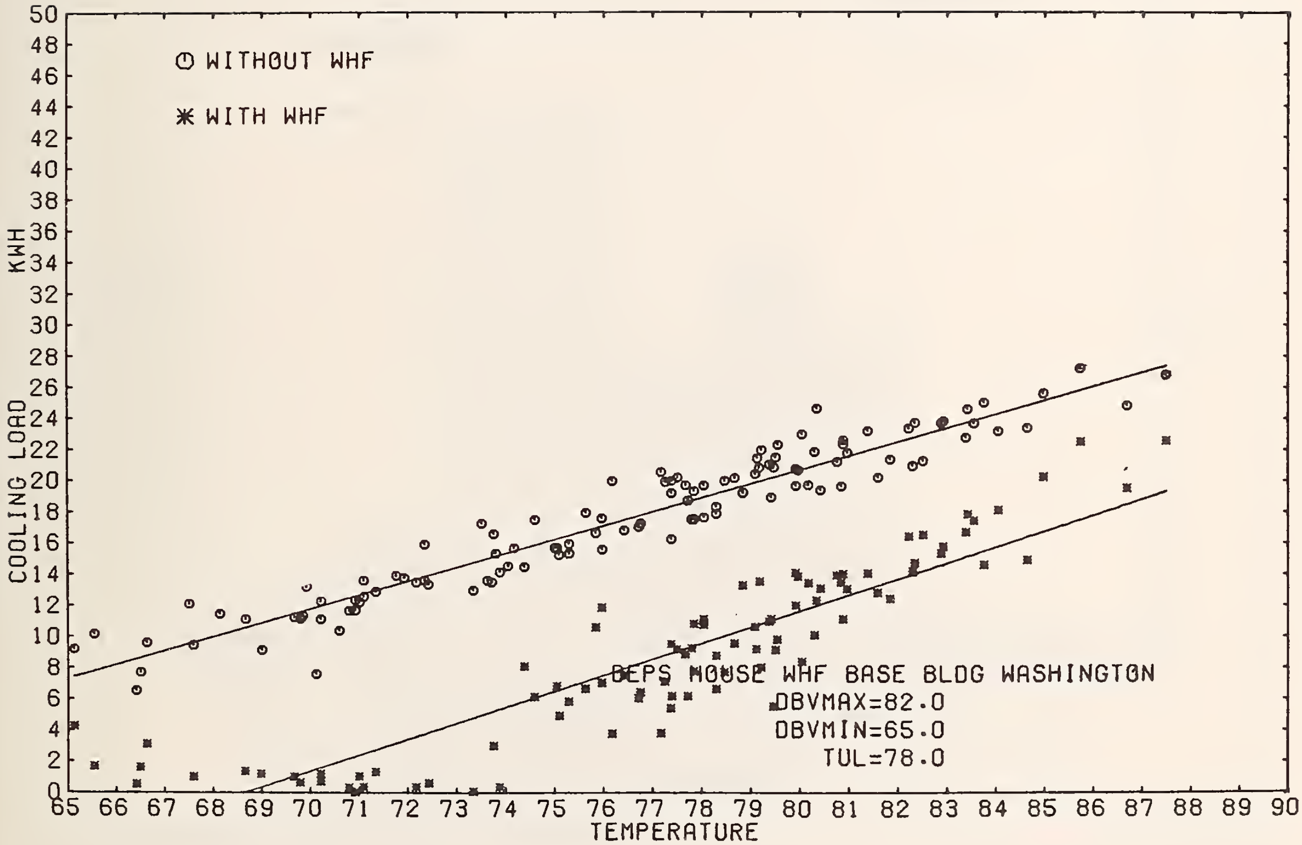

Figure 12. Predicted daily total cooling energy consumption vs. daily average outdoor temperature for a typical ranch house in Washington, DC with and without the use of whole-house fan (WHF).

