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Extending the Summer Comfort Envelope with Ceiling Fans in Hot, Arid Climates

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ABSTRACT

The purpose of this study was to determine if the summer comfort zone, as given in ASHRAE Standard 55-1981, Thermal Environmental Conditions for Human Occupancy, could be expanded to include conditions obtained in hot, dry climates with a combination of evaporative cooling and the air motion obtained with ceiling fans. The evaporative cooler can provide acceptable cooling for portions of the year in hot, dry climates but is not satisfactory for periods of higher wet-bulb conditions. The ceiling fan might extend the period of time that an evaporative cooler could be used.

A study conducted by Rohles, Konz, and Jones (1983) showed that ceiling fans could effectively extend the comfort range to as high as 85°F(29.4°C) and 50% RH. However, the Kansas State University study only investigated conditions at 50% RH, and it did not test conditions higher than 85°F.

This study was conducted on 96 human subjects in the spring of 1986 and attempted to determine the upper limits of the comfort envelope (not just along the 50% RH line) with the higher velocities attained with ceiling fans.

The study shows that velocities between 90 fpm (.46 m/s) and 200 fpm (1.02 m/s) that are provided by a ceiling fan can extend the time that a direct evaporative cooler can be used for thermal comfort in Phoenix. This amounts to extending the comfort period for 995 hours, or 34% of the time in which some form of cooling is required. With the indirect evaporative cooler, it is theoretically possible to provide cooling for the entire season by using the highest air velocities. However, these higher air velocities will not be acceptable to all people.

This study also suggests that the upper comfort limit proposed by Rohles et al. (1983) may be extended for humidities lower than 50% RH, but reduced for higher humidities.

INTRODUCTION

Of the major cities in the hot, arid southwestern region of the United States, Phoenix has the most severe summer dry-bulb temperature conditions (see Table 1). It can be assumed that, if the cooling strategy provides comfort in Phoenix, it will certainly provide comfort in Tucson, AZ; El Paso, TX; Las Vegas, NV; Fresno, CA; and Albuquerque, NM. A common method used in this region for summer cooling is the evaporative cooler. However, evaporative cooling alone has not been sufficient in Phoenix to provide acceptable conditions during periods of high wet-bulb temperatures. How much can the usefulness of an evaporative cooler be extended with the increased air velocities available from a ceiling fan?

A study of ASHRAE Standard 55-1981, Thermal Environmental Conditions for Human Comfort (Figure 2, p. 5), summer comfort region shows that 66°F (19°C) is the maximum outdoor air wet-bulb temperature that will provide acceptable indoor conditions with an evaporative cooler and "still air" conditions. This is arrived at by observing which is the highest wet-bulb temperature that passes through the comfort region. Average Phoenix climatic bin data from Engineering Weather Data (1978) show that 37%

Table 1
COMPARISON OF COOLING SEASONS FOR CITIES IN THE HOT ARID SOUTHWEST (IN HOURS)
From Data Provided in Engineering Weather Data (1978)

City	Cooler Than Comfort Range	Hours Within Comfort Range	Hours That Cooling Req'd
Albuquerque, NM	2015	1281	1120
El Paso, TX	1115	1484	1817
Fresno, CA	1958	1167	1291
Las Vegas, NV	1046	941	2429
Phoenix, AZ	693	876	2847
Tucson, AZ	859	1146	2411

Cooling season considered: May through October = 4416 Hours

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Table 2
PHOENIX COOLING REQUIREMENTS
Cooling Months — May through October = 4416 Hours
From Data Provided in Engineering Weather Data (1978)
and ASHRAE Handbook (1985)*

Climate Ranges	Total Hours	Percent of Cooling Season	Percent of the Time in which Cooling is Required
A. Cooler Than Comfort	693	16	–
B. Within Comfort Range	876	20	–
C. Some form of Cooling Required (above 80°F or a Wet-Bulb of 66°F)	2890	64	100
D. Evaporatively Cooled Air Effective for Comfort[1] (no increased air motion)	1238	28	43
E. Direct Evaporative Cooling extended due to increase in air motion from cooler[2]	332	8	12
F. Extend Comfort w/a Direct Evap. Cooler and High Velocity from Ceiling Fan[3]	995	23	34
G. Minimum Cooling by Refrigeration Required[4]	325	7	11
H. Hours at 76°F WB[5]	120*		
I. Hours above 76°F WB[6]	30*		

[1]66°F(19°C) WB and below when the dry-bulb is above 80°F(27°C).
[2]67°F(19°C) ≤ WB ≤ 71°F(22°C). In this range of outside air wet-bulb temperatures, the air can be evaporatively cooled to conditions that will be comfortable if air motion is also provided. The increase in air motion produced by the evaporative cooler will increase the amount of time shown in Condition D above. This study's results show that the increased air motion (0 to 200 fpm or 0 to 1.02 m/s) can provide comfort up to and including 71°F(22°C) WB. This increase in outdoor air wet-bulb temperature that can be used to produce indoor comfort represents a total increase of 46% of the time that cooling is required in which evaporatively cooled air is effective. But, some credit must be given to the air motion provided by the evaporative cooler. At design conditions, an evaporative cooler will typically change the air every two minutes. If the occupants are located near the exhaust, the air velocity over their body can measure 100 fpm (.51 m/s). It would not be unreasonable to assume that the average room air speed with an evaporative cooler running at design conditions to be 50 fpm (.25 m/s). So, of the 46% increase in time that the evaporative cooler can provide comfort because of increased air motion, 25% (50 fpm of the maximum 200 fpm or .26 m/s of the 1.02 m/s) of the extended comfort period should be credited to the air motion produced by the cooler. If no ceiling fan is used, the evaporative cooler should provide comfort for an additional 332 hours because of the air motion it provides. This is not to say that the cooler's air motion will provide comfort up to a 71°F WB.
[3]67°F(19°C) ≤ WB ≤ 71°F(22°C). The increase in air motion produced by the ceiling fan will increase the amount of time shown in Condition E above. Occupant must be in air motion from between 50 to 200 fpm (.25 to 1.02 m/s).
[4]This only includes periods when wet-bulb temperatures are above 71°F(22°C). It assumes direct evaporative cooling is used to 71°F(22°C) WB and air velocities of between 90 and 200 fpm (.46 to 1.02 m/s). This time will increase if higher air speeds are not available or are not desired.
[5]Hours above 75°F WB (5% ASHRAE wet-bulb, Handbook, 1985, Ch. 24) = 150 hours. Hours above 76°F WB (1% ASHRAE wet-bulb) = 30. Therefore, hours at 76°F WB = 150 − 30 = 120.
[6]From ASHRAE Handbook, 1981, Ch. 24, Table 1. See note 5 above.

of the summer cooling season has wet-bulb temperatures higher than 66°F (19°C) (see Table 2). Possibly, outdoor air wet-bulb temperatures higher than 66°F can be used with the evaporative cooler to provide comfort if higher air motions are obtained from a ceiling fan.

