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

(Volume Two)

by

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CONTENTS

APPENDIX A

MODEL COMPUTER PROGRAM LISTINGS AND EXAMPLE PREDICTIONS

LUT2 MODEL PROGRAM LISTING

```
C
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,KCLO,FACL,IM,WORK,WK,TCR,TSK,
     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
C
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
C OPEN RESULTS OUTPUT FILE
C
      CALL SETUP
      OPEN(UNIT=NDAT,FILE=LUT2,STATUS='UNKNOWN')
C
C DISPLAY PROGRAM 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
      CALL CLEAN
C
C DISPLAY MENU
C
      WRITE(NOUT,20)
20    FORMAT(/
     X15X'******************************************************'/
     X17X'LUT 2-Node Model of Human Thermoregulation (V1.0)'/
     X17X'     (adapted from J. B. Pierce 2-Node Model'/
     X15X'******************************************************'/
     X///20X'B    Begin New Exposure'///
     X20X'C    Continue Exposure (new environment)'///
     X20X'Q    Quit'////
     X15X'Results will be copied to a file called LUT2.DAT'///
     X8X'Enter Option: '$)
C
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 PRINT HEADER FOR DATA FILE
C
      WRITE(NDAT,55)
55    FORMAT(///////
     X34X'New Exposure'/
     X33X'**************'//)
C
C PROGRAM TIMER VARIABLES
C
C MTIME = ACTUAL TIME (MINS)
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
      NTIME=1
      DTIME=1./60.
      JTIME=0
C
C STEADY STATE CHARACTERISTICS OF MODEL AT THERMAL NEUTRALITY
C (ie SET POINTS AND COEFFICIENT VALUES) (FROM GAGGE et al. (1986)
C
```

```
      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
C INITIAL CONDITIONS-PHYSIOLOGICAL THERMAL NEUTRALITY
C
      TBM=ALPHA*TSK+(1.-ALPHA)*TCR
      SKBF=SKBFN
C
C TO HERE FOR CONTINUING AN EXPOSURE
C
60    CONTINUE
C
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 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
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
C CHC VALUE FOR STILL AIR IS 3.0 AT SEA LEVEL
C
      IF(CHC.LT.3.0)CHC=3.0
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
C CHCIM 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
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
C CALCULATE LR AT TCLIM
C
      LR=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/(LR*IM)-1./(FACL*LR*CHCIM)
C
C INITIALIZE OTHER VARIABLES
C
      TCL=0.0
      ESK=0.0
C
C **********************************************************************
C
C SIMULATION OF BODY TEMPERATURE REGULATION - START OF REG. LOOP
C
500   CONTINUE
C
C ITERATIVE LOOP TO CALCULATE CLOTHING TEMPERATURE (TCL) AND LINEAR
C RADIATION COEFFICIENT (CHR)
C
600   TCLOLD=TCL
      CHR=4.*5.67E-8*(((TCL+TR)/2.+273.2)**3)*0.725
      TCL=((1./(CLO*0.155))*TSK+FACL*(CHC*TA+CHR*TR))/
     X((1./(CLO*0.155))+FACL*(CHC+CHR))
      IF(ABS(TCL-TCLOLD).GT.0.01)GOTO 600
C
C RESPIRATORY HEAT LOSSES
C
      ERES=0.017251*MR*(5.8662-RH*SVP(TA))
      CRES=0.0014*MR*(34.-TA)
C
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
```

```
C AVERAGE MAN 70kg, 1.7m, 1.8 m2
C
      TCSK=0.97*ALPHA*70.
      TCCR=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
C DEFINITION OF REGULATORY CONTROL SIGNALS
C
      SKSIG=TSK-TTSK
      IF(SKSIG.LE.0.)THEN
       COLDS=-SKSIG
       WARMS=0.
      ELSE
       COLDS=0.
       WARMS=SKSIG
      ENDIF
      CRSIG=TCR-TTCR
      IF(CRSIG.LE.0.)THEN
       COLDC=-CRSIG
       WARMC=0.
      ELSE
       WARMC=CRSIG
       COLDC=0.
      ENDIF
C
C CONTROL SKIN BLOOD FLOW
C
      STRIC=CSTR*COLDS
      DILAT=CDIL*WARMC
      SKBF=(SKBFN+DILAT)/(1.+STRIC)
      IF(SKBF.LT.0.5)SKBF=0.5
      IF(SKBF.GT.90.0)SKBF=90.0
C
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
C DEFINITION OF CONTROL SIGNALS FOR SWEATING
C
      TBM=ALPHA*TSK+(1.-ALPHA)*TCR
      BYSIG=TBM-TTBM
      IF(BYSIG.LE.0.)THEN
       COLDB=-BYSIG
       WARMB=0.
      ELSE
       WARMB=BYSIG
       COLDB=0.
      ENDIF
C
C CONTROL OF REGULATORY SWEATING
C
      REGSW=CSW*WARMB*EXP(WARMS/10.7)
      IF(REGSW.GT.500.0)REGSW=500.0
      ERSW=0.68*REGSW
```

```
C
C EVALUATION OF HEAT TRANSFER BY EVAPORATION AT THE SKIN SURFACE
C
C LR VARIES WITH TCL (NOT TSK AS IN, GAGGE et al. (1986))
C
      LR=15.1512*(TCL+273.15)/273.15
C
C RT IS RESISTANCE OF CLOTHING AND SURROUNDING AIR LAYER TO VAPOUR
C PERMEATION, CALCULATED ACCORDING TO HASLAM AND PARSONS (1988)
C
      RT=IECL+1./(FACL*LR*CHC)
      EMAX=(1./RT)*(SVP(TSK)-RH*SVP(TA))
      PRSW=ERSW/EMAX
C
C EVAPORATIVE HEAT LOSS SECTION FROM GAGGE et al. (1986)
C
C GAGGE et al. (1986) INTRODUCE EVEFF, EQUIVALENT TO THE MAXIMUM
C SKIN WETTEDNESS ACHIEVABLE IN PRACTICE.  GAGGE et al. SAY THAT EVEFF
C LIES BETWEEN 0.7 AND 1.0.  WITHOUT FURTHER INFORMATION, 1.0 IS USED
C HERE
C
      EVEFF=1.0
C
C 0.06 IS PDIF FOR NONSWEATING SKIN - KERSLAKE
C
      PDIF=(1.0-PRSW)*0.06
      EDIF=PDIF*EMAX
      ESK=ERSW+EDIF
      PWET=ESK/EMAX
C
C BEGINNING OF DRIPPING (SWEAT NOT EVAPORATED ON SKIN SURFACE)
C
      IF((PWET.GE.EVEFF).AND.(EMAX.GE.0.))THEN
       PWET=EVEFF
       PRSW=(EVEFF-0.06)/0.94
       ERSW=PRSW*EMAX
       PDIF=(1.0-PRSW)*0.06
       EDIF=PDIF*EMAX
       ESK=ERSW+EDIF
      ENDIF
C
C WHEN EMAX<0. CONDENSATION ON SKIN OCCURS
C
      IF(EMAX.LT.0.)THEN
       PDIF=0.
       EDIF=0.
       ESK=EMAX
       PWET=EVEFF
       PRSW=EVEFF
       ERSW=0.
      ENDIF
C
C EDRIP = UNEVAPORATED SWEAT IN g/sq.m/hr
C
      EDRIP=(REGSW*0.68-PRSW*EMAX)/0.68
      IF(EDRIP.LT.0.)EDRIP=0.
C
C ADJUSTMENT OF METABOLIC HEAT DUE TO SHIVERING
C
```

```
      MR=WORK+19.4*COLDS*COLDC
C
C CALCULATE TOTAL EVAPORATIVE HEAT LOSS IN ORDER THAT BODY HEAT STORAGE
C RATE MAY BE CALCULATED (REQUIRED FOR SET AND OUTPUT)
C
      EV=ESK+ERES
C
C CALCULATE TOTAL DRY HEAT LOSS (REQUIRED FOR OUTPUT)
C
      DRYT=DRY+CRES
C
C INCREMENT TIMER
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
      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
```

```
      COMMON/UNIT/NIN,NOUT,NDAT
      CALL CLEAN
      WRITE(NOUT,10)
      WRITE(NDAT,10)
10    FORMAT(//
     X13X'**************************************************'//
     X14X'LUT 2-Node Model of Human Thermoregulation (V1.0)'/
     X14X'     (adapted from J. B. Pierce 2-Node Model)'//
     X14X'                  Roger Haslam'/
     X14X'           Department of Human Sciences'/
     X14X'      Loughborough University of Technology'//
     X13X'**************************************************'
     X//)
      CALL WAIT(7)
      RETURN
      END
C
C SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS
C
      SUBROUTINE INPUT
      REAL MR,IM,KCLO,LR,ITIM,IECL
      COMMON/IIN/TA,TR,V,RH,CLO,KCLO,FACL,IM,WORK,WK,TCR,TSK,
     XMTIME,ITIME,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
```

```
      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
      IF((OPT.EQ.BEGIN).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
      SUBROUTINE INPUT2
      REAL MR,IM,KCLO,LR,ITIM,IECL
      COMMON/IIN/TA,TR,V,RH,CLO,KCLO,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                     '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) : '$)
C
C DETERMINE RESPONSE
C
      READ(NIN,300)ICHNG
300   FORMAT(I1)
      CALL CLEAN
      IF(ICHNG.EQ.7)CALL INPUT
      IF(ICHNG.EQ.7)GOTO 9999
      GOTO (400,500,600,700,800,900)ICHNG
      GOTO 9998
C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400   WRITE(NOUT,1400)
1400  FORMAT(/' Air Temperature           (C) : '$)
      READ(NIN,*)TA
      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
```

```
      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,KCLO,FACL,IM,WORK,WK,TCR,TSK,
     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,WK
      WRITE(NDAT,100)TA,TR,V,RH,CLO,FACL,IM,WORK,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
       WRITE(NOUT,400)MTIME,TCR,TSK
       WRITE(NDAT,400)MTIME,TCR,TSK
      END IF
300   FORMAT(/
     X' Time    Tcr     Tsk     w       M      (C+R)     E       Esk
     XDrip  sk/cr'/
     X' (min)   (C)     (C)    (ND)   (W/m2)  (W/m2)  (W/m2)  (W/m2) (g
```

```
     X/h.m2)  (ND)'/
     X'*****************************************************************
     X**************')
400   FORMAT(I5,2F8.2,1X,7(2X,'******'))
      RETURN
      END
```

LUT2 MODEL EXAMPLE PREDICTIONS

****

LUT 2-Node Model of Human Thermoregulation (V1.0)
(adapted from J. B. Pierce 2-Node Model)

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Department of Human Sciences
Loughborough University of Technology

****

New Exposure
****

Air Temperature	=	40.00 (C)
Mean Radiant Temperature	=	40.00 (C)
Air Speed	=	0.10 (m/s)
Relative Humidity	=	0.60 (ND)
Intrinsic Clothing Insulation	=	1.00 (clo)
Clothing Area Factor	=	1.31 (ND)
Clothing Permeability Index (Woodcock Im)	=	0.38 (ND)
Initial Metabolic Rate	=	100.00 (W/m2)
Work Rate Accomplished	=	0.00 (W/m2)

