

THE ROLE OF CLOTHING IN MEETING FEA ENERGY CONSERVATION GUIDELINES

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During the summer and winter of 1974, the Federal Energy Administration (FEA) established temperature guidelines for winter heating and summer cooling by attempting to lower or raise the desired working condition by 6 deg F (or 3 deg C) respectively, about the optimum level 75 F (23.9 C) currently set by ASHRAE STANDARD 55-74. Their guidelines for winter indoor temperatures were 68 - 70 F (20 - 21.1 C) and for summer 78 - 80 F (25.6 - 26.7 C) or a proposed 80 - 82 F (26.7 - 27.8 C). The summer's settings should be accomplished without humidity control and reheat.

Both the Fanger comfort equation (1) and our earlier model of temperature regulation (2 and 3) can be used to deduce the options available to the heating, ventilating and air-conditioning engineer in meeting the above FEA guidelines. These options are briefly summarized in Table 1. During the summer, the discomfort caused by a 6 deg F (3 deg C) rise in T_a could be balanced theoretically by a drop to low relative humidity. Radiant cooling is impractical. The same level of comfort could be maintained if the air movement were raised to the 75 fpm (0.4 m/s) level. Both these solutions may well require extensive electric energy in the form of air-conditioning equipment and fans. The same 6 deg F (3 deg C) rise in T_a could also be balanced theoretically if the normal clothing insulation were reduced to a 0.2 Clo level, which insulation level was actually worn by only 5% of males but by 43% of females during our 1974 summer survey for FEA in New York[#]. An intrinsic Clo level of 0.4 was observed to be worn by about 50% of the males and females. During both these surveys people dressed for work according to season rather than for their expectations of the indoor temperature. From the above relationships, as has already been recognized by the FEA, the most practical first order compromise between a need for energy conservation and maintenance of thermal comfort in the summer is the use of less insulative clothing during office work.

In the cold, more insulative clothing is the obvious answer to stay comfortable if the air temperature is lower. Alternatively, radiant heat could be used to balance discomfort from cold air but this may require considerable energy.

[#]Final Report, dated 1 March 1976, FEA Contract #14-01-0001-1891-1975, available on request to Director, J. B. Pierce Lab., New Haven, CT 06519.

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The general feasibility of using various levels of clothing insulation to meet the FEA guideline temperatures in combination with various levels of humidity and air movement are indicated in the following series of charts (Fig. 1 - 5). The ordinate scales are the ASHRAE ET*. The temperature for ET* range for 80% comfort, as prescribed by ASHRAE STANDARD 55-74, is indicated by horizontal lines. The abscissa scale is always the ambient air temperature. The relationship between ET* for the indicated level of metabolic activity, and the environmental factors, described by T_a , Clo (intrinsic), and air movement, have been determined by our most recent two-node model of human temperature regulation. (See Appendix 1.) The original model was described in 1972 (1); the present up-dated model includes our most recent concepts in human temperature regulation and the use of intrinsic and effective clothing insulation factors (4 and 5). Each chart to follow shows how any ambient temperature can be made comfortable in the ASHRAE 72 - 78 F ET* range for 80% acceptability by proper choice of humidity, air movement or clothing.

1. EFFECT OF CLOTHING INSULATION ON AIR TEMPERATURES FOR THERMAL COMFORT AND ACCEPTABILITY AT CONSTANT RELATIVE HUMIDITY AT 40 - 60%

The Comfort Chart in Fig. 1 shows the ASHRAE standard effective temperature (ET*) calculated for various levels of intrinsic clothing insulation indicated at various ambient temperatures ($T_a = MRT$) on the abscissa. The ASHRAE STANDARD 55-74 environmental conditions involved are 1.0 - 1.2 mets of sedentary office work, a low air movement of 20 - 30 fpm (0.1 - 0.15 m/s), and an intrinsic clothing insulation of 0.6 Clo. The test conditions observed during the FEA 1975 winter survey in New York actually paralleled the ASHRAE standard conditions with the same average clothing insulation and air movement and the temperature range 72 - 78 F. The acceptable scale at 80% and 90% corresponds with the ET* values observed during this winter survey and are representative of the comfort expected for the 72 - 78 F ET* range specified by ASHRAE STANDARD 55-74.

