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The Effects of Fluctuating Temperature and Relative Humidity on the Thermal Sensation (Thermal Comfort) of Sedentary Subjects

Previous extensive thermal comfort studies, a few of which are documented in references (1-6), have attempted to establish steady state (static) conditions required for thermal comfort of lightly clothed young adult subjects under various practical conditions. The results of these tests, as well as others, have been used in establishing ASHRAE Standard 55-66, "Conditions for Thermal Comfort". This standard specifies the ranges of temperature, relative humidity and air velocity which should be acceptable for thermal comfort in many practical environments. Also specified in this standard are acceptable limits on fluctuation and rate of fluctuation of both temperature and relative humidity in the occupied zone. These sections of the standard are based largely on field experience. The purpose of the research documented in this paper was to provide data, obtained under controlled conditions, as a basis for confirming or modifying the existing specifications on fluctuating thermal conditions.

To fulfill the objectives of the research undertaken, two series of tests were conducted. The first was designed to study the effect of fluctuating dry bulb temperature on the thermal sensation of sedentary subjects. The second was designed to study the effects of fluctuating relative humidity (wet bulb temperature).

EXPERIMENTAL DESIGN

In order to investigate the effects of fluctuating temperature and humidity, 12 college age subjects, 6 male and 6 female, were subjected simultaneously and for three hours to the test conditions specified for the test. A new set of 12 subjects was selected for each additional test. Twelve is the largest number of subjects which can conveniently be fitted into the KSU-ASHRAE test chamber under conditions simulating a practical office or residential situation. The subjects were arranged in three rows of four each, males and females alternately. They sat in classroom type seats with a writing arm. Each subject was given a 2" thick foam pad for the seat and another for the feet. The subjects activity level was sedentary throughout the test. The subject wore the previously described (2) KSU standard uniform shown in Fig. 1 which has an insulating value of about 0.6 clo. For the first 12 temperature tests, the subjects recorded their thermal sensations on the ballots shown in Fig. 2. For temperature tests 12 through 16 and all humidity tests, the ballot shown in Fig. 3 was used. The ballots were handed out individually just before each voting period and collected immediately afterward.

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Fig. 1. Typical Test Subjects Wearing KSU Standard Uniforms

Previous tests (2) have shown that 78 F (dry bulb = mean radiant temperature), 45% RH and 25-30 ft/min air velocity specify a thermal condition preferred by similar subjects. Therefore, these thermal conditions were selected as the desired mean conditions for all tests. Fluctuation in temperature and humidity were made about these mean conditions during the tests. These fluctuations were designed to be triangular wave forms with rates of change representative of practical and expected future field experience. The amplitude and period of the waves were varied to reflect field experience and to test the subjects' responses. For the temperature effect tests, only the dry bulb temperature of the air was varied. Mean radiant temperature was held constant at 78 F to minimize the number of variables undergoing change. This was felt justified since in most practical applications, air temperature is the primary control variable. Under the expected cyclic conditions, mean radiant temperature is "lagged" enough by the building materials of the space so that it may be considered

SUBJECT
NAME________________________________ NO.______

Circle the number that describes how you feel.

1. cold
2. cool
3. slightly cool
4. neutral
5. slightly warm
6. warm
7. hot

____

____

Fig. 2. Discrete Scale Thermal Sensation Ballot

SUBJECT
NAME ______________________________ NO. ______

Mark the scale with an arrow at the point which describes the way you feel.

1 COLD

2 COOL

3 SLIGHTLY COOL

4 NEUTRAL

5 SLIGHTLY WARM

6 WARM

7 HOT

Fig. 3. Continuous Scale Thermal Sensation Ballot

constant. Only in the case of very light radiant heating panels will the mean radiant temperature change rapidly. When more massive radiant panels are used, mean radiant temperature also changes under controlled conditions, but not so rapidly. These tests were not designed nor intended to apply to these cases. For the humidity tests, moisture content of the air was varied while all other thermal conditions were held constant.

In order to assess the subjects' reactions to the fluctuations, the thermal sensation ballots had to be taken frequently. A 7½ minute interval was chosen. This interval could be managed efficiently and was short enough to test for correlation with the fluctuations. Towards the end of the temperature test series and for the entire humidity test series, the continuous thermal sensation ballot (Fig. 3) was used to provide the opportunity for test subjects to resolve small temperature or relative humidity changes.

As the tests proceeded, the data were analyzed for correlation of thermal sensation with the magnitudes and rates of change of the variables. Results of these analyses were used in selecting conditions for further tests.

