An evaluation of models of human response to hot and cold environments

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AN EVALUATION OF MODELS OF HUMAN RESPONSE
TO HOT AND COLD ENVIRONMENTS

(Volume Two)

by

Roger A Haslam

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University of Technology

1989

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APPENDIX A

MODEL COMPUTER PROGRAM LISTINGS AND EXAMPLE PREDICTIONS
C LUT 2-NODE MODEL OF HUMAN THERMOREGULATION (V1.0)
C (ADAPTED FROM J. B. PIERCE 2-NODE MODEL)
C
REAL MR, IM, KCLO, LR, ITIM, IECL
COMMON/IIN/TA, TR, V, RH, CLO, K Closet, FACI, IM, WORK, WK, TCR, TSK,
XMTIME, ITIME, TTIME
C COMMON BLOCKS UNIT AND SAVEF ARE INITIALIZED IN LIBRARY
C SUBROUTINE SETUP
C
COMMON/UNIT/NIN, NOUT, NDAT
COMMON/SAVEF/GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
COMMON/OPTION/BEGIN, BEGIN1, OPT
CHARACTER*20 GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
C DEFINE CHARACTER VARIABLES FOR MENU SUB-SECTION
C
CHARACTER*1 BEGIN, BEGIN1, CONT, CONT1, QUIT, QUIT1, OPT
BEGIN='B'
BEGIN1='b'
CONT='C'
CONT1='c'
QUIT='Q'
QUIT1='q'
C OPEN RESULTS OUTPUT FILE
C
CALL SETUP
OPEN(UNIT=NDAT, FILE=LUT2, STATUS='UNKNOWN')
C DISPLAY PROGRAM TITLE
C
CALL TITLE
C **********************************************************************
C PROGRAM SUB-SECTION TO PROVIDE MENU CONTROL FOR MAIN PROGRAM
C C CLEAR SCREEN
C 10 CONTINUE
CALL CLEAN
C C DISPLAY MENU
C
WRITE(NOUT, 20)
20 FORMAT(/X15X'*****************************************************'/
X15X'LUT 2-Node Model of Human Thermoregulation (V1.0)'/
X15X'(adapted from J. B. Pierce 2-Node Model)'/
X15X'************************************************************'/
X///20X'B	 Begin New Exposure'///
X20X'C	 Continue Exposure (new environment)'///
X20X'O	 Quit'///
X15X'Results will be copied to a file called LUT2.DAT'///
X8X'Enter Option: '$)
C C DETERMINE RESPONSE
READ(NIN,30)OPT

IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN 
CALL INPUT 
GOTO 50 
ENDIF 

IF((OPT.EQ.CONT).OR.(OPT.EQ.CONT1))THEN 
CALL INPUT2 
GOTO 60 
ENDIF 

IF((OPT.EQ.QUIT).OR.(OPT.EQ.QUIT1))GOTO 1000

C IF RESPONSE IS NOT RECOGNIZED, INFORM AND REDISPLAY MENU
C
CALL INFERR 
GOTO 10 
C END OF MENU SUB-SECTION
C

C TO HERE FOR A NEW EXPOSURE
C
50 CONTINUE
C
PRINT HEADER FOR DATA FILE
C
WRITE(NDAT,55)
55 FORMAT(/34X'New Exposure' /
X33X'**************'/)
C
PROGRAM TIMER VARIABLES
C
MTIME = ACTUAL TIME (MINS)
NTIME = INCREMENT TIME (MINS)
DTIME = INCREMENT TIME (HRS)
JTIME = TOTAL EXPOSURE TIME (MINS)
ITIME = TOTAL EXPOSURE TIME (HRS)
KTIME = OUTPUT INTERVAL TIME (MINS)
C (ALL COUNTING IS DONE IN MINUTES)
C
PROGRAM REQUIRES TWO TIMERS, MTIME AND KTIME. IF MTIME >= KTIME
RESULTS ARE PRINTED. MTIME AND KTIME ARE INCREMENTED BY NTIME
AND ITIME RESPECTIVELY
C
C INITIALIZE TIMERS
C
MTIME=0
NTIME=1
DTIME=1./60.
JTIME=0
C
STEADY STATE CHARACTERISTICS OF MODEL AT THERMAL NEUTRALITY
C (ie SET POINTS AND COEFFICIENT VALUES) (FROM GAGGE et al. (1986)
C
A-4
TTSK=33.7
TTCR=36.8
SKBFN=6.3
PWET=0.06
ALPHA=0.1
TTBM=ALPHA*TTSK+(1.-ALPHA)*TTCR
MR=WORK
CSW=170.
CSTR=0.1
CDIL=200

C INITIAL CONDITIONS - PHYSIOLOGICAL THERMAL NEUTRALITY
C
TBM=ALPHA*TTSK+(1.-ALPHA)*TTCR
SKBF=SKBFN
C
TO HERE FOR CONTINUING AN EXPOSURE
C
60 CONTINUE
C
SET OUTPUT TIMER AND DETERMINE TOTAL EXPOSURE TIME
C
KTIME=MTIME
KTIME=KTIME+ITIME
JTIME=JTIME+TTIME*60
C
PRINT ENVIRONMENTAL CONDITIONS AND TABULATE FOR OUTPUT
C
CALL TAB
C
CLOTHING AND ENVIRONMENTAL HEAT TRANSFER FACTORS AT SEA LEVEL
C CHCA IS EFF. CHC DUE TO WORK IN STILL AIR (TREADMILL WALKING)
C
IF(WORK.GE.58.2)THEN
  CHCA=5.66*(WORK/58.2-0.85)**0.39
ELSE
  CHCA=0
ENDIF
C
CHCV IS FUNCTION OF ROOM AIR MOVEMENT (V)
C
CHCV=8.6*V**0.53
IF(CHCV.GE.CHCA)CHC=CHCV
IF(CHCV.LT.CHCA)CHC=CHCA
C
CHC VALUE FOR STILL AIR IS 3.0 AT SEA LEVEL
C
IF(CHC.LT.3.0)CHC=3.0
C
RESISTANCE OF CLOTHING TO THE TRANSFER OF WATER VAPOUR:
C Iecl CALCULATED FROM Im, HASLAM AND PARSONS (1988). HEAT TRANSFER
C COEFFICIENTS ARE THOSE ESTIMATED TO HAVE PREVAILED WHEN Im WAS
C MEASURED, i.e. Ta = Tr = 24 C, V = 0.1 m/s, Tsk = 33 C, Ia = 0.71 clo
C
TAIM=24.0
TRIM=24.0
TSKIM=33.0
C
CHCIM CALCULATED BY SUBTRACTING CHRIM (NUDE) FROM Ia
C

C CHCIM=4.52

C CALCULATE CHRIM AND TCLIM
C
C ITERATIVE LOOP TO CALCULATE CLOTHING TEMPERATURE (TCLIM) AND LINEAR
C RADIATION COEFFICIENT (CHRIM)
C
C TCLIM=0.0

80

TCLOLD=TCLIM
CHRIM=4.*5.67E_8*(((TCLIM+TRIM)/2.+273.2)**3)*0.725
TCLIM=((1./(CLO*0.155))*TSKIM+FACL*(CHCIM*TAIM+CHRIM*TRIM))/
X((1./(CLO*0.155))+FACL*(CHCIM+CHRIM))
IF(ABS(TCLIM-TCLOLD).GT.0.01)GOTO 80

C CALCULATE LR AT TCLIM
C
LR=15.1512*(TCLIM+273.15)/273.15
C
C INITIALIZE OTHER VARIABLES
C
TCL=0.0
ESK=0.0

C SIMULATION OF BODY TEMPERATURE REGULATION - START OF REG. LOOP
C
500 CONTINUE
C
C CALCULATE ITIM (m2.C/W)
C
ITIM=CLO*0.155+1./((CHCIM+CHRIM)*FACL)
C
C CALCULATE IECL (m2.kPa/W)
C
IECL=ITIM/(LR*IM)-1./(FACL*LR*CHCIM)

C RESPIRATORY HEAT LOSSES
C
ERES=0.017251*MR*(5.8662*RH*SVP(TA))
CRES=0.0014*MR*(34.-TA)
C
C INITIALIZE OTHER VARIABLES
C
TCL=0.0
ESK=0.0

C CALCULATE HEAT FLOWS
C
DRY=FACL*(CHC*(TCL_TA)+CHR*(TCL_TR))
HFSK=(TCR_TSK)*(5.28+1.163*SKBF)_DRY_ESK
HFCR=MR_-(TCR_TSK)*(5.28+1.163*SKBF)-(CRES-ERES)_WK
C AVERAGE MAN 70kg, 1.7m, 1.8 m²

C
TCSK=0.97*ALPHA*70.
TCR=0.97*(1.-ALPHA)*70.
DTSK=(HFSK*1.8)/TCSK
DTCR=(HFCR*1.8)/TCCR
DTBM=ALPHA*DTSK+(1.-ALPHA)*DTCR
TSK=TSK+DTSK*DTIME
TCR=TCR+DTCR*DTIME

C DEFINITION OF REGULATORY CONTROL SIGNALS

C
SKSIG=TSK-TTSK
IF(SKSIG.LE.0.)THEN
  COLDS=-SKSIG
  WARM S=0.
ELSE
  COLDS=0.
  WARM S=SKSIG
ENDIF
CRSIG=TCR-TTCR
IF(CRSIG.LE.0.)THEN
  COLDC=-CRSIG
  WARM C=0.
ELSE
  WARM C=CRSIG
  COLDC=0.
ENDIF

C CONTROL SKIN BLOOD FLOW

C
STRIC=CSTR*COLDS
DILAT=CDIL*WARM C
SKBF=(SKBFN+DILAT)/(1.+STRIC)
IF(SKBF.LT.0.5)SKBF=0.5
IF(SKBF.GT.90.0)SKBF=90.0

C RELATIVE WT. OF SKIN SHELL TO BODY CORE VARIES WITH SKBF,
C GAGGE et al. (1986)
C
ALPHA=0.0417737+0.7451832/(SKBF+0.585417)

C DEFINITION OF CONTROL SIGNALS FOR SWEATING

C
TBM=ALPHA*TSK+(1.-ALPHA)*TCR
BYSIG=TBM-TTBM
IF(BYSIG.LE.0.)THEN
  COLDB=-BYSIG
  WARM B=0.
ELSE
  WARM B=BYSIG
  COLDB=0.
ENDIF

C CONTROL OF REGULATORY SWEATING

C
REGSW=CSW*WARM B*EXP(WARM S/10.7)
IF(REGSW.GT.500.0)REGSW=500.0
ERSW=0.68*REGSW

A-7
EVALUATION OF HEAT TRANSFER BY EVAPORATION AT THE SKIN SURFACE

LR varies with TCL (not TSK as in, Gagge et al. (1986))

\[ LR = 15.1512 \times \frac{(TCL + 273.15)}{273.15} \]

RT is resistance of clothing and surrounding air layer to vapour permeation, calculated according to Haslam and Parsons (1988)

\[ RT = \frac{IEXL + 1}{FACL \times LR \times CHC} \]
\[ EMAX = (1/RT) \times (SVP(TSK) - RH \times SVP(TA)) \]
\[ PRSW = ERSW / EMAX \]

Evaporative heat loss section from Gagge et al. (1986)

Gagge et al. (1986) introduce \( \text{EVEFF} \), equivalent to the maximum skin wettedness achievable in practice. Gagge et al. say that EVEFF lies between 0.7 and 1.0. Without further information, 1.0 is used here.

\[ \text{EVEFF} = 1.0 \]

0.06 is \( \text{PDIF} \) for nonsweating skin - Kerslake

\[ \text{PDIF} = (1.0 - \text{PRSW}) \times 0.06 \]
\[ \text{EDIF} = \text{PDIF} \times \text{EMAX} \]
\[ \text{ESK} = \text{ERSW} + \text{EDIF} \]
\[ \text{PWET} = \text{ESK} / \text{EMAX} \]

Beginning of dripping (sweat not evaporated on skin surface)

\[ \text{IF}((\text{PWET} \geq \text{EVEFF}) \text{ AND } (\text{EMAX} \geq 0)) \text{ THEN} \]
\[ \text{PWET} = \text{EVEFF} \]
\[ \text{PRSW} = (\text{EVEFF} - 0.06) / 0.94 \]
\[ \text{ERSW} = \text{PRSW} \times \text{EMAX} \]
\[ \text{PDIF} = (1.0 - \text{PRSW}) \times 0.06 \]
\[ \text{EDIF} = \text{PDIF} \times \text{EMAX} \]
\[ \text{ESK} = \text{ERSW} + \text{EDIF} \]
\[ \text{ENDIF} \]

When \( \text{EMAX} < 0 \). Condensation on skin occurs

\[ \text{IF}(\text{EMAX} \lt 0) \text{ THEN} \]
\[ \text{PDIF} = 0. \]
\[ \text{EDIF} = 0. \]
\[ \text{ESK} = \text{EMAX} \]
\[ \text{PWET} = \text{EVEFF} \]
\[ \text{PRSW} = \text{EVEFF} \]
\[ \text{ERSW} = 0. \]
\[ \text{ENDIF} \]

\( \text{EDRIP} = \) unevaporated sweat in g/sq.m/hr

\[ \text{EDRIP} = (\text{REGSW} \times 0.68 - \text{PRSW} \times \text{EMAX}) / 0.68 \]
\[ \text{IF}(\text{EDRIP} \lt 0) \text{ EDRIP} = 0. \]

Adjustment of metabolic heat due to shivering
MR=WORK+19.4*COLDSCOLDC

C CALCULATE TOTAL EVAPORATIVE HEAT LOSS IN ORDER THAT BODY HEAT STORAGE
C RATE MAY BE CALCULATED (REQUIRED FOR SET AND OUTPUT)
C
C EV=ESK+ERES
C
C CALCULATE TOTAL DRY HEAT LOSS (REQUIRED FOR OUTPUT)
C
C DRYT=DRY+CRES
C
C INCREMENT TIMER
C
C MTIME=MTIME+NTIME
C
C WHEN APPROPRIATE, OUTPUT RESULTS
C
IF(MTIME.GE.KTIME)THEN
  WRITE(NOUT,700)MTIME,TCR,TSK,PWET,MR,DRYT,EV,ESK,EDRIP,ALPHA
  WRITE(NDAT,700)MTIME,TCR,TSK,PWET,MR,DRYT,EV,ESK,EDRIP,ALPHA
700 FORMAT(I5,3F8.2,1X,5F8.2,F7.2)
  KTIME=KTIME+ITIME
ENDIF
C
C UNLESS TOTAL EXPOSURE TIME HAS BEEN REACHED, GOTO THE START OF THE
C REGULATORY LOOP. OTHERWISE OUTPUT FINAL RESULTS AND RETURN TO MENU
C
C IF(MTIME.LT.JTIME)GOTO 500
C
C END OF REGULATORY LOOP
C
C **********************************************************************
C
C PAUSE
C
CALL WAIT(3)
C
C CALCULATION OF HEAT STORAGE (REQUIRED FOR SET)
C
STORE=MR-WK-CRES-EV-DRY
C
C CALCULATION OF SKIN HEAT LOSS (REQUIRED FOR SET)
C
HSK=MR-ERES-CRES-WK-STORE
GOTO 10
1000 CONTINUE
CALL TIDYUP
END
C
C SVP AT T, USING ANTOINE'S EQUATION (kPa)
C
FUNCTION SVP(T)
SVP=0.133322*EXP(18.6686-4030.183/(T+235))
RETURN
END
C
C SUBROUTINE TO DISPLAY PROGRAM TITLE
C
SUBROUTINE TITLE
A-9
COMMON/UNIT/NIN, NOUT, NDAT
CALL CLEAN
WRITE(NOUT, 10)
WRITE(NDAT, 10)

10 FORMAT(/'**************************************************/
    'LUT 2-Node Model of Human Thermoregulation (V1.0)'/
    'adapted from J. B. Pierce 2-Node Model'/
    'Roger Haslam'/
    'Department of Human Sciences'/
    'Loughborough University of Technology'/
    '**************************************************/
    )
CALL WAIT(7)
RETURN
END

C
C SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS
C
SUBROUTINE INPUT
REAL MR, IM, KCLO, LR, ITIM, IECL
COMMON/IINITA, TR, V, RH, CLO, KCLO, FACL, IM, WORK, WK, TCR, TSK,
XMTIME, TTIME
COMMON/UNIT/NIN, NOUT, NDAT
COMMON/OPTION/BEGIN, BEGIN1, OPT
CHARACTER*1 BEGIN, BEGIN1, OPT
CALL CLEAN
WRITE(NOUT, 100)
100 FORMAT(/' Air Temperature (C)'
READ(NIN, *)TA
WRITE(NOUT, 200)
200 FORMAT(/' Mean Radiant Temperature (C)'
READ(NIN, *)TR
WRITE(NOUT, 300)
300 FORMAT(/' Air Speed (m/s)'
READ(NIN, *)V
WRITE(NOUT, 400)
400 FORMAT(/' Relative Humidity (fraction) (ND)'
READ(NIN, *)RH
WRITE(NOUT, 500)
500 FORMAT(/' Intrinsic Clothing Insulation (clo)'
READ(NIN, *)CLO
WRITE(NOUT, 600)
600 FORMAT(/' Clothing Area Factor (fcl) (0 if unknown) (ND)'
READ(NIN, *)FACL
WRITE(NOUT, 700)
700 FORMAT(/' Clothing Permeability Index (Woodcock Im) (ND)'
READ(NIN, *)IM
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0.)CLO=1.0E-8

C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
KCLO=0.31
IF(FACL.EQ.0.)FACL=1.+KCLO*CLO
IF(CLO.LT.0.01)FACL=1.
CALL CLEAN

A-10
WRITE(NOUT,800)
FORMAT(// Total Metabolic Rate (W/m2) : '$)
READ(NIN,*)WORK
WRITE(NOUT,900)
FORMAT(// External Work Accomplished (W/m2) : '$)
READ(NIN,*)WK
IF((OPT.EQ.BECIN).OR.(OPT.EQ.BEGIN1))THEN
WRITE(NOUT,1000)
1000 FORMAT(/' Initial Core Temperature (0 for 36.8) (C) : '$)
READ(NIN,*)TCR
IF(TCR.EQ.0.)TCR=36.8
WRITE(NOUT,1100)
1100 FORMAT(/' Initial Mean Skin Temperature (0 for 33.7) (C) : '$)
READ(NIN,*)TSK
IF(TSK.EQ.0.)TSK=33.7
END IF
WRITE(NOUT,1200)
1200 FORMAT(/' Output Time Interval (mins) : '$)
READ(NIN,*)ITIME
WRITE(NOUT,1300)
1300 FORMAT(/' Exposure Time To These Conditions (hours) : '$)
READ(NIN,*)TTIME
RETURN
END

C
C SUBROUTINE TO ENABLE ENVIRONMENTAL CONDITIONS TO BE REDEFINED IN
C ORDER TO CONTINUE AN EXPOSURE.
C
C SUBROUTINE INPUT2
REAL MR,IM,KCLO,LR,ITIM,IECL
COMMON/IIN,TA,TR,V,RH,CLO,FACL,IM,WORK,WK,TCR,TSK,
XMTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
100 CONTINUE
C
C CLEAR SCREEN
C CALL CLEAN
C
C DISPLAY MENU
C
WRITE(NOUT,200)TA,TR,V,RH,CLO,FACL,IM,WORK,WK,ITIME
200 FORMAT( X3X'Change: 1	 Air Temperature 'XF6.2' (C)'//,
X12X'1	 Mean Radiant Temperature 'XF6.2' (C)'/',
X12X'2	 Air Speed 'XF6.2' (m/s)'/',
X12X'3	 Relative Humidity 'XF6.2'
X' (ND)'//,
X12X'4	 Intrinsic Clothing Insulation 'XF6.2' (clo)'/',
X12X'4	 Clothing Area Factor (fcl) 'XF6.2'
X' (ND)'//,
X12X'4	 Clothing Permeability Index (Woodcock Im) 'XF6.2'
X' (ND)'//,
X12X'5	 Total Metabolic Rate 'XF6.2' (W/m2)'//
A-11
EXTERNAL WORK ACCOMPLISHED

F6.2
X' (W/m²)'/
X12X'6  Output Time Interval 'I6
X' (mins)'/
X12X'7  ALL'!!
X3X' Enter Change Required (RETURN when complete) : '$

C
C DETERMINE RESPONSE

READ(NIN,300)ICHNG
300 FORMAT(I1)
CALL CLEAN
IF(ICHNG.EQ.7)CALL INPUT
IF(ICHNG.EQ.7)GOTO 9999
GOTO (400,500,600,700,800,900)ICHNG
GOTO 9998

C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS

400 WRITE(NOUT,1400)
1400 FORMAT(//' Air Temperature (°C) : '
READ(NIN,*!)TA
WRITE(NOUT,1450)
1450 FORMAT(//' Mean Radiant Temperature (°C) : '
READ(NIN,*!)TR
GOTO 100
500 WRITE(NOUT,1500)
1500 FORMAT(//' Air Speed (m/s) : '
READ(NIN,*!)V
GOTO 100
600 WRITE(NOUT,1600)
1600 FORMAT(//' Relative Humidity (fraction) (ND) : '
READ(NIN,*!)RH
GOTO 100
700 WRITE(NOUT,1700)
1700 FORMAT(//' Intrinsic Clothing Insulation (clo) : '
READ(NIN,*!)CLO
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0)CLO=1.0E-8
WRITE(NOUT,1725)
1725 FORMAT(//' Clothing Area Factor (tel) (0 if unknown) (ND) : '
READ(NIN,*!)FACL
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
IF(FACL.EQ.0)FACL=1.+KCLO*CLO
IF(CLO.LT.0.01)FACL=1.
WRITE(NOUT,1750)
1750 FORMAT(//' Clothing Permeability Index (Woodcock Im) (ND) : '
READ(NIN,*!)IM
GOTO 100
800 WRITE(NOUT,1800)
1800 FORMAT(//' Total Metabolic Rate (W/m²) : '
READ(NIN,*!)WORK
WRITE(NOUT,1850)
1850 FORMAT(//' External Work Accomplished (W/m²) : '
READ(NIN,*!)WK
GOTO 100
900 WRITE(NOUT,1900)
1900 FORMAT(/' Output Time Interval (mins) : '$)
READ(NIN,*)ITIME
GOTO 100
9998 CALL CLEAN
WRITE(NOUT,65)
65 FORMAT(/' Exposure Time To These Conditions (hours) : '$)
READ(NIN,*)TTIME
9999 CONTINUE
RETURN
END

C C SUBROUTINE TO DISPLAY ENVIRONMENTAL CONDITIONS AND TABULATE
C FOR RESULTS.
C
SUBROUTINE TAB
REAL MR, IM,KCLO,LR,ITIM,IECL
COMMON/IIN/TA,TR,V,RH,CLO,FACL,IM,WORK,WK,TCR,TSK,
XTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
COMMON/OPTION/BEGIN,BEGIN1,OPT
CHARACTER*1 BEGIN,BEGIN1,OPT

C C DISPLAY RESULTS
C
CALL CLEAN
WRITE(NOUT,100)TA,TR,V,RH,CLO,FACL,IM,WORK,WK
WRITE(NDAT,100)TA,TR,V,RH,CLO,FACL,IM,WORK,WK
100 FORMAT(/'
X12X'Air Temperature
X12X'Mean Radiant Temperature
X12X'Air Speed
X12X'Relative Humidity
X12X'Intrinsic Clothing Insulation
X12X'Clothing Area Factor
X12X'Clothing Permeability Index (Woodcock Im)
X12X'Initial Metabolic Rate
X12X'Work Rate Accomplished
C
C PAUSE
C
CALL WAIT(7)
WRITE(NDAT,200)
200 FORMAT(/)

C C TABULATE FOR OUTPUT
C
CALL CLEAN
WRITE(NOUT,300)
WRITE(NDAT,300)
IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
WRITE(NOUT,400)MTIME,TCR,TSK
WRITE(NDAT,400)MTIME, TCR, TSK
END IF
300 FORMAT(/' Time	 Tcr	 Tsk	 w	 M	 (C+R)	 E	 Esk
XDrip sk/cr'/
X' (min) (C) (C) (ND) (W/m2) (W/m2) (W/m2) (g

A-13
X/h.m2) (ND)'/
X'*****************************************************************
X'*****************************************************************
400 FORMAT(I5,2F8.2,1X,7(2X,'**'))
RETURN
END
LUT 2-Node Model of Human Thermoregulation (V1.0)  
(adapted from J. B. Pierce 2-Node Model)

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Loughborough University of Technology

New Exposure

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
<th>w (ND)</th>
<th>M (W/m²)</th>
<th>(C+R) (W/m²)</th>
<th>E (W/m²)</th>
<th>Esk (W/m²)</th>
<th>Drip skicr (g/h.m²)</th>
<th>sk/cr (ND)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>36.80</td>
<td>33.70</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>5</td>
<td>36.90</td>
<td>35.31</td>
<td>1.00</td>
<td>100.00</td>
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LUT25 MODEL PROGRAM LISTING

(CLOTHING COVERS HEAD AND HANDS)
C
C LUT 25-NODE MODEL OF HUMAN THERMOREGULATION (V1.0a)
C (ADAPTED FROM STOLWIJK AND HARDY 25-NODE MODEL)
C CLOTHING COVERS HEAD AND HANDS
C
C PROGRAM ALSO REQUIRES DATA FILE: THERMO.DAT
C
DIMENSION T(25),TSET(25),RATE(25),C(25),QB(24),EB(24),BF(24)
DIMENSION TC(24),S(6),SKINR(6),SKINS(6),SKINV(6),SKINC(6),WORKM(6)
DIMENSION CHILM(6),HR(6),HCB(6),HC(6),F(25),H(6),WARM(25),COLD(25)
DIMENSION HF(25)
DIMENSION ERROR(25),Q(24),E(24),BF(24),EMAX(6),BC(24),TD(24)
DIMENSION ARAD(6),DRY(6),RT(6),TCL(6),LR(6)
REAL MR,IM,KCLO,LR,LRIM,ITIM,IECL
COMMON/XXVNA/TA,TR,V,RH,CLO,KCLO,FACL,IM,WORK,WK,SA,T,TS,C,
XMTIME,ITIME,TTIME
C
C COMMON BLOCKS UNIT AND SAVEF ARE INITIALIZED IN LIBRARY
C SUBROUTINE SETUP
C
COMMON/UNIT/NIN,NOUT,NDAT
COMMON! SAVEF/GOLD,GAGGE,ISO,STOLW,LUTTRE,LUT2,LUTISO,LUT25A,LUT25B
COMMON/OPTION/BEGIN,BEGIN1,OPT
CHARACTER*20 GOLD,GAGGE,ISO,STOLW,LUTTRE,LUT2,LUTISO,LUT25A,LUT25B
CHARACTER*1 BEGIN,BEGIN1,CONT,CONT1,QUIT,QUIT1,OPT
BEGIN='B'
BEGIN1='b'
CONT='C'
CONT1='c'
QUIT='Q'
QUIT1='q'

C OPEN INPUT DATA FILE AND RESULTS OUTPUT FILE
C
CALL SETUP
OPEN(UNIT=11,FILE='[haslam.models]THERMO.DAT',readonly,
xSTATUS='OLD',ERR=1250)
OPEN(UNIT=NDAT,FILE=LUT25A,STATUS='UNKNOWN')
C
C DISPLAY TITLE
C CALL TITLE
C
C ******************************************************
C
C PROGRAM SUB-SECTION TO PROVIDE MENU CONTROL FOR MAIN PROGRAM
C C CLEAR SCREEN
C 10 CONTINUE
C CALL CLEAN
C C DISPLAY MENU
C WRITE(NOUT,20)
20 FORMAT(/X13X'**************************************************'/
X15X'LUT 25-Node Model of Human Thermoregulation (V1.0a)'/
X15X' (adapted from Stolwijk and Hardy 25-Node Model)'/

A-18
X15X' Clothing covers Head and Hands' />
X13X'*****************************************************************************************' />
X/21X'B   Begin New Exposure' />
X21X'C   Continue Exposure (new environment)' />
X21X'Q   Quit' />
X16X' Results will be copied to a file called LUT25A.DAT' />
X9X'Enter Option: ')

C  DETERMINE RESPONSE
C
READ(NIN,30)OPT
30  FORMAT(A)
    IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
        GOTO 50
    ENDIF
    IF((OPT.EQ.CONT).OR.(OPT.EQ.CONT1))THEN
        CALL INPUT2
        GOTO 60
    ENDIF
    IF((OPT.EQ.QUIT).OR.(OPT.EQ.QUIT1))GOTO 1300

C  IF RESPONSE IS NOT RECOGNIZED, INFORM AND REDISPLAY MENU
C
    CALL INFERR
    GOTO 10

C  END OF MENU SUB-SECTION
C
C  ***********************************************************************
C  C TO HERE FOR A NEW EXPOSURE
C
50  CONTINUE
C
C  PRINT HEADER FOR DATA FILES
C
    WRITE(NDAT,55)
55  FORMAT(///,
            X34X'New Exposure' ,
            X33X'************' )

C  PROGRAM TIMER VARIABLES
C
C  MTIME = ACTUAL TIME (MINS)
C  RTIME = ACTUAL TIME (HRS)
C  NTIME = INCREMENT TIME (MINS)
C  DTIME = INCREMENT TIME (HRS)
C  JTIME = TOTAL EXPOSURE TIME (MINS)
C  TTIME = TOTAL EXPOSURE TIME (HRS)
C  ITIME = OUTPUT INTERVAL TIME (MINS)
C  KTIME = OUTPUT INTERVAL TIMER (MINS)
C
C  (ALL COUNTING IS DONE IN MINUTES)
C
C  PROGRAM REQUIRES TWO TIMERS, MTIME AND KTIME. IF MTIME >= KTIME
C  RESULTS ARE PRINTED. MTIME AND KTIME ARE INCREMENTED BY NTIME
C  AND ITIME RESPECTIVELY
C
C  INITIALIZE TIMERS

A-19
C MTIME=0
JTIME=0
RTIME=0
C C READ CONSTANTS FOR CONTROLLED SYSTEM
C REWIND(11)
READ(11,84)C
READ(11,82)QB
READ(11,82)EB
READ(11,90)BFB
READ(11,82)TC
READ(11,92)S
READ(11,80)HCB
READ(11,80)ARAD
C C READ CONSTANTS FOR THE CONTROLLER
C READ(11,84)TSET
READ(11,88)CSW,SSW,PSW,CDIL,SDIL,PDIL,CCON,SCON,PCON,CCHIL,SCHIL,
XPCHIL,BULL
READ(11,80)SKINR
READ(11,86)SKINS
READ(11,86)SKINV
READ(11,80)SKINC
READ(11,80)WORKM
READ(11,80)CHILM
C C READ INITIAL CONDITIONS
C READ(11,84)T
80 FORMAT(6F5.2)
82 FORMAT(24F5.2)
84 FORMAT(25F5.2)
86 FORMAT(6F5.3)
88 FORMAT(13F6.2)
90 FORMAT(24F6.2)
92 FORMAT(6F7.4)
C C CALCULATE TOTAL SURFACE AREA
C SA=0.
DO 110 K=1,6
110 SA=SA+S(K)
C C INPUT EXPERIMENTAL CONDITIONS
C CALL INPUT
C C SET F(N) TO ZERO
C DO 102 N=1,25
F(N)=0.
102 CONTINUE
C C TO HERE FOR CONTINUING AN EXPOSURE
C 60 CONTINUE
C SET OUTPUT TIMER AND DETERMINE TOTAL EXPOSURE TIME
C
KTIME=MTIME
KTIME=KTIME+ITIME
JTIME=JTIME+TTIME*60.
C
C PRINT ENVIRONMENTAL CONDITIONS AND TABULATE FOR OUTPUT
C
CALL TAB
C
C DETERMINE TOTAL EXTRA HEAT PRODUCTION IN THE WORKING MUSCLES
C
WEFFM=1.-(WK/(WORK-86.49))
WORKI=(WORK-86.49)*WEFFM
IF(WORK.LE.86.49)WORKI=0.
C
C CALCULATE CLOTHING AND ENVIRONMENTAL HEAT TRANSFER COEFFICIENTS
C
C RESISTANCE OF CLOTHING TO THE TRANSFER OF WATER VAPOUR:
C Iecl calculated from Im, Haslam and Parsons (1988). Heat transfer
C coefficients are those estimated to have prevailed when Im was
C measured, i.e. Ta = Tr = 24 C, V = 0.1 m/s, Tsk = 33 C, Ia = 0.71 clo
C
TAIM=24.0
TRIM=24.0
TSKIM=33.0
C
HCIM calculated by subtracting HRIM (nude) from Ia
C
HCIM=4.52
C
C CALCULATE HRIM AND TCLIM
C
C iterative loop to mean calculate clothing temperature (TCLIM)
C AND MEAN LINEAR RADIATION COEFFICIENT (HRIM)
C
TCLIM=0.0
150 TCLOLD=TCLIM
HRIM=4.*5.67E-8*(((TCLIM+TRIM)/2.+273.2)**3)*0.725
TCLIM=((1./(CLO*0.155))*TSKIM+FACL*(HCIM*TAIM+HRIM*TRIM))/
X((1./(CLO*0.155))+FACL*(HCIM+HRIM))
IF(ABS(TCLIM-TCLOLD).GT.0.01)GOTO 150
C
C CALCULATE LRIM AT TCLIM
C
LRIM=15.1512*(TCLIM+273.15)/273.15
C
C CALCULATE ITIM (m2.C/W)
C
ITIM=CLO*0.155+1./((HCIM+HRIM)*FACL)
C
C CALCULATE Iecl (m2.kPa/W)
C
Iecl=ITIM/(LRIM*IM)-1./(FACL*LRIM*HCIM)
C
C calculate convective heat transfer coefficient, HC(I),
C Stolwijk and Hardy (1977)
DO 202 I=1,6
HC(I)=3.16*HCB(I)*V**0.5
202 CONTINUE
C
C **********************************************************************
C
C START OF REGULATORY LOOP
C
300 CONTINUE
C
C CALCULATE RADIANT HEAT TRANSFER COEFFICIENT, HR(I), STOLWIJK AND
C HARDY (1977) AND CLOTHING SURFACE TEMPERATURE, TCL(I)
C
DO 225 I=1,6
TCL(I)=0.
250 TCLOLD=TCL(I)
HR(I)=4.*5.67E_8*(((TCL(I)+TR)/2.+273.2)**3.)*ARAD(I)
TCL(I)=((1./(CLO*0.155))*T(4*I)^FACL*(HC(I)*TA^HR(I)*TR))/X((1./(CLO*0.155)+FACL*(HC(I)+HR(I))))
IF(ABS(TCL(I)-TCLOLD).GT.0.01)GOTO 250
225 CONTINUE
C
C CALCULATE TOTAL ENVIRONMENTAL HEAT TRANSFER COEFFICIENT H(I),
C STOLWIJK AND HARDY (1977)
C
DO 275 I=1,6
H(I)=(HR(I)+HC(I))*S(I)
275 CONTINUE
C
C ESTABLISH THERMORECEPTOR OUTPUT
C
C NO VALUES ARE GIVEN BY STOLWIJK AND HARDY FOR RATE(N)
C THEREFORE THIS PARAMETER HAS BEEN SET TO ZERO
C
DO 302 N=1,25
ERROR(N)=0.
RATE(N)=0.
WARM(N)=0.
COLD(N)=0.
ERROR(N)=T(N)_TSET(N)-RATE(N)*F(N)
IF(ERROR(N).LT.0.)COLD(N)=-ERROR(N)
IF(ERROR(N).GT.0.)WARM(N)=ERROR(N)
302 CONTINUE
C
C INTEGRATE PERIPHERAL AFFERENTS
C
WARMS=0.
COLDS=0.
DO 305 I=1,6
K=4*I
WARMS=WARMS+WARM(K)*SKINR(I)
COLDS=COLDS+COLD(K)*SKINR(I)
305 CONTINUE
C
C DETERMINE EFFERENT OUTFLOW
C
SWEAT=CSW*ERROR(1)+SSW*(WARMS-COLDS)+PSW*ERROR(1)*(WARMS-COLDS)
DILAT=CDIL*ERROR(1)+SDIL*(WARMS-COLDS)+PDIL*WARM(1)*WARMS
STRIC=_CCON*ERROR(1)_SCON*(WARMS-COLDS)+PCON*COLD(1)*COLDS
\[
\text{CHILL} = (\text{CCHIL}*\text{ERROR(1)} + \text{SCHIL}*(\text{WARMS-COLDS})) * \text{PCHIL}*(\text{WARMS-COLDS})
\]

\[
\text{IF(SWEAT.LE.0.)SWEAT}=0.
\]

\[
\text{IF(DILAT.LE.0.)DILAT}=0.
\]

\[
\text{IF(STRIC.LE.0.)STRIC}=0.
\]

\[
\text{IF(CHILL.LE.0.)CHILL}=0.
\]

\[\text{C}\]

\[\text{C PREVENT CHILL FROM BECOMING POSITIVE IN HOT ENVIRONMENTS}\]

\[\text{C}\]

\[\text{IF((COLD(1).EQ.0.).AND.(COLDS.EQ.0.))CHILL}=0.\]

\[\text{C}\]

\[\text{C ASSIGN EFFECTOR OUTPUT}\]

\[\text{DO 401 I=1,6}\]

\[\text{N}=4*I_3\]

\[\text{Q(N)}=\text{QB(N)}\]

\[\text{BF(N)}=\text{BFB(N)}\]

\[\text{E(N)}=\text{EB(N)}\]

\[\text{Q(N+1)}=\text{QB(N+1)}+\text{WORKM(I)}*\text{WORKI}+\text{CHILM(I)}*\text{CHILL}\]

\[\text{E(N+1)}=0.\]

\[\text{BF(N+1)}=\text{BFB(N+1)}+\text{Q(N+1)}-\text{QB(N+1)}\]

\[\text{Q(N+2)}=\text{QB(N+2)}\]

\[\text{E(N+2)}=0.\]

\[\text{BF(N+2)}=\text{BFB(N+2)}\]

\[\text{Q(N+3)}=\text{QB(N+3)}\]

\[\text{E(N+3)}=\text{EB(N+3)}+\text{SKINS(I)}*\text{SWEAT}*2.**(T(N+3)_TSET(N+3))/\text{BULL})\]

\[\text{BF(N+3)}=(\text{BFB(N+3)}+\text{SKINV(I)}*\text{DILAT})/(1.+\text{SKINC(I)}*\text{STRIC})\]

\[\text{C}\]

\[\text{C CALCULATE MAXIMUM EVAPORATIVE CAPACITY OF THE ENVIRONMENT, EMAX(I)}\]

\[\text{C USING THE RESISTANCE TO VAPOUR PERMEATION, RT. RT CALCULATED ACCORDING}\]

\[\text{C TO HASLAM AND PARSONS (1988)}\]

\[\text{C}\]

\[\text{LR(I)}=15.1512*(TCL(I)+273.15)/273.15\]

\[\text{RT(I)}=\text{IECL}+1./\text{(FACL*LR(I)*HC(I))}\]

\[\text{EMAX(I)}=((1./\text{RT(I)})*(\text{SVF(T(N+3)}-\text{RH*SVF(TA)}))*\text{S(I)}\]

\[\text{IF(E(N+3).GT.EMAX(I))E(N+3)=EMAX(I)}\]

\[401\]

\[\text{CONTINUE}\]

\[\text{C}\]

\[\text{C CALCULATE DRY SKIN HEAT EXCHANGE WITH ENVIRONMENT, DRY(I)}\]

\[\text{C}\]

\[\text{DO 450 I=1,6}\]

\[\text{DRY(I)}=(\text{FACL}*(\text{HC(I)}*(\text{TCL(I)}-\text{TA})+\text{HR(I)}*(\text{TCL(I)}-\text{TR}))*\text{S(I)}\]

\[450\]

\[\text{CONTINUE}\]

\[\text{C}\]

\[\text{C CALCULATE HEAT FLOWS}\]

\[\text{C}\]

\[\text{DO 500 K=1,24}\]

\[\text{BC(K)}=\text{BF(K)}*(\text{T(K)}-\text{T(25)})\]

\[\text{TD(K)}=\text{TC(K)}*(\text{T(K)}-\text{T(K+1)})\]

\[500\]

\[\text{CONTINUE}\]

\[\text{DO 501 I=1,6}\]

\[\text{K}=4*I_3\]

\[\text{HF(K)}=\text{Q(K)}-\text{E(K)}-\text{BC(K)}-\text{TD(K)}\]

\[\text{HF(K+1)}=\text{Q(K+1)}-\text{BC(K+1)}+\text{TD(K)}-\text{TD(K+1)}\]

\[\text{HF(K+2)}=\text{Q(K+2)}-\text{BC(K+2)}+\text{TD(K+1)}-\text{TD(K+2)}\]

\[\text{HF(K+3)}=\text{Q(K+3)}-\text{BC(K+3)}-\text{E(K+3)}+\text{TD(K+2)}-\text{DRY(I)}\]

\[501\]

\[\text{CONTINUE}\]

\[\text{HF(25)}=0.\]

\[\text{DO 502 K=1,24}\]

\[\text{HF(25)}=\text{HF(25)}+\text{BC(K)}\]
502 CONTINUE
C
C SUBTRACT A CORRECTION FOR RESPIRATORY HEAT LOSSES FROM BLOOD HEAT FLOW
C
C    HF(25)=HF(25)-0.08*WORKI
C
C DETERMINE OPTIMUM INTEGRATION STEP
C
C      NTIME=1
C      DTIME=1./60.
C      DO 600 K=1,25
C      F(K)=HF(K)/C(K)
C      U=ABS(F(K))
C      IF(U*DTIME.GT.0.1)DTIME=0.1/U
C
600 CONTINUE
C
C CALCULATE NEW TEMPERATURES
C
C      DO 700 K=1,25
C      T(K)=T(K)+F(K)*DTIME
C 700 CONTINUE
C
C INCREMENT TIMER
C
C      RTIME=RTIME+DTIME
C      MTIME=60.*RTIME
C
C WHEN APPROPRIATE OUTPUT RESULTS
C
C      IF(MTIME.GE.KTIME)GOTO 701
C      GOTO 300
C 701 CONTINUE
C
C PREPARE FOR OUTPUT
C
C      CO=0.
C      HP=0.
C      EV=0.
C      DRYT=0.
C      ESK=0.
C      PWET=0.
C      TS=0.
C      TB=0.
C      HFLOW=0.
C      SBF=0.
C      DO 800 N=1,24
C
C CARDIAC OUTPUT, CO
C
C      CO=CO+BF(N)/60.
C
C HEAT PRODUCTION, HP
C
C      HP=HP+Q(N)
C
C TOTAL INSENSIBLE HEAT LOSS, EV
C
C      EV=EV+E(N)
C
800 CONTINUE
C METABOLIC RATE, MR
C
MR=HP+WK
C
ADD A CORRECTION TO TOTAL INSENSIBLE HEAT LOSS FOR ADDITIONAL
C RESPIRATORY HEAT LOSSES DUE TO WORK
C
EV=EV+0.08*WORKI
DO 802 I=1,6
C TOTAL SENSIBLE HEAT LOSS, DRYT
C
DRYT=DRYT+DRY(I)
C INSENSIBLE HEAT LOSS FROM SKIN, ESK
C
ESK=ESK+E(4*I)
C SKIN WETTEDNESS, PWET
C
PWET=PWET+(E(4*I)/EMAX(I))*(S(I)/SA)
C SKIN BLOOD FLOW, SBF
C
SBF=SBF+BF(4*I)/60.
C MEAN SKIN TEMPERATURE, TS
C
TS=TS+T(4*I)*C(4*I)/3.90
802 CONTINUE
DO 801 N=1,25
C MEAN BODY TEMPERATURE, TB
C
TB=TB+N(N)*C(N)/68.79
C TOTAL HEAT FLOW, HFLOW
C
HFLOW=HFLOW+HF(N)
801 CONTINUE
C CONVERT FROM W TO W/M2
C
EV=EV/SA
DRYT=DRYT/SA
ESK=ESK/SA
HP=HP/SA
MR=MR/SA
HFLOW=HFLOW/SA
C TISSUE CONDUCTANCE, COND
C
COND=(HP-(E(1)+E(5))/SA-HFLOW)/(T(25)-TS)
WRITE(NOUT,1000)MTIME,T(1),TS,T(16),T(24),PWET,MR,DRYT,EV,ESK
WRITE(NDAT,1000)MTIME,T(1),TS,T(16),T(24),PWET,MR,DRYT,EV,ESK
1000 FORMAT(15,5F8.2,1X,4F8.2)
KTIME=KTIME+ITIME
IF(MTIME.LT.JTIME)GOTO 300
CALL WAIT(1)
GOTO 10

1250 WRITE(NOUT,1255)
1255 FORMAT(‘ ERROR: THIS PROGRAM NEEDS THE THERMO.DAT DATA FILE’)
CALL WAIT(6)

1300 CONTINUE
CALL CLEAN
CLOSE(UNIT=11)
CALL TIDYUP
END

C

C SVP AT T, USING ANTOINE’S EQUATION (kPa)
C (REPLACES STOLWIJK AND HARDY’S STEAM TABLES)
C
FUNCTION SVP(T)
SVP=0.133322*EXP(18.6686-4030.183/(T+235.0))
RETURN
END

C

C SUBROUTINE TO DISPLAY PROGRAM TITLE
C
SUBROUTINE TITLE
COMMON/UNIT/NIN,NOUT,NDAT
CALL CLEAN
WRITE(NOUT,10)
WRITE(NDAT,10)
10 FORMAT(/X14X’ *****************************************************’
X15X’ LUT 25-Node Model of Human Thermoregulation (V1.0a)’
X15X’ (adapted from Stolwijk and Hardy 25-Node Model)’
X15X’ Clothing covers Head and Hands’
X15X’ Roger Haslam’
X15X’ Department of Human Sciences’
X15X’ Loughborough University of Technology’
X14X’ *****************************************************’
X/)’
CALL WAIT(7)
RETURN
END