For the lower FEA summer guideline, the allowable range for clothing insulation for both men and women would be 0.1 - 0.5 Clo at 79 F (26.1 C), to maintain an equivalent comfortable ET* within 72 - 78 F; the optimum is 0.3 Clo. For the extended FEA guidelines of 80 - 82 F, the optimum Clo would be less than 0.3 Clo.

For the FEA winter guidelines of 68 - 70 F the optimum Clo range for an 80% acceptable would be about 0.8 - 1.2 Clo.

2. EFFECT OF RELATIVE HUMIDITY ON THERMAL ACCEPTABILITY FOR VARIOUS CLOTHING INSULATIONS

The same type comfort charts as drawn in Fig. 1 have been redrawn for relative humidities of 60 - 80% rh (tropics)(Fig. 2) and 20 - 40% rh (desert or winter)(Fig. 3).

In Fig. 2 at the higher humidity the optimum temperature occurs near 70 F (21.1 C) for 1.0 Clo; at 74.3 F (23.5 C) for 0.6 Clo; at 77.7 F (25.4 C) for 0.3 Clo. For the winter guidelines range (68 - 70 F) high humidity does not affect significantly the clothing requirement for comfort. However, for summer temperature guideline range of 78 - 80 F at 60 - 70% rh, 0.15 Clo insulation would be required for comfort in comparison with the 0.3 Clo at ~50% rh. There would be no practical solution only by proper choice of clothing for comfort at 81 F at 60 - 80% rh. As will be seen later, increased air movement will improve the present example.

For the 20 - 40% rh range presented in Fig. 3, slightly more clothing (by plus 0.1 Clo) would be required by the FEA temperature 68 - 70 F range than if the humidity were 50%. At the other extreme - both the FEA summer guideline of 78 - 80 F and 80 - 82 F comfort could easily be maintained by clothing insulation in range 0.3 - 0.4 Clo.

The effect of humidity alone under ASHRAE standard conditions (1.1 met - 0.6 Clo - 20 to 30 fpm) is illustrated in Fig. 4. In the FEA winter zone 68 - 70 F relative humidity is an

insignificant factor over range 20 - 80% rh. For the FEA summer zone of 78 - 80 F, a change from 20% to 80% rh would cause ET* to rise from 77.5 F (25.3 C) to 81.5 F (27.5 C); for the 80 - 82 F range, the same humidity change would cause ET* to vary from 79 F (26.1 C) to 85 F (29.4 C).

3. EFFECTIVENESS OF LOW LEVELS OF AIR MOVEMENTS ON THERMAL ACCEPTABILITY IN WARMTH

Fig. 5 has been drawn using 0.3 Clo throughout since this level of clothing insulation appears so far as the most practical to make acceptable the upper FEA summer limits (78 - 80F; 80 - 82 F). In Fig. 5 three levels of air movement are illustrated while wearing 0.3 Clo. An air movement of 30 - 40 fpm (0.15 - 0.2 m/s) would easily make the lower FEA limits 78 - 80 F acceptable, but the upper limits 80 - 82 F would require almost double the air movement 60 - 70 fpm (0.3 - 0.35 m/s). In general the rise in acceptable temperature is roughly proportional to the square root of the room air movement.

In Appendix 2 and 3 various combinations of clothing for men and women that would probably result in insulation values that fall in 0.2 - 1.2 Clo range are illustrated and tabulated. The intrinsic values of the clothing insulation indicated were actually measured directly (4) at the time the photographs were taken.

