TWO TECHNIQUES FOR THE DEVELOPMENT OF AN INSTRUMENT TO EVALUATE THE QUALITY OF A THERMAL ENVIRONMENT

by

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LIST OF SYMBOLS

ET*	Effective temperature defined in text
f_{cl}	Ratio of the clothed body surface area to the nude body surface area
f_{eff}	Ratio of the effective body radiation area to the nude body surface area
h_c	Convective heat transfer coefficient
I_{cl}	Clothing insulation value, clo
M	Metabolic rate
m	Metabolic rate per unit nude body area
P_a	Water vapor partial pressure
PMV	Predicted mean vote
r	Radiation heat loss from clothed body surface per unit of nude body area
T_{cl}	Mean outer surface temperature of clothing (absolute degrees)
t_{cl}	Mean outer surface temperature of clothing
t_{db}	Dry bulb temperature
t_g	Pink globe temperature
T_{mrt}	Mean radiant temperature (absolute degrees)
t_{mrt}	Mean radiant temperature
t_{72}	Adjusted dry bulb temperatures on the 72 F ET* line
t_{78}	Adjusted dry bulb temperatures on the 78 F ET* line
$u_{I_{cl}}$	Uncertainty associated with the value of I_{cl}
u_M	Uncertainty associated with the value of M
u_{P_a}	Uncertainty associated with the value of P_a

u_{PMV} Uncertainty associated with the value of PMV

$u_{t_{db}}$ Uncertainty associated with the value of t_{db}

$u_{t_{mrt}}$ Uncertainty associated with the value of t_{mrt}

u_V Uncertainty associated with the value of V

V Relative air velocity

σ Stefan - Boltzmann constant (0.1713×10^{-8} BTU/ft^{2}hr°R^4) (4.96×10^{-8} Kcal/m^{2}hr°K^4)

ε Clothing emittance

η Mechanical efficiency of the body

I. INTRODUCTION

There is a growing need for instrumentation to be developed to collect environmental data and combine the data to evaluate the thermal quality of an inhabited space. Advancing techniques in the area of human thermal comfort have led to the development of sophisticated descriptions of the degree of comfort for persons in an interior environment. Most of the work has been accomplished in the last fifty years beginning with the investigations by Houghton and Yaglou in 1923 [1].* Their effective temperature scale was the first single index for thermal sensation in humans and is still in wide use today. The most recent of the comfort criteria has involved predicting the physiological responses to the environmental parameters of dry bulb temperature, water vapor partial pressure, relative air velocity, and mean radiant temperature and to the physical quantities of metabolic rate and clothing insulation value. This work has been accomplished by Gagge, Stolwijk, and Nishi [2] in their new effective temperature scale and by Fanger [3] with his predicted mean comfort vote.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers also provides a potential basis for instrumentation to evaluate thermal environments in their proposed standard [12]. ASHRAE has provided the major impetus to human comfort investigations. They have provided both project funding and comfort criteria standards for the industry. Although

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*Numbers in brackets refer to references listed on page 28.

limited in the range of clothing insulation value and metabolic rate which may be used, the proposed standard does provide a systematic technique for combining the environmental variables to determine acceptable comfort. The new standard consists of a quadrilateral plotted on a vapor pressure versus adjusted dry bulb temperature ($\frac{t_{mrt} + t_{db}}{2}$) graph. Points inside the plot correspond to environments in which at least 80% of the occupants are comfortable. A summary of the standard appears in Figure 4.

Efforts have been made to develop instrumentation to collect environmental data, evaluate these data and display the results of the evaluation as comfort vote, effective temperature, comfortable-uncomfortable, etc. Lund Madsen [4] developed an instrument in 1972 which performed the above functions based on Fanger's physiological model. The instrument consisted of a sensing body and an evaluation network. The sensing body was controlled to develop a surface temperature equal to the mean surface temperature of a person in thermal comfort. The sensing body was shaped so that the radiation area factors are nearly equal to those for persons and, in addition accounted for the fact that its radiative and convective surface areas were equal where a person's were not. The signal from the sensing body, indicating dry heat loss, was sent to a resistance network where it was combined with preset inputs of activity level, clothing insulation value, and vapor pressure to yield the local predicated mean vote. A major disadvantage of the instrument is its inability to provide individual parameter values. This is desirable when the environment is deemed unsuitable and corrections on some of the environmental variables must be made.

Another instrument, designed by the Bendix Corporation in 1972 for the National Institute for Occupational Safety and Health, scans and records dry bulb temperature, wet bulb temperature, air velocity, and black globe temperature. It provides both a linear analog output of each variable and a digital output of the monitored variable. Built as a work stress study unit, the device will presumably be integrated with the calculation of the NIOSH proposed standard, "Wet Bulb Globe Temperature" (WBGT) [5].

II. AVAILABLE INSTRUMENTATION

This development of an instrument to evaluate the quality of a thermal environment began with a search of available instrumentation to measure environmental variables. Requests were sent to manufacturers of environmental instrumentation for specification of units which were available to measure ambient temperature, mean radiant temperature, moisture content, and relative air velocity. The responses to the survey are shown in Appendix A. The most accurate measurement of dry bulb temperature in the comfort range was plus or minus 0.5 F. For the measurement of moisture content, the majority of instruments sensed relative humidity with the best absolute accuracy of plus or minus 2 1/2%. There were a few psychrometer devices having plus or minus 0.5 F wet bulb accuracy while the dew point sensors had a best accuracy of plus or minus 1.5 F. There were no instruments which specified a vapor pressure readout. Velocity measuring devices were mostly of the heated wire or heated thermocouple type, the most accurate quoting a plus or minus 2 fpm accuracy in the 0 to 60 fpm range of use. No instruments were available for purchase which measured globe temperature or mean radiant temperature.

III. PMV APPROACH TO INSTRUMENT

In 1967, P. O. Fanger [6] presented his thermal comfort equation for humans. In 1970, Fanger [3] published his book Thermal Comfort containing, along with the derivation of his comfort equation, the development of equations to calculate the Predicted Mean Vote, PMV, of average persons exposed to thermal environments. Fanger [3] established the approximate exponential relationship between the change in vote per unit change in thermal load and activity level based on his data and on the evidence presented by Nevins et. al [7] and McNall and his co-workers [8]. This enabled the PMV to be evaluated from environmental data of ambient temperature, relative air velocity, vapor pressure, and mean radiant temperature along with physical and physiological variables of clothing insulation value, clothing temperature, and activity level. The equation is shown at the bottom of Figure 1A.

Fanger's clothing temperature equation is associated with the vote equation. The clothing temperature must be obtained iteratively, usually by digital computer, before the vote equation can be solved. Tables and graphs appearing in Fanger's book [3] are intended to be used in most cases rather than calculation from the basic equations. However, this process is frequently difficult and time consuming. The need exists for modification of Fanger's equations to permit solution by hand or by use of an analog circuit.

Three assumptions were made to modify the clothing temperature equation and the vote equation (Figure 1A). They are as follows: (a) mechanical

Clothing Temperature Equation:

$$t_{cl} = 35.7 - 0.032m\,(1-\eta) - 0.18\, I_{cl}[(3.4)(10^{-8})\, f_{cl}$$
$$[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4] + f_{cl}\, h_c\, (t_{cl} - t_{db})]$$

where $h_c = 10.4 \sqrt{V}$ in forced convection

$= 2.05\,(t_{cl} - t_{db})^{0.25}$ in natural convection

Predicted Mean Vote Equation:

$$PMV = [0.352e^{-0.042m} + 0.032][m(1-\eta) - 0.35$$
$$(43 - 0.061\, m(1-\eta) - P_a) - 0.42(m(1-\eta) - 50)$$
$$-0.0023m\,(44 - P_a) - 0.0014\, m(34-t_{db})$$
$$-(3.4)(10^{-8})\, f_{cl}((t_{cl} + 273)^4 - (t_{mrt} + 273)^4)$$
$$-f_{cl}h_c(t_{cl} - t_{db})]$$

where PMV = Predicted mean vote (vote scale from -3 to +3)

Figure 1A: Fanger's Clothing Temperature Equation and Predicted Mean Vote Equation.

efficiency, η, for all considerations will be zero, (b) the radiation term will be approximated by (13.6) (10^{-8}) f_{cl} $T_{mrt}{}^3$ $(t_{cl}-t_{mrt})$, and (c) the convective heat transfer coefficient, h_c, will be equal to $10.4\sqrt{V}$ when the relative air velocity is greater than 0.1 meter/sec (20 fpm) or h_c will be equal to 3.2888 kcal/hr-m^{2}C when the relative air velocity is equal to or less than 0.1 meter/sec.

The first assumption requires little discussion as its effect is only to limit application of the modified equations to situations where mechanical efficiency is zero. The few practical applications excluded by this assumption are some outdoor exercises and a few heavy industrial tasks. The other two assumptions will be developed now.

The use of the Stefan-Boltzmann Law appears in the radiation heat transfer terms of Fanger's clothing temperature equation and his predicted mean vote equation (Figure 1A). This radiation term is expressed as heat transfer per unit of nude body surface area and is:

$$r = \varepsilon\sigma \, f_{eff} \, f_{cl} \, [(t_{cl} + 273)^4 - (t_{mrt} + 273)^4]. \qquad (1)$$

Fanger chooses average values for clothing emittance, ε, and effective area factor, f_{eff}, of 0.97 and 0.71, respectively. The resulting radiation term is:

$$r = (3.4)\,(10^{-8})\, f_{cl}\, (T_{cl}{}^4 - T_{mrt}{}^4). \qquad (2)$$

Factoring gives:

$$r = (3.4)\,(10^{-8})\, f_{cl}\, (T_{cl} - T_{mrt})\, (T_{cl}{}^3 + T_{cl}\, T_{mrt}{}^2 + T_{cl}{}^2\, T_{mrt} + T_{mrt}{}^3). \qquad (3)$$

For most environmental applications, the mean radiant temperature is within ±5 C of air temperature. Also, in most comfortable environments, clothing temperature will be within the same ±5 C range as air temperature. For practical purposes, clothing temperature should be within ±10 C of the mean radiant temperature. Therefore, the radiation term may be approximated by:

$$r = (3.4)\ (10^{-8})\ f_{cl}\ (T_{cl} - T_{mrt})\ (4\ T_{mrt}^{3}) \tag{4}$$

or

$$r = (13.6)\ (10^{-8})\ f_{cl}\ (t_{mrt} + 273)^{3}\ (t_{cl} - t_{mrt}).$$

An analysis was made of the error introduced into the radiation term by using this approximation. Using the worst conditions, obtained from Fanger [3], when the difference between mean radiant temperature and clothing temperature is at a maximum of about 16 C, the deviation between equation (2) and equation (4) is 7.95%. However, typical errors with a 10 C temperature difference will be less than 5% in the radiation term.

Finally, adjustments were made on the convective heat transfer coefficient. The original methods of calculating the convective coefficient are shown in Figure 1A. As seen in that figure, two coefficients were calculated, one as a function of the square root of relative air velocity developed by Winslow, Gagge, and Herrington [9], and the other as a function of the fourth root of the temperature difference between the clothing and ambient proposed by Nielsen and Pedersen [10]. The larger of the two coefficients calculated is used in the predicted mean vote equation and the clothing temperature equation. Under most circumstances, the point of transfer from the forced convection equation to the natural convection equation is around the 0.1 meter/sec (20 fpm) relative velocity. Therefore, to simplify calculation of the convective coefficient in the natural convection regime, the convection coefficient is considered constant at 3.2888 kcal/hr m^2 C, a value obtained by using the forced convection equation and substituting 0.1 meter/sec for the velocity variable. For relative air velocities greater than 0.1 meter/sec, the conventional coefficient equation for forced convection is used. Thus,

$$h_c = 10.4 \sqrt{V} \text{ for } V > 0.1 \text{ meter/sec (20 fpm)} \quad \text{(kcal/hr m}^2 \text{ C)}$$

and

$$h_c = 3.2888 \text{ for } V \leq 0.1 \text{ meter/sec (20 fpm)} \quad \text{(kcal/hr m}^2 \text{ C)}$$

An analysis of the error introduced by this approximation indicated that in the range of ambient temperature from 20 C to 30 C (68 F to 86 F), typical deviations in the convection coefficient using the modified technique were less than 10% when below 0.1 meter/sec velocity.