C

C SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS
C
SUBROUTINE INPUT
DIMENSION T(25),C(25)
REAL MR,IM,KCLO,LR,LRIM,ITIM,IECL
COMMON/UNITVNA/TA,TR,V,RH,CLO,KCLO,FACL,IM,WORK,WK,SA,T,TS,C,
XMTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
CALL CLEAN
WRITE(NOUT,100)
100 FORMAT(/X’ Air Temperature	 (C) : ’$)
READ(NIN,*),TA
WRITE(NOUT,200)
200 FORMAT(/X’ Mean Radiant Temperature	 (C) : ’$)
READ(NIN,*),TR
WRITE(NOUT,300)
300 FORMAT(/X’ Air Speed	 (m/s) : ’$)
READ(NIN,*),V
WRITE(NOUT,400)
400 FORMAT(‘/’ Relative Humidity (fraction) (ND) : ‘$)
READ(NIN,*),RH
WRITE(NOUT,500)
500 FORMAT(‘/’ Intrinsic Clothing Insulation (clo) : ‘$)
READ(NIN,*),CLO
WRITE(NOUT,600)
600 FORMAT(‘/’ Clothing Area Factor (fcl) (0 if unknown) (ND) : ‘$)
READ(NIN,*),FACL
WRITE(NOUT,700)
700 FORMAT(‘/’ Clothing Permeability Index (Woodcock Im) (ND) : ‘$)
READ(NIN,*),IM
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0.)CLO=1.0E-8
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCulloch and Jones, 1984)
C
KCLO=0.31
IF(FACL.EQ.0.)FACL=1.+KCLO*CLO
IF(CLO.LT.0.01)FACL=1.
CALL CLEAN
WRITE(NOUT,800)
800 FORMAT(‘/’ Total Metabolic Rate (W/m2) : ‘$)
READ(NIN,*),WORK
WRITE(NOUT,900)
900 FORMAT(‘/’ External Work Accomplished (W/m2) : ‘$)
READ(NIN,*),WK
C
C CONVERT FROM W/m2 TO W
C
WORK=WORK*SA
WK=WK*SA
WRITE(NOUT,1200)
1200 FORMAT(‘/’ Output Time Interval (mins) : ‘$)
READ(NIN,*),ITIME
WRITE(NOUT,1300)
1300 FORMAT(‘/’ Exposure Time To These Conditions (hours) : ‘$)
READ(NIN,*),ITIME
RETURN
END
C
C SUBROUTINE TO ENABLE ENVIRONMENTAL CONDITIONS TO BE REDEFINED IN
C ORDER TO CONTINUE AN EXPOSURE.
C
SUBROUTINE INPUT2
DIMENSION T(25),C(25)
REAL MR,IM,KCLO,LR,LRIM,ITIM,IECL
COMMON/XXVNA/TA,TR,V,RH,CLO,KCLO,FACL,IM,WORK,WK,SA,T,TS,C,
XMTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
100 CONTINUE
C
C CLEAR SCREEN
C
CALL CLEAN
C
C DISPLAY MENU
C
A-27
WRITE(NOUT,200)TA,TR,V,RH,CLO,FA,IM,WORK/SA,WK/SA,ITIME
200 FORMAT('Change: 1	 Air Temperature',
X3X' (C)'/',
X12X'1	 Mean Radiant Temperature	 '(C)'/',
X12X'2	 Air Speed	 (m/s)'/',
X12X'3	 Relative Humidity	 (ND)'/',
X12X'4	 Intrinsic Clothing Insulation	 (do)'/',
X12X'4	 Clothing Area Factor (fcl)	 (ND)'/',
X12X'4	 Clothing Permeability Index (Woodcock Im)'
X12X'5	 Total Metabolic Rate	 (W/m2)'/',
X12X'5	 External Work Accomplished	 (W/m2)'/',
X12X'6	 Output Time Interval	 (mins)'/',
X3X'7	 ALL'/',
X3X'Enter Change Required (RETURN when complete) : '$)

C DETERMINE RESPONSE
C
300 FORMAT(I1)
CALL CLEAN
IF(ICHNG.EQ.7)CALL INPUT
IF(ICHNG.EQ.7)GOTO 9999
GOTO (400,500,600,700,800,900)ICHNG
GOTO 9998
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400 WRITE(NOUT,1400)
1400 FORMAT(' Air Temperature	 (C) : '$)
READ(NIN,*)TA
WRITE(NOUT,1450)
1450 FORMAT(' Mean Radiant Temperature	 (C) : '$)
READ(NIN,*)TR
GOTO 100
500 WRITE(NOUT,1500)
1500 FORMAT(' Air Speed	 (m/s) : '$)
READ(NIN,*)V
GOTO 100
600 WRITE(NOUT,1600)
1600 FORMAT(' Relative Humidity (fraction)	 (ND) : '$)
READ(NIN,*)RH
GOTO 100
700 WRITE(NOUT,1700)
1700 FORMAT(' Intrinsic Clothing Insulation
	 (clo) : '$)
READ(NIN,*)CLO
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0.)CLO=1.0E-8

A-28
WRITE(NOUT,1725)
1725 FORMAT(/' Clothing Area Factor (fcl) (0 if unknown) (ND) :'$/)
READ(NIN,*)FACL
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (Mcculloch And Jones, 1984)
C IF(FACL.EQ.0.)FACL=1.+KCLO*CLO
IF(CLO.LT.0.01)FACL=1.
WRITE(NOUT,1750)
1750 FORMAT(/' Clothing Permeability Index (Woodcock Im) (ND) :'$/)
READ(NIN,*)IM
GOTO 100
800 WRITE(NOUT,1800)
1800 FORMAT(/' Total Metabolic Rate (W/m2) :'$/)
READ(NIN,*)WORK
WRITE(NOUT,1850)
1850 FORMAT(/' External Work Accomplished (W/m2) :'$/)
READ(NIN,*)WK
C CONVERT FROM W/m2 TO W
C WORK=WORK*SA
WK=WK*SA
GOTO 100
900 WRITE(NOUT,1900)
1900 FORMAT(/' Output Time Interval (mins) :'$/)
READ(NIN,*)ITIME
GOTO 100
9998 CALL CLEAN
WRITE(NOUT,65)
65 FORMAT(/' Exposure Time To These Conditions (hours) :'$/)
READ(NIN,*)TTIME
9999 CONTINUE
RETURN
END
C SUBROUTINE TO DISPLAY ENVIRONMENTAL CONDITIONS AND TABULATE
C FOR RESULTS
C SUBROUTINE TAB
DIMENSION T(25),C(25)
REAL MR,IM,KCLO,LR,LRIM,ITIM,IECL
COMMON/XXVNA/TA,TR,V,RH,CLO,KCLO,FACL,IM,WORK,WK,SA,T,TS,C,
XMTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
COMMON/OPTION/BEGIN,BEGIN1,OPT
CHARACTER*1 BEGIN,BEGIN1,OPT
C DISPLAY RESULTS
C CALL CLEAN
WRITE(NOUT,100)TA,TR,V,RH,CLO,FACL,IM,WORK/WK,SA/WK
WRITE(NDAT,100)TA,TR,V,RH,CLO,FACL,IM,WORK/WK,SA/WK
100 FORMAT(//'
X12X'Air Temperature =F7.2' (C)'/
X12X'Mean Radiant Temperature =F7.2' (C)'/
X12X'Air Speed =F7.2' (m/s)'/
X12X'Relative Humidity =F7.2' (ND)'/
X12X'Intrinsic Clothing Insulation =F7.2' (clo)'/
X12X 'Clothing Area Factor' = 'F7.2' (ND) /
X12X 'Clothing Permeability Index (Woodcock Im)' = 'F7.2' (ND) /
X12X 'Initial Metabolic Rate' = 'F7.2' (W/m2) /
X12X 'Work Rate Accomplished' = 'F7.2' (W/m2) /

C C PAUSE C
CALL WAIT(7)
WRITE(NDAT,200)
200 FORMAT(////)
C C TABULATE FOR OUTPUT C
CALL CLEAN
WRITE(NOUT,300)
WRITE(NDAT,300)
IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
C C CALCULATE INITIAL MEAN SKIN TEMPERATURE C
TS=0
DO 350 I=1,6
TS=TS+T(4*I)*C(4*I)/3.9O
350 CONTINUE
WRITE(NOUT,400)MTIME,T(1),TS,T(16),T(24)
WRITE(NDAT,400)MTIME,T(1),TS,T(16),T(24)
END IF
300 FORMAT(/X' Time Tcr Tsk Thd Tft w M (C+R) E Esk'/X' (min) (C) (C) (C) (C) (ND) (W/m2) (W/m2) (W/m2)'/X'**************************************************************'
X'**************************************************************')
400 FORMAT(15,4F8.2,1X,5(2X,'*****'))
RETURN
END
LUT25 MODEL PROGRAM LISTING

(HEAD AND HANDS UNCLOTHED)
LUT 25-NODE MODEL OF HUMAN THERMOREGULATION (V1.2b)
(ADAPTED FROM STOLWIJK AND HARDY 25-NODE MODEL)
HEAD AND HANDS UNCLOTHED

PROGRAM ALSO REQUIRES DATA FILE: THERMO.DAT

DIMENSION T(25), TSET(25), RATE(25), C(25), QB(24), EB(24), BFB(24)
DIMENSION TC(24), S(6), SKINR(6), SKINS(6), SKINV(6), SKINC(6), WORKM(6)
DIMENSION CHILM(6), HR(6), HCB(6), H(6), F(25), H(6), WARM(25), COLD(25)
DIMENSION HF(25)
DIMENSION ERROR(25), Q(24), E(24), BF(24), EMAX(6), BC(24), TD(24)
DIMENSION ARAD(6), DRY(6), RT(6), TCL(6), LR(6)
REAL MR, IM, KCL0, LR, LRIM, ITIM, ITIMM, IECL, IECLM, IET, IETM
COMMON/XXVNB/TA, TR, V, RH, CL0, KCL0, FACL, IM, WORK, WK, SA, T, TS, C,
XMTIME, ITIME, TTIME

COMMON BLOCKS UNIT AND SAVEF ARE INITIALIZED IN LIBRARY
SUBROUTINE SETUP

COMMON/UNIT/NIN, NOUT, NDAT
COMMON/SAVEF/GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
COMMON/OPTION/BEGIN, BEGIN1, OPT
CHARACTER*20 GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
CHARACTER*1 BEGIN, BEGIN1, CONT, CONT1, QUIT, QUIT1, OPT
BEGIN='B'
BEGIN1='b'
CONT='C'
CONT1='c'
QUIT='Q'
QUIT1='q'

OPEN INPUT DATA FILE AND RESULTS OUTPUT FILE

CALL SETUP
OPEN(UNIT=11, FILE=’[haslam.models]THERMO.DAT’, readonly,
STATUS=’OLD’, ERR=1250)
OPEN(UNIT=NDAT, FILE=’LUT25B’, STATUS=’UNKNOWN’)

DISPLAY TITLE
CALL TITLE

******************************************************************************

PROGRAM SUB-SECTION TO PROVIDE MENU CONTROL FOR MAIN PROGRAM
CLEAR SCREEN

10 CONTINUE
CALL CLEAN

DISPLAY MENU

WRITE(NOUT,20)
FORMAT(/X13$’**********************************************************************’/
X15$’LUT 25-Node Model of Human Thermoregulation (V1.2b)’/
X15$’ (adapted from Stolwijk and Hardy 25-Node Model)’/
X15X' Head and Hands Unclothed'/
X13X'******************************************************************************'/
X/21X'B Begin New Exposure'//
X21X'C Continue Exposure (new environment)'/
X21X'Q Quit'//
X16X' Results will be copied to a file called LUT25B.DAT'/
X9X'Enter Option: '$)

C
C DETERMINE RESPONSE
C
READ(NIN,30)OPT
30 FORMAT(A)
   IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
      GOTO 50
   ENDIF
   IF((OPT.EQ.CONT).OR.(OPT.EQ.CONT1))THEN
      CALL INPUT2
      GOTO 60
   ENDIF
   IF((OPT.EQ.QUIT).OR.(OPT.EQ.QUIT1))GOTO 1300
C
C IF RESPONSE IS NOT RECOGNIZED, INFORM AND REDISPLAY MENU
C
   CALL INFERR
   GOTO 10
C
C END OF MENU SUB-SECTION
C
C*******************************************************************************
C TO HERE FOR A NEW EXPOSURE
C
50 CONTINUE
C
C PRINT HEADER FOR DATA FILES
C
   WRITE(NDAT,55)
55 FORMAT(/!!!/!!!
   X34X'New Exposure'/
   X33X'******************************************************************************'/)
C
C PROGRAM TIMER VARIABLES
C
C MTIME = ACTUAL TIME (MINS)
C RTIME = ACTUAL TIME (HRS)
C NTIME = INCREMENT TIME (MINS)
C DTIME = INCREMENT TIME (HRS)
C JTIME = TOTAL EXPOSURE TIME (MINS)
C TTIME = TOTAL EXPOSURE TIME (HRS)
C ITIME = OUTPUT INTERVAL TIME (MINS)
C KTIME = OUTPUT INTERVAL TIMER (MINS)
C
C (ALL COUNTING IS DONE IN MINUTES)
C
C PROGRAM REQUIRES TWO TimERS, MTIME AND KTIME. IF MTIME >= KTIME
C RESULTS ARE PRINTED. MTIME AND KTIME ARE INCREMENTED BY NTIME
C AND ITIME RESPECTIVELY
C
C INITIALIZE TimERS
C
MTIME=0
JTIME=0
RTIME=0
C
C READ CONSTANTS FOR CONTROLLED SYSTEM
C
REWIND(11)
READ(11,84)C
READ(11,82)QB
READ(11,90)BFB
READ(11,82)TC
READ(11,92)S
READ(11,80)HCB
READ(11,80)ARAD
C
C READ CONSTANTS FOR THE CONTROLLER
C
READ(11,84)TSET
READ(11,88)CSW,SSW,PSW,CDIL,SDIL,PDIL,CCON,SCON,PCON,CCHIL,SCHIL,
XPHIL,BULL
READ(11,80)SKINR
READ(11,86)SKINS
READ(11,86)SKINV
READ(11,80)SKINC
READ(11,80)WORKM
READ(11,80)CHILM
C
C READ INITIAL CONDITIONS
C
READ(11,84)T
80 FORMAT(6F5.2)
82 FORMAT(24F5.2)
84 FORMAT(25F5.2)
86 FORMAT(6F5.3)
88 FORMAT(13F6.2)
90 FORMAT(24F6.2)
92 FORMAT(6F7.4)
C
C CALCULATE TOTAL SURFACE AREA
C
SA=0.
DO 110 K=1,6
110 SA=SA+S(K)
C
C INPUT EXPERIMENTAL CONDITIONS
C
CALL INPUT
C
C SET F(N) TO ZERO
C
DO 102 N=1,25
F(N)=0.
102 CONTINUE
C
C TO HERE FOR CONTINUING AN EXPOSURE
C
60 CONTINUE
C SET OUTPUT TIMER AND DETERMINE TOTAL EXPOSURE TIME
C
KTIME=MTIME
KTIME=KTIME+ITIME
JTIME=JTIME+TTIME*60.
C
C PRINT ENVIRONMENTAL CONDITIONS AND TABULATE FOR OUTPUT
C
CALL TAB
C
C DETERMINE TOTAL EXTRA HEAT PRODUCTION IN THE WORKING MUSCLES
C
WEFFM=1.-((WK/(WORK-86.49)))
WORKI=(WORK-86.49)*WEFFM
IF(WORK.LE.86.49)WORKI=0.
C
C CALCULATE CLOTHING AND ENVIRONMENTAL HEAT TRANSFER COEFFICIENTS
C
C RESISTANCE OF CLOTHING TO THE TRANSFER OF WATER VAPOUR:
C IceI CALCULATED FROM Im, HASLAM AND PARSONS (1988). HEAT TRANSFER
C COEFFICIENTS ARE THOSE ESTIMATED TO HAVE PREVAILED WHEN Im WAS
C MEASURED, i.e. Ta = Tr = 24 C, V = 0.1 m/s, Tsk = 33 C, Ia = 0.71 clo
C
TAIM=24.0
TRIM=24.0
TSKIM=33.0
C
HCIM CALCULATED BY SUBTRACTING HRIM (NUDE) FROM Ia
C
HCIM=4.52
C
C CALCULATE HRIM AND TCLIM
C
C ITERATIVE LOOP TO MEAN CALCULATE CLOTHING TEMPERATURE (TCLIM)
C AND MEAN LINEAR RADIATION COEFFICIENT (HRIM)
C
TCLIM=0.0
150 TCLOLD=TCLIM
HRIM=4.*5.67E-8*(((TCLIM+TRIM)/2.+273.2)**3)*0.725
TCLIM=((1./(CLO*0.155))*TSKIM+FACL*(HCIM*TAIM+HRIM*TRIM))/
X((1./(CLO*0.155))+FACL*(HCIM+HRIM))
IF(ABS(TCLIM-TCLOLD).GT.0.01)GOTO 150
C
C CORRECT CLOTHING INSULATION MEASURED ON MANIKIN FOR REDUCED SURFACE
C AREA DUE TO NUDE HEAD AND HANDS, STOLWIJK AND HARDY SURFACE AREAS
C USED IN THE ABSENCE OF ANY OTHER DATA
C
C CALCULATE ITIM (m2.C/W), AS MEASURED ON THE MANIKIN
C
ITIM=CLO*0.155+(1./((HCIM+HRIM)*FACL))
C
C CALCULATE ITIM THAT APPLIES TO THE CLOTHED SURFACE AREA
C
ITIMM=(SA-S(1)-S(4))/(SA/ITIM-(S(1)+S(4))/(1.)/(HCIM+HRIM))
C
C CALCULATE CORRECTED CLO
C
CLOM=(ITIMM-(1./(FACL*(HCIM+HRIM))))/0.155
IF CLOM IS LESS THAN 1.0E-8 THEN SET TO 1.0E-8

CALCULATE LRIM AT TCLIM

LRIM=15.1512*(TCLIM+273.15)/273.15

CALCULATE \( \text{i}_{\text{ET}} \) (m2.kPa/W), AS MEASURED ON THE MANIKIN

\[ \text{i}_{\text{ET}} = \frac{\text{ITIM}}{(LRIM*\text{IM})} \]

CORRECT \( \text{i}_{\text{ET}} \) DETERMINED FROM THE IM MEASURED ON THE MANIKIN, FOR THE REDUCED SURFACE AREA DUE TO THE NUDE HEAD AND HANDS. STOLWIJK AND HARDY SURFACE AREAS USED IN THE ABSENCE OF ANY OTHER DATA

\[ \text{i}_{\text{ETM}} = \frac{(\text{SA}_S \text{S}(1) - \text{S}(4))}{(\text{SA}/\text{i}_{\text{ET}} \text{(S}(1) + \text{S}(4))*LRIM*HCIM) \]

CALCULATE CORRECTED IECL

\[ \text{IECLM} = \text{i}_{\text{ETM}} - \frac{1}{(\text{FACL}*LRIM*HCIM)} \]

CALCULATE CONVECTIVE HEAT TRANSFER COEFFICIENT, HC(I), STOLWIJK AND HARDY (1977)

DO 202 I=1,6
\[ HC(I) = 3.16*HCB(I)*V**0.5 \]
202 CONTINUE

CALCULATE RADIANT HEAT TRANSFER COEFFICIENT, HR(I), STOLWIJK AND HARDY (1977) AND CLOTHING SURFACE TEMPERATURE, TCL(I)

DO 225 I=1,6
\[ TCL(I) = 0. \]
250 TCLOLD=TCL(I)
\[ HR(I) = 4.5*5.67E-8*(((TCL(I)+TR)/2.+273.2)**3.*ARAD(I) \]
\[ TCL(I) = ((1./CLOM*0.155)+FACL*(HC(I)*TA+HR(I)*TR))/X((1./CLOM*0.155)+FACL*(HC(I)+HR(I))) \]
\[ \text{IF(ABS(TCL(I)-TCLOLD).GT.0.01)GOTO 250} \]
225 CONTINUE

HEAD AND HANDS ARE UNCLOTHED

\[ HR(1) = 4.5*5.67E-8*(((T(4)+TR)/2.+273.2)**3.*ARAD(1) \]
\[ HR(4) = 4.5*5.67E-8*(((T(16)+TR)/2.+273.2)**3.*ARAD(4) \]

TCL(1)=T(4)
TCL(4)=T(16)

CALCULATE TOTAL ENVIRONMENTAL HEAT TRANSFER COEFFICIENT H(I), STOLWIJK AND HARDY (1977)

DO 275 I=1,6
H(I) = (HR(I) + HC(I)) * S(I)

C ESTABLISH THERMORECEPTOR OUTPUT
C
C NO VALUES ARE GIVEN BY STOLWIJK AND HARDY FOR RATE(N)
C THEREFORE THIS PARAMETER HAS BEEN SET TO ZERO
C
DO 302 N = 1, 25
ERROR(N) = 0.
RATE(N) = 0.
WARM(N) = 0.
COLD(N) = 0.
ERROR(N) = T(N) - TSET(N) + RATE(N) * F(N)
IF(ERROR(N) .LT. 0.) COLD(N) = -ERROR(N)
IF(ERROR(N) .GT. 0.) WARM(N) = ERROR(N)
CONTINUE
302
C INTEGRATE PERIPHERAL AFFERENTS
C
WARMS = 0.
COLDS = 0.
DO 305 I = 1, 6
K = 4 * I
WARMS = WARMS + WARM(K) * SKINR(I)
COLDS = COLDS + COLD(K) * SKINR(I)
CONTINUE
305
C DETERMINE EFFERENT OUTFLOW
C
SWEAT = CSW * ERROR(1) + SSW * (WARMS - COLDS) + PSW * ERROR(1) * (WARMS - COLDS)
DILAT = CDIL * ERROR(1) + SDIL * (WARMS - COLDS) + PDIL * WARM(1) * WARMS
STRIC = CCON * ERROR(1) - SCON * (WARMS - COLDS) + PCON * COLD(1) * COLDS
CHILL = (CCHIL * ERROR(1) + SCHIL * (WARMS - COLDS)) * PCHIL * (WARMS - COLDS)
IF(SWEAT .LE. 0.) SWEAT = 0.
IF(DILAT .LE. 0.) DILAT = 0.
IF(STRIC .LE. 0.) STRIC = 0.
IF(CHILL .LE. 0.) CHILL = 0.
C
C PREVENT CHILL FROM BECOMING POSITIVE IN HOT ENVIRONMENTS
C
IF((COLD(1) .EQ. 0.) .AND. (COLDS .EQ. 0.)) CHILL = 0.
C
C ASSIGN EFFECCTOR OUTPUT
C
DO 401 I = 1, 6
N = 4 * I - 3
Q(N) = QB(N)
BF(N) = BFB(N)
E(N) = EB(N)
Q(N+1) = QB(N+1) + WORKM(I) * WORKI + CHILM(I) * CHILL
E(N+1) = 0.
BF(N+1) = BFB(N+1) + Q(N+1) - QB(N+1)
Q(N+2) = QB(N+2)
E(N+2) = 0.
BF(N+2) = BFB(N+2)
Q(N+3) = QB(N+3)
E(N+3) = EB(N+3) + SKINS(I) * SWEAT * 2. ** ((T(N+3) - TSET(N+3)) / BULL)
BF(N+3) = (BFB(N+3) + SKINV(I) * DILAT) / (1. + SKINC(I) * STRIC)
CALCULATE MAXIMUM EVAPORATIVE CAPACITY OF THE ENVIRONMENT, EMAX(I) USING THE RESISTANCE TO VAPOUR PERMEATION, RT. RT IS CALCULATED ACCORDING TO HASLAM AND PARSONS (1988)

\[ LR(I) = 15.1512 \times (TCL(I) + 273.15) / 273.15 \]

HEAD AND HANDS ARE UNCLOTHED

\[
\begin{align*}
\text{IF}((I \text{EQ} 1) \text{.OR.}(I \text{EQ} 4)) \text{THEN} & \\
RT(I) & = 0.1 + (1.0 / (FACL*LR(I)*HC(I))) \\
\text{ELSE} & \\
RT(I) & = 1 + (1.0 / (FACL*LR(I)*HC(I))) \\
\text{ENDIF}
\end{align*}
\]

EMAX(I) = \((1.0 / RT(I)) \times (SVP(T(N+3) \times RH \times SVP(TA))) \times S(I)\)

IF(E(N+3) > EMAX(I)) E(N+3) = EMAX(I)

CALCULATE DRY SKIN HEAT EXCHANGE WITH ENVIRONMENT, DRY(I)

\[
\begin{align*}
\text{DO 450 I=1,6} & \\
DRY(I) & = (FACL \times (HC(I) \times (TCL(I) - TA) \times HR(I) \times (TCL(I) - TR))) \times S(I)
\end{align*}
\]

CALCULATE HEAT FLOWS

\[
\begin{align*}
\text{DO 500 K=1,24} & \\
BC(K) & = BF(K) \times (T(K) - T(25)) \\
TD(K) & = TC(K) \times (T(K) - T(K+1))
\end{align*}
\]

\[
\begin{align*}
\text{DO 501 I=1,6} & \\
K & = 4 \times I - 3 \\
HF(K) & = Q(K) - E(K) - BC(K) - TD(K) \\
HF(K+1) & = Q(K+1) - BC(K+1) + TD(K) - TD(K+1) \\
HF(K+2) & = Q(K+2) - BC(K+2) + TD(K+1) - TD(K+2) \\
HF(K+3) & = Q(K+3) - BC(K+3) - E(K+3) + TD(K+2) - DRY(I)
\end{align*}
\]

\[
\begin{align*}
\text{DO 502 K=1,24} & \\
HF(25) & = 0.1 \\
HF(25) & = HF(25) + BC(K)
\end{align*}
\]

SUBTRACT A CORRECTION FOR RESPIRATORY HEAT LOSSES FROM BLOOD HEAT FLOW

\[
HF(25) = HF(25) - 0.08 \times \text{WORKI}
\]

DETERMINE OPTIMUM INTEGRATION STEP

\[
\begin{align*}
\text{NTIME} & = 1 \\
\text{DTIME} & = 1.60.\\n\text{DO 600 K=1,25} & \\
F(K) & = HF(K) / C(K) \\
U & = \text{ABS}(F(K)) \\
\text{IF}(U \times \text{DTIME} \text{GT} 0.1) \text{DTIME} = 0.1 / U
\end{align*}
\]

CALCULATE NEW TEMPERATURES

\[
\begin{align*}
\text{DO 700 K=1,25}
\end{align*}
\]
\[ T(K) = T(K) + F(K) \times DTIME \]

700 CONTINUE
C
C INCREMENT TIMER
C
RTIME = RTIME + DTIME
MTIME = 60. * RTIME
C
C WHEN APPROPRIATE OUTPUT RESULTS
C
IF (MTIME .GE. KTIME) GOTO 701
GOTO 300
701 CONTINUE
C
C PREPARE FOR OUTPUT
C
CO = 0.
HP = 0.
EV = 0.
DRYT = 0.
ESK = 0.
FWET = 0.
TS = 0.
TB = 0.
HFLOW = 0.
SBF = 0.
DO 800 N = 1, 24
C
C CARDIAC OUTPUT, CO
C
CO = CO + BF(N) / 60.
C
C HEAT PRODUCTION, HP
C
HP = HP + Q(N)
C
C TOTAL INSENSIBLE HEAT LOSS, EV
C
EV = EV + E(N)
800 CONTINUE
C
C METABOLIC RATE, MR
C
MR = HP + WK
C
C ADD A CORRECTION TO TOTAL INSENSIBLE HEAT LOSS FOR ADDITIONAL
C RESPIRATORY HEAT LOSSES DUE TO WORK
C
EV = EV + 0.08 * WORKI
DO 802 I = 1, 6
C
C TOTAL SENSIBLE HEAT LOSS, DRYT
C
DRYT = DRYT + DRY(I)
C
C INSENSIBLE HEAT LOSS FROM SKIN, ESK
C
ESK = ESK + E(4*I)
C
A-39
C SKIN WETTEDNESS, PWET
    PWET = PWET + (E(4*I)/EMAX(I))*(S(I)/SA)
C SKIN BLOOD FLOW, SBF
    SBF = SBF + BF(4*I)/60.
C MEAN SKIN TEMPERATURE, TS
    TS = TS + T(4*I)*C(4*I)/3.90
802 CONTINUE
    DO 801 N = 1, 25
C MEAN BODY TEMPERATURE, TB
    TB = TB + T(N)*C(N)/68.79
C TOTAL HEAT FLOW, HFLOW
    HFLOW = HFLOW + HF(N)
801 CONTINUE
C CONVERT FROM W TO W/M2
    EV = EV/SA
    DRYT = DRYT/SA
    ESK = ESK/SA
    HP = HP/SA
    MR = MR/SA
    HFLOW = HFLOW/SA
C TISSUE CONDUCTANCE, COND
    COND = (HP - (E(1)+E(5))/SA-HFLOW)/(T(25)-TS)
    WRITE(NOUT,1000)MTIME,T(1),TS,T(16),T(24),PWET,MR,DRYT,EV,ESK
    WRITE(NDAT,1000)MTIME,T(1),TS,T(16),T(24),PWET,MR,DRYT,EV,ESK
1000 FORMAT(15,5F8.2,1X,4F8.2)
    KTIME = KTIME + ITIME
    IF(MTIME .LT.JTIME)GOTO 300
    CALL WAIT(1)
GOTO 10
1250 WRITE(NOUT, 1255)
1255 FORMAT(' ERROR: THIS PROGRAM NEEDS THE THERMO.DAT DATA FILE')
    CALL WAIT(6)
1300 CONTINUE
    CALL CLEAN
    CALL TIDYUP
    END
C SVP AT T, USING ANTOINE'S EQUATION (kPa)
C (REPLACES STOLWIJK AND HARDY'S STEAM TABLES)
C FUNCTION SVP(T)
    SVP = 0.133322*EXP(18.6686-4030.183/(T+235.0))
    RETURN
END
C SUBROUTINE TO DISPLAY PROGRAM TITLE
C
SUBROUTINE TITLE
COMMON/UNIT/NIN,NOUT,NDAT
CALL CLEAN
WRITE(NOUT,10)
WRITE(NDAT,10)
10 FORMAT(/' *****************************************************'/
X14X'LUT 25-Node Model of Human Thermoregulation (V1.2b)'/
X15X' (adapted from Stolwijk and Hardy 25-Node Model)'/
X15X' Head and Hands Unclothed'/
X15X' Roger Haslam'/
X15X' Department of Human Sciences'/
X15X' Loughborough University of Technology'/
X14X' *****************************************************'
X/)
CALL WAIT(7)
RETURN
END
C
C SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS
C
SUBROUTINE INPUT
DIMENSION T(25),C(25)
REAL MR,IM,KCLO,LR,LRIM,ITIM,ITIMM,IECL,IECLM,IET,IETM
COMMON/XXVNB/TA,TR,V,RH,CLO,KCLO,FACL,IH,WORK,WK,SA,T,TS,C,
XMTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
CALL CLEAN
WRITE(NOUT,100)
100 FORMAT(/' Air Temperature (C) 
READ(NIN,*),TA
WRITE(NOUT,200)
200 FORMAT(/' Mean Radiant Temperature (C) 
READ(NIN,*),TR
WRITE(NOUT,300)
300 FORMAT(/' Air Speed (m/s) 
READ(NIN,*),V
WRITE(NOUT,400)
400 FORMAT(/' Relative Humidity (fraction) 
READ(NIN,*),RH
WRITE(NOUT,500)
500 FORMAT(/' Intrinsic Clothing Insulation (clo) 
READ(NIN,*),CLO
WRITE(NOUT,600)
600 FORMAT(/' Clothing Area Factor (fcl) (0 if unknown) 
READ(NIN,*),FACL
WRITE(NOUT,700)
700 FORMAT(/' Clothing Permeability Index (Woodcock Im) 
READ(NIN,*),IM
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0.)CLO=1.0E-8
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
KCLO=0.31

A-41
IF (FACL .EQ. 0.) FACL = 1. + KCLO * CLO
IF (CLO .LT. 0.01) FACL = 1.
CALL CLEAN
WRITE (NOUT, 800)
800 FORMAT (/ 'Total Metabolic Rate (W/m2) : ' $)
READ (NIN, *) WORK
WRITE (NOUT, 900)
900 FORMAT (/ 'External Work Accomplished (W/m2) : ' $)
READ (NIN, *) WK
C
C CONVERT FROM W/m2 TO W
C
WORK = WORK * SA
WK = WK * SA
WRITE (NOUT, 1200)
1200 FORMAT (/ 'Output Time Interval (mins) : ' $)
READ (NIN, *) ITIME
WRITE (NOUT, 1300)
1300 FORMAT (/ 'Exposure Time To These Conditions (hours) : ' $)
READ (NIN, *) TTIME
RETURN
END

C SUBROUTINE TO ENABLE ENVIRONMENTAL CONDITIONS TO BE REDEFINED IN
C ORDER TO CONTINUE AN EXPOSURE.
C
SUBROUTINE INPUT2
DIMENSION T(25), C(25)
REAL MR, IM, KCLO, LR, LRIM, ITIM, ITIMM, IECL, IECLM, IET, IETM
COMMON/XXVNB/TA, TR, V, RH, CLO, KCLO, FACL, IM, WORK, WK, SA, T, TS, C,
XMTIME, ITIME, TTIME
COMMON/UNIT/NIN, NOUT, NDAT
100 CONTINUE
C
C CLEAR SCREEN
C
CALL CLEAN
C
C DISPLAY MENU
C
WRITE (NOUT, 200) TA, TR, V, RH, CLO, FACL, IM, WORK/S, WK/S, ITIME
200 FORMAT (X3X 'Change: 1   Air Temperature
XF6.2' (C)'/
X12X'1   Mean Radiant Temperature    'F6.2
X' (C)'/
X12X'2 Air Speed       'F6.2
X' (m/s)'/
X12X'3 Relative Humidity     'F6.2
X' (ND)'/
X12X'4 Intrinsic Clothing Insulation 'F6.2
X' (clo)'/
X12X'4 Clothing Area Factor (fcl) 'F6.2
X' (ND)'/
X12X'4 Clothing Permeability Index (Woodcock Im)'F6.2
X' (ND)'/
X12X'5 Total Metabolic Rate 'F6.2
X' (W/m2)'/
X12X'5 External Work Accomplished 'F6.2
X' (W/m²) //
X12X'6 Output Time Interval 'I6
X' (mins) //
X12X'7 ALL' //
X3X' Enter Change Required (RETURN when complete) : '$

C
C DETERMINE RESPONSE
C
READ(NIN,300)ICHNG
FORMAT(I1)
CALL CLEAN
IF(ICHNG.EQ.7)CALL INPUT
IF(ICHNG.EQ.7)GOTO 9999
GOTO (400,500,600,700,800,900)ICHNG
GOTO 9998

C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400 WRITE(NOUT,1400)
1400 FORMAT(//' Air Temperature (C) : '$)
READ(NIN,*TA)
WRITE(NOUT,1450)
1450 FORMAT(//' Mean Radiant Temperature (C) : '$)
READ(NIN,*TR)
GOTO 100
500 WRITE(NOUT,1500)
1500 FORMAT(//' Air Speed (m/s) : '$)
READ(NIN,*V)
GOTO 100
600 WRITE(NOUT,1600)
1600 FORMAT(//' Relative Humidity (fraction) (ND) : ')$
READ(NIN,*RH)
GOTO 100
700 WRITE(NOUT,1700)
1700 FORMAT(//' Intrinsic Clothing Insulation (clo) : '$)
READ(NIN,*CLO)
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0.)CLO=1.0E-8
WRITE(NOUT,1725)
1725 FORMAT(//' Clothing Area Factor (fcl) (0 if unknown) (ND) : '$)
READ(NIN,*FACL)
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
IF(FACL.EQ.0.)FACL=1.+KCLO*CLO
IF(CLO.LT.0.01)FACL=1.
WRITE(NOUT,1750)
1750 FORMAT(//' Clothing Permeability Index (Woodcock Im) (ND) :'$)
READ(NIN,*IM)
GOTO 100
800 WRITE(NOUT,1800)
1800 FORMAT(//' Total Metabolic Rate (W/m²) : '$)
READ(NIN,*WORK)
WRITE(NOUT,1850)
1850 FORMAT(//' External Work Accomplished (W/m²) : '$)
READ(NIN,*WK)
C

A-43
C CONVERT FROM W/m² TO W
C
WORK=WORK*SA
WK=WK*SA
GOTO 100

900 WRITE(NOUT,1900)
1900 FORMAT('/' Output Time Interval (mins) : '$)
READ(NIN,*)ITIME
GOTO 100

9998 CALL CLEAN
WRITE(NOUT,65)
65 FORMAT('/' Exposure Time To These Conditions (hours) : '$)
READ(NIN,*)ITIME

9999 CONTINUE
RETURN
END

C C SUBROUTINE TO DISPLAY ENVIRONMENTAL CONDITIONS AND TABULATE
C FOR RESULTS
C
SUBROUTINE TAB
DIMENSION T(25),C(25)
REAL MR,IM,KCLO,LR,LRIM,ITIM,ITIMM,IECL,IECLM,IET,IETM
COMMON/XXVNB/TA,TR,V,RH,CLO,KCLO,FACL,IM,WORK,WK,SA,T,TS,C,
XMTIME,ITIME,TTIME
COMMON/UNIT/NIN,NOUT,NDAT
COMMON/OPTION/BEGIN,BEGIN1,OPT
CHARACTER*1 BEGIN,BEGIN1,OPT

C C DISPLAY RESULTS
C
CALL CLEAN
WRITE(NOUT,100)TA,TR,V,RH,CLO,FACL,IM,WORK/SA,WK/SA
WRITE(NDAT,100)TA,TR,V,RH,CLO,FACL,IM,WORK/SA,WK/SA
100 FORMAT(/'/
X12X'Air Temperature	 ='F7.2' (C)'/
X12X'Mean Radiant Temperature	 ='F7.2' (C)'/
X12X'Air Speed	 ='F7.2' (m/s)'/
X12X'Relative Humidity	 ='F7.2' (ND)'/
X12X'Intrinsic Clothing Insulation	 ='F7.2' (clo)'/
X12X'Clothing Area Factor	 ='F7.2' (ND)'/
X12X'Clothing Permeability Index (Woodcock Im)	 ='F7.2' (ND)'/
X12X'Initial Metabolic Rate	 ='F7.2' (W/m²)'/
X12X'Work Rate Accomplished	 ='F7.2' (W/m²)'/

C C PAUSE
C
CALL WAIT(7)
WRITE(NDAT,200)
200 FORMAT(////)
C C TABULATE FOR OUTPUT
C
CALL CLEAN
WRITE(NOUT,300)
WRITE(NDAT,300)
IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
C C CALCULATE INITIAL MEAN SKIN TEMPERATURE
C
C

TS=0
DO 350 I=1,6
TS=TS+T(4*I)*C(4*I)/3.90
CONTINUE
WRITE(NOUT,400)MTIME,T(1),TS,T(16),T(24)
WRITE(NDAT,400)MTIME,T(1),TS,T(16),T(24)
END IF

300 FORMAT(/X'Time	Tcr	Tsk	Thd	Tft	w	M	(C+R)X
X'E	Esk'/X'(min)	(C)	(C)	(C)	(ND)	(W/m2)	(W/m2)	('/X'(W/m2)	(W/m2)'/
X'******************************************************
X'**************')
400 FORMAT(15,4F8.2,1X,5(2X,'*****'))
RETURN
END
LUT25 MODEL EXAMPLE PREDICTIONS
(CLOTHING COVERS HEAD AND HANDS)
LUT 25-Node Model of Human Thermoregulation (V1.0a)
(adapted from Stolwijk and Hardy 25-Node Model)
Clothing covers Head and Hands

Roger Haslam
Department of Human Sciences
Loughborough University of Technology

New Exposure

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<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
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<th>Tft (°C)</th>
<th>w (ND)</th>
<th>M (W/m²)</th>
<th>(C+R) (W/m²)</th>
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A-49
LUT25 MODEL EXAMPLE PREDICTIONS

(HEAD AND HANDS UNCLOTHED)
**LUT 25-Node Model of Human Thermoregulation (V1.2b)**
(adapted from Stolwijk and Hardy 25-Node Model)
Head and Hands Unclothed

Roger Haslam
Department of Human Sciences
Loughborough University of Technology

**New Exposure**

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<th>Time (min)</th>
<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
<th>Thd (°C)</th>
<th>Tft (°C)</th>
<th>w (ND)</th>
<th>M (W/m²)</th>
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A-51
LUT MODEL OF HUMAN RECTAL TEMPERATURE RESPONSE TO WORK, CLOTHING AND ENVIRONMENT (V1.1)
(ADAPTED FROM GIVONI AND GOLDMAN MODEL)

REAL IMCLO, IMCLOE, MRNET, MR, IM, LR, IECL, IA, IMV
COMMON/GG/TA, V, RH, CLO, PAACL, IM, MR, WK, TREI, NACC, MTIME, ITIME, TTIME, AD
COMMON/TABS/VE, CLOEG, IMCLOE, ERC, EREQ, EMAX, PWET, TREF, TREFA, CP
COMMON/OPTGG/BEGIN, BEGIN1, OPT, CSTAT
COMMON/ADDITION/CLOT, IMV

COMMON BLOCKS UNIT AND SAVEF ARE INITIALIZED IN LIBRARY

SUBROUTINE SETUP

COMMON/UNIT/NIN, NOUT, NDAT
COMMON/SAVEF/GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
CHARACTER*20 GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B

DEFINE CHARACTER VARIABLES FOR MENU SUB-SECTION ETC

CHARACTER*1 BEGIN, BEGIN1, CONT, CONT1, QUIT, QUIT1, OPT
CHARACTER*2 REST, REST1, WORK, WORK1, RCV, RCV1, STATUS, OPT2
CHARACTER*8 OSTAT, CSTAT
BEGIN='B'
BEGIN1='b'
CONT='C'
CONT1='c'
QUIT='Q'
QUIT1='q'

OPEN RESULTS OUTPUT FILE

CALL SETUP
OPEN(UNIT=NDAT, FILE=LUTTRE, STATUS='UNKNOWN')

DISPLAY TITLE

CALL TITLE

****************** **************************************************************

PROGRAM SUB-SECTION TO PROVIDE MENU CONTROL FOR MAIN PROGRAM

CLEAR SCREEN

CONTINUE
CALL CLEAN

DISPLAY MENU

WRITE(NOUT,20)
FORMAT(/)
X14X'***********************************************************************'/
X16X'LUT Model of Rectal Temperature Response (V1.1)'/
X16X' (adapted from Givoni and Goldman Model)'/
X14X'***********************************************************************'/
X20X' B Begin New Exposure (new subject)'/
X20X' C Continue Exposure (new environment)'/
X20X' Q Quit'/'
Results will be copied to a file called LUTTRE.DAT

Enter Option: '$

C DETERMINE RESPONSE
C
READ(NIN,30)OPT
30 FORMAT(A)
  IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
    CALL INPUT
    GOTO 50
  ENDIF
  IF((OPT.EQ.CONT).OR.(OPT.EQ.CONT1))THEN
    CALL INPUT2
    GOTO 60
  ENDIF
  IF((OPT.EQ.QUIT).OR.(OPT.EQ.QUIT1))GOTO 1000
C
C IF RESPONSE IS NOT RECOGNIZED, INFORM AND REDISPLAY MENU
C
  CALL INFERR
  GOTO 10
C
C END OF MENU SUB-SECTION
C
C **********************************************************************
C
C TO HERE FOR A NEW EXPOSURE
C
50 CONTINUE
C
C INITIALIZE STATUS CHARACTER STRING
C
  CSTAT=' NULL'
C
C PRINT HEADER FOR DATA FILE
C
  WRITE(NDAT,55)
55 FORMAT(///////
      X34X'New Exposure' /
      X33X'**************'/)
C
C PROGRAM TIMER VARIABLES
C
  MTIME = ACTUAL TIME (MINS)
  HTIME = ACTUAL TIME (HRS)
  LTIME = TIME OF EXPOSURE TO ACTIVITY (MINS)
  ATIME = TIME OF EXPOSURE TO ACTIVITY (HRS)
  JTIME = TOTAL EXPOSURE TIME (MINS)
  ITIME = OUTPUT INTERVAL TIME (MINS)
  FWTIME = FINAL WORK TIME (SAVED FOR ANY RECOVERY) (HRS)
  WTME = WORK TIME CONTINUING FOR TIME LAG PERIOD OF RECOVERY (HRS)
C
    MTIME=0
    JTIME=0
C
C TO HERE FOR CONTINUING AN EXPOSURE
C
60 CONTINUE
    LTIME=0
C DETERMINE TOTAL EXPOSURE TIME
C JTIME=JTIME+TTIME*60
C DETERMINE TYPE OF EXPOSURE
C EXPOSURE IS REST IF:
C MR < 120 W, NO PREVIOUS EXPOSURE
C MR < 120 W, TRE < 37.2 C, PREVIOUS EXPOSURE RECOVERY
C EXPOSURE IS WORK IF:
C MR >= 120 W
C EXPOSURE IS RECOVERY IF:
C MR < 120 W, PREVIOUS EXPOSURE WORK
C MR < 120 W, TRE > 37.2 C, PREVIOUS EXPOSURE RECOVERY
C
OSTAT=CSTAT
IF(MR.LT.120.0)THEN
IF((CSTAT.EQ. 'NULL').OR.(CSTAT.EQ. 'rest'))THEN
CSTAT=' rest'
ELSEIF(CSTAT.EQ. 'recovery') THEN
IF(TRE.LE.37.2)THEN
CSTAT=' rest'
ELSE
CSTAT='recovery'
ENDIF
ELSEIF(CSTAT.EQ. 'work') THEN
CSTAT='recovery'
ELSE
CSTAT='work'
ENDIF
ENDIF
C IF EXPOSURE IS WORK AND PREVIOUS EXPOSURE WAS NULL OR RECOVERY, THEN
C CALCULATE EQUILIBRIUM VALUES FOR REST. THESE VALUES ARE NEEDED FOR
C THE TIME LAG PERIOD AT THE START OF WORK.
C
IF((CSTAT.EQ. 'work').AND.
X((OSTAT.EQ. 'NULL').OR.(OSTAT.EQ. 'recovery'))) THEN
OMR=MR
MR=105.0
ENDIF
100 CONTINUE
C CALCULATE EXPERIMENTAL AND EQUILIBRIUM VALUES
C
C *******************************************
C STANDARD MAN 70 kg, 1.7 m and 1.81 m2
C SKIN TEMPERATURE (C)
C TSK=36.0
C
C EFFECTIVE AIR SPEED (m/s)

C $V_{E} = V + 0.004 \times (MR - 105.)$

C CONVERT INPUT CLOTHING PARAMETERS AS MEASURED AT $V = 0.1$ m/s TO THOSE
C THAT WOULD HAVE BEEN OBTAINED AT $V = 1.0$ m/s
C CALCULATED ASSUMING $T_a = T_r = 24$ C, $h_c = 4.57$ W/M$^2$.C (CALCULATED BY
C SUBTRACTING $h_r$ FROM $h$ ASSUMING $I_a = 0.71$ clo
C
C DEFINE CONSTANTS (V=0.1)

C $h_c = 4.57$
C $I_a = 16.5$
C $I_a = 0.71$

C TOTAL CLOTHING INSULATION (clo) (V=0.1)
C
C $C_{L} = C_{L} + I_a / F_a$

C INTRINSIC EVAPORATIVE RESISTANCE (M$^2$.kPa/W)
C
C $I_{ECL} = (C_{L} \times 0.155) / (L_{R} \times I_{M}) - 1 / (F_a \times h_c \times L_{R})$

C DEFINE CONSTANTS (V=1.0)
C (HC CALCULATED FROM 8.6*V**0.53)
C
C $h_c = 8.6$
C $I_a = 0.49$

C TOTAL CLOTHING INSULATION (clo) (V=1.0)
C
C $C_{L} = C_{L} + I_a / F_a$

C IM PERMEABILITY INDEX (V=1.0)
C
C $I_{MV} = (C_{L} \times 0.155) / (L_{R} \times (I_{ECL} + 1 / (F_a \times h_c \times L_{R})))$

C IM/CLOT COEFFICIENT (1/clo)
C
C $I_{MCLOT} = I_{MV} / C_{LOT}$

C VELOCITY MODIFIER (?)
C
C $V_{MOD} = 0.25$

C EFFECTIVE CLOTHING INSULATION COEFFICIENT (clo)
C
C $C_{LOG} = C_{LOT} \times V^{**(-V_{MOD})}$

C EFFECTIVE PERMEABILITY INDEX RATIO (1/clo)
C
C $I_{MCLOE} = I_{MCLOT} \times V^{**V_{MOD}}$

C REQUIRED EVAPORATIVE COOLING (W)
C
C $E_{REQ} = \text{TOTAL HEAT LOAD} + \text{ENVIRONMENTAL HEAT LOAD}$
C
C $M_{RNET} = M_{R} - WK$
C $E_{RC} = 6.45 \times A D \times (T_A - T_SK) / C_{LOG}$

A-56
EREQ=MRNET+ERC

C MAXIMUM EVAPORATIVE CAPACITY OF ENVIRONMENT (W)
C
EMAX=14.2*AD*IMCLOE*(SVP(TSK)-RH*SVP(TA))