Time (min)	Tcr (C)	Tsk (C)	w (ND)	M (W/m2)	(C+R) (W/m2)	E (W/m2)	Esk (W/m2)	Drip (g/h.m2)	sk/cr (ND)
0	36.80	33.70	******	******	******	******	******	******	******
5	36.90	35.31	1.00	100.00	-22.68	38.29	35.81	7.26	0.07
10	37.01	36.33	1.00	100.00	-17.48	47.46	44.97	39.32	0.06
15	37.15	36.72	1.00	100.00	-15.45	51.05	48.56	71.90	0.05
20	37.28	36.92	1.00	100.00	-14.41	52.96	50.48	103.86	0.05
25	37.42	37.04	1.00	100.00	-13.89	54.10	51.62	135.34	0.05
30	37.55	37.16	1.00	100.00	-13.37	55.22	52.73	166.66	0.05
35	37.68	37.27	1.00	100.00	-12.87	56.31	53.82	197.77	0.05
40	37.80	37.38	1.00	100.00	-12.39	57.37	54.89	228.68	0.05
45	37.92	37.49	1.00	100.00	-11.91	58.41	55.93	259.34	0.05
50	38.04	37.60	1.00	100.00	-11.45	59.43	56.95	289.74	0.05
55	38.15	37.70	1.00	100.00	-11.01	60.42	57.94	319.87	0.05
60	38.26	37.80	1.00	100.00	-10.57	61.39	58.91	349.70	0.05

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),BFB(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
C OPEN INPUT DATA FILE AND RESULTS OUPUT 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
      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)'/
```

```
     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
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
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(11,82)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
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
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)
C
```

```
      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
```

```
      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 EFFECTOR 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)
C
C CALCULATE MAXIMUM EVAPORATIVE CAPACITY OF THE ENVIRONMENT, EMAX(I)
C USING THE RESISTANCE TO VAPOUR PERMEATION, RT. RT CALCULATED ACCORDING
C TO HASLAM AND PARSONS (1988)
C
      LR(I)=15.1512*(TCL(I)+273.15)/273.15
      RT(I)=IECL+1./(FACL*LR(I)*HC(I))
      EMAX(I)=((1./RT(I))*(SVP(T(N+3))-RH*SVP(TA)))*S(I)
      IF(E(N+3).GT.EMAX(I))E(N+3)=EMAX(I)
401   CONTINUE
C
C CALCULATE DRY SKIN HEAT EXCHANGE WITH ENVIRONMENT, DRY(I)
C
      DO 450 I=1,6
      DRY(I)=(FACL*(HC(I)*(TCL(I)-TA)+HR(I)*(TCL(I)-TR)))*S(I)
450   CONTINUE
C
C CALCULATE HEAT FLOWS
C
      DO 500 K=1,24
      BC(K)=BF(K)*(T(K)-T(25))
      TD(K)=TC(K)*(T(K)-T(K+1))
500   CONTINUE
      DO 501 I=1,6
      K=4*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)
501   CONTINUE
      HF(25)=0.
      DO 502 K=1,24
      HF(25)=HF(25)+BC(K)
```

```
502   CONTINUE
C
C SUBTRACT A CORRECTION FOR RESPIRATORY HEAT LOSSES FROM BLOOD HEAT FLOW
C
      HF(25)=HF(25)-0.08*WORKI
C
C DETERMINE OPTIMUM INTEGRATION STEP
C
      NTIME=1
      DTIME=1./60.
      DO 600 K=1,25
      F(K)=HF(K)/C(K)
      U=ABS(F(K))
      IF(U*DTIME.GT.0.1)DTIME=0.1/U
600   CONTINUE
C
C CALCULATE NEW TEMPERATURES
C
      DO 700 K=1,25
      T(K)=T(K)+F(K)*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.
      PWET=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
C SKIN WETTEDNESS, PWET
C
      PWET=PWET+(E(4*I)/EMAX(I))*(S(I)/SA)
C
C SKIN BLOOD FLOW, SBF
C
      SBF=SBF+BF(4*I)/60.
C
C MEAN SKIN TEMPERATURE, TS
C
      TS=TS+T(4*I)*C(4*I)/3.90
802   CONTINUE
      DO 801 N=1,25
C
C MEAN BODY TEMPERATURE, TB
C
      TB=TB+T(N)*C(N)/68.79
C
C TOTAL HEAT FLOW, HFLOW
C
      HFLOW=HFLOW+HF(N)
801   CONTINUE
C
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
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(I5,5F8.2,1X,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/XXVNA/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(/' 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
      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
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
```

```
      WRITE(NOUT,200)TA,TR,V,RH,CLO,FACL,IM,WORK/SA,WK/SA,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) : '$)
C
C DETERMINE RESPONSE
C
      READ(NIN,300)ICHNG
300   FORMAT(I1)
      CALL CLEAN
      IF(ICHNG.EQ.7)CALL INPUT
      IF(ICHNG.EQ.7)GOTO 9999
      GOTO (400,500,600,700,800,900)ICHNG
      GOTO 9998
C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400   WRITE(NOUT,1400)
1400  FORMAT(/' Air Temperature           (C) : '$)
      READ(NIN,*)TA
      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
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
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
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
        TS=0
        DO 350 I=1,6
        TS=TS+T(4*I)*C(4*I)/3.90
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)
     X E      Esk'/
     X' (min)   (C)     (C)     (C)     (C)     (ND)   (W/m2)  (W/m2)  (
     XW/m2)  (W/m2)'/
     X'*******************************************************************
     X**************')
400   FORMAT(I5,4F8.2,1X,5(2X,'******'))
      RETURN
      END
```

LUT25 MODEL PROGRAM LISTING

(HEAD AND HANDS UNCLOTHED)

```
C
C LUT 25-NODE MODEL OF HUMAN THERMOREGULATION (V1.2b)
C (ADAPTED FROM STOLWIJK AND HARDY 25-NODE MODEL)
C HEAD AND HANDS UNCLOTHED
C
C PROGRAM ALSO REQUIRES DATA FILE: THERMO.DAT
C
      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),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,ITIMM,IECL,IECLM,IET,IETM
      COMMON/XXVNB/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
C OPEN INPUT DATA FILE AND RESULTS OUPUT FILE
C
      CALL SETUP
      OPEN(UNIT=11,FILE='[haslam.models]THERMO.DAT',readonly,
     xSTATUS='OLD',ERR=1250)
      OPEN(UNIT=NDAT,FILE=LUT25B,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
      CALL CLEAN
C
C DISPLAY MENU
C
      WRITE(NOUT,20)
20    FORMAT(/
     X13X'******************************************************'/
     X15X'LUT 25-Node Model of Human Thermoregulation (V1.2b)'/
     X15X'  (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
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(11,82)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
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
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
```

```
C
C IF CLOM IS LESS THAN 1.0E-8 THEN SET TO 1.0E-8
C
      IF(CLOM.LT.1.0E-8)CLOM=1.0E-8
C
C CALCULATE LRIM AT TCLIM
C
      LRIM=15.1512*(TCLIM+273.15)/273.15
C
C CALCULATE Iet (m2.kPa/W), AS MEASURED ON THE MANIKIN
C
      IET=ITIM/(LRIM*IM)
C
C CORRECT Iet DETERMINED FROM THE IM MEASURED ON THE MANIKIN, FOR
C THE REDUCED SURFACE AREA DUE TO THE NUDE HEAD AND HANDS.  STOLWIJK
C AND HARDY SURFACE AREAS USED IN THE ABSENCE OF ANY OTHER DATA
C
      IETM=(SA-S(1)-S(4))/(SA/IET-(S(1)+S(4))*LRIM*HCIM)
C
C CALCULATE CORRECTED IECL
C
      IECLM=IETM-1./(FACL*LRIM*HCIM)
C
C CALCULATE CONVECTIVE HEAT TRANSFER COEFFICIENT, HC(I),
C STOLWIJK AND HARDY (1977)
C
      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./(CLOM*0.155))*T(4*I)+FACL*(HC(I)*TA+HR(I)*TR))/
     X((1./(CLOM*0.155))+FACL*(HC(I)+HR(I)))
      IF(ABS(TCL(I)-TCLOLD).GT.0.01)GOTO 250
225   CONTINUE
C
C HEAD AND HANDS ARE UNCLOTHED
C
      HR(1)=4.*5.67E-8*(((T(4)+TR)/2.+273.2)**3.)*ARAD(1)
      HR(4)=4.*5.67E-8*(((T(16)+TR)/2.+273.2)**3.)*ARAD(4)
      TCL(1)=T(4)
      TCL(4)=T(16)
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
      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 EFFECTOR 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)
```

```
C
C CALCULATE MAXIMUM EVAPORATIVE CAPACITY OF THE ENVIRONMENT, EMAX(I)
C USING THE RESISTANCE TO VAPOUR PERMEATION, RT.  RT IS CALCULATED
C ACCORDING TO HASLAM AND PARSONS (1988)
C
      LR(I)=15.1512*(TCL(I)+273.15)/273.15
C
C HEAD AND HANDS ARE UNCLOTHED
C
      IF((I.EQ.1).OR.(I.EQ.4))THEN
        RT(I)=0.+1./(FACL*LR(I)*HC(I))
      ELSE
        RT(I)=IECLM+1./(FACL*LR(I)*HC(I))
      ENDIF
      EMAX(I)=((1./RT(I))*(SVP(T(N+3))-RH*SVP(TA)))*S(I)
      IF(E(N+3).GT.EMAX(I))E(N+3)=EMAX(I)
401   CONTINUE
C
C CALCULATE DRY SKIN HEAT EXCHANGE WITH ENVIRONMENT, DRY(I)
C
      DO 450 I=1,6
      DRY(I)=(FACL*(HC(I)*(TCL(I)-TA)+HR(I)*(TCL(I)-TR)))*S(I)
450   CONTINUE
C
C CALCULATE HEAT FLOWS
C
      DO 500 K=1,24
      BC(K)=BF(K)*(T(K)-T(25))
      TD(K)=TC(K)*(T(K)-T(K+1))
500   CONTINUE
      DO 501 I=1,6
      K=4*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)
501   CONTINUE
      HF(25)=0.
      DO 502 K=1,24
      HF(25)=HF(25)+BC(K)
502   CONTINUE
C
C SUBTRACT A CORRECTION FOR RESPIRATORY HEAT LOSSES FROM BLOOD HEAT FLOW
C
      HF(25)=HF(25)-0.08*WORKI
C
C DETERMINE OPTIMUM INTEGRATION STEP
C
      NTIME=1
      DTIME=1./60.
      DO 600 K=1,25
      F(K)=HF(K)/C(K)
      U=ABS(F(K))
      IF(U*DTIME.GT.0.1)DTIME=0.1/U
600   CONTINUE
C
C CALCULATE NEW TEMPERATURES
C
      DO 700 K=1,25
```

```
      T(K)=T(K)+F(K)*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.
      PWET=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
```

```
C SKIN WETTEDNESS, PWET
C
      PWET=PWET+(E(4*I)/EMAX(I))*(S(I)/SA)
C
C SKIN BLOOD FLOW, SBF
C
      SBF=SBF+BF(4*I)/60.
C
C MEAN SKIN TEMPERATURE, TS
C
      TS=TS+T(4*I)*C(4*I)/3.90
802   CONTINUE
      DO 801 N=1,25
C
C MEAN BODY TEMPERATURE, TB
C
      TB=TB+T(N)*C(N)/68.79
C
C TOTAL HEAT FLOW, HFLOW
C
      HFLOW=HFLOW+HF(N)
801   CONTINUE
C
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
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(I5,5F8.2,1X,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 (V1.2b)'/
     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,IM,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)   : '$)
      READ(NIN,*)V
      WRITE(NOUT,400)
400   FORMAT(/' Relative Humidity (fraction)              (ND)    : '$)
      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
      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
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/SA,WK/SA,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) : '$)
C
C DETERMINE RESPONSE
C
      READ(NIN,300)ICHNG
300   FORMAT(I1)
      CALL CLEAN
      IF(ICHNG.EQ.7)CALL INPUT
      IF(ICHNG.EQ.7)GOTO 9999
      GOTO (400,500,600,700,800,900)ICHNG
      GOTO 9998
C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400   WRITE(NOUT,1400)
1400  FORMAT(/' Air Temperature          (C) : '$)
      READ(NIN,*)TA
      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
```