Combining these two modifications into Fanger's clothing temperature equation and vote equation yields two equations in the variables of the environment, physical and physiological parameters. These equations appear in Figure 1B. The resulting clothing temperature equation is directly solved for clothing temperature, t_{cl}, thus eliminating the need for an iterative solution. This allows the determination of PMV by hand calculation or by use of the outputs from an environmental data acquisition system and dialed in values of activity level and clothing insulation value (clo).

A computer program was written to calculate convection coefficients, clothing temperatures, and predicted mean votes for Fanger's equations and for the modified equations outlined in this paper along with the deviation and percentage deviation between the two methods.

The program listing is in Appendix B along with sample output. The program was coded in FORTRAN for execution on the IBM 360 digital computer. Over two thousand sets of input data were examined which included the combinations of the ambient temperatures, velocities, mean radiant temperatures, activity levels, clo values, vapor pressures, and mechanical efficiencies shown in Figure 2.

Clothing Temperature Equation:

$$t_{cl} = \frac{35.7 - 0.032m + 0.18\ I_{cl}\ f_{cl}[h_c t_{db} + (13.6)(10^{-8})(t_{mrt} + 273)^3\ t_{mrt}]}{1 + 0.18\ I_{cl} f_{cl}[(13.6)(10^{-8})(t_{mrt} + 273)^3 + h_c]}$$

where $h_c = 10.4\sqrt{V}$ when $v > 0.1$ m/s

$= 3.2888$ when $v \leq 0.1$ m/s

Predicted Mean Vote Equation:

$$PMV = [0.352e^{-0.042m} + 0.032][5.95 + 0.453m + 0.0023m\ P_a + 0.0014m\ t_{db} + 0.35\ P_a - (13.6)(10^{-8})\ f_{cl}\ (t_{mrt} + 273)^3 (t_{cl} - t_{mrt}) - f_{cl}\ h_c\ (t_{cl} - t_{db})]$$

where PMV = Predicted mean vote (vote scale from -3 to +3)

Figure 1B: Modifications to Fanger's Clothing Temperature and Predicted Mean Vote Equations.

Ambient Temperature (°C)	-5.0	0.0	10.0	20.0	23.0	24.0	25.0	27.0	32.0	37.0
Relative Air Velocity (m/s)		0.05			0.1				0.8	
Mean Radiant Temp. (°C)		T_{db}			$T_{db} + 10.0$				$T_{db} - 10.0$	
Activity Level ($Kcal/m^2 hr$)		50			100				150	
Clo Value (clo)			0.5				1.5			
Vapor Pressure (m.m. Hg)			corresponding to 30% RH at T_{db}				corresponding to 70% RH at T_{db}			
Mechanical Efficiency			0.0				0.2			

Figure 2: Conditions Used in Computer Analysis of Modified Equations.

Examination of the results obtained by the computer analysis revealed good agreement between the modified equations and Fanger's equations when used in the range of ambient temperatures of 20 C and above. A few combinations of very low ambient temperatures, high activity levels, and low clo values gave deviations in the predicted mean vote frequently exceeding 0.2 vote and occasionally reached as high as 0.5 vote. However, when considering environments above 20 C, deviations in the calculated votes in the ±2.0 vote range (using voting scale from -3 to +3 with 0 as neutral) were less than 0.1 vote where mean radiant temperatures were equal to air temperatures, and less than 0.2 vote where mean radiant temperatures fluctuated ±10 C from ambient temperature. The median of the deviations in votes of the modified equations from Fanger's equation for votes between -3 and +3 in the range of ambient temperatures 20 C to 32 C was 0.02 vote with the largest deviation occuring, 0.194 vote. The program and a sample output taken at a 70 kcal/hr m^2 activity level appear in Appendix B.

An analog circuit which calculates PMV by the modified equations (see Figure 1B) is shown in Figure 3A. Its complexity makes it unfeasible for use in its discrete form. However, it does perform the intended function of an environmental evaluating instrument by combining environmental parameters and physical quantities to give the index, PMV. It serves as a model from which integrated circuits could be constructed to accomplish the calculations more economically. This analog circuit directly synthesizes the modified clothing temperature and predicted mean vote equations from Figure 1B.

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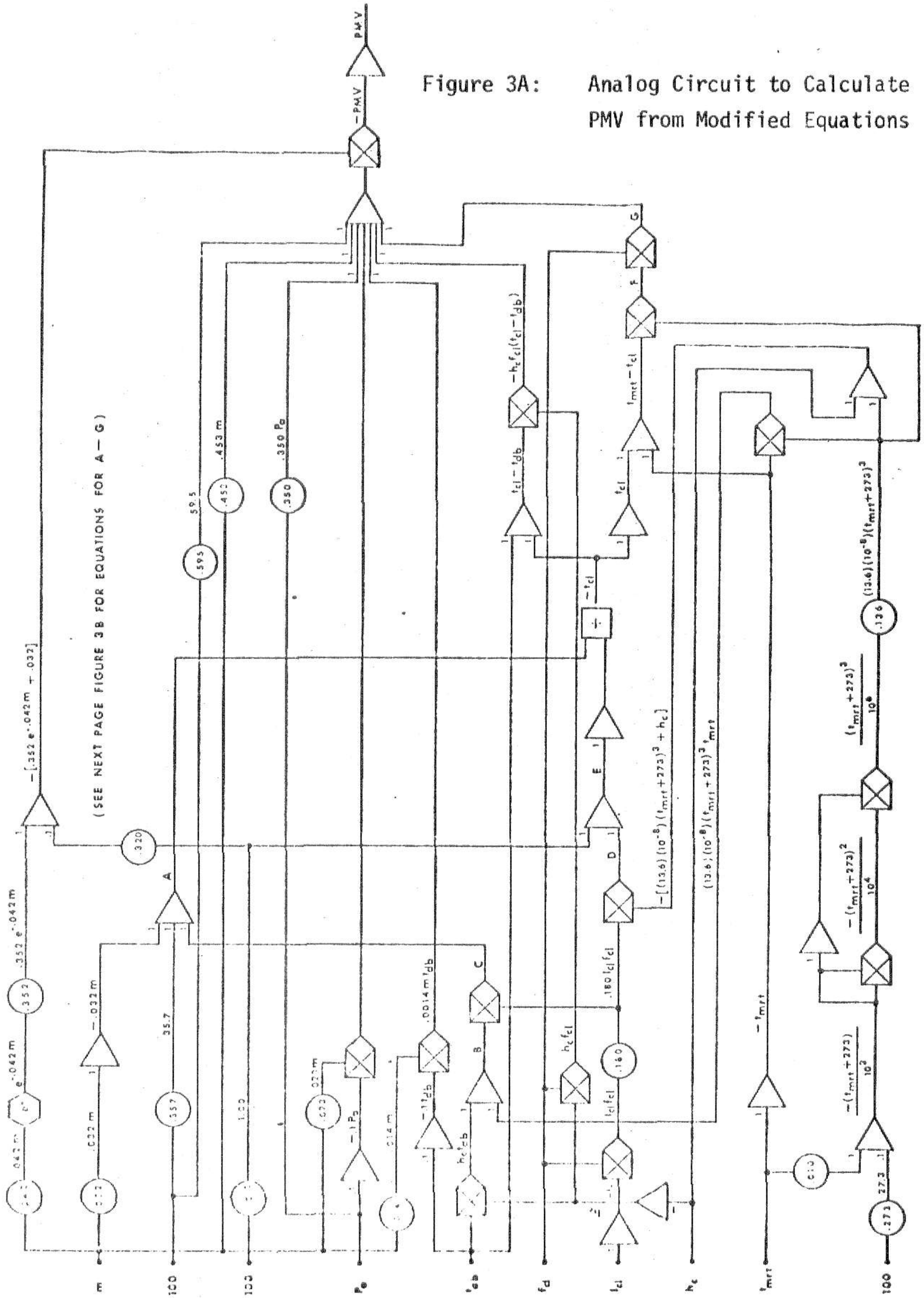
Figure 3A: Analog Circuit to Calculate PMV from Modified Equations



$$A = -[35.7-0.032m + 0.180I_{cl}f_{cl}[h_c t_{db} + (13.6)(10^{-8})(t_{mrt}+ 273)^3 t_{mrt}]]$$

$$B = -[h_c t_{db} + (13.6)(10^{-8})(t_{mrt} + 273)^3\ t_{mrt}]$$

$$C = 0.180I_{cl}f_{cl}[h_c t_{db} + (13.6)(10^{-8})(t_{mrt} + 273)^3\ t_{mrt}]$$

$$D = 0.180I_{cl}f_{cl}[(13.6)(10^{-8})\ (t_{mrt} + 273)^3 + h_c]$$

$$E = 1 + 0.180I_{cl}f_{cl}[(13.6)(10^{-8})\ (t_{mrt} + 273)^3 + h_c]$$

$$F = (13.6)(10^{-8})\ (t_{mrt} + 273)^3\ (t_{cl} - t_{mrt})$$

$$G = -(13.6)(10^{-8})\ f_{cl}\ (t_{mrt} + 273)^3\ (t_{cl} - t_{mrt})$$

Figure 3B: Equations for Letters A, B, C, D, E, F, and G shown on Figure 3A.

IV. ANALYSIS OF UNCERTAINTIES

The choice of instrumentation used to measure the environmental variables depends, in part, upon the sensitivity of the result, PMV, to the measurement of specific variables. Madsen [4] provided an evaluation of the uncertainty in Fanger's PMV as it depends upon the uncertainties of the individual measurements. Madsen notes that the uncertainty in the value of PMV, denoted u_{PMV}, is: (5)

$$u_{PMV}=\sqrt{\left(\frac{\partial PMV}{\partial t_{db}}.u_{t_{db}}\right)^2+\left(\frac{\partial PMV}{\partial t_{mrt}}.u_{t_{mrt}}\right)^2+\left(\frac{\partial PMV}{\partial P_a}.u_{Pa}\right)^2+\left(\frac{\partial PMV}{\partial V}.u_V\right)^2+\left(\frac{\partial PMV}{\partial M}.u_M\right)^2+\left(\frac{\partial PMV}{\partial I_{cl}}.u_{I_{cl}}\right)^2}$$

where u_x = Uncertainty in the measurement or establishment of variable x.

and $\frac{\partial PMV}{\partial x}$ = Partial derivative of PMV with respect to variable x at constant values of the other variables.

Tables for $\frac{\partial PMV}{\partial x}$ for each variable at various activity levels, clo values, and air velocities are listed in [4]. Madsen established the minimum values for u_M and u_{Icl} as ±10 w/m^2 (8.6 kcal/m^{2}hr) and ±0.1 clo, respectively. This means that even if the thermal variables could be measured with no uncertainty, there would be a minimum uncertainty in PMV of ±0.48.

The specifications set forth in the 1972 proposed ASHRAE comfort standard [12] were substituted into the equation for PMV uncertainty. Setting $u_{t_{db}}$ = ±0.25 F, $u_{t_{mrt}}$ = ±0.25 F, a selected u_{Pa} = ±0.75 mm, and u_V = ±15 fpm, and assuming velocity less than 0.1 m/s, activity level at 60 w/m^2, and a clo value of 0.5 with which to enter the partial derivation tables, the uncertainty in PMV was determined as plus or minus 0.6 vote.