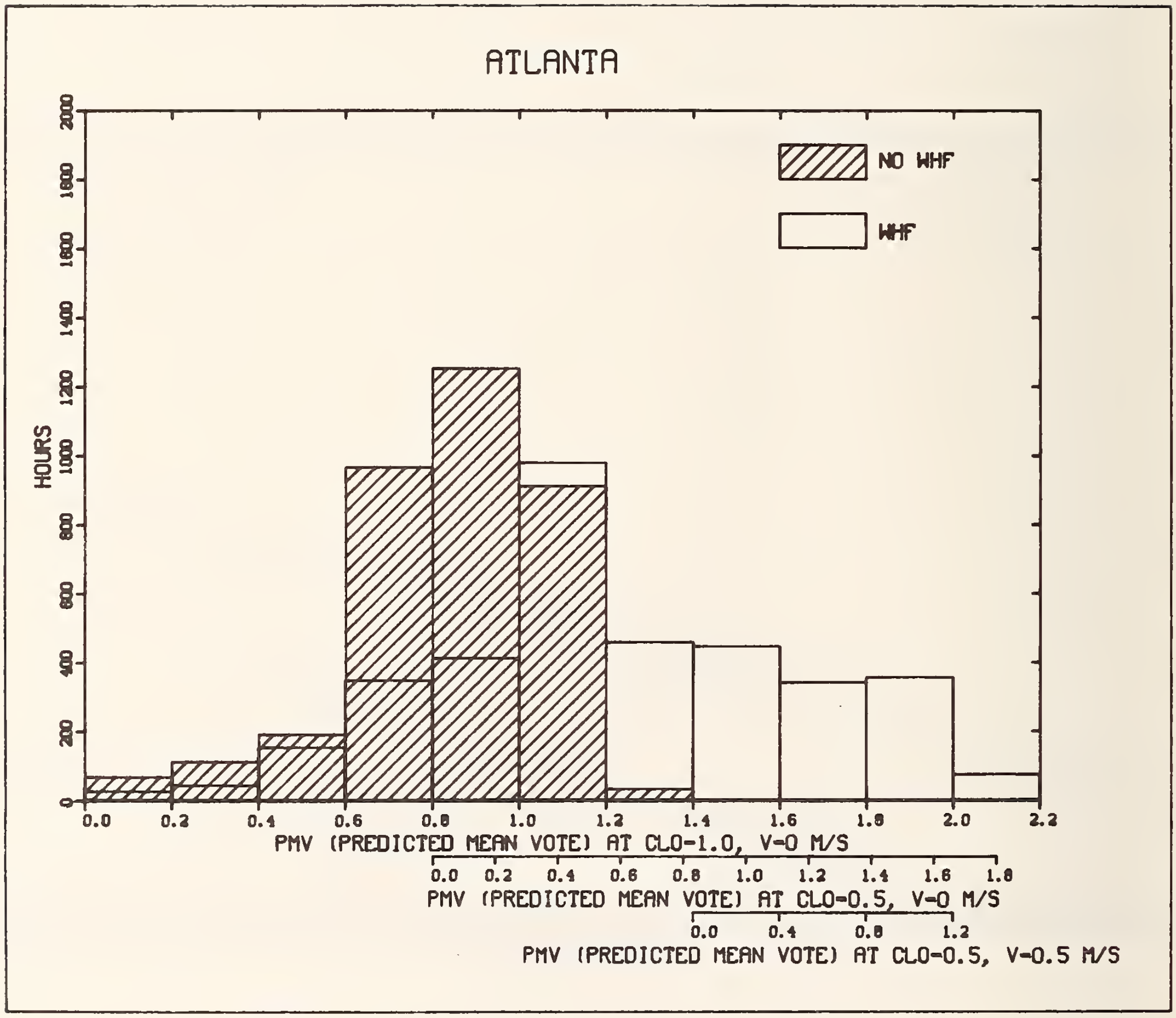

Figure 13. Predicted hourly frequency of comfort index in a typical ranch house in Atlanta, GA with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

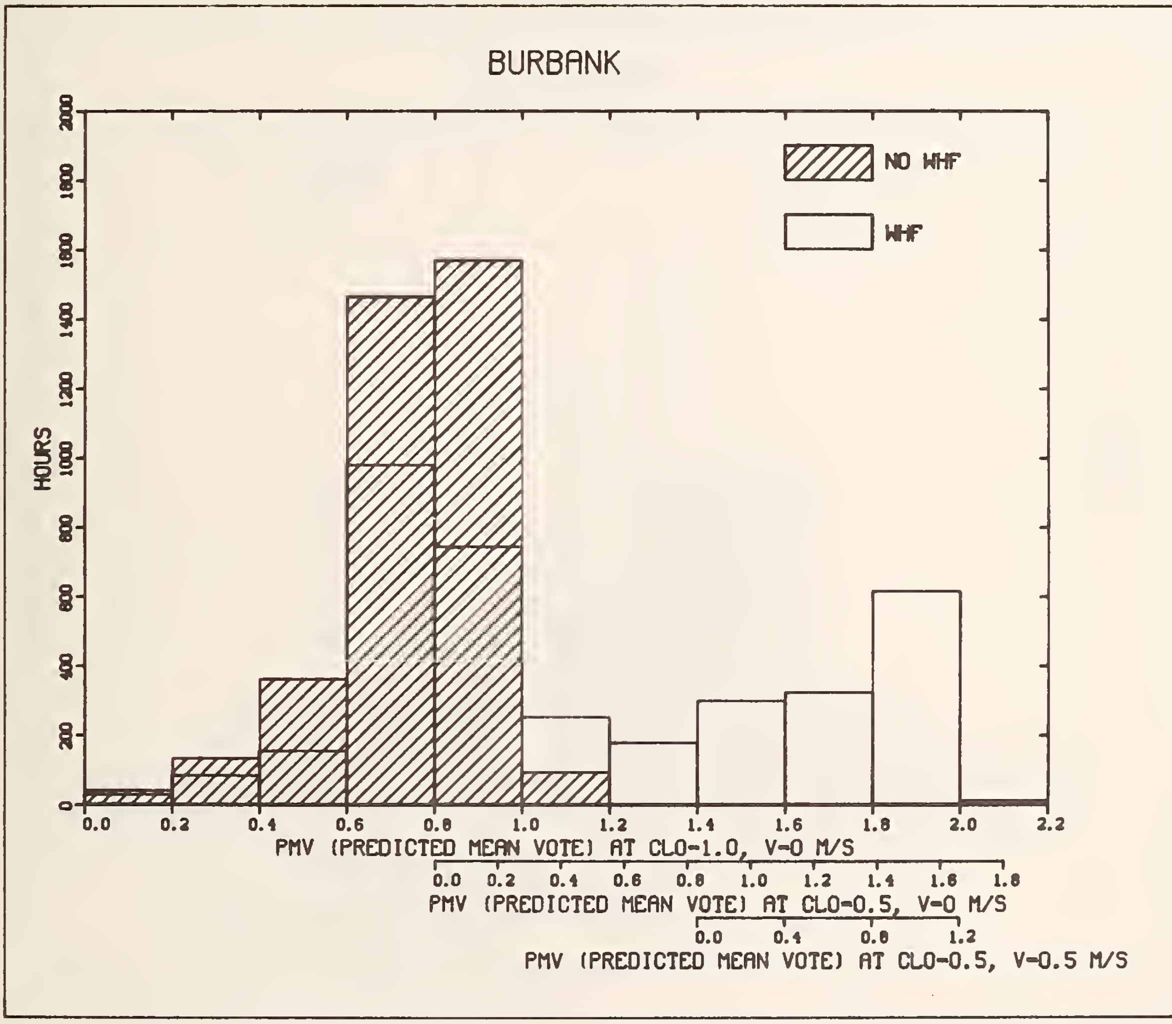

Figure 14. Predicted hourly frequency of comfort index in a typical ranch house in Burbank, CA with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