```
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
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
         TS=0
         DO 350 I=1,6
         TS=TS+T(4*I)*C(4*I)/3.90
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)
     X E      Esk'/
     X' (min)   (C)     (C)     (C)     (C)     (ND)   (W/m2)  (W/m2)  (
     XW/m2)  (W/m2)'/
     X'*******************************************************************
     X**************')
400    FORMAT(I5,4F8.2,1X,5(2X,'******'))
       RETURN
       END
```

LUT25 MODEL THERMO.DAT DATA FILE

```
 2.57 0.39 0.26 0.2811.4918.80 4.94 1.41 1.63 3.54 0.67 0.50 0.16 0.07 0.10 0.20 4.9410.67 1.66 1.25 0.27 0.07 0.15 0.26 2.60
14.95 0.12 0.13 0.1052.63 5.81 2.49 0.47 0.82 1.11 0.21 0.15 0.09 0.23 0.04 0.06 2.59 3.32 0.50 0.37 0.15 0.02 0.05 0.08
 0.00 0.00 0.00 0.8110.45 0.00 0.00 3.78 0.00 0.00 0.00 1.40 0.00 0.00 0.00 0.52 0.00 0.00 0.00 3.32 0.00 0.00 0.00 0.72
 45.00  0.12  0.13  1.44210.00  6.00  2.56  2.10  0.84  1.14  0.20  0.50  0.10  0.24  0.04  2.00  2.69  3.43  0.52  2.85  0.16  0.02
0.05  3.00
 1.6113.2516.10 0.00 1.59 5.5323.08 0.00 1.4010.3030.50 0.00 6.4011.2011.50 0.0010.5014.4074.50 0.0016.3020.6016.40 0.00
 0.1326 0.6804 0.2536 0.0946 0.5966 0.1299
 3.00 2.10 2.10 4.00 2.10 4.00
 0.74 0.75 0.66 0.56 0.65 0.62
36.9635.0734.8134.5836.8936.2834.5333.6235.5334.1233.5933.2535.4135.3835.3035.2235.8135.3035.3134.1035.1435.0335.1135.0436.71
372.00 33.70  0.00136.00  8.90  0.00 10.80 10.80  0.00 13.00  0.04  1.00 10.00
 0.21 0.42 0.10 0.04 0.20 0.03
0.0810.4810.1540.0310.2180.035
0.1320.3220.0950.1210.2300.100
 0.05 0.15 0.05 0.35 0.05 0.35
 0.00 0.30 0.08 0.01 0.60 0.01
 0.02 0.85 0.05 0.00 0.07 0.00
36.9635.0734.8134.5836.8936.2834.5333.6235.5334.1233.5933.2535.4135.3835.3035.2235.8135.3035.3134.1035.1435.0335.1135.0436.71
```

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
****

Air Temperature	=	40.00 (C)
Mean Radiant Temperature	=	40.00 (C)
Air Speed	=	0.10 (m/s)
Relative Humidity	=	0.60 (ND)
Intrinsic Clothing Insulation	=	1.00 (clo)
Clothing Area Factor	=	1.31 (ND)
Clothing Permeability Index (Woodcock Im)	=	0.38 (ND)
Initial Metabolic Rate	=	100.00 (W/m2)
Work Rate Accomplished	=	0.00 (W/m2)

Time (min)	Tcr (C)	Tsk (C)	Thd (C)	Tft (C)	w (ND)	M (W/m2)	(C+R) (W/m2)	E (W/m2)	Esk (W/m2)
0	36.96	33.97	35.22	35.04	******	******	******	******	******
5	36.74	35.20	36.16	35.97	0.22	100.00	-18.60	15.46	5.59
10	36.77	35.68	36.55	36.37	0.19	100.00	-16.57	15.46	5.59
15	36.91	35.85	36.71	36.58	0.80	100.00	-15.84	33.89	24.02
20	37.05	36.02	36.64	36.58	0.98	100.00	-15.24	41.50	31.63
25	37.18	36.25	36.69	36.59	1.00	100.00	-14.40	43.79	33.92
30	37.29	36.46	36.82	36.70	1.00	100.00	-13.55	45.33	35.46
35	37.42	36.66	36.97	36.84	1.00	100.00	-12.86	46.62	36.75
40	37.53	36.84	37.10	36.98	1.00	100.00	-12.09	48.06	38.19
45	37.67	37.02	37.25	37.14	1.00	100.00	-11.50	49.18	39.31
50	37.77	37.15	37.37	37.26	1.00	100.00	-10.87	50.37	40.50
55	37.90	37.31	37.51	37.40	1.00	100.00	-10.32	51.45	41.58
60	38.02	37.44	37.63	37.53	1.00	100.00	-9.86	52.33	42.46

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
****

Air Temperature	=	40.00 (C)
Mean Radiant Temperature	=	40.00 (C)
Air Speed	=	0.10 (m/s)
Relative Humidity	=	0.60 (ND)
Intrinsic Clothing Insulation	=	1.00 (clo)
Clothing Area Factor	=	1.31 (ND)
Clothing Permeability Index (Woodcock Im)	=	0.38 (ND)
Initial Metabolic Rate	=	100.00 (W/m2)
Work Rate Accomplished	=	0.00 (W/m2)

Time (min)	Tcr (C)	Tsk (C)	Thd (C)	Tft (C)	w (ND)	M (W/m2)	(C+R) (W/m2)	E (W/m2)	Esk (W/m2)
0	36.96	33.97	35.22	35.04	******	******	******	******	******
5	36.74	35.19	36.52	35.92	0.26	100.00	-19.08	15.46	5.59
10	36.79	35.66	36.97	36.31	0.23	100.00	-17.09	15.46	5.59
15	36.93	35.85	37.08	36.50	0.89	100.00	-16.24	33.71	23.84
20	37.07	36.08	36.90	36.54	0.95	100.00	-15.70	39.76	29.89
25	37.19	36.30	36.80	36.66	0.97	100.00	-15.22	43.37	33.50
30	37.30	36.51	36.77	36.79	0.98	100.00	-14.41	45.77	35.90
35	37.42	36.71	36.79	36.94	0.98	100.00	-13.76	47.71	37.84
40	37.53	36.87	36.84	37.07	0.99	100.00	-13.05	49.94	40.07
45	37.66	37.05	36.91	37.22	0.99	100.00	-12.43	51.93	42.06
50	37.75	37.16	36.97	37.32	1.00	100.00	-11.93	53.61	43.74
55	37.87	37.31	37.06	37.45	1.00	100.00	-11.33	55.48	45.61
60	37.98	37.44	37.19	37.56	1.00	100.00	-10.81	56.53	46.66

LUTTRE MODEL PROGRAM LISTING

```
C
C LUT MODEL OF HUMAN RECTAL TEMPERATURE RESPONSE TO WORK, CLOTHING AND
C ENVIRONMENT (V1.1)
C (ADAPTED FROM GIVONI AND GOLDMAN MODEL)
C
      REAL IMCLO,IMCLOE,MRNET,MR,IM,LR,IECL,IA,IMV
      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/OPTGG/BEGIN,BEGIN1,OPT,CSTAT
      COMMON/ADDIT/CLOT,IMV
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
      CHARACTER*20 GOLD,GAGGE,ISO,STOLW,LUTTRE,LUT2,LUTISO,LUT25A,LUT25B
C
C DEFINE CHARACTER VARIABLES FOR MENU SUB-SECTION ETC
C
      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'
C
C OPEN RESULTS OUTPUT FILE
C
      CALL SETUP
      OPEN(UNIT=NDAT,FILE=LUTTRE,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
      CALL CLEAN
C
C DISPLAY MENU
C
      WRITE(NOUT,20)
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'////
```

```
     X14X'Results will be copied to a file called LUTTRE.DAT'///
     X8X'Enter Option: '$)
C
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
C MTIME  = ACTUAL TIME (MINS)
C HTIME  = ACTUAL TIME (HRS)
C LTIME  = TIME OF EXPOSURE TO ACTIVITY (MINS)
C ATIME  = TIME OF EXPOSURE TO ACTIVITY (HRS)
C JTIME  = TOTAL EXPOSURE TIME (MINS)
C ITIME  = OUTPUT INTERVAL TIME (MINS)
C FWTIME = FINAL WORK TIME (SAVED FOR ANY RECOVERY) (HRS)
C WTIME  = 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
C DETERMINE TOTAL EXPOSURE TIME
C
      JTIME=JTIME+TTIME*60
C
C DETERMINE TYPE OF EXPOSURE
C
C EXPOSURE IS REST IF:
C
C   MR < 120 W, NO PREVIOUS EXPOSURE
C   MR < 120 W, TRE < 37.2 C, PREVIOUS EXPOSURE RECOVERY
C
C EXPOSURE IS WORK IF:
C
C   MR >= 120 W
C
C EXPOSURE IS RECOVERY IF:
C
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'
        ENDIF
      ELSE
        CSTAT='work'
      ENDIF
C
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
C CALCULATE EXPERIMENTAL AND EQUILIBRIUM VALUES
C
C **********************************************************************
C
C STANDARD MAN 70 kg, 1.7 m and 1.81 m2
C
C SKIN TEMPERATURE (C)
C
      TSK=36.0
C
```

```
C EFFECTIVE AIR SPEED (m/s)
C
      VE=V+0.004*(MR-105.)
C
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 Ta=Tr=24 C, hc=4.57 W/M2.C (CALCULATED BY
C SUBTRACTING hr FROM h ASSUMING Ia=0.71 clo
C
C DEFINE CONSTANTS (V=0.1)
C
      HC=4.57
      LR=16.5
      IA=0.71
C
C TOTAL CLOTHING INSULATION (clo) (V=0.1)
C
      CLOT=CLO+IA/FACL
C
C INTRINSIC EVAPORATIVE RESISTANCE (M2.kPa/W)
C
      IECL=(CLOT*0.155)/(LR*IM)-1/(FACL*HC*LR)
C
C DEFINE CONSTANTS (V=1.0)
C (HC CALCULATED FROM 8.6*V**0.53)
C
      HC=8.6
      IA=0.49
C
C TOTAL CLOTHING INSULATION (clo) (V=1.0)
C
      CLOT=CLO+IA/FACL
C
C IM PERMEABILITY INDEX (V=1.0)
C
      IMV=(CLOT*0.155)/(LR*(IECL+1/(FACL*HC*LR)))
C
C IM/CLOT COEFFICIENT (1/clo)
C
      IMCLO=IMV/CLOT
C
C VELOCITY MODIFIER (?)
C
      VMOD=0.25
C
C EFFECTIVE CLOTHING INSULATION COEFFICIENT (clo)
C
      CLOEG=CLOT*VE**(-VMOD)
C
C EFFECTIVE PERMEABILITY INDEX RATIO (1/clo)
C
      IMCLOE=IMCLO*VE**VMOD
C
C REQUIRED EVAPORATIVE COOLING (W)
C
C EREQ= TOTAL HEAT LOAD + ENVIRONMENTAL HEAT LOAD
C
      MRNET=MR-WK
      ERC=6.45*AD*(TA-TSK)/CLOEG
```