The terms under the radical sign, appearing in the same order as the uncertainty equation (5) were as follows:

$$u_{PMV} = \pm \quad 0.0008 + 0.0007 + 0.0008 + 0.130 + 0.194 + 0.040 \tag{6}$$

$$= \pm \quad 0.61 \quad \text{vote}$$

As may be seen from the above terms, most of the uncertainty contribution from measured variables came from the velocity measurement. The uncertainty equation was then solved for the measured variable uncertainties setting value of ±0.6 for u_{PMV} and dividing the total uncertainty equally among the measured variables. This approach is demonstrated by letting $a = \frac{\partial PMV}{\partial x} u_x$ in equation (5) and solving for a = ±0.1777 PMV. The uncertainty requirement for each variable is then determined from

$$u_x = \frac{a}{\frac{\partial PMV}{\partial X}} = \frac{\pm 0.1777 PMV}{\frac{\partial PMV}{\partial X}} \tag{7}$$

The results of the calculations indicate the following accuracy requirements to maintain the ± 0.6 vote accuracy obtained from the ASHRAE proposed standards:

$$u_{t_{db}} = \pm\ 1.6\ F$$

$$u_{t_{mrt}} = \pm\ 1.7\ F$$

$$u_{P_a} = \pm\ 4.6\ \text{mm of Hg}$$

and $$u_V = \pm\ 7.4\ \text{fpm}$$

These specifications maintain the ± 0.6 accuracy of the standards specifications, but allow much more flexibility with most of the measured variables. These uncertainties are available from presently manufactured instruments, but of course, with the exception of the unavailability of t_{mrt}. Most of the instruments listed in Appendix A meet or exceed these requirements. The Bendix "ENVIREC" instrument also meets these specifications with ± 1 F temperature accuracies and ± 2% for velocity accuracy.

V. PROPOSED ASHRAE STANDARDS APPROACH TO INSTRUMENT

In May, 1972, the ASHRAE Standards Committee issued the second draft of a proposed revision to the ASHRAE comfort standards [12]. The basic standard is shown by a graph of vapor pressure versus adjusted dry bulb temperature (see Figure 4). (Adjusted dry bulb temperature is defined as the average between dry bulb temperature and mean radiant temperature.) Data obtained within the environmental space must fall within the comfort envelope described by the graph on Figure 4. In addition to satisfaction of the comfort envelope, the local velocity must not exceed 70 feet per minute. Occupant metabolic rates and clothing insulation values should be planned at between 50 and 70 kcal/m^2hr and 0.5 and 1.0 clo, respectively for the standard to apply. Thus, to test the local environment, an instrument or set of instruments should (1) test the velocity criterion and (2) determine whether or not the state point falls within the comfort envelope on Figure 4.

The left-hand and right-hand borders of the proposed standard chart are taken to be lines corresponding to constant Effective Temperatures, (ET*)[†] of 72 F and 78 F, respectively. This new Effective Temperature is defined by Gagge, Stolwijk, and Nishi [2] as the dry bulb temperature at the point of intersection of the loci of constant percentage body

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† ET* is used to distinguish Gagge's new effective temperature from Houghton and Yaglou's effective temperature, ET.

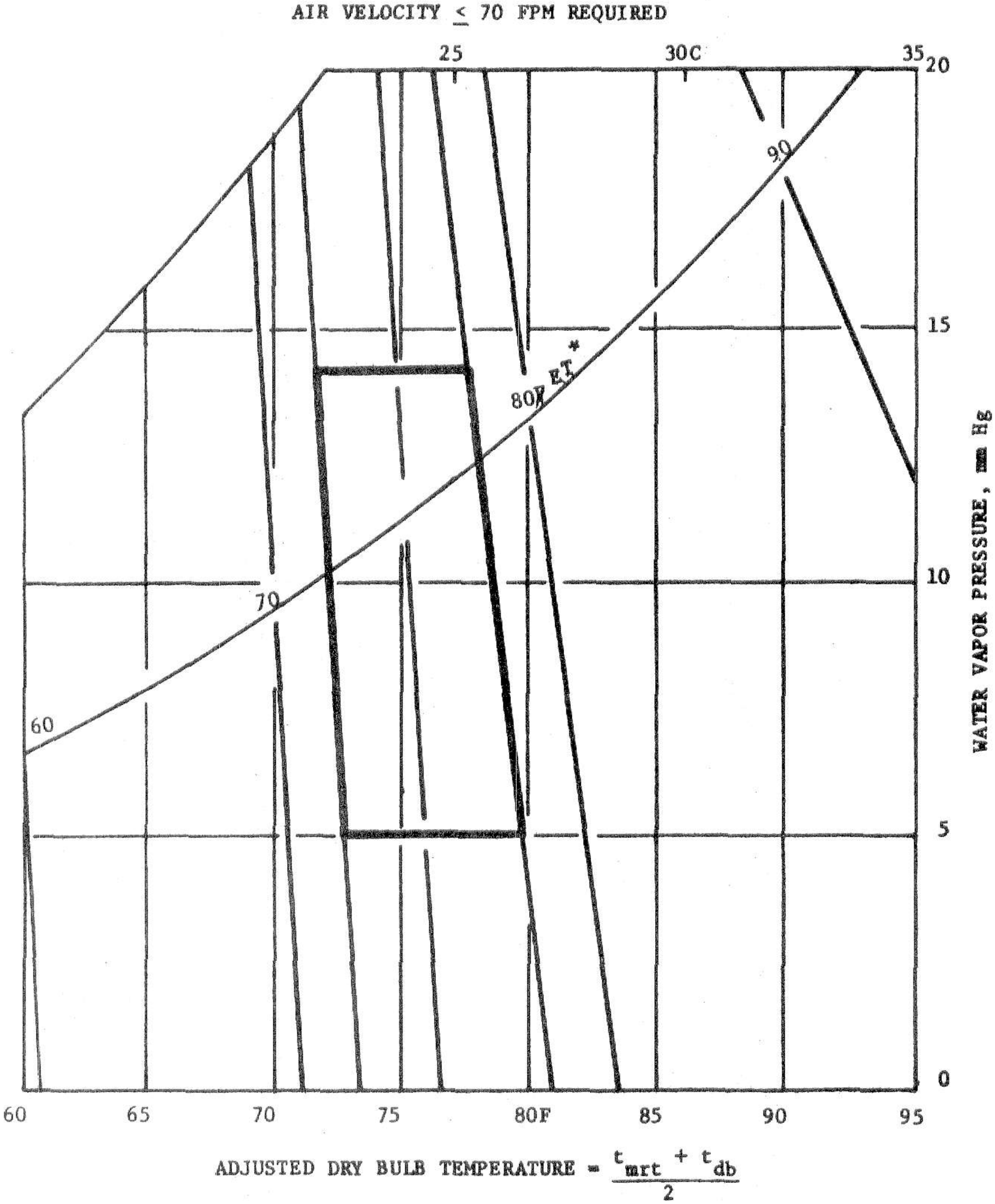


Figure 4: **Comfort Envelope from Proposed ASHRAE Standards**

wettedness due to regulatory sweating and the 50% relative humidity line on the psychrometric chart. Woods and Rholes [11] developed a computer program to calculate the value of Gagge's effective temperature given dry bulb temperature and relative humidity at 1 met activity, 0.6 clo, still air, and MRT equals dry bulb for 1, 2 and 3 hour exposures. Initial condition assume man at thermal comfort. Woods also formulated a program which calculated the slope of a constant wettedness line ($\Delta P_a/\Delta t_{db}$). This program was used to calculate the slopes of the two border lines on the proposed ASHRAE chart. The percent wettedness due to regulatory sweating as tabulated by Woods for an effective temperature of 78 F was about 6.3 percent. The program obtained seven pairs of dry bulb-vapor pressure data corresponding to 0.063 wettedness fraction at 7 relative humidities (20%, 30%, 40%, 50%, 60%, 70%, 80%). The program and output is included in Appendix C. A linear regression analysis of the output pairs yielded a slope of - 0.169 inches Hg/F (-4.30 mm Hg/F) with a correlation coefficient of 0.998. In his psychrometric tables, Woods lists the output pairs from the program for a wettedness of 0.0 which occurs at 72 F effective temperature. Similar analysis of these temperature and vapor pressure values gave a slope of -0.309 inches Hg/F (-7.84 mm Hg/F) and correlation coefficient 0.997 for the 72 F line. As a coarse check, four points were read from the left border line of the proposed standard chart. Regression analysis of these points suggested a slope of -0.304 inches of Hg/F which agrees closely with the rigidly calculated slope from the program output. The equations of the lines may now be easily established from the definition of Gagge's new effective temperature. By definition, the 72 F ET* line goes through the point 72 F, 50% RH on the psychrometric chart and 78 F ET* intersects the 78 F, 50% RH point which generates the following equations for the left and right borders on the comfort envelope in the proposed standard:

$$t_{72} = -0.128\ P_a + 74.9 \tag{8}$$

where t_{72} = adjusted dry bulb temperature on the 72 F ET* line and P_a = vapor pressure in mm of Hg.

and

$$t_{78} = -0.233\ P_a + 81.8 \tag{9}$$

where t_{78} = adjusted dry bulb temperature on the 78 F ET* line and P_a is as above.