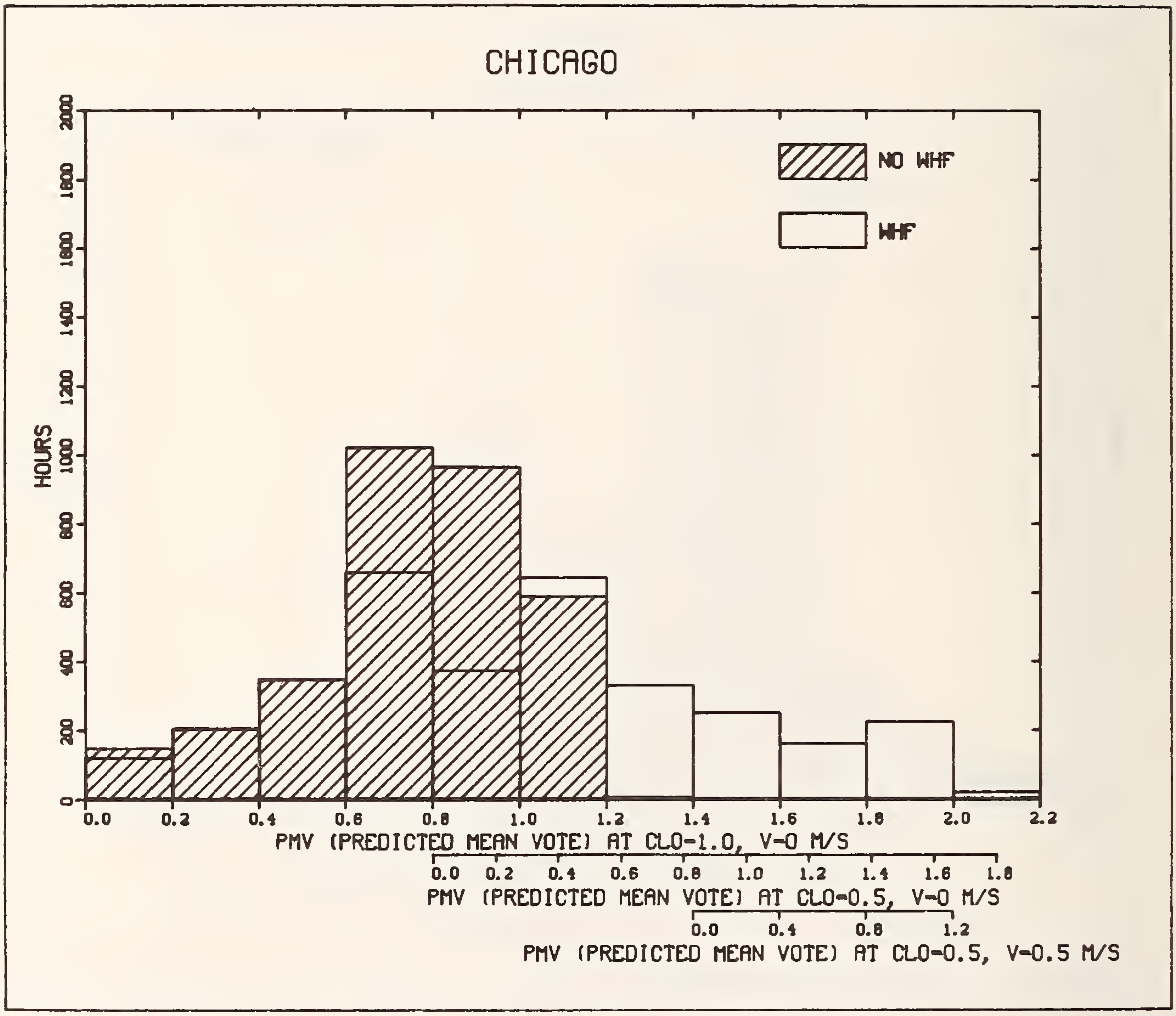

Figure 15. Predicted hourly frequency of comfort index in a typical ranch house in Chicago, IL with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

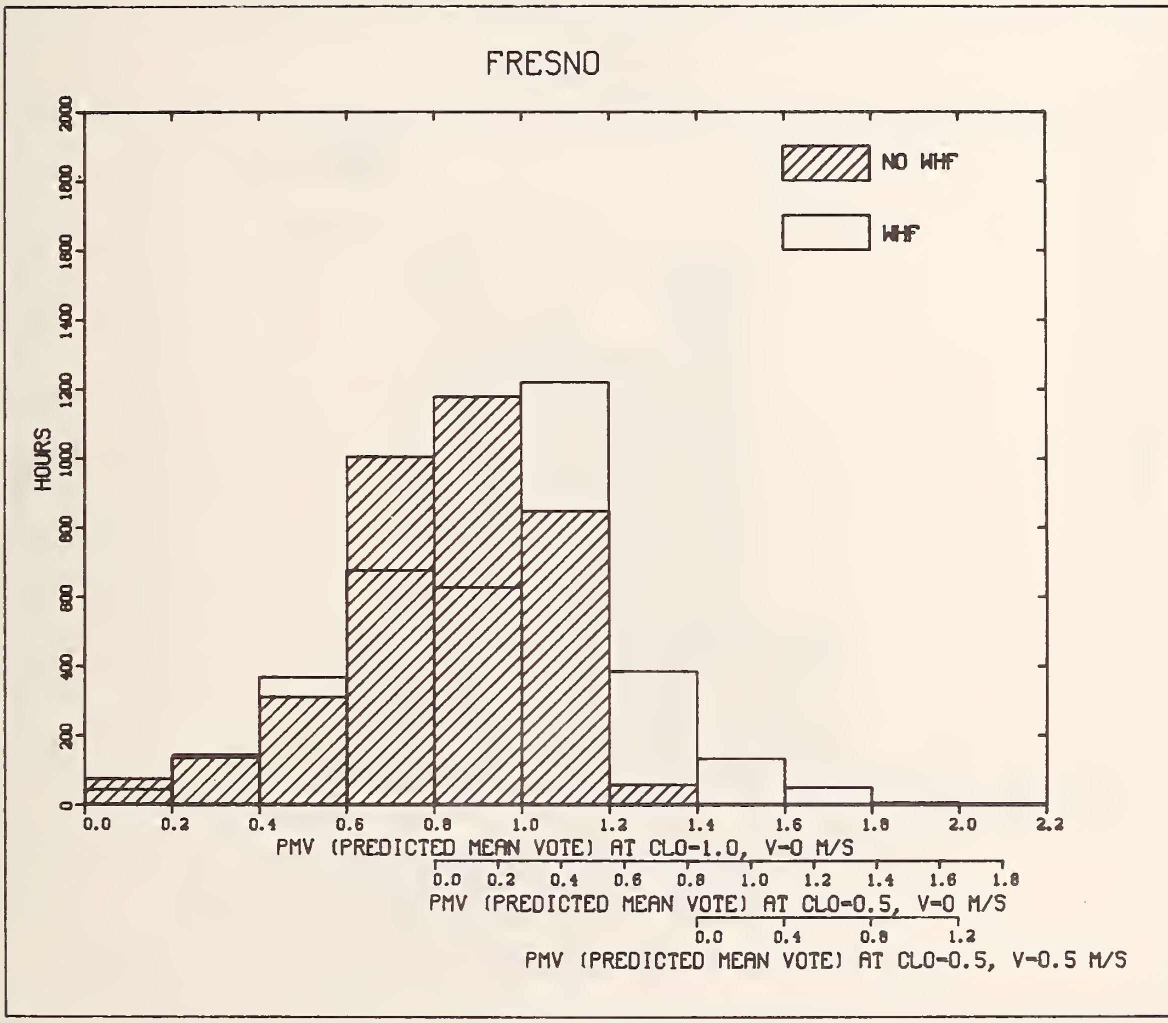

Figure 16. Predicted hourly frequency of comfort index in a typical ranch house in Fresno, CA with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