```
      EREQ=MRNET+ERC
C
C MAXIMUM EVAPORATIVE CAPACITY OF ENVIRONMENT (W)
C
      EMAX=14.2*AD*IMCLOE*(SVP(TSK)-RH*SVP(TA))
C
C SKIN WETTEDNESS (ND)
C
      PWET=EREQ/EMAX
      IF(PWET.LT.0.OR.PWET.GT.1)PWET=1
C
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
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
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
C THEREFORE FINAL EQUILIBRIUM TEMPERATURE OF PARTIALLY
C ACCLIMATIZED MEN EQUALS TREF + CTREFA (C)
C
      TREFA=TREF+CTREFA
      CTRE=TREFA-TREI
C
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
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
        CTRER=CTRE
        MR=OMR
        GOTO 100
      ENDIF
200   CONTINUE
C
```

```
C DISPLAY ENVIRONMENTAL CONDITIONS, EQUILIBRIUM VALUES AND TABULATE FOR
C OUTPUT
C
      CALL TAB
C
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
C REST
C
500   CONTINUE
C
C INCREMENT TIMERS
C
      MTIME=MTIME+ITIME
      LTIME=LTIME+ITIME
      ATIME=LTIME/60.
C
C RECTAL TEMPERATURE RESPONSE TO REST
C
      TRE=TREI+CTRE*0.1**(0.4**(ATIME-0.5))
C
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
C SAVE FOR WORK
C
      TREIR=TREI
      CTRER=CTRE
      TREI=TRE
      GOTO 10
C
C **********************************************************************
C **********************************************************************
C
C WORK
C
600   CONTINUE
C
C INITIAL LAG TIME (HRS)
C
      TD=58./MR
C
C WORK TIME CONSTANT
C
      TC=0.5+1.5*EXP(-0.3*CTRE)
650   CONTINUE
C
C INCREMENT TIMERS
```

```
C
      MTIME=MTIME+ITIME
      HTIME=MTIME/60.
      LTIME=LTIME+ITIME
      ATIME=LTIME/60.
C
C DURING 0<= 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
C AFTER TD<= T RECTAL TEMPERATURE FOLLOWS WORK RESPONSE
C
      ELSE
        TRE=TREI+CTRE*(1.-EXP(TC*(TD-ATIME)))
      ENDIF
C
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
C SAVE FOR RECOVERY
C
      WTIME=ATIME
      FWTIME=ATIME
      TREIW=TREI
      CTREW=CTRE
      TREWF=TRE
      TREI=TRE
      GOTO 10
C
C *********************************************************************
C *********************************************************************
C
C RECOVERY
C
700   CONTINUE
      FLAG=0
750   CONTINUE
C
C INCREMENT TIMERS
C
      MTIME=MTIME+ITIME
      LTIME=LTIME+ITIME
      ATIME=LTIME/60.
      WTIME=WTIME+ITIME/60.
C
C RECOVERY TIME LAG (HRS)
C
      TDRC=0.25*EXP(-0.5*CP)
C
C RECOVERY TIME CONSTANT
C
      A=1.5*(1.-EXP(-1.5*CP))
```

```
C
C DURING 0<= T < TDRC RECTAL TEMPERATURE RESPONSE TO RECOVERY FOLLOWS
C HALF WORK PATTERN:
C
      IF(ATIME.LT.TDRC)THEN
        TREW=TREIW+CTREW*(1.-EXP(TC*(TD-WTIME)))
        TCNG=TREW-TREWF
        TRE=TREWF+0.5*TCNG
      ELSE
C
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+CTREW*(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
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
C SAVE FOR NEXT EXPOSURE
C
      TREI=TRE
      GOTO 10
C
C ***********************************************************************
C ***********************************************************************
C
800   FORMAT(29X,I4,7X,F6.2)
1000  CONTINUE
      CALL TIDYUP
      END
C
C SVP AT T, USING ANTOINE'S EQUATION (mmHg)
C
      FUNCTION SVP(T)
      SVP=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)
10    FORMAT(//
     X15X'************************************************'//
     X16X'LUT Model of Rectal Temperature Response (V1.1)'/
     X16X'    (adapted from Givoni and Goldman Model)'//
     X16X'                 Roger Haslam'/
     X16X'           Department of Human Sciences'/
     X16X'     Loughborough University of Technology'/
     X16X' (This model is not valid for cold exposures)'//
     X15X'************************************************'//)
      CALL WAIT(7)
      RETURN
      END
C
C SUBROUTINE TO INPUT EXPERIMENTAL CONDITIONS
C
      SUBROUTINE INPUT
      REAL MR,IM
      COMMON/GG/TA,V,RH,CLO,FACL,IM,MR,WK,TREI,NACC,MTIME,ITIME,TTIME,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)   : '$)
      READ(NIN,*)FACL
      WRITE(NOUT,700)
700   FORMAT(/' Clothing Permeability Index  (Woodcock Im) (ND)   : '$)
      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
      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
C CONVERT FROM W/m2 TO W
```

```
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/GG/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                              '
     XF6.2'  (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) : '$)
C
C DETERMINE RESPONSE
C
      READ(NIN,300)ICHNG
300   FORMAT(I1)
      CALL CLEAN
      IF(ICHNG.EQ.7)CALL INPUT
      IF(ICHNG.EQ.7)GOTO 9999
      GOTO (400,500,600,700,800,900)ICHNG
      GOTO 9998
C
C INPUT REQUIRED ENVIRONMENTAL CONDITIONS
C
400   WRITE(NOUT,1400)
1400  FORMAT(/' Air Temperature           (C) : '$)
      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(////
     X12X'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                 ='I7' (days)')
C
C PAUSE
C
      CALL WAIT(9)
      WRITE(NDAT,200)
200   FORMAT(////)
      CALL CLEAN
      WRITE(NOUT,300)VE,CLOT,IMV,CLOEG,IMCLOE,-ERC/AD,EREQ/AD,EMAX/AD,
     XPWET,TREF,TREFA,CP
      WRITE(NDAT,300)VE,CLOT,IMV,CLOEG,IMCLOE,-ERC/AD,EREQ/AD,EMAX/AD,
     XPWET,TREF,TREFA,CP
300   FORMAT(////
     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
                     **************
```

Air Temperature	=	40.00 (C)
Air Speed	=	0.10 (m/s)
Relative Humidity	=	0.60 (ND)
Intrinsic Clothing Insulation	=	1.00 (clo)
Clothing Area Factor	=	1.31 (ND)
Clothing Permeability Index (Woodcock Im)	=	0.38 (ND)
Initial Metabolic Rate	=	100.00 (W/m2)
Work Rate Accomplished	=	0.00 (W/m2)
Number of Days Acclimatization	=	0 (days)

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 (?)

Time	Tre: work
0	36.80
5	36.86
10	36.88
15	36.90
20	36.84
25	37.08
30	37.30
35	37.50
40	37.68
45	37.85
50	38.00
55	38.13
60	38.25

LUTISO MODEL PROGRAM LISTING

```
C
C LUT ADAPTATION OF ISO/DIS 7933 (1987) HOT ENVIRONMENTS - ANALYTICAL
C DETERMINATION OF THERMAL STRESS USING CALCULATION OF REQUIRED SWEAT
C RATE (V1.0)
C
C (ADAPTED FROM FORTRAN TRANSLATION OF ORIGINAL BASIC PROGRAM)
C
      DIMENSION HEADER(4),HMAX(4),SMAXR(4),SMAXW(4),SMAX(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,LRIM,ITIM,IECL
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
      CHARACTER*20 GOLD,GAGGE,ISO,STOLW,LUTTRE,LUT2,LUTISO,LUT25A,LUT25B
      CHARACTER*35 HEADER,CMSG*28,DMSG*30,CCNG*3
C
C DEFINE CHARACTER VARIABLES FOR MENU SUB-SECTION
C
      CHARACTER*1 BEGIN,BEGIN1,TWO,TWO1,QUIT,QUIT1,OPT
      BEGIN='B'
      BEGIN1='b'
      TWO='T'
      TWO1='t'
      QUIT='Q'
      QUIT1='q'
C
C OPEN RESULTS OUTPUT FILE
C
      CALL SETUP
      OPEN(UNIT=NDAT,FILE=LUTISO,STATUS='UNKNOWN')
C
C DISPLAY PROGRAM 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
      CALL CLEAN
C
C DISPLAY MENU
C
      WRITE(NOUT,20)
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'*****************************************************'/
```

```
     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: '$)
C
C DFTERMINE RESPONSE
C
      READ(NIN,30)OPT
30    FORMAT(A)
      IF((OPT.EQ.BEGIN).OR.(OPT.EQ.BEGIN1))THEN
        CALL CLEAN
        CALL INPUT
        GOTO 50
      ENDIF
      IF((OPT.EQ.TWO).OR.(OPT.EQ.TWO1))THEN
        CALL CLEAN
        WRITE(NOUT,35)
35      FORMAT(' Sequence 1: ')
        CALL INPUT
        WRITE(NOUT,40)
40      FORMAT(/' Duration of Sequence 1                        (mins)  : '
     X$)
        READ(NIN,*)ITIME
        NSEQ=1
        MRT=0.0
        EREQT=0.0
        EMAXT=0.0
        ITIMET=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
      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
```

```
      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
C COEFFICIENTS AND THERMAL EXCHANGES
C
C ASSIGN CONSTANTS
C
      TSK=36.0
      ARADU=0.725
C
C PARTIAL VAPOUR PRESSURE OF WATER IN AIR
C
      PA=RH*SVP(TA)
C
C PARTIAL VAPOUR PRESSURE AT SKIN SURFACE
C
      PSK=SVP(TSK)
C
C EFFECTIVE AIR MOVEMENT:
C
      VACT=0.0052*(MR-58)
      IF(VACT.GT.0.7)VACT=0.7
      VEFF=V+VACT
C
C METABOLIC HEAT PRODUCTION:
C
      MH=MR-WK
C
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
C LINEAR RADIATION HEAT TRANSFER COEFFICIENT AND CLOTHING SURFACE
C TEMPERATURE (ITERATION)
C
84    TCLOLD=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-TCLOLD).GT.0.01)GOTO 84
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
C CH IM 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
```

```
      WREQ=EREQ/EMAX
      IF(EMAX.LE.0.0)WREQ=2.0
      IF(WREQ.GT.2.0)WREQ=2.0
C
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(
     X' Interpretation, Time Weighted Averages of Ereq and Emax:'/)
        ENDIF
      ENDIF
C
C INITIALIZE STRING VARIABLE DMSG
C
      DMSG=' '
C
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
```

```
C
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 M XIMUM 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
      SMAX(J)=SMAXR(J)
      IF(MR.GT.80.0)SMAX(J)=SMAXW(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=SMAX(J)
```