During the tests, the illumination intensity at desk top level was 133 foot candles and the noise level was 69 db measured on the all band-pass scale of an octave band sound analyzer. (General Radio type 1558-A S/N 253)

FACILITIES

All tests of the experimental program were carried out in the KSU-ASHRAE Environmental Test Chamber of the Institute for Environmental Research at Kansas State University. The chamber is 12 ft x 24 ft in plan and employed an 8 ft ceiling height. It has facilities for control of air temperature, and wet bulb temperature as well as surface temperature and air velocity. A description of the total chamber facilities is provided by Nevins, et al. (2).

PROCEDURE

All tests were conducted in the afternoon or evening during the period of June 1968 to June 1969, inclusive. The subjects were randomly assigned to a testing session; however, no subject was used more than once in either phase of the project. To be consistent with previous studies, subjects naive in the practice of voting on a thermal sensation ballot and interpreting the terms on the ballots were used. A registered nurse and an assistant served as monitors for each test.

As the subjects arrived for a testing session, they were given the KSU standard cotton twill uniforms to wear. The underclothing consisted of brassieres and underpants for the women and shorts (no undershirts) for the men. They wore cotton sweat socks but no shoes. The height, clothed weight, and oral temperature were taken for each subject in the pre-test room. The physical data collected for the subjects (means and standard deviations) used in each series of tests are shown in Table I. Additional information was obtained from the subjects which might aid in explaining unusual variations in the data, e.g. amount of alcohol consumed in the past 24 hrs., the amount of sleep and work in the past 24 hours, etc. The subjects remained for about one-half hour in the pre-test room before entering the test chamber immediately adjacent.

After an oral indoctrination explaining the purpose and procedure of the test (Appendix A), the subjects entered the test chamber. The men and women were randomly assigned to their respective positions.

The exposure time was 3 hrs for all tests. The subjects were allowed to study, read, or engage in limited conversation while in the test chamber. No subject was allowed to leave until the full 3 hrs were completed. A measured but unlimited supply of tap water was provided for each subject. No one was allowed to sleep. A ballot was handed individually to the subjects immediately upon entering the test chamber and a new ballot was presented at each succeeding interval. The ballots were collected immediately after each voting period and the results recorded. Dry bulb or wet bulb temperature, whichever was being varied, was also recorded at the time the subjects voted. A continuous recording of the fluctuating variable was also made and marked with an event marker at the time of voting to provide a time key for later correlation studies.

Following the last vote at the end of the third hour, the subjects were taken back into the pre-test room. Their final clothed weight was taken after which they were paid and allowed to leave.

TABLE I

A. PHYSICAL DATA FOR THE SUBJECTS USED IN THE TEMPERATURE TESTS

SEX	NO. OF SUBJECTS	AGE (YR)	HEIGHT (IN)	WEIGHT (LB) IN UNIFORM
Male	78	20.5 ± 2.5	69.8 ± 2.7	165.6 ± 17.3
Female	78	19.7 ± 1.9	64.4 ± 2.5	126.3 ± 14.3

B. PHYSICAL DATA FOR THE SUBJECTS USED IN THE HUMIDITY TESTS

SEX	NO. OF SUBJECTS	AGE (YR)	HEIGHT (IN)	WEIGHT (LB) IN UNIFORM
Male	48	20.0 ± 1.6	69.8 ± 2.0	169.2 ± 19.7
Female	48	19.7 ± 1.3	63.9 ± 2.0	125.6 ± 13.0

RESULTS AND DISCUSSION

Temperature Tests

The ASHRAE Standard 55-66 section on dry bulb temperature fluctuations within the comfort zone is restated below for convenience.

> "3.1.3 The rate of change of dry bulb temperature at any point in the occupied zone shall not exceed 4 deg/hr if the peak to peak variation in the temperature cycle is two degrees or greater within the limits stated in 3.1.1."

The zone of acceptable operation prescribed by this standard is shown in Fig. 4 on a rate of temperature change-temperature amplitude coordinate system. In terms of Fig. 4, one project objective was to verify or suggest modifications to the region of this plane which represents an acceptable operating region. It was deemed highly desirable to find a single numerical quantity of some type which could be used to define the acceptable region.

Table II shows the test conditions employed in the temperature tests. These conditions are also plotted in Fig. 4. It can be seen that they span the boundary of the acceptable region as currently specified in the ASHRAE standard.