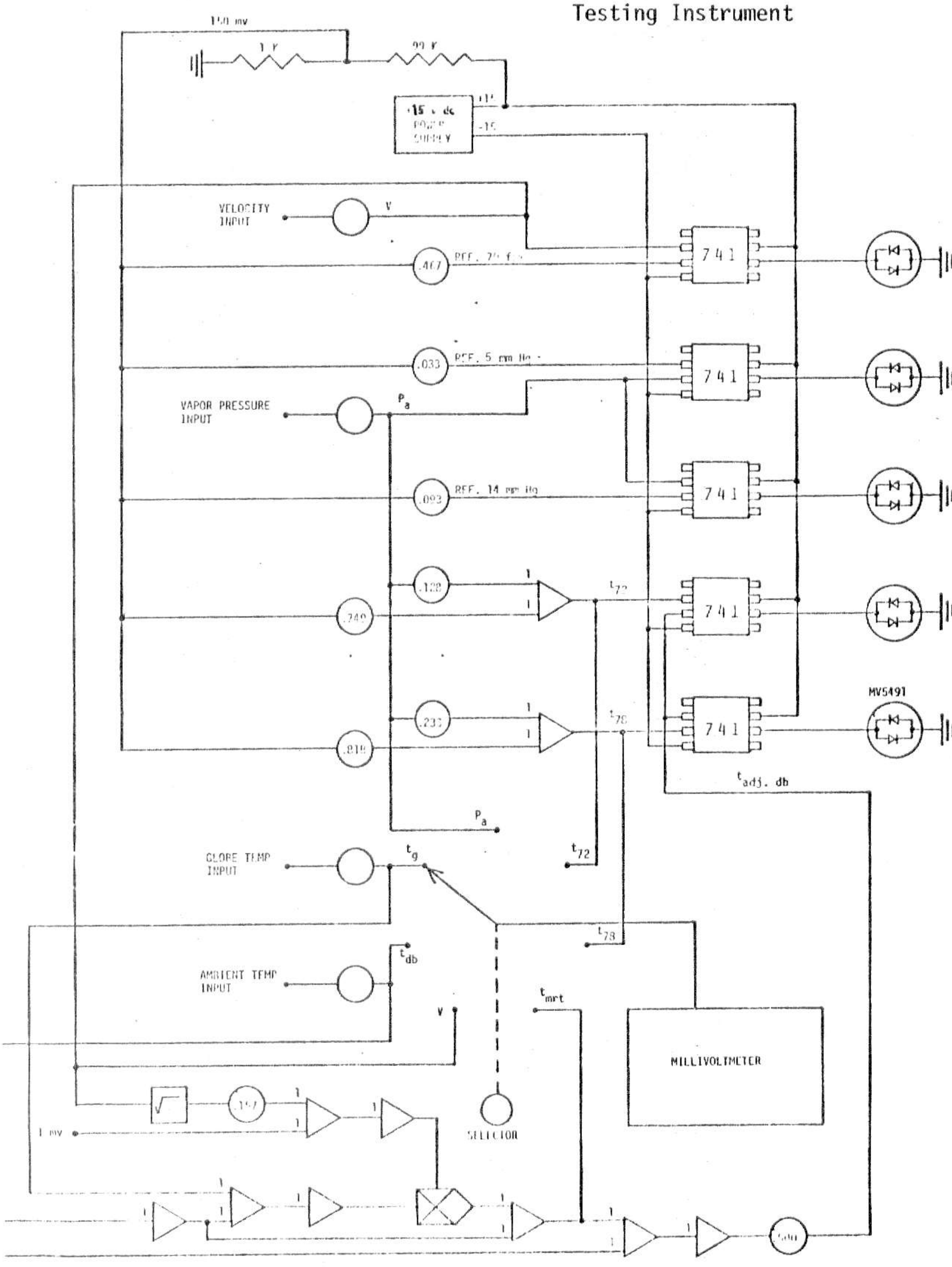
It is now possible to test the thermal variables in a space with the proposed standard by a series of comparing techniques. First, the velocity at the point must be compared to the reference velocity of 70 fpm. Next, the vapor pressure at the point must be tested in two directions, both lower than 14 mm of Hg and higher than 5 mm of Hg. Finally, calculation of the adjusted dry bulb is required for testing its position in relation to the 72 F and 78 F ET* lines. A state in the environment whose parameters pass the above tests satisfies the requirements for the proposed standard. The instrumentation problem is simplified if the available components have linear outputs available with the maximum magnitude on the output numerically larger than the corresponding measured maximum parameter level. This allows the use of a divider to reduce the output level to the exact parameter value which may then be displayed by a single meter or used in calculations. Therefore, a typical component instrument would contain a sensor and conditioning circuitry to provide the output voltages.

Even though a test sequence was established to determine the thermal quality of a point in the environment consistent with the proposed ASHRAE standard, there were no off-the-shelf instruments available that provided the specified accuracies for either dry bulb or mean radiant temperature measurement. Also, no instruments were calibrated for vapor pressure output. However, most of the available instruments calibrated for dew point indications provided sufficient accuracy, so the only requirement to indicate vapor pressure is recalibration of the same device. An allowable uncertainty of plus or minus 0.75 mm Hg in the vapor pressure corresponds to only a plus or minus 4 F accuracy in dew point. Specifications for the necessary instrument components will be discussed later.

Continuing with the plan for comparator circuits in the test instrument, the basic comparator element chosen was a type 741 operational amplifier. Operation with a plus and minus 15 volt power supply allows the maximum flexibility for component output levels. A schematic of the instrument appears in Figure 5. This schematic is constructed with the assumption that component output levels are of millivolt magnitudes, however, a different scaling technique would easily accomodate levels in the 0 to 15 volts range. Each signal from the appropriate component conditioning circuit is scaled to give the actual value of the environmental variable expressed in millivolts, and is directed to the comparator. Comparison is made to the reference voltage for the particular variable which has been generated by scaling the 15 volt power supply for the comparators. Note that t_{72}, t_{78} and adjusted dry bulb must be calculated by the circuit. Since the value of the vapor pressure is readily available, t_{72} and t_{78} may be obtained with four potentiometers and two operational ampliers by the equations derived previously.

Adjusted dry bulb is more difficult to obtain. The proposed ASHRAE

Figure 5: Schematic for Environmental Testing Instrument



standard [12] requires the calculation of mean radiant temperature from a globe temperature. They define the globe temperature as the equilibrium temperature at the center of a 6 inch diameter thin-walled sphere having a surface coating of a specified pink color. The equation for converting this globe temperature to mean radiant temperature is given as

$$t_{mrt} = (1 + 0.157 \sqrt{V})(t_g - t_{db}) + t_{db} \quad (10)$$

where V = velocity in fpm.

The analog circuit to perform this calculation and the subsequent determination of adjusted dry bulb by averaging the mean radiant temperature with dry bulb temperature ture appears in the lower portion of the schematic of Figure 5. The adjusted dry bulb (as seen in the schematic) is then compared to the calculated t_{72} and t_{78} and must lie between these two values for the point to fall within the comfort envelope. Indicator lights have been chosen as monitors of test successes in each of the five test sequences (a velocity test, two vapor pressure tests, and two temperature tests). Monsanto has recently marketed a bicolor LED lamp which emits one color with positive triggering and the other color with a negative signal. Red/green units are to be connected to the outputs of each of the five comparators so that green indicates a successful comparison and red, a failure. Thus, for a point in the environmental space to satisfy the standard, all five lights must be green. If any light is red, it also gives an indication of where on the chart the point really is. For instance, if the t_{72} test light is red and all other lights are green, it is known that the point lies somewhere to the left of the 72 F ET* line and between the 5 and 14 mm Hg vapor pressure lines. Whether to correct the problem by raising adjusted dry bulb temperature or by raising the vapor pressure, or both, may be determined by monitoring the values of vapor pressure or adjusted dry bulb temperature and optimizing from there. A proposed layout of the final design is shown in Figure 6.

Specifications for component instruments are based on the proposed ASHRAE standard and on the needs of the designed field instrument. The dry bulb temperature sensor is required by the standard to be 0.125 inches in diameter or smaller. Temperature measurements are to be made with an accuracy of plus or minus 0.25 F. Although there is no specified accuracy requirement in the proposed standard for vapor pressure measurement, it was demonstrated earlier that plus or minus 0.75 mm of Hg would provide consistency with the other standard specifications in terms of their contribution to the uncertainty in evaluating PMV. However, this corresponds to a dew point uncertainty of at least plus or minus 4 F. It is unclear from the proposed standard whether or not the 0.25 F requirement for temperature accuracy is intended to apply to dew bulb point measurement also. Required accuracy for velocity measurement is plus or minus 15 fpm. A nondirectional sensor is preferred. The constraint added to the specifications because of the circuit design is for each component system to provide a linear output voltage. The magnitude of the output is to be at least as large as the numerical value of the variable being measured.

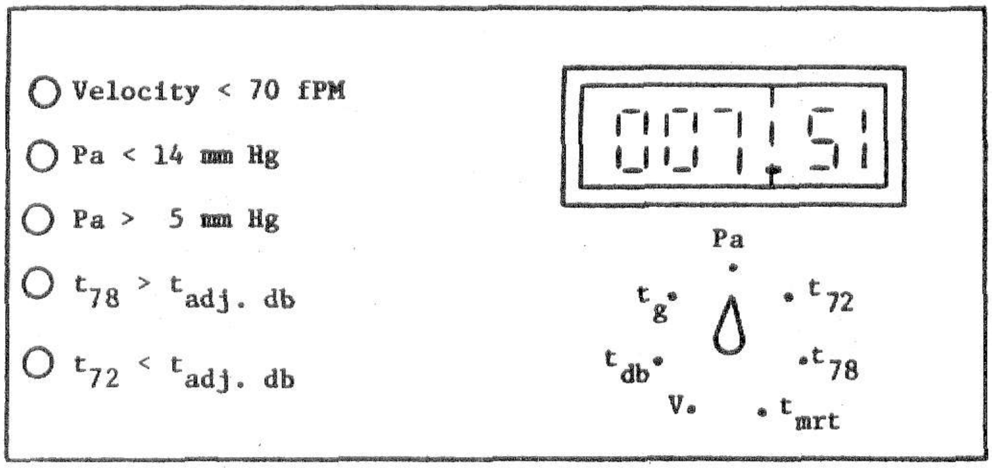


Figure 6: Proposed Layout for Environmental Testing Instrument.

VI. SUMMARY

Two proposals have been discussed for the development of an instrument to evaluate the thermal quality of an environment. The first of these was based on P.O. Fanger's Predicted Mean Vote Equation. His vote equation and clothing temperature equation were modified so that PMV could be determined directly from environmental data along with activity level and clo value. An integrated circuit package could be designed to calculate the vote from the modified equations using inputs from a data acquisition system.

The second proposed technique has as its foundation the proposed ASHRAE standard [12]. The proposed testing instrument measures dry bulb temperature, a globe temperature, vapor pressure, and air velocity, and calculates mean radiant temperature, adjusted dry bulb temperature, t_{72}, and t_{78}. Adjusted dry bulb is the average of the dry bulb and mean radiant temperature. t_{72} and t_{78} are the adjusted dry bulb temperatures corresponding to the measured vapor pressure on the 72 F and 78 F effective temperature lines, respectively. The calculated adjusted dry bulb is compared to both t_{72} and t_{78}, the vapor pressure measurement is compared to upper and lower limit standards of 5 and 14 mm Hg, and velocity is compared to the standard maximum of 70 fpm by the test circuit. Red/green idiot lights indicate compliance or non-compliance with the standards and individual variable monitoring is provided.

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APPENDIX A

Instrumentation Available from 23 Manufacturers for Measurement of Thermal Variables as of April, 1972.

HUMIDITY

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range	Accuracy	Costs		
						Sensor	Transducer	*Instrument
1	Phys-Chemical	Humeter	Impedance change of Polystyrene with RH by Adsorption; linear.	0-100% RH	±2 1/2% RH	w/temp compens. 57.50 w/o temp compens. 26.35		530.00
2	Alnor	dew pointer	Rapid expansion of gas sample and observation of fog.	T_a-10°F - 30°F dew point	±2°F dP			430.00
3	Honeywell	W611A	LiCl sensors; 7 sensors for 0-100% RH portable; temp. compens. gold leaf with LiCl film.	2-100% RH	±3% RH			
4	Cambridge	880	Thermoelectric cooler cools to dew point, sensed by neon lamps and photo resistor; Proportional signal to cooler locates dew point	-40°F - 120°F	±1.5°F dP	395.00		975.00
5	General Eastern	400	Same sensor as (1), sulphonated polystyrene (ion exchange); w/temp. compens; linear (also gives ambient temp)	0-100% RH	±3% RH between 10% and 95% RH			495.00
6	General Eastern	410	Transducer; linear, temp. compens.; same sensor as (5) 0-50 MV DC linear output	0-100% RH	±3% RH between 10% and 95% RH		395.00	

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range	Accuracy	Costs: Sensor	Costs: Transducer	Costs: *Instrument
7	Hygrodynamics (Am.Instr. Co.)	15-3008	Resistance change of film; meter read-out of RH and ambient temp.;linear	0-100% RH	±3% below 90% ±4% above 90%			355.00
8	Hygrodynamics	15-3057 15-3055	Same sensor as (7); digital readout; linear; can be simultaneous temp. and RH reading or alternate readings	10-99%	±3% below 90% ±4% above 90%		readout simultaneous alternate readout	915.00 635.00
9	Hygrodynamics	15-7012	Transducer; linear output; 0-5.4 V DC output (RH only)	same as (7)			362.50	
10	Atkins	32H65	LiCl sensor; 90 min. warm-up time; linear w/temp compens. (also gives ambient temp)	-20°F-80°F dP or (15% RH - 100%)	±3°F dP	60.00		295.00
11	Atkins	Z02B-3	Wet bulb - dry bulb psychrometer; thermistor.	7°F-192°F WB	±0.5°F WB			349.00
12	YSI	91	LiCl sensor; heated, temp. sensed with series 700 thermistor; linear;(Also gives ambient temp).	11°F-107°F dP	±1.6°F dP	single bobbin 70.00		375.00
13	Thunder Scientific	B.A. Sensor w/SC-1020M	Brady Array bulk effect, crystal lattice, semi-conduct sensor; used w/signal conditioner; output 0.1-5 VDC Prop. to RH; non-linear output.	w/temp comp. 0-100% RH	±4% RH Guaranteed ±2% typical	100.00		395.00

