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APPLICATION OF ACCEPTABLE TEMPERATURE DRIFTS TO BUILT ENVIRONMENTS AS A MODE OF ENERGY CONSERVATION

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INTRODUCTION

Energy conservation strategies for the built environment currently include altering thermostat settings, lighting levels and ventilation rates, increasing the thermal resistance of the building's skin, reducing infiltration and upgrading the efficiencies of environmental control equipment. Another suggested technique that appears to have promise is allowing the temperature of living space to drift with outside conditions and internal loads due to intermittent or reduced capacity of temperature control equipment, providing the rate and duration of the temperature drift is acceptable to the occupants.

In the summer, a building could be precooled at night with outside air or with refrigeration, when power rates are usually lower and when the coefficient of performance is usually higher. During the day the temperature in the building could be allowed to drift upward either without refrigeration or with the refrigeration capacity reduced. Some buildings could employ controlled temperature ramps. All such designs would decrease electrical demand during the day and should result in a net energy savings. The savings potential would depend on the thermal characteristics of the building, its internal load and the local climatic conditions. In the winter the temperature of a building could be ramped upward during the morning and allowed to drift down in the afternoon.

The question that remains unsolved is to what extent do the occupants react to such temperature drifts and under what conditions do they find them acceptable or objectionable. Little comfort information is available on temperature transients in the engineering literature. What has been studied deals with short term oscillating variations about comfort conditions (1, 2, 3) or the transient response of subjects entering a comfortable environment (4, 5, 6). One study by Griffiths and McIntyre (7) evaluated human responses to slow steady one-directional temperature changes of 0, 0.5, 1 and 1.5^{o} C/h, centered about 23^{o} C, over 6 hour periods. The clothing used is not clearly documented but appears to have been in the 0.7 to 0.9 clo range. From the mean thermal sensation votes of the subjects, Griffiths and McIntyre determined the corresponding Predicted Percent Dissatisfied (PPD) using the relationship developed by Fanger (13). Based on the calculated predicted percent dissatisfied they recommend a maximum rate of temperature change of 0.75^{o} C/h with a maximum deviation from the mean comfort temperature of 2.25^{o} C. The present study expands on the work of Griffiths and McIntyre by specifically asking the subjects if the environment is thermally acceptable or not as well as testing them in 3 different levels of clothing. The primary factors considered were rate of temperature change and level of clothing. The ultimate objective is to propose operating schedules that are compatible with comfort and thermal acceptability.

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METHOD

The study consisted of testing subjects dressed in 3 different levels of clothing (0.5, 0.7 and 0.9 clo) each of whom experienced 7 rates of temperature change (0, $\pm$0.5, $\pm$1 and $\pm$1.5^{o} C/h). 12 college age subjects (6 men and 6 women) were used at each of the 21 test conditions. The 0^{o} C/h tests were used as controls. Tests were conducted in the All Weather Test Chamber at the John B. Pierce Foundation Laboratory. This chamber, previously described (8) has a control system newly modified to automatically produce accurately controlled 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. Throughout the testing the dew point was 12^{o} C.

The subjects were solicited from the college communities in New Haven; their physical characteristics are summarized in Table 1. Each subject was randomly assigned to a group of 3 men and 3 women. There were 6 groups in all for a total of 36 participants. Each group tested 7 random combinations of clothing and temperature change including a control on 7 consecutive afternoons. Two different groups experienced each test condition.

The subjects provided their own test clothing, which they selected to conform to the list in Table 2 and the ensemble number assigned to them for a given test. The clothing levels are representative of summer, normal and warmer office type attire. The insulation values of the ensembles determined by three methods are given in Table 2.

The subjects entered the test chamber at 12:30 p.m. Until 1:00 the temperature was held constant at 25^{o} C at which time the temperature ramp commenced. Every half an hour starting at 1:00 the subjects marked a thermal response ballot (Fig. 1) to indicate their judgments of thermal sensation, discomfort and thermal acceptability. The subjects were not allowed to discuss the environment or how they felt. The subjects were not given any information about the environment or that it was changing. During the tests the subjects conversed, studied, played games or did other things like sewing and sketching. They were not completely sedentary but walked slowly about the test chamber for 5 minutes every thirty minutes ($\approx$ 1.2 met).

RESULTS

The means of the half hour votes for the 3 clothing levels at the 0, +0.5, +1 and +1.5^{o} C/h runs are plotted against time and temperature in Fig. 2, 3, 4 and 5. The effect of clothing on the subjects' responses during the steady 25^{o} C conditions is small (Fig. 2). The responses to the 0 and 0.5^{o} C/h ramps (Fig. 2 and 3) with summer and normal clothing are nearly identical indicating that the subjects, during the 0.5^{o} C/h test, probably did not realize that the temperature was slowly rising from 25 to 27^{o} C. An analysis of variance of the combined data from the 0 and 0.5^{o} C/h tests showed that the increases in cold or warm discomfort due to time or temperature were not significant (Table 3). Thermal acceptability remained above 91% throughout the 4 hours at these conditions. The warmer clothed (ensemble III) persons became uncomfortable only after the 3rd hour during the 0.5^{o} C/h ramp although this environment was always thermally acceptable to more than 83%.

The results of the 1 and 1.5^{o} C/h up ramps show (Fig. 4 and 5) that thermal sensation, discomfort and thermal acceptability often lagged for about one hour at the beginning of the ramps. After this first hour the responses generally became linear with temperature. Figure 5 indicates that even with lighter clothing the 1.5^{o} C/h ramp was acceptable to less than 80% after 3 hours or above 29.5^{o} C.