CONCLUSIONS

1. The FEA winter guidelines (68 - 70 F) are best met by wearing clothing with intrinsic insulation of 1.0 - 1.2 Clo with special emphasis on the distribution of the insulation over the legs and arms.
2. The FEA summer guidelines in range 78 - 80 F without reheat which would result in high humidities can best be met with intrinsic clothing insulation of 0.3 Clo or less. In the 80 - 82 F range, the 0.3 Clo must be reduced to 0.15 Clo, if practical and acceptable, or the local air movement in the work space should be raised at least to the 40 - 50 fpm (0.2 - 0.25 m/s) level. For the above temperature ranges humidity should still be below 70% rh.
3. For general use, an analytical method has been presented how to interpret any combination of environmental temperature, humidity, air movement and clothing worn in terms of the ASHRAE ET* scale, specified by ASHRAE STANDARD 55-74.

REFERENCES

1. Fanger, P. O., Thermal Comfort (facsimile of Danish 1970 Edition), McGraw-Hill, New York, 1972.
2. Gagge, A. P., J. A. J. Stolwijk and Y. Nishi, "An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Responses," ASHRAE TRANSACTIONS 77 (I), 247-262, 1971.
3. Nishi, Y. and A. P. Gagge, "A Psychrometric Chart for Graphical Prediction of Comfort and Heat Tolerance," ASHRAE TRANSACTIONS 80 (II), 115-130, 1974.
4. Nishi, Y., R. R. Gonzalez and A. P. Gagge, "Direct Measurement of Clothing Heat Transfer Properties During Sensible and Insensible Heat Exchange with Thermal Environment," ASHRAE TRANSACTIONS 81 (II), 183-200, 1975.
5. Nishi, Y., R. R. Gonzalez, R. G. Nevins and A. P. Gagge, "Field Measurement of Clothing Thermal Insulation," ASHRAE TRANSACTIONS 82 (II), 1976.

ACKNOWLEDGMENTS

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TABLE 1

Balance of Changes in Environment and in Ambient Temperature
for Baseline Thermal Comfort

Change of:	Made in:	Is Balanced by T_a Change of:
± 8 Torr (or $\sim 35\%$)	Ambient Vapor Pressure (or relative humidity)	∓ 2 F (1.1 C)
± 1.5 F (or ± 0.8 C)	Mean Radiant Temperature	∓ 2 F (1.1 C)
+ 20 fpm (+ 0.1 m/s)	Air Movement	+ 2 F (1.1 C)
± 0.15 Clo	Clothing (intrinsic)	∓ 2 F (1.1 C)
+ 0.5 mets	Activity	- 5.4 F (3 C)

Baseline Conditions:

T_a (= MRT) = 24 C (75 F)

P_a = 11 Torr (or 50% rh)

v = 0.1 - 0.15 m/s (30 fpm)

Clo = 0.6 (intrinsic)

M = 1.1 met (64 W/m²)

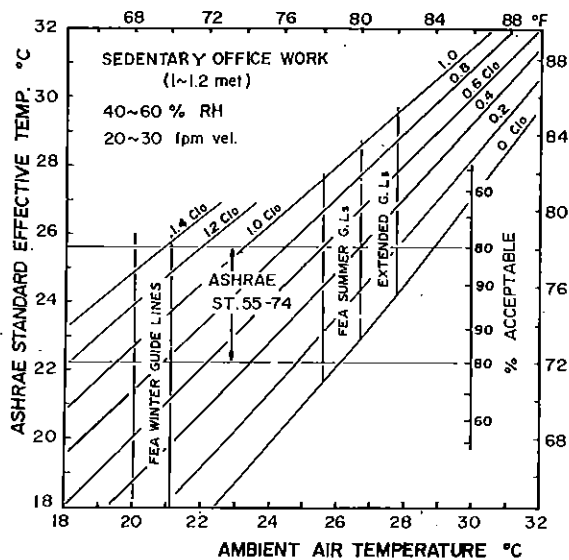


Fig. 1

The ASHRAE standard effective temperature (ET^*) for various levels of clothing insulation worn at ambient temperature T_a ($= MRT$) with normal relative humidity and air movement. By definition, ET^* always equals T_a for the 0.6 Clo locus in above chart