In previous studies, when steady state information was desired, data from the first hour or more were not used in the statistical analysis since there is always an adaptation period during which the votes usually decrease. In this study, where changes with time were desired, all votes were used. For each voting time, votes from the 12 subjects were averaged. Single and multiple regression analyses were used to check correlation of average vote with temperature (single regression) and with temperature and temperature rate (multiple regression). Temperature rate data were obtained by estimating the instantaneous slope, at the voting time, on the continuously recorded temperature-time chart. Average temperature rate data, used to categorize test conditions, were obtained by regarding the rates as fixed over one vote interval. These rate data

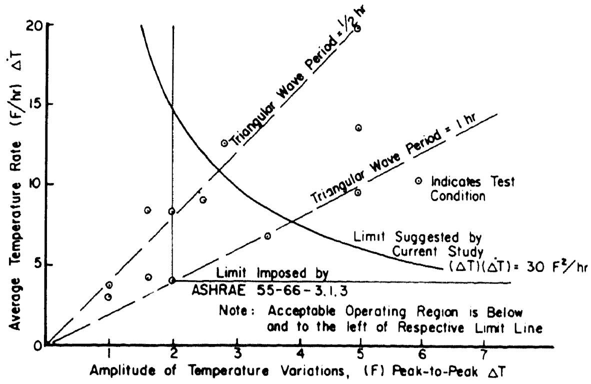

Fig. 4. Test Conditions and Suggested Thermal Comfort Limits for Fluctuating Temperature Tests Compared to the ASHRAE Standard 55-66

TABLE II

TEST CONDITIONS FOR FLUCTUATING TEMPERATURE TESTS

TEST NO.	FLUCTUATION PERIOD – (HR)	PEAK TO PEAK AMPLITUDE – (F)	AVERAGE FLUCTUATION RATE – (F/HR)
1	1	5.0	9.5
2	1	3.5	6.8
3	1	6.0	10.2
4	2/3	5.0	13.5
5	1	1.0	3.0
7	½	5.0	19.7
9	½	1.0	3.7
10	½	2.0	8.3
11	1	2.5	9.0
12	1	2.0	4.1
13	1	1.6	4.2
14	½	1.6	8.4
16	½	2.8	12.6

TABLE III

CORRELATION OF AVERAGE VOTE WITH TEMPERATURE AND RATE OF CHANGE OF TEMPERATURE

TEST CONDITIONS				REGRESSION COEFFICIENTS				CORRELATION COEFFICIENTS		
TEST NO.	TEMP RATE F/HR $\dot{\Delta T}$	AMPLITUDE PEAK TO PEAK F ΔT	$(\Delta T)(\dot{\Delta T})$ F^2/HR	MEAN VOTE	VOTE WITH TEMPERATURE VOTE/F		VOTE WITH TEMP RATE VOTE/F/HR	CORRELATION WITH TEMP		CORRELATION WITH TEMP RATE
				a_1	b_1	b_2	b_3	TEMP ONLY	TEMP AND TEMP RATE	
1	9.5	5.0	47.5	3.89	0.147	0.147	0.000	0.843	0.844	0.000
2	6.8	3.5	23.8	4.02	0.137	0.129	0.011	0.738	0.833	0.457
3	10.2	6.0	61.1	3.79	0.150	0.148	0.006	0.836	0.857	0.227
4	13.5	5.0	67.5	3.86	0.121	0.120	0.005	0.778	0.820	0.287
5	3.0	1.0	3.0	3.81	0.000	0.000	0.013	–0.113	0.231	0.142
7	19.7	5.0	98.5	3.73	0.208	0.212	0.006	0.814	0.881	0.295
9	3.7	1.0	3.7	3.96	0.289	0.283	0.007	0.771	0.778	0.215
10	8.3	2.0	16.6	4.17	0.183	0.174	0.008	0.611	0.682	0.359
11	9.0	2.5	22.5	4.10	0.284	0.277	0.016	0.885	0.932	0.353
12	4.1	2.0	8.2	4.06	0.169	0.163	0.005	0.617	0.634	0.246
13	4.2	1.6	6.7	4.14	0.308	*	*	0.611	*	*
14	8.4	1.6	13.5	4.10	0.066	*	*	0.335	*	*
16	12.6	2.8	35.2	4.25	0.156	*	*	0.805	*	*

* Numbers not calculated

were then averaged over the test length to get the average rate for the entire test. Although a perfect triangular wave form could never be generated, Fig. 4 shows that the test conditions, based on this average, fell quite close to the desired triangular wave. (Appendix B shows typical wave forms generated for both the temperature and humidity tests.)

