No. 2508 RP 208

OCCUPANT ACCEPTABILITY OF EIGHT-HOUR-LONG TEMPERATURE RAMPS IN THE SUMMER AT LOW AND HIGH HUMIDITIES

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INTRODUCTION

Previous studies have shown (1, 2) that slow rates of temperature change (0.5°C/h) from optimal comfort conditions are almost undetectable by occupants from traditional constant temperature conditions. In our previous 4-hr-long tests (1) thermal acceptability remained above 80% when temperature deviations from optimum were 2° C or less. Allowing the inside temperature of a building to drift with outside conditions and internal loads has important energy saving (3) and load shifting implications for both new and old buildings, provided the environment remains thermally acceptable to the building's occupants.

This paper reports on occupant responses to temperature drifts during an 8 1/2-hr working day. Since the energy and cost savings potential of temperature drifting appears to be largest during the summer (3), clothing and drift conditions appropriate for this season were chosen for these tests. Experiments were conducted where the temperature rose slowly throughout the day from a cool initial condition. Using a similar strategy, a building could be cooled at night with outside air and refrigeration when the air is cooler and when electrical demand and rates are lower and COP's are higher. Then during the day, the building's temperature could be allowed to drift upward with reduced refrigeration or without refrigeration. Many variations of this theme are possible such as using stored chilled water, increased building mass, and/or a temperature ramp control system.

METHOD

The study consisted of testing subjects wearing summer clothing in three different environments. One environment was a control with a constant temperature of 25° C and a dew point of 10° C; two were environments where the temperature rose at the rate of 0.6° C/h from 23 to 27.8° C, one with a dew point of 10° C and the other with a dew point of 20° C (Fig. 1). The lower humidity is in the middle of the acceptable humidity range of ASHRAE Standard 55-74. The higher humidity is about as high as could be expected in a building in the summer. The tests were conducted in the All Weather Test Chamber at the John B. Pierce Foundation Laboratory. This 5.3 x 5.3 x 2.4 m high chamber, previously described (4) has an electronic control system to automatically produce precise and repeatable temperature and humidity ramps. In our studies, air and wall temperatures were always equal and the air movement was constant at 0.1 m/s.

The subjects were solicited from the New Haven community. Their physical characteristics are summarized in Table 1. Each subject was randomly assigned to a group of 3 men and

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3 women. There were 4 groups in all for a total of 24 participants. Each group experienced all 3 test environments arranged in random order.

TABLE 1

Physical Characteristics of Subjects

	number	Age - yr mean/SD	range	Weight - kg mean/SD	range	Height - cm mean/SD	range	Clothing Insulation - clo mean/SD	range
Men	12	26.4/3.8	21-33	72.4/6.3	61.4-81.8	181.5/9.0	165.1-193	0.54/0.06	.40-.70
Women	12	23.8/4.2	19-32	61.8/12.0	47.7-86.4	165.1/6.5	154.9-180.3	0.49/0.11	.32-.72

The subjects provided their own summer office-type attire. Each day they evaluated the insulation value, in clo units, of their clothing ensemble by the Nevins' (5) method (Fig. 2). The mean clo values are listed in Table 1. The overall average was 0.51 clo. A winter business suit has an insulation value of approximately 1.0 clo and a bikini bathing suit about 0.05 clo.

The testing took place during the hot months of August and September in order that the subjects would be naturally acclimated to warm weather. The subjects entered the test chamber at 8:30 a.m. For the ramp tests, the temperature was held constant at 23° C until 9:00 when the ramp commenced. During the 12:00 to 12:30 lunch break, the subjects left the chamber and went out to one of the many neighborhood diners. The test ended at 5:00 p.m. each day. The subjects could leave the chamber at will for personal needs. We provided refreshments in the chamber consisting of coffee, tea, soft drinks and water. Every 1/2-hr starting at 9:00, the subjects marked a thermal responses ballot (Fig. 3) to indicate their judgments of thermal sensation, discomfort and thermal acceptability. The subjects were not permitted to discuss the environment or how they felt, and were not given any information about the environment or that it was changing. The study was designed to simulate office work conditions and the subjects responded accordingly by providing themselves with sufficient work of their own design. Some did school assignments, some worked on their thesis, some did art projects, four architects did design work, some read, others sewed and some periodically played board games.