Just what is the limit of the comfort region using a ceiling fan? Rohles et al. (1983) proposed a limit of 85°F (29.4°C) holding a constant 50% RH but did not investigate conditions higher than 85°F (29.4°C). This study explores other humidities, both higher and lower than 50%, that may be obtained in Phoenix with an evaporative cooling device.

If the period of time during which evaporative cooling can be used is extended, cooling operating costs can be reduced. A major evaporative cooler manufacturer claims that cooling energy costs can be reduced as much as 80% with the use of evaporative cooling.[1]

[1]Phoenix radio commercial claims, mornings of May 23 and June 13, 1988.

To determine the expanded comfort region at the more extreme dry- and wet-bulb temperatures, 96 human subjects were exposed to various conditions at varying velocities. This study's tests were modeled on the tests done for the Rohles et al. (1983) study.

ASHRAE Standard 55-1981 (Figure 2, p. 5) specifies two comfort zones — one for summer and one for winter. The summer comfort zone is based on sedentary or slightly active persons wearing 0.5 clo and an average air velocity of 50 fpm (.25 m/s) or less. At 50% RH, the high end of the comfort range is 79°F DB (26°C) (see Figure 1).

The ASHRAE Standard (Figure 1, p. 3) indicates that for clo values as low as 0.05, the upper end of the summer comfort range is 84°F (29°C). A value of 0.05 clo is obtained from men's underwear or briefs or swimming trunks. The ASHRAE Standard (p. 4) also suggests that the summer comfort zone can be increased to higher dry-bulb temperatures by increasing air movement. The same comfort level could be maintained if, for each increase in air

TABLE 3
Clo* Units for Individual Items of Clothing

Men		Women	
Clothing	Clo (I_{cl})	Clothing	Clo (I_{cl})
Underwear, briefs	0.05	Bra and panties	0.06
Light shirt, short-sleeved	0.14	Blouse, light	0.20
Light slacks	0.26	Light skirt	0.18
Soft-soled athletic shoes	0.04	Soft-soled athletic shoes	0.04
Ankle-length socks	0.03	Ankle-length socks	0.03
ΣI_{cl} =	0.52	ΣI_{cl} =	0.51
$\Sigma I_{clo} = 0.82\ \Sigma I_{cl} = 0.43$		$\Sigma I_{clo} = 0.82\ \Sigma I_{cl} = 0.42$	

*Individual Clo values (I_{cl}) from Ch. 8 of ASHRAE Handbook, 1985, and McCullough, Jones, and Huck (1985).

speed of 30 fpm (.15 m/s), there was a 1°F (.56°C) increase in the dry-bulb temperature. The ASHRAE Standard suggests a limit of 160 fpm (.82 m/s), reasoning that at this velocity a person is distracted by loose objects beginning to blow about. So, an air velocity of 160 fpm (.82 m/s) would allow an increase of approximately 5°F (2.8°C) above the established comfort limit and still maintain the same thermal comfort sensation. Thus, at 0.5 clo that range can be extended to 84°F (29°C).

As the clo value is reduced, the comfort range is increased. The ASHRAE Standard (Sec. 5.2, p. 7) indicates that, for the same thermal sensation, the air temperature can be increased 1°F (.56°C) for each 0.1 clo of decreased clothing. Thus, the upper temperature level for comfort at 160 fpm (.82 m/s) and 0.05 clo would appear to increase to 88.5°F (30°C).

METHODS

General

The methods used in this study were modeled after the Rohles et al. (1983) study. The present study is a natural extension of the knowledge gained in the earlier study that