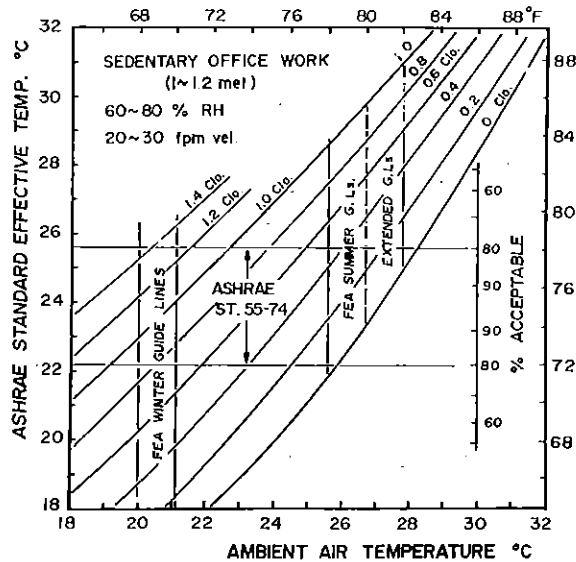


Fig. 2

Effect of clothing insulation on thermal acceptability for high relative humidities in determining ET^*

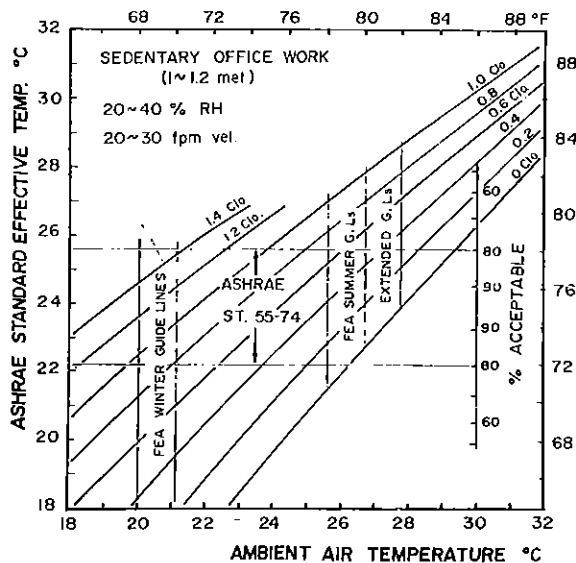


Fig. 3

Effect of clothing insulation on thermal acceptability for low relative humidities in determining ET^*

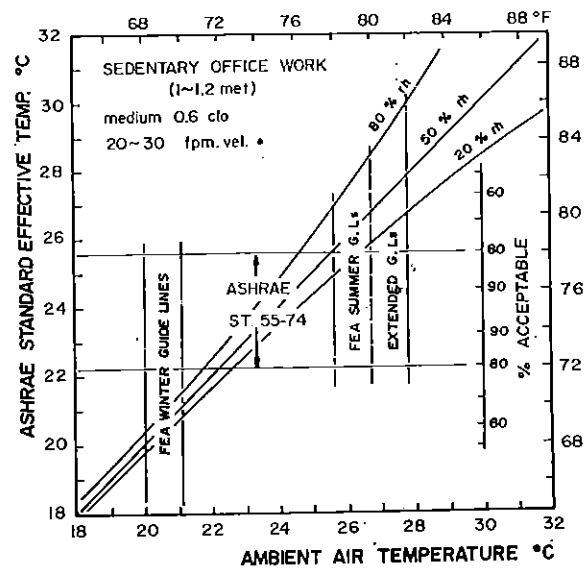


Fig. 4 Effect of relative humidity on thermal acceptability for ASHRAE standard clothing and air movement in determining ET*

