The Role of Clothing in Achieving Acceptability of Environmental Temperatures Between 65F and 85F (18C and 30C)

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Reports on thermal comfort are rare before the 1910 ASHVE report by Lyle on "Relative Humidity and Its Effect on Comfort and Health". However, the thermal environmental specification for comfort is little changed from the 1914 specifications of 75F and 35% RH for sedentary conditions (and 68F and 50% RH for moderate work loads) suggested in the 1923 Report of the New York State Commission on Ventilation[1], to the current ASHRAE Standard 55–74 recommended comfort zone. This is described by a rectangular area on the psychrometric chart, bounded by a 14 mmHg vapor pressure between 71.5 and 77.6F (21.9–25.3C) at the top (~60% RH) and 5 mmHg between 72.6 and 79.7F (22.6–26.5C) at the bottom (~20% RH), provided that "air velocity is 70 ft/min (35 cm/sec) or less and the temperatures specified are the "Adjusted Dry Bulb Temperature" (ADBT) derived as one half the sum of air temperature plus mean radiant temperature.[2]

Such a complicated specification of a thermal environment could have been simplified by using the 1923 development by Houghten and Yaglou[3] of the original "Effective Temperature" (ET) Scale. This scale incorporates the air temperature (T_{db}), measured with a dry bulb thermometer, the radiant temperature [$MRT = (1 + .222\sqrt{V})(T_g - T_{db}) + T_{db}$] if ET corrected for radiation as integrated by a 6" Vernon black thermometer globe (T_g) is desired, the humidity measured by a wet bulb thermometer (and expressed as T_{wb}) and air motion (V), into the single index "ET". This index expresses an equivalence (as originally sensed by a few subjects) bewteen the thermal sensation induced by the effects of a given combination of T_{db}, T_{wb}, V (and MRT if correction for radiation was included) and those induced by the ET temperature at 100% RH with low air motion.

ET was not a rational index, but rather a subjectively derived one. It overemphasizes humidity effects in cool and comfortable conditions and underemphasizes humidity in warm conditions as well as the importance of air motion as humidity rises in the heat. ET has served as the standard reference temperature for comfort and performance studies until recently, despite our general unfamiliarity with the sensations of any temperature at 100% RH, except perhaps in a Turkish bath steam room. The introduction of ET in 1971[4] as a rational index based on a simple model of human physiological regulatory response, references the revised index (ET*) to a more subjectively familiar 50% RH base. Therefore, ET* is replacing the older index in current comfort literature.

The usual range of purely physiological thermoregulation is from 75 to 80F (24–32C) for a 100% RH reference (as in the earlier ASHRAE ET scale), whereas with a 50% RH reference (ET*), the zone of purely physiological regulation ranges from 77 to 106F (25–41C). Outside the limits of physiological regulation, ET* closely follows T_{db} in the cold ($ET^* \simeq 1F < T_{db}$), while in intolerably hot conditions $ET^* \simeq 16F > T_{db}$.

Given the simplicity of ET for specifying the interactions of the four environmental factors of concern in comfort research (air temperature, radiant temperature, humidity and air motion), research was directed toward such factors as geographic and seasonal variation, and the activity level, sex and age of the exposed individuals in the specification of a comfortable condition. As early as 1902, Rubner[5] had postulated that "we cannot neglect those conditions of voluntary regulation which are required by the state of thermal comfort." He revealed a very sophisticated understanding of many factors: the interaction between activity, clothing and comfort; the dependence of clothing insulation on its thickness; the effects of humidity build-up in clothing; and the effects of wind on clothing insulation. He reported that, at absolute muscular rest, comfort could be found at three states: undressed at 33C; wearing summer clothing at 25C; and wearing fur clothing at 12C. By 1925, Yaglou and Miller[6] had even suggested how differences in clothing might be incorporated into the ET index for comfort specification. However, despite the critical contribution that even small differences in clothing could make to thermal comfort, clothing was generally ignored as a specific variable until publication of contribution #22 from the J. B. Pierce Laboratory, Gagge's 1938 study.[7] This omission was recognized in the sequence of seminal studies at the Pierce Laboratory involving Partitional Calorimetry[8], and Gagge's application to it of the Linearity Criterion.[9] Partitional calorimetry was used in separating radiation from convective exchanges[10] and their relative influence on vasomotor temperature regulation.[11] It also allowed studies on the physiological reactions to varying environmental temperatures[12] and to various atmospheric humidities[13] and led to key papers on "A New Physiological Variable Associated with Sensible and Insensible Perspiration"[14], "Thermal Interchange Between the Human Body and Its Atmospheric Environment"[15] and the Pierce group's studies on the relationships between the environment, physiological reactions and sensations of pleasantness.[16,17] Most of the concepts relating comfort to psychological sensation, skin temperature and the percent sweat wetted area of the body arise from these three years of studies at the Pierce Foundation.