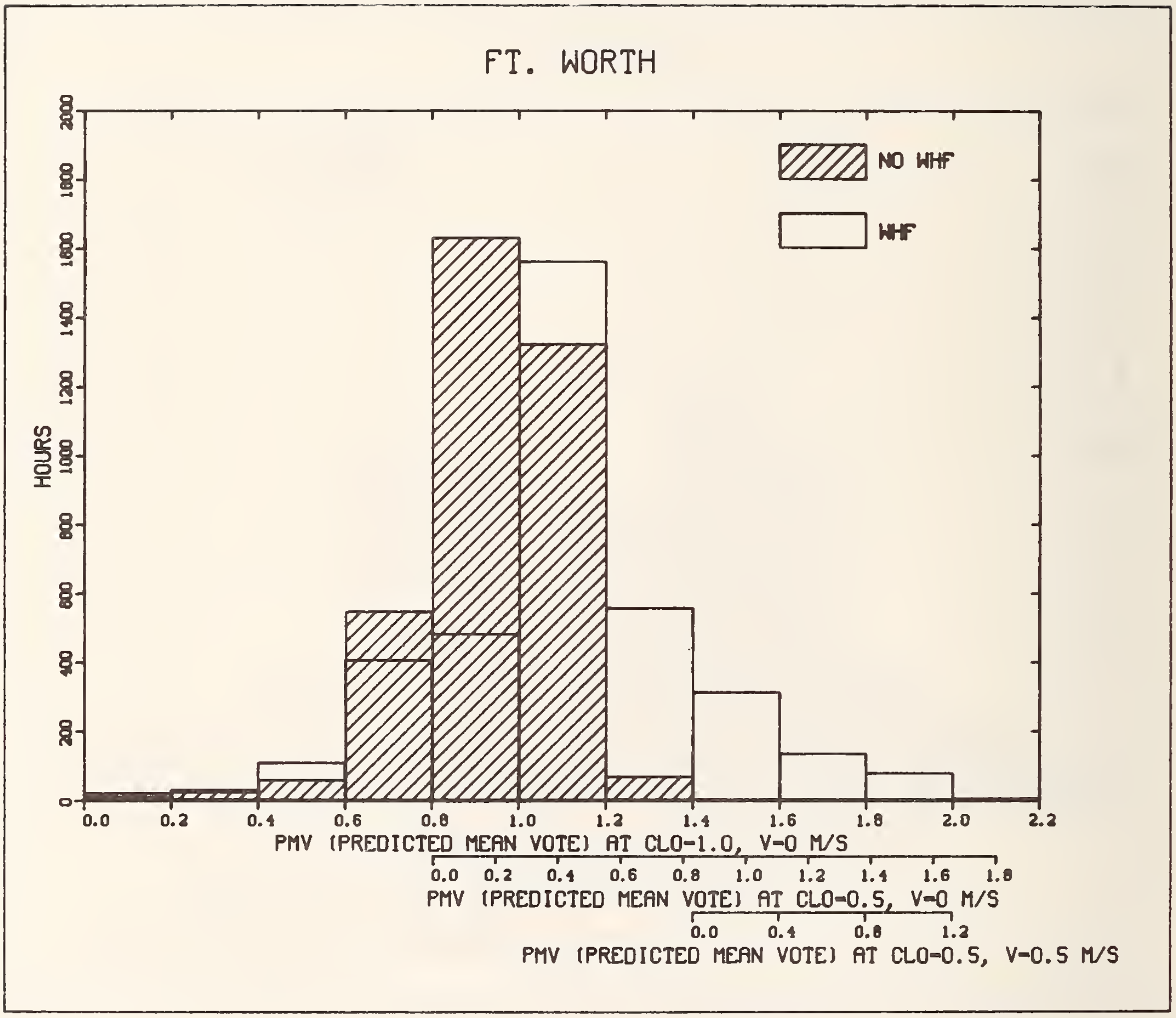

Figure 17. Predicted hourly frequency of comfort index in a typical ranch house in Ft. Worth, TX with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