RESULTS

The means of the subjects' 1/2-hr votes are plotted along with the temperature against time in Fig. 4. In the morning the subjects' responses of discomfort, thermal acceptability and sensation for the three different test environments were very similar, with thermal sensations warmer than might be expected for the conditions. It was not until after lunch that noticeable differences among the responses to the different conditions developed. The reason thermal sensation votes during the first two hr did not follow the temperature conditions is not certain but it has been generally found in other comfort studies (6). The response may be due to development of increased metabolism and the higher outside temperatures experienced in coming to work. From about 11:00 a.m. on, the thermal sensation responses tracked the inside air temperature. Thermal sensations for the 20° C dew point ramp were consistently higher than for the other conditions. Discomfort in the afternoon for the humid ramp was also consistently higher. Thermal acceptability during the humid ramps began to decrease when the temperature reached 26.3° C. During the low humidity ramps, thermal acceptability started to decrease at 26.9° C. Thermal acceptability had decreased to the 80% level at 27 and 27.2° C for the high and low humidity ramps. Thermal acceptability never fell below 96% during the constant 25° C control.

ASHRAE Standard 55-74 specifies the environmental conditions that will be thermally acceptable for most sedentary and normally clothed persons. However, this standard does not specify thermal acceptability criteria for slowly changing air temperature over a long period of time.

In Fig. 5, the temperature limits of the standard are compared to the air temperature limits for the 8 1/2-hr periods of this study for which thermal acceptability was 80% or higher.

Thermal acceptability is plotted against thermal sensation in Fig. 6. For the purpose of comparison, the relationship developed by Fanger (7) between predicted percent dissatisfied (PPD) and thermal sensation is also plotted. Fanger's PPD is the most popular method used by engineers to estimate occupant acceptability. Fanger used a different criteria for dissatisfaction; since his subjects had not been directly polled for thermal acceptability or dissatisfaction, he inferred it from their thermal sensation votes. His criteria was that a vote beyond ± 1 from neutral or comfortable represents a dissatisfied person. He analyzed the thermal sensation vote distributions to determine the percent dissatisfied. In comparison to our results, the Fanger dissatisfaction criteria appears to be reasonable although it overpredicts slightly the actual thermal dissatisfaction in the warm environments found in this study. A like comparison with our previous 4-hr-long ramp results (1) reached a similar conclusion.

At the end of the final experiment, each subject was asked to rate the three environments they had just experienced in terms of which they liked the best and least. The rating results presented in Table 2 show that this group of 24 people preferred the low humidity temperature ramp over the constant temperature control environment. In the least preferred category, the largest group was undecided with 46%, followed by the high humidity temperature ramp at 42%. Since so many were undecided, this least preferred category rating is rather inconclusive.

TABLE 2

Rating of Environments by Participants on the Last Day

	Preferred - %	Least Preferred - %
constant temperature control	29.2	4.2
low humidity temperature ramp	45.8	8.3
high humidity temperature ramp	20.8	41.7
undecided	4.2	45.8
	100.0	100.0

CONCLUSION

These tests show that a temperature ramp of 0.6° C/h between 23 and 27° C was thermally acceptable to more than 80% of the test population dressed in summer office attire (.5 clo). Humidity increased warmth sensation responses and discomfort but the 80% acceptability limit for the 20° C dew point was only about 0.2° C lower than the temperature limit for 80% acceptability at the 10° C dew point. Therefore, for sedentary applications humidity effects can be expected to be small when applying these slow rates of air temperature change, as long as the dew point is below 20° C. These 8 1/2-hr ramp results together with our previous 4-hr ramp results (1) now provide a good basis from which to rationally formulate energy management and load shedding plans, that consider both energy conservation and the thermal comfort of the building's occupants.

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ACKNOWLEDGEMENT

This research, supported by ASHRAE RP 208 under the guidance of TC 2.1, was first suggested to us by Dr. P. E. McNall, Jr. The authors are also grateful for the insight, counsel and encouragement provided throughout the project by Dr. A. P. Gagge. Others to whom we are indebted are: Richard Rascati for developing the chamber's automatic ramp control; James Casby for assistance with the data reduction; Frances Ahern for preparation of the manuscript and Wayne Chappell for the illustrations.