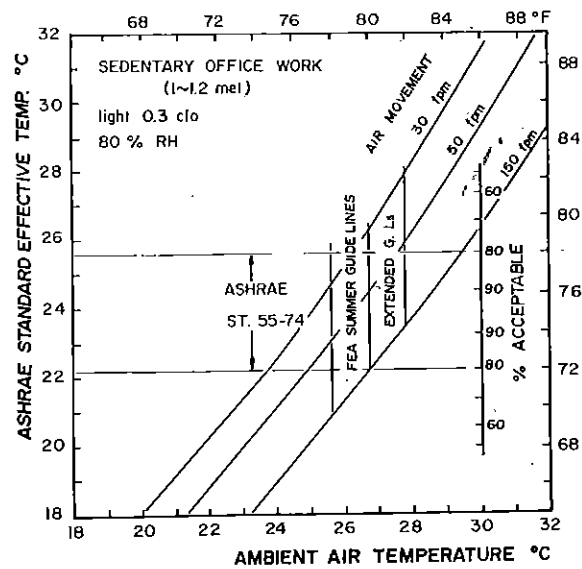


Fig. 5 Effect of varying air movement on thermal acceptability at high humidity under a typical tropical condition while lightweight clothing

APPENDIX 1

Annotated FORTRAN Program for Calculation of ASHRAE ET*

The present program is designed to calculate the ASHRAE ET* when the following basic factors are known and evaluated:

TA	-	ambient air or dry bulb temperature	C
TR	-	the mean radiant temperature	C
VEL	-	room air movement	m · s ⁻¹
RH	-	relative humidity	as fraction
CLO	-	intrinsic insulation of clothing worn	clo
ACT	-	level of activity in met units	met
(ACT = ACT*58.2 in W · m ⁻² in program)			
WK	-	work accomplished	W · m ⁻²

The above factors are defined by READ and DO statements.

The basic physiological terms used to describe the regulatory model are as follows. Secondary definitions will occur in the program itself.

TSK	=	mean skin temperature	C
TCR	=	internal body temperature	C
SKBF	=	skin blood flow	liters · m ⁻² · h ⁻¹
REGSW	=	regulatory sweating	g · m ⁻² · h ⁻¹

The following function relating saturation vapor pressure SVP in Torr to temperature T in C is used. The function is known as the Antoine Equation.