Unfortunately, many other researchers were either less cognizant that they were omitting effects of clothing differences as a variable in their studies of comfort, or neglected to specify or even to characterize the clothing worn in their studies. Thus, Yaglou and Miller[6] indicated that during the winter a 66 ET produced comfort for most people, while 63 to 71 ET would satisfy at least 50% of their subjects. Later studies by Houghten, involving radiation[18] in 1941 suggested 69 ET as the optimum. The 1950 Heating, Ventilating and Air Conditioning Guide[19] indicated that the 68 ET level would be comfortable for almost 98% of the population; the 1950 Guide also suggested that 71 ET, over the range of 30 to 70% RH, would satisfy 98% of the population in the summer, and that at least 50% of the population would be comfortable over the ET range 66.5 to 75F.

These summer-winter differences were extended to include differences within the U.S. as a function of latitude[20] with 73 ET preferred south of the 35th parallel, 72 ET between the 35th and 40th, 71 ET from the 40th to 45th and 70 ET above 45° of latitude. Canadian studies[21] supported the summer-winter difference, with a 66.5 ET optimum in winter and 70.5 ET optimum in summer. Studies of people (primarily women) working in light industry in Britain[22] suggested 60.8 ET as an optimum, with 60–68 ET judged comfortable by 70% or more. These British values were confirmed in a 1955 study of over 2,000 subjects in Britain[23] with 60.8 ET (61.7 CET [corrected effective temperature] reported as optimum and 66 ET (68 CET) as an upper limit in winter, and 62.9 ET (64.4 CET) as optimum in summer with 70 ET (71 CET) as an upper limit. Houghten, in 1941,[24] also suggested that the optimum condition for women was 1 ET higher than for men, and that men and women over 40 years of age preferred a 1 F greater ET than younger men and women.

We now recognize that, while some of these reported differences were associated with small differences in metabolic heat production, with an increase in heat production of 29 watts (25 kcal/hr) enough to offset a 1.7C (3F) reduction in the T_{db} for comfort[25], the majority of these reported differences reflect a failure to correct for clothing differences. Today, no differentiation of the comfort zone is recommended as a function of sex, season or geographic location[25, 26].

One possible explanation for the failure to specify clothing in these early studies was that there was no basis for comparing the insulation provided by various clothing systems. It was obvious, from the physics of heat transfer, that the convective heat exchange (H_c) between the skin surface and the ambient air could be described by a function of the form:

$$H_c = kA(T_s - T_{db})$$

where A was the skin surface area, T_s was the average skin surface temperature, T_{db} the air temperature and k was the convective heat transfer coefficient. Gagge's application of the first law of thermodynamics and its linearity criterion[9], helped suggest the form of the heat balance equation:

$$M + A_r R - C(T_s - T_A, V) - E + S = 0$$

where M was the metabolic heat production, A_r R represented the radiative heat exchange function, $C(T_s - T_A, V)$ represented the convective heat exchange function, E represented evaporative heat losses and S represented body heat storage.

He and Drs. Winslow and Herrington then explored this convective heat exchange function for two nude subjects[10] and showed that it could be expressed as:

$$C = k\sqrt{V}\,(T_s - T_{db})$$

where V was expressed in feet per minute and the temperatures were in °C. They reported k as 2.30 kcal/hr °C for the subject with 2.13 m^2 of surface area, and as 1.87 for the subject with 1.49 m^2. The group went on to introduce a new "operative temperature" (T_O), representing the net effect of both air and wall temperatures; i. e. convective and radiative heat exchanges[12]. In 1938 they presented work on Clothing and Bodily Reactions to Temperature[7] by Gagge, Winslow and Herrington, whereby "it is possible at any time to estimate the radiation exchange, R, and convection loss, C, by use of the following relations:

$$R = k_r(T_{cl} - T_w),$$

and

$$C = k_c(T_{cl} - T_A)$$

where T_{cl} is the mean surface temperature of body and clothing exposed to the environment. Adding...,

$$R + C = k_o(T_{cl} - T_o)$$

where k_o equals the sum of k_r and k_c, and the operative temperature, T_o," ....

The next 1938 study, on "The Relative Influence of Radiation and Convection upon the Temperature Regulation of the Clothed Body", Pierce Contribution #23,[27] led to a prediction equation for skin temperature ("valid where evaporation is minimal") and relationships between the skin temperature and subjective reports of pleasant, indifferent and unpleasant. The final Pierce study for 1938 in this area in Contribution #24[28] explored humidity effects for clothed subjects and the significance of the wetted area, while Contribution #25[29] explored "The Influence of Air Movement upon Heat Losses from the Clothed Human Body."