C SKIN WETTEDNESS (ND)
C
PWET=EREQ/EMAX
IF(PWET.LT.0.OR.PWET.GT.1)PWET=1

C COMBINED EFFECT OF METABOLIC AND ENVIRONMENTAL HEAT
C STRESS ON RECTAL TEMPERATURE OF ACCLIMATIZED MEN
C
C FINAL EQUILIBRIUM TEMPERATURE (C)
C
TREM=0.004*(MR-WK)
TREERC=(0.014*AD/CLOEG)*(TA-TSK)
TREEV=0.8*EXP(0.0047*(EREQ-EMAX))
TREF=36.75+TREM+TREERC+TREEV

C DIFFERENCE IN EQUILIBRIUM RECTAL TEMPERATURE
C BETWEEN ACCLIMATIZED AND NON-ACCLIMATIZED MEN (C)
C
CTREF=1.2*(1.-EXP(0.5*(37.15-TREF)))

C ACCOUNTING FOR DAYS IN THE HEAT AND THE CHANGE IN THE EVAPORATIVE
C CAPACITY OF THE ENVIRONMENT (C)
C
CTREFA=EXP(-0.3*NACC)*(0.5+CTREF)*(1.-EXP(-0.005*EMAX))

C THEREFORE FINAL EQUILIBRIUM TEMPERATURE OF PARTIALLY
C ACCLIMATIZED MEN EQUALS TREF + CTREFA (C)
C
TREFA=TREF+CTREFA
CTRE=TREFA-TREI

C EFFECTIVE COOLING POWER OF THE ENVIRONMENT (?)
C
CP=(0.15*AD*IMCLOE*(SVP(TSK)-(RH*SVP(TA))))
X+((0.097*AD/CLOEG)*(TSK-TA))-1.57

C *********************************************************
C
C IF EXPOSURE IS WORK AND PREVIOUS EXPOSURE WAS NULL OR RECOVERY, AND
C EQUILIBRIUM VALUES HAVE JUST BEEN CALCULATED FOR REST, THEN SAVE THE
C VALUES REQUIRED FOR TIME LAG PERIOD AT THE START OF WORK AND GO BACK
C AND CALCULATE EQUILIBRIUM VALUES FOR WORK
C
IF((CSTAT.EQ.'work').AND.
X((OSTAT.EQ.'NULL').OR.(OSTAT.EQ.'recovery')).AND.
X(MR.EQ.105.0))THEN
TREIR=TREI
CTREIR=CTRE
MR=OMR
GOTO 100
ENDIF
200 CONTINUE
C DISPLAY ENVIRONMENTAL CONDITIONS, EQUILIBRIUM VALUES AND TABULATE FOR
C OUTPUT
C
CALL TAB
C
MAKE APPROPRIATE EXPOSURE
C
IF(CSTAT.EQ.‘rest’)GOTO 500
IF(CSTAT.EQ.‘work’)GOTO 600
IF(CSTAT.EQ.‘recovery’)GOTO 700
C
************************************************************
C
************************************************************
C
C REST
C
500 CONTINUE
C
INCREMENT TIMERS
C
MTIME=MTIME+ITIME
LTIME=LTIME+ITIME
ATIME=LTIME/60.
C
RECTAL TEMPERATURE RESPONSE TO REST
C
TRE=TREI*CTRE*0.1**(0.4**(ATIME-0.5))
C
OUTPUT RESULTS AND CHECK TIME
C
WRITE(NOUT,800)MTIME,TRE
WRITE(NDAT,800)MTIME,TRE
IF(MTIME.LT.JTIME)GOTO 500
CALL WAIT(2)
C
SAVE FOR WORK
C
TREIR=TREI
CTRER=CTRE
TREI=TRE
GOTO 10
C
************************************************************
C
************************************************************
C
C WORK
C
600 CONTINUE
C
INITIAL LAG TIME (HRS)
C
TD=58./MR
C
WORK TIME CONSTANT
C
TC=0.5+1.5*EXP(-0.3*CTRE)
650 CONTINUE
C
INCREMENT TIMERS
C
MTIME=MTIME+ITIME
HTIME=MTIME/60.
LTIME=LTIME+ITIME
ATIME=LTIME/60.
C
DURING O<= T < TD RECTAL TEMPERATURE RESPONSE TO WORK FOLLOWS REST
C RESPONSE, EXCEPT WHEN WORK DIRECTLY FOLLOWS WORK
C
IF((ATIME.LT.TD).AND.(OSTAT.NE.‘work’) )THEN
  IF(OSTAT.NE.‘rest’)HTIME=ATIME
  TRE=TREIR+CTRER*0.1**(0.4**((HTIME-0.5))
C
AFTER TD<= T RECTAL TEMPERATURE FOLLOWS WORK RESPONSE
C
ELSE
  TRE=TREI+CTR*(1.-EXP(TC*(TD-ATIME)))
ENDIF
C
OUTPUT RESULTS AND CHECK TIME
C
WRITE(NOUT,800)MTIME,TRE
WRITE(NDAT,800)MTIME,TRE
IF(MTIME.LT.JTIME)GOTO 650
CALL WAIT(2)
C
SAVE FOR RECOVERY
C
WTIME=ATIME
FWTIME=ATIME
TREI=WTIME
CTREW=CTR
TREW=TRE
TREI=TRE
GOTO 10
C
**********************************************************************
C
**********************************************************************
C
RECOVERY
C
700 CONTINUE
  FLAG=0
750 CONTINUE
C
INCREMENT TIMERS
C
MTIME=MTIME+ITIME
LTIME=LTIME+ITIME
ATIME=LTIME/60.
WTIME=WTIME+ITIME/60.
C
RECOVERY TIME LAG (HRS)
C
TDRC=0.25*EXP(-0.5*CP)
C
RECOVERY TIME CONSTANT
C
A=1.5*(1.-EXP(-1.5*CP))
C DURING 0 <= T < TDRC RECTAL TEMPERATURE RESPONSE TO RECOVERY FOLLOWS
C HALF WORK PATTERN:
C
IF (ATIME.LT.TDRC) THEN
  TREW = TREIW + CTRREW * (1. - EXP(TC * (TD_WTIME)))
  TCNG = TREW - TREWF
  TRE = TREWF + 0.5 * TCNG
ELSE
C AFTER TIME LAG CALCULATE TREW AT TDRC FOR USE AFTER TDRC
C
IF (FLAG.EQ.0) THEN
  WTIME = FWTIME + TDRC
  FLAG = 1
  TREW = TREIW + CTRREW * (1. - EXP(TC * (TD_WTIME)))
  TCNG = TREW - TREWF
  TREW = TREWF + 0.5 * TCNG
ENDIF
C
C AFTER TDRC TEMPERATURE FOLLOWS RECOVERY RESPONSE
C
TRE = TREW - (TREW - TREFA) * (1. - EXP(A * (TDRC - ATIME)))
ENDIF
C
OUTPUT RESULTS AND CHECK TIME
C
WRITE (NOUT, 800) MTIME, TRE
WRITE (NDAT, 800) MTIME, TRE
IF (MTIME.LT.JTIME) GOTO 750
CALL WAIT(2)
C
SAVE FOR NEXT EXPOSURE
C
TREI = TRE
GOTO 10
C
**********************************************************************
C **********************************************************************
C
800 FORMAT (29X, 14, 7X, F6.2)
1000 CONTINUE
CALL TIDYUP
END
C
SVP AT T, USING ANTOINE'S EQUATION (mmHg)
C
FUNCTION SVP(T)
  SVP = EXP(18.6686 - 4030.183 / (T + 235))
RETURN
END
C
SUBROUTINE TO DISPLAY PROGRAM TITLE
C
SUBROUTINE TITLE
COMMON/UNIT/NIN, NOUT, NDAT
CALL CLEAN
WRITE (NOUT, 10)
SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS

C SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS
C
C SUBROUTINE INPUT
REAL MR,IM
COMMON/CC/TA,V,RH,CLO,FAACL,IM,MR,WK,TREI,NACC,MTIME,TIME,TIME,AD
COMMON/UNIT/NIN,NOUT,NDAT
COMMON/OPTGG/BEGIN,BEGIN1,OPT,CSTAT
CHARACTER*1 BEGIN, BEGIN1, OPT, CSTAT*8
CALL CLEAN
WRITE(NOUT,100)
100 FORMAT(/' Air Temperature	 (C)	 :', $)
READ(NIN,*)TA
WRITE(NOUT,300)
300 FORMAT(/' Air Speed	 (m/s)	 :', $)
READ(NIN,*)V
WRITE(NOUT,400)
400 FORMAT(/' Relative Humidity	 (fraction) (ND)	 :', $)
READ(NIN,*)RH
WRITE(NOUT,500)
500 FORMAT(/' Intrinsic Clothing Insulation	 (clo)	 :', $)
READ(NIN,*)CLO
WRITE(NOUT,600)
600 FORMAT(/' Clothing Area Factor (fcl) (0 if unknown) (ND)	 :', $)
READ(NIN,*)FAACL
WRITE(NOUT,700)
700 FORMAT(/' Clothing Permeability Index (Woodcock Im) (ND)	 :', $)
READ(NIN,*)IM
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0.)CLO=1.0E-8
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
IF(FAACL.EQ.0.)FAACL=1.+0.31*CLO
IF(CLO.LT.0.01)FAACL=1.
CALL CLEAN
WRITE(NOUT,800)
800 FORMAT(/' Total Metabolic Rate	 (W/m2)	 :', $)
READ(NIN,*)MR
WRITE(NOUT,900)
900 FORMAT(/' External Work Accomplished	 (W/m2)	 :', $)
READ(NIN,*)WK
C
C CONVERT FROM W/m2 TO W

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C
WT=70.0
HT=1.7
AD=0.202*(WT**0.425)*(HT**0.725)
MR=MR*AD
WK=WK*AD
IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
WRITE(NOUT,1000)
1000 FORMAT('/' Initial Core Temperature (0 for 36.8) (C) : '$)
READ(NIN,*)TREI
IF(TREI.EQ.0.)TREI=36.8
WRITE(NOUT,1100)
1100 FORMAT('/' Number of Days Acclimatization (days) : '$)
READ(NIN,*)NACC
END IF
WRITE(NOUT,1200)
1200 FORMAT('/' Output Time Interval (mins) : '$)
READ(NIN,*)ITIME
WRITE(NOUT,1300)
1300 FORMAT('/' Exposure Time To These Conditions (hours) : '$)
READ(NIN,*)TTIME
RETURN
END
C
C SUBROUTINE TO ENABLE ENVIRONMENTAL CONDITIONS TO BE REDEFINED IN
C ORDER TO CONTINUE AN EXPOSURE.
C
SUBROUTINE INPUT2
REAL MR,IM
COMMON/CC/TA, V,RH,CLO, FACL, IM, MR, WK, TREI, NACC, MTIME, ITIME, TTIME, AD
COMMON/UNIT/NIN, NOUT, NDAT
100 CONTINUE
C
C CLEAR SCREEN
C
CALL CLEAN
C
C DISPLAY MENU
C
WRITE(NOUT,200)TA, V, RH, CLO, FACL, IM, MR, AD, WK, AD, ITIME
200 FORMAT('X3X'Change: 1	 Air Temperature  
X'F6.2' (C)'/
X12X'2	 Air Speed  
X'F6.2  
X' (m/s)'/
X12X'3	 Relative Humidity  
X'F6.2  
X' (ND)'/
X12X'4	 Intrinsic Clothing Insulation  
X'F6.2  
X' (clo)'/
X12X'4	 Clothing Area Factor (fcl)  
X'F6.2  
X' (ND)'/
X12X'4	 Clothing Permeability Index (Woodcock Im)  
X'F6.2  
X' (ND)'/
X12X'5	 Total Metabolic Rate  
X'F6.2  
X' (W/m2)'/
X12X'5	 External Work Accomplished  
X'F6.2  
X' (W/m2)'/
X12X'6	 Output Time Interval  
X'I6  
X' (mins)'/

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X3X'Enter Change Required (RETURN when complete) : '$)

C
C DETERMINE RESPONSE
C
READ(NIN,300)ICHNG
300 FORMAT(I1)
CALL CLEAN
IF(ICHNG.EQ.7)CALL INPUT
IF(ICHNG.EQ.7)GOTO 9999
GOTO (400,500,600,700,800,900)ICHNG
GOTO 9998

C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400 WRITE(NOUT,1400)
1400 FORMAT(/' Air Temperature	 (C) : '$)
READ(NIN,*)TA
GOTO 100
500 WRITE(NOUT,1500)
1500 FORMAT(/' Air Speed (m/s) : '$)
READ(NIN,*)V
GOTO 100
600 WRITE(NOUT,1600)
1600 FORMAT(/' Relative Humidity (fraction) (ND) : '$)
READ(NIN,*)RH
GOTO 100
700 WRITE(NOUT,1700)
1700 FORMAT(/' Intrinsic Clothing Insulation (clo) : '$)
READ(NIN,*)CLO
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
IF(CLO.EQ.0)CLO=1.0E-8
WRITE(NOUT,1725)
1725 FORMAT(/' Clothing Area Factor (fcl) (0 if unknown) (ND) : '$)
READ(NIN,*)FACL
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
IF(FACL.EQ.0)FACL=1.+0.31*CLO
IF(CLO.LT.0.01)FACL=1.
WRITE(NOUT,1750)
1750 FORMAT(/' Clothing Permeability Index (Woodcock Im) (ND) : '$)
READ(NIN,*)IM
GOTO 100
800 WRITE(NOUT,1800)
1800 FORMAT(/' Total Metabolic Rate (W/m2) : '$)
READ(NIN,*)MR
WRITE(NOUT,1850)
1850 FORMAT(/' External Work Accomplished (W/m2) : '$)
READ(NIN,*)WK
C
C CONVERT FROM W/m2 TO W
C
MR=MR*AD
WK=WK*AD
GOTO 100
900 WRITE(NOUT,1900)
1900 FORMAT(/' Output Time Interval (mins) : '$)
READ(NIN,*)ITIME
GOTO 100
9998 CALL CLEAN
WRITE(NOUT,65)
65 FORMAT(/' Exposure Time To These Conditions (hours) : '$)
READ(NIN,*)TTIME
9999 CONTINUE
RETURN
END
C
C SUBROUTINE TO DISPLAY ENVIRONMENTAL CONDITIONS AND TABULATE
C FOR RESULTS.
C
SUBROUTINE TAB
REAL IMCLO,IMCLOE,MRNET,MR,IM
COMMON/GG/TA,V,RH,CLO,FACL,IM,MR,WK,TREI,NACC, MTIME, ITIME, TTIME, AD
COMMON/TABS/VE,CLOEG,IMCLOE,ERC,EREQ,EMAX,PWET,TREF,TREFA,CP
COMMON/UNIT/NIN,NOUT,NDAT
COMMON/OPTGG/BEGIN,BEGIN1,OPT,CSTAT
COMMON/ADDIT/CLOT,IMV
REAL IMV
CHARACTER*1 BEGIN,BEGIN1,OPT,CSTAT*8
C
C DISPLAY RESULTS
C
CALL CLEAN
WRITE(NOUT,100)TA,V,RH,CLO,FACL,IM,MR/AD,WK/AD,NACC
WRITE(NDAT,100)TA,V,RH,CLO,FACL,IM,MR/AD,WK/AD,NACC
100 FORMAT(/i12x'Air Temperature = F7.2' (C)/
   x12x'Air Speed = F7.2' (m/s)/
   x12x'Relative Humidity = F7.2' (ND)/
   x12x'Intrinsic Clothing Insulation = F7.2' (clo)/
   x12x'Clothing Area Factor = F7.2' (ND)/
   x12x'Clothing Permeability Index (Woodcock Im) = F7.2' (ND)/
   x12x'Initial Metabolic Rate = F7.2' (W/m2)/
   x12x'Work Rate Accomplished = F7.2' (W/m2)/
   x12x'Number of Days Acclimatization = '17' (days)/
C
C PAUSE
C
CALL WAIT(9)
WRITE(NDAT,200)
200 FORMAT(/i/
   x11x'Effective Air Speed = 'F6.2' (m/s)/
   x11x'Estimated IT at v=1.0 m/s = 'F6.2' (clo)/
   x11x'Estimated Im at v=1.0 m/s = 'F6.2' (ND)/
   x11x'Effective Clothing Insulation (not Icle) = 'F6.2' (clo)/
   x11x'Effective Permeability Index Ratio (im/It) = 'F6.2' (1/clo)/
   x11x'Dry Heat Transfer (C+R) = 'F6.2' (W/m2)/
   x11x'Required Evaporative Cooling = 'F6.2' (W/m2)/
   x11x'Maximum Evaporative Capacity of Env. = 'F6.2' (W/m2)/
X11X'Skin Wettedness = 'F6.2' (ND)'
X11X'Final Equilibrium Temp. (accl) = 'F6.2' (C)'
X11X'Final Equilibrium Temp. (part accl) = 'F6.2' (C)'
X11X'Cooling Power of Environment = 'F6.2' (?)'"

CALL WAIT(4)

C
C TABULATE FOR OUTPUT
C
CALL CLEAN
WRITE(NOUT,400)CSTAT
WRITE(NDAT,400)CSTAT
IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
WRITE(NOUT,800)MTIME,TREI
WRITE(NDAT,800)MTIME,TREI
END IF

400 FORMAT(!!!
X29X'Time	 Tre: ',A8!
X27X'**************************')
800 FORMAT(29X,I4,7X,F6.2)
RETURN
END
LUTTRE MODEL EXAMPLE PREDICTIONS
LUT Model of Rectal Temperature Response (V1.1)  
(adapted from Givoni and Goldman Model)

Roger Haslam  
Department of Human Sciences  
Loughborough University of Technology  
(This model is not valid for cold exposures)

New Exposure  
**************

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Air Temperature</td>
<td>40.00°C</td>
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<tr>
<td>Air Speed</td>
<td>0.10 m/s</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>0.60 (ND)</td>
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<tr>
<td>Intrinsic Clothing Insulation</td>
<td>1.00 (clo)</td>
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<tr>
<td>Clothing Area Factor</td>
<td>1.31 (ND)</td>
</tr>
<tr>
<td>Clothing Permeability Index (Woodcock Im)</td>
<td>0.38 (ND)</td>
</tr>
<tr>
<td>Initial Metabolic Rate</td>
<td>100.00 W/m²</td>
</tr>
<tr>
<td>Work Rate Accomplished</td>
<td>0.00 W/m²</td>
</tr>
<tr>
<td>Number of Days Acclimatization</td>
<td>0 (days)</td>
</tr>
</tbody>
</table>

Effective Air Speed = 0.40 (m/s)  
Estimated IT at v=1.0 m/s = 1.37 (clo)  
Estimated Im at v=1.0 m/s = 0.39 (ND)  
Effective Clothing Insulation (not Icle) = 1.73 (clo)  
Effective Permeability Index Ratio (im/It) = 0.22 (1/clo)  
Dry Heat Transfer (C+R) = -14.95 (W/m²)  
Required Evaporative Cooling = 114.95 (W/m²)  
Maximum Evaporative Capacity of Env. = 36.19 (W/m²)  
Skin Wettedness = 1.00 (ND)  
Final Equilibrium Temp. (accl) = 39.09 (°C)  
Final Equilibrium Temp. (part accl) = 39.44 (°C)  
Cooling Power of Environment = -1.29 (?)
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<thead>
<tr>
<th>Time</th>
<th>Tre: work</th>
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<tr>
<td>60</td>
<td>38.25</td>
</tr>
</tbody>
</table>
LUTISO MODEL PROGRAM LISTING
LUT ADAPTATION OF ISO/DIS 7933 (1987) HOT ENVIRONMENTS - ANALYTICAL
DETERMINATION OF THERMAL STRESS USING CALCULATION OF REQUIRED SWEAT RATE (V1.0)

(ADAPTED FROM FORTRAN TRANSLATION OF ORIGINAL BASIC PROGRAM)

DIMENSION HEADER(4), HMAX(4), SMAXR(4), SMAXW(4), DMAX(4), X, WMAXD(4), WMAXW(4)
COMMON/LUTISO/TA, TR, V, RH, CLO, FACL, IM, MR, WK
COMMON/LCOEFF/VEFF, PA, TSK, PSK, MH, CHC, CHR, TCL, IECL, RT, C, R, EREQ, XEMAX, WREQ
REAL MR, MH, MRT, IM, LR, LRM, ITIM, IECL

COMMON BLOCKS UNIT AND SAVEF ARE INITIALIZED IN LIBRARY
SUBROUTINE SETUP

COMMON/UNIT/NIN, NOUT, NDAT
COMMON/SAVEF/GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
CHARACTER*20 GOLD, GAGGE, ISO, STOLW, LUTTRE, LUT2, LUTISO, LUT25A, LUT25B
CHARACTER*35 HEADER, CMSG*28, DMSG*30, CCNG*3

DEFINE CHARACTER VARIABLES FOR MENU SUB-SECTION

CHARACTER*1 BEGIN, BEGIN1, TWO, TWO1, QUIT, QUIT1, OPT
BEGIN=’B’
BEGIN1=’b’
TWO=’T’
TWO1=’t’
QUIT=’Q’
QUIT1=’q’

OPEN RESULTS OUTPUT FILE

CALL SETUP
OPEN(UNIT=NDAT, FILE=LUTISO, STATUS=’UNKNOWN’)

DISPLAY PROGRAM TITLE

CALL TITLE

*****************************************************
LUT Adaptation of ISO/DIS 7933 (1987)
Required Sweat Rate Program
Analytical Determination of Thermal Stress (V1.0)

PROGRAM SUB-SECTION TO PROVIDE MENU CONTROL FOR MAIN PROGRAM

CLEAR SCREEN

10 CONTINUE
CALL CLEAN

DISPLAY MENU

WRITE(NOUT,20)
FORMAT(/X14X'*****************************************************'/
X16X' LUT Adaptation of ISO/DIS 7933 (1987)'/
X16X' Required Sweat Rate Program'/
X16X'Analytical Determination of Thermal Stress (V1.0)'/
X14X'*****************************************************'/

A-70
X///23X'B  Begin Single Exposure\///
X23X'T  Begin Two Successive Exposures\///
X23X'Q  Quit\///
X15X'Results will be copied to a file called LUTISO.DAT\///
X8X'Enter Option: 'S)

C
C DETERMINE RESPONSE
C
30     FORMAT(A)
       IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
          CALL CLEAN
          CALL INPUT
          GOTO 50
       ENDIF
       IF((OPT.EQ.TWO).OR.(OPT.EQ.TWO1))THEN
          CALL CLEAN
          WRITE(NOUT,35)
          35          FORMAT( ' Sequence 1: ')
                     CALL INPUT
                     WRITE(NOUT,40)
                     40          FORMAT(!' Duration of Sequence 1	 (mins) : '
          READ(NIN,*)ITIME
          NSEQ=1
          MRT=0.0
          EREQT=0.0
          EMX=0.0
          ITIME=0
          GOTO 50
       ENDIF
       IF((OPT.EQ.QUIT).OR.(OPT.EQ.QUIT1))GOTO 9999

C
C IF RESPONSE IS NOT RECOGNIZED, INFORM AND REDISPLAY MENU
C
 CALL INFERR
 GOTO 10
C
C END OF MENU SUB-SECTION
C
C **********************************************
C
C TO HERE FOR FIRST EXPOSURE
C
50     CONTINUE
C
C PRINT HEADER FOR DATA FILE
C
55     WRITE(NDAT,55)
      55          FORMAT( //////////
                  X34X'New Exposure'/
                  X33X'***************'/)
                 IF((OPT.EQ.TWO).OR.(OPT.EQ.TWO1))WRITE(NDAT,35)
                 GOTO 80

C
C TO HERE FOR SECOND OF TWO SUCCESSIVE EXPOSURES
C
60     CONTINUE
       CALL CLEAN

A-71
WRITE(NOUT,65)
WRITE(NDAT,65)
65 FORMAT(’ Sequence 2: ’)
CALL INPUT
WRITE(NOUT,70)
70 FORMAT(/' Duration of Sequence 2 (mins) : ')$)
READ(NIN,*)ITIME
NSEQ=2
C
C*****************************************************************************
C
80 CONTINUE
C
COEFFICIENTS AND THERMAL EXCHANGES
C
ASSIGN CONSTANTS
C
TSK=36.0
ARADU=0.725
C
PARTIAL VAPOUR PRESSURE OF WATER IN AIR
C
PA=RH*SVP(TA)
C
PARTIAL VAPOUR PRESSURE AT SKIN SURFACE
C
PSK=SVP(TSK)
C
EFFECTIVE AIR MOVEMENT:
C
VACT=0.0052*(MR_58)
IF(VACT.GT.0.7)VACT=0.7
VEFF=V+VACT
C
METABOLIC HEAT PRODUCTION:
C
MH=MR-VK
C
CONVECTIVE HEAT TRANSFER COEFFICIENT:
C
CHCA=3.5+5.2*VEFF
IF(VEFF.GT.1.0)CHCA=8.7*VEFF**0.6
CHC=2.38*ABS(TSK-TA)**0.25
IF(CHCA.GT.CHC)CHC=CHCA
C
LINEAR RADIATION HEAT TRANSFER COEFFICIENT AND CLOTHING SURFACE
C TEMPERATURE (ITERATION)
C
84 TCL0LD=TCL
CHR=4.0E-08*5.67*.97*ARADU*((TR+TCL)/2.0+273.0)**3.0
TCL=(1./((CLO*0.155))*TSK+FACL*(CHC*TA+CHR*TR))/
X((1./((CLO*0.155))+FACL*(CHC+CHR))
IF(ABS(TCL-TCL0LD).GT.0.01)GOTO 84
C
RESISTANCE OF CLOTHING TO THE TRANSFER OF WATER VAPOUR:
C IECL CALCULATED FROM IM, HASLAM AND PARSONS (1988). HEAT TRANSFER
C COEFFICIENTS ARE THOSE ESTIMATED TO HAVE PREVAILED WHEN IM WAS
C MEASURED, i.e. Ta = Tr = 24 C, V = 0.1 m/s, Tsk = 33 C, Ia = 0.71 clo
C
A-72
TAIM=24.0
TRIM=24.0
TSKIM=33.0
C
C CHRIM CALCULATED BY SUBTRACTING CHRIM (NUDE) FROM Ia
C
CHCIM=4.52
C
C CALCULATE CHRIM AND TCLIM
C
C ITERATIVE LOOP TO CALCULATE CLOTHING TEMPERATURE (TCLIM) AND LINEAR
C RADIATION COEFFICIENT (CHRIM)
C
TCLIM=0.0
85
TCLOLD=TCLIM
CHRIM=4.*5.67E-8*(((TCLIM+TRIM)/2.+273.2)**3)*0.725
TCLIM=((1./(CLO*0.155))*TSKIM+FACL*(CHCIM*TAIM+CHRIM+TRIM))/
X((1./(CLO*0.155))+FACL*(CHCIM+CHRIM))
IF(ABS(TCLIM-TCLOLD).GT.0.01)GOTO 85
C
C CALCULATE LR AT TCLIM
C
LRIM=15.1512*(TCLIM+273.15)/273.15
C
C CALCULATE ITIM (m2.C/W)
C
ITIM=CLO*0.155+1./((CHCIM+CHRIM)*FACL)
C
C CALCULATE Iecl (m2.kPa/W)
C
IECL=ITIM/(LRIM*IM)-1./(FACL*LRIM*CHCIM)
C
C CALCULATE LR AT TCL
C
LR=15.1512*(TCL+273.15)/273.15
C
C TOTAL RESISTANCE OF CLOTHING AND ENVIRONMENT TO EVAPORATIVE HEAT
C TRANSFER:
C
RT=IECL+1./(FACL*LR*CHC)
C
C CONVECTIVE HEAT TRANSFER:
C
C=FACL*CHC*(TCL-TA)
C
C RADIATION HEAT TRANSFER:
C
R=FACL*CHR*(TCL-TR)
C
C REQUIRED EVAPORATIVE COOLING:
C
EREQ=MH-C-R
C
C MAXIMUM EVAPORATIVE CAPACITY OF ENVIRONMENT:
C
EMAX=(PSK-PA)/RT
C
C REQUIRED SKIN WETTEDNESS:
C
A-73
WREQ=EREQ/EMAX
IF(EMAX.LE.0.0)WREQ=2.0
IF(WREQ.GT.2.0)WREQ=2.0

C OUTPUT VALUES AND TABULATE FOR OUTPUT
C
CALL TAB
90 CONTINUE
CALL CLEAN
IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
WRITE(NOUT,95)
WRITE(NDAT,95)
95 FORMAT(' Interpretation, Single Exposure: '/)
ELSEIF((OPT.EQ.TWO).OR.(OPT.EQ.TWO1))THEN
IF((NSEQ.EQ.1).OR.(NSEQ.EQ.2))THEN
WRITE(NOUT,100)NSEQ,ITIME
WRITE(NDAT,100)NSEQ,ITIME
100 FORMAT(' Interpretation, Sequence: ',I1,', (Duration: ',I3
X' mins):'/)
ELSE
WRITE(NDAT,105)
105 FORMAT(/) /)
WRITE(NOUT,110)
WRITE(NDAT,110)
110 FORMAT(' Interpretation, Time Weighted Averages of Ereq and Emax: '/)
ENDIF
ENDIF

C INITIALIZE STRING VARIABLE DMSG
C
DMSG=' '

C **********************************************************************
C C INTERPRETATION
C C DEFINE HEADERS
C HEADER(1)="Warning: Non Acclimatized Subject"
HEADER(2)="Danger: Non Acclimatized Subject"
HEADER(3)="Warning: Acclimatized Subject"
HEADER(4)="Danger: Acclimatized Subject"
C C LIMITING VALUES OF CRITERIA
C C HEAT STORAGE Hmax (W.h/m2)
C HMAX(1)=50.0
HMAX(2)=60.0
HMAX(3)=50.0
HMAX(4)=60.0

C C MAXIMUM SWEAT RATE - RESTING Smax (W/m2)
C SMAXR(1)=100.0
SMAXR(2)=150.0
SMAXR(3)=200.0
SMAXR(4)=300.0

A-74
C MAXIMUM SWEAT RATE AT WORK (W/m²)
C
SMAXW(1)=200.0
SMAXW(2)=250.0
SMAXW(3)=300.0
SMAXW(4)=400.0
C
C MAXIMUM SKIN WETTEDNESS Wmax1 - DANGER NON ACCL AND ACCL SUBJECT (ND)
C
WMAXD(1)=0.85
WMAXD(2)=0.85
WMAXD(3)=1.0
WMAXD(4)=1.0
C
C MAXIMUM SKIN WETTEDNESS Wmax2 - WARNING NON ACCL AND ACCL SUBJECT (ND)
C
WMAXW(1)=0.5
WMAXW(2)=0.5
WMAXW(3)=0.85
WMAXW(4)=0.85
C
C MAXIMUM DEHYDRATION Dmax (W.h/m²)
C
DMAX(1)=1000.0
DMAX(2)=1250.0
DMAX(3)=1500.0
DMAX(4)=2000.0
C
C HEAT STORAGE RATE AS A FUNCTION OF SKIN WETTEDNESS (W/m²)
C
STORE=50.0
C
C MAXIMUM THERMAL FLUX (W/m²)
C
FLUX=2000.0
C
C Smax DEPENDS ON METABOLIC RATE
C
DO 200 J=1,4
SMA(J)=SMA(J)
IF(MR.GT.80.0)SMA(J)=SMA(J)
200 CONTINUE
C
C ANALYSE FOR ACCL AND NON ACCL SUBJECTS FOR DANGER AND WARNING
C
DO 300 J=4,1,-1
C
C PRINT HEADER
C
WRITE(NOUT,400)HEADER(J)
WRITE(NDAT,400)HEADER(J)
400 FORMAT(1X,A35/)
C
C WHEN CONDENSATION OCCURS, Ep=Emax, Sp=Smax, Wp=Wmax
C
IF(EMAX.LT.0.0)THEN
EP=EMAX
SP=SMA(J)
C IF Emax IS LESS THAN HALF Smax (V. HUMID ENV.) Wo=1.0
C
C IF((EMAX/SMAX(J)).LT.0.5)THEN
   W0=1.0
   GOTO 600
ENDIF
C
C FOR LESS HUMID ENVIRONMENTS Wo IS CALCULATED BY ITERATION
C
C CHOOSE STRUCTURE OF EQUATION TO ENSURE CONVERGENCE
C
C W2=1.0
700 IF((EMAX/SMAX(J)).GT.1.0)THEN
    W0=(1.0-0.5*EXP(-6.6*(1.0-W2)))*SMAX(J)/EMAX
ELSE
    W0=ALOG((1.0-W2*EMAX/SMAX(J))*2)/6.6+1
ENDIF
IF(ABS(W2-W0).GT.5.0E-04)THEN
   W2=(W2+W0)/2
   GOTO 700
ENDIF
C
C Wp IS THE SMALLEST OF Wreq, Wmax, Wo
C
WP=WREQ
IF(WP.GT.WMAXD(J))WP=WMAXD(J)
IF(WP.GT.W0)WP=W0
EP=WP*EMAX
IF(WP.EQ.WREQ)EP=EREQ
C
C IF Ep IS LESS THAN Ereq, Sp=Smax, OTHERWISE Sp IS CALCULATED FROM
C Ep, ro AND Wp
C
C IF(EP.LT.EREQ)THEN
   SP=SMAX(J)
ELSE
   SP=EP/(1.0-EXP(6.6*(WP-1.0))/2)
ENDIF
C
C PRINT PREDICTED VALUES
C
500 WRITE(NOUT,800)WP,EP,SP,SP/0.68
WRITE(NDAT,800)WP,EP,SP,SP/0.68
800 FORMAT(
   X' Predicted Skin Wettedness : Wp = 'F7.2' (ND)'!,
   X' Predicted Evaporation Rate : Ep = 'F7.2' (W/m2)'!,
   X' Predicted Sweat Rate	: Sp = 'F7.2' (W/m2) = 'F7.2
   X' (g/h.m2)'!)
C
C DETERMINE ALLOWABLE EXPOSURE TIMES (DLE)
C
DLE1=480.0
DLE2=480.0
DLE3=480.0
C DLE1: REQUIRED EVAPORATION RATE IS NOT ACHIEVABLE:
C IF(EP.LT.EREQ)DLE1=60.0*HMAX(J)/(EREQ-EP)
C
C DLE2: REQUIRED SKIN WETTEDNESS EXCESSIVE (IE. > THAN WARNING LEVELS):
C IF(WREQ.GT.WMAXW(J))DLE2=60.0*HMAX(J)/STORE/(WREQ-WMAXW(J))
C
C DLE3: REQUIRED SWEAT RATE CAUSES EXCESSIVE DEHYDRATION:
C IF(SP.GT.(DMAX(J)/8.0))DLE3=60.0*DMAX(J)/SP
C
C IF THESE CRITERIA ARE MET THE EXPOSURE IS OF UNLIMITED DURATION
C IF((DLE1.GE.480.0).AND.(DLE2.GE.480.0).AND.(DLE3.GE.480.0))THEN
DLE=480.0
CMSG='Unlimited Duration'
GOTO 1000
ENDIF
C
C OTHERWISE DLE IS THE SHORTEST OF DLE1, DLE2 AND DLE3
C IF DLE1 IS THE SHORTEST DLE THEN:
C IF((DLE1.LE.DLE2).AND.(DLE1.LE.DLE3))THEN
C IF DLE1 IS LESS THAN 2 MINS HIGH LEVELS OF THERMAL FLUX EXIST
C CALCULATE Ereq FOR NUDE SKIN TO PREVENT BURNS
C IF(DLE1.LE.2.0)THEN
DLE=DLE1
IF(CLO.GT.0.)THEN
DMSG='Restart Calculation With Icl=0'
GOTO 1000
ENDIF
IF((EREQ-EMAX).GE.FLUX)DMSG='Prohibit Any Exposure'
ENDIF
C IF DLE1 IS LESS THAN 30 MINUTES CORRECT FOR THE DELAY IN THE ONSET
C OF SWEATING
C IF(DLE1.LT.30.0)THEN
C IF DLE1 IS BETWEEN 0 AND 10 MINS SET Ep TO 0
C IF(EP.GT.0.0)THEN
IF(DLE1.LT.10.0)THEN
EP=0.0
DMSG='(Ep Taken As 0)'
ELSE
EPO=EP
EP=EP*(DLE1-10.0)/20.0
ICNG=(EPO-EP)/EPO*100.0
ENDIF
ENDIF

C CONVERT FROM INTEGER TO CHARACTER FOR DMSG BY WRITING TO FILE AND
C READING BACK
C
OPEN(UNIT=11, STATUS='SCRATCH')
WRITE(11,1010)ICNG
1010 FORMAT(I3)
REWIND(11)
READ(11,1020)CCNG
1020 FORMAT(A3)
CLOSE(A3)
DMSG='(Ep Reduced By *** %)'
DMSG(16:18)=CCNG
ENDIF
ENDIF
ENDIF
C
C REC LULATE DLE1
C
DLE=(60.0*HMAX(J))/(EREQ-EP)
CMSG='Body Temperature Increase'
C
C IF DLE2 IS THE SHORTEST DLE THEN:
C
ELSE IF((DLE1.GT.DLE2).AND.(DLE2.LE.DLE3))THEN
DLE=DLE2
CMSG='Excessive Wettedness'
C
C IF DLE3 IS THE SHORTEST DLE THEN:
C
ELSE
DLE=DLE3
CMSG='Excessive Dehydration'
ENDIF
C
C PRINT MESSAGES AND DLE
C
1000 CONTINUE
IDLE=DLE
IHR=DLE/60
IMIN=DLE-IHR*60
WRITE(NOUT,1100)CMSG,IDLE,DMSG,IHR,IMIN
WRITE(NDAT,1100)CMSG,IDLE,DMSG,IHR,IMIN
1100 FORMAT(1X,A28,2X,'DLE = ',13,1X,'ruins' ,2X,A30/
X35X,=' ',2X,1I1,1X,'h',1X,13,1X,'mins'/)
IF(J.EQ.3)THEN
CALL WAIT(1)
CALL CLEAN
ELSEIF(J.EQ.1)THEN
CALL WAIT(3)
CALL CLEAN
ENDIF
WRITE(NDAT,1150)
1150 FORMAT(/)
300 CONTINUE
C
C FOR TWO SUCCESSIVE EXPOSURES, CALCULATE TIME WEIGHTED AVERAGES OF Mr,
C Ereq, Emax AND Wreq
C
IF((OPT.EQ.TWO).OR.(OPT.EQ.TWO1))THEN
MRT=MRT+MR*ITIME
A-78
EREQT = EREQ + EREQ * ITIME
EMAXT = EMAX + EMAX * ITIME
ITIMET = ITIMET + ITIME
IF (NSEQ .EQ. 1) THEN
   GOTO 60
ELSEIF (NSEQ .EQ. 2) THEN
   MR = MRT / ITIMET
   EREQ = EREQ / ITIMET
   EMAX = EMAX / ITIMET
   IF (EMAX .GE. 0.0) WRITE(WREQ = 2.0
   WREQ = EREQ / EMAX
   IF (WREQ .GT. 2.0) WRITE(WREQ = 2.0
   CALL CLEAN
   WRITE(NOUT, 1200) MR, EREQ, EMAX, WREQ
   WRITE(NDAT, 1200) MR, EREQ, EMAX, WREQ
   1200 FORMAT(' Time Weighted Averages: '//
             ' Metabolic Rate : Mr = ' F7.2 ' (W/
             ' Required Evaporative Cooling : Ereq = ' F7.2 ' (W/
             ' Maximum Evaporative Capacity of Environment: Emax = ' F7.2 ' (W/
             ' Required Skin Wettedness : Wreq = ' F7.2 ' (ND
               CALL WAIT(13)
   NSEQ = 3
   GOTO 90
ELSEIF (NSEQ .EQ. 3) THEN
   GOTO 10
ENDIF
ENDIF
C
C PRINT TIME WEIGHTED VALUES
C
   CALL CLEAN
   WRITE(NOUT, 1200) MR, EREQ, EMAX, WREQ
   WRITE(NDAT, 1200) MR, EREQ, EMAX, WREQ
   1200 FORMAT(' Time Weighted Averages: '//
             ' Metabolic Rate : Mr = ' F7.2 ' (W/
             ' Required Evaporative Cooling : Ereq = ' F7.2 ' (W/
             ' Maximum Evaporative Capacity of Environment: Emax = ' F7.2 ' (W/
             ' Required Skin Wettedness : Wreq = ' F7.2 ' (ND
               CALL WAIT(13)
   NSEQ = 3
   GOTO 90
ELSEIF (NSEQ .EQ. 3) THEN
   GOTO 10
ENDIF
ENDIF
C
C RETURN TO MENU
C
   GOTO 10
C
C **********************************************************************
C
9999 CONTINUE
   CALL TIDYUP
END
C
C SVP AT T, USING ANTOINE'S EQUATION (KPa)
C
   FUNCTION SVP(T)
   SVP = 0.133322 * EXP(18.6686 - 4030.183/(T + 235))
   RETURN
END
C
C SUBROUTINE TO DISPLAY PROGRAM TITLE
C
   SUBROUTINE TITLE
   COMMON/UNIT/NIN,NOUT,NDAT
   CALL CLEAN
   WRITE(NOUT,10)
   WRITE(NDAT,10)
CALL WAIT(6)
RETURN
END

C
SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS

C SUBROUTINE INPUT
REAL MR, MH, MRT, IM, LR, LRIM, ITIM, IECL
COMMON/LUTISO/TA, TR, V, RH, CLO, FACL, IM, MR, WK
COMMON/LCOEFF/VEFF, PA, TSK, PSK, MH, CHC, CHR, TCL, IECL, RT, C, R, EREQ,
XENAX, WREQ
COMMON/UNIT/NIN, NOUT, NDAT
WRITE(NOUT,100)
100 FORMAT(/' Air Temperature	 (C)
READ(NIN,*)TA
WRITE(NOUT,200)
200 FORMAT(/' Mean Radiant Temperature	 (C)
READ(NIN,*)TR
WRITE(NOUT,300)
300 FORMAT(/' Air Speed	 (m/s)
READ(NIN,*)V
WRITE(NOUT,400)
400 FORMAT(/' Relative Humidity	 (fraction)
READ(NIN,*)RH
WRITE(NOUT,500)
500 FORMAT(/' Intrinsic Clothing Insulation	 (clo)
READ(NIN,*)CLO
WRITE(NOUT,600)
600 FORMAT(/' Clothing Area Factor (fcl) (0 if unknown)
READ(NIN,*)FACL
WRITE(NOUT,700)
700 FORMAT(/' Clothing Permeability Index (Woodcock Im)
READ(NIN,*)IM

C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C IF(CLO.EQ.0.)CLO=1.0E-8

C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C IF(FACL.EQ.0.)FACL=1.+0.31*CLO
IF(CLO.LT.0.01)FACL=1.
CALL CLEAN
WRITE(NOUT,800)
800 FORMAT(/' Total Metabolic Rate	 (W/m2)
READ(NIN,*)MR
WRITE(NOUT,900)
900 FORMAT(/' External Work Accomplished	 (W/m2)
READ(NIN,*)WK
C SUBROUTINE TO DISPLAY ENVIRONMENTAL CONDITIONS AND TABULATE RESULTS.