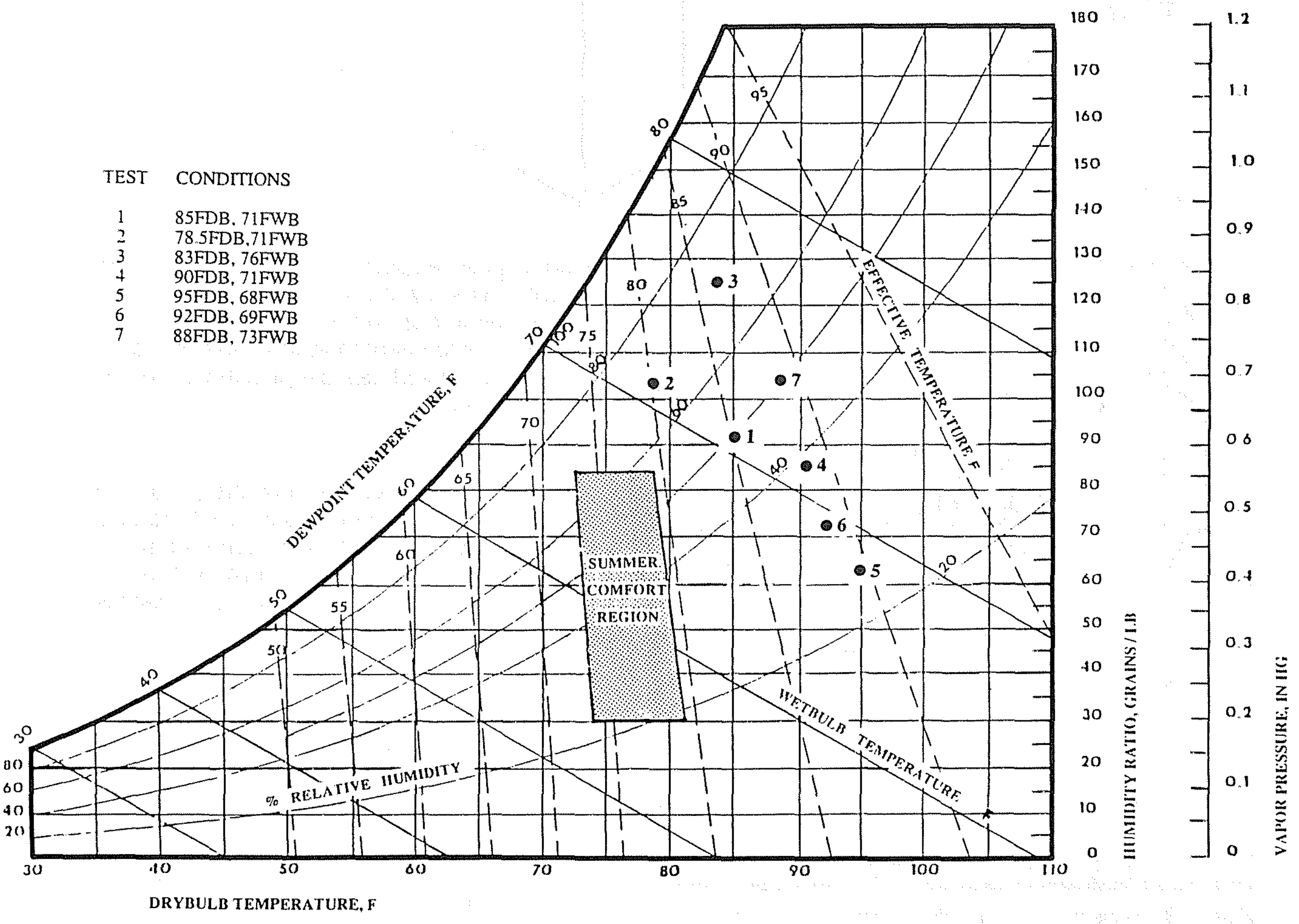

Figure 1 *Pshchrometric conditions of test*

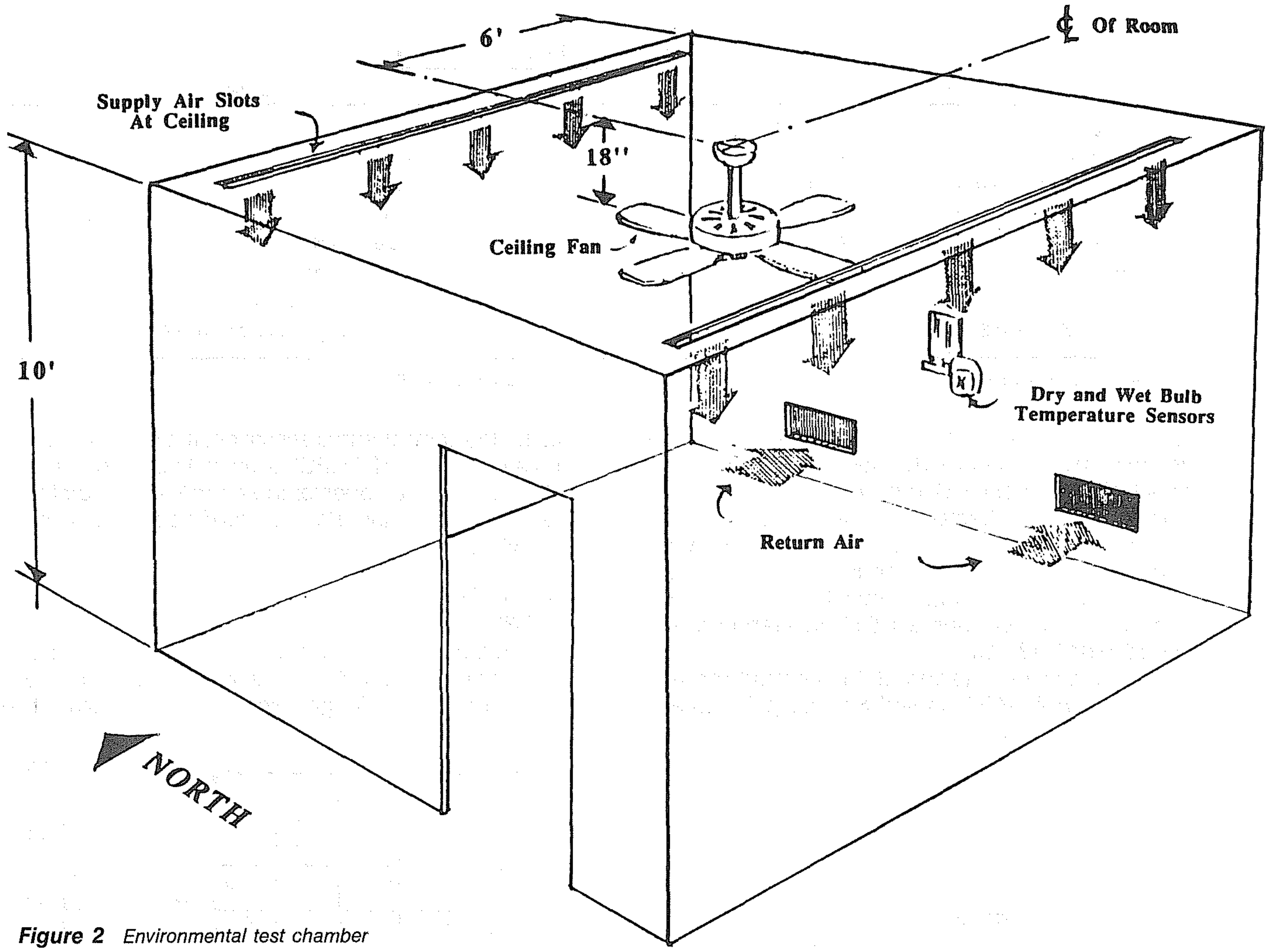

Figure 2 Environmental test chamber

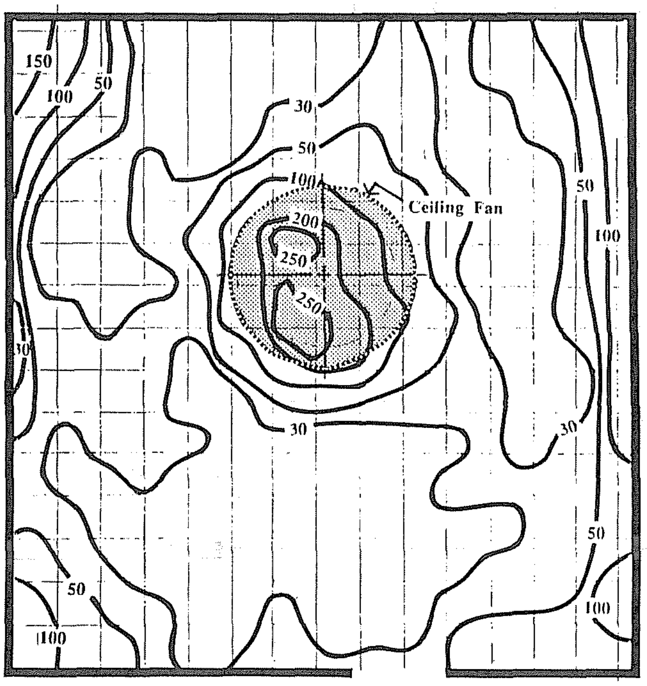

Figure 3 Isopleths at 43 in height indicating velocities in feet per minute

is specifically applicable to the hot, arid southwestern United States. By using the same methods and measuring the same dependent variables, we hope to use a common benchmark to validate the process. Thus, the first test conducted was to repeat the upper limit found in the earlier study.