HUMIDITY

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range	Accuracy	Costs: Sensor	Costs: Transducer	Costs: *Instrument
14	Thunder Scientific	HS-ICHDT-1	Same sensor as (13); includes above sensor and conditioner along with Doric Scientific DS-100-T3D digital and BCD readout instrument;(also gives ambient temp).	0-100% RH	±4% RH ±2% RH Typical			2,720.00

VELOCITY

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range (fpm)	Accuracy (fpm)	Costs: Sensor	Costs: Transducer	Costs: *Instrument
1	DISA	55D80/81	Vibrating Hot Wire.	linear 0-60 low non-linear 0-400 high	±2 low range	45.00		1,038.00
2	CGS/Data-metrics	700-1	Heated Wire.	linearized 0-1000	±(2% rdg + 2 fpm)	95.00		590.00 w/temp comfens. 675.00
3	Alnor	AVT	Constant current, heated thermocouple (air velocity transducer; AVT) output 0-5 mv D.C. non-linear.	20-500	±2 or 3% rdg whichever larger		195.00	
4	Alnor	8500	Constant current; heated thermocouple;non-linear.	10-300 low 100-2000 high	±2 or 3% rdg. whichever larger	150.00		395.00
5	CGS/Data-metrics	800-VTP	Heated wire; non-directional sensor;portable; (also gives ambient temperature).	10-6000 on 3 scales low scale: 0-1000	±(2% rdg + 10 fpm)			385.00
6	Thermo-Systems inc. (tsi)	4100	Ion deflection; ion field generated from central disc travels to outside plate, being deflected in its path by air flow through the probe; linear; bidirectional; (low as 1 fpm); gives mass flow digital display.	0-±1,999 (low) 0-±12,000 0-±150 Std. cfm	±(2% Rdg + 0.1% FS		94.00	1,785.00

VELOCITY

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range (fpm)	Accuracy (fpm)	Costs Sensor	Costs Transducer	Costs *Instrument
7	Bowles Fluidic Corp.	CS-106	Air jet sheer interaction.	0-9000	±15	175.00		
8	Davis Instruments		Vane Anemometer.	30-2000				161.00

TEMPERATURE

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range (°F)	Accuracy ±°F	Costs Sensor	Transducer	*Instrument
1	General Eastern	400	Thermistor; linear; (Also gives RH)	-40 -120	2	Rectal probe		495.00
2	Hygrodynamics (Am.Instr.Co.)	15-3008	(Also gives RH).	40 - 120	2			355.00
3	Atkins	32H65	Thermistor; (Also gives dew point) linear.	-20 -120	2	30.00		295.00
4	Atkins	Z028-3	Dry bulb -wet bulb psychrometer, thermistor.	7-192	0.5			349.00
5	YSI	91	Thermistor;(Also gives dew point);(series 700).	11-107	1.6	30.00		375.00
6	YSI	43	Thermistor (series 400); batt power; linear; meter reading or 0-100mv output; one Jack Plug (1 channel).	TD 32-122 TV 30-110	1.0 0.5			115.00
7	CGS/Data-metrics	800-VTP	Resistance thermometer; portable;(also gives velocity).	0-300	2			385.00
8	Thunder Scientific	HS-1cHDT-1	Thermistor; also gives RH using Brady Array sensor; uses Doric Scientific meter (See 14 on Humidity).	-20 - 140	1			2,720.00

RADIATION

*includes sensor(s)

Number	Manufacturer	Model	Technique of Measurement	Range	Accuracy	Costs: Sensor	Costs: Transducer	Costs: *Instrument
1	YSI	65A	2 thermistors; meter read out in J/m^2s; one thermistor attached to target, one shielded ambient-compensating thermistor, both in bridge circuit.	(0.3μ - 2.7μ) 7 scales from $0-2.5 J/m^2.s$ to $0-2500\ J/m^2s$.		100.0	collector cone 100.0	with collector cone 625.00
2	International Thermal Instrument Co.	Solid State Radiometer Model A	Thermopile behind target plate; hemispherical range; mv output from thermopile.	flux range 0.01-1000 $BTU/hr/ft^2$	±1% indication		175.00	

APPENDIX B

Program and Sample Output for Calculation of Fanger's PMV and PMV from Modified Equations.

Input variables include:

	TA	=	ambient temperature (C)
	VEL	=	relative air velocity (m/s)
	TMRT	=	mean radiant temperature (C)
	ACT	=	activity level = metabolic rate divided by body area (Kcal/m^2hr)
	CLO	=	clothing insulation value (clo)
	FCL	=	area factor (clothing area divided by nude area) (dimensionless)
	PA	=	vapor pressure (m.m. of Hg)
and	ETA	=	mechanical efficiency (dimensionless)

Output data are:

	HCFOR	=	$10.4\sqrt{VEL}$ (Kcal/hr m^2 C)
	HC	=	convection coefficient found by using Fanger's techniques (Kcal/hr m^2 C)
	HCSG	=	convection coefficient found by using the modified methods (Kcal/hr m^2 C)
	TCLF	=	clothing temperature calculated by iteration from Fanger's equation (C)
	TCLSG	=	clothing temperature calculated by using the modified equation (C)
	TDEV	=	TCLSG - TCLF (C)
	TDPCT	=	(TDEV/TCLF) 100% (%)
	PMVF	=	predicted mean vote determined from Fanger's equation (-3 to +3) (vote)
	PMVSG	=	modified predicted mean vote (vote)
	VDEV	=	PMVSG - PMVF (vote)
and	VDPCT	=	(VDEV/PMVF) 100% (%)

```
     $JOB            GUY,TIME=1,PAGES=17
     C THIS PROGRAM CALCULATES THE PREDICTED CLOTHING TEMPERATURE AND THE
     C PREDICTED MEAN VOTE FOR PERSONS IN A SPECIFIC ENVIRONMENT WITH A
     C PARTICULAR TYPE OF CLOTHING AND AT A GIVEN RATE OF ACTIVITY.
     C COMPUTATION IS PERFORMED USING TWO METHODS, THE FIRST OF WHICH IS THE
     C TECHNIQUE PRESENTED BY P. O. FANGER IN HIS BOOK THERMAL COMFORT. THE
     C SECOND METHOD USED IS A MODIFICATION OF FANGER'S EQUATION WHICH
     C REQUIRES THE FOLLOWING ASSUMPTIONS : (1) MECHANICAL EFFICIENCY = ETA=0
     C (2) RADIATION HEAT TRANSFER = C*(TMRT**3)*(TCL-TMRT), (3) CONVECTIVE
     C COEFFICIENT=HC=10.4*SQRT(VEL) WHEN THE VELOCITY IS GREATER THAN 0.1M/S
     C AND HC=3.28877 WHEN THE VELOCITY IS LESS THAN OR EQUAL TO 0.1M/S, AND
     C (4) ALL ASSUMPTIONS INCURRED IN THE USE OF FANGER'S EQUATIONS. INPUT
     C VARIABLES ARE TA=AMBIENT TEMPERATURE (DEGREE C), PA=VAPOR PRESSURE
     C (MM OF HG), TMRT=MEAN RADIANT TEMPERATURE (DEGREE C), VEL=ABSOLUTE AIR
     C VELOCITY (M/S), ACT=METABOLIC RATE/DUBOIS AREA (KCAL/(M**2)*HR),
     C CLO=CLOTHING INSULATION VALUE (CLO), FCL=AREA FACTOR (CLOTHED AREA/
     C NUDE AREA), AND ETA=MEHANICAL EFFICIENCY. DEVIATION AND PERCENT
     C DEVIATION BETWEEN THE TWO METHODS ARE CALCULATED AND APPEAR AS TDEV
     C AND VDEV FOR THE DEVIATIONS OF CLOTHING TEMPERATURE AND VOTE AND TDPCT
     C AND VDPCT FOR THE PERCENT DEVIATIONS, RESPECTIVELY.
     C
     C
 1         DIMENSION TA(100 ),PA(100 ),TMRT(100 ),VEL(100 ),ACT(100 ),
          1    CLO(100 ),FCL(100 ),ETA(100 ),PMV(100 )
 2         READ(5,11) N
 3      11 FORMAT(I4)
     C READ DATA CARDS
 4         READ(5,12)(TA(I),VEL(I),TMRT(I),ACT(I),CLO(I),FCL(I),PA(I),
          1   ETA(I),I=1,N)
 5      12 FORMAT(8F8.3)
     C INITIALIZE PARAMETERS
     C
     C
 6         HCSG=0.0
 7         TDPCT=0.0
 8         VDPCT=0.0
 9         PMVF=0.0
10         HCFOR=0.0
11         HCNAT=0.0
12         TCLNEW=0.0
13         HC=0.0
14         TCLSG = 0.0
15         TDEV=0.0
16         PMVSG=0.0
17         VDEV=0.0
18         TCLF=0.0
19         ERROR=0.0
20         POWER=0.0
21         K=0
22         J=1
23      17 FORMAT('1')
24         WRITE(6,17)
25      13 FORMAT('+',6X,'TA',8X,'VEL',7X,'TMRT',7X,'ACT',7X,'CLO',7X,'FCL',
          1    7X,'PA',8X,'ETA',38X,'PAGE',2X,I3)
26         WRITE(6,13) J
27      15 FORMAT('0',5X,'HCFOR',7X,'HC',7X,'HCSG',6X,'TCLF',5X,'TCLSG',6X,
          1'TDEV',5X,'TDPCT',6X,'PMVF',5X,'PMVSG',6X,'VDEV',5X,'VDPCT')
28         WRITE(6,15)
29         DO 100 I=1,N
30         II=0
```

```
      JJ=C
      TCLCLC=TA(I)
C CALCULATE COEFFICIENT FCR FORCEC CONVECTION
C
C
      HCFOR = 10.4 * SQRT(VEL(I))
C COMPUTE TCLNEW
C
C
  200 TCLNEW = 35.7 - 0.032 * ACT(I) * (1.0-ETA(I)) - 0.18 * CLO(I) *
     1   (3.4E-8 * FCL(I) * ((TCLCLD + 273.0) ** 4 - (TMRT(I) + 273.0)
     1   ** 4) + FCL(I) * HCFOR * (TCLCLD - TA(I)))
C COMPUTE ERROR
C
C
      ERROR = TCLNEW - TCLOLD
C TEST ERRCR. IF ERROR IS SMALL, STOP ITERATION PROCESS. IF ERROR IS
C LARGE, CCNTINUE ITERATING.
C
C
      IF (ABS(ERROR).LT.C.05) GO TO 30C
      II=II+1
      IF(II.EC.50) GO TO 999
C ESTABLISH A DIFFERENT TCLOLD BASED ON AMOUNT OF ERROR
C
C
      TCLCLC = TCLOLD + 0.3 * ERRCR
      GO TC 200
C CCMPUTE CCEFFICIENT FCR NATURAL CONVECTION BASEC ON ABOVE TCLNEW.
C
C
  300 CONTINUE
      HCNAT = 2.05 * (ABS(TCLNEW - TA(I))) ** 0.25
C TEST WHICH IS GREATER, HCFOR CR HCNAT.
C
C
      IF (HCNAT.LE.HCFCR.CR.ABS(HCNAT-HCFCR).LE.0.01) GO TO 400
C IF THE ABCVE TEST FAILS, THEN NATURAL CONVECTICN EXISTS AND ANOTHER
C ITERATICN PRCCESS MUST PE PERFORMED TO GET THE PROPER TCLNEW.
C
C
  500 TCLNEW = 35.7 - 0.C32 * ACT(I) * (1.0-ETA(I)) - C.18 * CLO(I) *
     1   (3.4E-8 * FCL(I) * ((TCLCLD + 273.0) ** 4 - (TMRT(I) + 273.0)
     1   ** 4) + FCL(I) * 2.05 * (TCLOLD - TA(I))
     1   * (ABS(TCLOLD - TA(I))) ** 0.25)
C COMPUTE ERROR.
C
C
      ERROR = TCLNEW - TCLOLD
C TEST ERRCR. IF ERROR IS SMALL, STOP ITERATION PROCESS. IF ERROR IS
C LARGE, CCNTINUE ITERATING.
C
C
      IF (ABS(ERRCR).LT.0.05) GO TO 600
      JJ=JJ+1
      IF(JJ.EQ.50) GO TO 998
C ESTABLISH A DIFFERENT TCLCLD BASED ON AMOUNT OF ERROR.
C
C
      TCLOLC = TCLOLD + 0.3 * ERROR
```

```
          GO TC 500
C THE FINAL CONVECTION COFFFICIENT IS NOW COMPUTED USING FINAL TCLNEW
C
C
  600 CONTINUE
          HC     = 2.05 * (ABS(TCLNEW - TA(I))) ** 0.25
          GO TC 700
  400 HC = HCFOR
  700 CONTINUE
C SET TCLF EQUAL TO TCLNEW
C
C
          TCLF= TCLNEW
C CALCULATICN IS MADE FOR CLOTHING TEMPERATURE USING THE REVISED
C EQUATION WHERE THE CONVECTIVE CCEFFICIENT IS ASSUMED EQUAL
C TO 10.4 * SQRT(VEL(I)) WHEN VEL(I).GT.0.1 AND ECUAL TO 3.28877 WHEN
C VELOCITY IS LESS THAN OR EQUAL TO 0.1 M/S.
          IF(VEL(I).GT.0.1) HCSG = HCFOR
          IF(VEL(I).LE.0.1) HCSG = 3.28877
          TCLSG = (35.7 - 0.032 * ACT(I) + 0.18 * CLO(I) * FCL(I)
     1    * (HCSG  * TA(I) + 13.6E-8 * (TMRT(I) + 273.0) ** 3 * TMRT(I)))
     1    / (1.0 + 0.18 * CLO(I) * FCL(I) * (13.6E-8 * (TMRT(I) + 273.0)
     1    ** 3 + HCSG))
C CALCULATE THE DEVIATION AND PERCENT DEVIATION BETWEEN THE REVISED
C CLOTHING TEMPERATURE AND FANGER'S EQUATION CLOTHING TEMPERATURE
C
C
          TDEV = TCLSG - TCLF
          TDPCT = ((TCLSG - TCLF) / TCLF) * 100.0
C COMPUTE PREDICTED MEAN VOTE USING FANGER'S ECUATION
C
C
          POWER = EXP(-0.042 * ACT(I))
          PMVF= (0.352 * POWER + 0.032) * (ACT(I) * (1.0-ETA(I))
     1 - 0.35 * (43.0 - 0.061 * ACT(I) * (1.0-ETA(I)) - PA(I))
     1 - 0.42 * (ACT(I) * (1.0-ETA(I)) - 50.0) - 0.0023 * ACT(I)
     1 * (44.0 - PA(I)) - 0.0014 * ACT(I) * (34.0 - TA(I))
     1 - 3.4E-8 * FCL(I) * ((TCLF+ 273.0) ** 4 - (TMRT(I) + 273.0) ** 4)
     1 - FCL(I) * HC * (TCLF- TA(I)))
C CALCULATE THE PREDICTED MEAN VOTE USING THE REVISED VOTE EQUATION
C AND THE REVISED CLOTHING TEMPERATURE
C
C
          PMVSG = (0.352 * POWER + 0.032) * (5.95 + 0.453 * ACT(I)
     1    + 0.0023 * ACT(I) * PA(I) + 0.0014 * ACT(I) * TA(I)
     1    + 0.35 * PA(I) - 13.6E-8 * FCL(I) * (TMRT(I) + 273.0) ** 3
     1    * (TCLSG - TMRT(I)) - FCL(I) * HCSG  * (TCLSG - TA(I)))
C CALCULATE THE DEVIATION AND PERCENT DEVIATION  BETWEEN THE REVISED
C PREDICTED MEAN VOTE AND FANGER'S PREDICTED MEAN VOTE
C
C
          VDEV = PMVSG - PMVF
          VDPCT = ((PMVSG - PMVF) / PMVF) * 100.0
   14 FORMAT('0',3X,8(F7.2,3X))
          WRITE(6,14) TA(I),VEL(I),TMRT(I),ACT(I),CLO(I),FCL(I),PA(I),
     1    ETA(I)
   16 FORMAT(' ',3X,11(F7.3,3X))
          WRITE(6,16) HCFOR, HC, HCSG, TCLF, TCLSG, TDEV, TDPCT, PMVF,
     1PMVSG, VDEV, VDPCT
    7 K=K+1
```

```
      IF(K.EC.19) J=J+1
   18 FORMAT(' ',6X,'TA',PX,'VEL',7X,'TMRT',7X,'ACT',7X,'CLC',7X,'FCL',
     1    7X,'PA',8X,'ETA',38X,'PAGE',2X,I3)
      IF(K.EC.19) WRITE(6,18)J
      IF(K.EC.19) WRITE(6,15)
      IF(K.EC.19) K=0
      GC TC 100
  999 WRITE(6,9)
    9 FORMAT('-',10X,'I ITERATED 5C TIPES FOR TCL IN FCRCEC CONV')
      GO TC 100
  998 WRITE(6,8)
    8 FORMAT('-',10X,'I ITERATED 50 TIMES FOR TCL IN NAT CONV')
  100 CONTINUE
      STOP
      END

$ENTRY
```