The responses to the down ramps are plotted in Fig. 6, 7 and 8. As would be expected the warmer clothed subjects were more comfortable under these conditions. The responses to the -0.5^{o} C/h ramp (Fig. 6) from subjects wearing the normal and warmer clothing levels are nearly identical to those from the similarly dressed subjects at the steady 25^{o} C conditions (Fig. 2). Thus a 0.5^{o} C/h ramp appears to be essentially indistinguishable from a constant 25^{o} C environment from 25 to 27^{o} C and from 25 to 23^{o} C for sedentary persons wearing normal clothing, from 25 to 27^{o} C for persons wearing the summer clothing and from 25 to 23^{o} C for persons wearing the warmer clothing. The initial discomfort and thermal sensation response lags for the steeper down ramps (Fig. 7 and 8) were less consistent than with the previously discussed up ramps. These responses were again approximately linear with temperature. Thermal acceptability when wearing the warmer ensemble III remained above 80% all the way to the end of the 4 hours with the slower down ramps and down to 20° C or for 3 hours with the steeper -1.5° C/h ramp. With the light clothing and temperatures above 22° C 80% or more judged the environment to be thermally acceptable for all down ramps.

As the dew point was constant in these tests the relative humidity increased during the down ramps and decreased during the up ramps. Natural fibers (wool, cotton, silk) respond to changes in relative humidity. When the relative humidity rises, the moisture in the clothing increases. The heat from condensation then could be a heat source in the clothing tending to offset the effect of falling temperature. The opposite effect would occur with a temperature rise. Sprague and McNall (1) estimate that for the KSU uniform (0.6 clo) the heat from moisture changes in the clothing would be less than 0.5 wh/Δ% RH. The maximum rate of relative humidity change in our tests was about 5%/h. Thus the maximum rate of heat flow due to condensation or evaporation in ensemble II would be about 2.5 watts. This represents only a 2% alteration in the normal total heat flow rate from the body. Being so small it would not be expected to have had an effect on the thermal sensations experienced during these ramp tests.

Figure 9 gives the mean responses to all the ramps for subjects wearing ensemble I. Similarly Fig. 10 and 11 show the responses for subjects wearing ensembles II and III. The responses to the different ramps are the most varied and pronounced for subjects wearing light clothing. Figure 9 shows that with 0.5 clo the subjects were less sensitive in terms of discomfort and thermal sensation to the faster changing environments. The slower ramps probably permitted more physiological adjustments to the environment to occur like vasoconstriction, vasodilitation and altered blood flow to the extremities than in the faster ramps. With more clothing, differences in sensory response due to the rate of temperature change is less (Fig. 10 and 11) though the trends are similar to the 0.5 clo responses. The thermal sensitivity (Δ thermal sensation/ΔT) for the different test conditions determined from the linear regression lines through the last 3 hours of data are tabulated in Table 3. They range from 0.16 to 0.73 with an overall mean of 0.305. The mean is similar to those reported by others (12). The sensitivity during the 1° C/h ramps was consistently higher than during the 1.5° C/h ramps but had an inconsistent relationship to the 0.5° C/h ramps. From Table 3 it appears that thermal sensitivity is unaffected by clothing. This is also evident in Figure 12 which shows the thermal sensation votes plotted against temperature for all test conditions. The mean thermal sensation votes can be described fairly well ($r = .95$) by a multiple linear regression in terms of operative temperature and clo.

The ambient temperatures that bound the region where the thermal acceptability of the subjects was 80% or higher is summarized in Table 5 for all the test conditions. The thermal sensation votes at the corresponding bounds are also listed. The average thermal sensation at the lower and upper 80% thermal acceptability limits are -1.06 and $+1.43$ respectively. Implying a slightly warm environment is more thermally acceptable than a slightly cool one.

In Fig. 13 thermal acceptability is plotted against discomfort for all test conditions. The two are related linearly at low levels of discomfort but the relationship becomes curvilinear for thermal acceptabilities below 70%. Thermal acceptability is plotted against thermal sensation in Fig. 14. The points are not quite symmetrical about a thermal sensation of neutral. For purposes of comparison the relationship developed by Fanger (13) between the percent dissatisfied (PPD) and thermal sensation is also given in Fig. 14. He used a different criteria for dissatisfaction as his subjects had not been polled for thermal acceptability or dissatisfaction so he inferred it from their thermal votes. Fanger's criteria was that a vote beyond ± 1 represents a dissatisfied person. He analyzed the thermal sensation vote distributions to determine the percent dissatisfied. The Fanger dissatisfaction criteria appears conservative when compared to the test results of Fig. 14.

The discomfort votes for each ramp were compared to the 0° C/h ramp or the control data by an analysis of variance. The results are summarized in Table 4. The variation in discomfort from the controls due to time or temperature was significant for every temperature ramp except $+0.5^{\circ}$ C/h as previously noted. Similarly, the discomfort variation due to clothing was significant for every ramp except -1.5° C/h. The effect of sex was less consistent with only half of the ramps showing a significant discomfort variation due to sex. Closer inspection of the data shows that women had less warm discomfort than men. Table 6 shows that the average 80% thermal acceptability temperature limits for all ramps were consistently higher for women. Gonzalez has summarized similar responses (14).

ASHRAE Standard 55-74 (15) specifies the environmental conditions that will be thermally acceptable for most sedentary and normally clothed persons. In Fig. 15 the upper and lower temperature limits of the standard are compared to the 80% thermal acceptability limits determined for the various clothing and temperature drift conditions of these experiments. Our results indicate that the present ASHRAE standard may be conservative, particularly its upper limit when temperatures are drifting.

CONCLUSION

This work shows that for sedentary persons slow temperature drifts ($\pm 0.5^{\circ}$ C/h) about the thermal neutral temperature are almost indistinguishable from the traditionally preferred constant temperature conditions. The neutral temperature is determined by the clothing level of the occupants in the space. A 0.5° C/h drift which causes the ambient temperature to deviate from the neutral point by 2° C will only reduce thermal acceptability to about 80% according to our studies. With faster rates of temperature change the permissible deviation for 80% acceptability is larger.

These results provide a bases from which to build energy conservation and load shedding strategies that consider occupant comfort and thermal acceptability. The building's temperature may be ramped steadily all day, for parts of the day, ramped up and then down or many other combinations. The savings potential will depend on the building, local climate and internal loads. Presumably the acceptance level would be improved over those found in this study if the occupants made clothing adjustments, like adding or removing a sweater, as a normal population might be expected to do during the course of temperature drift. Temperature drifting is particularly attractive for existing buildings where energy conservation possibilities are more limited than in the design of a new building.