Objectives

The objectives of this study are (1) to determine the upper boundary of conditions (dry-bulb and wet-bulb temperatures) that will produce human comfort with the air motion available from a ceiling fan and (2) to determine the amount of time an evaporative cooler's usefulness can be extended when used in combination with a ceiling fan.

Subjects

The test subjects were 96 college students varying in age from 18 to 25 years. Each had lived within the continental United States for at least six months prior to the test, and each was paid $12 for participating. No one served as a subject more than once during the study. Test subjects were essentially equally divided between male and female.

The subjects were instructed on the appropriate dress (as listed in Table 3). It was suggested that they bring study materials to make effective use of their time.

Facilities

The tests were conducted in a university's environmental test room (see Figure 2). This facility is able to control temperature, humidity, and air flow rate. The room is 15 ft 2 in by 14 ft 3½ in with a 10-ft-high ceiling (4.6m by 4.3m by 3.05m high).

Area lighting was provided with 240 watts of fluorescent valance lighting along two opposite walls. Figure 2 shows the general relationship of the air supply to the ceiling fan. Air was supplied through slot diffusers and distributed downward along two parallel walls. The ceiling fan was mounted 6 ft (1.8 m) from the east wall. The blades of the fan were 18 in (46 cm) below the ceiling.

Air Velocity Determinations

Initial room isopleths at 43 in (1.09 m) height are shown in Figure 3. This information was used to first establish the general table locations. The final arrangement was based on measurements at proposed chair locations and is shown in Figure 4. Measurements for the final locations were taken with the tables in place, but not the chairs.

Seating arrangements provided for two locations at each of four different velocities whose nominal values were 30, 50, 90, and 200 fpm (0.15, 0.25, 0.46, and 1.02 m/s). These velocities were selected to match those used in the Rohles et al. (1983) study. Nominally, each velocity is doubled. A velocity between 90 and 200 fpm (.46 and 1.02 m/s) was not selected because of the steep velocity gradients found between 100 and 200 fpm (.5 and 1.02 m/s). This made it difficult to locate areas large enough for test subjects that could reliably be identified as an intermediate velocity.

Air velocities were measured at 43 in (1.1 m) above the floor. Comments in the discussion of the 1983 study expressed concern for not having used an average velocity from three height locations at 4 in, 24 in, and 43 in (0.1, 0.6, and 1.1 m) above the floor. Although it was agreed that velocities at locations other than 43 in (1.1 m) are important, air movement over the upper part of the body has the greatest effect on thermal comfort. A simple mean of the three velocities would not seem appropriate. For the lack of a more reliable method of determining an appropriate average air velocity, the single 43 in (1.1 m) high velocity was used.

Air velocity measurements were taken using a portable anemometer with sensitivity and readability down to ± 6 fpm (0.03 m/s). It incorporates a solid-state sensing element in the probe and has accuracy of ± 2% for each full-scale range. The 0 to 2V output was fed to a data logger. The probe orientation was adjusted to give the highest average indication. The probe should be used perpendicular to the direction of air flow; however, the output is not greatly affected by angular orientation until there is a change of about ± 40° to the direction of flow.

For each measurement, the sensing device was supported on a post stand to maintain proper location and elevation. Data were collected for 80 seconds at each location and recorded on a data logger. Means and standard deviations were then determined using 10 values equally spaced in time over the 80 seconds. Table 4 presents these results. The color code shown in the table was used to facilitate the movement of test subjects to appropriate seating.

The gusty nature at many locations indicates that wide tolerances must be given to the numbers in Table 4. Air velocity standard deviations found in the Rohles study averaged 40% of the mean velocities, while this study's standard deviations averaged 33% of its mean values. This high variation from the mean is apparently the nature of the ceiling fan, which may differentiate it from other air-moving devices.

Test Conditions

Tests were conducted to determine the upper range of the comfort envelope at five different velocity conditions. The starting point was to repeat the conditions used as the upper limit in the Rohles study, namely, 85°F (29.4°C) DB and 50% RH. This was designated as Test 1. The next test (Test 2) was of 78°F (25.5°C) DB and 71°F (22°C) WB [69% RH]. This condition was chosen because 71°F (21.7°C) WB is the mean coincident wet-bulb for the 1%, 2.5%, and 5% summer ASHRAE design conditions in Phoenix (ASHRAE Handbook 1981, p. 24.3). Phoenix has the most severe cooling conditions of all the population centers in the hot, arid Southwest, and if comfort can be achieved with an evaporative cooler and a ceiling fan there, then it can be achieved at any other location in the desert Southwest.

Since Test 2 showed more than 80% of the test subjects to be comfortable at the higher air velocities (V_3 and

POSITION VELOCITIES

Seat	Velocity (fpm)
1	50
2	200
3	30
4	90
5	200
6	90
7	30
8	50

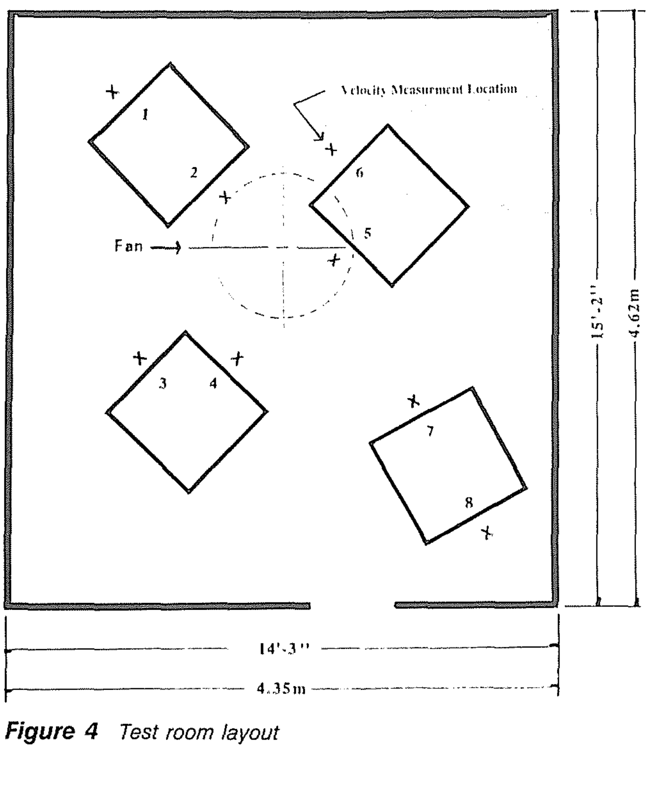

Figure 4 *Test room layout*

Experiment for Cooling Strategies in Hot, Arid Climates

STUDENT I.D. #_____ SEX___ TIME________ SEAT#_______

o Green o Yellow
o White o Brown

CEILING FAN ON: ______YES ______NO

	1	2	3	4	5	6	7	8	9	
COMFORTABLE	___	___	___	___	___	___	___	___	___	UNCOMFORTABLE
BAD TEMPERATURE	___	___	___	___	___	___	___	___	___	GOOD TEMPERATURE
PLEASANT	___	___	___	___	___	___	___	___	___	UNPLEASANT
UNACCEPTABLE	___	___	___	___	___	___	___	___	___	ACCEPTABLE
SATISFIED	___	___	___	___	___	___	___	___	___	DISSATISFIED
UNCOMFORTABLE TEMPERATURE	___	___	___	___	___	___	___	___	___	COMFORTABLE TEMPERATURE