TA	VEL	TPRT	ACT	CLO	FCL	PA	ETA			
HCFCR	HC	FCSG	TCLF	TCLSG	TDEV	TDPCT	PMVF	PMVSG	VDEV	VDPCT
14.00	0.05	14.00	70.00	1.00	1.15	5.99	0.00			
2.326	3.454	3.289	22.063	22.294	0.231	1.046	-1.066	-1.009	0.057	-5.324
14.00	0.10	14.00	70.00	1.00	1.15	5.99	0.00			
3.289	3.455	3.289	22.069	22.294	0.225	1.020	-1.068	-1.009	0.059	-5.549
14.00	0.15	14.00	70.00	1.00	1.15	5.99	0.00			
4.028	4.028	4.028	21.711	21.786	0.075	0.347	-1.181	-1.152	0.029	-2.456
14.00	0.20	14.00	70.00	1.00	1.15	5.99	0.00			
4.651	4.651	4.651	21.351	21.404	0.053	0.249	-1.290	-1.259	0.031	-2.400
14.00	0.30	14.00	70.00	1.00	1.15	5.99	0.00			
5.696	5.696	5.696	20.815	20.841	0.026	0.123	-1.452	-1.418	0.034	-2.371
14.00	0.40	14.00	70.00	1.00	1.15	5.99	0.00			
6.578	6.578	6.578	20.388	20.429	0.040	0.198	-1.553	-1.534	0.019	-1.226
14.00	0.50	14.00	70.00	1.00	1.15	5.99	0.00			
7.354	7.354	7.354	20.079	20.105	0.025	0.125	-1.647	-1.625	0.023	-1.384
14.00	1.00	14.00	70.00	1.00	1.15	5.99	0.00			
10.400	10.400	10.400	19.081	19.096	0.015	0.080	-1.923	-1.908	0.015	-0.778
14.00	1.50	14.00	70.00	1.00	1.15	5.99	0.00			
12.737	12.737	12.737	18.471	18.523	0.053	0.286	-2.042	-2.069	-0.028	1.355
16.00	0.05	16.00	70.00	1.00	1.15	6.82	0.00			
2.326	3.365	3.289	23.257	23.397	0.141	0.605	-0.700	-0.668	0.033	-4.687
16.00	0.10	16.00	70.00	1.00	1.15	6.82	0.00			
3.289	3.364	3.289	23.255	23.397	0.142	0.610	-0.700	-0.668	0.032	-4.622
16.00	0.15	16.00	70.00	1.00	1.15	6.82	0.00			
4.028	4.028	4.028	22.867	22.947	0.060	0.262	-0.818	-0.794	0.024	-2.912
16.00	0.20	16.00	70.00	1.00	1.15	6.82	0.00			
4.651	4.651	4.651	22.566	22.608	0.042	0.187	-0.915	-0.890	0.026	-2.790
16.00	0.30	16.00	70.00	1.00	1.15	6.82	0.00			
5.696	5.696	5.696	22.088	22.108	0.020	0.089	-1.059	-1.030	0.029	-2.704
16.00	0.40	16.00	70.00	1.00	1.15	6.82	0.00			
6.578	6.578	6.578	21.709	21.741	0.033	0.150	-1.149	-1.133	0.016	-1.354
16.00	0.50	16.00	70.00	1.00	1.15	6.82	0.00			
7.354	7.354	7.354	21.432	21.453	0.021	0.100	-1.232	-1.214	0.018	-1.458
16.00	1.00	16.00	70.00	1.00	1.15	6.82	0.00			
10.400	10.400	10.400	20.545	20.556	0.011	0.053	-1.480	-1.467	0.014	-0.915
16.00	1.50	16.00	70.00	1.00	1.15	6.82	0.00			
12.737	12.737	12.737	19.997	20.045	0.048	0.239	-1.583	-1.610	-0.027	1.705
18.00	0.05	18.00	70.00	1.00	1.15	7.74	0.00			
2.326	3.267	3.289	24.449	24.511	0.062	0.253	-0.333	-0.321	0.012	-3.574