REFERENCES

1. Sprague, C. H. and P. E. McNall, Jr., Effects of Fluctuating Temperature and Relative Humidity on the Thermal Sensation (Thermal Comfort) of Sedentary Subjects, ASHRAE Trans. 77(1): 183-199, 1971.
2. Wyon, D. P., Th. Asgeirsdottir, P. Kjerulf-Jensen and P. O. Fanger, The Effects of Ambient Temperature Swings on Comfort, Performance and Behavior, Arch. Sci. Physiol. 27: 441-458, 1973.
3. Nevins, R. G., R. R. Gonzalez, Y. Nishi and A. P. Gagge, Effect of Changes in Ambient Temperature and Level of Humidity on Comfort and Thermal Sensations, ASHRAE Trans. 81 (2): 169-182, 1975.
4. Rohles, F. H. and R. Nevins, Short Duration Adaptation to Comfortable Temperatures, ASHRAE Trans. 74 (1): IV.1.1-1.4, 1968.
5. McNall, P. E. and J. C. Schlegel, The Relative Effects of Convection and Radiation Heat Transfer on Thermal Comfort for Sedentary and Active Human Subjects, ASHRAE Trans. 74(2): 131-143, 1968.
6. Rohles, F. H., J. E. Woods and R. G. Nevins, The Influence of Clothing and Temperature on Sedentary Comfort, ASHRAE Trans. 79 (2): 71-80, 1973.
7. Griffiths, I. D. and D. A. McIntyre, Sensitivity to Temporal Variations in Thermal Conditions, Ergonomics 17(4): 499-507, 1974.

8. Kjerulf-Jensen, P., Y. Nishi, H. Graichen and R. Rascati, A Test Chamber Design for Investigating Man's Thermal Comfort and Physiological Response, ASHRAE Trans. 81 (1): 73-82, 1975.
9. Sappanen, O., P. E. McNall, D. M. Munson and C. H. Sprague, Thermal Insulating Values for Typical Indoor Clothing Ensembles, ASHRAE Trans. 78 (1): 120-130, 1972.
10. Sprague, D. H and D. M Munson, A Composite Ensemble Method for Estimating Thermal Insulating Values of Clothing, ASHRAE Trans. 80 (1): 120-129, 1974.
11. Nishi, Y., R. Gonzalez, R. G. Nevins and A. P. Gagge, Field Measurement of Clothing Thermal Insulation, ASHRAE Trans. 82 (2): 248-259, 1976.
12. McIntyre, D. A. and R. R. Gonzalez, Man's Thermal Sensitivity During Temperature Changes at Two Levels of Clothing Insulation and Activity, ASHRAE Trans. 82 (2): 219-233, 1976.
13. Fanger, P. O., Thermal Comfort, McGraw-Hill, New York, 1972. p. 128-133.
14. Gonzalez, R. R., Experimental Analysis of Thermal Acceptability. Proceedings of Symposium on Thermal Analysis-Human Comfort-Indoor Environments, February 11, 1977, National Bureau of Standards, Gaithersburg, Maryland. NBS-Special Publication 491 issued September 1977.
15. ASHRAE Standard 55-74, Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1974.

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Table 1

Physical Characteristics of Subjects

	number	Age - yr mean/SD	range	Weight - kg mean/SD	range	Surface Area - m^2 mean/SD	range	Weight/Area kg/m^2
Men	18	23.3/2.4	20-26	77.06/11.9	65-106	1.98/.17	1.79-2.37	38.9
Women	18	22.9/3.3	18-28	59.6/9.4	45-82	1.63/.13	1.42-1.92	36.6

Table 2

ENSEMBLES that subjects wore for a given experiment (designated as I, II, III) and their insulation value as determined by various methods (all units are in clo).

Clothing Ensemble	MEN	$\overline{I_{clo \cdot N\ \&\ S}}$	WOMEN
I	Lightweight trousers Short sleeve shirt No undershirt Underwear Socks Oxford shoes $I_{clo \cdot S}$ = 0.48-0.57 $I_{clo \cdot N}$ = 0.5 $I_{clo \cdot i}$ = 0.4	0.48	Lightweight slacks Sleeveless or short sleeve blouse Stockings Underwear Sandals $I_{clo \cdot S}$ = 0.51 $I_{clo \cdot N}$ = 0.45 $I_{clo \cdot i}$ = 0.36
II	Medium weight trousers Long sleeve shirt & tie Short sleeve undershirt Underwear Ankle socks Oxford shoes $I_{clo \cdot S}$ = 0.65 $I_{clo \cdot N}$ = 0.68-0.73 $I_{clo \cdot i}$ = 0.54-0.58	0.67	Medium weight slacks Long sleeve blouse Underwear Stockings or panty hose Shoes (no high tops or thin heeled) $I_{clo \cdot S}$ = 0.83 $I_{clo \cdot N}$ = 0.59-0.69 $I_{clo \cdot i}$ = 0.47-0.55
III	Medium weight jacket Medium weight trousers Long sleeve dress shirt & tie Short sleeve undershirt Underwear Socks Oxford shoes $I_{clo \cdot S}$ = 0.92-1.00 $I_{clo \cdot N}$ = 0.91-1.06 $I_{clo \cdot i}$ = 0.72-0.84	0.93	Add winter sweater to above $I_{clo \cdot S}$ = 1.09 $I_{clo \cdot N}$ = 0.80-0.97 $I_{clo \cdot i}$ = 0.63-0.77

$I_{clo \cdot S}$ from copper manikin tests of similar ensembles by Seppanen et al. (9)

$I_{clo \cdot N}$ from method of Sprague and Munson (10, 11)

$I_{clo \cdot i}$ intrinsic clo as determined by method of Nishi et al. (11)

$\overline{I_{clo \cdot N\ \&\ S}}$ average of $I_{clo \cdot S}$ & $I_{clo \cdot N}$ values for men and women

Table 3

Thermal sensitivity of the subjects with 3 levels of clothing during 4 hour temperature ramps from an initial 25° C.