```
        WP=WMAXD(J)
        GOTO 500
      ENDIF
C
C IF Emax IS LESS THAN HALF Smax (V. HUMID ENV.) Wo=1.0
C
      IF((EMAX/SMAX(J)).LT.0.5)THEN
        WO=1.0
        GOTO 600
      FNDIF
C
C F)R LESS HUMID ENVIRONMENTS Wo IS CALCULATED BY ITERATION
C
C CH)OSE STRUCTURE OF EQUATION TO ENSURE CONVERGENCE
C
      W2=1.0
700   IF((EMAX/SMAX(J)).GT.1.0)THEN
        WO=(1.0-0.5*EXP(-6.6*(1.0-W2)))*SMAX(J)/EMAX
      ELSE
        WO=ALOG((1.0-W2*EMAX/SMAX(J))*2)/6.6+1
      ENDIF
      IF(ABS(W2-WO).GT.5.0E-04)THEN
        W2=(W2+WO)/2
        GOTO 700
      ENDIF
600   CONTINUE
C
C Wp IS THE SMALLEST OF Wreq, Wmax, Wo
C
      WP=WREQ
      IF(WP.GT.WMAXD(J))WP=WMAXD(J)
      IF(WP.GT.WO)WP=WO
      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
      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
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
C IF DLE1 IS THE SHORTEST DLE THEN:
C
      IF((DLE1.LE.DLE2).AND.(DLE1.LE.DLE3))THEN
C
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
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
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)'
C
C IF DLE1 IS BETWEEN 10 AND 30 MINS REDUCE BY A FACTOR BETWEEN 0 AND 1
C
            ELSE
              EP0=EP
              EP=EP*(DLE1-10.0)/20.0
              ICNG=(EP0-EP)/EP0*100.0
C
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(11)
              DMSG='(Ep Reduced By *** %)'
              DMSG(16:18)=CCNG
            ENDIF
          ENDIF
        ENDIF
C
C REC LCULATE 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 = ',I3,1X,'mins',2X,A30/
     X35X,'= ',2X,I1,1X,'h',1X,I3,1X,'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 Vreq
C
      IF((OPT.EQ.TWO).OR.(OPT.EQ.TWO1))THEN
        MRT=MRT+MR*ITIME
```

```
        EREQT=EREQT+EREQ*ITIME
        EMAXT=EMAXT+EMAX*ITIME
        ITIMET=ITIMET+ITIME
        IF(NSEQ.EQ.1)THEN
          GOTO 60
        ELSEIF(NSEQ.EQ.2)THEN
          MR=MRT/ITIMET
          EREQ=EREQT/ITIMET
          EMAX=EMAXT/ITIMET
          IF(EMAX.GE.0.0)WREQ=2.0
          WREQ=EREQ/EMAX
          IF(WREQ.GT.2.0)WREQ=2.0
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: '///
     X4X,'Metabolic Rate                          : Mr   = 'F7.2' (W/
     Xm2)'/
     X4X,'Required Evaporative Cooling            : Ereq = 'F7.2' (W/
     Xm2)'/
     X4X,'Maximum Evaporative Capacity of Environment: Emax = 'F7.2' (W/
     Xm2)'/
     X4X,'Required Skin Wettedness                : Wreq = 'F7.2' (ND
     X)')
          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)
```

```
10    FORMAT(//
     X16X'**************************************************'//
     X19X'LUT Adaptation of ISO/DIS 7933 (1987) (V1.0)'/
     X19X'        Required Sweat Rate Program'/
     X19X' Analytical Determination of Thermal Stress'//
     X19X'                Roger Haslam'/
     X19X'        Department of Human Sciences'/
     X19X'   Loughborough University of Technology'//
     X16X'**************************************************'
     X//)
      CALL WAIT(6)
      RETURN
      END
C
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,
     XEMAX,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)    : '$)
      READ(NIN,*)V
      WRITE(NOUT,400)
400   FORMAT(/' Relative Humidity              (fraction) (ND)     : '$)
      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)    : '$)
      READ(NIN,*)IM
C
C IF NUDE, SET CLO TO 1.0E-8 TO PREVENT DIVISION BY ZERO
C
      IF(CLO.EQ.0.)CLO=1.0E-8
C
C CALCULATE CLOTHING AREA FACTOR IF UNKNOWN (McCULLOUGH AND JONES, 1984)
C
      IF(FACL.EQ.0.)FACL=1.+0.31*CLO
      IF(CLO.LT.0.01)FACL=1.
      CALL CLEAN
      WRITE(NOUT,800)
800   FORMAT(/' Total Metabolic Rate                      (W/m2)   : '$)
      READ(NIN,*)MR
      WRITE(NOUT,900)
900   FORMAT(/' External Work Accomplished                (W/m2)   : '$)
      READ(NIN,*)WK
```

```
      RETURN
      END
C
C SUBROUTINE TO DISPLAY ENVIRONMENTAL CONDITIONS AND TABULATE
C FOR 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
C
C DISPLAY RESULTS
C
      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
C PAUSE
C
      CALL WAIT(9)
      CALL CLEAN
      WRITE(NDAT,200)
200   FORMAT(////)
C
C DISPLAY COEFFICIENTS AND THERMAL EXCHANGES
C
      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
     X.kPa/W)'/
     X4X 'Total Evaporative Clothing Resistance      : IeT  = 'F7.2' (m2
     X.kPa/W)'/
     X4X,'Convective Heat Transfer                   : C    = 'F7.2' (W/
     Xm2)'/
     X4X,'Radiation Heat Transfer                    : R    = 'F7.2' (W/
     Xm2)'/
     X4X 'Required Evaporative Cooling               : Ereq = 'F7.2' (W/
     Xm2)'/
     X4X,'Maximum Evaporative Capacity of Environment: Emax = 'F7.2' (W/
     Xm2)'/
     X4X,'Required Skin Wettedness                   : Wreq = 'F7.2' (ND
     X)')
      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
****

Air Temperature	=	40.00 (C)
Mean Radiant Temperature	=	40.00 (C)
Air Speed	=	0.10 (m/s)
Relative Humidity	=	0.60 (ND)
Intrinsic Clothing Insulation	=	1.00 (clo)
Clothing Area Factor	=	1.31 (ND)
Clothing Permeability Index (Woodcock Im)	=	0.38 (ND)
Initial Metabolic Rate	=	100.00 (W/m2)
Work Rate Accomplished	=	0.00 (W/m2)

Effective Air Movement	:	Veff	=	0.32 (m/s)
Partial Vapour Pressure	:	Pa	=	4.43 (kPa)
Mean Skin Temperature	:	Tsk	=	36.00 (C)
Saturated Vapour Pressure on Skin	:	Psk	=	5.94 (kPa)
Metabolic Heat Production	:	Mh	=	100.00 (W/m2)
Convective Heat Transfer Coefficient	:	Hc	=	5.16 (W/m2.C)
Linear Radiation Heat Transfer Coefficient	:	Hr	=	4.86 (W/m2.C)
Mean Clothing Surface Temperature	:	Tcl	=	38.68 (C)
Intrinsic Evaporative Clothing Resistance	:	Iecl	=	0.03 (m2.kPa/W)
Total Evaporative Clothing Resistance	:	IeT	=	0.04 (m2.kPa/W)
Convective Heat Transfer	:	C	=	-8.91 (W/m2)
Radiation Heat Transfer	:	R	=	-8.39 (W/m2)
Required Evaporative Cooling	:	Ereq	=	117.30 (W/m2)
Maximum Evaporative Capacity of Environment	:	Emax	=	41.60 (W/m2)
Required Skin Wettedness	:	Wreq	=	2.00 (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
```

ADDITIONAL SUBROUTINES USED BY MODEL PROGRAMS

```
C
C SUBROUTINE TO SET UP SYSTEM DEPENDENT CONDITIONS FOR MODELS
C
      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
C
C DEFINE LOGICAL UNIT NUMBER FOR I/O (SYSTEM DEPENDENT)
C
      NIN=5
      NOUT=6
      NDAT=10
C
C DEFINE FILE FOR SAVING RESULTS (SYSTEM DEPENDENT)
C
      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
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
```

```
C
C SUBROUTINE TO CLEAR VT100 SCREEN AND RETURN CURSOR TO HOME POSITION
C
      SUBROUTINE CLEAN
      CHARACTER*7 CLS
C
C TO CLEAR SCREEN ESC[2J:
C
      CLS(1:1)=CHAR(27)
      CLS(2:4)='[2J'
C
C TO RETURN CURSOR HOME ESC[f:
C
      CLS(5:5)=CHAR(27)
      CLS(6:7)='[f'
C
      WRITE(*,100)CLS
100   FORMAT('+',7A,$)
      RETURN
      END
```

```
C
C SUBROUTINE TO INFORM USER THAT AN UNDEFINED OPTION HAS BEEN SELECTED
C
      SUBROUTINE INFERR
      CALL CLEAN
      CALL BELL
      WRITE(*,40)
40    FORMAT(//////,28X,'RESPONSE NOT RECOGNIZED!!!')
      CALL WAIT(14)
      RETURN
      END
```

```
C
C SUBROUTINE TO PROVIDE A SYSTEM INDEPENDENT PAUSE (VT100)
C
      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

Th 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 en ble 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:

$$Dry = h\ (Tsk - Ta) \qquad (W/m^2)$$

where:

h = total environmental heat transfer coefficient ($W/m^2.^\circ C$)
= hc + hr ($W/m^2.^\circ C$)

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

$$Dry = hc\ (Tsk - Ta) + hr\ (Tsk - Tr) \qquad (W/m^2)$$

For the clothed case this equation becomes:

$$Dry = hc\ .\ fcl\ (Tcl - Ta) + hr\ .\ fcl\ (Tcl - Tr) \qquad (W/m^2)$$

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.

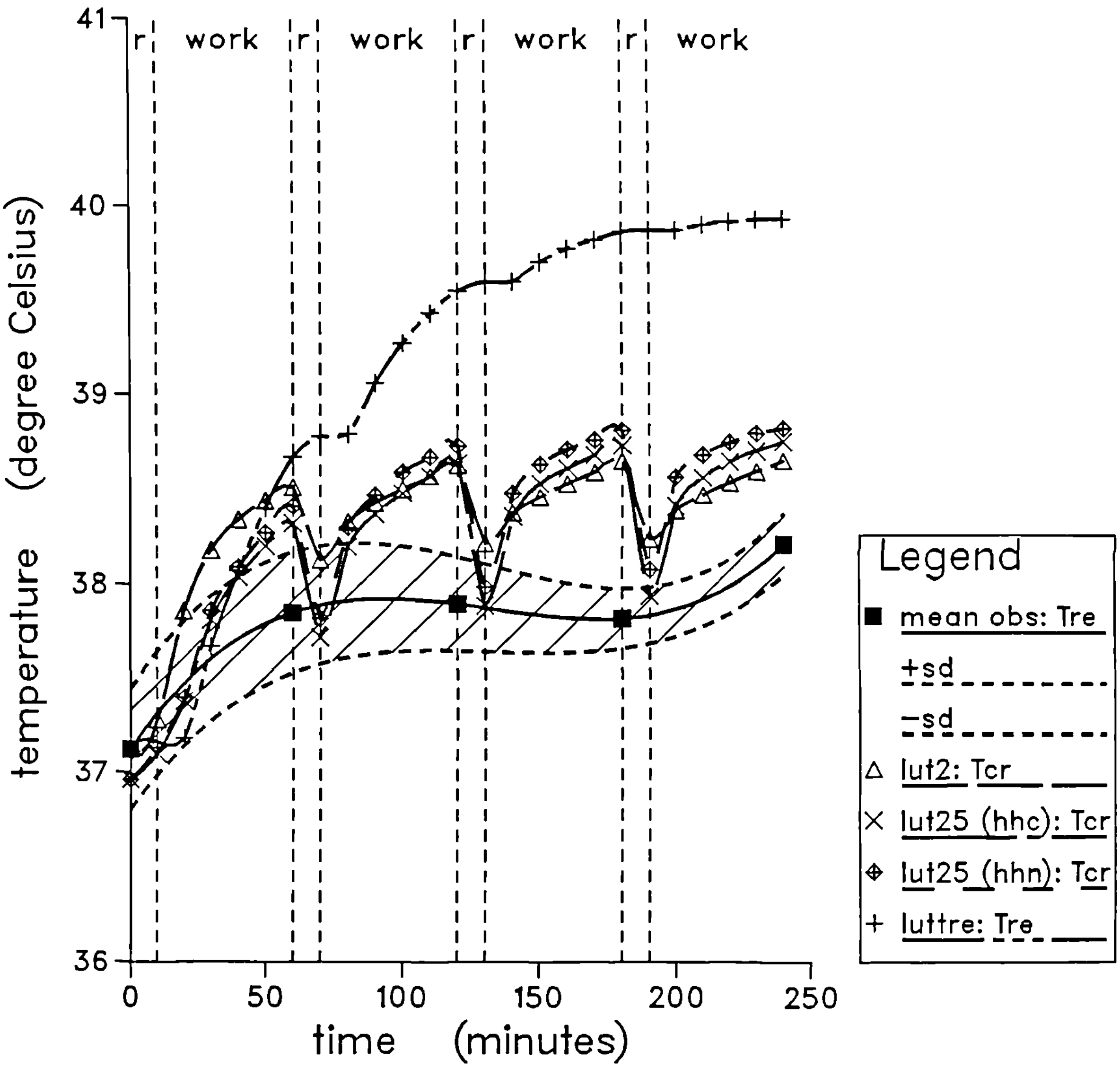
	head	trunk	arms	hands	legs	feet
Ar/Ab	0.74	0.75	0.66	0.56	0.65	0..62