C SUBROUTINE TAB
REAL MR,MH,MRT,IM,LR,LRIM,ITIM,IECL
COMMON/LUTISO/TA,TR,V,RH,CLO,FACL,IM,MR,WK
COMMON/LCOEFF/VEFF,PA,TSK,PSK,MH,CHC,CHR,TCL,IECL,RT,C,R,EREQ,
XEMAX,WREQ
COMMON/UNIT/NIN,NOUT,NDAT

RETURN
END

C DISPLAY RESULTS

CALL CLEAN
WRITE(NOUT, 100)TA,TR,V,RH,CLO,FACL,IM,MR,WK
WRITE(NDAT, 100)TA,TR,V,RH,CLO,FACL,IM,MR,WK

100 FORMAT(//
      X12X'Air Temperature  ','F7.2' (C)'/
      X12X'Mean Radiant Temperature ','F7.2' (C)'/
      X12X'Air Speed  ','F7.2' (m/s)'/
      X12X'Relative Humidity ','F7.2' (ND)'/
      X12X'Intrinsic Clothing Insulation ','F7.2' (clo)'/
      X12X'Clothing Area Factor ','F7.2' (ND)'/
      X12X'Clothing Permeability Index (Woodcock Im) ','F7.2' (ND)'/
      X12X'Initial Metabolic Rate ','F7.2' (W/m2)'/
      X12X'Work Rate Accomplished ','F7.2' (W/m2)' )

C PAUSE

CALL WAIT(9)
CALL CLEAN
WRITE(NDAT, 200)

200 FORMAT(/llI)

C DISPLAY COEFFICIENTS AND THERMAL EXCHANGES

WRITE(NOUT,300)VEFF,PA,TSK,PSK,MH,CHC,CHR,TCL
WRITE(NOUT, 400)IECL,RT,C,R,EREQ,EMAX,WREQ
WRITE(NDAT,300)VEFF,PA,TSK,PSK,MH,CHC,CHR,TCL
WRITE(NDAT,400)IECL,RT,C,R,EREQ,EMAX,WREQ

300 FORMAT(///
      X4X,'Effective Air Movement : Veff = ','F7.2' (m/ 
Xs)'/
      X4X,'Partial Vapour Pressure : Pa = ','F7.2' (kP 
Xa)'/
      X4X,'Mean Skin Temperature : Tsk = ','F7.2' (C) 
X'/
      X4X,'Saturated Vapour Pressure on Skin : Psk = ','F7.2' (kP 
Xa)'/
      X4X,'Metabolic Heat Production : Mh = ','F7.2' (W/ 
Xm2)'/
      X4X,'Convective Heat Transfer Coefficient : Hc = ','F7.2' (W/ 
Xm2.C)'/
      X4X,'Linear Radiation Heat Transfer Coefficient : Hr = ','F7.2' (W/ 
Xm2.C)'/
      X4X,'Mean Clothing Surface Temperature : Tcl = ','F7.2' (C) 
X')
400 FORMAT(
    X4X,'Intrinsic Evaporative Clothing Resistance : Iecl = 'F7.2' (m2 kPa/W)/
    X4X 'Total Evaporative Clothing Resistance : IeT = 'F7.2' (m2 kPa/W)/
    Y4X,'Convective Heat Transfer : C = 'F7.2' (W/m2)/
    Y4X,'Radiation Heat Transfer : R = 'F7.2' (W/m2)/
    X4X 'Required Evaporative Cooling : Ereq = 'F7.2' (W/m2)/
    Y4X,'Maximum Evaporative Capacity of Environment: Emax = 'F7.2' (W/m2)/
    X4X,'Required Skin Wettedness : Wreq = 'F7.2' (ND)
)
    CALL WAIT(3)
    WRITE(NDAT,500)
500 FORMAT(/////)
    RETURN
END
LUTISO MODEL EXAMPLE PREDICTIONS
LUT Adaptation of ISO/DIS 7933 (1987) (V1.0)
Required Sweat Rate Program
Analytical Determination of Thermal Stress

Roger Haslam
Department of Human Sciences
Loughborough University of Technology

New Exposure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>40.00 (C)</td>
</tr>
<tr>
<td>Mean Radiant Temperature</td>
<td>40.00 (C)</td>
</tr>
<tr>
<td>Air Speed</td>
<td>0.10 (m/s)</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>0.60 (ND)</td>
</tr>
<tr>
<td>Intrinsic Clothing Insulation</td>
<td>1.00 (clo)</td>
</tr>
<tr>
<td>Clothing Area Factor</td>
<td>1.31 (ND)</td>
</tr>
<tr>
<td>Clothing Permeability Index (Woodcock Im)</td>
<td>0.38 (ND)</td>
</tr>
<tr>
<td>Initial Metabolic Rate</td>
<td>100.00 (W/m2)</td>
</tr>
<tr>
<td>Work Rate Accomplished</td>
<td>0.00 (W/m2)</td>
</tr>
</tbody>
</table>

Effective Air Movement: \[ V_{eff} = 0.32 \text{ (m/s)} \]
Partial Vapour Pressure: \[ P_a = 4.43 \text{ (kPa)} \]
Mean Skin Temperature: \[ T_{sk} = 36.00 \text{ (C)} \]
Saturated Vapour Pressure on Skin: \[ P_{sk} = 5.94 \text{ (kPa)} \]
Metabolic Heat Production: \[ M_h = 100.00 \text{ (W/m2)} \]
Convective Heat Transfer Coefficient: \[ H_c = 5.16 \text{ (W/m2.C)} \]
Linear Radiation Heat Transfer Coefficient: \[ H_r = 4.86 \text{ (W/m2.C)} \]
Mean Clothing Surface Temperature: \[ T_{cl} = 38.68 \text{ (C)} \]
Intrinsic Evaporative Clothing Resistance: \[ I_{ecl} = 0.03 \text{ (m2.kPa/W)} \]
Total Evaporative Clothing Resistance: \[ I_{eT} = 0.04 \text{ (m2.kPa/W)} \]
Convective Heat Transfer: \[ C = -8.91 \text{ (W/m2)} \]
Radiation Heat Transfer: \[ R = -8.39 \text{ (W/m2)} \]
Required Evaporative Cooling: \[ E_{req} = 117.30 \text{ (W/m2)} \]
Maximum Evaporative Capacity of Environment: \[ E_{max} = 41.60 \text{ (W/m2)} \]
Required Skin Wettedness: \[ W_{req} = 2.00 \text{ (ND)} \]
Interpretation, Single Exposure:

Danger: Acclimatized Subject

Predicted Skin Wettedness : Wp = 1.00 (ND)
Predicted Evaporation Rate : Ep = 41.60 (W/m²)
Predicted Sweat Rate : Sp = 400.00 (W/m²) = 588.24 (g/h.m²)
Body Temperature Increase DLE = 47 mins
= 0 h 47 mins

Warning: Acclimatized Subject

Predicted Skin Wettedness : Wp = 1.00 (ND)
Predicted Evaporation Rate : Ep = 41.60 (W/m²)
Predicted Sweat Rate : Sp = 300.00 (W/m²) = 441.18 (g/h.m²)
Body Temperature Increase DLE = 39 mins
= 0 h 39 mins

Danger: Non Acclimatized Subject

Predicted Skin Wettedness : Wp = 0.85 (ND)
Predicted Evaporation Rate : Ep = 35.36 (W/m²)
Predicted Sweat Rate : Sp = 250.00 (W/m²) = 367.65 (g/h.m²)
Body Temperature Increase DLE = 43 mins
= 0 h 43 mins

Warning: Non Acclimatized Subject

Predicted Skin Wettedness : Wp = 0.85 (ND)
Predicted Evaporation Rate : Ep = 35.36 (W/m²)
Predicted Sweat Rate : Sp = 200.00 (W/m²) = 294.12 (g/h.m²)
Body Temperature Increase DLE = 36 mins
= 0 h 36 mins

A-85
ADDITIONAL SUBROUTINES USED BY MODEL PROGRAMS
SUBROUTINE TO SET UP SYSTEM DEPENDENT CONDITIONS FOR MODELS

SUBROUTINE SETUP
COMMON/UNIT/NIN,NOUT,NDAT
COMMON/SAVEF/GOLD,GAGGE,ISO,STOLW,LUTTRE,LUT2,LUTISO,LUT25A,LUT25B
CHARACTER*20 GOLD,GAGGE,ISO,STOLW,LUTTRE,LUT2,LUTISO,LUT25A,LUT25B

NIN=5
NOUT=6
NDAT=10

GOLD='GOLD.DAT;1'
GAGGE='GAGGE.DAT;1'
ISO='ISO.DAT;1'
STOLW='STOLW.DAT;1'
LUTTRE='LUTTRE.DAT;1'
LUT2='LUT2.DAT;1'
LUTISO='LUTISO.DAT;1'
LUT25A='LUT25A.DAT;1'
LUT25B='LUT25B.DAT;1'

RETURN
END
C SUBROUTINE TO TIDY UP AFTER MODEL PROGRAMS (SYSTEM DEPENDENT)
C
SUBROUTINE TIDYUP
COMMON/UNIT/NIN,NOUT,NDAT
CALL CLEAN
CLOSE(UNIT=NDAT)
RETURN
END
SUBROUTINE TO CLEAR VT100 SCREEN AND RETURN CURSOR TO HOME POSITION

SUBROUTINE CLEAN
CHARACTER*7 CLS

C TO CLEAR SCREEN ESC[2J:
CLS(1:1)=CHAR(27)
CLS(2:4)='[2J'

C TO RETURN CURSOR HOME ESC[f:
CLS(5:5)=CHAR(27)
CLS(6:7)='[f'

WRITE(*, 100)CLS
100 FORMAT( '+',7A,$)
RETURN
END
SUBROUTINE TO INFORM USER THAT AN UNDEFINED OPTION HAS BEEN SELECTED

SUBROUTINE INFERR
    CALL CLEAN
    CALL BELL
    WRITE(*,40)
40 FORMAT(////////,28X,'RESPONSE NOT RECOGNIZED!!!')
    CALL WAIT(14)
    RETURN
END
SUBROUTINE TO PROVIDE A SYSTEM INDEPENDENT PAUSE (VT100)

SUBROUTINE WAIT(N)
CHARACTER*4 RVIDEO, NVIDEO
RVIDEO(1:1) = CHAR(27)
RVIDEO(2:4) = ' [7m'
NVIDEO(1:1) = CHAR(27)
NVIDEO(2:4) = ' [0m'
IF(N.GE.1) THEN
DO 150 I = 1, N
WRITE(*,100)
100 FORMAT('+'/$)
150 CONTINUE
END IF
WRITE(*,200) RVIDEO, NVIDEO
200 FORMAT(28X,A4,' Press RETURN to continue ',A4,$)
READ(*,300) IDUM
300 FORMAT(A)
RETURN
END
APPENDIX B

ADDITIONAL MODIFICATIONS TO THE STOLWIJK AND HARDY 25-NODE MODEL OF HUMAN THERMOREGULATION
The published version of the Stolwijk and Hardy 25-node model of human thermoregulation assumes that the air temperature and the mean radiant temperature of the surroundings are the same. The model has been modified to enable it to predict for environments where these temperatures are different.

The published version of the Stolwijk and Hardy model calculates the dry heat flow between the skin and the environment as:

\[ \text{Dry} = h (T_{sk} - T_a) \quad (W/m^2) \]

where:

\[ h = \text{total environmental heat transfer coefficient (W/m}^2.\text{°C)} \]
\[ = hc + hr \quad (W/m^2.\text{°C}) \]

To enable the air temperature and the mean radiant temperature to differ, this equation has been modified so that:

\[ \text{Dry} = hc (T_{sk} - T_a) + hr (T_{sk} - T_r) \quad (W/m^2) \]

For the clothed case this equation becomes:

\[ \text{Dry} = hc \cdot fcl (T_{cl} - T_a) + hr \cdot fcl (T_{cl} - T_r) \quad (W/m^2) \]

In the published model, values of hc are calculated for each body segment according to an experimental formula. Values used for hr are basal values and are not changed regardless of the environmental conditions. In order to account for environments where Ta and Tr are not the same it is necessary to know the body surface temperature Tsk, or Tcl when clothed, and the corresponding hr. The value of hr for
a body segment may be calculated using equation 2.7.

Values of $Ar/Ab$ have been determined for each body segment, using the basal values of $hr$ and the neutral compartment and environmental temperatures given by Stolwijk and Hardy substituted in equation 2.7. The values of $Ar/Ab$ obtained are given in table B-1.

Table B-1. $Ar/Ab$ values calculated from Stolwijk and Hardy Data.

<table>
<thead>
<tr>
<th></th>
<th>head</th>
<th>trunk</th>
<th>arms</th>
<th>hands</th>
<th>legs</th>
<th>feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ar/Ab$</td>
<td>0.74</td>
<td>0.75</td>
<td>0.66</td>
<td>0.56</td>
<td>0.65</td>
<td>0.62</td>
</tr>
</tbody>
</table>

When clothing is not worn, the skin temperatures are known and $hr$ may be calculated directly. When clothing is worn the clothing surface temperatures and the corresponding $hr$ may be calculated using an iterative procedure such as that given by Gagge et al. (1986, appendix B).
APPENDIX C

COMPARISON GRAPHS FOR FULL SET OF EXPERIMENTAL DATA
Tre from Avellini et al (1980) (n=10, accl, males)

Ta-Ti=49°C, v=1 m/s, rh=20%,
lcl=0.3 clo, fec=1.09 (ND), im=0.45 (ND), M=62, 200 W/m², W=0 W/m²

Legend

- mean obs: Tre
- ±sd
- ±sd
- Δ lut2: Tcr
- × lut25 (hhg): Tcr
- + lut25 (hng): Tcr
- + luflre: Tre

Lutisol Allowable Exposure Times
(time weighted averages):
warning non-accl: 20 min; body temperature increase
danger non-accl: 45 min; body temperature increase
warning accl: 54 min; body temperature increase
danger accl: 123 min; body temperature increase
Tsk from Avellini et al (1980) (n=10, accl, males)

Ta=34 C, v=1 m/s, rh=20 %,
lc=0.3 clo, fd=0.08 (ND), lim=0.45 (ND), M=62, 200 W/m2, W=0 W/m2

Legend
- mean obs: Tsk
- ±sd
- ±sd
- lut2: Tsk
- lut25 (hnc): Tsk
- lut25 (hnn): Tsk
Tre from Avellini et al (1980) (n=9, accl, females)
Te=T=49 C, v=1 m/s, rh=20 %,
cli=0.3 clo, fcl=1.09 (ND), im=0.45 (ND), M=63, 189 W/m², W=0 W/m²

<table>
<thead>
<tr>
<th>time (minutes)</th>
<th>temperature (degree Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>100</td>
<td>38</td>
</tr>
<tr>
<td>150</td>
<td>39</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>250</td>
<td>41</td>
</tr>
</tbody>
</table>

Legend
- mean obs: Tre
- ±sd
- ±sd
- lut2: Tcr
- lut25 (hnc): Tcr
- lut25 (hnn): Tcr
- luttre: Tre

Allowable Exposure Times
(time weighted averages):
- warning non-accl: 34 min; body temperature increase
- danger non-accl: 66 min; body temperature increase
- warning accl: 95 min; body temperature increase
- danger accl: 300 min; excessive dehydration
Tsk from Avellini et al (1980) \(n=9\), acl, females

\(T_s=49\) C, \(v=1\) m/s, \(r_h=20\) %,

\(k_i=0.3\) clo, \(f_{cl}=1.09\) (ND), \(i_m=0.45\) (ND), \(M=63, 169\) W/m\(^2\), \(W=0\) W/m\(^2\)

**Legend**
- mean obs: Tsk
- \(\pm sd\)
- \(\pm sd\)
- \(\Delta\) lut2: Tsk
- \(\times\) lut25 (hhc): Tsk
- \(\Phi\) lut25 (hhn): Tsk
Tre from Budd (1965) (n=6)
$T_a=3.7 \, ^\circ C, \, T_r=6.7 \, ^\circ C, \, v=0.18 \, m/s, \, r_h=90 \, \%$, $l_c=0.22 \, clo$, $f_c=1.07 \, (ND)$, $i_m=0.48 \, (ND)$, $M=58 \, W/m2$, $W=0 \, W/m2$
Ty from Chappuis et al (1976) (n=9) (exp code: A)

Ta=Tr=20 C, v=0.2 m/s, rh=30 %, lcl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2

Legend

■ mean obs: Ty
+sd
−sd
△ lut2: Tcr
× lut25 (hhe): Tcr
+ luttre: Tre

Lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl: 480 min; unlimited duration
warning acll: 480 min; unlimited duration
danger acll: 480 min; unlimited duration
Tsk from Chappuis et al (1976) (n=9) (exp code: A)
Ta=Tr=20 C, v=0.2 m/s, rh=30 %, lcl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2
C+R from Chappuis et al (1976) (n=9) (exp code: A)
$T_a = T_r = 20\, ^\circ C$, $v = 0.2\, \text{m/s}$, $r_h = 30\%$, $I_{cl} = 0.1\, \text{clo}$, $f_{cl} = 1\, (\text{ND})$, $i_{m} = 0.5\, (\text{ND})$, $M = 150, 257, 57\, \text{W/m}^2$, $W = 22, 49, 0\, \text{W/m}^2$

**Legend**
- mean obs: C+R
- lut2: C+R
- lut25 (hhc): C+R
E from Chappuis et al (1976) (n=9) (exp code: A)

Ta=Tr=20 C, v=0.2 m/s, rh=30 %, clo=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2
Ttly from Chappuis et al (1976) (n=11) (exp code: B)
Te=Tr=25 C, v=0.2 m/s, rh=30 %, fcl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2

Legend
- mean obs: Ttly
+ sd
- sd
△ lut2: Tcr
× lut25 (hhe): Tcr
+ luttre: Tre

Allowable Exposure Times (time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl: 480 min; unlimited duration
warning accl: 480 min; unlimited duration
danger accl: 480 min; unlimited duration
Tsk from Chappuis et al (1976) (n=11) (exp code: B)

\( T_a = T_r = 25^\circ C, \ v = 0.2 \ m/s, \ r_h = 30 \%, \ \text{cI}=0.1 \ \text{clo}, \ \text{fcl}=1 \ \text{(ND)}, \ \text{im}=0.5 \ \text{(ND)}, \ M=150, 257, 57 \ W/m^2, \ W=22, 49, 0 \ W/m^2 \)
C+R from Chappuis et al (1976) (n=11) (exp code: B)
$T_a=T_r=25$ C, $v=0.2$ m/s, $r_h=30\%$, $l_{cl}=0.1$ clo, $f_{cl}=1$ (ND),
im=0.5 (ND), $M=150, 257, 57$ W/m$^2$, $W=22, 49, 0$ W/m$^2$
E from Chappuis et al (1976) (n=11) (exp code: B)
Ta=Tr=25 C, v=0.2 m/s, rh=30 %, lcl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2.
Temperature data from Chappuis et al. (1976) (n=11) (exp code: C)

$T_{a} = T_{r} = 30 \, ^{\circ}C$, $v = 0.2 \, m/s$, $r_{h} = 30 \, %$, $l_{cl} = 0.1 \, clo$, $f_{cl} = 1 \, (ND)$,

$im = 0.5 \, (ND)$, $M = 150, 257, 57 \, W/m^2$, $W = 22, 49, 0 \, W/m^2$

**Legend**

- mean obs: $T_{ly}$
- $+sd$
- $-sd$
- $\Delta$ lut2: $T_{cr}$
- $\times$ lut25 (hhc): $T_{cr}$
- $+$ luttre: $T_{re}$

**Lutiso Allowable Exposure Times**
(time weighted averages):
- warning non-accl: 480 min; unlimited duration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration
Tsk from Chappuis et al (1976) (n=11) (exp code: C)
Ta=Tr=30 C, v=0.2 m/s, rh=30 %, lcl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2
C+R from Chappuis et al (1976) (n=11) (exp code: C)
Ta=Tr=30 C, v=0.2 m/s, rh=30 %, lcl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2
E from Chappuis et al (1976) (n=11) (exp code: C)
$T_a = T_r = 30 \, ^\circ C$, $v = 0.2 \, m/s$, $r_h = 30 \%$, $l_c = 0.1 \, clo$, $f_c = 1 \, (ND)$,
$im = 0.5 \, (ND)$, $M = 150, 257, 57 \, W/m^2$, $W = 22, 49, 0 \, W/m^2$
Tre from Haismann and Goldman (1974)
(n=7 reducing to 4, accl) (exp. code: ds)

$Ta = 48.9 \, ^\circ C, v = 0.8 \, m/s, r_h = 21 \%, k_{cl} = 0.83 \, \text{clo}, f_{cl} = 1.25 \, (ND)$,

im = 0.41 \, (ND), M = 193, 58, 193 \, W/m^2, W = 0 \, W/m^2

\begin{itemize}
  \item work
  \item rest
  \item work
\end{itemize}

**Legend**

- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- ♦ lut25 (hhn): Tcr
- + luttre: Tre

\text{lutiso Allowable Exposure Times (to work):}

- warning non accl: 14 min; body temperature increase
- danger non accl: 19 min; body temperature increase
- warning accl: 17 min; body temperature increase
- danger accl: 25 min; body temperature increase
Tsk from Haisman and Goldman (1974)
(n=7 reducing to 4, accl) (exp. code: ds)
$T_a=48.9 \, ^C, \, v=0.8 \, m/s, \, rh=21 \, \%, \, lcl=0.83 \, clo, \, fcl=1.25 \, (ND),$
$im=0.41 \, (ND), \, M=193, \, 58, \, 193 \, W/m^2, \, W=0 \, W/m^2$

Legend
- ■ mean obs: Tsk
- △ lut2: Tsk
- × lut25 (hhc): Tsk
- ◊ lut25 (hhn): Tsk

(time (minutes))

(temperature (degree Celsius))

work  rest  work
Tre from Haisman and Goldman (1974)

(n=7 reducing to 3, accl) (exp. code: dl)
T_a=T_r=48.9°C, v=0.8 m/s, r_h=21%, k_i=0.83 clo, f_c=1.25 (ND),
    i_m=0.41 (ND), M=193, 58, 193 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hnc): Tcr
- luttre: Tre

lutt is Allowable Exposure Times
(to work):
warning non accl: 14 min; body temperature increase
danger non accl: 19 min; body temperature increase
warning accl: 17 min; body temperature increase
danger accl: 25 min; body temperature increase
Tsk from Haisman and Goldman (1974)
(n=7 reducing to 3, accl) (exp. code: dl)
Ta=Tr=48.9 C, \(v=0.8\) m/s, \(\text{rh}=21\%\), \(\text{lcl}=0.83\) clo, \(\text{fcl}=1.25\) (ND),
\(\text{im}=0.41\) (ND), \(M=193, 58, 193\) W/m², \(W=0\) W/m²

Legend
- **mean obs:** Tsk
- ▲ lut2: Tsk
- ℹ lut25 (hhc): Tsk
- ✶ lut25 (hhn): Tsk
Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: dn)
Ta=Tr=48.9°C, v=0.8 m/s, rh=21%, clo=0.55, fcl=1.19 (ND),
im=0.44 (ND), M=188, 58, 188 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hbc): Tcr
- lut25 (hbn): Tcr
- luttre: Tre

Lutiso Allowable Exposure Times
(to work):
warning non accl: 19 min; body temperature increase
danger non accl: 31 min; body temperature increase
warning accl: 32 min; body temperature increase
danger accl: 43 min; body temperature increase
Tsk from Haisman and Goldman (1974)
(n=8, accl) (exp. code: dn)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, lcl=0.55 clo, fcl=1.19 (ND),
im=0.44 (ND), M=188, 58, 188 W/m2, W=0 W/m2
Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: ws)
Ta=Tr=35.0°C, v=0.8 m/s, rh=70%, lcl=0.83 clo, tcld=1.25 (ND),
im=0.41 (ND), M=197, 58, 197 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hho): Tcr
- lut25 (hnn): Tcr
- luttre: Tre

Lutiso Allowable Exposure Times
(to work):
warning non accl: 20 min; body temperature increase
danger non accl: 28 min; body temperature increase
warning accl: 23 min; body temperature increase
danger accl: 31 min; body temperature increase
Tsk from Haisman and Goldman (1974)
\( n = 8 \), accl (exp. code: ws)
\( T_a = 35.0 \, ^\circ C, v = 0.8 \, m/s, r_h = 70 \% \),
\( cl = 0.83 \),
\( fcl = 1.25 \) (ND),
\( im = 0.41 \) (ND),
\( M = 197, 58, 197 \, W/m^2 \), \( W = 0 \, W/m^2 \)

---

[Graph showing temperature over time with different symbols representing different conditions and observations.]
Tre from Haisman and Goldman (1974)

(n=8, accl) (exp. code: w1)

$T_a=35.0 \, ^\circ C$, $v=0.8 \, m/s$, $r_h=70\%$, $l_c=0.83 \, clo$, $f_c=1.25 \, (N D)$,

$im=0.41 \, (N D)$, $M=194, 58, 194 \, W/m^2$, $W=0 \, W/m^2$

Legend

- mean obs: Tre
- lut2: Tcr
- lut25 (hhe): Tcr
- lut25 (hhn): Tcr
- luttre: Tre

* lutiso Allowable Exposure Times
  (to work):
  - warning non accl: 21 min; body temperature increase
  - danger non accl: 29 min; body temperature increase
  - warning accl: 24 min; body temperature increase
  - danger accl: 32 min; body temperature increase
Tsk from Haisman and Goldman (1974)

\( n=8, \text{ acl} \) (exp. code: wi)

\( Ta=\bar{v}=35.0 \, ^\circ C, \, v=0.8 \, m/s, \, rh=70 \, \%, \, clo=0.83 \, \text{clo}, \, fcl=1.25 \, (\text{ND}), \)
\( im=0.41 \, (\text{ND}), \, M=194, \, 58, \, 194 \, W/m^2, \, W=0 \, W/m^2 \)

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hho): Tsk
- lut25 (hhn): Tsk

C-28
Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: wn)
Ta = Tr = 35.0°C, v = 0.8 m/s, rh = 70%, ict = 0.55 clo, fclo = 1.19 (ND),
im = 0.44 (ND), M = 195, 58, 195 W/m², W = 0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hhn): Tcr
- lutfre: Tre

Lutiso Allowable Exposure Times
(to work):
warning non accl: 32 min; body temperature increase
danger non accl: 39 min; body temperature increase
warning accl: 40 min; body temperature increase
danger accl: 48 min; body temperature increase
Tsk from Haisman and Goldman (1974)
(n=8, acc) (exp. code: wn)

$T_e = t_r = 35.0 \, ^\circ C$, $v = 0.8 \, m/s$, $\text{rh} = 70 \, %$, $l_c = 0.55 \, \text{clo}$, $f_c = 1.19$ (ND),
$\text{im} = 0.44$ (ND), $M = 195, 58, 195 \, W/m^2$, $W = 0 \, W/m^2$

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hhc): Tsk
- lut25 (hhn): Tsk
Tre from Hampton & Knibbs (1986) (n=14) (exp. code: dry)

Ta=Tr=4.4°C, v=2.88 m/s, rh=86%.
Rest: lcl=0.7 clo, fcl=122 (ND), im=0.38 (ND).
Work: lcl=0.1 clo, fcl=122 (ND), im=0.50 (ND).
M=221, 342, 486, 640, 108, 432, 87, 444, 93, 455 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2.
Tga from Hampton & Knibbs (1986) (n=14) (exp. code: dry)

Ta=Tr=4.4 C, v=2.86 m/s, rh=85 %,
Rest: lc=0.7 clo, fcl=122 (ND), im=0.38 (ND),
Work: lc=0.1 clo, fcl=122 (ND), im=0.50 (ND),
M=221, 342, 486, 640, 108, 432, 87, 444, 93, 455 W/m²,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m²

Legend
- mean obs: Tga
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hhn): Tcr

(c-32)
Tsk from Hampton & Kribbs (1986) (n=14) (exp. code: dry)

Ta=Tr=4.4 C, v=2.88 m/s, rh=85 %,
Rest: kl=0.7 clo, fcl=1.22 (ND), im=0.38 (ND),
Work: kl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=221, 342, 468, 640, 108, 432, 87, 444, 93, 455 W/m²,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m²

![Graph showing temperature changes over time]
Tre from Hampton & Knibbs (1986) (n=14 decreasing to 7)
(exp. code: wet), Ta=Tr=4.3 C, v=2.88 m/s, rh=85 %,
Rest: kl=0.3 clo, fc=1.22 (ND), im=0.50 (ND),
Work: kl=0.1 clo, fc=1.22 (ND), im=0.50 (ND),
M=226, 345, 484, 608, 97, 433, 146, 432 W/m²,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m²
Tga from Hampton & Knibbs (1986) (n=14 decreasing to 7) (exp. code: wet), T_{a-t}=4.3 C, v=2.86 m/s, rh=85 %,
Rest: icl=0.3 clo, fcl=1.22 (ND), im=0.50 (ND),
Work: icl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=226, 345, 484, 608, 97, 433, 148, 432 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2
Tsk from Hampton & Knibbs (1986) \((n=14\) decreasing to 7\) (exp. code: wet), \(T_e=T_r=4.3\) C, \(v=2.86\) m/s, \(rh=85\) %,
Rest: \(cl=0.3\) clo, \(fc=122\) (ND), \(im=0.50\) (ND),
Work: \(cl=0.1\) clo, \(fc=122\) (ND), \(im=0.50\) (ND),
\(M=226, 345, 484, 608, 97, 433, 143, 445, 148, 432\) W/m²,
\(W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78\) (W/m²)

Legend
- **mean obs: T_e**
- **lut2: Tsk**
- **lut25 (hho): Tsk**

<table>
<thead>
<tr>
<th>Temperature (degree Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>15</td>
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</table>

<table>
<thead>
<tr>
<th>Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>150</td>
</tr>
</tbody>
</table>
Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f1)

T_e = 29.0, 22.0, 29.0 °C, v = 0.1 m/s, m = 44, 39, 41 %
lcl = 0.1 clo, fcl = 1 (ND), im = 0.5 (ND), M = 47 W/m², W = 0 W/m²
Tty from Hardy & Stolwijk (1966) (n=3) (exp code: f1)
Te=Tr=29.0, 22.0, 29.0 C, v=0.1 m/s, rh=44, 39, 41 %
lcl=0.1 clo, tcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f1)
Ta=Tr=29.0, 22.0, 29.0 C, v=0.1 m/s, rh=44, 39, 41 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

Legend
■ mean obs: Tsk
△ lut2: Tsk
× lut25 (hhc): Tsk
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f1)

$T_a=T_r=29.0, 22.0, 29.0 \, ^\circ C, v=0.1 \, m/s, r_h=44, 39, 41 \%$

$clo=0.1 \, clo, fcl=1 \, (ND), im=0.5 \, (ND), M=47 \, W/m^2, W=0 \, W/m^2$

Legend

- mean obs: Esk
- lut2: Esk
- lut25 (hhc): Esk

Evaporative cooling (W/m²)

Time (minutes)
M from Hardy & Stolwijk (1966) (n=3) (exp code: f1)
T_a=\bar{T}_r=29.0, 22.0, 29.0 \, \text{C}, \, \nu=0.1 \, \text{m/s}, \, \text{rh}=44, 39, 41\% 
I_c=0.1\, \text{clo}, \, f_c=1\, (\text{ND}), \, \text{im}=0.5\, (\text{ND}), \, M=47 \, \text{W/m2}, \, W=0 \, \text{W/m2}

Legend
- mean obs: M
- lut2: M
- lut25 (hhc): M
Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f3)

Te=Ttr=22.3, 43.5, 22.6 C, v=0.1 m/s, rh=40, 38, 36 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.3 C</td>
<td>40%</td>
</tr>
<tr>
<td>43.5 C</td>
<td>38%</td>
</tr>
<tr>
<td>22.6 C</td>
<td>36%</td>
</tr>
</tbody>
</table>

Temperature (degree Celsius)

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- luttre: Tre

允許可暴露時間（時間加權平均值）：
警告非適應：480 min; 无限 duration
警告適應：480 min; 无限 duration
危险非適應：480 min; 无限 duration
危险適應：480 min; 无限 duration
From Hardy & Stolwijk (1966) (n=3) (exp code: f3)

\[ T_a = T_r = 22.3, 43.5, 22.6 \degree C, v = 0.1 \text{ m/s}, rh = 40, 38, 36 \% \]

\[ lcl = 0.1 \text{ clo}, fcl = 1 \text{ (ND)}, \text{im} = 0.5 \text{ (ND)}, M = 47 \text{ W/m2}, W = 0 \text{ W/m2} \]

\[ \text{luts1o Allowable Exposure Times} \]
(time weighted averages):

- warning non-accl: 480 min; unlimited duration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration
Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
$T_a=T_i=22.3, 43.5, 22.6 \text{ C}, v=0.1 \text{ m/s}, rh=40, 38, 36 \%$
$cl=0.1 \text{ clo}, tcl=1 (ND), im=0.5 (ND), M=47 \text{ W/m}^2, W=0 \text{ W/m}^2$

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hhg): Tsk
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
$T_a=\bar{T}_r=22.3, 43.5, 22.6 \, ^\circ C$, $v=0.1 \, m/s$, $rh=40, 38, 36\%$
$cl=0.1 \, clo$, $fcl=1$ (ND), $im=0.5$ (ND), $M=47 \, W/m^2$, $W=0 \, W/m^2$

Legend
- mean obs: Esk
- lut2: Esk
- lut25 (hhc): Esk

C-45
M from Hardy & Stolwijk (1966) (n=3) (exp code: f3)

Ta=T=22.3, 43.5, 22.6 C, v=0.1 m/s, rh=40, 38, 36 %

Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²
Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f6)

Ta=Tr=17.7 C, v=0.1 m/s, rh=31 %
lcl=0.1 clo, fcl=1 (ND), im=0.6 (ND), M=47 W/m2, W=0 W/m2

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhg): Tcr
- luttre: Tre

(time (minutes)

(degree Celsius)
Ty from Hardy & Stolwijk (1966) (n=3) (exp code: f6)

\[ Ta=Tr=17.7 \, ^\circ C, v=0.1 \, m/s, rh=31 \% \]

\[ tr=0.1 \, clo, fc=1 \, (ND), im=0.5 \, (ND), M=47 \, W/m^2, W=0 \, W/m^2 \]
Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f6)

\[ T_a = 17.7 \, ^\circ C, \, v = 0.1 \, m/s, \, rh = 31\% \]

\[ lci = 0.1 \, clo, \, fci = 1 \, (ND), \, im = 0.5 \, (ND), \, M = 47 \, W/m^2, \, W = 0 \, W/m^2 \]
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f6)  
Ta=Tr=17.7 C, w=0.1 m/s, rh=31 %  
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²
M from Hardy & Stolwijk (1966) (n=3) (exp code: f6)
$Ta=17.7 \, ^\circ C, \, v=0.1 \, m/s, \, rh=31\%$
$lcl=0.1 \, clo, \, fcl=1 \, (ND), \, im=0.5 \, (ND), \, M=47 \, W/m^2, \, W=0 \, W/m^2$

Legend
- mean obs: M
- lut2: M
- lut25 (hhc): M
Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f7)

Ta=Tr=13.0°C, v=0.1 m/s, rh=45%
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²
Temperature data from Hardy & Stolwijk (1966) (n=3) (exp code: f7)

\( T_a = T_r = 13.0 \) °C, \( v = 0.1 \) m/s, \( r_h = 45 \% \)

\( l_c = 0.1 \) clo, \( f_c = 1 \) (ND), \( i_m = 0.5 \) (ND), \( M = 47 \) W/m², \( W = 0 \) W/m²

Legend:
- ■ mean obs: Tty
- △ lut2: Tcr
- × lut25 (hnc): Tcr

Temperature (degree Celsius) vs. time (minutes)
Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f7)

\[ T_a = 13.0 \text{ C, } v = 0.1 \text{ m/s, } \text{rh} = 45 \% \]
\[ I_{ci} = 0.1 \text{ clo, } f_{ci} = 1 \text{ (ND), } \text{im} = 0.5 \text{ (ND), } M = 47 \text{ W/m}^2, W = 0 \text{ W/m}^2 \]
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f7)
Ta=Tr=13.0 C, v=0.1 m/s, rh=45 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
M from Hardy & Stolwijk (1966) (n=3) (exp code: f7)
$T_a = T_r = 13.0 \, ^{\circ} \mathrm{C}$, $v = 0.1 \, \text{m/s}$, $\text{rh} = 45 \%$
$I_c = 0.1 \, \text{clo}$, $f_c = 1 \, (\text{ND})$, $i_m = 0.5 \, (\text{ND})$, $M = 47 \, \text{W/m}^2$, $W = 0 \, \text{W/m}^2$

Legend
- mean obs: $M$
- lut2: $M$
- lut25 (hhc): $M$
Tre from Henane et al (1979) (n=11) (exp. code: nude)
\[ Ta=35 \text{ C, } v=1 \text{ m/s, } rh=54 \%, \]
\[ lcl=0.1 \text{ clo, } fc=1.00 \text{ (ND), } im=0.50 \text{ (ND), } M=185 \text{ W/m}^2, \text{ } W=0 \text{ W/m}^2 \]

**Legend**
- ■ mean obs: Tre
- +sd
- -sd
- △ lut2: Tcr
- × lut25 (hho): Tcr
- + luttre: Tre

**Lutiso Allowable Exposure Times:**
- warning non-accl: 476 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

C-57
Tre from Henane et al (1979) (n=11) (exp. code: A1)
Tre=35°C, v=1 m/s, rh=54%,
lcl=1.0 clo, fcl=1.30 (ND), im=0.35 (ND), M=191 W/m², W=0 W/m²

lutiso Allowable Exposure Times:
warning non-accl: 33 min; body temperature increase
danger non-accl: 40 min; body temperature increase
warning accl: 39 min; body temperature increase
danger accl: 47 min; body temperature increase
Tre from Henane et al (1979) (n=11) (exp. code: A2)
Ta=Tr=35 C, v=1 m/s, rh=64 %,
lc=2.6 clo, fcl=1.40 (ND), im=0.30 (ND), M=209 W/m2, W=0 W/m2
Toe from Hirata et al (1983) (n=4) (exp code: 20)

$T_a=20\ C, v=0.2\ m/s, \ r_h=50\%,$

$k_l=0.1\ clo, f_c=1\ (ND), \ im=0.5\ (ND), \ M=126\ W/m^2, \ W=17\ W/m^2$
Tsk from Hirata et al (1983) (n=4) (exp code: 20)

$T_a = T_r = 20$ $\text{C}$, $v = 0.2$ $\text{m/s}$, $r_h = 50$ $\%$,
$I_c = 0.1$ clo, $f_c = 1$ (ND), $i_m = 0.5$ (ND), $M = 126$ $\text{W/m}^2$, $W = 17$ $\text{W/m}^2$
Toe from Hirata et al (1983) (n=4) (exp code: 35)
$T_a=T_r=20$ C, $v=0.2$ m/s, $m=50$ %,
$k_c=0.1$ clo, $f_c=1$ (ND), $i_m=0.5$ (ND), $M=194$ W/m$^2$, $W=32$ W/m$^2$

**Legend**
- mean obs: Toe
  - $+sd$
  - $-sd$
- lut2: Tcr
- lut25 (hho): Tcr
- luttre: Tre

**Lutiso Allowable Exposure Times:**
- warning non-acci: 480 min; unlimited duration
- danger non-acci: 480 min; unlimited duration
- warning acci: 480 min; unlimited duration
- danger acci: 480 min; unlimited duration
Tsk from Hirata et al (1983) (n=4) (exp code: 35)
Ta=Tr=20 °C, v=0.2 m/s, rh=50 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=194 W/m², W=32 W/m²
Toe from Hirata et al (1983) (n=4) (exp code: 45)
Ta=Tr=20 C, \(v=0.2\) m/s, \(r_h=65\) %,
\(lcl=0.1\) clo, \(fcl=1\) (ND), \(im=0.6\) (ND), \(M=258\) W/m2, \(W=47\) W/m2

Legend
- mean obs: Toe
- \(\pm sd\)
- \(-sd\)
- lut2: Tcr
- lut25 (hcc): Tcr
- luttre: Tre

Ict iso Allowable Exposure Times:
- warning non-accl: 480 min; unlimited duration
- danger non-accl : 480 min; unlimited duration
- warning accl : 480 min; unlimited duration
- danger accl : 480 min; unlimited duration
Tsk from Hirata et al (1983) (n=4) (exp code: 45)

$T_a = T_i = 20 \, ^\circ C$, $v = 0.2 \, m/s$, $r_h = 60 \%$

$\dot{q} = 0.1 \, clo$, $f_{cl} = 1 \, (ND)$, $im = 0.5 \, (ND)$, $M = 258 \, W/m^2$, $W = 47 \, W/m^2$

Legend

- mean obs: Tsk
- $\pm sd$
- $-sd$
- $\triangle lut2: Tsk$
- $\times lut25 \, (hhc): Tsk$
Tre from Lampietro and Buskirk (1960) (n=6) (exp. code: e1)

Ta=Ti=10.0°C, v=4.5 m/s, rh=32 %, clo=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

Legend

- mean obs: Tre
- lut2: Tcr
- lut25 (hho): Tcr
- lut25 (hho): Tcr
Tsk from Lampietro and Buskirk (1960) (n=6) (exp. code: e1)

$T_a = T_r = 10.0 \, \text{C}, \, v = 4.5 \, \text{m/s}, \, r_h = 32 \, \%$, $l_{cl} = 0.77 \, \text{clo}$,

$f_{cl} = 1.24 \, (\text{ND}), \, b_{im} = 0.37 \, (\text{ND}), \, M = 48 \, \text{W/m2}, \, W = 0 \, \text{W/m2}$

Legend

- **mean obs: Tsk**
- **lut2: Tsk**
- **lut25 (hhc): Tsk**
- **lut25 (hhn): Tsk**
M from lampietro and Buskirk (1960) (n=6) (exp. code: e1)
$T_a=T_r=10.0\;^\circ C$, $v=4.5\;m/s$, $r_h=32\%$, $l_cl=0.77\;clo$,
$f_cl=1.24\;ND$, $i_m=0.37\;ND$, $M=48\;W/m^2$, $W=0\;W/m^2$
Tre from lampietro and Buskirk (1960) (n=6) (exp. code: e2)

\( T_a=T_r=4.4\) C, \( v=4.5\) m/s, \( r_h=100\%\), \( U_c=0.77\) clo,
\( f_c=1.24\) (ND), \( m=0.37\) (ND), \( M=48\) W/m², \( W=0\) W/m²

Legend:
- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hhe): Tcr
- ♦ lut25 (hhe): Tcr
Tsk from lampietro and Buskirk (1960) (n=6) (exp. code: e2)

Ta=Tr=4.4 °C, v=4.5 m/s, rh=100 %, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m², W=0 W/m²
M from lampietro and Buskirk (1960) (n=6) (exp. code: e2)
Ta=Tr=4.4 C, v=4.5 m/s, rh=100 %, clo=0.77 clo, fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

Legend
■ mean obs: M
△ lut2: M
× lut25 (hhc): M
★ lut25 (hhn): M
Tre from Lampietro and Buskirk (1960) (n=6) (exp. code: a3)

Te=Ti=4.4 C, v=0.4 m/s, rh=100 %, clo=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m², W=0 W/m²

Legend

- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- ♦ lut25 (hhh): Tcr
Tsk from Lampietro and Buskirk (1960) (n=6) (exp. code: e3)
$T_a=\bar{T}=4.4 \, ^\circ C$, $v=0.4 \, m/s$, $r_h=100 \, \%$, $l_c=0.77 \, clo$
$fcl=1.24 \, (ND)$, $im=0.37 \, (ND)$, $M=48 \, W/m^2$, $W=0 \, W/m^2$
M from lampietro and Buskirk (1960) (n=6) (exp. code: e3)
Ta=Tr=4.4 C, v=0.4 m/s, rh=100 %, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e4)
Ta=Tr=10.0 C, v=4.5 m/s, rh=100 %, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m², W=0 W/m²

Legend:
- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- ♦ lut25 (hhn): Tcr
Tsk from lampietro and Buskirk (1960) (n=6) (exp. code: e4)

$T_a = T_r = 10.0 \, \text{C}$, $v = 4.5 \, \text{m/s}$, $r_h = 100 \, \%$, $l_cl = 0.77 \, \text{clo}$,
$f_cl = 1.24 \, (\text{ND})$, $i_m = 0.37 \, (\text{ND})$, $M = 48 \, \text{W/m}^2$, $W = 0 \, \text{W/m}^2$

Legend

- ■ mean obs: Tsk
- Δ lut2: Tsk
- × lut25 (hhc): Tsk
- ♦ lut25 (hhn): Tsk
M from Jampietro and Buskirk (1960) (n=6) (exp. code: e4)
\[ T_a = T_r = 10.0 \, ^\circ C, \, v = 4.5 \, \text{m/s}, \, r_h = 100 \, \%, \, l_c = 0.77 \, \text{clo}, \]
\[ f_c = 1.24 \, (\text{ND}), \, i_m = 0.37 \, (\text{ND}), \, M = 48 \, \text{W/m}^2, \, W = 0 \, \text{W/m}^2 \]
Tre from lampietro and Buskirk (1960) (n=6) (exp. code: e5)
Ta=Ti=4.4 C, v=0.4 m/s, rh=37 %, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
Tsk from Lampietro and Buskirk (1960) (n=6) (exp. code: e5)

$T_a = 11^\circ C$, $v = 0.4$ m/s, $r_h = 37\%$, $clo = 0.77$ clo,

$fcl = 1.24$ (ND), $im = 0.37$ (ND), $M = 48$ W/m$^2$, $W = 0$ W/m$^2$
M from Lampietro and Buskirk (1960) (n=6) (exp. code: e5)

Ta=4.4°C, v=0.4 m/s, rh=37%, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m², W=0 W/m²
Tre from Lampietro and Buskirk (1960) (n=6) (exp. code: e6)

Ta=Tr=10.0 C, v=0.4 m/s, rh=100 %, lc1=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hnn): Tcr
Tsk from Lampietro and Buskirk (1960) (n=6) (exp. code: e6)

$T_a = T_r = 10.0 \, ^\circ C$, $v=0.4 \, m/s$, $r_h=100 \, %$, $I_c_l=0.77 \, c_l o$,

$F_c l=1.24 \, (N D)$, $i_m=0.37 \, (N D)$, $M=48 \, W/m^2$, $W=0 \, W/m^2$
M from lampietro and Buskirk (1960) (n=6) (exp. code: e6)

Ta=Ti=10.0 C, v=0.4 m/s, rh=100 %, clo=0.77 clo,
fcl=124 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
Tre from Lampietro and Buskirk (1960) (n=6) (exp. code: e7)

$T_a=T_r=10.0 \, ^\circ C$, $v=0.4 \, m/s$, $r_h=32 \%$, $l_{cl}=0.77 \, clo$, $f_{cl}=1.24 \, (ND)$, $m=0.37 \, (ND)$, $M=48 \, W/m^2$, $W=0 \, W/m^2$
Tsk from lampietro and Buskirk (1960) (n=6) (exp. code: e7)

Ta=Tr=10.0 C, v=0.4 m/s, rh=32 %, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m², W=0 W/m²

Legend
- **mean obs: Tsk**
- ▲ lut2: Tsk
- × lut25 (hhc): Tsk
- ♦ lut25 (hhn): Tsk
M from Lampietro and Buskirk (1960) (n=6) (exp. code: e7)

$T_a - T_r = 10.0 \, ^\circ C$, $v=0.4 \, m/s$, $rh=32\%$, $I_c=0.77 \, clo$, $f_c=1.24 \, (ND)$, $I_m=0.37 \, (ND)$, $M=48 \, W/m^2$, $W_0=0 \, W/m^2$
Tre from Lampietro and Buskirk (1960) (n=6) (exp. code: e8)
Ta=li=5.0 C, v=4.5 m/s, rh=30 %, lcl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=4.8 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhs): Tcr
- lut25 (hhn): Tcr
Tsk from Lampietro and Buskirk (1960) (n=6) (exp. code: e8)

Ta=5.0 C, v=4.5 m/s, rh=30 %, lcl=0.77 cl0,
flcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
M from lampietro and Buskirk (1960) (n=6) (exp. code: e8)

$T_a = T_r = 5.0 \, ^\circ C$, $v = 4.5 \, m/s$, $r_h = 30 \%$, $l_c l = 0.77 \, c_l o$, $f_c l = 1.24 \, (N D)$, $i_{m} = 0.37 \, (N D)$, $M = 48 \, W/m^2$, $W = 0 \, W/m^2$
Tre from lampietro et al (1958) (n=6) (exp code: 1)
Ta=Tr=10.2 C, v=0.4 m/s, rh=34 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
Tsk from lampietro et al (1958) (n=6) (exp code: 1)

$T_a = T_r = 10.2 \, ^oC, \, v = 0.4 \, m/s, \, r_h = 34 \%,$

$l_c = 0.1 \, clo, \, f_c = 1 \, (ND), \, i_m = 0.5 \, (ND), \, M = 49 \, W/m^2, \, W = 0 \, W/m^2$
M from lampietro et al (1958) (n=6) (exp code: 1)
Ta=Tr=10.2 C, v=0.4 m/s, rh=34 %,
lc=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2

Legend
- mean obs: M
- lut2; M
- lut25 (hhc); M
Tre from Jampietro et al (1958) (n=6) (exp code: 2)
Ta=Tr=16.5 C, v=0.4 m/s, rh=95 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- luttre: Tre
Tsk from Lampietro et al (1958) (n=6) (exp code: 2)  
$T_a = T_i = 16.5 \, ^\circ C$, $v=0.4 \, m/s$, $r_h=95 \, \%$,  
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), $M=49 \, W/m^2$, $W=0 \, W/m^2$  

Legend  
- mean obs: Tsk  
- lut2: Tsk  
- lut25 (hlc): Tsk
M from lampietro et al (1958) (n=6) (exp code: 2)
$T_a=T_r=16.5 \, ^\circ C$, $v=0.4 \, m/s$, $r_h=95 \, \%$,
$lcl=0.1 \, \text{clo}$, $fcl=1 \, \text{(ND)}$, $im=0.5 \, \text{(ND)}$, $M=49 \, \text{W/m}^2$, $W=0 \, \text{W/m}^2$
Tre from lampietro et al (1968) (n=6) (exp code: 3)

Ta=Tr=9.9 C, v=3.2 m/s, rh=39 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhe): Tcr
Tsk from lampietro et al (1958) (n=6) (exp code: 3)

T_T=9.9 C, v=3.2 m/s, rh=39 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m², W=0 W/m²

Legend

- ■ mean obs: Tsk
- △ lut2: Tsk
- × lut25 (hce): Tsk
M from lampietro et al (1958) (n=6) (exp code: 3)
Ta=39°C, v=3.2 m/s, rh=39%,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m², W=0 W/m²

Legend
■ mean obs: M
△ lut2: M
× lut25 (hhc): M
Tre from Lampietro et al (1958) (n=6) (exp code: 4)

$T_a = T_r = 14.2 \, ^\circ C$, $v = 0.4 \, m/s$, $r_h = 32 \%$,
$\text{i} = 0.1 \, \text{clo}$, $\text{f} = 1 \, \text{(ND)}$, $\text{im} = 0.5 \, \text{(ND)}$, $M = 49 \, W/m^2$, $W = 0 \, W/m^2$

Legend

- mean obs: $T_r$
- lut2: $T_c$
- lut25 (hhe): $T_c$
Tsk from Lampietro et al. (1958) (n=6) (exp code: 4)

\( T_a = T_{ri} = 14.2 \) °C, \( v = 0.4 \) m/s, \( \text{rh} = 32 \% \),
\( \text{lcl} = 0.1 \) clo, \( fcl = 1 \) (ND), \( \text{im} = 0.5 \) (ND), \( M = 49 \) W/m², \( W = 0 \) W/m²

**Legend**

- **mean obs: Tsk**
- **lut2: Tsk**
- **lut25 (hhe): Tsk**
M from lampiastro et al (1958) (n=6) (exp code: 4)

$Ta=14.2\ C, v=0.4\ m/s, rh=32\%,$

$lcl=0.1\ cm, fcl=1\ (ND), \ im=0.5\ (ND), \ M=49\ W/m^2, \ W=0\ W/m^2$

Legend
- mean obs: $M$
- lut2: $M$
- lut25 (hhc): $M$
Tre from lampietro et al (1958) (n=6) (exp code: 5)