Clo	ramp	ΔThermal Sensation/ΔT ± S.E.	Correlation Coefficient r
.5	+0.5	0.27 ± 0.01	0.87
	+1	0.54 ± 0.04	0.98
	+1.5	0.33 ± 0.02	0.99
	-0.5	0.73 ± 0.06	0.97
	-1	0.42 ± 0.03	0.99
	-1.5	0.26 ± 0.02	0.98
.7	+0.5	0.30 ± 0.07	0.90
	+1	0.36 ± 0.03	0.98
	+1.5	0.27 ± 0.02	0.99
	-0.5	0.27 ± 0.05	0.91
	-1	0.49 ± 0.03	0.98
	-1.5	0.29 ± 0.04	0.94
.9	+0.5	0.16 ± 0.07	0.70
	+1	0.33 ± 0.05	0.94
	+1.5	0.20 ± 0.02	0.96
	-0.5	0.35 ± 0.05	0.95
	-1	0.45 ± 0.04	0.97
	-1.5	0.41 ± 0.02	0.99
all	all	.305 ± 0.009	0.93

Table 4

Summary of analysis of variance of thermal discomfort votes in comparison to controls.

Ramp	Parameter	P	Ramp	Parameter	P
+ 0.5	time*	N.S.	- 0.5	time*	< 0.01
	clothing	< 0.01		clothing	< 0.01
	sex	< 0.05		sex	N.S.
+ 1.0	time	< 0.01	- 1.0	time*	< 0.01
	clothing	< 0.01		clothing	< 0.05
	sex	N.S.		sex	< 0.05
+ 1.5	time*	< 0.01	- 1.5	time*	< 0.01
	clothing	< 0.05		clothing	N.S.
	sex	< 0.01		sex	N.S.

*temperature is linearly related to time

Table 5

Summary of Ambient Temperature Limits
for 80% Thermal Acceptability

Clothing Clo	Ramp $^{o}C/h$	T_a limit for 80% Thermal Acceptability		Corresponding Thermal Sensation	
		Lower	Upper	Lower	Upper
.5	.5	23	> 27.2	-1.3	>+ .3
	1.	22.2	28.2	-1	+1.3
	1.5	20.	29.9	-1.1	+1.6
.7	.5	< 23	> 27.4	<- .2	>+ .8
	1.	22.1	> 29.7	- .7	> 1.7
	1.5	< 19.4	28.6	<-1.3	+1.2
.9	.5	< 23	> 27.2	<- .4	>+1
	1.	< 20.4	29.1	<-1.2	+1.8
	1.5	20	27.2	-1.2	+1.25
			MEAN	-1.06	+1.43

Table 6

80% thermal acceptability temperature boundaries
for the men and women of this study.

	Lower	Upper
Men		
0.5 clo	21.75	28.7
0.7	21.8	28.3
0.9	20.2	27.2
Women		
0.5 clo	22.5	29.3
0.7	21.6	30.5
0.9	20.3	29.0