THERMAL COMFORT

( ) VERY HOT
( ) HOT
( ) WARM
( ) SLIGHTLY WARM
( ) NEUTRAL
( ) SLIGHTLY COOL
( ) COOL
( ) COLD
( ) VERY COLD

THERMAL SENSATION

TEMPERATURE PREFERENCE

We wish to know if you would like the temperature in this room to be WARMER (and by how many degrees), or remain the same. Your decision should be indicated on the scale below. For example, if you want the temperature to remain the same, put an X in the box labeled NO CHANGE. If you want the temperature to be 3 degrees F WARMER, mark the box opposite +3; for 5 degrees WARMER, mark +5; if you want the temperature to be 5 degrees COOLER; mark -5, etc.

°F		
+10	☐	WARMER
+9	☐	
+8	☐	
+7	☐	
+6	☐	
+5	☐	
+4	☐	
+3	☐	
+2	☐	
+1	☐	
0	☐	NO CHANGE
-1	☐	COOLER
-2	☐	
-3	☐	
-4	☐	
-5	☐	
-6	☐	
-7	☐	
-8	☐	
-9	☐	
-10	☐	

Figure 5 *Ballots*

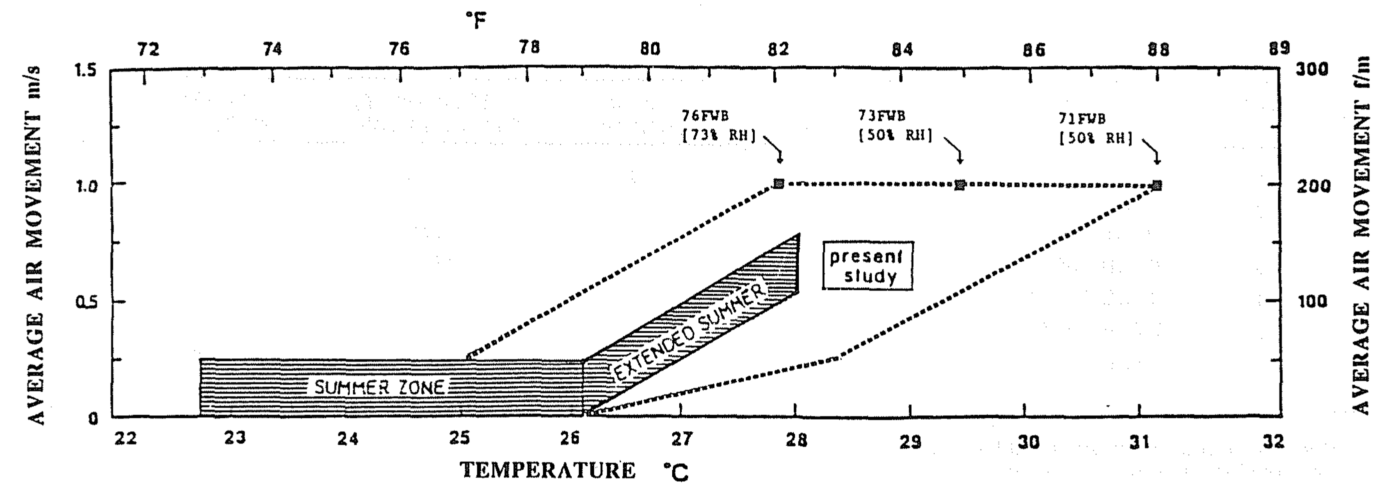

Figure 6 *Modification of the summer comfort zone based on data from the present study*

V_4), it was then decided to raise the wet-bulb to 76°F (24.4°C), the 1% design wet-bulb for Phoenix. Test 3 was conducted at 83°F (28°C) DB and 76°F (24°C) WB [73% RH] and showed to be on the edge of the comfort envelope. At the highest air velocity, V_4, exactly 80% of the subjects claimed comfort.

The next test attempted to find the highest dry-bulb temperature at which the subjects would be comfortable if the wet-bulb temperature were lowered. Test 4 used 90°F (32°C) DB and 71°F (21.7°C) WB [39% RH]. Again, this proved acceptable to just over 80% of the subjects at only the highest air velocity, V_4. This condition, it was surmised, was at or near the upper comfort limit.

During Test 5, an even higher dry-bulb temperature was tried, but a lower wet-bulb; 95°F (35°C) DB and 68°F (20°C) WB [24% RH]. This was beyond the comfort region since only 29% of the subjects were comfortable at the highest air velocity, V_4. No one was comfortable at air velocity V_3.

Test 6 dropped the dry-bulb to 92°F (33°C), while raising the wet-bulb to 69°F (20.6°C) [32% RH]. This was only acceptable to 66% of the subjects at the highest velocity.

Finally, Test 7 checked 88°F (31°C) DB and 50% RH, that is, along the same constant RH line the Rohles study used, but 3° (1.7°C) dry-bulb higher. This showed 90% of the subjects were comfortable at V_4 and only 69% comfortable at V_3. The 1983 study did not test this condition.

These seven various test conditions are plotted on the psychrometric chart of Figure 1 and are shown in Table 5.

Test Design

Each subject experienced five air velocity conditions throughout the three-hour exposure. During the first hour, the fan was not used. This represents the "still air" condition V_0 (10 fpm or 0.06 m/s). Thereafter, the subjects moved to different locations in the room each half hour. Color codes were used to facilitate their selecting seats with each of the test velocities (as shown in Table 4). This exposed them to four velocities measured at 43 in (1.1 m) above the floor: V_1 (30 fpm or 0.15 m/s), V_2 (50 fpm or 0.25 m/s), V_3 (90 fpm or 0.46 m/s), and V_4 (200 fpm or 1.02 m/s). The sequence of exposure to the various velocities was randomized for each of the subjects within the total group of eight subjects. Thus, for the first hour of exposure, the subjects were exposed to "still air." Then, for subsequent half-hour periods, they were exposed to each of the remaining four velocities.