The equations used in the regression analyses are

$$Y = a_1 + b_1 (T_{DB} - \bar{T}_{DB}) \qquad (1)$$

$$Y = a_1 + b_2 (T_{DB} - \bar{T}_{DB}) + b_3 \frac{dT_{DB}}{d\theta} \qquad (2)$$

where

Y = average vote of twelve subjects

T_{DB} = instantaneous dry bulb temperature F

$\bar{T}_{DB}$ = mean dry bulb temperature F

b_1 & b_2 = regression coefficient-temperature

a_1 = mean vote taken over all temperatures

b_3 = regression coefficient-temperature rate

$\frac{dT_{DB}}{d\theta}$ = instantaneous rate of change of dry bulb temperature F/hr

Results of these analyses, along with correlation coefficients, are shown in Table III. Although there is some correlation with temperature rate it is erratic and not significant at the 5% level. From this analysis it was concluded that average vote is not correlated in a direct way with temperature rate to any important extent. This does not preclude the possibility, however, as will be shown later, that rate is important in an indirect way.

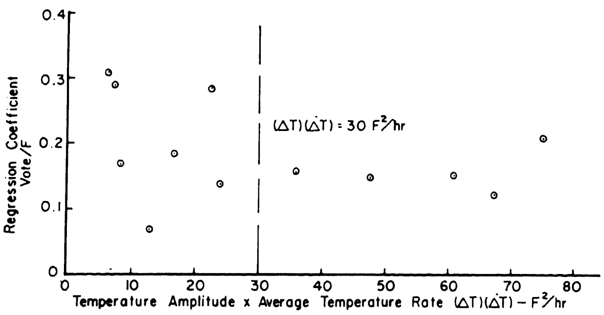

Fig. 5. Regression Coefficient (Vote with Temperature) Versus Temperature Amplitude Times Average Temperature Rate for the Fluctuating Temperature Tests

A careful examination of Table III reveals that, although votes and rate are not directly correlated to a significant level, votes and temperature correlate more closely when the temperature rates are high. This suggests that rate is important but in a more subtle way than previously considered. Fig. 5 shows a plot of regression coefficients for the individual tests as a function of the fluctuation parameter $(\Delta T)(\Delta\dot{T})$, where ΔT is the peak to peak amplitude and $\Delta\dot{T}$ the average rate of temperature variation. From this data presentation, one notes that the regression coefficient is essentially constant at about 0.150 for $(\Delta T)(\Delta\dot{T})$ values above approximately 30 F^2/hr. Below this value the regression coefficients are very erratic with values ranging from 0.00 to over 0.30. Further, one notes that the correlation coefficients from Table III are higher for the higher $(\Delta T)(\Delta\dot{T})$ values. This suggests that, on the average, the test subjects cannot consistently correlate with fluctuating temperatures if $(\Delta T)(\Delta\dot{T})$ is less than about 30 F^2/hr. The line of constant $(\Delta T)(\Delta\dot{T})$ is a hyperbola in the $\Delta\dot{T}$ – ΔT plane and the line for $(\Delta T)(\Delta\dot{T}) = 30\ F^2/hr$ is shown in Fig. 4.

Humidity Tests

The ASHRAE Standard 55-66 section on acceptable relative humidity fluctuations within the comfort zone is restated below for convenience.

> "3.2.2 The rate of change of relative humidity at any point in the occupied zone shall not exceed 20 percent/hr if the peak to peak variation of the humidity cycle is 10 percent or more within the limits stated in 3.2.1."

The region of operation prescribed by this standard is shown in Fig. 6 on a rate of humidity change $(\Delta\dot{RH})$ – humidity amplitude (ΔRH) coordinate system. Test conditions used for the tests are listed in Table IV and also shown on this figure. In terms of this figure, another project objective was to verify or suggest modifications to the region of this plane which is an acceptable operating region.

For all tests in the humidity series, the continuous thermal sensation ballot (Fig. 3) marked at 7½ minute intervals, was used. Thermal sensation votes, averaged over the twelve subject responses taken at the end of each 7½ minute interval, were correlated with relative humidity by using a linear correlation equation. The results of this analysis are shown in Table V. Only two of these tests, numbers 1 and 2, show average vote-humidity correlation which is significant at even the 5% level. The other test results show little correlation. In the first two tests in the series difficulty was experienced with the programmer as a consequence of which the average relative humidity in the test room slowly increased as the test proceeded. By contrast, in the other tests, the time averaged humidity remained constant. It thus appears that in all tests but the first two the humidity changed in a periodic way with such a short period that the test subjects could not respond. In the first two tests the subjects experienced a slowly changing humidity which they were able to detect. It appears then, that all of the test conditions employed lie within an acceptable operating range.