TA	VEL	TMRT	ACT	CLO	FCL	PA	ETA			
HCFOR	HC	HCSG	TCLF	TCLSG	TDEV	TDPCT	PMVF	PMVSG	VDEV	VDPCT
18.00	0.10	18.00	70.00	1.00	1.15	7.74	0.00			
3.289	3.289	3.289	24.462	24.511	0.049	0.200	-0.346	-0.321	0.025	-7.294
18.00	0.15	18.00	70.00	1.00	1.15	7.74	0.00			
4.028	4.028	4.028	24.091	24.117	0.026	0.107	-0.460	-0.432	0.028	-6.162
18.00	0.20	18.00	70.00	1.00	1.15	7.74	0.00			
4.651	4.651	4.651	23.788	23.820	0.032	0.134	-0.536	-0.515	0.021	-3.885
18.00	0.30	18.00	70.00	1.00	1.15	7.74	0.00			
5.696	5.696	5.696	23.367	23.381	0.014	0.061	-0.662	-0.638	0.023	-3.542
18.00	0.40	18.00	70.00	1.00	1.15	7.74	0.00			
6.578	6.578	6.578	23.034	23.060	0.026	0.111	-0.741	-0.729	0.013	-1.693
18.00	0.50	18.00	70.00	1.00	1.15	7.74	0.00			
7.354	7.354	7.354	22.790	22.807	0.018	0.077	-0.814	-0.800	0.014	-1.715
18.00	1.00	18.00	70.00	1.00	1.15	7.74	0.00			
10.400	10.400	10.400	22.012	22.019	0.007	0.032	-1.034	-1.021	0.012	-1.186
18.00	1.50	18.00	70.00	1.00	1.15	7.74	0.00			
12.737	12.737	12.737	21.527	21.570	0.043	0.198	-1.122	-1.148	-0.026	2.297
20.00	0.05	20.00	70.00	1.00	1.15	8.77	0.00			
2.326	3.159	3.289	25.640	25.634	-0.006	-0.023	0.037	0.032	-0.006	-15.622
20.00	0.10	20.00	70.00	1.00	1.15	8.77	0.00			
3.289	3.289	3.289	25.599	25.634	0.036	0.140	0.012	0.032	0.020	171.307
20.00	0.15	20.00	70.00	1.00	1.15	8.77	0.00			
4.028	4.028	4.028	25.278	25.295	0.018	0.069	-0.087	-0.064	0.023	-26.255
20.00	0.20	20.00	70.00	1.00	1.15	8.77	0.00			
4.651	4.651	4.651	25.016	25.040	0.023	0.093	-0.152	-0.136	0.017	-10.885
20.00	0.30	20.00	70.00	1.00	1.15	8.77	0.00			
5.696	5.696	5.696	24.652	24.662	0.010	0.039	-0.261	-0.242	0.019	-7.207
20.00	0.40	20.00	70.00	1.00	1.15	8.77	0.00			
6.578	6.578	6.578	24.366	24.385	0.019	0.079	-0.330	-0.320	0.010	-3.027
20.00	0.50	20.00	70.00	1.00	1.15	8.77	0.00			
7.354	7.354	7.354	24.153	24.167	0.014	0.058	-0.392	-0.381	0.010	-2.669
20.00	1.00	20.00	70.00	1.00	1.15	8.77	0.00			
10.400	10.400	10.400	23.482	23.486	0.004	0.017	-0.583	-0.572	0.011	-1.857
20.00	1.50	20.00	70.00	1.00	1.15	8.77	0.00			
12.737	12.737	12.737	23.060	23.098	0.038	0.163	-0.657	-0.682	-0.024	3.676
22.00	0.05	22.00	70.00	1.00	1.15	9.91	0.00			
2.326	3.036	3.289	26.810	26.768	-0.042	-0.156	0.418	0.390	-0.029	-6.813
22.00	0.10	22.00	70.00	1.00	1.15	9.91	0.00			
3.289	3.289	3.289	26.743	26.768	0.025	0.093	0.375	0.390	0.015	4.078

TA	VEL	THRT	ACT	CLO	FCL	PA	ETA			
HCFOR	HC	HCSG	TCLF	TCLSG	TCEV	TCPCT	PMVF	PMVSG	VDEV	VDPCT
22.00	0.15	22.00	70.00	1.00	1.15	9.91	0.00			
4.028	4.028	4.028	26.472	26.483	0.011	0.040	0.292	0.310	0.018	6.089
22.00	0.20	22.00	70.00	1.00	1.15	9.91	0.00			
4.651	4.651	4.651	26.251	26.267	0.016	0.061	0.236	0.249	0.013	5.429
22.00	0.30	22.00	70.00	1.00	1.15	9.91	0.00			
5.696	5.696	5.696	25.943	25.949	0.006	0.022	0.145	0.160	0.015	10.158
22.00	0.40	22.00	70.00	1.00	1.15	9.91	0.00			
6.578	6.578	6.578	25.702	25.716	0.014	0.054	0.086	0.094	0.008	8.830
22.00	0.50	22.00	70.00	1.00	1.15	9.91	0.00			
7.354	7.354	7.354	25.521	25.532	0.011	0.042	0.035	0.042	0.008	22.395
22.00	1.00	22.00	70.00	1.00	1.15	9.91	0.00			
10.400	10.400	10.400	24.956	24.957	0.001	0.006	-0.129	-0.119	0.010	-7.398
22.00	1.50	22.00	70.00	1.00	1.15	9.91	0.00			
12.737	12.737	12.737	24.596	24.629	0.033	0.132	-0.189	-0.212	-0.022	11.710
24.00	0.05	24.00	70.00	1.00	1.15	11.19	0.00			
2.326	2.895	3.289	28.002	27.912	-0.090	-0.321	0.791	0.754	-0.036	-4.593
24.00	0.10	24.00	70.00	1.00	1.15	11.19	0.00			
3.289	3.289	3.289	27.917	27.912	-0.005	-0.019	0.734	0.754	0.020	2.706
24.00	0.15	24.00	70.00	1.00	1.15	11.19	0.00			
4.028	4.028	4.028	27.674	27.679	0.005	0.020	0.675	0.689	0.013	1.989
24.00	0.20	24.00	70.00	1.00	1.15	11.19	0.00			
4.651	4.651	4.651	27.493	27.503	0.010	0.036	0.630	0.640	0.010	1.533
24.00	0.30	24.00	70.00	1.00	1.15	11.19	0.00			
5.696	5.696	5.696	27.241	27.243	0.003	0.010	0.555	0.566	0.011	2.009
24.00	0.40	24.00	70.00	1.00	1.15	11.19	0.00			
6.578	6.578	6.578	27.069	27.053	-0.016	-0.060	0.492	0.513	0.021	4.291
24.00	0.50	24.00	70.00	1.00	1.15	11.19	0.00			
7.354	7.354	7.354	26.894	26.902	0.008	0.028	0.465	0.470	0.006	1.204
24.00	1.00	24.00	70.00	1.00	1.15	11.19	0.00			
10.400	10.400	10.400	26.390	26.432	0.041	0.157	0.364	0.338	-0.026	-7.147
24.00	1.50	24.00	70.00	1.00	1.15	11.19	0.00			
12.737	12.737	12.737	26.135	26.163	0.027	0.104	0.282	0.263	-0.019	-6.901
26.00	0.05	26.00	70.00	1.00	1.15	12.60	0.00			
2.326	2.739	3.289	29.188	29.066	-0.123	-0.420	1.166	1.125	-0.040	-3.443
26.00	0.10	26.00	70.00	1.00	1.15	12.60	0.00			
3.289	3.289	3.289	29.073	29.066	-0.007	-0.024	1.111	1.125	0.015	1.307
26.00	0.15	26.00	70.00	1.00	1.15	12.60	0.00			
4.028	4.028	4.028	28.883	28.884	0.002	0.005	1.065	1.074	0.010	0.917

TA	VEL	TMRT	ACT	CLO	FCL	PA	ETA			
HCFOR	HC	HCSG	TCLF	TCLSG	TCEV	TDPCT	PMVF	PMVSG	VDEV	VDPCT
26.00	0.20	26.00	70.00	1.00	1.15	12.60	0.00			
4.651	4.651	4.651	28.765	28.747	-0.018	-0.061	1.018	1.036	0.018	1.788
26.00	0.30	26.00	70.00	1.00	1.15	12.60	0.00			
5.696	5.696	5.696	28.544	28.545	0.001	0.002	0.971	0.979	0.008	0.842
26.00	0.40	26.00	70.00	1.00	1.15	12.60	0.00			
6.578	6.578	6.578	28.408	28.396	-0.013	-0.044	0.922	0.937	0.015	1.649
26.00	0.50	26.00	70.00	1.00	1.15	12.60	0.00			
7.354	7.354	7.354	28.273	28.278	0.005	0.018	0.900	0.904	0.004	0.435
26.00	1.00	26.00	70.00	1.00	1.15	12.60	0.00			
10.400	10.400	10.400	27.877	27.910	0.033	0.120	0.822	0.800	-0.022	-2.671
26.00	1.50	26.00	70.00	1.00	1.15	12.60	0.00			
12.737	12.737	12.737	27.678	27.700	0.022	0.079	0.758	0.741	-0.016	-2.165
28.00	0.05	28.00	70.00	1.00	1.15	14.18	0.00			
2.326	2.540	3.289	30.356	30.230	-0.126	-0.414	1.547	1.503	-0.044	-2.841
28.00	0.10	28.00	70.00	1.00	1.15	14.18	0.00			
3.289	3.289	3.289	30.237	30.230	-0.008	-0.025	1.493	1.503	0.010	0.672
28.00	0.15	28.00	70.00	1.00	1.15	14.18	0.00			
4.028	4.028	4.028	30.100	30.099	-0.001	-0.003	1.460	1.466	0.007	0.463
28.00	0.20	28.00	70.00	1.00	1.15	14.18	0.00			
4.651	4.651	4.651	30.013	30.000	-0.014	-0.046	1.426	1.438	0.013	0.890
28.00	0.30	28.00	70.00	1.00	1.15	14.18	0.00			
5.696	5.696	5.696	29.854	29.853	-0.001	-0.002	1.391	1.397	0.006	0.409
28.00	0.40	28.00	70.00	1.00	1.15	14.18	0.00			
6.578	6.578	6.578	29.754	29.745	-0.009	-0.030	1.357	1.367	0.010	0.757
28.00	0.50	28.00	70.00	1.00	1.15	14.18	0.00			
7.354	7.354	7.354	29.657	29.660	0.003	0.009	1.340	1.343	0.003	0.211
28.00	1.00	28.00	70.00	1.00	1.15	14.18	0.00			
10.400	10.400	10.400	29.367	29.393	0.025	0.086	1.285	1.268	-0.017	-1.337
28.00	1.50	28.00	70.00	1.00	1.15	14.18	0.00			
12.737	12.737	12.737	29.223	29.240	0.016	0.056	1.237	1.225	-0.012	-1.008

CORE USAGE   OBJECT CODE= 5560 BYTES,ARRAY AREA= 3600 BYTES,TOTAL AREA AVAILABLE= 46888 BYTES

DIAGNOSTICS   NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 0

COMPILE TIME= 9.62 SEC,EXECUTION TIME= 19.03 SEC, WATFIV - VERSION 1 LEVEL 3 MARCH 1971   DATE= 72/208

APPENDIX C

Program and Output for calculation of Slope for 72F ET and 78F ET Lines, Corresponding to 0.0 percent and 6.3 percent Body Wetness due to Regulatory Sweating.