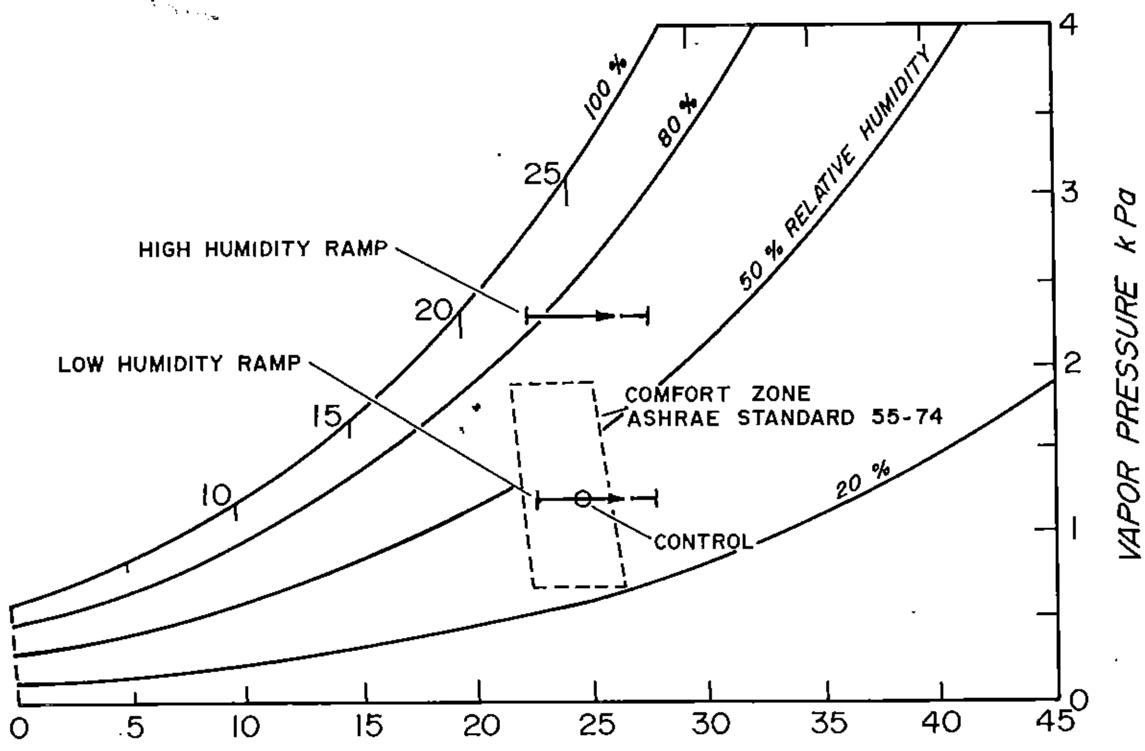

Fig. 1 Test conditions

MEN

Undershirt:	Sleeveless - 0.06	"T" - 0.09
Trousers:	Light - 0.26	Heavy - 0.32
Shirt:	Light	Heavy
	Short sleeves - 0.14	Short sleeves - 0.25
	Long sleeves - 0.22	Long sleeves - 0.29
	Add: 5% for Turtleneck	
	Add: 5% for tie	
Sweater:	Light - 0.20	Heavy - 0.37
	Deduct 10% for short or no sleeves	
Vest:	Light - 0.15	Heavy - 0.29
Jacket:	Light - 0.22	Heavy - 0.49
Socks:	Ankle - 0.04	Knee High - 0.10
Shoes:	Sandals - 0.02 Oxfords - 0.04	Boots - 0.08

Determination of Clothing Insulation

$I_{cl} = 0.727 I_s + 0.113$ men

$I_{cl} = 0.770 I_s + 0.05$ women

I_{cl} = total ensemble clo-value (Nevins)

I_s = sum of individual clo-values

Note: Add 0.05 for men's undershorts; 0.05 for women's bra and panties

WOMEN

Slip:	Full - 0.19		Half - 0.13
Dress:	Light - 0.20		Heavy - 0.63
	Add - 10% for long sleeves		
	Deduct - 5% for above knee		
	Add - 5% for below knee		
Blouse:	Light - 0.20	Med - 0.25	Heavy - 0.29
	Deduct - 10% for short or no sleeves		
Skirt:	Light - 0.10		Heavy - 0.22
	Deduct - 5% for above knee		
	Add - 5% for below knee		
Slacks:	Light - 0.26		Heavy - 0.44
Jacket:	Light - 0.17		Heavy - 0.37
Sweater:	Light - 0.17		Heavy - 0.37
	Deduct 10% for short or no sleeves		
Stockings:	Short - 0.01	Long - 0.01	Panty Hose - 0.01
Shoes:	Pumps - 0.04	Sandals - 0.02	Boots - 0.08

Fig. 2 Form used by subjects to determine the clo-value of their clothing (5)

Elapsed time ____________

Your initials ____________

Date ____________

Do you feel any discomfort:

No discomfort ____________ Intolerable

How do you feel at this moment?