The tests discussed above have shown that relative humidity variations which occur rapidly, that is, periodically with periods of an hour or less are not noticeable. Variations in humidity which occur very slowly, that is, quasi-steady humidity conditions, have been shown to be noticeable to persons in the occupied zone with a 40% change in RH corresponding to a half vote change in comfort vote (2). The exact cycling rate at which humidity variations become noticeable has not yet been established. The results presented above are for a restricted range of amplitudes, rates, and periods

TABLE IV

TEST CONDITIONS FOR FLUCTUATING HUMIDITY TESTS

TEST NO.	FLUCTUATION PERIOD – (HR)	PEAK-TO-PEAK FLUCTUATION AMPLITUDE – (%RH)	AVERAGE FLUCTUATION RATE – (%/HR)
1	1	12	24
2	1	13	26
3	1	8	16
4	1	14	28
6	1	5	10
7	½	3	12
8	½	13	42
9	½	6	24

TABLE V

CORRELATION OF AVERAGE VOTE TO RELATIVE HUMIDITY

TEST NO.	CONDITIONS AMP (%) PK-PK	PERIOD (HRS)	$(\Delta RH)(\dot{\Delta} RH)$	REGRESSION COEFFICIENT	CORRELATION COEFFICIENT
1	12	1	288	0.023	0.649
2	13	1	338	0.024	0.710
3	8	1	128	0.003	0.081
4	14	1	392	0.022	0.308
6	5	1	50	0.000	–0.003
7	3	½	36	0.000	–0.354
8	13	½	676	0.000	–0.331
9	6	½	144	0.000	–0.432

ΔRH = Peak to peak amplitude – %
$\dot{\Delta} RH$ = Average rate – %/hr

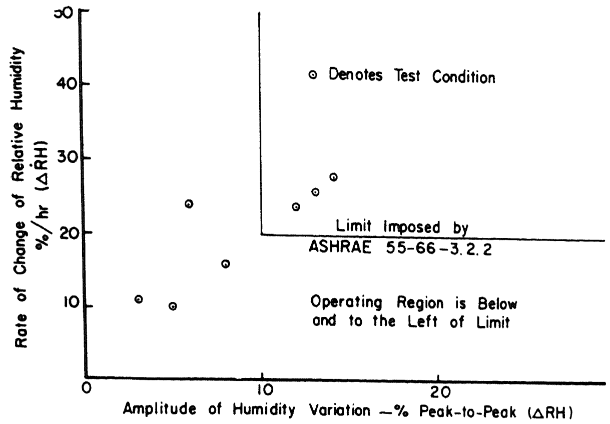

Fig. 6. Test Conditions for Fluctuating Humidity Tests Compared to the ASHRAE 55-66 Standard

of humidity fluctuations. Therefore, the conclusions drawn from these results may not hold for conditions outside the ranges tested.

Over the range of humidity amplitudes and cycling frequencies employed in this series of tests, little correlation between thermal sensation vote and the fluctuating component of relative humidity has been found. Apparently these cycling humidity conditions did not affect the heat exchange of the test subjects to a noticeable degree. In an attempt to verify that this was the case a transient humidity adsorption test was run on the type of uniform (including socks and underwear) used in all the tests. The uniform was draped over a frame constructed to represent, as nearly as possible, the shape of the human body. It was then placed in the test room and allowed to reach equilibrium with the surroundings at 78 F and 20% RH. The uniform and assembly were then moved to an adjacent room where the relative humidity was 33%. Weight change as a function of time was then monitored using a very sensitive metabolic scale. The uniform increased in weight in an exponential fashion. The total steady state weight change corresponding to the 13% humidity change was 9 grams and the time constant was determined to be about 10 minutes.

Assuming that moisture enters the uniform by condensing from the air then the heat input to the test subject resulting from changes in relative humidity may be calculated by using the heat of vaporization (condensation) of water at a saturation temperature corresponding to the ambient dry bulb. It should be noted that moisture in materials is "bound" with a molecular bond requiring more energy than with liquid water so that the effective latent heat of condensation may be from 5-20% higher than the steam table values. For the calculations summarized below, the steam table value has been used. Therefore, the actual rate of change of heat loss would be larger than the sample calculations shown. By using the steam table value of 1050 Btu/lbm for the heat of condensation it is estimated that about 1.6 Btu are received (increasing humidity) or given up (decreasing humidity) by the test subject for each percentage change in relative humidity. This applies only for fluctuating conditions where the test subject and uniform are never in static equilibrium with the surroundings. Because of the time constant of the uniform and the cycling test conditions, the effect of humidity will be even less than the 1.6 Btu/% and the effect will decrease progressively as the cycling rate increases.