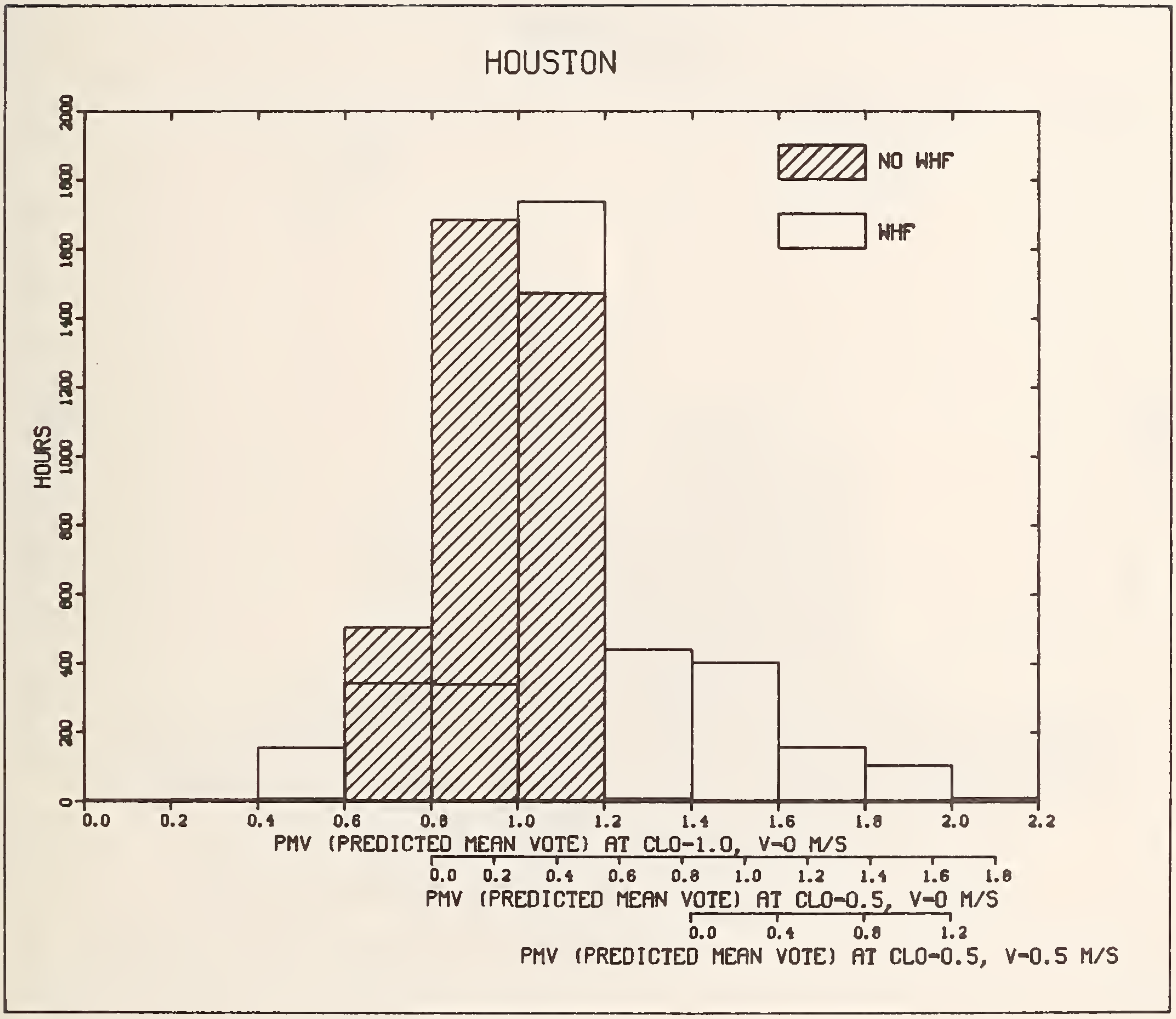

Figure 18. Predicted hourly frequency of comfort index in a typical ranch house in Houston, TX with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

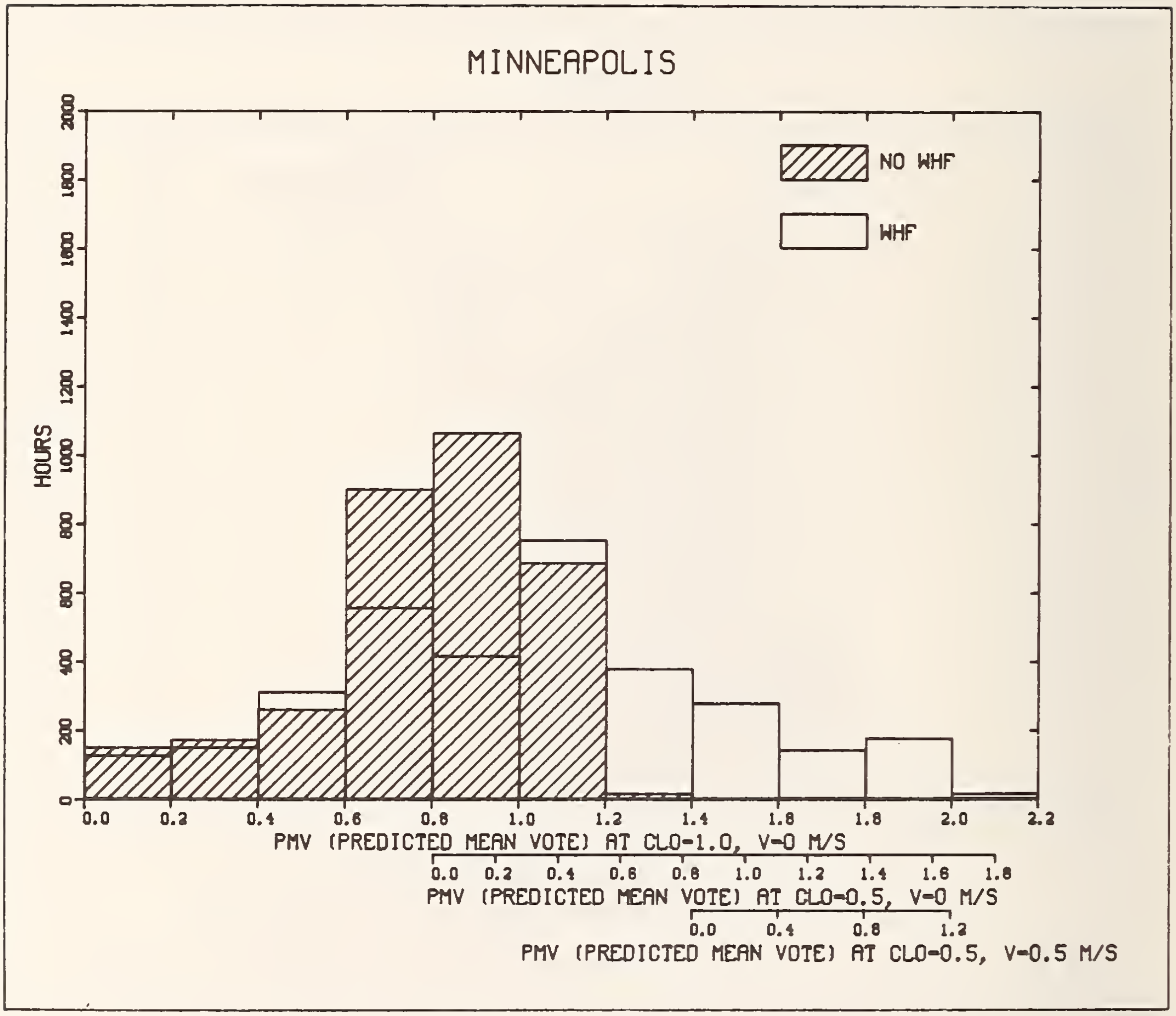

Figure 19. Predicted hourly frequency of comfort index in a typical ranch house in Minneapolis, MN with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