\( T_a = T_r = 15.0 \) C, \( v = 4.7 \) m/s, \( rh = 91 \% \),
\( k = 0.1 \) clo, \( f_c = 1 \) (ND), \( i_m = 0.5 \) (ND), \( M = 49 \) W/m², \( W = 0 \) W/m²

Legend:
- mean obs: Tre
- \( \triangle \): lut2: Tcr
- \( \times \): lut25 (hhc): Tcr
- +: luttre: Tre
Tsk from lampietro et al (1958) (n=6) (exp code: 5)

Ta=Tr=15.0 C, v=4.7 m/s, rh=91 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hhe): Tsk
M from lampiетro et al (1958) (n=6) (exp code: 5)
Ta=15.0 C, v=4.7 m/s, rh=91 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2

Legend
■ mean obs: M
△ lut2: M
× lut25 (hhc): M
Tre from lampietro et al (1958) (n=6) (exp code: 6)

Ta=Tr=11.0 C, v=0.4 m/s, rh=94 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m², W=0 W/m²

Legend

- mean obs: Tre
- lut2: Tcr
- lut25 (hhe): Tcr
Tsk from lampietro et al (1958) (n=6) (exp code: 6)

Ta=Tr=11.0 C, v=0.4 m/s, rh=94 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hinc): Tsk
M from lampietro et al (1958) (n=6) (exp code: 6)

$T_a=T_r=11.0$ C, $v=0.4$ m/s, $r_h=94\%$

$I_c=0.1$ clo, $f_c=1$ (ND), $i_m=0.5$ (ND), $M=49$ W/m$^2$, $W=0$ W/m$^2$

Legend

- **mean obs: M**
- ▲ lut2: M
- × lut25 (hhc): M
Tre from Lampietro et al (1958) (n=6) (exp code: 7)

Ta=Tr=10.1 C, v=4.5 m/s, rh=98 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
Tsk from lampietro et al (1958) (n=6) (exp code: 7)
Ta=Tr=10.1 °C, v=4.5 m/s, rh=98 %,
lc=0.1 clo, fc=1 (ND), im=0.5 (ND), M=49 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hrc): Tsk
M from lampietro et al (1958) (n=6) (exp code: 7)

$T_a=T_i=10.1 \, ^{\circ}C$, $v=4.5$ m/s, $r_h=98\%$,

$c_l=0.1$ clo, $f_c=1$ (ND), $i_m=0.5$ (ND), $M=49$ W/m², $W=0$ W/m²

Legend

- mean obs: M
- lut2: M
- lut25 (hhc): M
Tre from lampietro et al (1958) (n=6) (exp code: 8)

Ta=Tr=15.6 C, v=4.6 m/s, rh=14 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
Tsk from Lampietro et al (1958) (n=6) (exp code: 8)

$T_a = T_r = 15.6 \, ^\circ C$, $v = 4.6 \, m/s$, $m = 14 \, \%$,
$l_{cl} = 0.1 \, clo$, $f_{cl} = 1$ (ND), $i_m = 0.5$ (ND), $M = 49 \, W/m^2$, $W = 0 \, W/m^2$
M from Lampietro et al (1958) (n=6) (exp code: 8)
$T_a=T_r=15.6 \degree C$, $v=4.6 \text{ m/s}$, $r_h=14 \%$, $l_{cl}=0.1 \text{ clo}, f_{cl}=1$ (ND), $i_m=0.5$ (ND), $M=49 \text{ W/m}^2$, $W=0 \text{ W/m}^2$

Legend
- mean obs: $M$
- lut2: $M$
- lut25 (hhc): $M$
Tre from Kobayashi et al. (1980) (n=5) (moderate work)

Ta=Tr=49.5 C, v=0.1 m/s, rh=32%
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m² (rest), M=204 W/m², W=28 W/m² (work)

Legend

- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- luttre: Tre

**Lutiso Allowable Exposure Times**
(time weighted averages):
warning non-accl: 34 min; body temperature increase
danger non-accl: 41 min; body temperature increase
warning accl: 45 min; body temperature increase
danger accl: 59 min; body temperature increase
Tao from Kobayashi et al. (1980) (n=5) (moderate work)

\[ T_a = T_r = 49.5 \, ^\circ\mathrm{C}, \, v = 0.1 \, \text{m/s}, \, \text{rh} = 32 \% \]

\[ l_{cl} = 0.1 \, \text{clo}, \, f_{cl} = 1 \, (\text{ND}), \, i_{m} = 0.5 \, (\text{ND}) \]

\[ M = 58 \, \text{W/m}^2 \, (\text{rest}), \, M = 204 \, \text{W/m}^2, \, W = 28 \, \text{W/m}^2 \, (\text{work}) \]

Legend:
- mean obs: \( T_{ac} \)
- lut2: \( T_{cr} \)
- lut25 (hhc): \( T_{cr} \)
- luttre: \( T_{re} \)

**Lutiso Allowable Exposure Times**
(time weighted averages):
- warning non-accl: 34 min; body temperature increase
- danger non-accl: 41 min; body temperature increase
- warning accl: 45 min; body temperature increase
- danger accl: 59 min; body temperature increase
Tsk from Kobayashi et al. (1980) (n=5) (moderate work)

Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m² (rest), M=204 W/m², W=28 W/m² (work)
Esk from Kobayashi et al. (1980) (n=5) (moderate work)

\[ T_a = T_r = 49.5 \text{ C}, \ v = 0.1 \text{ m/s}, \ r_h = 32 \% \]

\[ \text{lcl} = 0.1 \text{ clo}, \ fcl = 1 \text{ (ND)}, \ im = 0.5 \text{ (ND)} \]

\[ M = 58 \text{ W/m}^2 \text{ (rest)}, \ M = 204 \text{ W/m}^2, \ W = 28 \text{ W/m}^2 \text{ (work)} \]
Tre from Kobayashi et al. (1980) (n=5) (heavy work)

\[ T_a = T_r = 49.5 \, ^\circ C, \, v = 0.1 \, m/s, \, rh = 32 \% \]
\[ \text{clo} = 0.1, \, fcl = 1 \, (ND), \, \text{im} = 0.5 \, (ND) \]

\[ M = 58 \, W/m^2 \, \text{(rest)}, \, M = 306 \, W/m^2, \, W = 49 \, W/m^2 \, \text{(work)} \]

### Legend

- **mean obs**: Tre
- ▲ lut2: Tcr
- ✗ lut25 (hho): Tcr
- + luttre: Tre

**lutsiso Allowable Exposure Times (time weighted averages):**
- **warning non-accl**: 16 min; body temperature increase
- **danger non-accl**: 24 min; body temperature increase
- **warning accl**: 23 min; body temperature increase
- **danger accl**: 34 min; body temperature increase
Tac from Kobayashi et al. (1980) (n=5) (heavy work)

Ta=Tr=49.5 °C, v=0.1 m/s, rh=32 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m² (rest), M=306 W/m², W=49 W/m² (work)

Legend
- mean obs: Tac
- lut2: Tcr
- lut25 (hhc): Tcr
- luttre: Tre

 lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 16 min; body temperature increase
danger non-accl: 24 min; body temperature increase
warning accl: 23 min; body temperature increase
danger accl: 34 min; body temperature increase
Tsk from Kobayashi et al. (1980) (n=5) (heavy work)

\[ T_a = T_r = 49.5 \text{ C}, \ v = 0.1 \text{ m/s}, \ r_h = 32\% \]

\[ l_{cl} = 0.1 \text{ clo}, \ t_{cl} = 1 \text{ (ND)}, \ i_m = 0.5 \text{ (ND)} \]

M=58 W/m² (rest), M=306 W/m², W=49 W/m² (work)

Legend

- ■ mean obs: Tsk
- △ lut2: Tsk
- × lut25 (hhc): Tsk

C-120
Esk from Kobayashi et al. (1980) (n=5) (heavy work)

$T_a=T_r=49.5\,^\circ C$, $v=0.1\,m/s$, $r_h=32\%$

$lcl=0.1\,clo$, $fcl=1\,(ND)$, $im=0.5\,(ND)$

$M=58\,W/m^2\,(rest)$, $M=306\,W/m^2$, $W=49\,W/m^2\,(work)$

Legend

- mean obs: Esk
- lut2: Esk
- lut25 (hhe): Esk
Tre from Mairiaux et al. (1986) (n=5) (exp. code: WD-1)

\[ T_a = T_r = 45 \pm 28 \text{ C, } v = 0.2 \text{ m/s, } rh = 21-53 \% , \]
\[ h_l = 0.1 \text{ clo, } f_c = 1 \text{ (ND), } im = 0.5 \text{ (ND), } M = 172 \text{ W/m}^2, \]
\[ W = 28 \text{ W/m}^2 \]

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<td>39.5</td>
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**Legend**
- **mean obs: Tre**
- \(+sd\)
- \(-sd\)
- \(\triangle lut2: Tcr\)
- \(\times lut25 (nhg): Tcr\)
- \(+ luttre: Tre\)

**Lutiso Allowable Exposure Times**
(time weighted averages):
- warning non-accl: 395 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

C-122
Toe from Mairiaux et al. (1986) (n=6) (exp. code: WD-1)

$T_e=T_\text{ir}=45-28 \, \text{C}$, $v=0.2 \, \text{m/s}$, $r=21-53 \, \%$,

$\text{lcl}=0.1 \, \text{clo}$, $\text{fcl}=1 \, (\text{ND})$, $\text{im}=0.5 \, (\text{ND})$, $M=172 \, \text{W/m2}$, $W=28 \, \text{W/m2}$

**Legend**
- mean obs: $\text{Toe}$
- $+\text{sd}$
- $-\text{sd}$
- $\Delta \, \text{lut2: Tc}$
- $\times \, \text{lut25 (hce): Tc}$
- $+ \, \text{lutter: Tr}$

**Lutiso Allowable Exposure Times**
(time weighted averages):
- warning non-accl: 395 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration
Tre from Mairiaux et al. (1986) (n=5) (exp. code: WD-2)
Ta=Tr=50-23 C, v=0.2 m/s, rh=16-71 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m², W=28 W/m²

Legend
- mean obs: Tre
- ±sd
- -sd
- Δ lut2: Tcr
- × lut25 (hhc): Tcr
- + luttre: Tre

Lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 390 min; excessive dehydration
danger non-accl: 480 min; unlimited duration
warning accl: 480 min; unlimited duration
danger accl: 480 min; unlimited duration

C-124
Toe from Mairiaux et al. (1986) (n=5) (exp. code: WD-2)

Ta=Tr=50-23 °C, v=0.2 m/s, rh=16-71 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m², W=28 W/m²

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<td>36.5</td>
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Legend
- mean obs: Toe
- sd
- lut2: Ter
- lut25 (hho): Ter
+ luttre: Tre

Lutisio Allowable Exposure Times
(time weighted averages):
- warning non-accl: 390 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

C-125
Tre from Mairiaux et al. (1986) (n=5) (exp. code: WD-3)

$T_a = T_r = 36.5\, ^\circ C$, $v=0.2\, m/s$, $rh=33\, \%$

$cl=0.1\, clo$, $fcl=1\, (ND)$, $im=0.5\, (ND)$, $M=172\, W/m^2$, $W=28\, W/m^2$

Legend

- mean obs: $T_{re}$
- $+sd$
- $-sd$
- $\triangle lut2: T_{cr}$
- $\times lut25\, (hho): T_{cr}$
- $+$ luttre: $T_{re}$

Lutiso Allowable Exposure Times

- warning non-accl: 399 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

C-126
Toe from Mairiaux et al. (1986) (n=5) (exp. code: WD-3)

$T_a=36.5\, ^\circ C$, $v=0.2\, m/s$, $\text{rh}=33\, \%$,

$t_c=0.1\, \text{clo}$, $f_c=1\, (\text{ND})$, $m=0.5\, (\text{ND})$, $M=172\, \text{W/m}^2$, $W=28\, \text{W/m}^2$

---

**Legend**

- **Mean obs:** Toe
- $\pm sd$
- $\pm sd$
- $\triangle$ lut2: $T_{cr}$
- $\times$ lut25 (hho): $T_{cr}$
- $+$ luttre: $T_{re}$

---

**Lutiso Allowable Exposure Times**

- **Warning non-accl:** 399 min; excessive dehydration
- **Danger non-accl:** 480 min; unlimited duration
- **Warning accl:** 480 min; unlimited duration
- **Danger accl:** 480 min; unlimited duration
Tre from Mairiaux et al. (1986) (n=5) (exp. code: WH-1)

\[ T_e = T_r = 36.5 \text{ C}, \ v = 0.2 \text{ m/s}, \ r_h = 65-33 \% \]
\[ l_c = 0.1 \text{ clo, } f_c = 1 \text{ (ND), } m_i = 0.5 \text{ (ND), } M = 172 \text{ W/m}^2, \ W = 28 \text{ W/m}^2 \]

### Legend
- **mean obs: Tre**
- **±sd**
- **=sd**
- **Δ lut2: Tcr**
- **× lut25 (hhc): Tcr**
- **+ luttre: Tre**

**Lutiso Allowable Exposure Times**
(time weighted averages):
- **warning non-accl**: 395 min; excessive dehydration
- **danger non-accl**: 480 min; unlimited duration
- **warning accl**: 480 min; unlimited duration
- **danger accl**: 480 min; unlimited duration
Toe from Mairiaux et al. (1986) (n=5) (exp. code: WH-1)

$Ta=T_{ir}=36.5^\circ C, v=0.2\ m/s, rh=65-33\ %,$

$cl=0.1\ clo, fcl=1\ (ND), im=0.5\ (ND), M=172\ W/m^2, W=28\ W/m^2$

Legend

- **mean obs:** Toe
- $\pm sd$
- $-sd$
- $\triangle lut2: Tcr$
- $\times lut25\ (hhc): Tcr$
- $+ luttre: Tre$

**Lutiso Allowable Exposure Times**

(time weighted averages):

- **warning non-accl**: 395 min; excessive dehydration
- **danger non-accl**: 480 min; unlimited duration
- **warning accl**: 480 min; unlimited duration
- **danger accl**: 480 min; unlimited duration

C-129
$T_e$ from Mairiaux et al. (1986) ($n=5$) (exp. code: WH-2)

$Ta=T_r=36.5$ C, $v=0.2$ m/s, $\theta=75\%-23\%$,

$lcl=0.1$ clo, $fcl=1$ (ND), $im=0.5$ (ND), $M=172$ W/m$^2$, $W=28$ W/m$^2$

Legend

- mean obs: $T_e$
- +sd
- -sd
- $\Delta$ lut2: $T_r$
- $\times$ lut25 (hho): $T_cr$
- + luttre: $T_e$

LTISO Allowable Exposure Times
(time weighted averages):

warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration
Toe from Mairiaux et al. (1986) (n=5) (exp. code: WH-2)

$T_e=T_i=36.5\, ^\circ C$, $v=0.2\, m/s$, $r_h=75\%-23\%$

$\text{clo}=0.1\, \text{clo}, \text{fcl}=1\, (\text{ND}), \text{im}=0.5\, (\text{ND}), \text{M}=172\, W/m^2, \text{W}=28\, W/m^2$

Legend

• mean obs: Toe
+ sd
- sd
$$\triangle$$ lut2: Tor
$$\times$$ lut25 (hho): Tor
+ luttre: Tre

Lutiso Allowable Exposure Times
(time weighted averages):
- warning non-accl: 395 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

C-131
T\(\text{r}_m\) from Mairiaux et al. (1986) (\(n=5\)) (exp. code: WH-3)

\(T_e=T_m=36.5\, ^\circ\text{C}, \nu=0.2\, \text{m/s}, \, r_h=49\, \%\),
\(h_i=0.1\, \text{clo}, \, f_{cl}=1\, (\text{ND}), \, i_m=0.5\, (\text{ND}), \, M=172\, \text{W/m}^2, \, W=28\, \text{W/m}^2\)

---

**Legend**
- ■ mean obs: \(T_{re}\)
- ±sd
- =sd
- △ lut2: \(T_{cr}\)
- × lut25 (hhd): \(T_{cr}\)
- + luttre: \(T_{re}\)

**Lutiso Allowable Exposure Times**
- warning non-accl: 395 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration
Toe from Mairiaux et al. (1986) (n=5) (exp. code: WH-3)

$T_a = T_r = 36.5 \, ^\circ\text{C}$, $v = 0.2 \, \text{m/s}$, $r_h = 49 \, \%$, $k_l = 0.1 \, \text{clo}$, $f_c = 1 \, (\text{ND})$, $i_m = 0.5 \, (\text{ND})$, $M = 172 \, \text{W/m}^2$, $W = 28 \, \text{W/m}^2$

**Legend**
- mean obs: Toe
- $\pm$sd
- $\pm$sd
- lut2: Tcr
- lut25 (hhc): Tcr
- luttre: Tre

**Lutiso Allowable Exposure Times**
- warning non-accl: 395 min; excessive dehydration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

C-133
Tre from Mitchell et al (1976) (n=4) (exp code: day 1)

$T_a=T_r=45 \, ^\circ C$, $v=1 \, m/s$, $rh=42 \%$

$lcl=0.1 \, clo$, $fcl=1 \, (ND)$, $im=0.5 \, (ND)$, $M=211 \, W/m^2$, $W=39 \, W/m^2$

 lutiso AET's

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<th>temperature (degree Celsius)</th>
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<tr>
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<th>time (minutes)</th>
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</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>250</td>
</tr>
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</table>

Legend
- mean obs: Tre
- +sd
- =sd
- $\triangle$ lut2: Tre
- $\times$ lut25 (hlc): Tre
- + luttre: Tre

lutiso Allowable Exposure Times
warning non-accl: 26 min; body temperature increase
danger non-accl: 50 min; body temperature increase
warning accl: 60 min; body temperature increase
danger accl: 142 min; body temperature increase
Tsk from Mitchell et al (1976) (n=4) (exp code: day 1)

Ta=Tr=45 C, v=1 m/s, rh=42 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m², W=39 W/m²

Legend
- mean obs: Tsk
- ±sd
- lut2: Tsk
- lut25 (hhc): Tsk
C+R from Mitchell et al (1976) (n=4) (exp code: day 1)
Ta=Ti=45 C, v=1 m/s, rh=42 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2
E from Mitchell et al (1976) (n=4) (exp code: day 1)
Ta=45°C, v=1 m/s, rh=42%
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m², W=39 W/m²

Legend
■ mean obs: E
+sd
−sd
△ lut2: E
× lut25 (hhc): E

C-137
Tre from Mitchell et al (1976) (n=4) (exp code: day 10)

\[ Ta = T_r = 45 \, ^\circ C, \, v = 1 \, m/s, \, rh = 42 \% \]
\[ cl = 0.1 \, clo, \, fcl = 1 \, (ND), \, im = 0.5 \, (ND), \, M = 211 \, W/m^2, \, W = 39 \, W/m^2 \]

**Legend**
- **mean obs: Tre**
- +sd
- -sd
- \( \Delta \) lut2: Tcr
- \( \times \) lut25 (hhe): Tcr
- + luttre: Tre

**Lutiso Allowable Exposure Times**
- **warning non-accl:** 26 min; body temperature increase
- **danger non-accl:** 50 min; body temperature increase
- **warning accl:** 60 min; body temperature increase
- **danger accl:** 142 min; body temperature increase
Tsk from Mitchell et al (1976) (n=4) (exp code: day 10)

$Ta=Ti=45 \text{ C, } v=1 \text{ m/s, } rh=42 \%$

$Icl=0.1 \text{ clo, } fcl=1 \text{ (ND), } im=0.5 \text{ (ND), } M=211 \text{ W/m}^2, \ W=39 \text{ W/m}^2$

Legend

- mean obs: Tsk
- $\pm$sd
- $\mp$sd
- $\Delta$ lut2: Tsk
- $\times$ lut25 (hnc): Tsk
C+R from Mitchell et al (1976) (n=4) (exp code: day 10)

\[ T_a=T_r=45 \, ^\circ C, \, v=1 \, m/s, \, r_h=42 \, \% \]

\[ l_c=0.1 \, clo, \, f_c=1 \, (ND), \, im=0.5 \, (ND), \, M=211 \, W/m^2, \, W=39 \, W/m^2 \]

**Legend**
- mean obs: C+R
- ±sd
- ±sd
- lut2: C+R
- lut25 (hhc): C+R
E from Mitchell et al (1976) (n=4) (exp code: day 10)

Ta=Tr=45 °C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2
Tre from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: ct)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, clo=1.22 clo, fclo=1.38 (ND),
im=0.35 (ND), M=151, 52 W/m2, W=19, 0 W/m2

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hho): Tcr
- lut25 (hhn): Tcr
Toe from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: ct)
Ta=Tt=9.8 °C, v=0.1 m/s, rh=52 %, lcl=1.22 clo, fcl=1.38 (ND),
im=0.35 (ND), M=151, 52 W/m², W=19, 0 W/m²

Legend
- mean obs: Toe
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hhn): Tcr

c-143
Tsk from Nielsen and Nielsen (1984) (n=10) (7 males, 3 females) (exp. code: ct)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Io=1.22 clo, fcl=1.38 (ND),
im=0.35 (ND), M=151, 52 W/m², W=19, 0 W/m²

Legend
■ mean obs: Tsk
△ lut2: Tsk
× lut25 (hho): Tsk
◆ lut25 (hhn): Tsk

C-144
Tre from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: cl)
\( T_a = T_r = 9.8 \, ^\circ C, \, v = 0.1 \, m/s, \, r_h = 52 \, %, \, l_c = 1.67 \, clo, \, f_c = 1.52 \, (ND), \)
\( i_m = 0.30 \, (ND), \, M = 150, \, 51 \, W/m^2, \, W = 19, \, 0 \, W/m^2 \)

Legend
- mean obs: Tre
- \( \Delta \) lut2: Tcr
- \( \times \) lut25 (hhs): Tcr
- \( \Phi \) lut25 (hhn): Tcr
Toe from Nielsen and Nielsen (1984) (n=10) (7 males, 3 females) (exp. code: cl)
$T_a = T_r = 9.8 \ C, \ v = 0.1 \ m/s, \ r_h = 52 \ %, \ \rho_{clo} = 1.67 \ \rho_{fcl} = 1.52 \ (ND),$
$\rho_{im} = 0.30 \ (ND), \ M = 150, 51 \ W/m^2, \ W = 19, 0 \ W/m^2$

Legend

- • mean obs: Toe
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- ✶ lut25 (hhn): Tcr

C-146
Tsk from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: cl)
\( T_a = T_r = 9.8 \, ^\circ C, \, v = 0.1 \, m/s, \, rh = 52 \, \%, \, lcl = 1.67 \, clo, \, fcl = 1.52 \, (ND), \)
\( im = 0.30 \, (ND), \, M = 150, \, 51 \, W/m^2, \, W = 19, \, 0 \, W/m^2 \)

Legend

- ■ mean obs: Tsk
- △ lut2: Tsk
- × lut25 (hho): Tsk
- ♦ lut25 (hnh): Tsk
Tre from O'Hanlon and Horvath (1970) (n=34)

$T_a=7.7 \, ^\circ C$, $v=0.2 \, m/s$, $rh=85 \%$

$Icl=0.1 \, clo$, $fcl=1 \, (ND)$, $im=0.5 \, (ND)$, $M=58 \, W/m^2$, $W=0 \, W/m^2$
M from O'Hanlon and Horvath (1970) (n=34)
Ta=Tr=7.7 °C, v=0.2 m/s, rh=85 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=58 W/m², W=0 W/m²

Legend
■ mean obs: M
+sd
−sd
△ lut2: M
× lut25 (hhc): M
Tre from Pimental et al (1987) (n=4, acc) (exp. code: IW)

$T_e = 49 \, ^\circ C$, $v=1.1 \, m/s$, $rh=20 \%$

$cl=22 \, clo$, $fc=1.45 \, (ND)$, $im=0.30 \, (ND)$, $M=68$, $204 \, W/m^2$, $W=0 \, W/m^2$

---

**Legend**
- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hkc): Tcr
- + luttre: Tre

**Tutiso Allowable Exposure Times**
(time weighted averages):
- warning non-accl: 33 min; body temperature increase
- danger non-accl: 40 min; body temperature increase
- warning accl: 36 min; body temperature increase
- danger accl: 43 min; body temperature increase
Tre from Pimental et al (1987) (n=4, accl) (exp. code: hw)

\[ T_e = T_r - 49 \text{ C}, v = 1.1 \text{ m/s}, \text{ rh} = 20 \% \]
\[ kl = 2.2 \text{ clo}, fcl = 1.45 \text{ (ND)}, im = 0.30 \text{ (ND)}, M = 204, 68 \text{ W/m}^2, W = 0 \text{ W/m}^2 \]

**Legend**

- ■ mean obs: Tre
- △ lut2: Tor
- × lut25 (hhc): Tor
- + luttre: Tre

**Allowable Exposure Times**
(to work):
- warning non-accl: 13 min; body temperature increase
- danger non-accl: 16 min; body temperature increase
- warning accl: 13 min; body temperature increase
- danger accl: 16 min; body temperature increase

C-151
Tac from Randle and Legg (1985) (n=8) (exp. code: wk)
Ta=Tr=32.8°C, v=0.2 m/s, rh=62 %,
l=0.5 clo, fcl=1.2 (ND), im=0.39 (ND), M=310 W/m2, W=47 W/m2

Tac vs. time (minutes)

 lutiso Allowable Exposure Times:
warning non-accl: 25 min; body temperature increase
danger non-accl: 34 min; body temperature increase
warning accl: 36 min; body temperature increase
danger accl: 44 min; body temperature increase

Legend
■ mean obs: Tac
+sd
−sd
△ lut2: Tcr
× lut25 (hhow): Tcr
• lut25 (hhon): Tcr
+ luttre: Tre
Tsk from Randle and Legg (1985) (n=8) (exp. code: wk)

\( T_a = T_r = 32.8 \degree C, \theta = 0.2 \text{ m/s, rh} = 52 \% \),
\( l_c = 0.5 \text{ clo, fcl}=12 \text{ (ND)}, \text{ im}=0.39 \text{ (ND)}, M=310 \text{ W/m}^2, W=47 \text{ W/m}^2 \)
Tac from Randle and Legg (1985)
(n=8, decreasing to 2) (exp. code: cy)
Tₑ=ₜ=32.8 °C, v=0.2 m/s, rh=52 %,
lcl=0.5 clo, fcl=1.2 (ND), im=0.39 (ND), M=353 W/m², W=46 W/m²

Legend
- mean obs: Tac
  ±sd
  ±sd
  △ lut₂: Tₑr
  × lut₂5 (hhc): Tₑr
  ♦ lut₂5 (hhn): Tₑr
  + luttre: Tₑr

lutiso Allowable Exposure Times:
warning non-accl: 13 min; body temperature increase
danger non-accl: 19 min; body temperature increase
warning acl: 16 min; body temperature increase
danger acl: 26 min; body temperature increase
Tsk from Randle and Legg (1985)
(n=8, decreasing to 2) (exp. code: cy)
Te=Tr=32.8 °C, v=0.2 m/s, rh=62 %.
lcl=0.5 clo, fcl=12 (ND), im=0.39 (ND), M=353 W/m², W=48 W/m²
Tre from Raven and Horvath (1970) (n=11)

$T_a=T_r=5 \, ^{\circ}C$, $v=0.1 \, m/s$, $r_h=70 \%$

$\text{lcl}=0.1 \, \text{clo}$, $fcl=1$ (ND), $im=0.5$ (ND), $M=45 \, W/m^2$, $W=0 \, W/m^2$
Tsk from Raven and Horvath (1970) (n=11)
Ta=15°C, v=0.1 m/s, rh=70%,
lc=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=45 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- ±sd
- =sd
- lut2: Tsk
- × lut25 (hho): Tsk
M from Raven and Horvath (1970) (n=11)

Ta=Tr=5 C, v=0.1 m/s, rh=70 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=45 W/m2, W=0 W/m2

Legend
- mean obs: M
- +sd
- -sd
- Δ lut2: M
- × lut25 (hhc): M

metabolic rate (W/m2)

0  50  100  150

time (minutes)

0  50  100  150  200

C-158
Tre from Shvartz (1976) (n=6) (exp code: cool)

Ta=Tr=23.2 C, v=0.2 m/s, rh=48 %
kcl=0.1 clo, fccl=1 (ND), im=0.5 (ND), M=200 W/m², W=0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hlc): Tcr
+ luttre: Tre

 lutiso Allowable Exposure Times
warning non-accl: 480 min; unlimited duration
danger non-accl: 480 min; unlimited duration
warning accl: 480 min; unlimited duration
danger accl: 480 min; unlimited duration
Tsk from Shvartz (1976) (n=6) (exp code: cool)
Ta=23.2 °C, v=0.2 m/s, rh=48 %
k=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=200 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hnc): Tsk
Tre from Shvartz (1976) (n=6) (exp code: hot)

\[ T_e = T_r = 39.5 \, ^\circ C, \, v = 0.2 \, m/s, \, r_h = 52 \, \% \]

\[ lClo = 0.1 \, clo, \, fcl = 1 \, (ND), \, im = 0.5 \, (ND), \, M = 196 \, W/m^2, \, W = 0 \, W/m^2 \]

**Legend**
- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- + luttre: Tre

**Lutiso Allowable Exposure Times**
- warning non-accl: 57 min; body temperature increase
- danger non-accl: 131 min; body temperature increase
- warning accl: 242 min; body temperature increase
- danger accl: 325 min; excessive dehydration

C-161
Tsk from Shvartz (1976) (n=6) (exp code: hot)
Ta=33.5°C, v=0.2 m/s, rh=52 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=196 W/m², W=0 W/m²
Tac from Smith (1986) (n=8) (exp. code: wc)
Ta=Tr=28.9 C, v=0.1 m/s, rh=45 %,
lcl=0.7 clo, fcl=1.2 (ND), im=0.38 (ND),
M=190, 60 W/m2, W=0, 0 W/m2

Legend
- mean obs: Tac
- +sd
- -sd
- △ lut2: Tcr
- × lut25 (hho): Tcr
- + luttre: Tre

lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 190 min; excessive wettedness
danger non-accl: 228 min; excessive wettedness
warning accl: 480 min; unlimited duration
danger accl: 480 min; unlimited duration

C-163
Tsk from Smith (1986) (n=8) (exp. code: wc)

Ta=Tr=28.9 C, v=0.1 m/s, rh=45 %,
lcl=0.7 clo, fcl=1.2 (ND), im=0.38 (ND),
M=190, 60 W/m², W=0, 0 W/m²

Legend
- mean obs: Tsk
- ±sd
- ±sd
- lut2: Tsk
- lut25 (h+h): Tsk
Tac from Smith (1986) (n=8) (exp. code: wa)

Ta=Tr=28.9 C, v=0.1 m/s, rh=45 %,
lcl=1.0 clo, fcl=1.33 (ND), im=0.36 (ND),
M=190, 60 W/m2, W=0, 0 W/m2

Legend
- mean obs: Tac
- ±sd
- ±sd
- lut2: Tcr
- lut25 (hhg): Tcr
- luttre: Tre

Lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 96 min; excessive wettedness
danger non-accl: 116 min; excessive wettedness
warning accl: 222 min; excessive wettedness
danger accl: 267 min; excessive wettedness
Tsk from Smith (1986) (n=8) (exp. code: wa)

$T_a = T_r = 28.9\, \text{C, } v = 0.1\, \text{m/s, } \text{rh} = 45\%$, 
$l_c = 1.0, f_c = 1.33\, \text{(ND)}, \text{im} = 0.36\, \text{(ND)}$, 
$M = 190, 60\, \text{W/m}^2, W = 0, 0\, \text{W/m}^2$

Legend:
- **mean obs: Tsk**
- $\pm \text{sd}$
- $-\text{sd}$
- $\Delta$ lut2: Tsk
- $\times$ lut25 (hho): Tsk
Tac from Smith (1986) (n=8) (exp. code: hc)

$T_a = T_r = 39.6 \text{ C, } v = 0.1 \text{ m/s, } r_h = 35\%$

$l_c = 0.7 \text{ clo, } f_c = 1.2 \text{ (ND), } i_m = 0.38 \text{ (ND), }$

$M = 190, 60 \text{ W/m}^2, W = 0, 0 \text{ W/m}^2$

**Legend**

- mean obs: Tac
- +sd
- -sd
- $\triangle lut2$: Tc
- $\times lut25$ (hhc): Tc
- $\oplus lutre$: Tc

**Allowable Exposure Times (time weighted averages):**

- warning non-accl: 65 min; body temperature increase
- danger non-accl: 78 min; body temperature increase
- warning accl: 104 min; body temperature increase
- danger accl: 124 min; body temperature increase
Tsk from Smith (1986) (n=8) (exp. code: hc)
Ta=Tr=39.6 C, v=0.1 m/s, rh=35 %,
lcl=0.7 clo, fcl=1.2 (ND), im=0.38 (ND),
M=190, 60 W/m², W=0, 0 W/m²

Legend
- mean obs: Tsk
- ±sd
- ±sd
- lut2: Tsk
- lut25 (hcc): Tsk
Tac from Smith (1986) (n=8, decreasing to 4),
(exp. code: ha) Ta=Tr=39.6 °C, v=0.1 m/s, rh=35 %,
lcl=1.0 clo, fcl=1.33 (ND), im=0.36 (ND),
M=190, 60 W/m2, W=0, 0 W/m2

Legend
- mean obs: Tac
+sd
-sd
\triangle lut2: Tcr
\times lut25 (hhg): Tcr
\times luttre: Tre

Allowable Exposure Times
(time weighted averages):
warning non-accl: 46 min; body temperature increase
danger non-accl: 55 min; body temperature increase
warning accl: 58 min; body temperature increase
danger accl: 70 min; body temperature increase
Tsk from Smith (1986) (n=8, decreasing to 4),
(exp. code: ha) \( T_a=T_r=39.6 \) C, \( v=0.1 \) m/s, \( r_h=35 \) %,
\( lcl=1.0 \) clo, \( fcl=1.33 \) (ND), \( im=0.36 \) (ND),
\( M=190, 60 \) W/m2, \( W=0, 0 \) W/m2
Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f3)

T<sub>a</sub>=T<sub>r</sub>=28.0 C, v=0.1 m/s, rh=31 %

I<sub>c</sub>=0.1 clo, f<sub>c</sub>=1 (ND), im=0.5 (ND), M=47 W/m<sup>2</sup>, W=0 W/m<sup>2</sup>
Tty from Stolwijk & Hardy (1966) (n=3) (exp code: f3)

\[ T_a = T_r = 28.0 \, \text{C}, \quad v = 0.1 \, \text{m/s}, \quad \text{rh} = 31\% \\
\text{lcl} = 0.1 \, \text{clo}, \quad \text{fcl} = 1 \, (\text{ND}), \quad \text{im} = 0.5 \, (\text{ND}), \quad \text{M} = 47 \, \text{W/m}^2, \quad W = 0 \, \text{W/m}^2 \]
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f3)
Ta=Tr=28.0°C, v=0.1 m/s, rh=31%
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hho): Tsk
Esk from Stolwijk & Hardy (1986) (n=3) (exp code: f3)

$T_a = T_i = 28.0 \, ^\circ C, \, v = 0.1 \, m/s, \, r_h = 31 \%$

$c_l = 0.1 \, clo, \, f_c = 1 \, (ND), \, im = 0.5 \, (ND), \, M = 47 \, W/m^2, \, W = 0 \, W/m^2$

Legend

- ■ mean obs: Esk
- △ lut2: Esk
- ☓ lut25 (hhc): Esk
M from Stolwijk & Hardy (1966) (n=3) (exp code: f3)

$T_a=T_r=28.0\,\text{C}$, $v=0.1\,\text{m/s}$, $r_h=31\%$

$l_c=0.1\,\text{clo}$, $f_c=1\,(\text{ND})$, $i_m=0.5\,(\text{ND})$, $M=47\,\text{W/m2}$, $W=0\,\text{W/m2}$

**Legend**
- mean obs: $M$
- lut2: $M$
- lut25 (hhc): $M$
Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f4)

T_e=T_t=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
l_cl=0.1 clo, f_cl=1 (ND), i_m=0.5 (ND), M=47 W/m^2, W=0 W/m^2

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hgc): Tcr
- luttre: Tre

Lutiso Allowable Exposure Times
(time weighted averages):
- warning non-accl: 480 min; unlimited duration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration
Ty from Stolwijk & Hardy (1966) (n=3) (exp code: f4)

Ta=Tr=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²

Legend

- mean obs: Ty
- lut2: Tcr
- lut25 (hac): Tcr
- luttre: Ttre

Lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl: 480 min; unlimited duration
warning accl: 480 min; unlimited duration
danger accl: 480 min; unlimited duration
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f4)

Ta=Tr=27.8, 33.3, 28.0 °C, v=0.1 m/s, rh=37, 34, 37 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hhc): Tsk
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f4)

$T_a = T_r = 27.8, 33.3, 28.0 \, ^\circ C$, $v = 0.1 \, m/s$, $r_h = 37, 34, 37 \%$

$l_d = 0.1 \, hlo, f_c = 1 \, (ND)$, $i_m = 0.5 \, (ND)$, $M = 47 \, W/m^2$, $W = 0 \, W/m^2$

**Legend**
- mean obs: Esk
- lut2: Esk
- lut25 (hhc): Esk
M from Stolwijk & Hardy (1966) (n=3) (exp code: f4)
Ta=Tr=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

Legend
- mean obs: M
- lut2: M
- lut25 (hhc): M
$T_{re}$ from Stolwijk & Hardy (1966) ($n=3$) (exp code: f5)

$T_a = 28.5, 37.5, 28.5$ C, $v=0.1$ m/s, $r_h=40, 33, 41$

$I_c=0.1$ clo, $f_c=1$ (ND), $i_m=0.5$ (ND), $M=47$ W/m2, $W=0$ W/m2

Legend:
- mean obs: $T_{re}$
- lut2: $T_c$
- lut25 (hhc): $T_c$
- luttre: $T_{re}$

Lutiso Allowable Exposure Times (time weighted averages):
- warning non-accl: 480 min; unlimited duration
- danger non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration
Tty from Stolwijk & Hardy (1966) (n=3) (exp code: f5)
Te=Tt=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

Legend
- mean obs: Tty
- lut2: Tcr
- lut25 (hho): Tcr
- lutfre: Tre

lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f5)
Ta=Tr=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²

Legend
■ mean obs: Tsk
△ lut2: Tsk
× lut25 (hhc): Tsk
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f5)
Ta=Tr=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

**Legend**
- ■ mean obs: Esk
- △ lut2: Esk
- × lut25 (thc); Esk
M from Stotwijk & Hardy (1966) (n=3) (exp code: f5)

Ta=Tr=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
lc=0.1 clo, fc=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

Legend
- mean obs: M
- lut2: M
- lut25 (hhc): M
Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f6)

\[ Ta = \{28.0, 42.5, 28.1 \} \text{ C}, v = 0.1 \text{ m/s}, rh = \{37, 28, 33\} \%
\]

\[ lc = 0.1 \text{ clo}, fc = 1 \text{ (ND)}, im = 0.5 \text{ (ND)}, M = 47 \text{ W/m}^2, W = 0 \text{ W/m}^2 \]

---

**Legend**

- **mean obs: Tre**
- \( \triangle \) lut2: Tcr
- \( \times \) lut25 (hhg): Tcr
- \( + \) luttre: Tre

---

**Lutiso Allowable Exposure Times**

(time weighted averages):

- **warning non-accl**: 480 min; unlimited duration
- **danger non-accl**: 480 min; unlimited duration
- **warning accl**: 450 min; excessive dehydration
- **danger accl**: 400 min; excessive dehydration

---

C-186
Tty from Stolwijk & Hardy (1966) (n=3) (exp code: f6)

Ta=Tr=28.0, 42.5, 28.1 C, v=0.1 m/s, rh=37, 28, 33 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
Ta=Tr=28.0, 42.5, 28.1°C, v=0.1 m/s, rh=37, 28, 33 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
$T_a=28.0$, 42.5, 28.1°C, $v=0.1$ m/s, $r_h=37$, 28, 33%
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), $M=47$ W/m², $W=0$ W/m²
M from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
\( T_a=T_r=28.0, 42.5, 28.1 \, ^\circ C, \, v=0.1 \, m/s, \, r_h=37, 28, 33 \, % \)
\( l_c=0.1 \, c, \, f_c=1 \, (ND), \, i_m=0.5 \, (ND), \, M=47 \, W/m2, \, W=0 \, W/m2 \)
Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f7)

Ta=Tt=28.1, 47.8, 28.3°C, v=0.1 m/s, rh=43, 27, 44% 
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m², W=0 W/m²

Legend

- ■ mean obs: Tre
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- + luttre: Tre

Lutiso Allowable Exposure Times
(to 47°C, 27%):
- warning non-accl: 65 min; body temperature increase
- (time weighted averages):
  - danger non-accl: 480 min; unlimited duration
  - warning accl: 480 min; unlimited duration
  - danger accl: 480 min; unlimited duration

C-191
Temperature from Stolwijk & Hardy (1966) (n=3) (exp code: f7)
Ta=Tt=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

Legend
- mean obs: Tty
- lut2: Tcr
- lut25 (hhe): Tcr
- luttre: Tre

Lutiso Allowable Exposure Times
(to 47 C, 27 %):
warning non-accl: 65 min; body temperature increase
(time weighted averages):
danger non-accl: 480 min; unlimited duration
warning accl: 480 min; unlimited duration
danger accl: 480 min; unlimited duration

C-192
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f7)

Ta=Tr=28.1, 47.8, 28.3 °C, v=0.1 m/s, rh=43, 27, 44 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

Legend
■ mean obs: Tsk
△ lut2: Tsk
× lut25 (hhc): Tsk
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f7)
Ta=T=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
lcl=0.1 clo, fcl=1 (ND), im=0.6 (ND), M=47 W/m2, W=0 W/m2

Legend
- mean obs: Esk
- lut2: Esk
- lut25 (hhc): Esk
M from Stolwijk & Hardy (1966) (n=3) (exp code: f7)

Ta=Tr=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 28)

\[
\begin{align*}
T_a &= 28 \, \text{C}, \, v = 0.1 \, \text{m/s}, \, r_h = 40 \, \%, \\
I_c &= 0.1 \, \text{clo}, \, f_c = 1, \, \text{im} = 0.5, \, M = 53 \, \text{W/m}^2, \, W = 0 \, \text{W/m}^2
\end{align*}
\]

Legend

- mean obs: Tre
- +sd
- -sd
- \(\Delta\) lut2: T_c
- \(\times\) lut25 (hhc): T_c
- + luttre: Tre
Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 28)

Ta=28 C, v=0.1 m/s, rh=40 %,
lcl=0.1 clo, fcl=1, im=0.5, M=53 W/m², W=0 W/m²

Legend
- mean obs: Tsk
- ±sd
- ±sd
- lut2: Tsk
- lut25 (hhc): Tsk
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 20)

$T_a = 20 \, ^\circ C$, $v=0.1 \, m/s$, $r_h=40 \, \%$,

$l_c=0.1 \, clo$, $f_c=1$, $i_m=0.5$, $M=53 \, W/m^2$, $W=0 \, W/m^2$
Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 20)

Ta=20 C, v=0.1 m/s, rh=40 %,
lcl=0.1 clo, fcl=1, im=0.5, M=53 W/m², W=0 W/m²
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 15)

$T_a = 15\, ^\circ C$, $v=0.1\, m/s$, $r_h=40\%$

$I_c = 0.1\, clo$, $f_c = 1$, $im=0.5$, $M=53\, W/m^2$, $W=0\, W/m^2$
Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 15)

$T_a = 15 \, ^\circ C$, $v = 0.1 \, m/s$, $r_h = 40 \%$

$\text{lcl} = 0.1 \, \text{clo}$, $fcl = 1$, $\text{i}m = 0.5$, $M = 53 \, W/m^2$, $W = 0 \, W/m^2$

Legend
- ■ mean obs: $T_{sk}$
- +sd
- -sd
- △ $I_{ut}2$: $T_{sk}$
- × $I_{ut}25$ (hhe): $T_{sk}$
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 10)

$T_a=10 \, ^\circ C$, $v=0.1 \, m/s$, $r_h=40 \, \%$.