$$SVP(T) = \text{EXP}(18.6686 - 4030.183 / (T + 235.))$$

C STEADY STATE CHARACTERISTICS OF MODEL AT THERMAL NEUTRALITY

```

TTSK=34.0
TTCR=36.6
ALPHA=0.1
TTBM=ALPHA*TTSK+(1.-ALPHA)*TTCR
CSW=200.
CSTR=0.5
CDIL=150.

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C INITIAL CONDITIONS-PHYSIOLOGICAL THERMAL NEUTRALITY

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TSK=TTSK
TCR=TTCR
TBM=ALPHA*TSK+(1.-ALPHA)*TCR
SKRFN=6.3
SKBF=SKRFN
EV=0.1*ACT

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C CLOTHING AND ENVIRONMENTAL HEAT TRANSFER FACTORS AT SEA LEVEL
C CHCA IS EFF. CHC DUE TO ACT IN STILL AIR (TREADMILL WALKING)
  CHCA=5.66*(ACT/58.2-0.85)**0.39
C CHCV IS FUNCTION OF ROOM AIR MOVEMENT (VEL)
  CHCV=8.6*VEL**0.53
  IF(CHCV-CHCA) 4,4,5
4   CHC=CHCA
   GO TO 6
5   CHC=CHCV
6   CONTINUE
C CHC VALUE FOR STILL AIR IS 3.0 AT SEA LEVEL
7   IF(CHC-3.) 8,9,9
8   CHC=3.0
9   CONTINUE
   FACL=1.+0.15*CLO
   CHR=4.7
   CTC=CHC+CHR
   TO=(CHR*TR+CHC*TA)/CTC
   CLOE=CLO-(FACL-1.)/(0.155*FACL*CTC)
   FCLE=1./(1.+0.155*CLOE)
   FPCL=1./(1.+0.143*CHC*CLOE)
C TIME OF EXPOSURE SET AT ONE HOUR
  TIM=0.
  TIME=1.

C SIMULATION OF BODY TEMPERATURE REGULATION - START OF REG. LOOP
100 CONTINUE
    CLOE=CLO-(FACL-1.)/(0.155*FACL*CTC)
    FCLE=1./(1.+0.155*CTC*CLOE)
    TCL=TO+FCLE*(TSK-TO)
    CHR=4.*5.67E-8*((TCL+TR)/2.+273.2)**3)*0.725
    CTC=CHR+CHC
    TO=(CHR*TR+CHC*TA)/CTC
    ERES=0.0023*ACT*(44.-RH*SVP(TA))
    CRES=0.0014*ACT*(34.-TA)
C HEAT FLOW EQUATION AT SKIN SURFACE
  DRY=FCLE*CTC*(TSK-TO)
  ESK=EV-ERES
  HFSK=(TCR-TSK)*(5.28+1.163*SKBF)-DRY-ESK
  HFCR=ACT-(TCR-TSK)*(5.28+1.163*SKBF)-CRES-ERES-WK
C AVERAGE MAN 70KG, 1.8 SQ.METER
  TCSK=0.97*ALPHA*70.
  TCCR=0.97*(1.-ALPHA)*70.
  DTSK=(HFSK*1.8)/TCSK
  DTCR=(HFCR*1.8)/TCCR
  DTIM=1./60.
  DTBM=ALPHA*DTSK+(1.-ALPHA)*DTCR
  TIM=TIM+DTIM
  TSK=TSK+DTSK*DTIM
  TCR=TCR+DTCR*DTIM
C DEFINITION OF REGULATORY CONTROL SIGNALS
  SKSIG=TSK-TTSK
  IF(SKSIG) 10,10,15
10  COLDS=-SKSIG
    WARMS=0.
    GO TO 20
15  COLDS=0.
    WARMS=SKSIG
20  CRSIG=TCR-TTCR
    IF(CRSIG) 30,30,35
30  COLDC=-CRSIG
    WARMC=0.
    GO TO 40
35  WARMC=CRSIG
    COLDC=0.
40  CONTINUE

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```

C CONTROL SKIN BLOOD FLOW
  STRIC=CSTR*COLDS
  DILAT=CDIL*WARMC
  SKBF=(SKBFN+DILAT)/(1.+STRIC)
C RELATIVE WT. OF SKIN SHELL TO BODY CORE VARIES WITH SKBF
  ALPHA=0.04415+0.351/(SKBF-0.014)
C DEFINITION OF CONTROL SIGNALS FOR SWEATING
  TRM=ALPHA*TSK+(1.-ALPHA)*TCR
  BYSIG=TRM-TTBM
  IF(BYSIG) 50,50,55
50  COLDB=-BYSIG
  WARMB=0.
  GO TO 60
55  WARMB=BYSIG
  COLDB=0.
60  CONTINUE
C CONTROL OF REGULATORY SWEATING
  REGSW=CSW*WARMB*EXP(WARMB/10.7)
  ERSW=0.68*REGSW
  EMAX=2.2*CHC*(SVP(TSK)-RH*SVP(TA))*EPCL
  PRSW=ERSW/EMAX
  PWET=0.06+0.94*PRSW
  EDIF=PWET*EMAX-ERSW
  EV=ERES+ERSW+EDIF
  IF(EMAX-ERSW) 70,70,75
70  EV=ERES+EMAX
  FRSW=EMAX
  EDIF=0.
  PRSW=1.
  PWET=1.
75  CONTINUE
  IF(TIM-TIME) 100,110,110
110 CONTINUE
C END OF REGULATORY LOOP