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

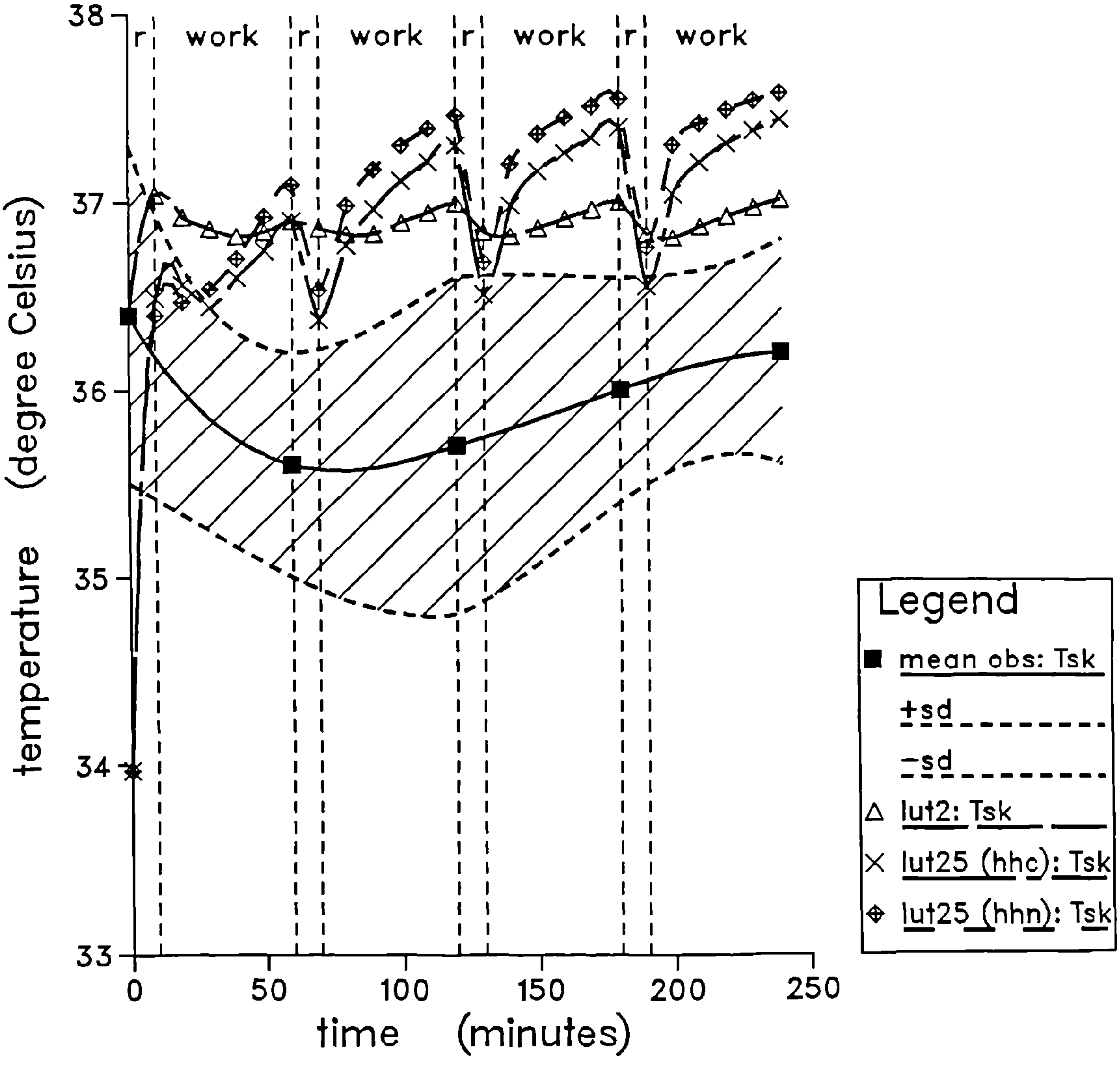
COMPARISON GRAPHS FOR FULL SET OF EXPERIMENTAL DATA

Tre from Avellini et al (1980) (n=10, accl, males)
Ta=Tr=49 C, v=1 m/s, rh=20 %,
Icl=0.3 clo, fcl=1.09 (ND), im=0.45 (ND), M=52, 200 W/m2, W=0 W/m2

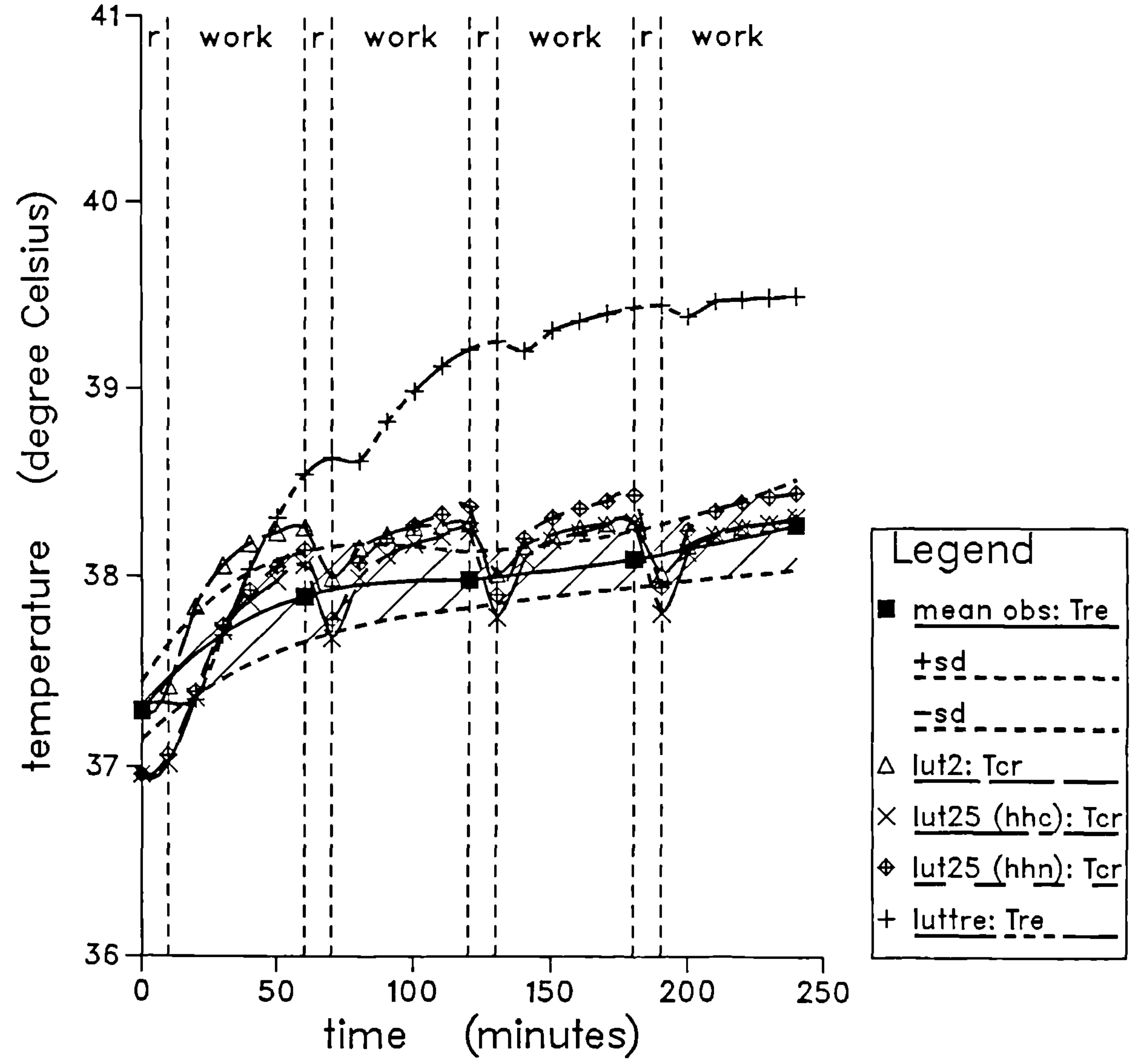


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 20 min; body temperature increase
danger non-accl : 45 min; body temperature increase
warning accl : 54 min; body temperature increase
danger accl : 123 min; body temperature increase

Tsk from Avellini et al (1980) (n=10, accl, males)
Ta=Tr=49 C, v=1 m/s, rh=20 %,
Icl=0.3 clo, fcl=1.09 (ND), im=0.45 (ND), M=62, 200 W/m2, W=0 W/m2