$m=0.1 \, clo$, $fcl=1$, $im=0.5$, $M=53 \, W/m^2$, $W=0 \, W/m^2$
Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 10)
\( T_a=10 \, ^\circ C, \, \nu=0.1 \, m/s, \, r_h=40 \% \),
\( t_{cl}=0.1 \, \text{clo}, \, f_{cl}=1, \, i_m=0.5, \, M=53 \, W/m^2, \, W=0 \, W/m^2 \)
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e1)

$T_a = T_r = 10.0, 21.7 \, ^\circ C, v=0.15 \, m/s, \, r_h=81.69 \, \%, \, l_c=1.1 \, \text{clo,}$

$f_c=1.34 \, (\text{ND}), \, i_m=0.35 \, (\text{ND}), \, M=196, 56 \, W/m^2, \, W=32, 0 \, W/m^2$

---

**Legend**

- **mean obs: Tre**
- $\Delta$ lut2: Tcr
- $\times$ lut25 (hhc): Tcr
- $\phi$ lut25 (hhn): Tcr
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e1)
Ta=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, lcl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e2)

Ta=Tr=3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, lc=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hnc): Tcr
- lut25 (hnr): Tcr

Graph showing temperature changes over time with various conditions and symbols indicating different experimental conditions.
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e2)
Ta=Tr=3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, lcl=1.1 clo,
fc=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2

Legend
■ mean obs: Tsk
△ lut2: Tsk
× lut25 (hhc): Tsk
♦ lut25 (hhn): Tsk
Tre from Walsh and Graham (1988) (n=8, males) (exp. code: e3)

Ta=Tr-3.5, 21.7°C, v=0.15 m/s, rh=81, 59 %, kcl=1.1 clo,
fc=1.34 (ND), ilm=0.35 (ND), M=196, 66 W/m², W=32, 0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hhn): Tcr
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e3)

Ta=Tr=-3.5, 21.7 °C, v=0.15 m/s, rh=81, 59 %, lcl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 66 W/m², W=32, 0 W/m²

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hhc): Tsk
- lut25 (hhn): Tsk

Ta=-3.5 °C, rh=81 %
Ta=21.7 °C, rh=59 %,
rest

Temperature (degree Celsius vs. time (minutes))
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e4)

$T_a = T_r = 10.0^\circ C$, $v=0.15$ m/s, $rh=81$, $59 \%$, $clo=1.1$ clo,
$fcl=1.34$ (ND), $im=0.35$ (ND), $M=196$, $56$ W/m$^2$, $W=32$, $0$ W/m$^2$

Legend

- mean obs: $T_{re}$
- lut2: $T_{cr}$
- lut25 (hhc): $T_{cr}$
- lut25 (hhn): $T_{cr}$
Ta=T=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, kcl=1.1 clo, fcl=1.34 (ND), im=0.35 (ND), M=196, 66 W/m2, W=32, 0 W/m2

Legend:
- mean obs: Tsk
- lut2: Tsk
- lut25 (hhc): Tsk
- lut25 (hhh): Tsk

Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e4)
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: el)

Ta=Tr=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, clo=1.1 clo,
fclo=1.34 (ND), im=0.35 (ND), M=218, 62 W/m², W=36, 0 W/m²

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hhn): Tcr
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e1)
Ta=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, lc=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m², W=36, 0 W/m²
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e2)

\[ \text{Ta}=3.5, 21.7 \text{ C, } v=0.15 \text{ m/s, rh}=81, 59 \% \text{, kcl}=1.1 \text{ clo,} \]
\[ \text{fcl}=1.34 \text{ (ND), im}=0.35 \text{ (ND), M}=218, 62 \text{ W/m2, W}=36, 0 \text{ W/m2} \]

**Legend**
- ■ mean obs: Tcr
- △ lut2: Tcr
- × lut25 (hhc): Tcr
- Φ lut25 (hhn): Tcr

![Graph showing temperature changes over time](image-url)
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e2)

\[ T_a = T_r = 3.5, \ 21.7 \ \text{C}, \ v = 0.15 \ \text{m/s}, \ rh = 81, 59 \%, \ \text{clo} = 1.1 \ \text{clo}, \ fcl = 1.34 \ \text{(ND)}, \ \text{im} = 0.35 \ \text{(ND)}, \ M = 218, 62 \ \text{W/m2}, \ W = 38, 0 \ \text{W/m2} \]
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e3)

Ta=Tt=3.5, 21.7°C, v=0.15 m/s, rh=81, 59 %, acl=1.1 clo,
fd=134 (ND), im=0.35 (ND), M=218, 62 W/m², W=36, 0 W/m²

Legend

- mean obs: Tre
- lut2: Tcr
- lut25 (hhc): Tcr
- lut25 (hhn): Tcr

C-216
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e3)
Ta=Tt = -3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, lcl=1.1 clo, fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=38, 0 W/m2

Legend
- mean obs: Tsk
- lut2: Tsk
- lut25 (hnc): Tsk
- lut25 (hnn): Tsk
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e4)

Ta=Tm=-10.0, 21.7 C, v=0.15 m/s, rh=81, 69 %, kcl=11 clo,

fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2

Legend
- mean obs: Tre
- lut2: Tcr
- lut25 (hhe): Tcr
- lut25 (hhn): Tcr
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e4)
Ta=Tt=-10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, kcl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2

![Graph showing temperature changes over time with legends for different conditions.]
Tre from Young et al (1986) (n=7)

Ta=Tr=5 C, v=0.1 m/s, rh=30 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m², W=0 W/m²
Tsk from Young et al (1986) (n=7)
Ta=Tr=5°C, v=0.1 m/s, rh=30%,
cl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m², W=0 W/m²
M from Young et al (1986) (n=7)
Ta=Tr=5 C, v=0.1 m/s, rh=30 %,
lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m², W=0 W/m²

Legend
- mean obs: M
+sd
-sd
Δ lut2: M
X lut25 (hhc): M
APPENDIX D

TABLES OF RMSDS BETWEEN OBSERVED AND PREDICTED RESPONSES
FOR EACH EXPERIMENTAL DATA SET
### Table D-1. Rmsd’s (°C) between observed and predicted responses for Avellini et al. (1980) core (Tcr, rectal) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Males Tcr</th>
<th>Males Tsk</th>
<th>Females Tcr</th>
<th>Females Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.25</td>
<td>0.73</td>
<td>0.19</td>
<td>0.54</td>
</tr>
<tr>
<td>lut2</td>
<td>0.61</td>
<td>1.00</td>
<td>0.23</td>
<td>0.39</td>
</tr>
<tr>
<td>lut25 (h hc)</td>
<td>0.62</td>
<td>1.65</td>
<td>0.22</td>
<td>1.27</td>
</tr>
<tr>
<td>lut25 (h hn)</td>
<td>0.69</td>
<td>1.76</td>
<td>0.31</td>
<td>1.33</td>
</tr>
<tr>
<td>luttre</td>
<td>1.45</td>
<td>/</td>
<td>1.01</td>
<td>/</td>
</tr>
</tbody>
</table>

### Table D-2. Rmsd’s (°C) between observed and predicted responses for Budd (1965) core (Tcr, rectal) temperature data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Tcr</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.35</td>
</tr>
<tr>
<td>lut25 (h hc)</td>
<td>0.78</td>
</tr>
<tr>
<td>lut25 (h hn)</td>
<td>0.79</td>
</tr>
<tr>
<td>Environment</td>
<td>A</td>
</tr>
<tr>
<td>-------------</td>
<td>---------</td>
</tr>
<tr>
<td>sd (obs)</td>
<td>0.16</td>
</tr>
<tr>
<td>lut2</td>
<td>0.23</td>
</tr>
<tr>
<td>lut25</td>
<td>0.29</td>
</tr>
<tr>
<td>luttre</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table D-3. Rmsd's (°C) between observed and predicted responses for Chappuis et al. (1976) core (Tcr, tympanic), and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>Environment</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>C+R</td>
<td>E</td>
<td>C+R</td>
</tr>
<tr>
<td>lut2</td>
<td>37</td>
<td>35</td>
<td>32</td>
</tr>
<tr>
<td>lut25</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Table D-4. Rmsd's (W/m²) between observed and predicted responses for Chappuis et al. (1976) dry cooling (C+R) and total evaporative cooling (E) data.
### Table D-5. Rmsd's (°C) between observed and predicted responses for Haisman and Goldman (1974) core (Tre, rectal) and mean skin temperature (Tsk) data for hot/wet environments.

<table>
<thead>
<tr>
<th>Experiment Code</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.83</td>
<td>2.08</td>
<td>0.87</td>
<td>1.95</td>
<td>0.37</td>
<td>1.63</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.32</td>
<td>1.46</td>
<td>0.37</td>
<td>1.36</td>
<td>0.27</td>
<td>1.16</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>0.25</td>
<td>1.29</td>
<td>0.26</td>
<td>1.19</td>
<td>0.27</td>
<td>1.12</td>
</tr>
<tr>
<td>luttre</td>
<td>0.55</td>
<td></td>
<td>0.61</td>
<td></td>
<td>0.51</td>
<td></td>
</tr>
</tbody>
</table>

### Table D-6. Rmsd's (°C) between observed and predicted responses for Haisman and Goldman (1974) core (Tre, rectal) and mean skin temperature (Tsk) data for hot/dry environments.

<table>
<thead>
<tr>
<th>Experiment Code</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>1.03</td>
<td>1.78</td>
<td>1.03</td>
<td>1.96</td>
<td>0.53</td>
<td>1.73</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.50</td>
<td>1.40</td>
<td>0.55</td>
<td>1.63</td>
<td>0.29</td>
<td>1.52</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>0.48</td>
<td>1.45</td>
<td>0.52</td>
<td>1.66</td>
<td>0.33</td>
<td>1.67</td>
</tr>
<tr>
<td>luttre</td>
<td>0.69</td>
<td></td>
<td>0.69</td>
<td></td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>model</td>
<td>Tga</td>
<td>Tre</td>
<td>Tsk</td>
<td>Tga</td>
<td>Tre</td>
<td>Tsk</td>
</tr>
<tr>
<td>-----------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>sd (obs)</td>
<td>0.33</td>
<td>0.42</td>
<td>1.27</td>
<td>0.35</td>
<td>1.10</td>
<td>2.09</td>
</tr>
<tr>
<td>lut2</td>
<td>0.65</td>
<td>0.79</td>
<td>5.59</td>
<td>0.56</td>
<td>0.51</td>
<td>5.74</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.30</td>
<td>0.36</td>
<td>2.89</td>
<td>0.86</td>
<td>1.05</td>
<td>4.34</td>
</tr>
<tr>
<td>lut25 (hnn)</td>
<td>0.40</td>
<td>0.38</td>
<td>1.49</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Table D-7. Rmsd's (°C) between observed and predicted responses for Hampton and Knibbs (1986) gastric (Tga), rectal (Tre) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>model</th>
<th>Tga</th>
<th>Tre</th>
<th>Tsk</th>
<th>Tga</th>
<th>Tre</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.33</td>
<td>0.42</td>
<td>1.27</td>
<td>0.35</td>
<td>1.11</td>
<td>2.09</td>
</tr>
<tr>
<td>lut2</td>
<td>0.94</td>
<td>1.07</td>
<td>5.60</td>
<td>0.61</td>
<td>0.54</td>
<td>1.15</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.38</td>
<td>0.40</td>
<td>4.42</td>
<td>0.74</td>
<td>0.90</td>
<td>1.90</td>
</tr>
<tr>
<td>lut25 (hnn)</td>
<td>0.40</td>
<td>0.44</td>
<td>4.99</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Table D-8. Rmsd's (°C) between observed and predicted responses for Hampton and Knibbs (1986) gastric (Tga), rectal (Tre) and mean skin temperature (Tsk) data, clothing insulation adjusted during exercise periods.
Table D-9. Rmsd's (°C) between observed and predicted responses for Hardy and Stolwijk (1966) tympanic (Tty) and rectal (Tre) temperature data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.13</td>
<td>0.44</td>
<td>0.17</td>
<td>0.46</td>
<td>0.49</td>
<td>0.80</td>
<td>0.44</td>
<td>0.78</td>
</tr>
<tr>
<td>lut25</td>
<td>0.12</td>
<td>0.29</td>
<td>0.14</td>
<td>0.28</td>
<td>0.53</td>
<td>0.82</td>
<td>0.41</td>
<td>0.74</td>
</tr>
<tr>
<td>luttre</td>
<td>0.84</td>
<td>0.61</td>
<td>0.70</td>
<td>0.54</td>
<td>0.38</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table D-10. Rmsd's (°C) between observed and predicted responses for Hardy and Stolwijk (1966) mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>Model</th>
<th>M</th>
<th>Esk</th>
<th>M</th>
<th>Esk</th>
<th>M</th>
<th>Esk</th>
<th>M</th>
<th>Esk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>15</td>
<td>5</td>
<td>6</td>
<td>16</td>
<td>32</td>
<td>1</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>lut25</td>
<td>6</td>
<td>9</td>
<td>2</td>
<td>13</td>
<td>18</td>
<td>5</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

Table D-11. Rmsd's (W/m²) between observed and predicted responses for Hardy and Stolwijk (1966) metabolic rate (M) and evaporative cooling from the skin (Esk) data.
<table>
<thead>
<tr>
<th>clothing</th>
<th>nude</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.33</td>
<td>0.33</td>
<td>0.27</td>
</tr>
<tr>
<td>lut2</td>
<td>0.20</td>
<td>0.37</td>
<td>1.27</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.22</td>
<td>0.20</td>
<td>0.60</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>/</td>
<td>0.21</td>
<td>/</td>
</tr>
<tr>
<td>luttre</td>
<td>0.36</td>
<td>0.56</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Table D-12. Rmsd's (°C) between observed and predicted responses for Henane et al. (1979) core (Tcr, rectal) temperature data.

<table>
<thead>
<tr>
<th>experiment code</th>
<th>20</th>
<th>35</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>Tcr</td>
<td>Tsk</td>
<td>Tcr</td>
</tr>
<tr>
<td>sd (obs)</td>
<td>0.16</td>
<td>0.50</td>
<td>0.16</td>
</tr>
<tr>
<td>lut2</td>
<td>0.24</td>
<td>1.10</td>
<td>0.57</td>
</tr>
<tr>
<td>lut25</td>
<td>0.18</td>
<td>1.83</td>
<td>0.19</td>
</tr>
<tr>
<td>luttre</td>
<td>0.31</td>
<td>/</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table D-13. Rmsd's (°C) between observed and predicted responses for Hirata et al. (1983) core (Tcr, oesophageal) and mean skin temperature (Tsk) data.
Table D-14. Rmsd's (°C) between observed and predicted responses for Lampietro et al. (1958) core (rectal) temperature data.

<table>
<thead>
<tr>
<th>environment</th>
<th>model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lut2</td>
<td>0.37</td>
<td>0.49</td>
<td>0.41</td>
<td>0.38</td>
<td>0.36</td>
<td>0.47</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lut25</td>
<td>0.81</td>
<td>0.75</td>
<td>1.02</td>
<td>0.72</td>
<td>0.90</td>
<td>0.77</td>
<td>1.10</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>luttre</td>
<td>0.20</td>
<td>/</td>
<td>/</td>
<td>0.21</td>
<td>/</td>
<td>/</td>
<td>0.16</td>
<td></td>
</tr>
</tbody>
</table>

Table D-15. Rmsd's (°C) between observed and predicted responses for Lampietro et al. (1958) mean skin temperature data.

<table>
<thead>
<tr>
<th>environment</th>
<th>model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lut2</td>
<td>2.34</td>
<td>1.44</td>
<td>1.76</td>
<td>1.58</td>
<td>1.47</td>
<td>1.99</td>
<td>1.91</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>lut25</td>
<td>1.23</td>
<td>0.84</td>
<td>1.89</td>
<td>0.92</td>
<td>0.75</td>
<td>1.08</td>
<td>0.93</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table D-16. Rmsd's (W/m²) between observed and predicted responses for Lampietro et al. (1958) metabolic rate data.

<table>
<thead>
<tr>
<th>environment</th>
<th>model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lut2</td>
<td>18</td>
<td>25</td>
<td>38</td>
<td>27</td>
<td>23</td>
<td>30</td>
<td>28</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>lut25</td>
<td>18</td>
<td>17</td>
<td>47</td>
<td>16</td>
<td>21</td>
<td>20</td>
<td>34</td>
<td>28</td>
</tr>
</tbody>
</table>

D-8
### Table D-17. Rmsd’s (°C) between observed and predicted responses for Iampietro and Buskirk (1960) rectal (Tre) temperature data.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td></td>
<td>0.70</td>
<td>0.77</td>
<td>0.53</td>
<td>0.66</td>
<td>0.64</td>
<td>0.43</td>
<td>0.52</td>
<td>0.82</td>
</tr>
<tr>
<td>lut25 (hkc)</td>
<td></td>
<td>0.97</td>
<td>1.14</td>
<td>0.74</td>
<td>0.93</td>
<td>0.87</td>
<td>0.59</td>
<td>0.65</td>
<td>1.17</td>
</tr>
<tr>
<td>lut25 (hkn)</td>
<td></td>
<td>1.09</td>
<td>1.25</td>
<td>0.83</td>
<td>1.06</td>
<td>0.95</td>
<td>0.68</td>
<td>0.75</td>
<td>1.28</td>
</tr>
</tbody>
</table>

### Table D-18. Rmsd’s (°C) between observed and predicted responses for Iampietro and Buskirk (1960) mean skin (Tsk) temperature data.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td></td>
<td>1.62</td>
<td>1.66</td>
<td>0.94</td>
<td>1.48</td>
<td>0.71</td>
<td>0.41</td>
<td>0.58</td>
<td>1.98</td>
</tr>
<tr>
<td>lut25 (hkc)</td>
<td></td>
<td>2.14</td>
<td>2.28</td>
<td>0.81</td>
<td>1.95</td>
<td>0.85</td>
<td>0.58</td>
<td>0.78</td>
<td>2.60</td>
</tr>
<tr>
<td>lut25 (hkn)</td>
<td></td>
<td>1.78</td>
<td>1.91</td>
<td>0.65</td>
<td>1.62</td>
<td>0.64</td>
<td>0.44</td>
<td>0.63</td>
<td>2.22</td>
</tr>
</tbody>
</table>

### Table D-19. Rmsd’s (W/m²) between observed and predicted responses for Iampietro and Buskirk (1960) metabolic rate (M) data.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td></td>
<td>5</td>
<td>8</td>
<td>15</td>
<td>9</td>
<td>13</td>
<td>17</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>lut25 (hkc)</td>
<td></td>
<td>16</td>
<td>18</td>
<td>11</td>
<td>18</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>lut25 (hkn)</td>
<td></td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>8</td>
<td>13</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>model</td>
<td>Tac (°C)</td>
<td>Tre (°C)</td>
<td>Tsk (°C)</td>
<td>Esk (°C)</td>
<td>Tac (°C)</td>
<td>Tre (°C)</td>
<td>Tsk (°C)</td>
<td>Esk (°C)</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>lut²</td>
<td>0.52</td>
<td>0.50</td>
<td>0.73</td>
<td>59</td>
<td>0.40</td>
<td>0.66</td>
<td>0.79</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>lut₅</td>
<td>0.30</td>
<td>0.73</td>
<td>0.36</td>
<td>67</td>
<td>0.48</td>
<td>1.05</td>
<td>0.69</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>lut re</td>
<td>0.75</td>
<td>0.25</td>
<td>/</td>
<td>/</td>
<td>0.72</td>
<td>0.30</td>
<td>/</td>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>

Table D-20. Rmsd’s between observed and predicted responses for K bayashi et al. (1980) auditory canal (Tac), rectal (Tre) and mean skin temperature (Tsk), and the evaporative cooling from the skin (Esk) data.

<table>
<thead>
<tr>
<th>model</th>
<th>WD-1</th>
<th>WD-2</th>
<th>WD-3</th>
<th>WH-1</th>
<th>WH-2</th>
<th>WH-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.39</td>
<td>0.24</td>
<td>0.17</td>
<td>0.30</td>
<td>0.22</td>
<td>0.25</td>
</tr>
<tr>
<td>lut²</td>
<td>0.33</td>
<td>0.46</td>
<td>0.19</td>
<td>0.12</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>lut₅</td>
<td>0.18</td>
<td>0.27</td>
<td>0.27</td>
<td>0.14</td>
<td>0.16</td>
<td>0.11</td>
</tr>
<tr>
<td>lut tre</td>
<td>0.51</td>
<td>0.47</td>
<td>0.98</td>
<td>0.66</td>
<td>0.59</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table D-21. Rmsd’s (°C) between observed oesophageal and predicted core temperature responses for Mairiaux et al. (1986) data.

<table>
<thead>
<tr>
<th>model</th>
<th>WD-1</th>
<th>WD-2</th>
<th>WD-3</th>
<th>WH-1</th>
<th>WH-2</th>
<th>WH-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.44</td>
<td>0.29</td>
<td>0.23</td>
<td>0.20</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>lut²</td>
<td>0.34</td>
<td>0.53</td>
<td>0.18</td>
<td>0.34</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>lut25 (hcc)</td>
<td>0.19</td>
<td>0.29</td>
<td>0.10</td>
<td>0.28</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>lut tre</td>
<td>0.34</td>
<td>0.20</td>
<td>0.67</td>
<td>0.36</td>
<td>0.27</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table D-22. Rmsd’s (°C) between observed rectal and predicted core temperature responses for Mairiaux et al. (1986) data.

D-10
Table D-23. Rmsd’s between observed and predicted responses for Mitchell et al. (1976) core (Tcr, rectal) and mean skin temperature (Tsk), and the dry (C+R) and total evaporative cooling (E) data.

<table>
<thead>
<tr>
<th>model</th>
<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
<th>C+R (W/m²)</th>
<th>E (°C)</th>
<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
<th>C+R (W/m²)</th>
<th>E (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.48</td>
<td>0.55</td>
<td>26</td>
<td>51</td>
<td>0.34</td>
<td>0.59</td>
<td>24</td>
<td>35</td>
</tr>
<tr>
<td>lut2</td>
<td>0.55</td>
<td>0.57</td>
<td>62</td>
<td>40</td>
<td>0.33</td>
<td>0.78</td>
<td>62</td>
<td>55</td>
</tr>
<tr>
<td>lut25</td>
<td>0.43</td>
<td>0.58</td>
<td>75</td>
<td>61</td>
<td>0.37</td>
<td>1.05</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>lut'tre</td>
<td>1.19</td>
<td>/</td>
<td>/</td>
<td>0.93</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td></td>
</tr>
</tbody>
</table>

Table D-24. Rmsd’s (°C) between observed and predicted responses for Nielsen and Nielsen (1984) rectal (Tre), oesophageal (Toe) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>model</th>
<th>Tre</th>
<th>Toe</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.08</td>
<td>0.16</td>
<td>1.39</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.39</td>
<td>0.22</td>
<td>1.27</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>0.36</td>
<td>0.21</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table D-25. Rmsd’s between observed and predicted responses for O’Hanlon and Horvath (1970) core (Tcr, rectal) and metabolic rate (M) data.

<table>
<thead>
<tr>
<th>model</th>
<th>Tcr (°C)</th>
<th>M (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.38</td>
<td>20</td>
</tr>
<tr>
<td>lut2</td>
<td>0.64</td>
<td>28</td>
</tr>
<tr>
<td>lut25</td>
<td>1.09</td>
<td>24</td>
</tr>
</tbody>
</table>
### Table D-26. Rmsd’s (°C) between observed and predicted responses for Pimental et al. (1987) core (Tcr, rectal) temperature data.

<table>
<thead>
<tr>
<th>Walk</th>
<th>Carry</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>Tcr</td>
</tr>
<tr>
<td>sd (obs)</td>
<td>0.23</td>
</tr>
<tr>
<td>lut2</td>
<td>0.27</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.51</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>0.47</td>
</tr>
<tr>
<td>luttre</td>
<td>0.56</td>
</tr>
</tbody>
</table>

### Table D-27. Rmsd’s (°C) between observed and predicted responses for Randle and Legg (1985) core (Tcr, auditory canal) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th></th>
<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
<th>M (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>Tcr</td>
<td>Tsk</td>
<td>M</td>
</tr>
<tr>
<td>sd (obs)</td>
<td>/</td>
<td>0.29</td>
<td>4</td>
</tr>
<tr>
<td>lut2</td>
<td>1.27</td>
<td>0.87</td>
<td>15</td>
</tr>
<tr>
<td>lut25</td>
<td>1.57</td>
<td>0.98</td>
<td>20</td>
</tr>
</tbody>
</table>

### Table D-28. Rmsd’s between observed and predicted responses for Raven and Horvath (1970) core (Tcr, rectal), mean skin temperature (Tsk), and metabolic rate (M) data.
Table D-29. Rmsd’s (°C) between observed and predicted responses for Shvartz (1976) core (Tcr, rectal) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>model</th>
<th>cool Tcr</th>
<th>cool Tsk</th>
<th>hot Tcr</th>
<th>hot Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.90</td>
<td>1.96</td>
<td>0.58</td>
<td>0.47</td>
</tr>
<tr>
<td>lut25</td>
<td>0.52</td>
<td>1.88</td>
<td>0.31</td>
<td>1.69</td>
</tr>
<tr>
<td>luttre</td>
<td>0.47</td>
<td>/</td>
<td>0.49</td>
<td>/</td>
</tr>
</tbody>
</table>

Table D-30. Rmsd’s (°C) between observed and predicted responses for core (Tcr, auditory canal) and mean skin temperature (Tsk) data (Smith, 1986); wc = warm/control, wa = warm/action coverall, hc = hot/control, ha = hot/action coverall.
Table D-31. Rmsd’s (°C) between observed and predicted responses for Stolwijk and Hardy (1966) tympanic (Tty) and rectal (Tre) temperature data.

<table>
<thead>
<tr>
<th>mode</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
<th>Tty</th>
<th>Tre</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.37</td>
<td>0.39</td>
<td>0.16</td>
<td>0.32</td>
<td>0.16</td>
<td>0.31</td>
<td>0.32</td>
<td>0.31</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>lut2</td>
<td>0.19</td>
<td>0.20</td>
<td>0.03</td>
<td>0.19</td>
<td>0.05</td>
<td>0.18</td>
<td>0.20</td>
<td>0.21</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>luttre</td>
<td>0.35</td>
<td>0.33</td>
<td>0.45</td>
<td>0.31</td>
<td>0.49</td>
<td>0.34</td>
<td>0.33</td>
<td>0.36</td>
<td>0.15</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table D-32. Rmsd’s (°C) between observed and predicted responses for Stolwijk and Hardy (1966) mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>model</th>
<th>f3</th>
<th>f4</th>
<th>f5</th>
<th>f6</th>
<th>f7</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.34</td>
<td>0.39</td>
<td>0.33</td>
<td>0.62</td>
<td>0.36</td>
</tr>
<tr>
<td>lut25</td>
<td>0.47</td>
<td>0.32</td>
<td>0.36</td>
<td>0.22</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table D-33. Rmsd’s (W/m^2) between observed and predicted responses for Stolwijk and Hardy (1966) metabolic rate (M) and evaporative cooling from the skin (Esk) data.

<table>
<thead>
<tr>
<th>model</th>
<th>f3</th>
<th>f4</th>
<th>f5</th>
<th>f6</th>
<th>f7</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>7</td>
<td>8</td>
<td>1</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>lut25</td>
<td>6</td>
<td>9</td>
<td>1</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>
### Table D-34. Rmsd’s (°C) between observed and predicted responses for Wagner and Horvath (1985) core (Tcr, rectal) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd obs</td>
<td>0.32</td>
<td>0.79</td>
<td>0.32</td>
<td>0.79</td>
<td>0.32</td>
<td>0.79</td>
<td>0.32</td>
<td>0.79</td>
</tr>
<tr>
<td>lut2</td>
<td>0.09</td>
<td>0.48</td>
<td>0.19</td>
<td>0.28</td>
<td>0.33</td>
<td>0.61</td>
<td>0.37</td>
<td>1.16</td>
</tr>
<tr>
<td>lut β</td>
<td>0.20</td>
<td>0.44</td>
<td>0.21</td>
<td>1.22</td>
<td>0.49</td>
<td>1.35</td>
<td>0.64</td>
<td>1.62</td>
</tr>
<tr>
<td>lut tre</td>
<td>0.31</td>
<td>/</td>
<td>0.38</td>
<td>/</td>
<td>0.35</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

### Table D-35. Rmsd’s (°C) between observed and predicted responses for Walsh and Graham (1986) male core (Tcr, rectal) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.53</td>
<td>2.50</td>
<td>0.56</td>
<td>1.42</td>
<td>0.58</td>
<td>2.24</td>
<td>0.58</td>
<td>3.87</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.26</td>
<td>1.25</td>
<td>0.28</td>
<td>0.77</td>
<td>0.38</td>
<td>0.44</td>
<td>0.56</td>
<td>0.45</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>0.29</td>
<td>1.24</td>
<td>0.36</td>
<td>0.68</td>
<td>0.51</td>
<td>0.42</td>
<td>0.66</td>
<td>0.47</td>
</tr>
</tbody>
</table>

### Table D-36. Rmsd’s (°C) between observed and predicted responses for Walsh and Graham (1986) female core (Tcr, rectal) and mean skin temperature (Tsk) data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
<th>Tcr</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.55</td>
<td>1.27</td>
<td>0.54</td>
<td>0.70</td>
<td>0.59</td>
<td>1.75</td>
<td>0.65</td>
<td>4.18</td>
</tr>
<tr>
<td>lut25 (hhc)</td>
<td>0.22</td>
<td>0.34</td>
<td>0.21</td>
<td>0.82</td>
<td>0.29</td>
<td>0.71</td>
<td>0.48</td>
<td>1.14</td>
</tr>
<tr>
<td>lut25 (hhn)</td>
<td>0.23</td>
<td>0.41</td>
<td>0.25</td>
<td>0.87</td>
<td>0.42</td>
<td>0.89</td>
<td>0.62</td>
<td>1.21</td>
</tr>
</tbody>
</table>

D-15
Table D-37. Rmsd’s between observed and predicted responses for Young et al. (1980) core (Tcr, rectal), mean skin temperature (Tsk), and metabolic rate (M) data.

<table>
<thead>
<tr>
<th>model</th>
<th>Tcr (°C)</th>
<th>Tsk (°C)</th>
<th>M (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.24</td>
<td>1.60</td>
<td>21</td>
</tr>
<tr>
<td>lut2</td>
<td>0.67</td>
<td>1.88</td>
<td>24</td>
</tr>
<tr>
<td>lut25</td>
<td>1.06</td>
<td>3.31</td>
<td>23</td>
</tr>
</tbody>
</table>
APPENDIX E

TABULATED TEMPERATURE CHANGES AT LUTISO MODEL'S PREDICTED ALLOWABLE EXPOSURE TIMES
Table E-1. The temperature changes observed at the lutiso model's predicted allowable exposure times, assuming starting temperatures of 37.0 °C for deep body and 33.5 °C for mean skin temperatures (the changes should correspond to increases of 0.8 and 1.0 °C for deep body temperature and 2.4 and 3.0 °C for mean skin temperature, for warning and danger respectively).

<table>
<thead>
<tr>
<th>experiment code</th>
<th>warning unacclimatized subjects</th>
<th>danger unacclimatized subjects</th>
<th>warning acclimatized subjects</th>
<th>danger acclimatized subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>nude/rest/no-wind</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25&lt;Ta&lt;35 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stolwijk and Hardy (1966)</td>
<td>f4</td>
<td>Tre</td>
<td>0.3₁²</td>
<td>0.3₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tty</td>
<td>0.1₁²</td>
<td>0.1₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tsk</td>
<td>1.1₁²</td>
<td>1.1₁²</td>
</tr>
<tr>
<td>35&lt;Ta ≥ 35 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardy and Stolwijk (1966)</td>
<td>f3</td>
<td>Tre</td>
<td>0.5₁²</td>
<td>0.5₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tty</td>
<td>0.2₁²</td>
<td>0.2₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tsk</td>
<td>2.6₁²</td>
<td>2.6₁²</td>
</tr>
<tr>
<td>Stolwijk and Hardy (1966)</td>
<td>f5</td>
<td>Tre</td>
<td>0.2₁²</td>
<td>0.2₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tty</td>
<td>0.1₁²</td>
<td>0.1₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tsk</td>
<td>2.4₁²</td>
<td>2.4₁²</td>
</tr>
<tr>
<td>Stolwijk and Hardy (1966)</td>
<td>f6</td>
<td>Tre</td>
<td>0.4₁²</td>
<td>0.4₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tty</td>
<td>0.4₁²</td>
<td>0.4₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tsk</td>
<td>2.4₁²</td>
<td>2.4₁²</td>
</tr>
<tr>
<td>Stolwijk and Hardy (1966)</td>
<td>f7</td>
<td>Tre</td>
<td>0.6₁</td>
<td>0.9₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tty</td>
<td>0.8₁</td>
<td>1.0₁²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tsk</td>
<td>3.3₁</td>
<td>3.4₁²</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Experiment code</th>
<th>15°C&lt;25°C</th>
<th>25°C&lt;35°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Chappuis et al. (1976)</td>
<td>Chappuis et al. (176)</td>
</tr>
<tr>
<td></td>
<td>Ty Tsk</td>
<td>Ty Tsk</td>
</tr>
<tr>
<td></td>
<td>0.312</td>
<td>0.312</td>
</tr>
<tr>
<td></td>
<td>-1.312</td>
<td>-1.312</td>
</tr>
<tr>
<td>B</td>
<td>Chappuis et al. (1976)</td>
<td>Chappuis et al. (176)</td>
</tr>
<tr>
<td></td>
<td>Ty Tsk</td>
<td>Ty Tsk</td>
</tr>
<tr>
<td></td>
<td>0.612</td>
<td>0.612</td>
</tr>
<tr>
<td></td>
<td>0.512</td>
<td>0.512</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>-2.62</td>
<td>-2.62</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>-1.22</td>
<td>-1.22</td>
</tr>
<tr>
<td></td>
<td>1.22</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>-0.42</td>
<td>-0.42</td>
</tr>
<tr>
<td></td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Chappuis et al. (1976)</td>
</tr>
<tr>
<td></td>
<td>Ty Tsk</td>
<td>Ty Tsk</td>
</tr>
<tr>
<td></td>
<td>0.912</td>
<td>0.912</td>
</tr>
<tr>
<td></td>
<td>1.912</td>
<td>1.912</td>
</tr>
<tr>
<td>Experiment</td>
<td>Code</td>
<td>Moderate Work</td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
<td>---------------</td>
</tr>
<tr>
<td>Kobayashi et al. (1980)</td>
<td>moderate</td>
<td>work</td>
</tr>
<tr>
<td>Kobayashi et al. (1980)</td>
<td>heavy</td>
<td>work</td>
</tr>
<tr>
<td>Mairiaux et al. (1986)</td>
<td>WD-1</td>
<td>Tre</td>
</tr>
<tr>
<td>Mairiaux et al. (1986)</td>
<td>WD-2</td>
<td>Tre</td>
</tr>
<tr>
<td>Mairiaux et al. (1986)</td>
<td>WD-3</td>
<td>Tre</td>
</tr>
<tr>
<td>Mairiaux et al. (1986)</td>
<td>WH-1</td>
<td>Tre</td>
</tr>
<tr>
<td>Mairiaux et al. (1986)</td>
<td>WH-2</td>
<td>Tre</td>
</tr>
<tr>
<td>Mairiaux et al. (1986)</td>
<td>WH-3</td>
<td>Tre</td>
</tr>
</tbody>
</table>

Shvartz (1976) | hot | Tre | 1.5 | 2.4 |
|              |     | Tsk  | 2.6 | 2.6 |
Table E-1 (continued)

<table>
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<td>dl, Tsk 0.3, 0.2, 0.2, 0.5</td>
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<td>hw, Tre 0.1, 0.2, 0.1, 0.2</td>
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</table>

1 Time weighted average allowable exposure time.
2 Allowable exposure time was greater than the duration of the experimental exposure, increase in temperature given was the maximum increase over the exposure.
APPENDIX F

JOURNAL PUBLICATIONS ARISING FROM RESEARCH
MODELS OF HUMAN RESPONSE TO HOT AND COLD ENVIRONMENTS

R. A. Haslam and K.C. Parsons

Department of Human Sciences,
University of Loughborough.

INTRODUCTION

Environmental ergonomics would benefit from being able to accurately predict the effects of human exposure to hot and cold environments. It would be possible to determine safe exposure times, predict the effects of such exposures on health, comfort and performance, and identify efficient working practices.

There are a number of models that attempt to predict human response to thermal environments. However, even though some of these models are sophisticated and recommended by influential institutions (ISO, ASHRAE etc), their predictions of human response to a given set of environmental conditions are often different.

Four models are described in this paper, and their predictions compared. These models have been selected because of their influence or because they form the basis of other models.

STOLWIJK AND HARDY 25-NODE MODEL.

The Stolwijk and Hardy (1977) model is a model of human thermoregulation, from which a number of other models have been developed. It attempts to describe the behaviour of the human thermoregulatory controlled (human body) and controlling (anterior and posterior hypothalamus centres, skin thermoreceptors, and the various effector mechanisms) systems with time, given an exposure to a thermal environment. The model represents the human body as cylinders and a sphere. Each of these
segments is divided into four layers: bone, muscle, fat and skin compartments. The blood is represented as a 25th. compartment. The model requires air temperature, air speed, relative humidity and the metabolic rate of any exercise as inputs, and from these predicts the change of sweat rate, skin wettedness and temperature of each of the 25 compartments with time.

This model may be used for both hot and cold environments. Although the Stolwijk and Hardy model is complex, its usefulness is limited because it does not allow predictions to be made for clothed subjects or environments that include a radiant load. However, the model could be extended to include these parameters.

GAGGE AND NISHI 2-NODE MODEL.

The Gagge and Nishi (see Nishi and Gagge (1977)) model has been used by ASHRAE in conjunction with the standard effective temperature index. It is also a model of human thermoregulation, similar to the Stolwijk and Hardy model, but representing the human body as two compartments. It considers the body to comprise of a body core surrounded by a skin shell. In addition to the inputs required by the Stolwijk and Hardy model, it allows mean radiant temperature and level of clothing insulation to be defined. The model predicts sweat rate, skin wettedness, and the temperature change of the two compartments with time.

THE GIVONI AND GOLDMAN PREDICTION EQUATIONS.

The Givoni and Goldman model of rectal temperature response, used by the US military, is comprised of a set of prediction equations. These equations were derived by fitting curves to data obtained from human subjects, exposed to a range of experimental conditions. These equations give the time response of rectal temperature and heart rate to a set of environmental conditions. The model allows definition of the same environmental parameters as the Gagge and Nishi model, excluding radiant load and using an alternative method of describing clothing insulation. This model is only applicable to hot environments.
ISO DIS 7933 (1983)

ISO DIS 7933 attempts to provide a method of analytical evaluation and interpretation of the thermal stress experienced by a subject in a hot environment. It makes a rational analysis of the heat exchange between the person and the environment, and determines the sweat rate and skin wettedness required for the body to achieve thermal equilibrium. From a knowledge of the sweat rates and wettednesses that acclimatized and non-acclimatized people can reach and maintain, and the degree of heat storage and dehydration that can be tolerated, the model suggests allowable exposure times.

COMPARISON OF THE MODELS' PREDICTIONS.

It is only possible to directly compare the models predictions for a hot environment, with no radiant load, and with no clothing insulation present. Such a comparison is shown in Figure 1.

---

Figure 1
Figure 1 shows that although the Stolwijk and Hardy, and Gagge and Nishi predictions of core temperature agree closely, there is a discrepancy between these and the Givoni and Goldman predictions of over 1 C. Although the Givoni and Goldman model has not been validated for nude exposures, comparison of its predictions with those from the Gagge and Nishi model for clothed exposures shows a similar discrepancy. Moreover, the ISO DIS 7933's allowed exposure times appear to be low against the predictions of core temperature change, only allowing a predicted core temperature increase of approximately 0.5 C.

Figure 2 shows a comparison between the Stolwijk and Hardy, and Gagge and Nishi predictions for a cold environment. It can be seen that after sixty minutes exposure, the core temperatures differ by approximately 0.8 C, and the mean skin temperatures by approximately 1.5 C.

CONCLUSIONS.

Four models have been described that make predictions of human response to hot and cold environments that are of potential use to ergonomists. It
has been shown that the models' predictions for the same environments can differ considerably. Ergonomists seeking advice as to human response to thermal environments may therefore draw different conclusions depending on which source of guidance is consulted (ISO, ASHRAE etc).

Evaluation against the responses of real subjects, other than those used to develop the models, is required in order to identify the accuracy of the different predictions and for which environments the different models are most appropriate.

REFERENCES.


GIVONI, B., and GOLDMAN, R.F., 1973a, Predicting heart rate response to work, environment and clothing. J. Appli Physiol., 34, (2), 201-204.


STOLWIJK, J. A. J., and HARDY, J.D., 1977, Control of body temperature. In Handbook of Physiology, Section 9: Reaction to Environmental Agents, American Physiological Society, Chapter 4, 45-68.

ACKNOWLEDGEMENTS

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A comparison of models for predicting human response to hot and cold environments

R. A. HASLAM and K. C. PARSONS

Keywords: Body temperature; Body temperature regulation; Models, biological; Computers; Skin temperature.

Four influential models which make predictions of human response to hot or cold environments have been described and their predictions compared. The models considered were the Givoni and Goldman prediction equations, ISO/DIS 7933, the J. B. Pierce Lab. 2-node and the Stolwijk and Hardy 25-node models of human thermoregulation. The models integrate the important environmental variables, (air temperature, mean radiant temperature, air speed and relative humidity) with subject variables (insulation of clothing worn and metabolic heat production), in order to make predictions such as core and skin temperature response and allowable exposure times. The models' predictions have been compared for a range of hot and cold environments. This comparison has shown that while for some environments the models' predictions are similar, for other environments they are very different. These differences would result in different practical decisions being made. The models should be used with caution until further evaluation for a wide range of subjects and environmental conditions has determined the accuracy of the models and for which environments they are most appropriate.

1. Introduction

The thermal environment can have an important influence on a person's health, comfort and performance. Prolonged exposure to extreme heat or cold may result in hyperthermia or hypothermia. Extreme thermal environments have been shown to affect performance at certain mental tasks (e.g. Wilkinson et al. 1964, Wing 1965). Skin wettedness (Gagge 1937) has been shown to be correlated with discomfort in the heat and mean skin temperature can be related to discomfort in the cold (Fanger 1970, Gagge et al. 1967). Extreme heat or cold may also have localized effects. For example, cold hands may result in a decrease in manual dexterity, reducing the ability to perform fine manipulative tasks (e.g. Fox 1967, Parsons and Egerton 1985). The effects of the thermal environment are confounded with the insulative effects of clothing and the metabolic heat production of exercise.

Although the need for humans to be subjected to extreme environments has reduced greatly with the progress of air-conditioning technology, it is not always possible to avoid such exposure, for example in deep mining or military operations. In certain cases a degree of protection may be afforded by special clothing. However, protective clothing itself may also cause problems if high levels of activity are required because of the restriction placed on the evaporation of sweat.

Where human response to an extreme thermal environment cannot be avoided it may be possible for it to be tolerated for short periods. It would therefore be useful to be able to predict for how long such an environment could be endured, without a threat to health or performance being posed. There are a number of models that can make...
predictions of human responses to hot and cold environments. The more sophisticated of these models combine the thermal characteristics of the human body (e.g. mass and specific heat of body tissues) with a description of a human thermoregulatory controller (thermoregulatory control system), to provide a dynamic model of how man will respond to environmental conditions. This paper discusses four of the more influential models of human response, which may be used for practical applications, and compares their predictions for a range of hot and cold environments.

2. Models of human response to hot and cold environments

A large number of models of human thermoregulatory control and response have been presented in the literature during the last 50 years (see reviews by Fan et al. 1971, Hardy 1972, Hwang and Konz 1977, Iberall 1972, Mitchell et al. 1972, Richardson 1985, and Shitzer 1973).

For a model to be of use to ergonomists it should be easily used and provide accurate predictions which may be applied in practical situations. The models included for this comparison are those that can make useful predictions for exposure to either hot or cold air environments and can be easily implemented. In addition, the four models discussed below have been adopted, or are being considered for adoption, by influential organizations or have already been used in practical applications.

The Givoni and Goldman model was developed during the 1970s at the US Army Research Institute of Environmental Medicine (USARIEM) and the model has been used by the US Army. ISO/DIS 7933 'Hot environments—Analytical determination and interpretation of thermal stress using calculation of required sweat rates' is being considered (at the time of writing—1987) for adoption by the International Standards Organization (ISO) as part of a series of standards concerning the assessment of the thermal environment. The J. B. Pierce (2-node) model is an integral component of the American Society of Heating, Refrigerating and Air-conditioning Engineers' (ASHRAE) revised effective temperature, ET* (Gagge et al. 1971, ASHRAE 1985). The Stolwijk and Hardy (25-node) model has formed the basis of many other more specialized models and was used during the Apollo and Skylab space programs (Waligora, data unknown).

2.1. Givoni and Goldman prediction equations

Givoni and Goldman (1972, 1973) provided a series of empirically derived equations that enable the prediction of rectal temperature response with time to hot environmental conditions. The equations were derived from curves fitted to the observed responses of subjects to a wide range of hot environmental conditions. A major advantage of this model is that it can be implemented on a programmable calculator enabling its use in the field.

The Givoni and Goldman model assumes that for any combination of metabolic rate, environment and clothing, there must be an internal body temperature and corresponding skin temperature at which the human body will reach equilibrium. This state of final equilibrium may be beyond the limits of human endurance.

The required evaporative cooling is calculated according to the heat balance equation:

\[ E_{\text{req}} = M - W - C - R \]  

where:

- \( E_{\text{req}} \) = required evaporative cooling (W)
- \( M \) = metabolic heat production (W)
The final equilibrium rectal temperature is then calculated as:

\[ T_{\text{ref}} = F_1(M - W) + F_2(C + R) + F_3(E_{\text{req}} - E_{\text{max}}) \]

Where:
- \( T_{\text{ref}} \) = final equilibrium rectal temperature (C)
- \( M - W \) = metabolic heat load (W)
- \( C + R \) = dry environmental heat load (W)
- \( E_{\text{req}} \) = required evaporative cooling (W)
- \( E_{\text{max}} \) = maximum evaporative capacity of environment (W)

\( E_{\text{max}} \) depends on the humidity of the air and the resistance of the clothing, if any is worn, to evaporative heat transfer. \( F_1, F_2 \) and \( F_3 \) are experimentally derived functions that are applied to each component of the equation.

The Givoni and Goldman method then fits an equation to the curve that the human rectal temperature would follow, from an initial rectal temperature to the final equilibrium temperature, as a function of time, given an exposure to a particular set of environmental conditions. From this equation it is possible to predict the rectal temperature at any moment in time during an environmental exposure. Givoni and Goldman provide three different sets of equations for rest, work and recovery from work. This is necessary because of the different rectal temperature response profile of each type of activity. The computer program for the version of the model used for this paper was developed using the information given by Givoni and Goldman (1972, 1973) and Berlin et al. (1975).

ISO/DIS 7933 (1987)
ISO/DIS 7933 is based on work conducted by Vogt et al. (1981, 1982) and attempts to provide a method of analytical evaluation and interpretation of the thermal stress experienced by a subject in a hot environment. It makes a rational analysis of the heat exchange between the person and the environment, and determines the sweat rate and skin wettedness that would be required for the body to achieve thermal equilibrium. The required sweat rate is derived from the required evaporative cooling by taking account of the efficiency of sweating.

The required evaporative cooling is calculated according to the heat balance equation (1) above. The required skin wettedness \( (W_{\text{req}}) \) is then calculated as:

\[ W_{\text{req}} = E_{\text{req}} / E_{\text{max}} \]  

(WD)

The required sweat rate is calculated from \( E_{\text{req}} \) accounting for the reduction of efficiency due to any sweat dripping from the body rather than evaporating:

\[ S W_{\text{req}} = E_{\text{req}} / r \]  

(W)

where:
- \( S W_{\text{req}} \) = required sweat rate (W)
- \( r \) = evaporation efficiency of sweating (ND)
From a knowledge of the sweat rates and skin wettednesses that acclimatized and non-acclimatized people can reach and maintain, and the degree of heat storage and dehydration that can be tolerated, the model suggests allowable exposure times.

The computer program for the ISO/DIS 7933 model used for this paper was adapted from the BASIC program listing given in the draft standard.

2.3. J. B. Pierce Lab. 2-Node Model of human thermoregulation

The J. B. Pierce Lab. (2-node) model of human thermoregulation (Nishi and Gagge 1977) makes a conceptual distinction between the passive (controlled) and active (controlling) systems of human thermoregulation. The model represents the passive system, the human body, as two compartments: a body core surrounded by a skin shell, (see figure 1). The relative masses of the two compartments are adjusted according to the blood flow. For example, if the blood flow is high the body is taken to be mostly core and the relative mass of the core to the skin shell is increased. Heat is transferred between the two compartments by conduction and by convective transfer from the blood. Metabolic heat production occurs in the body core. The skin shell exchanges heat with the environment by means of convection, radiation and the evaporation of sweat.

The controlling system assumes a fixed 'set-point' theory of human thermoregulation, where controlling signals result from a deviation of the body's actual temperatures from reference temperatures. These signals are integrated by the controller, which then produces appropriate effector commands. Effector action takes the form of shivering, vasoconstriction, vasodilation and sweating. A schematic depiction of the 2-node model controller is given in figure 2.

The computer program for the version of the model that was used for this paper was based on the FORTRAN program listing given by Nishi and Gagge (1977) and modified according to the information given by Gagge (1985). The reference set-point temperatures used by the model have been changed to 33.7 and 36.8°C for the skin and core body compartments respectively; the control coefficient for sweating (CSW) has been modified from 200 to 170 (g/m².hr); the control coefficient for vasodilation (CDIL) has been changed from 150 to 200 (l/m².hr.°C); and the constant 0.143 in the equation for calculating the permeation efficiency factor (Fpcl) for clothing has been changed to 0.344.

Figure 1. J. B. Pierce Lab. 2-node model representation of the human thermoregulatory controlled (passive) system.
2.4. Stolwijk and Hardy 25-Node Model of human thermoregulation

The Stolwijk and Hardy (1977) (25-node) model is a model of human thermoregulation which represents the human body as 25 compartments, as shown in figure 3.

The model represents the head as a sphere, and the trunk, arms, hands, legs and feet as cylinders. Each of these segments is divided into four layers: core, muscle, fat and skin compartments. The model assumes that the body is symmetrical in order to reduce the number of calculations required. The blood is represented as a 25th compartment. Each compartment is assigned a mass, volume and specific heat. These values were obtained in part from experimentation and in part from the literature and relate to an average sized male with a body weight of 74.4 Kg and a surface area of 1.89 m².

Heat flows by conduction from a compartment to the adjacent compartment; and from segment to segment, by convective transfer to and from the blood. Metabolic heat...
production is divided proportionately between the various segments and their layers. External body compartments exchange heat with the environment by means of convection, radiation and by the evaporation of sweat.

A schematic representation of the Stolwijk and Hardy controlling system is given in figure 4. The controlling system is based on a fixed 'set-point' theory of human thermoregulatory control. Signals controlling vasodilation, vasoconstriction, sweating and shivering are calculated as a function of the difference of the actual temperatures of the compartments from the 'set-point' temperatures for those compartments. The local signals are modified according to the density of thermoreceptors for a compartment. These signals are then integrated to produce core, core and skin signals. The effector regulator interprets the integrated signals and produces effector commands. The effector commands are implemented as effector action: shivering, vasodilation, vasoconstriction and sweating, after being modified according to compartmental conditions.