```

At the end of exposure TIME, all the basic physiological terms listed above are now evaluated for activity and environment defined above. The state of thermal equilibrium (STORE) and the skin heat loss to the environment (HSK) now follow:

```

C CALCULATION OF HEAT STORAGE
  STORE=ACT-WK-CRES-EV-DRY
C CALCULATION OF SKIN HEAT LOSS ( HSK )
  HSK=ACT-ERES-CRES-WK-STORE
C CALCULATION OF ASHRAE STANDARD EFFECTIVE TEMPERATURE - SET
C DEFINITION OF ASHRAE STANDARD ENVIRONMENT
  CHRS=CHR
C CHCS IS CHCA VALUE FOR ACT SELECTED IN STILL AIR
  CHCS=CHCA
  CLOS=0.6
  FACLS=1.09
  CTCS=CHRS+CHCS
  CLOES=CLOS-(FACLS-1.)/(0.155*FACLS*CTCS)
  FCLES=1./(1.+0.155*CTCS*CLOES)
  FPCLS=1./(1.+0.143*CHCS*CLOES)
C STANDARD ACTIVITY POINT
  TACTS=TSK-HSK/(CTCS*FCLES)

```

```

C  AT START OF ITERATION
    SET=TACTS
C  DEF. OF SET IS SOLUTION OF HEAT BAL. EQ. WHEN ERROR=0.
200  ERROR=HSK-CTCS*FCLES*(TSK-SET)-PWET*2.2*CHCS*FPCLS*(SVP(TSK)
    X-0.5*SVP(SET))
    IF(ERROR)210,220,220
210  SET=SET+0.1
    GO TO 200
220  CONTINUE

```

For the present analysis, the following printout is useful.

```

    WRITE(1,4000)TA,CLO,ACT,PWET,EMAX,TSK,TCR,TBN,HSK,DRY,EV,STORE,SET
4000  FORMAT(13F7.2)

```

END of program

The above program applies for sea level conditions and may be used to develop psychrometric tables for clothed subjects in heated, ventilated and air-conditioned environments encountered in normal engineering practice and for prediction of comfortable-acceptable environments, when basic indoor temperatures are determined by a Building Simulation Program such as the Bureau of Standards NBSLN.