After one half hour, the subjects voted and then moved to different work stations. At the end of the second half hour, they voted again and moved to different work stations; at

TABLE 4
Mean Velocities and Standard Deviations at Eight Work Stations

Work Station	Color Code	Velocity at 43 in (109 cm) fpm	Velocity at 43 in (109 cm) m/s	Velocity Designation
1	Yellow	45 ± 15	.23 ± .08	V_2
2	Brown	200 ± 79	1.04 ± .41	V_4
3	White	31 ± 12	.16 ± .06	V_1
4	Green	87 ± 25	.45 ± .13	V_3
5	Brown	209± 48	1.08 ± .25	V_4
6	Green	86 ± 43	.45 ± .22	V_3
7	White	27 ± 11	.13 ± .06	V_1
8	Yellow	50 ± 7	.25 ± .04	V_2

TABLE 5
Test Results

Test	Conditions	ET*[1]	%RH	No. of Subjects	At 200 fpm V_4 % Comfortable[2]	At 90 fpm V_3 % Comfortable[2]
1	85FDB, 71FWB	85	50%	8	100%	63%
2	78.5FDB, 71FWB	80	69%	16	100%	81%
3	83FDB, 76FWB	86.5	73%	8	80%	63%
4	90FDB, 71FWB	88	39%	22	83%	70%
5	95FDB, 68FWB	90	24%	7	29%	0%
6	92FDB, 69FWB	88	32%	22	66%	25%
7	88FDB, 73FWB	88	50%	14	90%	69%

[1]The ASHRAE Effective Temperature. ASHRAE Handbook 1981, Ch. 8, Figure 16.
[2]Based on Thermal Sensation votes. A comfort vote indicates that the subject voted as either neutral (5) or cooler (below 5). A vote of 3 (cool) would be counted as comfortable since it is assumed the person could be comfortable by stopping the fan.

this time the fan was turned on. Then, for the four remaining half-hour periods, they followed the same procedure (i.e., voting and moving to new work stations).

Each person was dressed as follows: Males with short-sleeved shirts, trousers, undershorts, socks, and light shoes or sandals. Females dressed with light skirts, light blouses, light shoes or sandals, panties, and a bra. The insulation provided by this garment ensemble was predicted based on the sum of the individual component garment's clo values found in the ASHRAE Handbook (1985) and McCullough, Jones, and Huck (1985). This ensemble measures 0.43 for men and 0.42 clo for women, as shown in Table 3.

It was not discovered until after testing was complete that the above clo values did not total 0.5. Because of this, the results of testing will be modified based on the relationship 0.1 clo = 1°F. This is from ASHRAE Standard 55-1981 (p. 7, sec. 5.2), which states that the temperature can be lowered 1°F for each 0.1 clo raised.

When not moving and marking their ballots, the subjects generally spent their time studying.

Measured Criteria

Three criteria were measured and were the same as those used in the Rohles et al. (1983) study. (See the ballots shown in Figure 5.) The first ballot measured thermal comfort. This consisted of six bi-polar adjective pairs. A score of nine is given to the most favorable adjective (say, "comfortable"), while a value of one is given to the least favorable ("uncomfortable"). Note, this ballot differs from that used in the 1983 study. The latter ballot uses seven adjective pairs, including "cool-warm," which was not used in this study.

The second ballot shown in Figure 5 measured thermal sensation on a nine-category rating scale. A vote of five (neutral) or less was listed in the comfort range, since a lower vote (4-slightly cool, 3-cool, etc.) could be corrected by dropping the air velocity. A vote of six (slightly warm) was not counted as comfortable.

The third ballot, temperature preference, indicated whether the subject desired the temperature to be warmer and by how many degrees, cooler and by how many degrees, or left unchanged.

TABLE 6
Significance of the F Ratios for the Sources of Variance for the Three Dependent Measures. (Type III Sums of Squares)

SOURCE	TS	TC	TP
Test	.0001	.0001	.0001
Velocity	.0001	.0001	.0001
Sex	.1291	.0258	.0481
Test × Sex	.0776	.0027	.0003
Velocity × Test	.0713	.0005	ns
Velocity × Sex	ns	ns	ns
Velocity × Test × Sex	ns	ns	ns

TS — Thermal Sensation
TC — Thermal Comfort
TP — Temperature Preference
ns — Not significant at p < .05

RESULTS

A recap of the voting based on thermal sensation at the two higher air motions, V_3 and V_4, is given in Table 7 for each of the seven tests. Each of the measured criteria was treated by analysis of variance. Table 6 presents the resulting F ratios for the three dependent measures: thermal sensation, thermal comfort, and temperature preference. Because the number of observations varied for each test, the results are based on unbalanced testing procedures using Type III sums of squares.

Thermal Sensation

The mean and standard deviation for responses to thermal sensation ballots for each of the seven tests are shown in Table 7. Table 8 shows a significant difference between the mean thermal sensation votes for each of the five velocity conditions. Unlike the 1983 study's results, this study showed a significant difference between the mean thermal sensation of V_2 (50 fpm or 0.25 m/s) and V_3 (90 fpm or 0.46 m/s). Another difference between this and the earlier study is shown in Table 6. This study shows no significant difference (based on α = .05) in the mean thermal sensation vote due to the independent variable sex,

TABLE 7
Mean Thermal Sensation Votes at the Seven Test Conditions and Five Velocity Conditions.

TEST	V_4	V_3	V_2	V_1	V_0
1	4.5 ± 0.8	5.5 ± 0.8	5.3 ± 0.5	6.0 ± 0.8	6.0 ± 0.5
2	3.0 ± 1.3	3.9 ± 1.4	4.2 ± 1.1	4.9 ± 1.3	5.1 ± 1.0
3	4.6 ± 1.3	5.0 ± 0.9	5.5 ± 1.1	5.6 ± 0.7	6.1 ± 1.2
4	4.8 ± 0.8	5.1 ± 0.9	5.2 ± 0.7	5.5 ± 0.8	6.6 ± 0.9
5	6.1 ± 1.1	6.5 ± 0.8	6.3 ± 1.1	6.6 ± 0.5	7.4 ± 0.8
6	5.0 ± 1.0	5.7 ± 1.0	5.9 ± 0.9	6.3 ± 0.9	7.1 ± 0.8
7	4.6 ± 1.0	4.7 ± 1.4	5.5 ± 0.8	5.5 ± 1.4	7.0 ± 1.5

while the Rohles et al. (1983) study did show a difference in the mean of the thermal sensation votes.