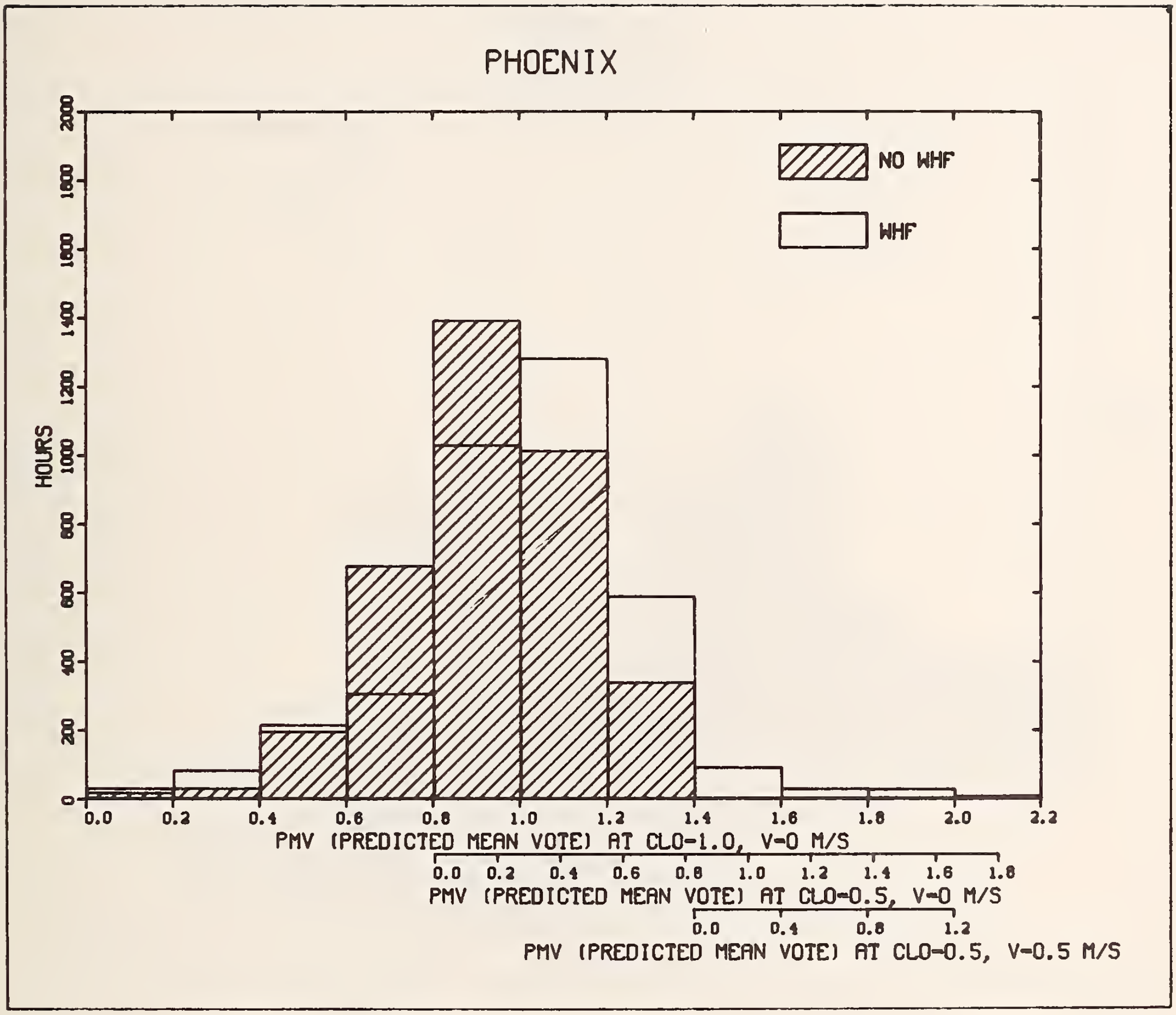

Figure 20. Predicted hourly frequency of comfort index in a typical ranch house in Phoenix, AZ with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

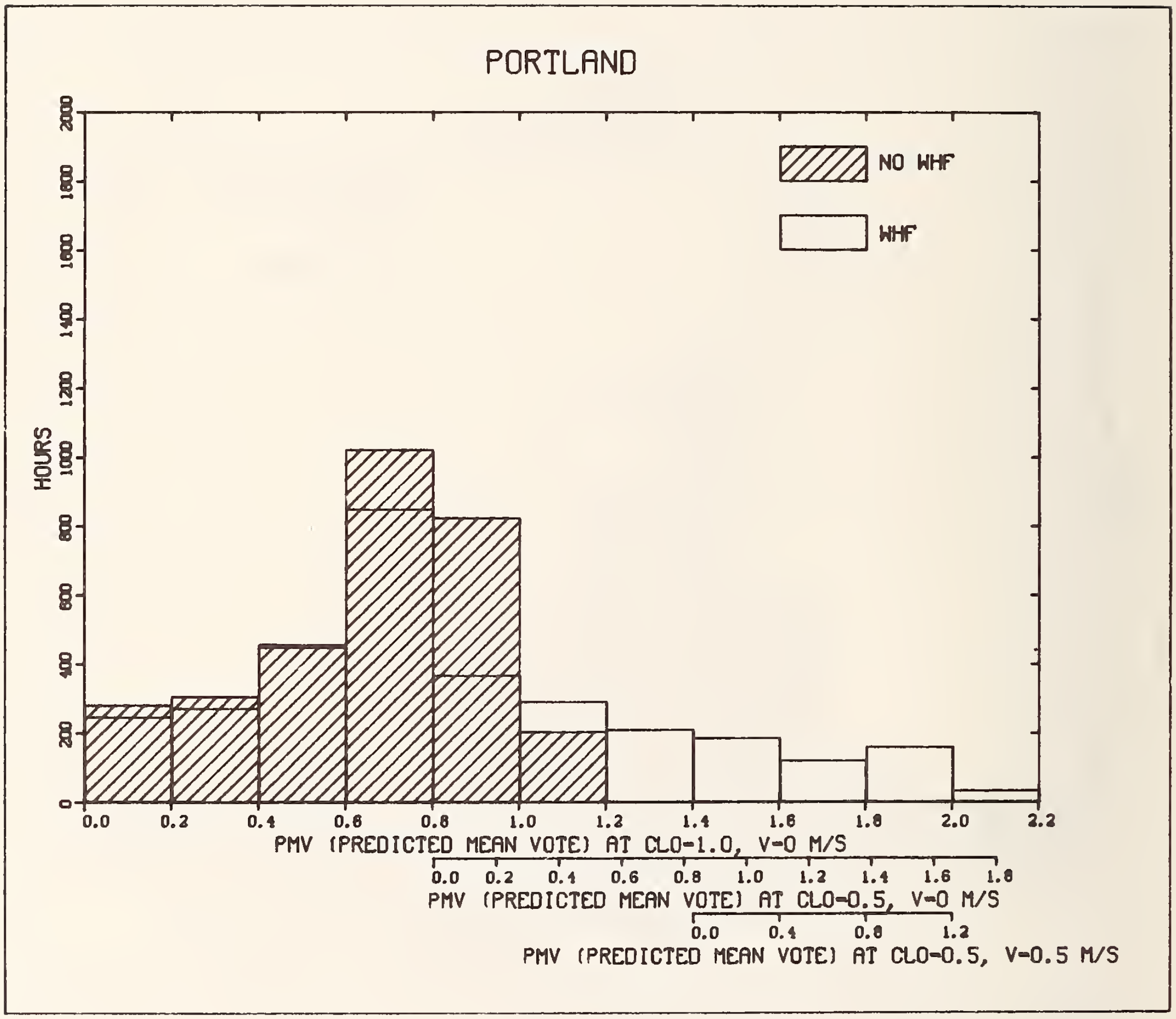

Figure 21. Predicted hourly frequency of comfort index in a typical ranch house in Portland, OR with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