To put the above numbers in proper prospective it is useful to consider sinusoidal variations in relative humidity. Under comfortable conditions, the average male test subject should be generating and losing heat at the rate of about 400 Btu/hr. By assuming that the test subject's response to changes in heat transfer due to moisture content variation in the clothing is practically instantaneous with respect to the clothing lag of 10 minutes, then it is possible to write

$$\frac{\Delta Btu}{hr} = \frac{(\Delta RH)\,(\omega)\,(0.0015)\,(1050)\,\cos \omega t}{2\sqrt{1+\left(\frac{\omega}{6}\right)^2}} \qquad (3)$$

where

$\Delta Btu/hr$ = change in heat transfer rate from 400 Btu/hr – (Btu/hr)

ΔRH = peak to peak humidity variation – (%)

ω = frequency of variation in rad/hr = 2π (CPH)

CPH = cycles per hour

$1/\sqrt{1+\left(\frac{\omega}{6}\right)^2}$ = attenuation factor due to clothing lag

1050 = heat of vaporization of water – (Btu/lbm)

0.0015 lbm/% = water absorbed by KSU standard uniform for each % increase in relative humidity

Eq (3) gives the instantaneous change in heat transfer rate for sinusoidally varying relative humidity. If it is assumed that the test subject will object to a change in the environment which will alter the heat exchange rate by 10% or 40 Btu/hr above or below 400 Btu/hr then this may be used to estimate the bounds of acceptable humidity variations. For average rather than instantaneous deviations in heat transfer rate – a more realistic measure of significance of varying humidity – and the assumed 40 Btu/hr change in heat transfer rate, equation (3) may be rearranged and simplified to bound ΔRH by

$$\Delta RH < \frac{80\sqrt{1+(\frac{\omega}{6})^2}}{\omega} = \frac{80\sqrt{1+(\frac{2\pi CPH}{6})^2}}{2\pi CPH} \qquad (4)$$

Eq (4) defines the relationship between peak to peak amplitude (ΔRH) and the number of cycles per hour (CPH) for RH variations which should be acceptable (or unnoticeable) to the average human occupant, lightly clothed and in a sedentary state of activity. Acceptable is defined here as the RH variation which would, on the average, cause about a $\pm$ 40 Btu/hr (10%) change from the heat transfer rate associated with thermal comfort (neutrality). Results of numerous previous temperature tests have shown that a 10% variation in heat loss corresponds to a thermal sensation vote change of about 0.4. The "comfort zone" has been commonly defined as encompassing average votes from 3.5 to 4.5. Therefore, a 10% change in heat loss should be a reasonable but conservative number for this purpose. Gagge, et al. (7) have also stated that comfort should occur if the rate of storage of metabolic heat is maintained below 10% of the metabolic rate, or 40 Btu/hr in this case.

A similar evaluation was performed on a light business suit ensemble of the type commonly worn by men. The bounding relation for the suit, derived under similar assumptions, is

$$\Delta RH < \frac{45\sqrt{1+(\frac{2\pi CPH}{2})^2}}{2\pi CPH} \qquad (5)$$

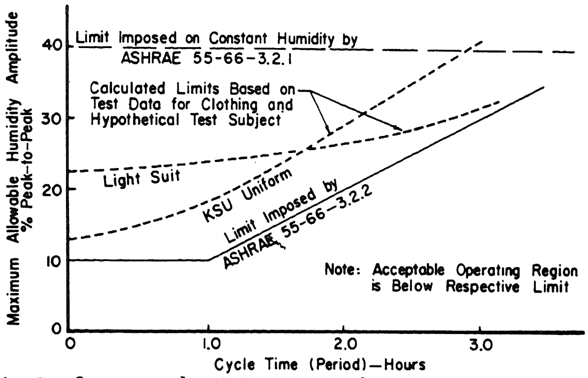

Fig. 7. Suggested Maximum Humidity Amplitude for Thermal Comfort Versus Cycle Time for Triangular Wave Humidity Variations

Data obtained from equations (4) and (5) are plotted in Fig. 7 as maximum peak to peak humidity variation versus cycle time in hours. The bounds established by this figure are above both the test conditions employed in the humidity test series (Table IV) and the conditions allowed by ASHRAE 55-66-3.2.2. If the assumptions on which the data in Fig. 7 are based are valid, then the lack of correlation experienced from the humidity tests is the expected result.