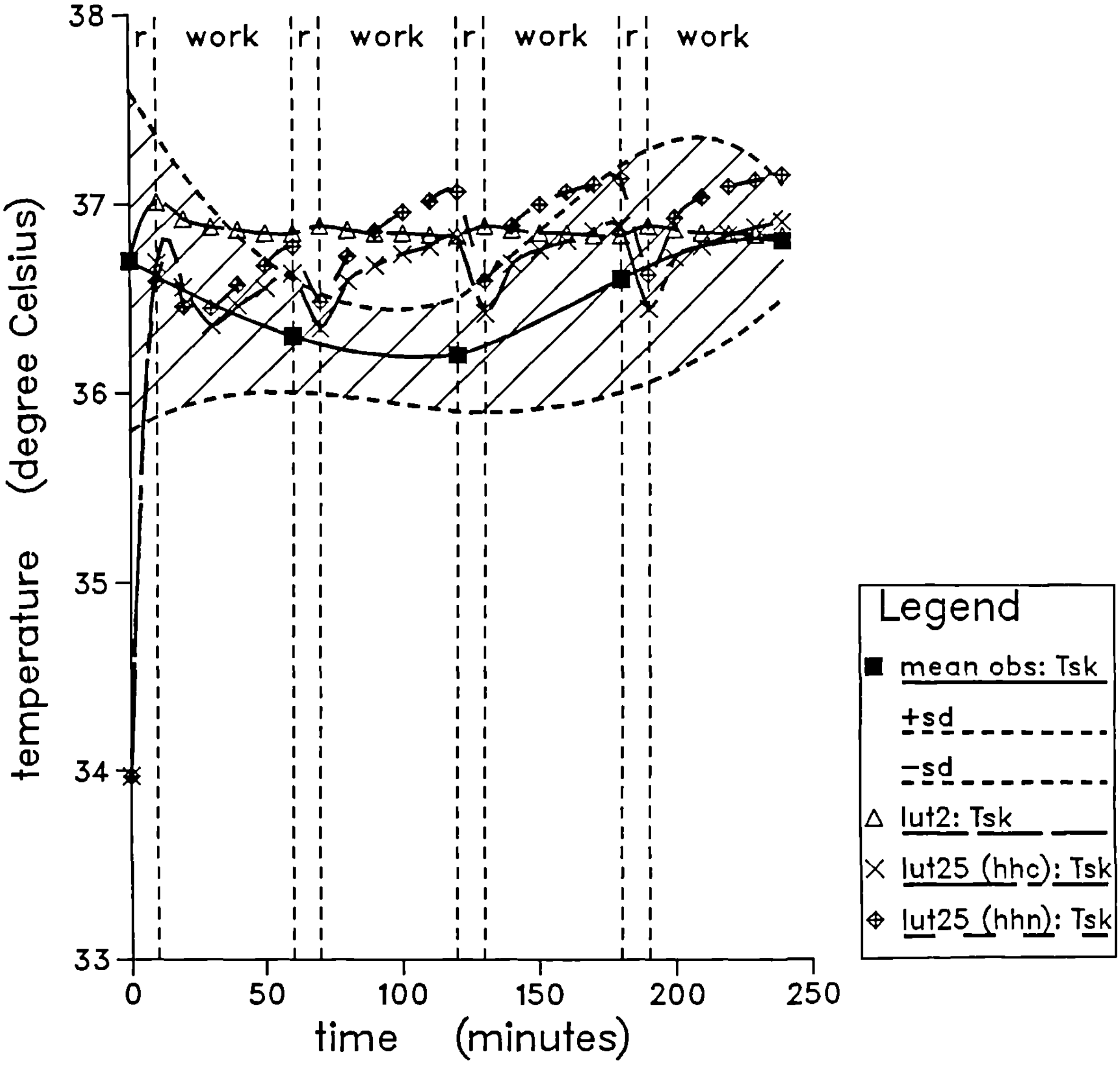
Tre from Avellini et al (1980) (n=9, accl, females)
Ta=Tr=49 C, v=1 m/s, rh=20 %,
Icl=0.3 clo, fcl=1.09 (ND), im=0.45 (ND), M=63, 169 W/m2, W=0 W/m2

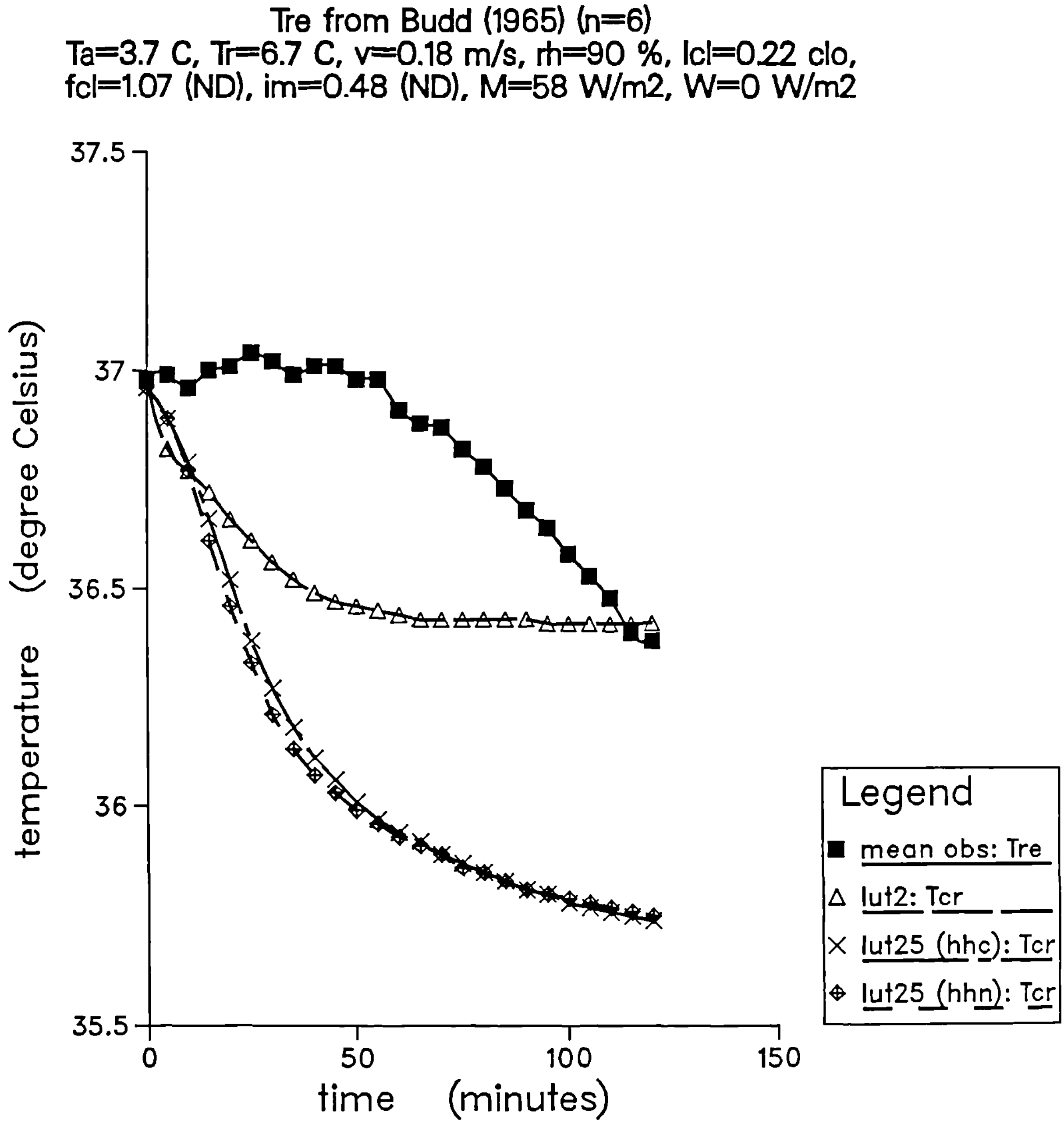


lutiso Allowable Exposure Times
(time weighted averages):

```
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
```

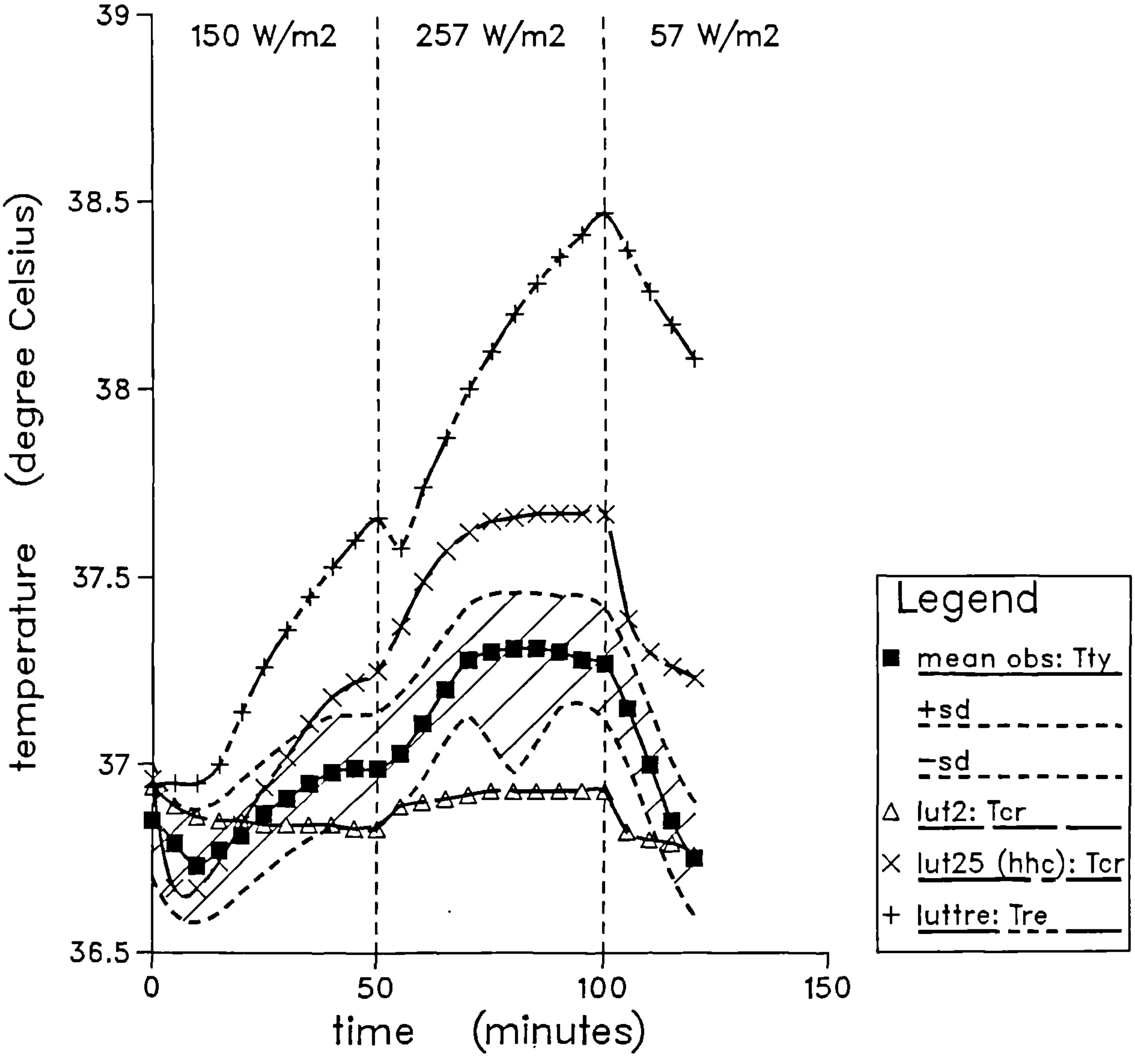
Tsk from Avellini et al (1980) (n=9, accl, females)
Ta=Tr=49 C, v=1 m/s, rh=20 %,
Icl=0.3 clo, fcl=1.09 (ND), im=0.45 (ND), M=63, 169 W/m2, W=0 W/m2