- Hot
- Warm
- Slightly warm
- Neutral
- Slightly cool
- Cool
- Cold

Is the present environment thermally acceptable?

Yes ____________

No ____________

Fig. 3 Human responses ballot

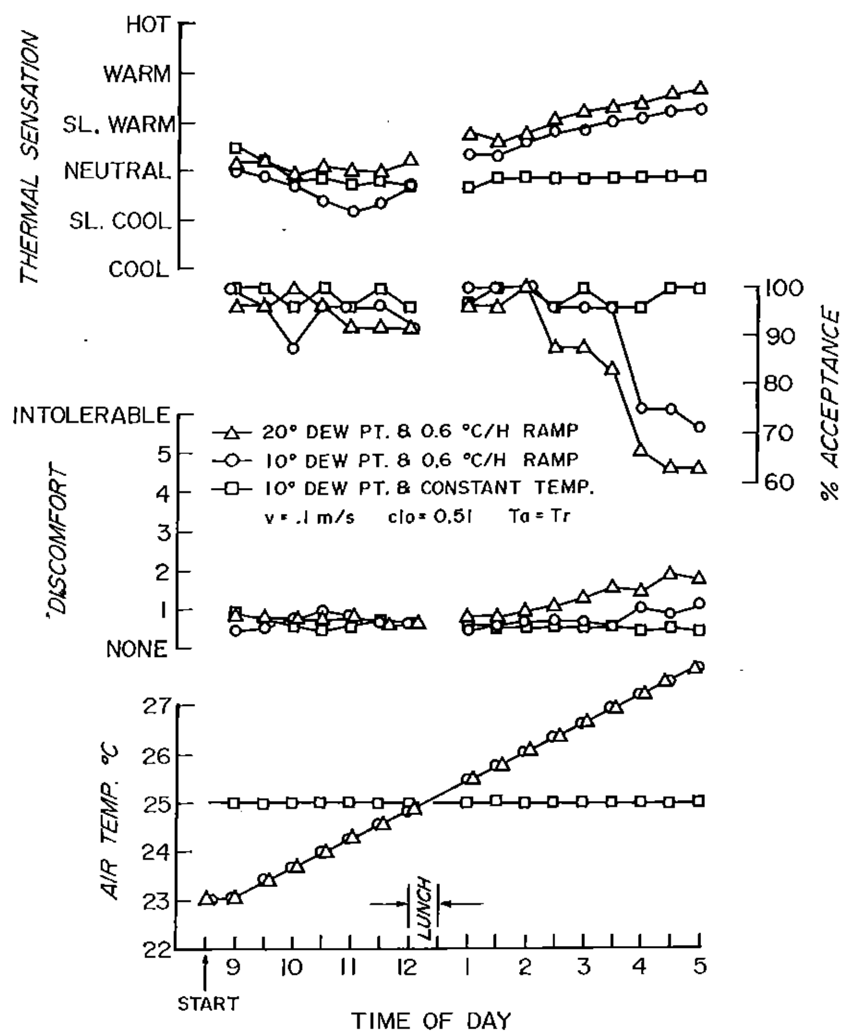

Fig. 4 Mean temperatures and subject responses during the 8½-hr-long tests. The mean standard error (S.E.) for the various responses and conditions are