Thermal Comfort

Thermal comfort ballots were scored by assigning values ranging from nine for the most favorable adjective in the pairs to one for the least favorable. These six values were summed. A total score of 54 would represent a perfect score. The resulting value constituted the thermal comfort vote. This was treated by analysis of variance.

Table 9 shows a similarity in the comfort response for V_2, V_3, and V_4. The mean thermal comfort votes for each velocity and test are presented in Table 10. Unlike the thermal sensation ballot, the thermal comfort means did show a significant difference between men and women.

Temperature Preference

The mean preferred change in temperature (°F) was treated by analysis of variance. Each independent variable—test, sex, and velocity—was independently significant in varying temperature preference. Table 11 shows the mean degrees change in preferred temperature for the seven test conditions and for the five velocity conditions.

DISCUSSION

Comfort at the Highest Air Velocities

Evidence from Tests 3, 4, and 7 of this study confirms the upper comfort limit proposed by the Rohles et al. (1983) study with the 200 fpm (1.02 m/s) mean velocities of a ceiling fan. This study also suggests that the upper limit can be extended even further with lower humidity conditions, and the upper limit will decrease with higher humidities.

At the highest air velocities (200 fpm or 1.02 m/s) the comfort indicator, thermal sensation, found at least 80% of the subjects comfortable in Tests 3, 4, and 7. The thermal sensation votes shown in Table 7 indicate an average vote of less than five. A vote of five indicates comfort — neither too hot nor too cold. This might imply that persons were slightly cooler than "just right."

However, looking at another indicator, temperature preference, the mean response at 200 fpm (1.02 m/s) in Test 7, for example, is −1.4°F ± 1.7°F (−.78°C ± .94°C). This might imply that persons were slightly warmer (by 1.4°F or .78°C) than "just right." So, the temperature preference indicator implies that a temperature of 88°F (31°C) DB with 200 fpm (1.02 m/s) air flow in Test 7 is slightly warmer than optimum. This anomaly between the thermal sensation response and the temperature preference response may be difficult to resolve without further questioning of the subjects. A reasonable assumption might be to lower the maximum temperature by the amount of the mean temperature preference vote.

Table 12 shows these suggested upper limit temperatures. Data from Table 5 and Table 9 are combined and expanded in Table 12. The upper comfort level temperatures are corrected for temperature preference and then again due to the clo value discrepancy as discussed in "Test Design."

Is it realistic to expect these higher velocities to be used for comfort? To be comfortable at the higher temperatures and humidities investigated in this study, a person would have to sit directly under the tips of the fan; locations in this study where the air velocities are in the range of 90 to 200 fpm (.46 to 1.02 m/s) included only 13% of the room area. The area of 200 fpm (1.02 m/s) or higher

TABLE 8
Mean Thermal Sensation Votes for the Five Velocity Conditions

Velocity	Mean	Grouping**
V_0	6.48	A
V_1	5.71	B
V_2	5.37	C
V_3	5.09	D
V_4	4.6	E

**Means with different letter designations differ from one another, $p < .05$

TABLE 9
Mean Thermal Comfort Votes for the Five Velocity Conditions

Velocity	Mean Thermal Comfort Vote	Grouping**
V_4	42.4 (76%)	A
V_3	40.1 (74%)	A
V_2	39.3 (73%)	A
V_1	36.1 (67%)	B
V_0	29.6 (55%)	C

**Means with the same letter designations are not significantly different at $p < .05$

TABLE 10
Mean Thermal Comfort Votes for the Seven Test Conditions

TEST	V_4	V_3	V_2	V_1	V_0
1	44 ± 10	43 ± 11	42 ± 10	35 ± 5	37 ± 8
2	32 ± 14	31 ± 15	39 ± 12	37 ± 13	37 ± 11
3	38 ± 14	38 ± 11	34 ± 12	35 ± 1	27 ± 10
4	47 ± 6	46 ± 7	44 ± 9	40 ± 11	29 ± 14
5	31 ± 6	27 ± 6	26 ± 7	25 ± 5	21 ± 5
6	47 ± 8	41 ± 11	38 ± 13	35 ± 13	27 ± 12
7	46 ± 10	45 ± 10	42 ± 9	38 ± 14	25 ± 14

TABLE 11
Mean Degrees Change in Preferred Temperature for the Seven Test Conditions

TEST	V_4	V_3	V_2	V_1	V_0
1	−0.3 ± 0.7	−0.5 ± 0.8	−0.8 ± 0.9	−1.0 ± 1.8	−1.5 ± 1.3
2	+3.6 ± 4.8	1.6 ± 4.3	−0.1 ± 2.5	−0.1 ± 3.3	−1.5 ± 2.5
3	+0.4 ± 2.4	−0.3 ± 2.0	−1.1 ± 2.3	−1.9 ± 2.4	−2.3 ± 3.2
4	−1.0 ± 1.4	−1.7 ± 1.7	−1.7 ± 1.5	−2.3 ± 2.1	−4.9 ± 3.1
5	−4.0 ± 1.8	−4.6 ± 2.1	−4.0 ± 2.7	−5.6 ± 2.1	−6.4 ± 1.9
6	−1.2 ± 1.5	−2.5 ± 1.7	−2.7 ± 2.1	−3.5 ± 2.3	−5.1 ± 2.2
7	−1.4 ± 1.7	−1.5 ± 2.1	−2.2 ± 1.5	−2.6 ± 2.4	−4.6 ± 5.1

includes only 3% of the area. With a fixed ceiling fan, this would limit the occupant's choices of location and mobility within the space. Although possibly of limited use in most situations, the knowledge of the higher velocity upper limits of the comfort envelope can have application on a spot cooling basis, for instance, at workstations.

The study's proposed upper limit of comfort conditions is shown in Figure 6. At the high humidity conditions of 76°F (24°C) WB, the highest temperature at which comfort can be achieved using 200 fpm is 83°F (28°C) DB. As the airspeed drops off, so does the acceptable temperature. The rate of decrease should follow that given in ASHRAE Standard 55-1981 (p.4) — 1°F per 30 fpm (0.275 m/s for each °C). When the velocity falls from 200 fpm (1.02 m/s) to 50 fpm (.26 m/s) the acceptable air temperature must drop 5°F.

Extending the Range of the Direct Evaporative Cooler

Test 2 was probably the most significant as related to the evaporative cooler. Its conditions of 78.5°F DB and 71°F WB (69% RH) can be achieved by all but 325 hours (see Table 2) in the average Phoenix cooling season with a direct evaporative cooler. This assumes that the cooler is 80% efficient and that outdoor air conditions are equal to or less than 108.5°F (42.5°C) DB and 71°F (22°C) WB.