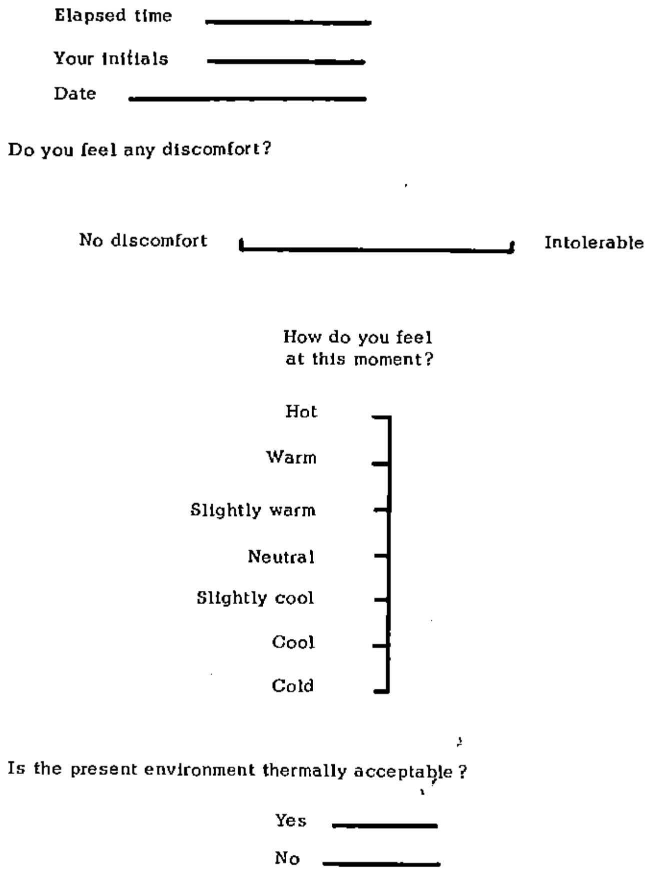

Fig. 1 Human responses ballot

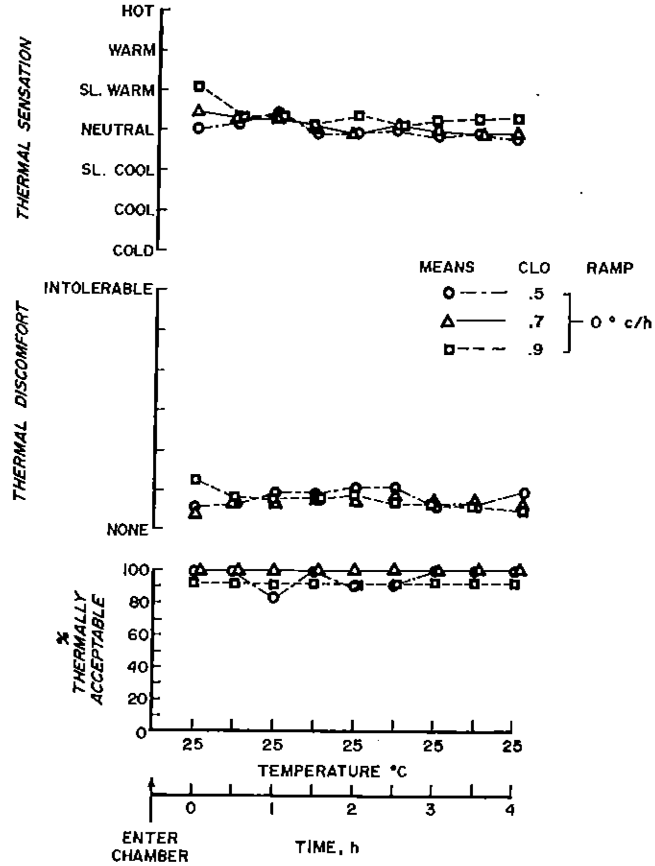

Fig. 2 Mean of subject responses to steady 25^{o}C conditions

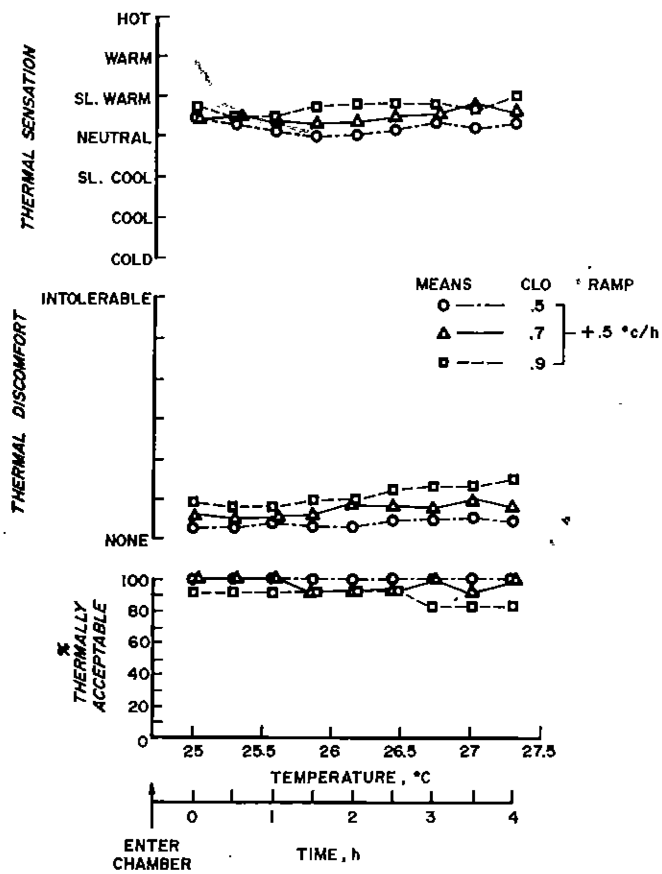

Fig. 3 Mean of subject responses to +0.5 C/h temperature ramp

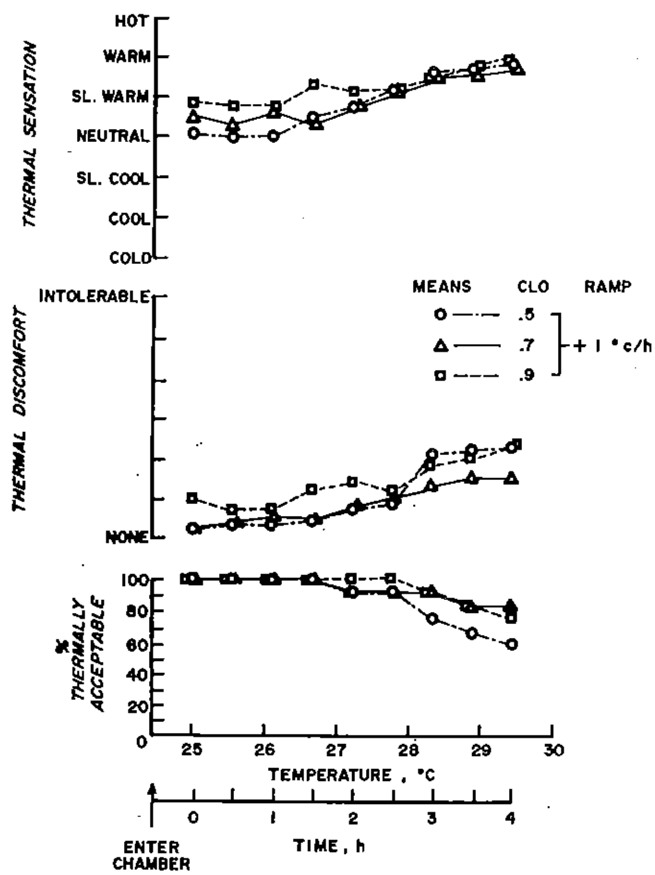

Fig. 4 Mean of subject responses to the +1 C/h temperature ramp

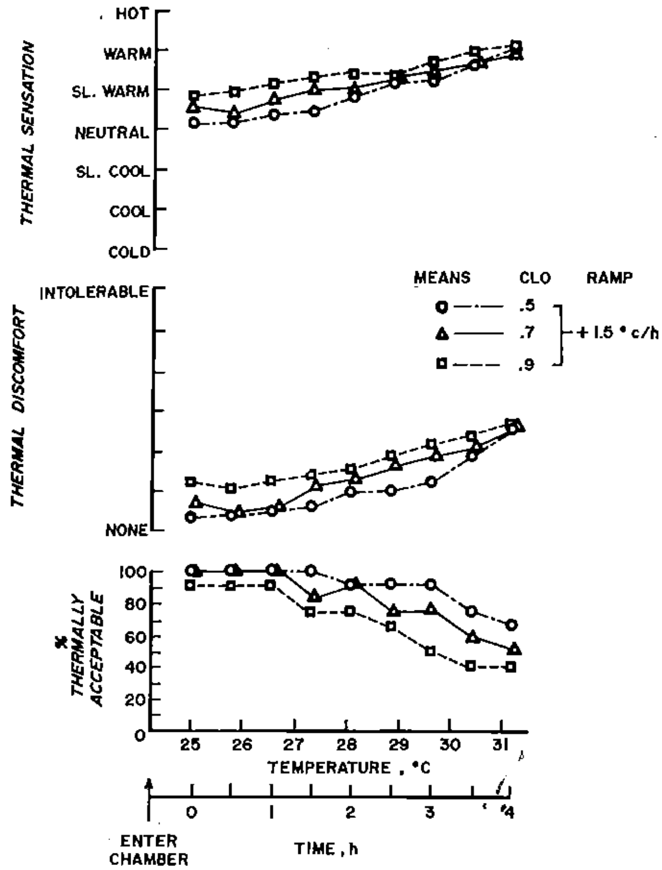