Discomfort: —□— *S.E. = 0.14*
—○— *S.E. = 0.11*
—△— *S.E. = 0.14*

Thermal Sensation: —□— *S.E. = 0.14*
—○— *S.E. = 0.18*
—△— *S.E. = 0.16*

Thermal Acceptability:
—□— *S.E. = 0.06*
—○— *S.E. = 0.04*
—△— *S.E. = 0.06*

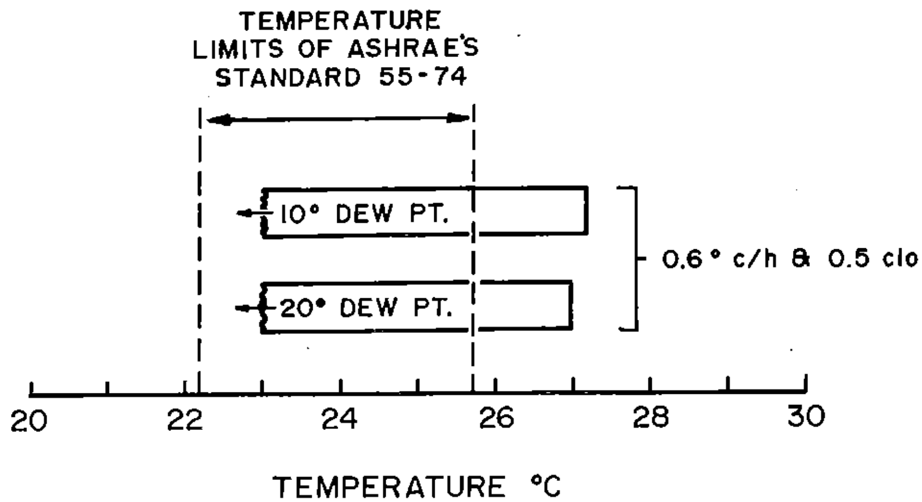

Fig. 5 Comparison of this study's 80% thermal acceptability temperature limits with those of ASHRAE Standard 55-74. Note: ← *indicates 80% thermal acceptability temperature limit was not defined but lies beyond this point in direction of arrow.*

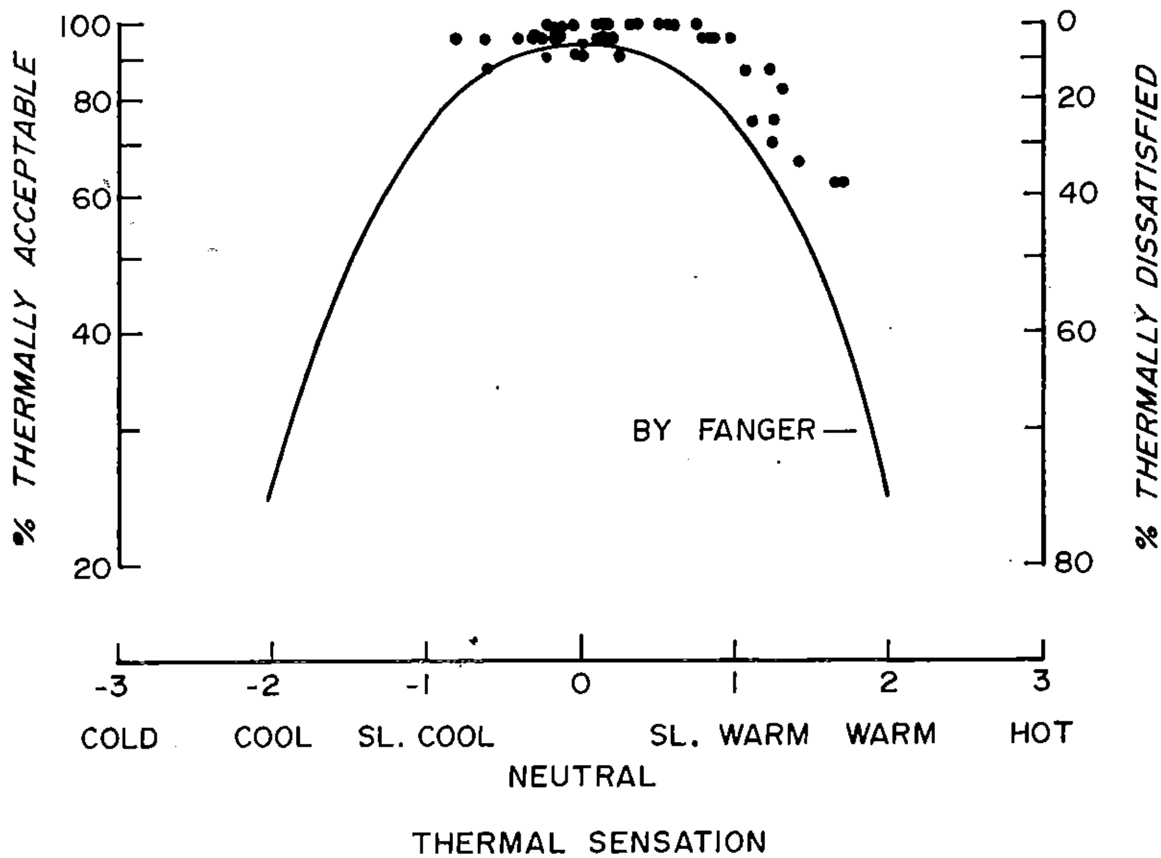

Fig. 6 Mean thermal acceptability and thermal sensation votes of this study compared to those predicted by Fanger