The stage was now set to define a clothing insulation unit and, in 1941[30], Gagge, in collaboration with Burton and

Bazett, defined the clo unit, referenced to a typical business suit of that era, from the physical relationship:

$$\text{Resistance} = \text{Potential Difference}/\text{Flow}$$

The potential difference for non-evaporative heat loss (i.e. $H_{R\&C}$ from the human skin) is, obviously, the difference between skin temperature (T_S) and ambient temperature (T_{db} or, if $T_{db} \neq MRT$, T_O). The available heat flow was taken as the total resting heat production ($M = 1\ MET = 50\ kcal/m^2 hr$) minus the 24% of M lost by both evaporation of the moisture diffusing from the skin and respiratory heat exchange. Thus:

$$\text{Resistance} = (T_S - T_O)/(0.76 \times 50)$$

With a "comfortable" skin temperature of 33C and a typical office temperature (for 1941), of 21C (70F), the resistance (R) to convective and radiative heat loss for a man dressed for the office was:

$$R = (33\text{-}21)/38 = 0.32 C/kcal\ m^2\ hr$$

Previous work at the Pierce Laboratory on nude men[31] had suggested that 0.14C/kcal m^2 hr of resistance to heat loss was provided simply by the still air layer surrounding the body (I_A), leaving 0.18C/kcal m^2 hr as the defined 1 clo resistance of a standard business suit. For simplicity, the heat loss allowed through insulation of clothing is usually presented rather than the resistance; i.e. 1 clo of insulation allows 1/0.18 or 5.55 kcal/m^2 hr of heat loss per °C of difference between the skin and surrounding temperature.

This empirically derived original definition still serves as a common base for characterizing clothing. The intrinsic insulation (I_{clo}) value of today's typical items office clothing can be characterized as shown in Table 1, derived from studies at Kansas State University.[32] Suggested formula-

Table I. clo insulation units for individual items of clothing and formulae for obtaining total intrinsic insulation.

Clothing	**Men**	**Women**	
Underwear			
Sleeveless	0.06	Bra and Panties	0.05
T shirt	0.09	Half Slip	0.13
Underpants	0.05	Full Slip	0.19
Torso			
Shirt		Blouse	
Light, short sleeve	0.14	Light	0.20[1]
long sleeve	0.22	Heavy	0.29[1]
Heavy, short sleeve	0.25	Dress	
long sleeve	0.29	Light	0.22[1,2]
(Plus 5% for tie or turtleneck)		Heavy	0.70[1,2]
Vest		Shirt	
Light	0.15	Light	0.10[2]
Heavy	0.29	Heavy	0.22[2]
Trousers		Slacks	
Light	0.26	Light	0.26
Heavy	0.32	Heavy	0.44
Sweater		Sweater	
Light	0.20[1]	Light	0.17[1]
Heavy	0.37[1]	Heavy	0.37[1]
Jacket		Jacket	
Light	0.22	Light	0.17
Heavy	0.49	Heavy	0.37
Footwear			
Socks		Stockings	
Ankle Length	0.04	Any length	0.01
Knee High	0.10	Panty Hose	0.01
Shoes		Shoes	
Sandals	0.02	Sandals	0.02
Oxfords	0.04	Pumps	0.04
Boots	0.08	Boots	0.08

Total $I = 0.727 \sum \text{items} + 0.113 = 0.770 \sum \text{items} + 0.05$

1. Less 10% if short sleeve or sleeveless
2. Plus 5% if below knee length, less 5% if above.

tions for summing to obtain a "TOTAL" insulation for men's and women's clothing are included at the bottom of the table. Typical indoor clothing worn in offices today range from 0.4 clo in summer (short, light dress; light slacks and short sleeved shirt) to 0.6 clo in spring and fall (heavy, short sleeved top and skirt; long sleeved shirt and trousers) to perhaps 1.0 in winter (heavy slacks, light sweater and blouse and jacket; heavy trousers, sweater and shirt and jacket). As a rule of thumb, it has been suggested[25] that the air temperature for comfort can be offset by 1F for each 0.1 clo deviation from the usual 0.6 clo insulation baseline for individuals doing sedentary to light office work (100 to 200 kcal/hr), and by 2F for each 0.1 clo deviation at higher work levels; i.e. if 1.0 clo of insulation were worn, the 78F mid-point in the ASHRAE comfort chart for office workers wearing the usual 0.6 clo of insulation could be lowered to 74F for light work and to 70F for heavier work, just by this behavioral temperature regulation of clothing selection.

There are limits to how far such behavioral regulation can go[33, 34], especially in the practical case of office work. As can be seen in Table II, where we have attempted to relate the classic ASHRAE comfort vote (where 4 is neutral, 1 is cold and 7 is hot) to a range of ET* and associated comfort sensations, mean skin temperatures and % wettedness, the onset of cool thermal discomfort is initially a function of toe (and finger) temperatures. Adding more torso clothing[33, 34] may help delay vasoconstriction. (Similarly, wearing a hat prevents heat loss from the head, where vasoconstriction does not occur and thus a great proportion of the body's heat production can be lost, thus maintaining circulatory heat flow to the toes and fingers but it is only a temporary expedient unless total heat balance can be maintained.)