Fig. 5 Mean of subject responses to the +1.5 C/h temperature ramp

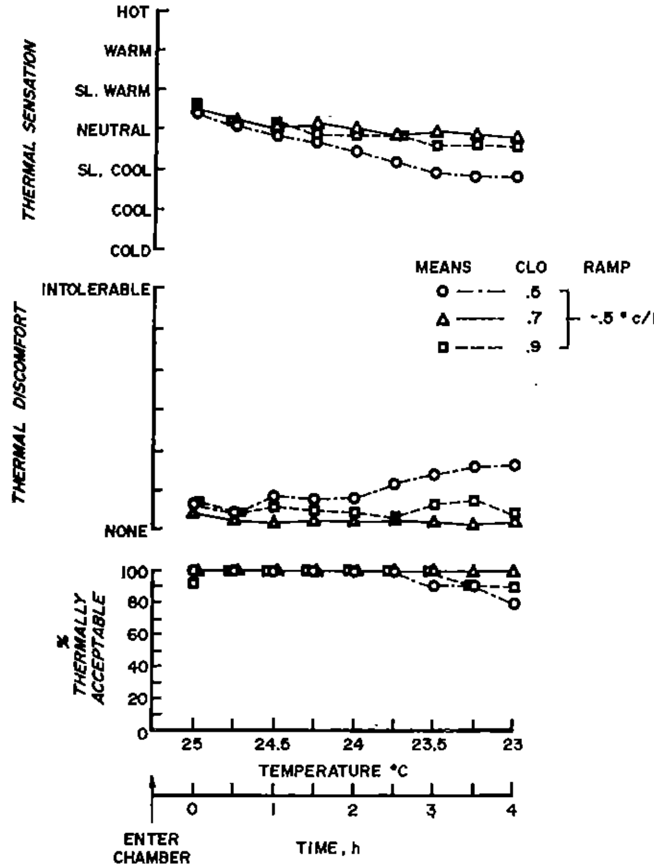

Fig. 6 Mean of subject responses to the -0.5 C/h temperature ramp

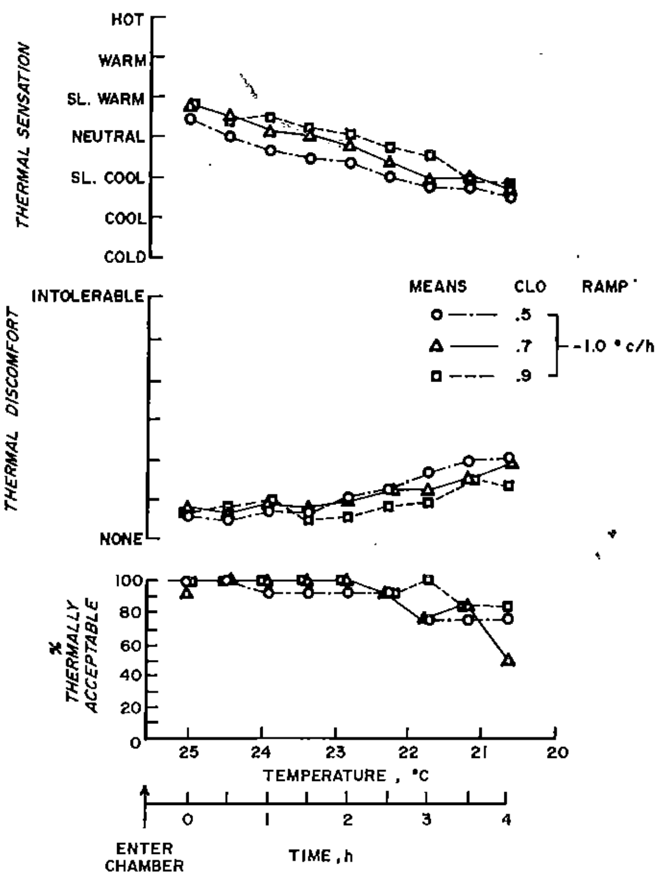

Fig. 7 Mean of subject responses to the -1 C/h temperature ramp

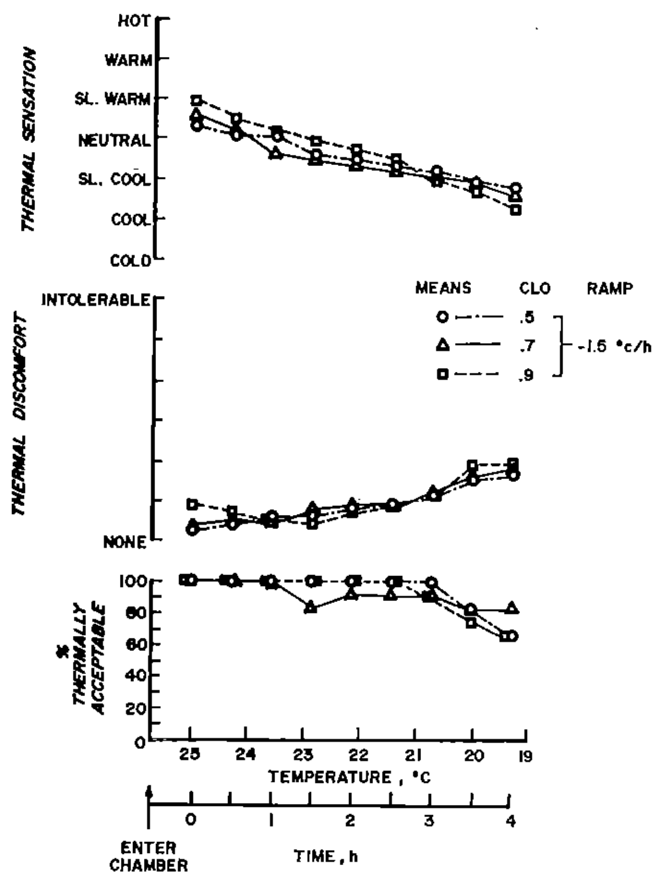

Fig. 8 Mean of subject responses to the -1.5 C/h temperature ramp

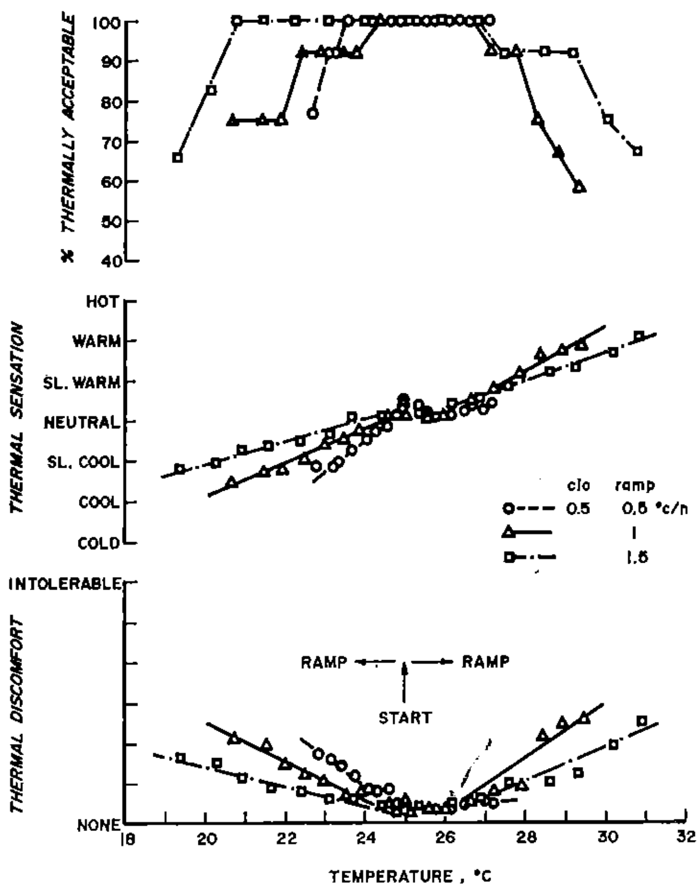

Fig. 9 Mean responses of subjects wearing summer clothing