Test 2 conditions can provide comfort in most of the test room. One hundred percent of the subjects stated that they were comfortable at V_4, 81% were comfortable at V_3, 87% were comfortable at V_2, and 62% were comfortable at V_1. Actually, at the higher air speeds, the mean temperature preference vote was +3.6°F for V_4 and +1.6°F for V_3; cooler than desired (see Table 11). The mean thermal sensation votes were 4.2, 4.9, and 5.1 for V_3, V_2, and V_1, respectively (see Table 7). In this condition, more than 60% of the room could be considered comfortable. Thirty-nine percent of the test room is at 30 fpm (.15 m/s) or less, not providing 80% of the occupants with comfortable conditions.

It has been shown that, for the higher air speeds, the increased air motion achieved by a ceiling fan can increase the percentage of time that a direct evaporative cooler can be effective. In the Phoenix area, and based on the acceptable comfort region shown in ASHRAE Standard 55-1981, 37% of the time that cooling is required (see Table 2), an evaporative cooler cannot be used unless air motion is increased above "still air" conditions.

An evaporative cooler does produce some increased air motion. The air speed achieved depends on the placement and area of supply and exhaust openings. To achieve velocities in an occupied zone above 50 fpm (.25 m/s), some supplemental air-moving device will be needed. Even if air motion around the occupants is increased to 200 fpm (1.02 m/s), comfort will not be achieved at all times during a typical summer with direct evaporative cooling. Where the outdoor wet-bulb is 76°F (24.4°C) or above, the percentage of people comfortable will drop below 80%. This can occur for as many as 146 hours, or about 5% of the time that cooling is normally required.

Using the Indirect Evaporative Cooler

At Phoenix's worst conditions, a completely indirect evaporative cooler can achieve indoor conditions midway between test condition 3 and test condition 7 (see Figure 1). This is approximately 85°F (29°C) DB and 75°F (24°C) WB. Although this condition was not tested, it could be reasonably assumed (based on the results of tests 3 and 7) that at least 80% of the occupants would be comfortable

Table 12
CONDITIONS AT THE UPPER COMFORT LIMITS

Test	Conditions DB	Conditions WB	Conditions RH	Percent Comfortable at 200 fpm	Preferred Temp. Change °F	Suggested Limit °F	Corrected Limit* °F
3	83°F	76°F	73%	80	+0.4 ± 2.4	83°F	82
4	90°F	71°F	39%	83	−1.0 ± 1.4	89°F	88
7	88°F	73°F	50%	90	−1.4 ± 1.7	86°F	85

*Because the test clo values were .4 (and not .5) the results should be reduced by 1°F.

at air speeds of 200 fpm (1.02 m/s). Likewise, from previous test results, less than 80% of the occupants will be comfortable at air speeds up to and including 90 fpm.

This study suggests that comfort can theoretically be achieved with indirect evaporative cooling even when the outdoor wet-bulb temperature reaches 78°F. This assumes that the system is working perfectly and that the person is located in a position where the air speed is 200 fpm. Again, the test room only had 3% of the area with velocities of 200 fpm (1.02 m/s), and not everyone will accept this velocity as comfortable.

Although this study has primarily considered the ceiling fan in conjunction with evaporative cooling, a ceiling fan providing 200 fpm (1.02 m/s) can allow a conventional air-conditioning system's setpoint to be raised as much as 6°F (4.5°C) (from 79°F to 85°F at 50% RH).

This study has made quite clear the critical importance of proper design for air motion and air distribution in the lower energy-consuming methods of cooling. Not that it is unimportant with refrigerated air conditioning, but a conventional air-conditioning system can often compensate for poor air distribution and air motion with lower temperatures. This is not always possible with evaporative cooling.

Study Limitations

The Testing Situation. The sequencing and length of tests at the various air speeds may have affected the way test subjects evaluated their thermal comfort. If the test had been longer or had been sequenced differently, the votes may have changed. The students entered the test chamber from comfortable conditions. They then experienced one hour of conditions that were unacceptable for thermal comfort. The increased air motion when the fans were finally turned on would be quite an improvement. This same effect could occur when moving from an uncomfortable condition to one that was less uncomfortable. Relatively, they may have considered the new situation comfortable. Possibly, the subject should enter the new test conditions from a neutral or comfortable situation. This would be analogous to the wine taster, who must wash out his palate before trying a new sample.

Also, the novelty of the test situation may have influenced their perceptions. Conducting the test in an actual working environment for longer periods of time may be more valid.

Group Interaction. Some test groups (eight individuals — four men and four women) were observed to be much more friendly and outgoing, while with others there was little, if any, talking. This may have had an effect on the voting since the time might tend to pass more quickly for the friendlier groups. Future studies should control this aspect.

Higher Air Velocities. The voting did not specifically address the aspects of higher air motions. The ballots did not address overall comfort, but only asked questions relating to thermal satisfaction, not air velocities. Subjects knew they were there to evaluate thermal conditions. Several complaints were made, in written comments, about the distractions of the high velocities.

Subject Population. The young, undergraduate population may not be as discerning about what they consider acceptable comfort conditions as a general cross section of the population.

Clo Values. The subjects' clo values should be monitored more closely. Students were instructed on what to wear but there could be ±0.15 clo difference in ensembles. The clothing ensemble shown in Table 3 was established from the Rohles et al. (1983) study and initially believed to be 0.5 clo. However, after the test and reviewing McCullough (1985), it was found that the nominal clo value being tested was approximately 0.1 clo less. Because of this, the comfort limit temperatures in Table 12 have been adjusted downward by 1°F.

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DISCUSSION

V. Goldschmidt, Purdue Univ., West Lafayette, IN: It is my perception that most of our ASHRAE comfort studies to date have been limited in two aspects: a) accounting for only mean velocity rather than mean velocity as well as turbulence intensity and scales and b) providing a statistically significant sample including different ages and cultures. (I also suspect that preceding activities, such as nature of food ingested and sleep, could affect an individual's comfort.) Could you then comment further on the limits to generalization of your data?

D.G. Scheatzle: These appear to be valid observations. We would not want to generalize beyond the population of our study. Available funds limited the number of subjects tested. Our purpose was to extend the knowledge obtained by the Rohles et al. study. To make a valid comparison, we used the same method and the same independent variables.

J. Verschoor, Consultant, Verschoor Associates, Bailey, CO: Were air velocities from the ceiling fan measured with or without tables and a panel of observers?

Scheatzle: Velocities were measured with tables in place, but without chairs and subjects.

D.M. Burch, Research Mechanical Engineer, National Institute of Standards and Technology, Gaithersburg, MD: Did you compare your results to the Fanger Comfort Model?

Scheatzle: No.