The computer program for the version of the 25-node model used for this paper was adapted from the FORTRAN program listing given by Stolwijk and Hardy (1977).

2.5. Model inputs and predictions

Table I shows the various inputs required by the models and the predictions that are made. In the forms of the models considered in this paper, only the 2-node model can make predictions for hot and cold air environments both with and without clothing being worn. The 25-node model can predict for hot and cold conditions without clothing. The Givoni and Goldman and ISO/DIS 7933 models are limited to hot environments, with both models able to predict where clothing is and is not worn.
### Table 1. Model inputs and predictions.

<table>
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<th>Inputs:</th>
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<th>ISO DIS 7933</th>
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<th>25-node</th>
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<td>Air temperature ($T_a$)</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Mean radiant temperature ($T_r$)</td>
<td>$T_r = T_a$</td>
<td>Yes</td>
<td>Yes</td>
<td>$T_r = T_a$</td>
</tr>
<tr>
<td>Air speed (v)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Relative humidity (rh)</td>
<td>Yes</td>
<td>From vapour pressure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
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<td>Clothing insulation</td>
<td>$I_T$</td>
<td>$I_{et}$</td>
<td>$I_{et}$</td>
<td>Nude only</td>
</tr>
<tr>
<td>Clothing moisture permeation resistance</td>
<td>$I_m$</td>
<td>From $I_{et}$</td>
<td>From $I_{et}$</td>
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<td>Metabolic rate ($M$)</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>External work ($W$)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Fixed assuming bicycle exercise</td>
</tr>
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</table>

| Predictions: | | | | |
| Core ($T_c$) | $T_c$ | No | $T_c$ | $T$ head-core |
| Mean skin temperature ($T_{sk}$) | Fixed at 36°C | Fixed at 36°C | Temperature of skin shell | Weighted average of each skin compartment |
| Other | Equilibrium heat exchanges and rectal temperature | Allowable exposure times; equilibrium heat exchanges and sweat rate | Dynamic heat exchanges; shivering and sweat rate | Dynamic heat exchanges; shivering and sweat rate |

Note: $I_T$=total and $I_{et}$=intrinsic clothing insulation (McCullough and Wyon 1983). $I_m$ is after Woodcock (1962).

3. Comparison of the models' predictions for a range of thermal conditions

The comparisons made have been confined to those of most immediate practical use: the Givoni and Goldman, 2-node and 25-node models' predicted temperature responses and the ISO/DIS 7933 models' allowable exposure times. Comparison of the equilibrium heat exchanges predicted by the Givoni and Goldman and ISO/DIS 7933 models is not straightforward because of the empirically based adjustments and interpretation made by the Givoni and Goldman model. Furthermore, while the 2-node and 25-node models' predicted heat exchanges may be compared over the duration of an exposure, they must attain equilibrium before they can be compared with the ISO/DIS 7933 models' predicted equilibrium values. For environments that impose a heat stress on the human body, such a state of equilibrium may often not be attained until after the thermoregulatory system has failed.
The models are compared below for examples of the types of environment for which they are able to make predictions. The environments considered are given in table 2. Possible reasons for discrepancies between the models' predictions are put forward in the discussion.

3.1. Cold environments

Figures 5 and 6 show the predictions of the 2-node and 25-node models for cold environments, for nude subjects at rest and working respectively.

For the cold environment, with the subjects at rest (environment A, figure 5), the 2-node model predicts a decrease of approximately 0.2°C for the core temperature, compared with 1°C predicted by the 25-node model. The models both predict similar decreases for mean skin temperature of approximately 9°C and 10°C. The 25-node model has been affected more by the environment than the 2-node model.

For an identical cold environment with the subjects working (environment B), the models exhibit similar core temperature predictions, predicting little change over the 60 minutes duration of the exposure (figure 6). However, the models' predictions for mean skin temperature vary considerably. The 2-node model predicts a decrease of 15°C while the 25-node model predicts a decrease of only 7°C.

Comparing the predictions made for work with those for rest (figure 5 with figure 6), the 25-node models' predictions show a warming effect on the skin temperatures of the heat produced by the exercise. However, the 2-node model's predictions for the skin compartment show a greater decrease for the working compared with the resting subjects. This occurs because the 2-node model anticipates that the convective heat exchange with the air will be increased during exercise compared with that at rest because of greater body movement.

3.2. Hot environments

Figure 7 shows the four models' predictions for a hot and humid environment (environment C). The predictions are for unclothed and resting subjects.

For this environment, the models' predictions are in broad agreement, with the exception of the Givoni and Goldman (G & G) model. The 2-node and 25-node models' core temperature predictions are very close for the 60 minutes of the exposure. The ISO/DIS 7933 model's predicted allowable exposure times coincide with predicted core temperature increases of 0.7°C and 0.9°C by the 2-node and 25-node models. This

Table 2. Environmental conditions for comparison of models' predictions.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Exposure Time (mins)</th>
<th>Ta (°C)</th>
<th>v (m/s)</th>
<th>rh (ND)</th>
<th>Iet (clo)</th>
<th>M (W/m²)</th>
<th>W (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>60</td>
<td>30</td>
<td>0.10</td>
<td>0.70</td>
<td>0.0</td>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
<td>5</td>
<td>0.10</td>
<td>0.70</td>
<td>0.0</td>
<td>167</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>45</td>
<td>0.25</td>
<td>0.65</td>
<td>0.0</td>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>120</td>
<td>40</td>
<td>0.25</td>
<td>0.50</td>
<td>0.6</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>E work</td>
<td>60</td>
<td>35</td>
<td>0.50</td>
<td>0.55</td>
<td>0.0</td>
<td>222</td>
<td>22</td>
</tr>
<tr>
<td>E recovery</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58</td>
<td>0</td>
</tr>
</tbody>
</table>

Note:
For all environments \( T_r = T_a \).
For Environment D, \( i_m = 0.5 \) (ND).
Human response to hot and cold environments

Figure 5. Comparison of the models' predictions for nude, resting subjects in the cold (environment A).

Figure 6. Comparison of the models' predictions for nude, working subjects in the cold (environment B).
agrees with the limiting criteria of body heat storage set by the ISO/DIS 7933 model (rises in deep body temperature of 0.8°C and 1.0°C for warning and danger limits respectively). The Givoni and Goldman model's predicted rectal temperature response is considerably lower than that exhibited by the other models.

The 2-node and 25-node models' predictions of mean skin temperature differ by 0.6°C after 10 minutes of the exposure, with this difference decreasing to less than 0.1°C after 60 minutes.

Figure 8 displays the Givoni and Goldman, 2-node and ISO/DIS 7933 models' predictions for a hot environment with the subjects wearing clothes and working (environment D). It is clear that all of the models considered this to be a severe environment, with only a limited exposure possible. The Givoni and Goldman model predicts that the rectal temperature will have increased by 2.9°C after the 120 minutes of the exposure, while the 2-node model predicts that core temperature will have increased by 2°C. The ISO/DIS 7933 danger allowable exposure time of 122 minutes for unacclimatized subjects, implying an increase in core temperature of 1.0°C, is considerably less than that predicted by the other models.

3.3. Rest, work and recovery
The four models' predictions for a rest, work and recovery exposure, in the heat and for unclothed subjects (environment E) are given in figure 9.

The predicted core temperature responses for the 30 minutes initial rest-period are in close agreement. During the work period the 2-node and 25-node models predict that the core temperature will increase by approximately 0.6°C. However, the Givoni
Figure 8. Comparison of the model's predictions for clothed, working subjects in the heat (environment D).

Figure 9. Comparison of the model's predictions for nude subjects, resting, working and recovering in the heat (environment E).
and Goldman model predicts a much greater increase of 1.7°C. The predictions for the core temperature response during the recovery period show comparable decreases.

The ISO/DIS 7933 model's predicted allowable exposure times for the work period are compatible with the predictions from the 2-node and 25-node models.

4. Discussion
The models presented above provide several approaches to the problem of predicting human response to the thermal environment, ranging from the empirical nature of the Givoni and Goldman model to the rational description of human thermoregulation offered by the 2-node and 25-node models. ISO/DIS 7933 makes a rational analysis of the heat exchange between a person and the environment but does not attempt to provide a dynamic description of human thermoregulatory control.

The models' predictions are of use to ergonomists if they are sufficiently accurate for practical applications. The predictions of core and skin temperatures could be compared with limits beyond which either health, comfort or performance would be impaired. Predictions such as the allowable exposure times made by ISO/DIS 7933 require no further interpretation, as they would be of immediate practical use.

Some evaluation has been made of the accuracy of the models' predictions against experimental data. Haisman and Goldman (1974) evaluated the Givoni and Goldman prediction equations against experimental data for clothed men walking in hot-wet and hot-dry environments. Haisman and Goldman considered the accuracy of prediction to be acceptable and within expected military and industrial population variability. Wissler (1982) has evaluated the Givoni and Goldman prediction equations against experimental data reported in the literature. Wissler concluded that while agreement between computed and measured rectal temperatures was generally quite good, the model had a tendency to overestimate the increase in rectal temperature during heavy exercise in a hot environment.

Wadsworth and Parsons (1986) report an experimental evaluation of ISO/DIS 7933. For the limited range of environments considered it was found that ISO/DIS 7933 did not protect the subjects. Parsons (1987) has compared the approaches of ISO and ASHRAE to the assessment of human response to hot environments. A comparison of predictions from the ISO/DIS 7933 and 2-node models showed that for the conditions investigated, similar practical decisions would be made based on either of the models. An important factor was the method for quantifying heat transfer through clothing.

Stolwijk and Hardy (1977) evaluated their model against data collected from three subjects exposed to three experimental conditions. These conditions involved transient exposures to heat and cold, periodic exercise at different ambient temperatures and heavy exercise. From these evaluations Stolwijk and Hardy conclude that the model can predict with reasonable accuracy although discrepancies occur for environments that cause cooling and during the onset of exercise. For cool environments the model's core temperature fell more than it should. Stolwijk and Hardy attribute this difference to errors caused in the heat flow calculations by the large temperature gradients that occur between the body compartments, and suggest that the introduction of additional compartments may improve the predictions. During the onset of exercise the model predicted a fall in core temperature. Stolwijk and Hardy suggest that this may have two causes. Firstly the model does not make allowance for the development and repayment of an oxygen debt. At the onset of exercise extra blood is supplied to the relatively cool muscle compartments which tends to draw heat from the core. The second possible
cause put forward by Stolwijk and Hardy is that in human muscle 'compartments', not all muscles are likely to be active, so that those groups which are warm up faster and cause less initial blood cooling than predicted by the model.

Cooper et al. (1987), Hancock (1980, 1981a, 1981b), Konz (1979), Konz and Hwang (1977), Konz et al. (1977), Parsons and Haslam (1984), Watkins and Parsons (1985) and Wissler (1982) have also made evaluations of the 25-node model. The consensus of these evaluations has been to support the finding of Stolwijk and Hardy that this model provides reasonable predictions of human response to hot, warm, and neutral environments, while the models predictions for the cold are less accurate. Wissler also adds from his evaluation that while the Stolwijk and Hardy core temperature prediction in the cold tends to decrease excessively, the predicted mean skin temperature falls less than that observed.

The comparisons described in this paper show that the models' predictions for the same environment may differ considerably. For the cold environments examined, the 2-node and 25-node models’ predictions could result in different practical decisions being made in both cases. For the two environments considered, the 25-node model predicts that the core temperature will fall more and the skin temperature will fall less than predicted by the 2-node model. These comparisons and the evidence from the previous evaluations suggest that the 2-node model’s predictions may be more accurate for exposure to the cold.

For the hot environments, the 2-node and 25-node models provide similar predictions, and would result in similar practical decisions being made. The ISO/DIS 7933s predictions agree with those of the 2-node and 25-node models for an environment with the subjects unclothed and at rest. Although for an environment with the subjects wearing clothes and working the ISO/DIS 7933 model predicts the environment to be much less severe than predicted by the Givoni and Goldman and the 2-node models. This difference may in part be due to the manner in which the ISO/DIS 7933 model accounts for the resistance of clothing to evaporative heat transfer. ISO/DIS 7933 uses a constant value in its calculation of the permeation efficiency factor \((F_{pcm})\) of clothing which has been shown to be incorrect (Lotens and Linde 1983). A revised value has been given for this constant by ASHRAE (1985) and Gagge (1985). Use of the incorrect constant causes ISO/DIS 7933 to allow excessive evaporative cooling when clothing is worn, this results in a reduced environmental stress causing it to predict longer allowable exposure times.

The predictions of core temperature response made by the Givoni and Goldman model disagree with those from the other models. The core temperature prediction made by the Givoni and Goldman model is of rectal temperature while the core temperature referred to by the ISO/DIS 7933 and 2-node models is an average core temperature. The predicted core temperature of the 25-node model is that of the head core compartment, representing the location of the hypothalamus. However, the differences exhibited by the Givoni and Goldman predictions are too great to be explained by the different characteristic response shown by rectal temperature. The difference for the working conditions may possibly be explained by Wissler’s (1982) finding that the model had a tendency to overestimate rectal temperature increase during heavy exercise. However, this would not account for the large discrepancy seen for the environment with the subject nude and at rest.

5. Conclusions

Four models of human response to hot and cold environments have been described and their predictions have been compared. The comparison of the models' predictions for a
range of environments has shown that while the models' predictions are often similar they may also disagree considerably. Previous evaluations reported in the literature have used only small numbers of subjects and have considered only few combinations of environmental conditions. Their findings are therefore limited. Ergonomists seeking advice as to human response to thermal environments may therefore draw different conclusions depending on which source of guidance is consulted (ISO, ASHRAE etc.), and caution is required when interpreting the models' predictions.

As the models' predictions are potentially useful and have been shown to be reasonably by the above investigations, further evaluation is required for a wider range of environmental conditions and with larger numbers of subjects. If further evaluation provided additional evidence that models make accurate predictions, then they would provide a useful tool for the design and assessment of thermal environments.

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References

BERLIN, H. M., STROSCHEIN, L., and GOLDMAN, R. F., 1975, A computer program to predict energy cost, rectal temperature, and heart rate response to work, clothing and environment (Department of the Army, Edgewood Arsenal, MD).


GAGGE, A. P., 1985, Personal communication.


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IBERALL, A. S., 1972, Comments on 'A review on mathematical models of the human thermal system'. IEEE Transactions on Biomedical Engineering, BME-19, 67.


NISHI, Y., and GAGGE, A. P., 1977, Effective temperature scale useful for hypo- and hyperbaric environments, Aviation Space and Environmental Medicine, 48, 93–107.


STOLWIJK, J. A. J., and HARDY, J. D., 1977, Control of body temperature. In Handbook of Physiology, Section 9: Reactions to Environmental Agents (American Physiological Society, Bethesda, MD), Chapter 4, 45–68.


Human response to hot and cold environments


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On décrit et on évalue les capacités prédictives de quatre modèles importants relatifs à la réponse de l'Homme à des ambiances chaudes ou froides. Il s'agit des équations de prédiction de Givoni et Goldman, d'ISO/DIS 7933, du modèle bi-nodal du laboratoire J. B. Pierce et du modèle de thermorégulation humaine à 25 points de Stolwijk et Hardy. Ces modèles tiennent compte des paramètres importants de l'environnement (température de l'air, température radiante moyenne, vitesse de l'air et humidité relative) ainsi que des variables liées à l'individu (isolation de la vêture et production de chaleur métabolique), afin de pouvoir prédire la réponse relative à la température du noyau et celle de la peau, ainsi que les temps d'exposition admissibles. On a fait des comparaisons entre ces prédictions sur un éventail d'ambiances chaudes et froides. Ces comparaisons ont montré que l'on obtenait des prédictions comparables pour certaines ambiances, mais différentes pour d'autres. Ces différences entraînent, dans la pratique, des décisions différentes. Il convient donc d'utiliser ces modèles avec prudence avant que l'on n'ait pu évaluer leur précision sur un large éventail de sujets et d'ambiances thermiques et déterminer pour quelles ambiances ils conviennent le mieux.


Die modelle sollten mit Vorsicht verwendet werden, solange, bis weitere Auswertungen für eine große Anzahl von Personen und Umgebungsbedingungen die Exaktheit der Modelle bestimmt haben. Sie sollten für diejenigen Klimaten verwendet werden, für die sie jeweils am meisten geeignet sind.
AN EVALUATION OF COMPUTER-BASED MODELS THAT PREDICT HUMAN RESPONSES TO THE THERMAL ENVIRONMENT

R.A. Haslam   K.C. Parsons, Ph.D.

ABSTRACT

Four influential models that predict human responses to the thermal environment are briefly described. The models considered are the Pierce 2-node model of human thermoregulation, the Stolwijk and Hardy 25-node model of human thermoregulation, the Givoni and Goldman model of rectal temperature response, and ISO/DIS 7933. The models' predictions of human responses to a wide range of thermal conditions have been compared with the responses of human subjects as described in reports of laboratory experiments. This paper discusses representative examples from these comparisons. These examples suggest that few of the models' predictions are wildly inaccurate and that often at least one of the models is able to provide predictions of sufficient accuracy for them to be of practical use. Possible reasons for discrepancies between the observed data and the models' predictions are discussed.

INTRODUCTION

The complex interaction of air temperature, radiant temperature, air velocity, humidity, clothing and activity that makes up the human thermal environment has implications for health, comfort and performance. When dealing with interior environments the aim of the air-conditioning engineer is to try to ensure that the occupants' health, comfort and performance are maintained at acceptable levels. Outdoor environments are generally beyond our control but can usually be moderated by adjusting the amount of clothing worn or the level of activity.

To achieve a satisfactory thermal environment it is useful to be able to predict what the effects of a particular combination of thermal conditions will be on its human occupants. A number of computer based models have been proposed that make predictions of human responses to the thermal environment. The more sophisticated of these models combine the thermal characteristics of the human body (e.g. mass and specific heat of body tissues) with a description of a human thermoregulatory controller (thermoregulatory control system) to provide a dynamic model of how man will respond to the environmental conditions.

Haslam and Parsons (1987a) described in detail four of the more influential models of human response that may be used for practical applications and compared their predictions for several sets of environmental conditions. It was found that although the models' predictions were often similar, for some environments they disagreed considerably. A review of previous experimental evaluations of the models reported in the literature helped to explain some of the discrepancies found between the models' predictions, but it was concluded that further evaluation is required against data for a wide range of subjects and experimental conditions.
This paper compared the four models' predictions of human responses to a range of thermal environments with the actual responses of human subjects as described in reports of laboratory experiments.

MODELS OF HUMAN RESPONSE TO THE THERMAL ENVIRONMENT

For a model to be of practical use it should be easily used and provide accurate predictions that may be interpreted for practical situations. The models included for this evaluation are those that can make useful predictions for exposure to air environments and that can be easily implemented. In addition, the four models discussed below have been adopted, or are being considered for adoption, by influential organizations, or have already been used for practical applications.

The four models examined by this paper are the Stolwijk and Hardy (1977) 25-node model of human thermoregulation, the Pierce 2-node model of human thermoregulation (Nishi and Gagge 1977), the Givoni and Goldman (1972, 1973) model of rectal temperature response, and ISO/DIS 7933 (1987), "Hot Environments: Analytical Determination and Interpretation of Thermal Stress Using Calculation of Required Sweat Rate". These four models have been described before by Naslan and Parsons (1987a) and only brief descriptions are given here.

Stolwijk and Hardy 25-node Model of Human Thermoregulation

The Stolwijk and Hardy 25-node model is a model of human thermoregulation that represents the human body as 25 compartments, as shown in Figure 1. The model represents the head as a sphere and the trunk, arms, hands, legs, and feet as cylinders. Each of these segments is divided into four layers: core, muscle, fat, and skin compartments. The model assumes that the body is symmetrical in order to reduce the number of calculations required. The blood is represented as a 25th compartment. Each compartment is assigned a mass, volume, and specific heat. These values were obtained in part from experimentation and in part from the literature and relate to an average sized male, with a body weight of 74.4 Kg and a surface area of 1.89 m².

Heat flows by conduction from a compartment to the adjacent compartment and from segment to segment by convective transfer to and from the blood. Metabolic heat production is divided proportionately between the various segments and their layers. External body compartments exchange heat with the environment by means of convection and radiation and by the evaporation of sweat.

A schematic representation of the Stolwijk and Hardy controlling system is given in Figure 2. The controlling system is based on a "set-point" theory of human thermoregulatory control. Signals controlling vasodilation, vasoconstriction, sweating, and shivering are calculated as a function of the difference of the actual temperatures of the compartments, from reference temperatures for those compartments. The local signals are modified according to the density of thermoreceptors for a compartment. These signals are then integrated to produce core, core and skin, and skin signals. The effector regulator interprets the integrated signals and produces effector commands which are implemented as effector action -- shivering, vasodilation, vasoconstriction, and sweating -- after being modified according to compartmental conditions.

The computer program for the version of the 25-node model used for this paper was adapted and extended from the FORTRAN program listing given by Stolwijk and Hardy (1977).

Pierce 2-node Model of Human Thermoregulation

The Pierce 2-node model of human thermoregulation is similar to the Stolwijk and Hardy model but uses only two compartments to represent the human body. The model represents the passive system, the human body, as two compartments: a body core surrounded by a skin shell. The relative masses of the two compartments are adjusted according to the blood flow. For example, if the blood flow is high, the body is taken to be mostly core and the relative mass of the core to the skin shell is increased. Heat is transferred between the two compartments by conduction and by convective transfer from the blood. Metabolic heat production occurs in
the body core. The skin shell exchanges heat with the environment by means of convection, radiation, and the evaporation of sweat.

The controlling system follows the same principles as the Stolwijk and Hardy model but with only the two-compartment resolution. The computer program for the version of the model that was used for this paper was based on the FORTRAN program listing given by Nishi and Gagge (1977) and modified according to information given by Gagge et al. (1986).

Givoni and Goldman Prediction Equations

Givoni and Goldman have provided a series of empirically derived equations that enable the prediction of rectal temperature response with time to hot environmental conditions. The equations were derived from curves fitted to the observed responses of subjects to a wide range of hot environmental conditions. A major advantage of this model is that it can be implemented on a programmable calculator, enabling its use in the field.

The Givoni and Goldman model assumes that for any combination of metabolic rate, environment, and clothing, there must be an internal body temperature and corresponding skin temperature at which the human body will reach equilibrium. This state of final equilibrium may be beyond the limits of human endurance. The final equilibrium rectal temperature is calculated as:

\[ T_{ref} = F_1(M-W) + F_2(C+R) + F_3(E_{req} - E_{max}) \]

where:
- \( T_{ref} \) = final equilibrium rectal temperature (°C)
- \( M-W \) = metabolic heat load (W)
- \( C+R \) = sensible environmental heat load (W)
- \( E_{req} \) = required evaporative cooling (W) = \((M-W) + (C+R)\)
- \( E_{max} \) = maximum evaporative capacity of environment (W)

\( F_1, F_2, \) and \( F_3 \) are experimentally derived functions that are applied to each component of the equation.

The Givoni and Goldman method then fits an equation to the curve that the human rectal temperature would follow, from an initial rectal temperature to the final equilibrium temperature, as a function of time, given an exposure to a particular set of environmental conditions. From this equation, it is possible to predict the rectal temperature at any time during an environmental exposure. Givoni and Goldman provide three different sets of equations for rest, work, and recovery from work. This is necessary because of the different rectal temperature response profile of each type of activity.

The FORTRAN computer program for the version of the model used for this paper was developed using the information given by Givoni and Goldman (1972, 1973) and Berlin et al. (1975).

ISO/DIS 7933

ISO/DIS 7933 attempts to provide a method of analytical evaluation and interpretation of the thermal stress experienced by a subject in a hot environment. It makes a rational analysis of the heat exchange between the person and the environment and determines the sweat rate and skin wettedness that would be required for the body to achieve thermal equilibrium. The required sweat rate is related to required evaporative cooling by taking account of the efficiency of sweating. The required evaporative cooling is calculated according to the heat balance equation:

\[ E_{req} = M - W - C - R \]

where:
- \( E_{req} \) = required evaporative cooling (W/m²)
- \( M \) = metabolic heat production (W/m²)
- \( W \) = external work (W/m²)
- \( C \) = heat loss by convection (W/m²)
- \( R \) = heat loss by radiation (W/m²)
From a knowledge of the sweat rates and skin wettednesses that acclimatized and nonacclimatized people can reach and maintain and the degree of heat storage and dehydration that can be tolerated, the model suggests allowable exposure times.

A FORTRAN computer program for this model was adapted from the BASIC program listing given in the ISO/DIS 7933 (1987) standard.

DESCRIBING THE INSULATIVE EFFECTS OF CLOTHING

The forms in which the four models being considered by this paper were originally published used a variety of different methods to describe the insulative effects of clothing. The Stolwijk and Hardy model as published does not allow for clothing and can therefore only predict for environments where the subjects are nude. The Pierce model uses the intrinsic clothing insulation (I01) and Woodcock's (1962) moisture permeability index (1m). The Givoni and Goldman model uses the total clothing insulation (I7) and 1m. ISO/DIS 7933 (1987) uses the effective clothing insulation (Icel) and the permeation efficiency coefficient (Fpcl) (Nishi and Gagge 1970). The definitions of I01, Icel, and I7 are those given by McCullough et al. (1985).

The different methods available for describing the insulative effects of clothing to dry and evaporative heat transfer have been discussed by Haslam and Parsons (1987b). While this review recognizes the limitations of the two-parameter approach to describing clothing insulation, for example, the inability to adequately account for the decrease in clothing insulation that often accompanies exercise, it concludes that at present no alternative exists that is suitable for practical use. It is recommended that the insulation offered by clothing should be described in terms of I01, the clothing area factor (fcl), and 1m. I01 is the insulation of the clothing alone to dry heat transfer; fcl is the ratio of the surface area of the clothed body to the surface area of the nude body and enables the increased surface area of the clothed body available for heat transfer to be taken into account; and 1m describes the effects of the clothing worn on its resistance to evaporative heat transfer. Tabulated values of these parameters are given by ASHRAE (1985) and by McCullough et al. (1982, 1985).

The four models have all been modified so that they use I01, fcl, as 1m and their clothing inputs. The Pierce model, for example, does not allow for clothing and can therefore only predict for environments where the subjects are nude. The Pierce model uses the intrinsic clothing insulation (I01) and Woodcock's (1962) moisture permeability index (1m). The Givoni and Goldman model uses the total clothing insulation (I7) and 1m. ISO/DIS 7933 (1987) uses the effective clothing insulation (Icel) and the permeation efficiency coefficient (Fpcl) (Nishi and Gagge 1970). The definitions of I01, Icel, and I7 are those given by McCullough et al. (1985).

IMPLEMENTATION OF THE MODELS

In view of the changes that have been made to the models concerning the way in which they account for the insulative effects of clothing and other slight modifications (such as the correction of typographical mistakes), the revised versions of the models that have been used to provide the predictions given in this paper will be referred to as the LUT versions of the models. Thus, lut2 refers to the Pierce 2-node model, lut25 refers to the Stolwijk and Hardy 25-node model, lutvre refers to the Givoni and Goldman model of rectal temperature response, and lutiso refers to the ISO/DIS 7933 model. In addition, the two versions of the lut25 model, where clothing covers the head and the hands and where the head and the hands are left uncovered, will be denoted by lut25 (hhc) and lut25 (hhn), respectively.

While the lut2, lut25 and lutvre models' predictions are similar to those of the original published versions, the lutiso model's predicted allowable exposure times can differ considerably from those of the published version. This is because the lutiso version corrects an error in the manner by which the ISO model calculates the Fpcl coefficient, which would under certain conditions have allowed excessive evaporative cooling (see Parsons 1986 and Haslam and Parsons 1987b).
Where the evaluation of the models' prediction takes the form of comparing an observed with a predicted temperature time course (see Figure 3 for example), a summary statistic has been developed called the root mean squared deviation (rmsd). This statistic is defined as:

\[
\text{rmsd} = \left( \frac{1}{n} \sum_{i=1}^{n} d_i^2 \right)^{1/2}
\]

where:
- \(d_i\) = difference between observed and predicted temperature at each time point
- \(n\) = number of time points of interest

This statistic provides a figure for an average difference between the observed and predicted time courses (observed human responses in laboratory experiments and predicted responses of the models) in units of °C and allows a direct comparison to be made with the average standard deviation of the observed data (if available).

EVALUATION OF MODELS OF HUMAN RESPONSE AGAINST EXPERIMENTAL LABORATORY DATA

Method

The evaluation of the models of human response has taken the form of comparing the models' predicted core (Tcr) and mean skin temperature (Tsk) responses with mean observations reported in the literature for a wide range of environmental conditions. Data from 24 papers, including observations for exposures to some 85 environments, formed the basis of the evaluation. While most of the data were collected from unacclimatized male subjects, some data from acclimatized and female subjects were also considered.

The evaluation was divided into two parts: an evaluation for simple thermal conditions where no clothing is worn and an evaluation for more complex thermal conditions, including clothing. In order to model the transfer of heat through a clothing system, which is a complex process, it is necessary to make a number of assumptions that may not always be valid. Evaluating the models' predictions for conditions with and without the presence of clothing enables the effects of making these assumptions to be examined.

The environmental conditions used as inputs to the models were those reported by the experimenters. For those experimental exposures where the subjects wore clothing, the experimenters reported clothing insulation values were used, if given. Otherwise, the insulation characteristics of the clothing were estimated using the tabulations of McCullough et al. (1982, 1985). For environments where the subjects were exposed minimally clothed, values of \(I_{cl}=0.1\) clo, \(f_{cl}=1\), and \(I_m=0.5\) (ND) have been assumed.

Results

While it is not possible to consider all the comparisons in detail, some representative examples will be discussed. Figures 3 to 9 show example evaluations, while Tables 1 to 3 provide the corresponding rmsd's. In addition, Tables 4 and 5 provide the rmsd's for environments for which the accompanying graphs have not been included. Each graph displays the mean observed data and the appropriate models' predictions. Where data are available for the standard deviation of the observed response, the interval between plus and minus one standard deviation is shaded on the graphs in order to provide an indication of the distribution of the observed data.

The lutiso model's predicted allowable exposure times are tabulated on the graphs of deep body temperature responses. Each comparison is discussed in turn.

Data from Chappuis et al. (1976). Chappuis et al. (1976) provide data for the exposure of eleven male subjects to three sets of environmental conditions with air temperature (Ta) = 1346
20, 25, and 30 °C (experiment codes: A, B, and C, respectively). In all three environments, the subjects performed 50 minutes of exercise on a bicycle ergometer with metabolic rate ($M$) = 150 W/m², 50 minutes with $M=257$ W/m², and 30 minutes rest ($M=57$ W/m²). $T_a$ was equal to mean radiant temperature ($T_r$), relative humidity ($rh$) = 30 %, room air movement ($v$) = 0.2 m/s, and the subjects wore shorts ($I_{cl}=0.1$ clo, $f_{cl}=1$, (ND), and $I_m=0.5$ (ND)).

Figures 3 and 4 show the observed and predicted tympanic ($T_{ty}$) and Tsk temperatures for experimental condition C. Figure 3 shows that lut25 predictions are closest to the mean observed core temperature response, while lut2 underestimates the body heating due to the exercise, and luttre overestimates it. The lutiso allowable exposure times predict that this combination of environmental conditions could be endured safely for at least eight hours. This is supported by the observed data where equilibrium at a safe level appears to have been reached even during the heaviest work period.

Figure 4 displays the comparison for the Tsk predictions and shows that both the lut2 and lut25 models provide accurate predictions (note - lutiso assumes a constant Tsk of 36 °C). Table 1 provides the rmsd's for the three environments. It can be seen from Table 1 that the rmsd's for the lut2 and lut25 models' core temperature predictions are generally within 0.4 °C and for the mean skin temperature predictions within, 0.85 °C. These compare favourably with the average observed standard deviations. The luttre predictions are less accurate.

Data from Kobayashi et al. (1980). Kobayashi et al. (1980) provide data for the exposure of five minimally clothed male subjects to two experimental conditions (moderate work and heavy work). In both of these environments $T_a=T_r=49.5$ °C, $v=0.1$ m/s, $rh=32$ %, $I_{cl}=0.1$ clo, $f_{cl}=1$ (ND), and $I_m=0.5$ (ND). Both conditions began with 45 minutes of rest followed by 45 minutes of exercise on a bicycle ergometer with $M=204$ W/m² for the moderate work and $M=306$ W/m² for the heavy work conditions.

Figures 5, 6, 7 show the responses of the auditory canal ($T_{ac}$), rectal ($T_{re}$), and Tsk. The responses indicate that this is a very severe hot environment that is only tolerable for a limited period of time. Figures 5 and 6 show that the location used to measure the deep body temperature provides differing estimations of the core temperature. The models tend to overestimate the observed Tre while underestimating the observed Tao temperature response. The lutiso allowable exposure times, with a maximum time of 34 minutes for acclimatized subjects, provide a conservative estimate of how long the environment can be endured, with the subjects actually remaining exposed for 90 minutes. The lutiso warning and danger times for unacclimatized subjects correspond approximately to deep body temperature increases of 0.8 and 1.0 °C. These agree reasonably well with the observed Tao increase but not with the observed Tre response.

The predicted skin temperature response (Figure 7) shows that the models' predictions are most accurate for the rest period but less so for the 45 minutes of work.

The rmsd's given in Table 2 show that the lut2 and lut25 models' core temperature predictions predict more accurately the observed Tao temperatures, while the luttre models' predictions are less accurate.

Data from Young et al. (1986). Young et al. (1986) provide data from the exposure of seven minimally clothed and resting males to an environment where $T_a=T_r=5$ °C, $v=0.1$ m/s, $rh=30$ %, $I_{cl}=0.1$ clo, $f_{cl}=1$ (ND), $I_m=0.5$ (ND), and $M=60$ W/m² for 90 minutes. Figures 8 and 9 show the observed Tre and Tsk responses; Table 3 provides the corresponding rmsd's. It can be seen from Figure 8 that the Tre response exhibits a slight increase over the first 30 minutes if the exposure and then begins a steady decline. To a differing degree, the lut2 and lut25 predictions both show an immediate decrease and finish approximately 0.5 and 1.0 °C below the observed response after the 90 minutes.

The models' Tsk predictions (Figure 9) are less accurate in this cold environment than for the hotter environments already considered. However, it can also be seen that the variation exhibited by the observed response is much greater. For this example, the lut2 predictions are the most accurate, following the observed response reasonably closely. The lut25 predicted response underestimates the observed cooling.

Data from Henane et al. (1979). Henane et al. (1979) conducted an experiment to compare the physiological effects of two clothing ensembles compared with the nude response to a hot environment. Henane et al. exposed 11 subjects wearing each clothing ensemble (nude: $I_{cl}=0.1$ clo, $f_{cl}=1$ (ND), and $I_m=0.5$ (ND); A1: $I_{cl}=1.0$ clo, $f_{cl}=1.3$ 0 (ND), and $I_m=0.35$ (ND); A2: $I_{cl}=2.6$ clo, $f_{cl}=1.40$ (ND), and $I_m=0.30$ (ND)) to the environmental conditions of $T_a=T_r=35$ °C,
The subjects exercised for 60 minutes on a bicycle ergometer, and the metabolic rates associated with each clothing ensemble were M=165, 191, and 209 W/m² for the nude, A1, and A2 ensembles, respectively.

The rmsd's between the observed Tre responses and the models' predictions are given in Table 4. It can be seen from this table that the accuracy of the models' predictions tends to decrease as the clothing insulation increases. The lut2 model's predictions are less accurate than those of the lut25 model.

Data from Nielsen and Nielsen (1984). Nielsen and Nielsen (1984) provide data for a mixed group of seven male and three female subjects for exposures to an environment of Ta=9.8 °C, v=0.1 m/s, and rh=52 %. Nielsen and Nielsen exposed the subjects twice with different clothing ensembles (experiment code cl: Icl=1.22 clo, fcl=1.38 (ND), and tcl=0.35 (ND); experiment code cl: Icl=1.67 clo, fcl=1.52 (ND), and tcl=0.30 (ND)). For both conditions, the subjects exercised on a bicycle ergometer for 60 minutes and then rested for a further 60 minutes. The mean metabolic rate during the exercise period was 150 W/m².

Table 5 gives the rmsd's between the observed and predicted data. It can be seen from Table 5 that, for both conditions, the lut2 model provides the most accurate predictions of Tre and esophageal (Toe) temperatures, while the lut25 model provides the most accurate Tsk predictions. The predictions from the two versions of the lut25 model are of a similar accuracy for both of the conditions. With the exception of the lut2 model in the ct environment, all of the models provide more accurate predictions of Toe than of Tre.

DISCUSSION

The aim of this evaluation was to identify which of the models that predict human responses to the thermal environment provide predictions accurate enough for practical use. In order to achieve this aim, it is necessary to consider how accurate a model's predictions should be for them to be considered accurate. The comparisons described by this paper have compared predicted temperature time courses with the mean observed responses of subjects. Information concerning the variability of the observed responses has been provided in the form of standard deviations (when available).

Typically, the observed core temperature responses had an average standard deviation over time of approximately 0.3 °C, while the mean skin temperature responses had standard deviations of as much as 1.6 °C. If it is assumed that the interval between plus or minus two standard deviations (0.6 and 3.3 °C) will contain approximately 95% of the observed responses obtained after repeated random sampling, examination of the rmsd's given in Tables 1 to 5 shows that most of the predictions fall within these intervals. This demonstrates that most of the models' predictions are not wildly inaccurate. However, in order to be usable as the basis of practical decisions, greater accuracy than this is required. Fortunately, the example comparisons considered above suggest that often at least one of the models is able to predict to the accuracy of at least plus or minus one standard deviation.

The example comparisons considered here, although representative of the large number that have been made, do not provide enough information for more detailed conclusions to be drawn regarding the categories of environment for which a particular model is likely to be most accurate. However, some useful observations can be made.

The experimental data described above have demonstrated the variation in response that is observed at the different sites used for measuring deep body temperature. The evaluation against the data of Kobayashi et al. (1980) showed that the models' predictions tended to underestimate Tac and overestimate Tre. Similarly, the comparison of the models' predictions with the responses observed by Nielsen and Nielsen (1984) showed that the models predicted Toe more accurately than Tre. The lut2 and lut25 models' predictions for the Tre data of Young et al. (1986) show large variations from the observed response.

The differing characteristics of the different sites are well recognized (e.g., Cranston et al. 1954 and Edwards et al. 1978). The lut2 model's predicted core temperature does not have a physiological counterpart. The lut25 core temperature is taken as being the temperature of the head core, as this is the reference compartment for the thermoregulatory controlling system. The Tty and Tac temperatures should provide the best estimate of the temperature that the lut25 model is trying to predict, although it is recognized that the tympanic and particularly the auditory canal temperatures may both be affected by the environmental
conditions (Greenleaf and Castle 1972). The lut25 model's trunk core compartment responds similarly to the head core compartment and does not exhibit any of the characteristics of Tre temperature response.

The luttre model predicts Tre temperature response, and it should predict this more accurately than responses observed at other body sites. This is generally reflected in the above comparisons, although, for the Tre data of Henane et al. (1979), the luttre model's predictions are less accurate than those of the other models.

The lutiso model does not predict deep body temperature as such, but its predictions of changes in body heat content, and consequently allowable exposure times, may be related to an average deep body temperature. Comparing the lutiso allowable exposure times with the observed core temperature responses for the data of Kobayashi et al. (1980), the times may be more closely related to the observed Tao response than the Tre.

The experimental data considered by this evaluation indicate that the variability of the observed data is greater for cooler environments. This can be seen by comparing the evaluations for the Chappuis et al. (1976) and Young et al. (1986) data, particularly for the Tao responses. It is generally true that the observed variation in responses to hot environments is much less than that observed for cold environments, and this may be attributed to the increased temperature gradients in the cold, allowing greater variability.

From the above discussion, it might be expected that the predictions of the lut2 and lut25 models would differ from those of the luttre, as its predictions are of rectal temperature response. It could be expected that the lut2 and lut25 models would produce similar predictions. However, examination of Figures 3, 4 and 6 shows that, for the work periods in particular, the models' predictions may differ quite considerably. A difference between the models in the manner by which they determine the convective cooling from the skin might explain some of these differences. Both the lut2 and lut25 models determine the convective heat transfer coefficient (ho) as a function of the air speed. However, when the metabolic rate input to the lut2 model is high enough to suggest that the subjects are exercising, the model calculates ho as a function of the metabolic rate. This is done as an attempt to account for the increased effective air movement over the body caused by the body motion that accompanies exercise. The lut25 model does not make any allowance for this phenomenon. It is possible that the lut25 model underestimates the convective cooling of the body when exercise occurs.

It has been noted above that the data considered by this paper suggest that the accuracy of the models' predictions appear to decrease as the clothing insulation worn increases. Nielsen and Nielsen (1984) provided insulation values for the clothing ensembles examined by their experiment. For the data of Henane et al. (1979), it was necessary to estimate the insulation of the clothing ensembles using tables from the description of the clothing garments provided by the experimenters. In practice it is difficult to match a description of a clothing garment with an entry in a table of clothing insulations. McCullough et al. (1985) investigated the accuracy with which people could perform this task and found that the accuracy was poor, even for trained subjects. It is likely that as the quantity of clothing increases, the errors made in estimating the insulation of the ensemble will also be greater. It is, therefore, not surprising that the accuracy of the models' predictions should be reduced by using these estimated clothing insulation values.

CONCLUSIONS

Brief descriptions have been given of four influential models that predict human responses to the thermal environment. Example evaluations are presented from a large number of comparisons that have been made. The evaluations have taken the form of comparing an observed body temperature response with experimental data obtained from the literature.

For the example comparisons considered by this paper, few of the models' predictions are wildly inaccurate, and often at least one of the models is able to provide predictions of sufficient accuracy for them to be of practical use. The limited range of data examined here do not provide enough information for detailed advice to be given as to the categories of environment for which a particular model is likely to be most accurate. However, some observations have been made regarding the nature of the models' predictions.
The lut2 and lut25 models appear to more accurately predict Tty, Tao, and Toe estimates of deep body temperature response than Tre. The lut2 model's predictions are similar to those of the lut25 model but can differ considerably in the cold or when subjects are exercising.

As would be expected, the luttre model predicts rectal temperature response more accurately than core temperatures obtained from other sites. However, for some conditions, the lut2 and lut25 models provide more accurate predictions of rectal temperature response than the luttre model.

The allowable exposure times predicted by the lutiso model using its criteria of increases in body temperature compare well with the increases observed with Tty and Tao response but less accurately with the observed Tre responses. The more detailed analysis of the results of this extensive evaluation, currently in progress, should enable statements to be made regarding which models are most suitable for which environments. It will also be possible to identify aspects of individual models that require further refinement in order to improve the accuracy of prediction.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the Ministry of Defence, and to thank Dr. M. F. Haisman, Dr. R. F. Goldman, and Professor A. P. Gagge for their advice. The opinions and conclusions expressed in this paper are solely those of the authors.

REFERENCES


Berlin, H.M.; Stroschein, L.; and Goldman, R.F. 1975. A computer program to predict energy cost, rectal temperature and heart rate response to work, clothing, and environment. Department of the Army, Edgewood Arsenal, Maryland, USA.


Stolwijk, J.A.J.; and Hardy, J.D. 1977. Control of body temperature. In: Handbook of Physiology, Section 9: Reactions to Environmental Agents (Bethesda, Maryland: American Physiological Society), Chapter 4, pp. 45-68.


### TABLE 1

Rmsd's (°C) between observed and predicted responses for Chappuis et al. (1976) core (Tcr, tympanic), and mean skin temperature (Tsk) data

<table>
<thead>
<tr>
<th>Environment</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.16</td>
<td>0.37</td>
<td>0.22</td>
</tr>
<tr>
<td>lut2</td>
<td>0.23</td>
<td>0.78</td>
<td>0.37</td>
</tr>
<tr>
<td>lut25</td>
<td>0.29</td>
<td>0.84</td>
<td>0.13</td>
</tr>
<tr>
<td>luttre</td>
<td>0.96</td>
<td>/</td>
<td>0.74</td>
</tr>
</tbody>
</table>

### TABLE 2

Rmsd's Between Observed and Predicted Responses for Kobayashi et al. (1980) Auditory Canal (Tac), Rectal (Tre) and Mean Skin Temperature (Tsk) Data

<table>
<thead>
<tr>
<th>Model</th>
<th>Tac</th>
<th>Tre</th>
<th>Tsk</th>
<th>Tac</th>
<th>Tre</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.52</td>
<td>0.50</td>
<td>0.73</td>
<td>0.40</td>
<td>0.66</td>
<td>0.79</td>
</tr>
<tr>
<td>lut25</td>
<td>0.30</td>
<td>0.73</td>
<td>0.36</td>
<td>0.48</td>
<td>1.05</td>
<td>0.69</td>
</tr>
<tr>
<td>luttre</td>
<td>0.71</td>
<td>0.30</td>
<td>/</td>
<td>0.66</td>
<td>0.43</td>
<td>/</td>
</tr>
</tbody>
</table>

### TABLE 3

Rmsd's Between Observed and Predicted Responses for Young et al. (1980) Core (Tcr, Rectal), and Mean Skin Temperature (Tsk) Data

<table>
<thead>
<tr>
<th>Model</th>
<th>Tcr</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.24</td>
<td>1.60</td>
</tr>
<tr>
<td>lut2</td>
<td>0.67</td>
<td>1.88</td>
</tr>
<tr>
<td>lut25</td>
<td>1.06</td>
<td>3.31</td>
</tr>
</tbody>
</table>

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F-33
TABLE 4

Rmsd's (°C) Between Observed and Predicted Responses for Henane Et Al. (1979) Core (Tcr, Rectal) Temperature Data

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Nude</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>sd (obs)</td>
<td>0.33</td>
<td>0.33</td>
<td>0.27</td>
</tr>
<tr>
<td>lut25 (hmc)</td>
<td>0.22</td>
<td>0.20</td>
<td>0.60</td>
</tr>
<tr>
<td>lut25 (hnn)</td>
<td>(\text{na} )</td>
<td>0.21</td>
<td>(\text{na} )</td>
</tr>
<tr>
<td>luttre</td>
<td>0.46</td>
<td>0.59</td>
<td>0.69</td>
</tr>
</tbody>
</table>

TABLE 5

Rmsd's (°C) Between Observed and Predicted Responses for Nielson and Nielson (1984) Rectal (Tre), Oesophageal (Toe) and Mean Skin Temperature (Tsk) Data

<table>
<thead>
<tr>
<th>Clothing</th>
<th>Tre</th>
<th>Toe</th>
<th>Tsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>lut2</td>
<td>0.08</td>
<td>0.16</td>
<td>1.39</td>
</tr>
<tr>
<td>lut25 (hmc)</td>
<td>0.39</td>
<td>0.22</td>
<td>1.27</td>
</tr>
<tr>
<td>lut25 (hnn)</td>
<td>0.36</td>
<td>0.21</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Figure 1 Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlled (passive) system (6 body x 4 layers + 1 blood = 25 compartments)
Figure 2 Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlling (active) system
Figure 3  Tty from Chappuis et al (1976) (n=11) (exp code: C), Ta=Tr=30 C, v=0.2 m/s, rh=30%, lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0, 0 W/m2

Figure 4  Tsk from Chappuis et al (1976) (n=11) (exp code: C), Ta=Tr=30 C, v=0.2 m/s, rh=30%, lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0, 0 W/m2

Legend
- mean obs: Tty
- ±sd
- ±-sd
- lut2; Tcr
- lut25 (hhe); Tcr
- lutre; Tte

lutiso Allowable Exposure Times (time weighted averages):
- warning non-accl: 480 min; unlimited duration
- warning accl: 480 min; unlimited duration
- danger accl: 480 min; unlimited duration

39
38.5
38
37.5
37
36.5
0 50 100 150
150 W/m2 257 W/m2 57 W/m2

Legend
- mean obs: Tsk
- ±sd
- ±-sd
- lut2; Tsk
- lut25 (hhe); Tsk

0 50 100 150
150 W/m2 257 W/m2 57 W/m2
Figure 5  Tac from Kobayashi et al (1980) (n=5) (heavy work), Ta=Tr=49.5 C, v=0.1 m/s, rh=32%, lcl=0.1 clo, fc=1 (ND), im=0.5 (ND), H=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)

Figure 6  Tre from Kobayashi et al (1980) (n=5) (heavy work), Ta=Tr=49.5 C, v=0.1 m/s, rh=32%, lcl=0.1 clo, fc=1 (ND), im=0.5 (ND), H=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)
Figure 9  

Tsk from Young et al (1986) (n=7), Ta=Tr=5 C, v=0.1 m/s,  
rh=30%, 1cl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m², W=0  
W/m²

Legend

- mean obs: Tsk
- ±sd
- ±±d
- Δ lut2: Tsk
- × lut25 (hhc): Tsk
Discussion

J.W. MITCHELL, University of Wisconsin, Madison: In your paper, you compared model predictions of skin and core temperature to measured values. The temperature predictions are very sensitive to model parameters. It seems reasonable to also compare predictions of other measurements, such as dry and sensible heat loss, metabolism, sweat rate, etc. Were comparisons made, and, if so, how do predictions compare to measurements? Were the models used to predict the influence of clothing level and environment on heat flows, and, if so, how do the results compare? These comparisons are important to allow evaluation and selection of the various models for engineering purposes.