It is important to note that the initial rate of moisture gain in the KSU standard uniform clothing ensemble for a step change of only 13% RH corresponds to an instantaneous heat transfer rate change of about 125 Btu/hr or nearly 1/3 of the sedentary metabolic rate. This is a substantial amount, and seems to be ample evidence to explain the discrepancy between the "effective temperature" and the more recent Nevins, et al. (2) concept of thermal comfort. As a person suddenly enters an environment of different RH, the condensation or evaporation of moisture in the clothing gives rise to an immediate heat gain or loss, which disappears after a period of time as the clothing ensemble reaches moisture equilibrium, usually within an hour, according to the voting experience of the subjects.

The results on acceptable temperature fluctuations for thermal comfort are presented in this paper in terms of the parameter (ΔT) ($\Delta\dot{T}$). These results have shown that acceptable fluctuations are characterized by (ΔT) ($\Delta\dot{T}$) < 30 F^2/hr. This is the single parameter description of the acceptable operating region which was mentioned earlier as being desirable. For field application it may be

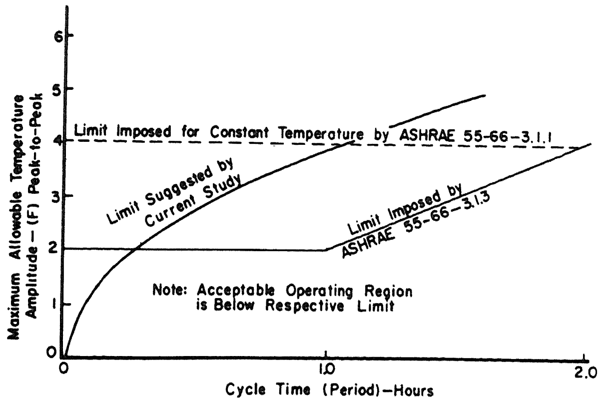

Fig. 8. Suggested Maximum Temperature Amplitude for Thermal Comfort Versus Cycle Time for Triangular Wave Temperature Variations

more convenient, however, to express the data in another way. This may be done by assuming that cyclic variations in temperature are typical of many air conditioning installations and further assuming that these variations are approximately triangular in nature. Under these assumptions (ΔT) (ΔT) = 30 F^2/hr may be expressed as

$$\Delta T = \sqrt{15 \text{ Period}} \qquad (6)$$

where ΔT is the peak to peak temperature variation which must not be exceeded and PERIOD is the cycle time in hours. This relationship is plotted in Fig. 8. The limits of acceptable steady state temperature imposed by Section 3.1.1 of the ASHRAE Standard 55-66 are also shown on this figure.

In evaluating the test conditions achieved, the waveforms, and other aspects of the cyclic temperature and humidity conditions, one should bear in mind the difficulty of providing carefully controlled variations of 1 or 2 F or %. The temperature programming problem proved to be particularly difficult and was a continual source of agony. This problem was finally solved satisfactorily by designing a new electro-pneumatic control system which employed a thermistor as the sensing element. The high sensitivity to temperature of the thermistor resistance, combined with the electronic link (as opposed to a pneumatic amplifier link) to the final control element alleviated the resolution problem encountered with the conventional controller.

CONCLUSIONS

1. In practical, air conditioned spaces where dry bulb air temperatures normally fluctuate periodically under control, no serious occupancy complaints should occur due to temperature fluctuations if [ΔT^2(CPH)] < 15. ΔT is the peak to peak amplitude of the temperature fluctuation (F) and CPH is the cycling frequency (cycles/hr). For example, if ΔT = 2 F, then CPH < 3.75 cycles/hr would be an acceptable cycling rate. If CPH = 7.5 cycles/hr, then $\Delta T < \sqrt{2} = 1.4$ would be an acceptable temperature fluctuation amplitude. This does not apply to controlled radiant systems, where the mean radiant temperature fluctuates, since the effect of varying radiant temperature was not investigated.
2. The current ASHRAE Standard 55-66 "Conditions for Thermal Comfort" employs an oversimplified concept to specify acceptable rate of change limits on dry bulb temperature, but these limits, although somewhat conservative, agree well with the results of this study.
3. Until further work is done to establish acceptable radiation fluctuations, it is recommended that the present information in ASHRAE Standard 55-66 be employed.
4. In practical air conditioned spaces where relative humidity variations can be expected, no serious occupancy complaints should occur if the current ASHRAE standard, Section 3.2.2, on fluctuating relative humidity is followed. Fluctuations more severe than those allowed by the ASHRAE standard may not be objectionable but the range and extent of test conditions employed in this series is not sufficient to justify relaxing the Standard at this time.