For Fig. 1-5 the following common inputs were used:

```

ACT  = 1.1 mets for sedentary office work
WK   = 0.    W·m-2
TIME = 1.    hour
TA   = TR = TO    °C

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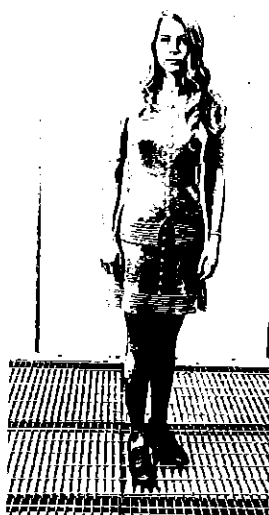
Other environmental factors used are indicated on the figures themselves.

APPENDIX 2

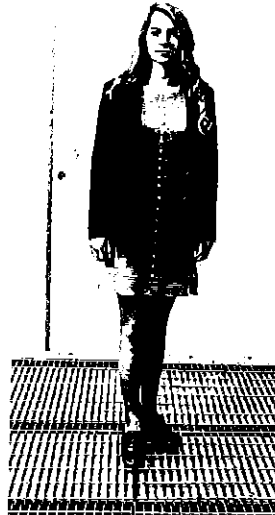
Photographs of Clothing Ensembles for FEA Summer and Winter Guideline Temperature Ranges



0.15 ~ 0.25 clo
Summer - FEA



0.4 ~ 0.5 clo
Summer - Normal



0.7 ~ 0.8 clo
Winter - Normal



0.9 ~ 1.1 clo
Winter - FEA



0.3 ~ 0.4 clo
Summer - FEA



0.4 ~ 0.6 clo
Summer - Normal



0.7 ~ 0.9 clo
Winter - Normal



1 ~ 1.1 clo
Winter - FEA

Clothing Combinations for Protection Against Discomfort in FEA Winter and Summer Guideline Zone

A. Winter zone 58 - 70 F; required 0.9-1.2 Clo.

(I)	(II)	(III)
Winter jacket		0.49
Winter trousers	Add winter vest to (I)	0.32
Heavy long-sleeve dress shirts	0.29	or Add winter sweater to (I)
T-under shirts		0.37
Underpants		0.09
		0.05
Knee high socks		0.10
Oxford shoes		0.04

(I)	(II)	(III)	(IV)	(V)
Winter dress	Add Winter sweater to (I) 0.37	Winter pants suits	Add blouse to (III) 0.29	Add Winter sweater to (IV) 0.37
Full slip		dress 0.66		
Underwear		pants 0.44		
Stocking		Underwear 0.05		
Shoes		Stocking 0.01		
		Shoes 0.04		
$I_s = 1.01$	$I_s = 1.38$	$I_s = 1.20$	$I_s = 1.49$	$I_s = 1.86$
$I_{clo \cdot N} = 0.83$	$I_{clo \cdot N} = 1.11$	$I_{clo \cdot N} = 0.97$	$I_{clo \cdot N} = 1.20$	$I_{clo \cdot N} = 1.48$
$I_{clo \cdot i} = 0.65$	$I_{clo \cdot i} = 0.88$	$I_{clo \cdot i} = 0.77$	$I_{clo \cdot i} = 0.95$	$I_{clo \cdot i} = 1.17$

FEA Summer Guideline

B. Summer zone 78 - 80 F; 80 - 82 F; required 0.15-0.45 Clo.

Men

(I)	(II)	(III)	(IV)
Summer jacket	Remove Jacket and Tie	Remove Undershirts from (II)	Shorts
Summer trousers	0.22		Short sleeveless shirts
Short sleeve shirts	0.26		Underpants
with tie	0.15		Sandal
Sleeveless undershirt	0.06		
Underpants	0.05		
Ankle socks	0.04		
Oxford shoes	0.04		
	$I_s = 0.82$ $I_{clo \cdot N} = 0.71$ $I_{clo \cdot i} = 0.56$	$I_s = 0.53$ $I_{clo \cdot N} = 0.50$ $I_{clo \cdot i} = 0.40$	$I_s = 0.34$ $I_{clo \cdot N} = 0.38$ $I_{clo \cdot i} = 0.30$

Women

(I)	(II)	(III)	(IV)
Summer blouse	Summer dress	Summer pants suit	Summer blouse
Summer skirts	Underwear	Summer blouse	Summer shorts
Underwear	Stocking	Summer pants	Underwear
Stocking	Sandal	Stocking	Sandals
Sandal		Underwear	
		Sandal	
	$I_s = 0.36$ $I_{clo \cdot N} = 0.33$ $I_{clo \cdot i} = 0.26$	$I_s = 0.52$ $I_{clo \cdot N} = 0.45$ $I_{clo \cdot i} = 0.36$	$I_s = 0.40$ $I_{clo \cdot N} = 0.36$ $I_{clo \cdot i} = 0.28$

DISCUSSION

JOHN E. JANSSEN (Honeywell Corp., Bloomington, MN): This paper shows how clothing can be effectively used to widen the comfort range. Women do dress with a wide variation in clo value but the style for men's clothing seems more restrictive. How can we encourage the fashion designers, especially for men's clothes, to conceive acceptable styles that will yield the needed variation in clo value?

A. PHARO GAGGE: As a matter of interest to Mr. Janssen, there is an article, "Playing It Cool In Hot Weather - and Vice Versa: Tips from a Famous Scientific Laboratory," by Lydia McClean, Health Editor, in the August issue (Vol. 166, -8 1976) of Vogue magazine in which proper dress for both winter and summer FEA conditions is discussed.