R.A. HASLAM: We have taken the view that as the models' predictions are already being used in practice, we should concentrate our evaluation on the predictions that are most likely to be used. Core and skin temperatures may be related to human safety and comfort, and data exist in the literature for the responses of these temperatures to a wide range of environmental conditions.

However, we recognize that, depending on the nature of the model, the predictions may depend on the accuracy of the underlying simulation, including the predicted heat exchanges. We have identified experimental data for the dry and evaporative heat exchanges of nude subjects and the metabolic response of subjects in the cold. The appropriate predictions from the models have been compared with these data, and we are preparing the results for publication.

We have not attempted to examine directly the accuracy of the models' simulations of human physiological responses, such as vasodilation or vasoconstriction or the exchanges of heat through the clothing. The indirect evaluation of these parameters, using the accuracy of the models' core and skin temperature predictions, suggests that as the environmental conditions become more extreme, the accuracy of the models' predictions of these factors may become less accurate.

A. FOBELETS, John B. Pierce Foundation, New Haven, CT: The first presentation in this session focused on the uncertainty of clothing evaluation. The same uncertainty exists for the other physical properties of the environment (convective heat transfer coefficient, for example) and the physiological inputs (metabolic rate) of the model. Therefore, the analysis that you conducted should be complemented by an error analysis (error on the model output as a function of estimated error on the input parameters).

Also, the models include many parameters that reflect the subjects' physiological characteristics. A sensitivity analysis on these parameters and matching to real subjects' characteristics may also be necessary.

HASLAM: The accuracy with which a model is able to predict clearly depends on the accuracy of the values supplied to it by the user and the validity of its internal assumptions. However, because the models that we are investigating have already been used for practical applications, we have attempted to evaluate the models from the user's point of view, using coefficient values, etc., published by the model authors and providing the environmental information to the models to the degree of accuracy possible using standard equipment and tables. It is, therefore, possible, if a model's predictions prove to be inaccurate for a given experimental exposure, that this is not because the model is a poor one but because the clothing was estimated inaccurately using tables or because the authors' published coefficients were not appropriate for the subject population being studied, for example.

We agree that information concerning the accuracy of the different components of a model's simulation should enable us to understand why a model's predictions might be inaccurate, rather
We agree that information concerning the accuracy of the different components of a model's simulation should enable us to understand why a model's predictions might be inaccurate, rather than just that they are.

W.A. LOTENS, TNO Institute for Perception, Soesterberg, The Netherlands: Is it correct to calculate standard deviations (rmsds) between measured Tac and predicted Tre for the luttre model and compare these to similar values for models that aim to predict head core temperature (lut25)?

HASLAM: Tac and Tre, etc., responses are all used as indices of deep body temperature, although it has long been recognized that each has its own characteristic response pattern. As we are interested in evaluating how the models might be used in practice, we have compared the lut25 head core, lut2 core, and luttre rectal temperature predictions with Tac, Tty, Tre, Tes, and Tga estimates of core temperatures. We believe that this is justified, providing that the differing characteristic responses are borne in mind, as these comparisons provide useful information. For example, in many cases the lut25 model's predictions are closer to observed Tre response that those of the luttre model.

We agree, however, that caution should be exercised when comparing the rmsds for the different models without the benefit of the time course information contained on the graphs.
Quantifying the effects of clothing for models of human response to the thermal environment

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Keywords: Clothing; Biological models; Temperature

Models that predict human responses to the thermal environment must be able to account adequately for the insulative effects of clothing in order to be of practical use. The mechanisms of heat transfer between the human body and the environment and the resistive effects of clothing on this heat transfer are reviewed. The widely used two-parameter method for quantifying the resistance of clothing to dry and evaporative heat transfer is described and the limitations of this description are noted. However, it is argued that not enough information exists to allow other more complex methods to be used for practical applications. Until further information becomes available enough data exist for the two-parameter description to enable its use by the models of human response. An example of the ISO/DIS 7933 model's predictions is given to demonstrate the effect that using different methods of describing the insulative effects of clothing can have on a model's predictions.

1. Introduction

Recent developments in our understanding of the heat transfer processes between man and his environment, of the human thermoregulatory system and the technological advancement of digital computing have enabled computer models of human response to thermal environments to be made available to researchers and practitioners. The models are potentially very useful, being able to predict, for example, the effects of the thermal environment on workers' health, comfort and performance.

Previous papers (Haslam and Parsons 1987, 1988) have described several computer-based models capable of predicting the responses of humans to hot and cold environments (e.g. ISO/DIS 7933 1987). Other models consider the effects of moderate environments on the occupants' thermal comfort (e.g. Fanger 1970). As clothing is worn under most circumstances, for example to keep human body heat in or environmental heat and noxious substances out, a model usable for practical application must be able to account adequately for the insulative effects of clothing.

This paper reviews methods for describing the heat transfer properties of clothing and discusses their limitations and suitability for use with prediction models. An example is then given of the different predictions that may be obtained from the models depending on the method used to quantify the resistance of clothing.

2. Heat transfer between the nude human body and the environment

The mechanisms of heat transfer between the human body and the environment are well understood (e.g. Burton and Edholm 1955, and Kerslake 1972). For an unclothed subject, dry heat is transferred at the skin by convection (C), conduction (K) and radiation (R). Evaporative heat (E) is transferred by the evaporation of sweat or the condensation of water vapour on the skin. The human body produces metabolic heat (M) and if this metabolic heat production is insufficient to maintain the deep body temperature at its preferred level (around 37°C), or too great to be dissipated to the environment, there will be net heat storage (S). In addition to the heat transfer at the skin there are also convective and evaporative heat flows due to respiration (Res). Thus, a heat balance equation may be constructed:

\[ M = C + K + R + E + S + \text{Res} \quad (\text{W/m}^2) \quad (1) \]

Each of the terms on the right of the equation may be positive or negative, that is representing either heat losses or gains.

2.1. Heat transfer by conduction and respiration

Heat transfer to or from the human body by conduction is usually considered to be negligible, as for most human activities the surface of the body is mainly in contact with air or soft furnishings which have a high resistance to conductive heat transfer. Respiratory heat flows are not usually affected by clothing and are not considered here.

2.2. Heat transfer by convection

Heat transfer by convection may be described by the equation:

\[ C = h_{c}(T_{sk} - T_{a}) \quad (\text{W/m}^2) \quad (2) \]

where:
- \( h_{c} \) = convective heat transfer coefficient (W/m².°C)
- \( T_{sk} \) = mean skin temperature (°C)
- \( T_{a} \) = air temperature (°C)

The theoretical determination of the convective heat transfer coefficient \( (h_{c}) \) for an object in a fluid is complex and depends on the shape of the object, and the physical properties of the fluid (Kerslake 1972). A number of experimental determinations have been made of \( h_{c} \) for the human form in air, for a range of air speeds and body postures (e.g., Colin and Houdas 1967, Mitchell et al. 1969, and Nishi and Gagge 1970a). The findings of these experiments have often been expressed as equations that are the product of the air speed raised to a fractional power and a constant, in view of the theoretical expectation for forced convection (Kerslake 1972). The formula of Nishi and Gagge (1970a) is typical:

\[ h_{c} = 8.6 \, v^{0.53} \quad (\text{W/m}^2.°\text{C}) \quad (3) \]

where:
- \( v \) = air speed (m/s)

Thus, \( h_{c} \) may be estimated if the air speed is known. There are also experimental equations that determine \( h_{c} \) as a function of the subject's activity (e.g., Nishi and Gagge 1970a). As activity increases, so the movement of the body and limbs tends to increase.
This results in a greater effective air movement over the body, and greater convective cooling.

2.3. Heat transfer by radiation

Heat transfer by radiation is related to the difference between the fourth powers of the absolute temperatures of the radiating surfaces. However, where the difference between the temperatures of the radiating surfaces is small (less than 20°C), as is the case with most indoor environments that humans experience, this relation may be approximated by:

\[ R = h_r(T_{sk} - T_r) \quad (W/m^2) \]  

where:

- \( h_r \) = linear radiation heat transfer coefficient (W/m²°C)
- \( T_r \) = mean radiant temperature (°C)

The linear radiation heat transfer coefficient \( (h_r) \) is defined (Gagge and Nishi, 1977) as:

\[ h_r = 4.\sigma \cdot (A_r/A_d) (T_{sv})^3 \quad (W/m^2.°C) \]  

where:

- \( \sigma \) = Stefan Boltzman Constant = \( 5.67 \times 10^{-8} \) (W/m².k⁴)
- \( A_r/A_d \) = fraction of skin surface involved in radiative heat exchange (ND)
- \( T_{sv} = (T_{surf} + T_r)/2 + 273.2 \) (K)
  
Thus, \( h_r \) can be calculated if the radiation area factor and the mean surface temperature are known. Fanger (1970) reports values of 0.70 sitting and 0.73 standing for \( A_r/A_d \) from experiments using optical methods.

2.4. Heat transfer by evaporation

Evaporative heat transfer involves the transfer of mass. The gradient in the concentration of water molecules is the driving potential for this process. However, when the temperature difference between the evaporating surface and the ambient air is small, as is the case in most physiological applications, the evaporative heat flow may be adequately expressed in terms of the vapour pressure gradient. Therefore, evaporative heat transfer from the skin is usually expressed by physiologists as:

\[ E = h_e(P_{sk} - P_a) \quad (W/m^2) \]  

where:

- \( h_e \) = evaporative heat transfer coefficient (W/m².kPa)
- \( P_{sk} \) = mean partial pressure of water vapour at the skin (kPa)
- \( P_a \) = partial pressure of water vapour in the air (kPa)

The process of vapour diffusion into the air layer surrounding the human body shares many similarities with that of convective heat transfer. It has been shown by Rapp (1970) that the ratio of \( h_e \) to \( h_r \) is nearly constant and is equal to 16.5°C.kPa at 25°C. This ratio is known as the Lewis relation. Therefore, if \( h_e \) is known, \( h_r \) may be calculated.
3. The effects of clothing on heat transfer between the human body and the environment

Clothing usually reduces the heat flow between the human body and environment. Figure 1 shows how heat may pass through clothing.

![Diagram of heat transfer through clothing](image)

**Figure 1. Heat transfer through clothing.**

3.1. **Dry heat transfer**

Dry heat is transferred within clothing by conduction through and radiation between the clothing fibres, and by any convection that may occur within the air pockets held in the clothing.

The resistance or insulation of a clothing ensemble depends on the area of body surface covered by the clothing, the clothing thickness, the fabric properties of its constituent garments and the amount of air that is trapped between or within them. If the air trapped within a clothing ensemble remains still, the insulation of the clothing will be greater, because the resistance offered by air to heat transfer by conduction is high.

The resistance of clothing to dry heat may be affected both by internal and external air movement. If the air within the clothing moves as a consequence of the wearer's activity, the insulation of the ensemble may be reduced. If the environmental air movement is great enough, the wind may enter the clothing fabrics and displace still air trapped within them, thus reducing the insulation.

3.2. **Evaporative heat transfer**

Evaporative heat transfer between nude skin and the environment occurs either because of the evaporation of sweat from the skin or, in very hot and humid environments, the condensation of water vapour onto it. When a clothed person sweats, some of the sweat may wick into the clothing and pass through the fabric fibres by capillary action. The absorption of sweat by the clothing fibres may produce heat
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This heat of absorption is in addition to any latent heat that may be liberated by condensation and results from similar processes to those that cause heat to be produced in some chemical reactions. Alternatively, the sweat may evaporate at the skin and pass through the clothing as vapour. Any vapour passing through the clothing may condense, liberating heat, just as any sweat or water contained within the clothing may evaporate, taking up heat. In a very humid environment water vapour from the environment may diffuse into the clothing and either condense within the clothing or at the skin.

The site at which the evaporation or condensation occurs may affect the amount of heat that is taken or given up to the skin, further complicating the effects of clothing on evaporative heat transfer. It has been argued that moisture evaporating within clothing is less efficient at removing heat from the skin than if it evaporates at the skin surface (Burton and Edholm 1955, and Kerslake 1972). This is because more of the latent heat of evaporation is drawn from the environment than if the evaporation occurs at the skin.

Evaporative heat transfer may still occur within clothing that is completely impermeable (Linde and Lotens 1983). This occurs because evaporated sweat within the clothing micro-climate condenses on the inside of the impermeable clothing layer, giving up heat. This heat may then conduct through the impermeable clothing and pass to the environment.

The process of evaporative heat transfer through clothing may affect the dry heat transfer. When moisture is absorbed into the clothing it may displace dead air spaces that are trapped within it (Burton and Edholm, 1955). As water at 20°C and at sea level has a thermal conductivity of 0.6 W/m°C compared with 0.0257 W/m°C for air (Cornwell, 1977), the resistance of the wet clothing to heat transfer by conduction will be considerably reduced.

4. Quantifying the insulative effects of clothing with a two-parameter description

The transfer of heat through clothing is a complex process. It has been customary to simplify matters by considering the dry and evaporative heat transfer through clothing as distinct, unrelated processes (e.g. ASHRAE 1985, Burton and Edholm 1955, and Kerslake 1972). The resistance offered by clothing to each of these processes is expressed by two single average resistances (or conductances) for the ensemble. The resistance values for the dry and evaporative heat transfer processes encompass all of the mechanisms by which heat may be transferred within the clothing, that is conduction, convection and radiation for dry heat transfer and evaporation, condensation and absorption for evaporative heat transfer. Moreover, it is also assumed that the skin, clothing, environment system has reached equilibrium, so that the heat entering the clothing is equal to the heat leaving the clothing, and there is no change in the heat content of the clothing. This simplified view of the effects of clothing on the heat transfer between the human and environment is depicted in figure 2.

Heat transfer through materials is analogous to the flow of electricity in circuits, with the same rules for the addition of serial and parallel conductances and resistances. The heat transfer coefficients in equations 2 to 6 are thermal conductances and are therefore equivalent to the reciprocals of the respective resistances. For convenience, the convective and radiative heat transfer coefficients are often combined so that:

\[ I_e = \text{resistance of environment to dry heat transfer} \]

\[ (m^2 \cdot°C/W) \]
Figure 2. Simplified two-parameter description of heat transfer through clothing.

Also:

\[ I_e = \frac{1}{h_e} \text{ (m}^2\text{kPa/W)} \]  \hspace{1cm} (8)

where:

\( I_e \) = resistance of environment to evaporative heat transfer (m\(^2\text{kPa/W})

It is customary to consider the effects of clothing in terms of resistance rather than conductance. Thus, the equation for dry heat transfer through clothing becomes:

\[ \text{Dry} = \frac{(T_{sk} - T_{cl})}{I_{cl}} \text{ (W/m}^2\text{)} \]  \hspace{1cm} (9)

where:

\( \text{Dry} \) = dry heat transfer through clothing (W/m\(^2\))
\( I_{cl} \) = resistance of clothing to dry heat transfer (m\(^2\text{.°C/W})
\( T_{cl} \) = mean surface temperature of clothed body (°C)

and for the evaporative heat transfer:

\[ E = \frac{(P_{sh} - P_{cl})}{I_{cest}} \text{ (W/m}^2\text{)} \]  \hspace{1cm} (10)

where:

\( E \) = evaporative heat transfer through clothing (W/m\(^2\))
\( I_{cest} \) = resistance of clothing to evaporative heat transfer (m\(^2\text{kPa/W})
\( P_{sh} \) = mean partial pressure of water vapour at surface of clothed body (kPa)
The equations for the heat flow from the clothing surface to the environment are then:

\[ C = h_c \cdot f_{cl} (T_{cl} - T_e) \quad (\text{W/m}^2) \quad (11) \]

\[ R = h_e \cdot f_{cl} (T_{cl} - T_r) \quad (\text{W/m}^2) \quad (12) \]

\[ E = h_e \cdot f_{cl} (P_{cl} - P_e) \quad (\text{W/m}^2) \quad (13) \]

where:

\[ f_{cl} = \text{clothing area factor} \]

\[ = \frac{\text{surface area clothed}}{\text{surface area nude}} \quad (\text{ND}) \]

The clothing area factor accounts for the increased surface area of the clothed compared to the nude body.

5. Measuring the insulative effects of clothing

In order to describe the heat flow from a clothed human body to the environment in terms of a two-parameter description of clothing insulation, it is most convenient to know the resistances \( R_{cl} \) and \( R_{est} \) and the coefficient \( f_{cl} \) for the clothing environment system of interest.

5.1. Resistance of clothing to dry heat transfer, and clothing area factor

The resistance of clothing to dry heat transfer can be estimated using an electrically heated human-shaped and sized manikin (e.g., McCullough et al. 1982, and Sprague and Munson 1974).

The manikin is heated internally to simulate the skin temperature distribution of a human. The electrical power consumption required by the manikin to maintain a constant skin temperature is then proportional to the insulation of the clothing worn by the manikin.

Winslow et al. (1937) introduced the concept of operative temperature. Operative temperature \( (T_0) \) is an average of the air and mean radiant temperatures weighted by their respective heat transfer coefficients:

\[ T_0 = \frac{(h_c \cdot T_s + h_r \cdot T_r)}{(h_c + h_r)} \quad (^\circ \text{C}) \quad (14) \]

Using operative temperature, the dry heat exchange for an unclothed person in terms of the temperature gradient between the skin and the environment is given by:

\[ \text{Dry} = \frac{(T_{sk} - T_0)}{I_s} \quad (\text{W/m}^2) \quad (15) \]

where \( I_s \) is defined as above (equation 7).

When clothing is worn:

\[ \text{Dry} = \frac{(T_{sk} - T_0)}{I_T} \quad (\text{W/m}^2) \quad (16) \]

where:

\[ I_T = \text{total resistance of clothing and environment to dry heat transfer} \]

\[ = I_{cl} + \frac{I_s}{f_{cl}} \quad (\text{m}^2 \cdot \text{C/W}) \quad (17) \]
For the special case when the air and mean radiant temperatures are equal it can be shown that $T_0$ is equal to $T_a$. $T_1$ may therefore be substituted for $T_0$ in equation 16.

Thus, for a clothed, dry manikin that has reached equilibrium in an environment where $T_a$ and $T_r$ are equal:

$$I_T = \frac{(T_{sk} - T_a)A_d}{H} \quad (m^2 \cdot ^\circ C/W)$$

(18)

where:

$H =$ power input to manikin (W)

$A_d =$ manikin surface area (m$^2$)

Equation 17 shows that in order to calculate $I_{et}$ it is also necessary to know $I_e$ and $f_{et}$. $I_e$ can be obtained by operating the manikin nude and $f_{et}$ can be estimated using photographic techniques (e.g., Fanger 1970, and Olesen et al. 1982).

Tabled values for the resistance of different clothing garments and ensembles to dry heat transfer, as measured on a manikin, are available in the literature (e.g., ASHRAE 1985, McCullough et al. 1982, McCullough et al. 1985, and Seppanen et al. 1972).

ASHRAE (1985), McCullough et al. (1985), Olesen (1985), and Sprague and Munson (1974) provide summation formula, the use of which enables the insulation values of individual garments to be selected from a list and added together to give the insulation of an ensemble. The ensemble insulation is usually less than the sum of the insulation values of its constituent garments because of compression and the increased surface area for heat loss.

In order to estimate $f_{et}$, Fanger (1970) suggests the relationship:

$$f_{et} = 1.0 + 0.15 \cdot I_{et} \quad (ND)$$

McCullough et al. (1985), McCullough et al. (1983), and Olesen (1985) have examined this relationship and have found that it tends to underestimate the $f_{et}$ associated with a clothing ensemble. From a study on a large number of clothing ensembles McCullough et al. (1985) suggest a relationship of:

$$f_{et} = 1.0 + 0.31 \cdot I_{et} \quad (ND)$$

However, they emphasize that the relationship between $f_{et}$ and $I_{et}$ is poor. Wherever possible measured values of $f_{et}$ should be used.

Caution is required with interpretation of the clothing insulation values reported and used in the literature, as a variety of different terms have been used. These terms have been interchanged and it is not always clear which insulation is intended. Most often clothing insulation has been termed total insulation ($I_T$), intrinsic insulation ($I_e$) and effective insulation ($I_{et}$). $I_T$ and $I_e$ are as defined above; the effective clothing insulation is defined as:

$$I_{et} = I_T - I_e \quad (m^2 \cdot ^\circ C/W)$$

(19)

The effective clothing insulation is obtained by subtracting the resistance of the environment, as obtained by operating a nude manikin, from the total resistance of the clothing and environment to dry heat transfer without correcting for the increased surface area due to the clothing. $I_{et}$ is more convenient than $I_{et}$ for use in heat transfer analysis but requires that $f_{et}$ is known or can be estimated. $I_T$ varies with the
environmental conditions. If $I_{cl}$ or $I_T$ and the conditions under which they were measured are known for a clothing ensemble, then it is possible to estimate $I_{el}$ from them.

The clothing insulation values reported in the literature for the resistance of clothing to dry heat transfer are usually reported in clo units, with 1 clo = 0.155 m²°C/W (Gagge et al. 1941).

5.2. Resistance of clothing to evaporative heat transfer

The resistance of clothing to evaporative heat transfer ($I_{sed}$) can be measured using a 'sweating' manikin. Sweating manikins have been developed that comprise a copper manikin covered with a cotton skin, which can be made wet (Breckenridge and Goldman 1977, and McCullough et al. 1982).

The equation for the evaporative heat transfer through the clothing, in terms of the vapour pressure gradient between the skin and the environment is given by:

$$E = \frac{(P_{sk} - P_a)}{I_{ev}} \quad \text{(W/m}^2\text{)}$$

where:

- $I_{ev}$ = total resistance of clothing and environment to evaporative heat transfer

$$I_{ev} = I_{sed} + \frac{I_e}{f_{el}} \quad \text{(W/m}^2\text{)} \quad (21)$$

$I_{sed}$ is the parameter that describes the resistance of clothing to evaporative heat transfer. However, researchers who have examined the effects of clothing on evaporative heat transfer using sweating manikins have generally reported the effects of the clothing in terms of several permeability indices, although measurements of $I_{ev}$ have been reported from studies on human subjects (Holmer and Elnas 1981). These indices may aid interpretation but are cumbersome to use with the heat transfer equations. Fortunately, the various indices are related and provided enough information is given, it is possible to determine $I_{sed}$.

5.3. Woodcock moisture permeability index

A moisture permeability index ($i_m$), first introduced by Woodcock (1962) has been used extensively to describe the effects of clothing on the transmission of water vapour between the skin and the environment (e.g. Givoni and Goldman 1972, and McCullough et al. 1982). Woodcock proposed that the evaporative heat transfer for a clothing system could be expressed as the ratio of the actual evaporative heat transfer, as hindered by any clothing, to that of an aspirated wet bulb thermometer with the same dry heat transfer resistance. The $i_m$ index expands the equation for evaporative heat transfer so that:

$$E = \frac{16.5 \cdot i_m}{I_T} (P_{sk} - P_a) \quad \text{(W/m}^2\text{)} \quad (22)$$

where:

- $i_m$ = the moisture permeability index

$$i_m = \frac{h_{ev}/h_T}{h_e/h_c} \quad \text{(ND)} \quad (23)$$
where:

\[ h_T = \text{the total dry heat transfer coefficient for the clothing and environment} \]
\[ = \frac{1}{I_T} \text{ (W/m}^2\text{.°C)} \]

\[ h_e = \text{the total evaporative heat transfer coefficient for the clothing and air system} \]
\[ = \frac{1}{I_e} \text{ (W/m}^2\text{.kPa)} \]

The Woodcock permeability index has been measured on a wetted manikin for a range of clothing garments and ensembles (Breckenridge and Goldman 1977, and McCullough et al. 1982). \( I_T \) is measured with the manikin dry. As \( I_T \) varies with the environmental conditions, the same conditions should be used when the manikin is wet. \( P_{sk} \) and \( P_a \) can be calculated from \( T_{sk}, T_a \) and the air humidity. The index can then be derived from equation 22.

In theory \( i_m \) varies from 0 to 1, with a value of 1 indicating that the maximum evaporative heat transfer can occur. In practice \( i_m \) does not often approach unity, even for a nude subject, because the air movement is usually much less than that applied to a ventilated wet bulb thermometer. A value of approximately 0.5 would be expected for a nude subject in still air conditions.

In order to use values of \( i_m \) given in the literature, it is also necessary to know the thermal conditions such as \( T_a, T_n, T_{sk}, v \) etc. prevailing when they were measured.

5.4. Nishi permeation efficiency factor

Nishi and Gagge (1970b) introduced a factor \( F_{pel} \) to describe the resistive effects of clothing on evaporative heat transfer, so that the equation for \( E \) becomes:

\[ E = F_{pel} \cdot h_e \cdot (P_{sk} - P_a) \]  \( \text{(W/m}^2\text{)} \)  \( (24) \)

where:

\[ F_{pel} = \text{permeation efficiency factor} \]
\[ = \frac{I_e}{I_{pel} + I_e} \text{ (ND)} \]  \( (25) \)

Nishi and Gagge (1970b) report a series of experiments which used naphthalene sublimation to determine the permeation efficiency factor of light cotton clothing. From these experiments they obtained the empirical equation:

\[ F_{pel} = \frac{1}{1 + 0.92 \cdot h_e \cdot I_{ele}} \text{ (ND)} \]  \( (26) \)

However, Lotens and Linde (1983) showed that the constant value of 0.92 in this equation is theoretically incorrect. In the light of further work by Oohori et al. (1984) this constant value has been modified to 2.22 (ASHRAE, 1985).

There are few reported values of \( F_{pel} \) available in the literature and equation 26 is valid only for light cotton clothing.
5.5. Lotens permeation ratio
Oohori et al. (1984) introduced a factor \( i_L \) that they called the Lotens permeation ratio. This ratio is similar to the Woodcock \( i_m \) and is the ratio of the Lewis number for the clothing layer alone, to the Lewis number for the air layer:

\[
i_L = \frac{h_{cel}/h_{cl}}{h_{cl}/h_e} \quad \text{(ND)}
\]  

where:

\[
h_{cl} = \frac{1}{I_{cl}} \quad \text{W/m}^2 \cdot °C \quad \text{and} \quad h_{cel} = \frac{1}{I_{cel}} \quad \text{W/m}^2 \cdot \text{kPa}
\]

The equation for evaporative heat transfer can then be expanded to:

\[
E = \frac{(P_{ve} - P_a)}{I_{cl} + \frac{1}{16.5 \cdot i_L \cdot f_{cl}}} \quad \text{(W/m}^2) \quad \text{(28)}
\]

Unlike \( i_m \), \( i_L \) is not affected by air speed, or radiative heat exchange. Oohori et al. (1984) give values of \( i_L \) measured by weighing the evaporation of water from a vessel covered with clothing samples, for a range of fabrics. 

Lotens and Linde (1983) and Lotens (1988) define a slightly different ratio \( i_{ml} \), where:

\[
i_{ml} = \frac{h_{cel}/h_{cl}}{h_{cl}/h_e} \quad \text{(ND)}
\]  

where:

\[
h_{ce} = \text{the total dry non-radiative heat transfer coefficient for the clothing and air system (W/m}^2 \cdot °C\)
\]

Thus, \( i_{ml} \) is the ratio of the Lewis number for the clothing plus air layer, to the Lewis number for the air layer, and although independent of radiative heat exchange it is not independent of air movement.

5.6. Determining \( I_{cel} \) from \( i_m \), \( F_{pol} \) or \( i_L \)
If \( i_m \) or \( F_{pol} \) and the conditions under which they were measured or \( i_L \) are known for a clothing ensemble, then it is possible to calculate \( I_{cel} \) from these factors.

At present the literature contains few reported values of \( F_{pol} \) or \( i_L \) and only the method for calculating \( I_{cel} \) from \( i_m \) will be derived here.

Substituting \( I_{ce} \) in equation 20 with equation 21, equating with equation 22 and rearranging gives:

\[
I_{cel} = \frac{I_T}{16.5 \cdot i_m \cdot f_{cl}} \quad \text{m}^2 \cdot \text{kPa/W} \quad \text{(30)}
\]

\( I_e \) (the resistance of the environment to evaporative heat transfer from the nude body) in this equation is that prevailing when \( i_m \) was measured, and may be determined from the value of \( I_{ce} \) (the resistance of the environment to dry heat transfer from the nude body) obtained from operating the manikin dry and nude. However, it is necessary to remove the \( h_{e} \) (the linear radiation heat transfer coefficient) component from \( I_{ce} \); \( h_r \) is in turn
dependent on $T_{el}$ (the mean surface temperature) and $T_r$ (the mean radiant temperature). $T_{el}$ is not usually measured, but both $h$ and $T_{el}$ may be determined using numerical iteration (e.g., see Gagge et al. 1986, appendix B).

6. Limitations of laboratory manikin measurements of clothing insulation
The resistance of clothing to both dry and evaporative heat transfer depends not only on the fabric and thickness of the clothing but also on the air that is trapped within it. The amount and behaviour of air within clothing depends on the fit of the clothing, how the clothing is worn, the activity of the person wearing the clothing and external air movement. In addition, the age of the clothing and how it has been laundered affect how it interacts with both air and water vapour. The effect of these variables is very difficult to quantify in terms of the resistance of the clothing to heat transfer.

The insulation measured for a clothing ensemble on a rigid standing manikin will not necessarily be the insulation that is provided when the clothing is worn by human subjects. Experiments have been conducted with human subjects, where their metabolic heat production and heat exchanges with the environment have been measured, either by direct (Mitchell and Rensburg 1973) or indirect (Holmer and Elnas 1981) calorimetry, thus enabling the insulation of their clothing to be determined.

6.1. Effects of wearers' activity on the insulation of clothing
The effects of wearers' activity on the insulation of their clothing have been demonstrated in several experiments with human subjects (Breckenridge 1977, Nielsen et al. 1985, Olesen and Nielsen 1984, Vogt et al. 1983, 1984). Nielsen et al. (1985) and Olesen and Nielsen (1984) have observed decreases in $I_C$ of between 30-50% for cycling and walking and 8-18% seated, when compared with the clothing worn standing stationary. Whereas the ventilation of clothing caused by the wearer's activity usually decreases the insulation of the clothing, Vogt et al. (1983, 1984) demonstrated that for environments with the mean radiant temperature much lower or higher than the air temperature, the insulation of the clothing may be increased. This occurs because although the surface of the clothing is heated or cooled by the radiant load, the convection of air at nearer skin temperature through the clothing reduces the heating or cooling effect at the skin.

Birnbaum and Crockford (1978), Breckenridge (1977), Givoni and Goldman (1972), Lotens and Havenith (1988) and Sullivan et al. (1987 a, 1987 b) have attempted to quantify the effects of clothing ventilation. Birnbaum and Crockford (1978), Lotens and Havenith (1988) and Sullivan et al. (1987 a, 1987 b) describe methods for measuring the air exchange between clothing and environment on human subjects. Givoni and Goldman (1972) and Breckenridge (1977) describe an experimental equation developed in an attempt to quantify the effects of exercise and air speed on clothing insulation. An effective air speed is calculated as a function of metabolic rate. $I_T$ and $I_m$ are then adjusted as a function of this effective air speed. However, these equations were derived as those that maximized the accuracy of the predictions of the Givoni and Goldman (1972) model of rectal temperature response, and are only of use for the limited number of clothing ensembles for which they were determined, and for use with this model.

6.2. Movable thermal manikins
It is very time consuming and expensive to measure the thermal insulation of clothing on human subjects and differences found between subjects may be large (Olesen and
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Nielsen 1984). The range of values found over subjects may be due to inaccuracies of the measuring methods and to differences between subjects. In order to simulate the effects of activity on clothing insulation and to standardize the testing method, several laboratories have developed movable thermal manikins (Mecheels and Umbach 1977, Olesen and Nielsen 1984, Olesen et al. 1982, and Umbach 1988). Olesen and Nielsen (1984) compared the clothing insulation measured on a movable manikin with that measured on human subjects. For the standing and seated conditions, the measured values of $I_o$ on the thermal manikin were within one standard deviation of those measured on human subjects. There was however, a difference of between 0.24 and 0.39 clo for a minimally clothed condition. Olesen and Nielsen suggest that this difference might be due to the lower accuracy of the measurements made on the human subjects. Comparable measurements were found for walking in still and moving air conditions from the two methods. However, for a cycling condition the insulation measured on the manikin was up to 22% higher than that found for the subjects. Olesen and Nielsen attribute these differences to the manikin moving its legs only, when cycling, compared to the subjects, who moved their legs and the upper parts of their bodies, thereby increasing the convective cooling.

Although several studies have been made into the effects of activity on clothing insulation, and have demonstrated that the activity may alter the insulation by as much as 50%, an adequate method for quantifying these effects for use in practical applications does not exist. Further research is required. Research is also required into the effects of clothing ventilation on the resistance of clothing to evaporative heat transfer.

6.3. External air movement
The effects of external air movement on the resistance of the boundary air layer around the human body to dry and evaporative heat transfer are accounted for by the heat transfer coefficients $h_e$ and $h_v$. However, the effects of possible wind displacement of air trapped within the clothing are not. Breckenridge (1977) demonstrated that the use of wind-breaks within clothing may reduce the heat transfer coefficient by as much as 80%. However, there is insufficient information available to enable the effects of wind penetration to be quantified for practical applications.

6.4. Estimating clothing insulation from garment insulations
McCullough et al. (1985) investigated the accuracy with which the insulation of a clothing ensemble can be estimated from the individual insulations of its constituent garments using summation formulae. They found that when the garment insulation values were known from manikin measurements or were estimated from their fabric thickness and the body surface area covered, the predictions were accurate. However, when the garment insulations were estimated from charts of insulation values, the predictions were less satisfactory.

6.5. Clothing area factor
Care is required when using measured values of the clothing area factor ($f_{cl}$) for clothing that may be worn in a variety of different ways as this may affect the $f_{cl}$. For example, a shirt may be worn tucked into trousers or left hanging loose. For some types of clothing, the measured $f_{cl}$ may have been considerably affected by the way in which the manikin was dressed when the $f_{cl}$ was measured (McCullough et al. 1982).
7. Theoretical limitations of the two-parameter description of the insulative effects of clothing

The two-parameter description of clothing insulation described above has been criticized as being theoretically inadequate (Lotens and Linde 1983). The two-parameter description assumes that the dry and evaporative heat transfer processes are independent, but it is clear that this is not the case. The evaporative heat transfer through clothing may affect the dry heat transfer when water vapour either condenses or evaporates within the clothing. In addition, condensation of water vapour may displace air within the clothing and consequently reduce its resistance to dry heat.

Moreover, the evaporative heat transfer may affect the dry heat transfer because of the heat produced by the absorption of water or water vapour into the clothing fibres (Lotens and Linde 1983, and Renbourn and Rees 1972). The absorption of water by textiles is an exothermic process, liberating heat. This heat of absorption is in addition to any latent heat that may be liberated by condensation and results from similar processes to those that cause heat to be produced in some chemical reactions. Significant quantities of heat may be produced under dynamic conditions.

Another shortcoming of the two-parameter description is that it does not recognize that the clothing itself has a thermal mass, and that it may store heat. This will not matter when equilibrium conditions occur, but becomes more important when conditions are changing. Moreover, the two parameter approach does not consider the distribution of the clothing insulation over the body. Olesen et al. (1988) examined the effects of clothing insulation asymmetry and found that comfort ratings, for example, were affected by clothing distribution even for neutral environmental conditions.

The two-parameter approach is not valid for environments that have a high solar radiant load. Clothing colour is irrelevant for the long wave infra-red radiation emitted by the surroundings, but for short wave solar radiation it does become important (Fourt and Harris 1949). Although this effect may be quantified, the emissivity of the clothing fabric must be available.

More complex theoretical descriptions have been proposed that account for some or all of the assumptions made by the two-parameter approach (Ho and Fan 1975, Lotens and Linde 1983, Shitzer and Chato 1985, and Stewart and Goldman 1978). Unfortunately, the more accurate a description becomes, the more information about the clothing, its constituent fabrics and the conditions in which it is worn is required. Not enough data exist at present for these descriptions to be of much use in practice. Although the two-parameter description of clothing insulation does have limitations, it is suitable for practical use. Moreover, data have been collected for a wide range of clothing garments and ensembles.

The most appropriate factors for implementing the two-parameter description of clothing insulation are $I_{cl}$ and $I_{ect}$. While suitable data exist for $I_{cl}$ for a varied range of clothing ensembles, little data are available for $I_{ect}$. However, as described above, $I_{ect}$ may be calculated from $I_{cl}$ for which some data are available.


ISO/DIS 7933 (1987) attempts to provide a method of analytical evaluation and interpretation of the thermal stress experienced by a subject in a hot environment. The model makes a rational analysis of the heat exchange between a person and the environment, and determines the sweat rate and skin wettedness that would be required for the body to achieve thermal equilibrium. Using accepted values of the sweat rates and skin wettedness that acclimatized and unacclimatized people can reach
and maintain, and the degree of heat storage and dehydration that can be tolerated, the model suggests allowable exposure times.

The published computer program for ISO/DIS 7933 (1987) uses the effective clothing insulation ($I_{ct}$) and the Nishi permeation efficiency factor ($F_{pet}$) to describe the insulative effects of clothing. The factor $F_{pet}$ is estimated using equation 26 above, with the theoretically invalid constant of 0.92. A revised version of the program has been developed at Loughborough that uses the intrinsic clothing insulation ($I_{ci}$), the clothing area factor ($f_{cl}$), and the Woodcock moisture permeability index ($m$) as its inputs. Figure 3 shows an example run of the revised Loughborough version of ISO/DIS 7933. Table 1 compares the predicted allowable exposure times (duration limited exposures, DLE) of the revised Loughborough version with those obtained from the published ISO/DIS 7933 (1987) program, and from this program using the revised coefficient of 2.22 in the calculation of $F_{pet}$.

The example environment considered is hot, dry and with the subjects wearing a clothing ensemble measured by McCullough et al. (1982). The ensemble comprised underwear, polyester/cotton shirt and trousers, a flame retardant cotton apron, socks and shoes. The measured insulation characteristics were $I_T = 1.33$ clo, $I_{cl} = 0.77$ clo, $f_{cl} = 1.26$ (ND) and $m_I = 0.40$ (ND). From these, the effective clothing insulation can be calculated as being $I_{cie} = 0.61$ clo. The metabolic rate of 175 W/m² is given by ASHRAE (1985) as being typical for certain types of foundry work.

Table 1 shows the effect that using different methods to describe the insulative effects of clothing can have on a model's predictions of human response. The allowable warning exposure times for an unacclimatized subject, for example, range from 46 to 300 min. predicted by the revised Loughborough version of ISO/DIS 7933 and the version as published with the incorrect calculation of $F_{pet}$ respectively. The prediction of the published version of the model for unacclimatized subjects, with the calculation of $F_{pet}$ corrected, of 94 min. is still double that of the Loughborough version that is believed to more accurately account for the resistance of clothing to evaporative heat transfer.

Table 1. The ISO/DIS 7933 model's predictions using different methods to account for the insulative effects of clothing.

<table>
<thead>
<tr>
<th>Allowable exposure times (DLE) (mins)</th>
<th>Warning non-accl. subject</th>
<th>Danger non-accl. subject</th>
<th>Warning accl. subject</th>
<th>Danger accl. subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO/DIS 7933 (1987) (using 0.92 coeff.)</td>
<td>300</td>
<td>355</td>
<td>426</td>
<td>480</td>
</tr>
<tr>
<td>ISO/DIS 7933 (1987) (using 2.22 coeff.)</td>
<td>94</td>
<td>155</td>
<td>300</td>
<td>364</td>
</tr>
<tr>
<td>Loughborough revised version</td>
<td>46</td>
<td>55</td>
<td>70</td>
<td>87</td>
</tr>
</tbody>
</table>
LUT Adaptation of ISO/DIS 7933 (1987) (V1.0)  
Required Sweat Rate Program  
Analytical Determination of Thermal Stress  
Roger Haslam and Ken Parsons  
Department of Human Sciences  
Loughborough University of Technology  
***************************************************************  

New Exposure  
****************  

Air Temperature = 35.00 (°C)  
Mean Radiant Temperature = 50.00 (°C)  
Air Speed = 0.25 (m/s)  
Relative Humidity = 0.30 (ND)  
Intrinsic Clothing Insulation = 0.77 (clo)  
Clothing Area Factor = 1.26 (ND)  
Clothing Permeation Index (Woodcock Im) = 0.40 (ND)  
Initial Metabolic Rate = 175.00 (W/m²)  
Work Rate Accomplished = 0.00 (W/m²)  

Effective Air Movement : \( v_{eff} = 0.86 \) (m/s)  
Partial Vapour Pressure : \( P_a = 1.69 \) (kPa)  
Mean Skin Temperature : \( T_{sk} = 36.00 \) (°C)  
Saturated Vapour Pressure on Skin : \( P_{sk} = 5.94 \) (kPa)  
Metabolic Heat Production : \( M_h = 175.00 \) (W/m²)  
Convective Heat Transfer Coefficient : \( H_c = 7.96 \) (W/m²·C)  
Linear Radiation Heat Transfer Coefficient : \( H_r = 5.11 \) (W/m²·C)  
Mean Clothing Surface Temperature : \( T_{cl} = 39.22 \) (°C)  
Intrinsic Evaporative Clothing Resistance : \( I_{incl} = 0.02 \) (m²·kPa/W)  
Total Evaporative Clothing Resistance : \( I_{eT} = 0.03 \) (m²·kPa/W)  
Convective Heat Transfer : \( C = 42.38 \) (W/m²)  
Radiation Heat Transfer : \( R = -69.39 \) (W/m²)  
Required Evaporative Cooling : \( E_{req} = 202.01 \) (W/m²)  
Maximum Evaporative Capacity of Environment: \( E_{max} = 161.01 \) (W/m²)  
Required Skin Wettedness : \( W_{req} = 1.25 \) (ND)  

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Interpretation, Single Exposure:

Danger: Acclimatized Subject

Predicted Skin Wettedness: \( W_p = 1.00 \) (ND)
Predicted Evaporation Rate: \( E_p = 161.01 \) (W/m²)
Predicted Sweat Rate: \( S_p = 400.00 \) (W/m²) = 588.24 (g/h.m²)

Body Temperature Increase: \( DLE = 87 \) mins
= 1 h 27 mins

Warning: Acclimatized Subject

Predicted Skin Wettedness: \( W_p = 0.99 \) (ND)
Predicted Evaporation Rate: \( E_p = 159.42 \) (W/m²)
Predicted Sweat Rate: \( S_p = 300.00 \) (W/m²) = 441.18 (g/h.m²)

Body Temperature Increase: \( DLE = 70 \) mins
= 1 h 10 mins

Danger: Non Acclimatized Subject

Predicted Skin Wettedness: \( W_p = 0.85 \) (ND)
Predicted Evaporation Rate: \( E_p = 136.86 \) (W/m²)
Predicted Sweat Rate: \( S_p = 250.00 \) (W/m²) = 367.65 (g/h.m²)

Body Temperature Increase: \( DLE = 55 \) mins
= 0 h 55 mins

Warning: Non Acclimatized Subject

Predicted Skin Wettedness: \( W_p = 0.85 \) (ND)
Predicted Evaporation Rate: \( E_p = 136.86 \) (W/m²)
Predicted Sweat Rate: \( S_p = 200.00 \) (W/m²) = 294.12 (g/h.m²)

Body Temperature Increase: \( DLE = 46 \) mins
= 0 h 46 mins

Figure 3. Example of the ISO/DIS 7933 (1987) models predictions.

9. Conclusions

The insulative effects of clothing on dry and evaporative heat transfer between the human body and the environment have been described, and a widely used two-parameter method of accounting for the resistance offered by clothing to heat transfer has been detailed. The limitations of this approach have been recognized and the requirements for a more rigorous account are given. In particular, the effects on the clothing insulation of the wearer's activity, wind penetration and the interaction between the dry and evaporative heat transfer processes are not adequately accounted for by the two-parameter method.

While more complex descriptions of the insulative effects of clothing are available in the literature these descriptions are difficult to apply in practice because of the extensive data required about the clothing, its constituent garments, its fabrics, how it is worn, and the activity of the wearer. Further research is required into how the factors affecting
clothing insulation may be quantified to enable that information to be used in practice.

For the present, sufficient data exist in the literature to enable the two-parameter description to be used to predict the thermal responses of clothed subjects. Although, when interpreting such predictions, the limitations of the two-parameter description should be borne in mind.

Acknowledgement
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References
HOLMER, I., and ELNAS, S., 1981, Physiological evaluation of the resistance to evaporative heat transfer by clothing, Ergonomics, 24, 63–74.
LOTENS, W. A., 1988, Comparison of thermal predictive models for clothed humans, ASHRAE Transactions, 94 (1).
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Nielsen, R., Olesen, B. W., and FANGER, P. O., 1985, Effect of physical activity and air velocity on the thermal insulation of clothing, Ergonomics, 28, 1617–1631.


Olesen, B. W., Hasse, Y., and DEAR, R. J. DE, 1988, Clothing insulation asymmetry and thermal comfort. ASHRAE Transactions, 94 (1).


Quantifying the effects of clothing for models


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Les modèles prédictifs de la réponse de l'individu à l'environnement thermique doivent, afin de pouvoir être vraiment utiles dans la pratique, tenir compte des propriétés isolantes du vêtement. Dans cet article, on examine les mécanismes du transfert de chaleur entre l'organisme et le milieu ambiant, ainsi que les effets de résistivité du vêtement sur ce transfert. On décrit la classique méthode à deux paramètres qui sert à quantifier la résistivité du vêtement au transfert de chaleur sèche et évaporative et on relève les limitations de ce modèle descriptif. Pour le moment on possède suffisamment de données pour justifier l'emploi de ce modèle, mais il est perfectible. On fournit un exemple du modèle de prédiction ISO/DIS 7933 afin de montrer l'effet que peut avoir, sur les prédictions, les différentes méthodes de prise en compte de propriétés isolantes du vêtement.


Es wird ein Beispiel der Modellvorhersage nach ISO/DIS 7933 dargestellt, um den Effekt, den die Benutzung von unterschiedlichen Methoden zur Beschreibung des isolierenden Effekts der Kleidung auf die Modellvorhersage haben kann, zu demonstrieren.