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FORTRAN IV G LEVEL  21            MAIN              DATE = 73102          01/00/45                PAGE 0001

            C THIS PROGRAM CALCULATES THE SLOPE OF A CONSTANT PRSW LINE (DEG F/IN HG)
            C OR A LINE OF CONSTANT THERMAL SENSATION. TWO CARDS NEEDED TO EXECUTE
            C THE PROGRAM FOR VARIOUS VALUES OF PRSW MUST BE CHECKED. THESE ARE :
            C (1) PRSW = DESIRED VALUE
            C (2) TDB = XX.X+T/2.0     THE VALUE OF TEMP FOR THE XX.X SHOULD BE SUCH
            C                          THAT THE PRSW FOR THAT TEMP IS 0 AT ANY HUMIDITY
            C THIS PROGRAM MAY BE USED FOR PRSW VALUES BETWEEN 0.0 AND 1.0.
            C FOR PRSW OF 0.0 OR 1.0 , THE TEST STATEMENTS AT THE END MUST BE ALTERED.
0001              DIMENSION TIN(7),VPIN(7),RELHU(7),PRSW2(7),SLOPE(7)
0002              REAL KMIN
0003              PRSW1 = 0.0636
0004              N = 0
0005              WE = 0.0
0006              HC = 2.91
0007              HR = 5.23
0008              CLO =0.60
0009              RM = 58.2
0010              H = HC+ HR
0011              BAR = 29.921
0012              TDB1 =0.0
0013              K = 0
0014              VPW1 = 0.0
0015            1 FORMAT('1',6X,'DRY BULB TEMP    VAPOR PRESSURE    RELATIVE HUMIDITY
                 1  PERCENT BODY WETTEDNESS    SLOPE'/9X,'(OF)',12X,'(IN.HG)',12X,'(%
                 2)',14X,'DUE TO REGULATORY'/64X,'SWEATING')
0016            2 FORMAT(7X,F10.6,7X,F10.6,10X,F5.2,13X,F10.6)
0017            3 FORMAT(7X,F10.6,7X,F10.6,10X,F5.2,13X,F10.6,13X,F10.6)
0018              WRITE(6,1)
0019              DO 1200 J=20,80,10
0020              HH =J
0021              RH =HH/100.0
0022              K = K+1
0023              T = 0.0
0024              DO 1100 I=1,100
0025              TDB=74.0+T/2.0
0026              T = T+1.0
0027           30 VPSD = VP(TDB)
0028              VPW = RH*VPSD
0029              TSK = 34.1
0030              TCR = 36.6
0031              WK = WE*RM
0032              FCL = 1.0/(1.0+0.155*H*CLO)
0033              FPCL = 1.0/(1.0+0.143*HC+CLO)
0034              PRSW = 0.0
0035              EDIF = 5.0
0036              VPHG = VPW*25.4
0037              ERES = 0.0023*RM*(44.0-RH*VPHG)
0038              EV = ERES+EDIF
0039              EDRIP =0.0
0040              WRSW = 0.0
            C     MINIMUM SKIN CONDUCTANCE (W/SQ.M.-C)
0041              KMIN = 5.28
            C     SKBFN = NORMAL SKIN BLOOD FLOW (L/SQ.M.-HR)
0042              SKBFN = 6.3
0043              SKFB = SKBFN
0044              TIME = 0.0
0045              TA =(TDB-32.0)/1.8
            C     HEAT BALANCE EQUATIONS FOR PASSIVE SYSTEM
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FORTRAN IV G LEVEL  21                MAIN              DATE = 73102          01/00/45              PAGE 0002

0046           400 HFSK =(TCR-TSK)*(KMIN+1.163*SKFB)-(H*(TSK-TA)*FCL)-(EV-ERES)
0047               HFCR =RM-(TCR-TSK)*(KMIN+1.163*SKFB)-ERES-WK
              C    THERMAL CAPACITY FOR CORE OF AVERAGE MAN IN W-HR/C
0048               TCCR = 0.97*78.3
              C    THERMAL CAPACITY OF SKIN SHELL FOR AVERAGE MAN IN W-HR/C
0049               TCSK = 0.97*2.4
              C    CHANGE IN SKIN SHELL AND CORE IN DEG.C/HR
0050               DTSK = (HFSK*2.0)/TCSK
0051               DTCR = (HFCR*2.0)/TCCR
              C    UNIT OF TIME IS ONE HOUR
0052               DTIM = 0.016667
              C    TO ADJUST INTEGRATION OVER SMALL STEPS FOR LARGE CHANGER IN DTSK OR DTCR
0053               U = ABS(DTSK)
0054               IF(U*DTIM-0.1) 502,502,503
0055           503 DTIM = 0.1/U
0056           502 CONTINUE
0057               TIME = TIME +DTIM
0058               TSK = TSK+DTSK*DTIM
0059               TCR = TCR+DTCR*DTIM
              C    CONTROL SYSTEM
              C    DEFINING SIGNAL FOR CONTROLS FOR VASO-CONSTRICT-DIALATION
              C    SKIN SIGNAL
0060               SKSIG = (TSK-34.1)
0061               IF(SKSIG.LE.0.0) GO TO 520
0062               COLDS = 0.0
0063               WARMS = SKSIG
0064               GO TO 525
0065           520 COLDS = -SKSIG
0066               WARMS = 0.0
              C    CORE SIGNAL
0067           525 CRSIG =TCR-36.6
0068               IF(CRSIG.LE.0.0) GO TO 530
0069               COLDC = 0.0
0070               WARMC = CRSIG
0071               GO TO 535
0072           530 COLDC = -CRSIG
0073               WARMC = 0.0
              C    FACTORS 0.5(COLD) AND 75.0(WARM) GOVERN VASOCONSTRICTION AND VASODILATION
0074           535 STRIC = 0.5*COLDS
0075               DILAT = 75.0*WARMC
              C    NEW SKIN BLOOD FLOW
0076               SKFB = (SKBFN+DILAT)/(1.0+STRIC)
              C    CONTROL OF REGULATORY SWEATING
              C    DURING REST
0077               IF(RM-60.0) 550,550,555
0078           550 REGSW =100.0*WARMC*WARMS
0079               GO TO 560
              C    DURING EXERCISE
0080           555 REGSW=25.0*WARMS+250.0*WARMC
              C    HEAT LOSSS FROM REGULATION SWEATING
0081           560 ERSW=0.7*REGSW*EXP(SKSIG/10.0)
              C    WRSW IS REGULATORY SWEATING IN 100 CC/HR.UNITS PER AVERAGE MAN
0082               WRSW = WRSW+(ERSW*2.0/(0.7*100.0))*DTIM
0083               TSKF = (TSK*1.8)+32.0
0084               TCRF = (TCR*1.8)+32.0
0085               VPTSK = VP(TSKF)
              C    MAXIMUM EVAPORATIVE HEAT LOSS
0086               EMAX = 2.2*HC*(VPTSK-RH*VPSD)*25.4*FPCL
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              C      PERCENT BODY WETTEDNESS DUE TO REGULATORY SWEATING
0087                 PRSW = ERSW/EMAX
              C      PERCENT TOTAL BODY WETTEDNESS
0088             710 PWET = (0.06+0.94*PRSW)
              C      NOTE TOTAL EVAPORATIVE HEAT LOSS FROM SKIN IS PWET*EMAX
0089                 EDIF = PWET*EMAX-ERSW
              C      TOTAL EVAPORATIVE HEAT LOSS INCLUDING RESPIRATION
0090                 EV = ERES+ERSW+EDIF
0091                 IF(ERSW.LE.EMAX) GO TO 600
0092                 EDRIP = ERSW-EMAX
0093                 EV = ERES+EMAX
0094                 ERSW = EMAX
0095                 EDIF = 0.0
0096                 PRSW=1.0
0097                 PWET = 1.0
0098             600 CONTINUE
              C      CALCULATE QUASI-EQUILIBRIUM AFTER EXPOSURE TIME
              C      DETERMINE EXPOSURE TIME (SELECT 3.0 HRS)
0099                 IF(TIME.LT.3.0) GO TO 400
0100                 IF((PRSW1-PRSW).GT.0.25E-4) GO TO 900
0101                 IF(ABS(PRSW1-PRSW).LT.0.25E-4) GO TO 1150
0102                 TDB=(TDB+TDB1)/2.0
0103                 GO TO 30
0104             900 TDB1=TDB
0105            1100 CONTINUE
0106            1150 VPIN(K)=VPW
0107                 TIN(K)=TDB
0108                 RELHU(K)=HH
0109                 PRSW2(K)=PRSW
0110            1200 CONTINUE
0111                 DO 1500 M=1,7
0112                 IF(M.GT.1) GO TO 1300
0113                 WRITE(6,2) TIN(M),VPIN(M),RELHU(M),PRSW2(M)
0114                 GO TO 1500
0115            1300 N=M-1
0116                 SLOPE(M)=(VPIN(M)-VPIN(N))/(TIN(M)-TIN(N))
0117                 WRITE(6,3) TIN(M),VPIN(M),RELHU(M),PRSW2(M),SLOPE(M)
0118            1500 CONTINUE
0119                 STOP
0120                 END
```

```
      FUNCTION VP(T)
      Y1 = (16.386396+(0.00137804*T))-(5656.0/(459.67+T))
      Y2 = ALOG((459.67+T)/100.0)
      Y3 = Y1-(3.560573*Y2)
      VP = 10**Y3
      RETURN
      END
```

DRY BULB TEMP (OF)	VAPOR PRESSURE (IN.HG)	RELATIVE HUMIDITY (%)	PERCENT BODY WETTEDNESS DUE TO REGULATORY SWEATING	SLOPE
79.549225	0.203422	20.00	0.063611	
79.055962	0.300229	30.00	0.063617	-0.196219
78.547806	0.393678	40.00	0.063603	-0.183933
78.029083	0.483763	50.00	0.063594	-0.173667
77.500000	0.570480	60.00	0.063584	-0.163901
76.964111	0.653853	70.00	0.063605	-0.155578
76.420105	0.733897	80.00	0.063601	-0.147140

APPENDIX D

Ramifications of Revisions to the May, 1972 ASHRAE Proposed Standard.

The ASHRAE Standards Project Committee 55-66 R adopted a revised standard 55-66 R, Thermal Environmental Conditions for Human Occupancy, in January 1973. These revisions of the May 1972 draft of the proposed ASHRAE Standard have explicity defined the four points in the corners of the comfort envelope of Figure 4, page 19. The lines through these points differ slightly from the lines developed earlier for the left and right hand borders of the comfort envelope. Below are the equations introduced earlier and the defined ASHRAE lines.

$$t_{72} = -0.122\ P_a + 73.2 \quad \text{new ASHRAE definition}$$

$$t_{72} = -0.128\ P_a + 74.9 \quad \text{old derived line}$$

$$t_{78} = -0.233\ P_a + 79.7 \quad \text{new ASHRAE definition}$$

$$t_{78} = -0.233\ P_a + 81.8 \quad \text{old derived line}$$

The only effect on the newly defined lines is to alter the settings of the potentiometers used to calculate t_{72} and t_{78}.

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TWO TECHNIQUES FOR THE DEVELOPMENT OF AN INSTRUMENT TO EVALUATE THE QUALITY OF A THERMAL ENVIRONMENT

by

HARRY POMEROY GUY

B. S., Kansas State University, 1971

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

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Department of Mechanical Engineering

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ABSTRACT

There is a recognized need for instrumentation to collect environmental data and evaluate it in a way to give a measure of the thermal quality of an interior environment. Two alternative approaches were followed to develop a model for this instrumentation, one involving P.O. Fanger's clothing temperature and predicted mean vote (PMV) equations, and the other based on the May, 1972 proposed ASHRAE standard.

Data on available instrumentation to monitor environmental parameters was tabulated giving measurement techniques, accuracies and costs. Instrument outputs were also tabulated to aid in the development of an evaluating circuit.

The first evaluating circuit had as its basis Fanger's clothing temperature and PMV equations. The fundamental equations were modified by three assumptions: (1) the body mechanical efficiency is always zero, (2) the radiation exchange is linear with respect to clothing temperature and (3) the convective heat transfer coefficient is equal to $10.4\sqrt{V}$ when the relative air velocity is greater than 0.1 meter/sec (20 fpm) or equal to 3.2888 kcal/hr m^2 C when the relative air velocity is equal to or less than 0.1 meter/sec. The resulting clothing temperature equation is directly solved for clothing temperature with no iteration required as was the case in Fanger's original equations. Analysis by digital computer of the error incurred in using the modified equations to obtain PMV showed an average deviation of only 0.02 vote for ambient temperatures of 20 C to 32 C over a wide range of other conditions. An analog circuit was developed which

synthesizes the modified equations of clothing temperature and PMV from inputs of ambient data, activity level, and clothing data.

The other environmental evaluating circuit incorporated the May, 1972 ASHRAE comfort standard. The standard proposes a quadrilateral comfort envelope on a graph of vapor pressure versus adjusted dry bulb temperature. The evaluating instrument developed tests the position of the state of the local environment on the ASHRAE chart; i.e., whether the state of the local environment lies inside or outside the comfort envelope. Compliance with the proposed standard also dictates a maximum velocity of 70 fpm, therefore the test of ambient air velocity was included in the evaluating circuit.