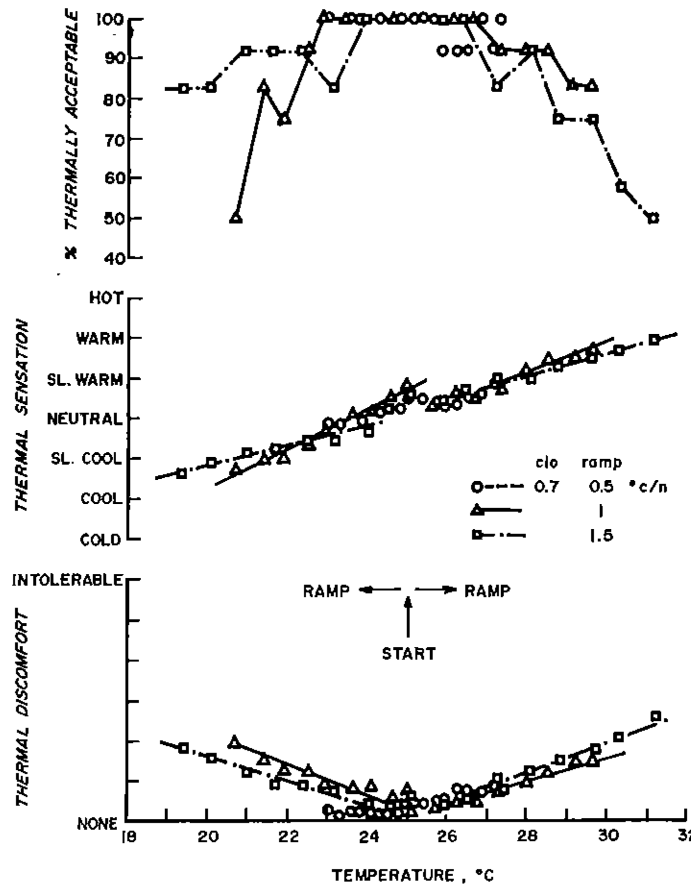

Fig. 10 Mean responses of subjects wearing normal office clothing

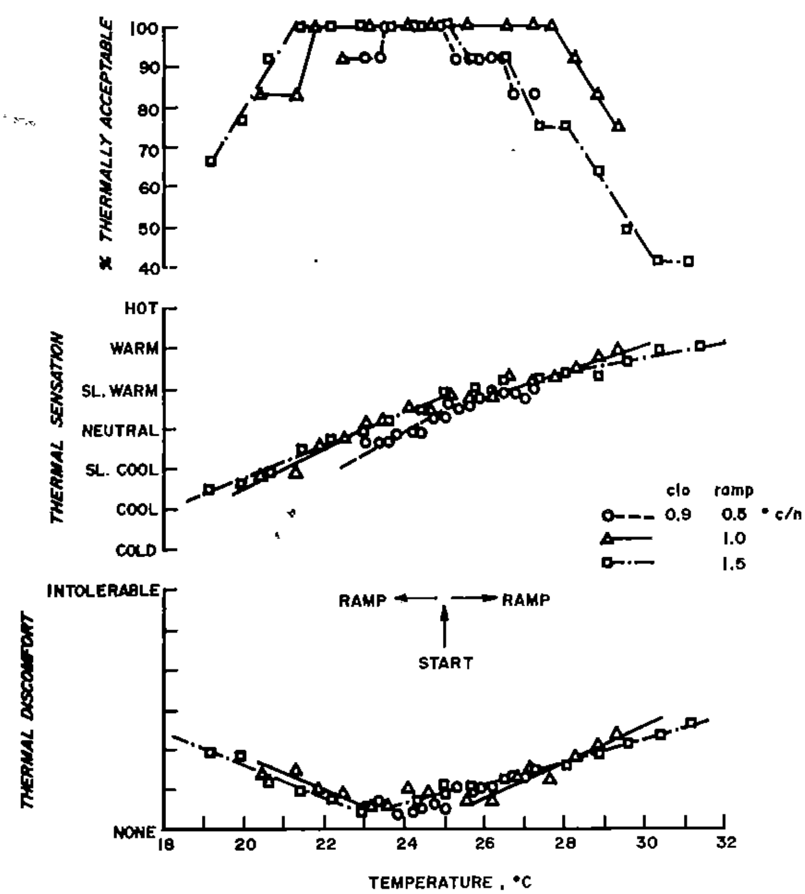

Fig. 11 Mean responses of subjects wearing warmer office clothing

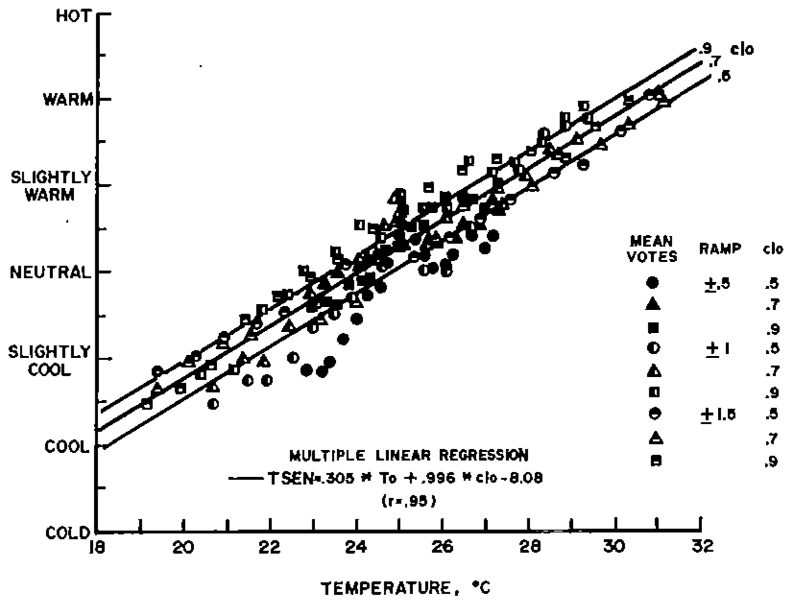

Fig. 12 Thermal sensation results from all the temperature ramps

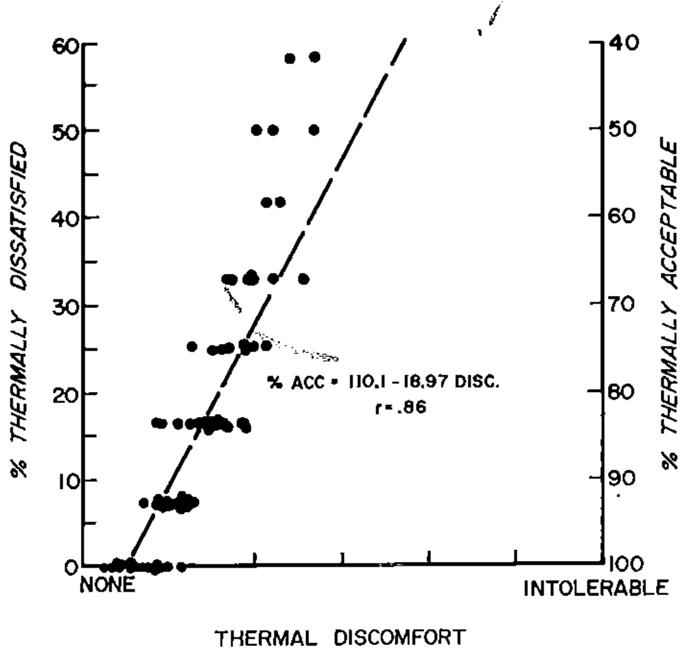

Fig. 13 Relationship between discomfort and acceptability; each point is average of 12 subjects.