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REFERENCES

1. P. E. McNall, Jr., J. Jaax, F. H. Rohles, R. G. Nevins, and W. E. Springer, Thermal Comfort (Thermally Neutral) Conditions for Three Levels of Activity, ASHRAE Transactions, Vol. 73, Part 1, 1967.
2. R. G. Nevins, F. H. Rohles, W. E. Springer, and A. M. Feyerherm, A Temperature-Humidity Chart for

Thermal Comfort of Seated Persons, ASHRAE Journal, Vol. 8, No. 4, 1966.
3. P. O. Fanger, Calculation of Thermal Comfort, ASHRAE Transactions, Vol. 73, Part II, III 4.1, III 4.20, 1967.
4. A. P. Gagge, J. A. J. Stolwijk and J. D. Hardy, Comfort and Thermal Sensations and Associated Physiological Responses at Various Ambient Temperatures, Environmental Research, 1, 1-20, 1967.
5. P. E. McNall, Jr. Jay C. Schlegel, The Relative Effects of Convection and Radiation Heat Transfer on Thermal Comfort (Thermal Neutrality) for Sedentary and Active Human Subjects, ASHRAE Transactions, Vol. 74, 1968.
6. P. E. McNall, Jr., J. C. Schlegel, The Effect of Asymmetric Radiation on the Thermal and Comfort Sensations of Sedentary Subjects, ASHRAE Transactions, Vol. 74, 1968.
7. A. P. Gagge, J. A. J. Stolwijk and Y. Nishi, The Prediction of Thermal Comfort When Thermal Equilibrium is Maintained by Sweating, ASHRAE Transactions, 1969. Presented at the Semi-Annual Meeting of ASHRAE, Denver, Colorado, July 1969.

APPENDIX A

Indoctrination Information – Read to Subjects Before Each Test

The purpose of this test is to determine the effect of temperature on how you feel. As soon as preparations are completed in the pre-test room, we will take you into the test room next door. Select your assigned chair and be seated. Do not move the chairs from their original locations.

During the test, you may read, study, or engage in quiet conversation. You may smoke, but keep it to a minimum. At various intervals, you will be asked to vote on your feeling of thermal sensation (show sample ballot). You will record your votes on the ballots provided. Do not discuss your votes with one another. Remember, we want to know the way you feel at the time the ballot is handed to you! The thermal sensation ballot has seven conditions from which you can select the one which best describes your feeling at that time. (For the continuous scale thermal sensation ballot the instruction would read: The thermal sensation ballot has a continuous scale running from 1 to 7. Please mark the scale with an arrow at the point which describes the way you feel.)

Water will be provided and since the amount you drink will be measured, you should drink only out of the cup assigned to you. You may have all the water you wish.

When the test is finished, go to your respective dressing rooms and get dressed. The women should put their shirts, trousers, and socks in one pile in the dressing room. The men should place their uniforms and socks on the table by the pre-test room door. Do not leave uniforms in the men's restroom.

Each of you will sign a receipt for your pay, $5.00, which you will receive at the end of the test.

Are there any questions?

APPENDIX B

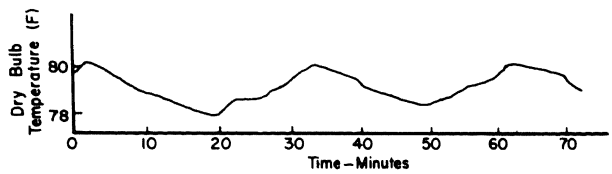

Fig. B-1. A Portion of a Typical Dry Bulb Temperature-Time Record for the Fluctuating Temperature Tests

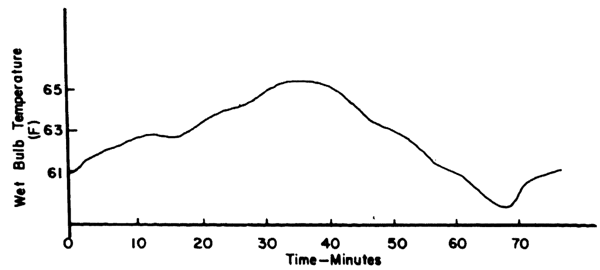

Fig. B-2. A Portion of a Typical Wet Bulb Temperature-Time Record for the Fluctuating Humidity Tests