As Sheard suggested in 1938[35], the hands and feet act as error regulators for the body and the reduction of their circulatory heat input is dramatic. We agree with Van Dilla[36] that the 72 kcal/m² hr of circulatory heat input to the fingers of a comfortable resting subject falls actutely to 7 kcal/m² hr when the subject is chilled. Adding insulation

Table II Comfort vote, and the temperature sensation as a function of ET* and the associated mean skin temperature and percent wettedness.

Comfort Vote	Temperature Sensation	ET*(1)	Comfort Sensation	$\bar{T}_s$ (2)	$\%A_{sw}$ (3)
	Very Cold	10C	Uncomfortable	30C	
1	Cold	15C		30.5C	
2	Cool		Slightly Uncomfortable	32C	
3	Slightly Cool	20C		32.5C ($T_{toes/fingers}$)	
4	Neutral	25C	Comfortable	34C	6
5	Slightly Warm	30C		35C	
6	Warm	35C	Slightly Uncomfortable	–	20
7	Hot	40C	Very Uncomfortable	–	40
	Very Hot			–	60
		45C	Limited Tolerance	($T_{core} - \bar{T}_s$)	80 100

(1) Air temperature (T_{db}) at 50% RH with air movement ≈ 0.41 m/s wearing standard long sleeved shirt or trousers (0.6 clo intrinsic).

(2) Mean Weighted Skin Temperature

(3) Percent of skin area sweat wetted ≈ Skin relative humidity ≈ E_{req}/E_{max}

directly to the feet, in the form of heavier socks and larger (i. e. thicker) footwear can provide some delay in cooling, but the key is maintenance of circulatory heat input at comfortable levels by increased metabolic heat production (through increased work, since shivering is not associated with comfort) and by decreasing over all heat loss by adding clothing over all the body. Ultimately, since clothing insulation is a function of the thickness of the trapped air layer, the bulkiness of the clothing becomes a practical limitation to foot and torso insulation; ~4 clo of insulation is provided on a flat surface by a 1 inch thickness of conventional clothing materials, whether of wool, cotton or synthetic fiber, so there is no foreseeable solution from improved clothing materials.

The hands, ultimately, are the limiting factor to dropping office temperatures to conserve energy, since: a) it is difficult to perform most work wearing gloves; b) the resistance of a glove to heat loss is a function of its thickness; c) for a thin cylinder such as a finger, the increase in surface area for heat loss parallels the increase in thickness, so that it has proven impossible to design a practical mitten ensemble which will provide more than about 1.2 clo intrinsic insulation around the fingertips. Thus the hands, and to a more treatable degree the feet, are the ultimate limitation to energy conservation by lowering the thermostat.

In his more recent studies, Gagge and his later collaborators at the Pierce Laboratories, especially Nishi and Gonzalez, have developed methods for describing the evaporative heat transfer limitations imposed by conventional clothing. However, the problem of avoiding discomfort in the heat is, as shown in Table II, primarily a function of minimizing the percent of the body surface area that is wetted by sweat; this is most easily accomplished by removing clothing and exposing bare skin. If one avoids special treatments, or impermeable items like plastic raincoats or the "wind shirts" used by skiers, the evaporative heat transfer coefficient (h_e) is directly relatable to the convective heat transfer coefficient (h_c) by the Lewis

Relationship:

$$h_e = 2.2h_c$$

so there is little that can be done with clothing to reduce the percent sweat wetted area, other than to remove as much clothing and expose as much skin as possible. While raising the thermostat level for air conditioning as an energy conservation measure, social standards will therefore be the limiting feature to avoid an increase of the body's sweat wetted surface area to, and above, the 20% level considered as the threshold for discomfort in the heat. While it is accepted practice for men in Australia to wear shorts as office clothing, shorts for men and women are far from acceptable norms in even the hottest areas of the United States today; the blossoming of industry in the Southern U. S. has been a function of the air-conditioning industry as much as anything else.

It seems clear that the trend, since the 1920's, to lighter weight and less clothing will have to be reversed completely in the winter if thermal comfort is to be achieved at the present FEA guidelines of 68 to 70F for winter thermostat settings [37, 38], and, because of the problem of the hands, thermal comfort may not be achievable to allow for sedentary office work at temperatures below that level. The present summertime guidelines of 78 to 80F can be achieved with conventional summer clothing, and even the proposed extended guidelines of 80 to 82F could be made thermally comfortable if bathing suits become acceptable as office wear.

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