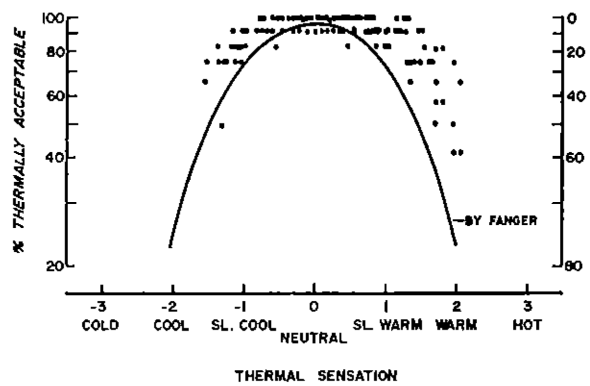

Fig. 14 Mean thermal acceptability and thermal sensation votes of this study compared to those predicted by Fanger

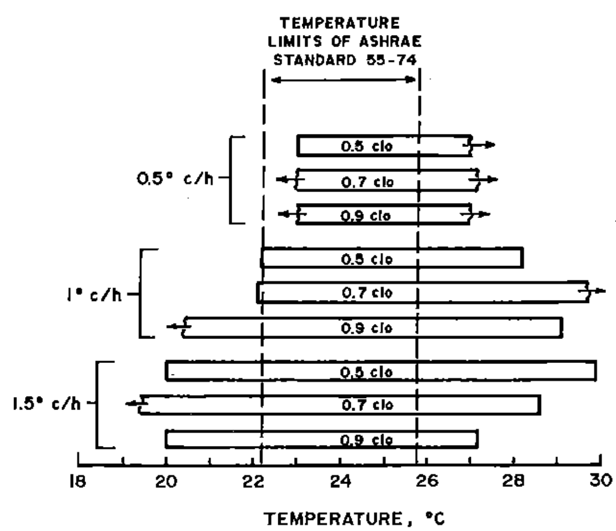

Fig. 15 Comparison of this study's 80% thermal acceptability temperature limits with those of ASHRAE Standard 55-74

Note: ⟶{ indicates 80% thermal acceptability temperature limit was not defined but lies beyond this point in direction of arrow.