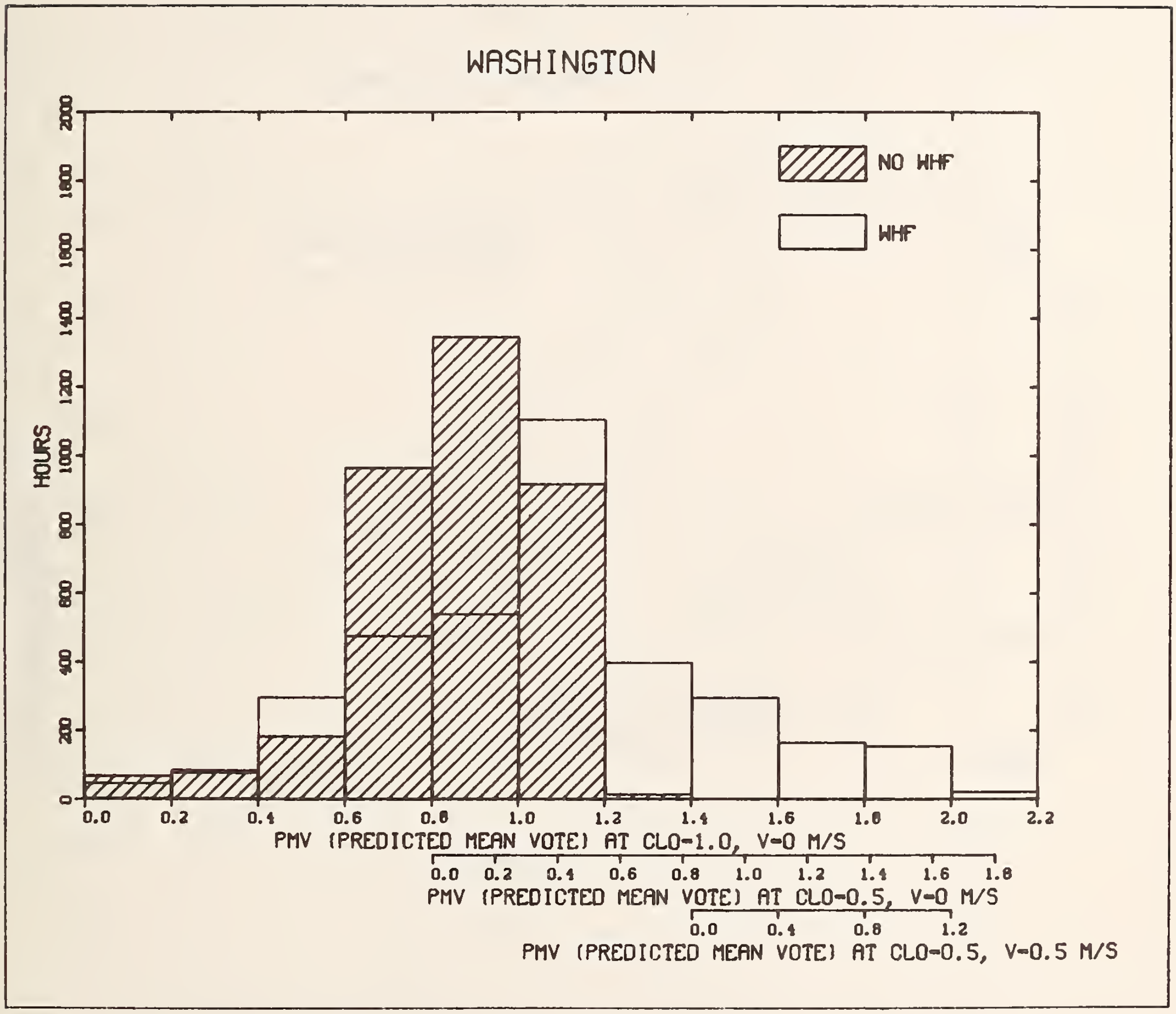

Figure 22. Predicted hourly frequency of comfort index in a typical ranch house in Washington, DC with and without the use of whole-house fan (WHF).

PMV=Fanger's Predicted Mean Vote
PMV=0 comfortable; PMV=1 slightly warm; PMV=2 warm.

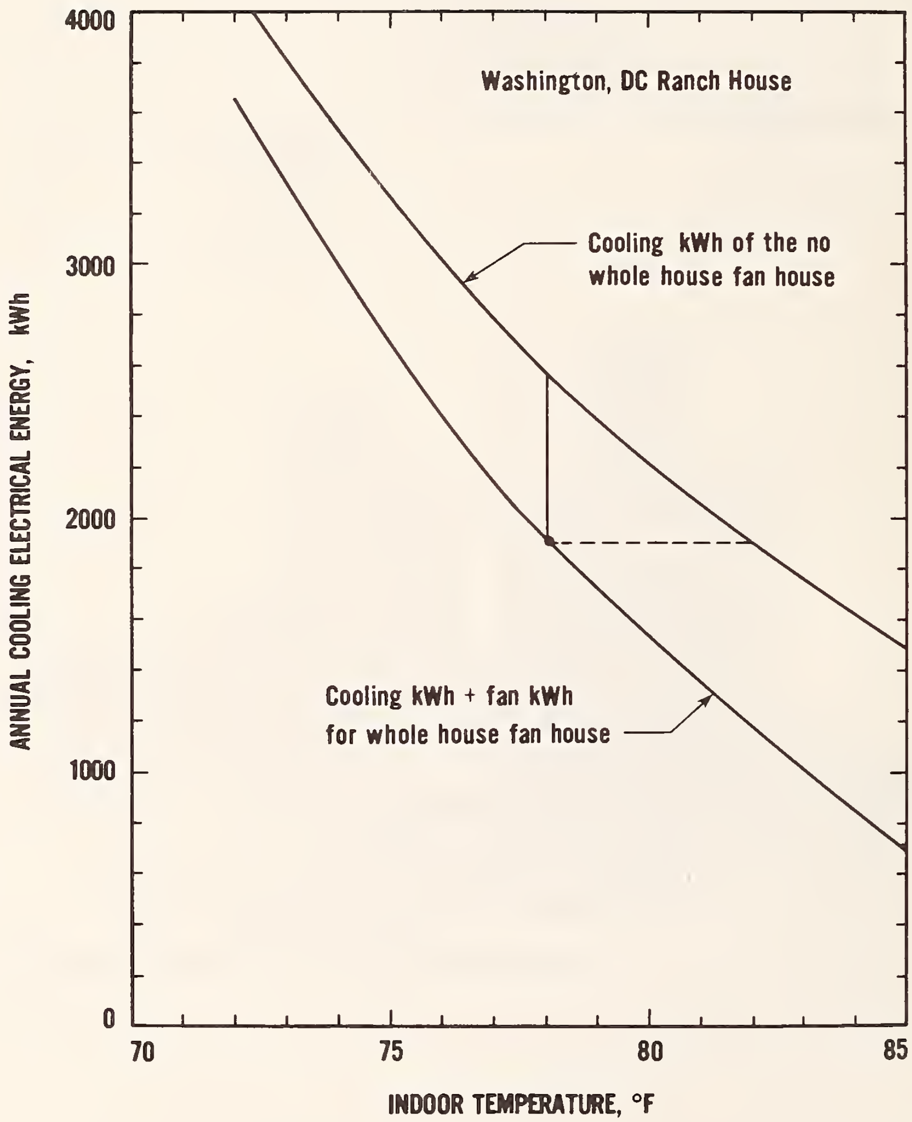

Figure 23. Annual cooling kWh vs indoor thermostat settings in a Washington D.C. ranch house.

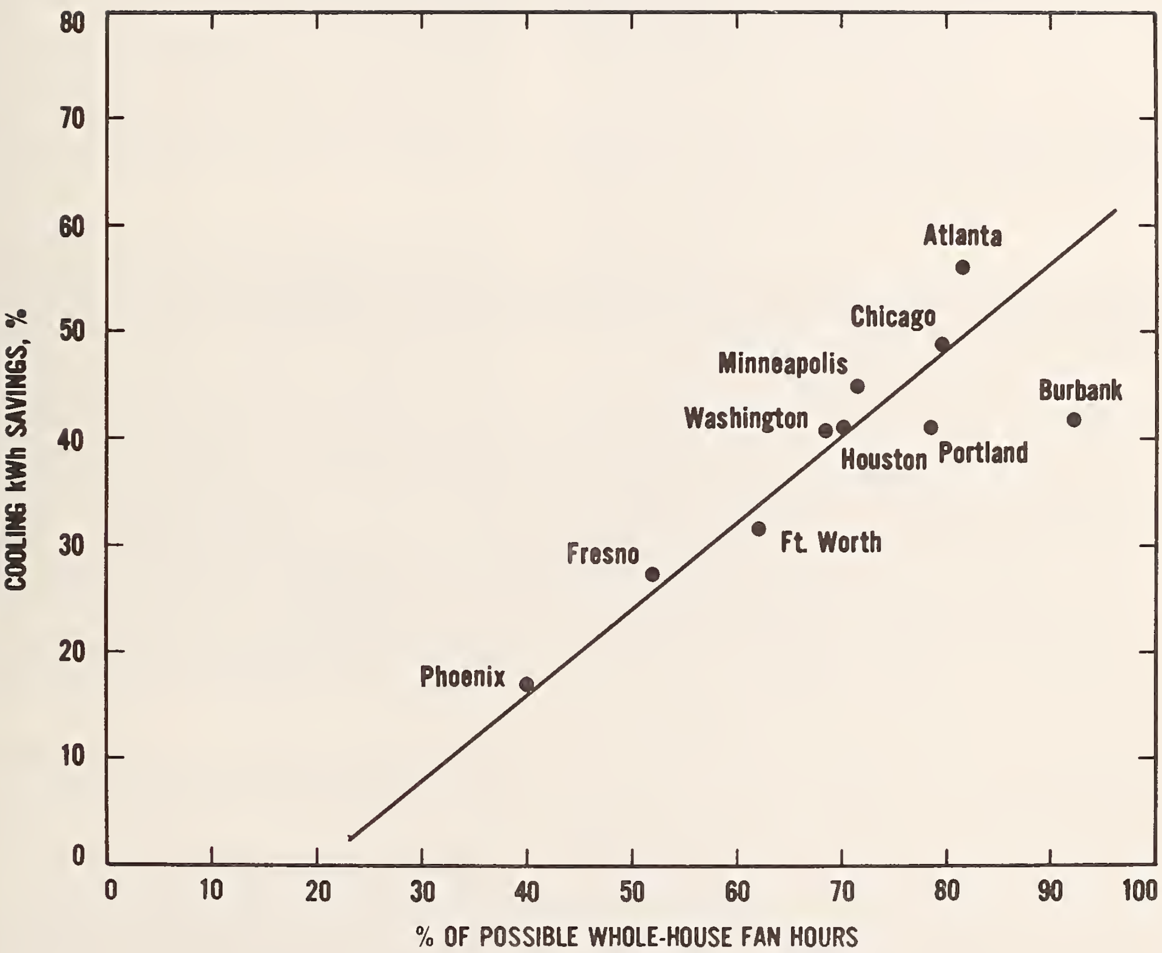

Figure 24. Cooling kWh savings vs percent of possible whole-house fan hours.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Hour-by-hour cooling performances of a typical ranch house, with and without the use of a whole-house fan, were compared for the climate conditions throughout the contiguous United States. The comparative analyses were made by the use of NBSWHF, a modified version of NBSLD, to simulate the complex thermal coupling of whole-house-fan ventilated attic space. The calculations were performed for two operational modes: a cyclic fan mode and a stepwise continuous mode. The calculation predicted a large cooling energy savings as compared to the house without the use of the whole-house fan, without significant deterioration of indoor thermal comfort.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

building thermal performance; energy calculation; energy conservation; thermal comfort; whole-house ventilation

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