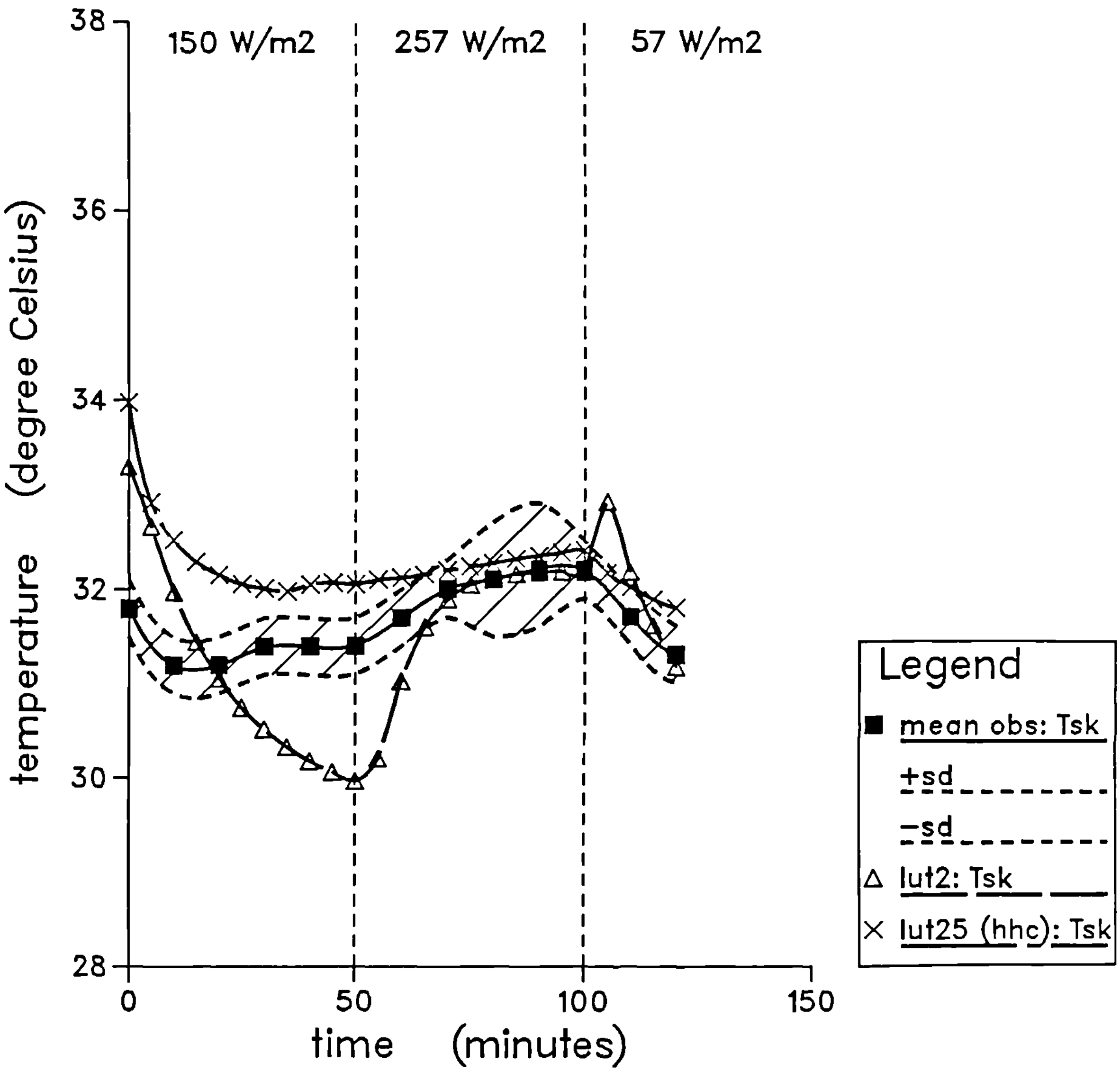
Tre from Budd (1965) (n=6)
Ta=3.7 C, Tr=6.7 C, v=0.18 m/s, rh=90 %, Icl=0.22 clo,
fcl=1.07 (ND), im=0.48 (ND), M=58 W/m2, W=0 W/m2
37.5
37
36.5
36
35.5
temperature (degree Celsius)
0
50
100
150
time (minutes)
Legend
mean obs: Tre
lut2: Tcr
lut25 (hhc): Tcr
lut25 (hhn): Tcr

Tty from Chappuis et al (1976) (n=9) (exp code: A)
Ta=Tr=20 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2

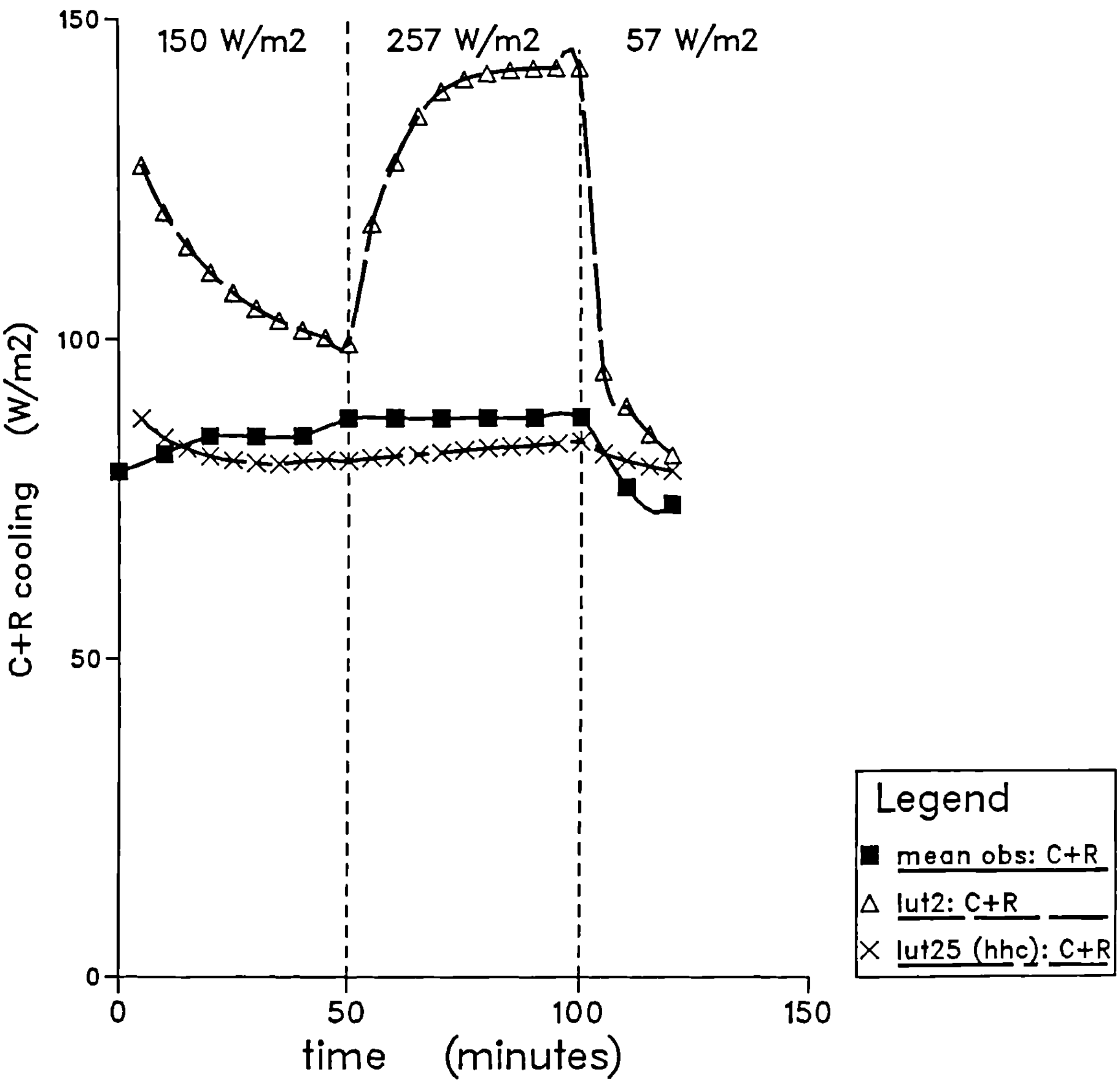


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

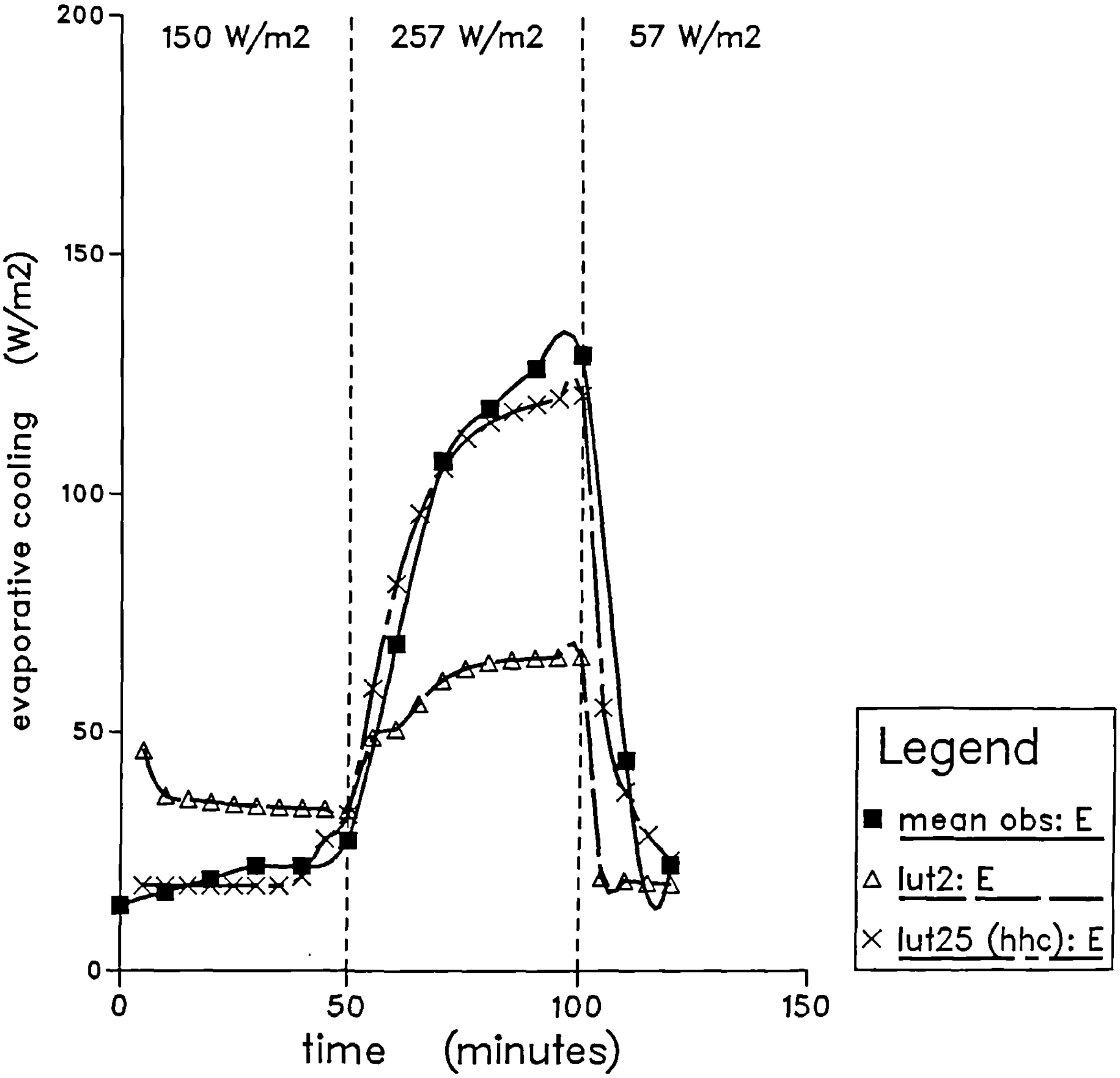
Tsk from Chappuis et al (1976) (n=9) (exp code: A)
Ta=Tr=20 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2



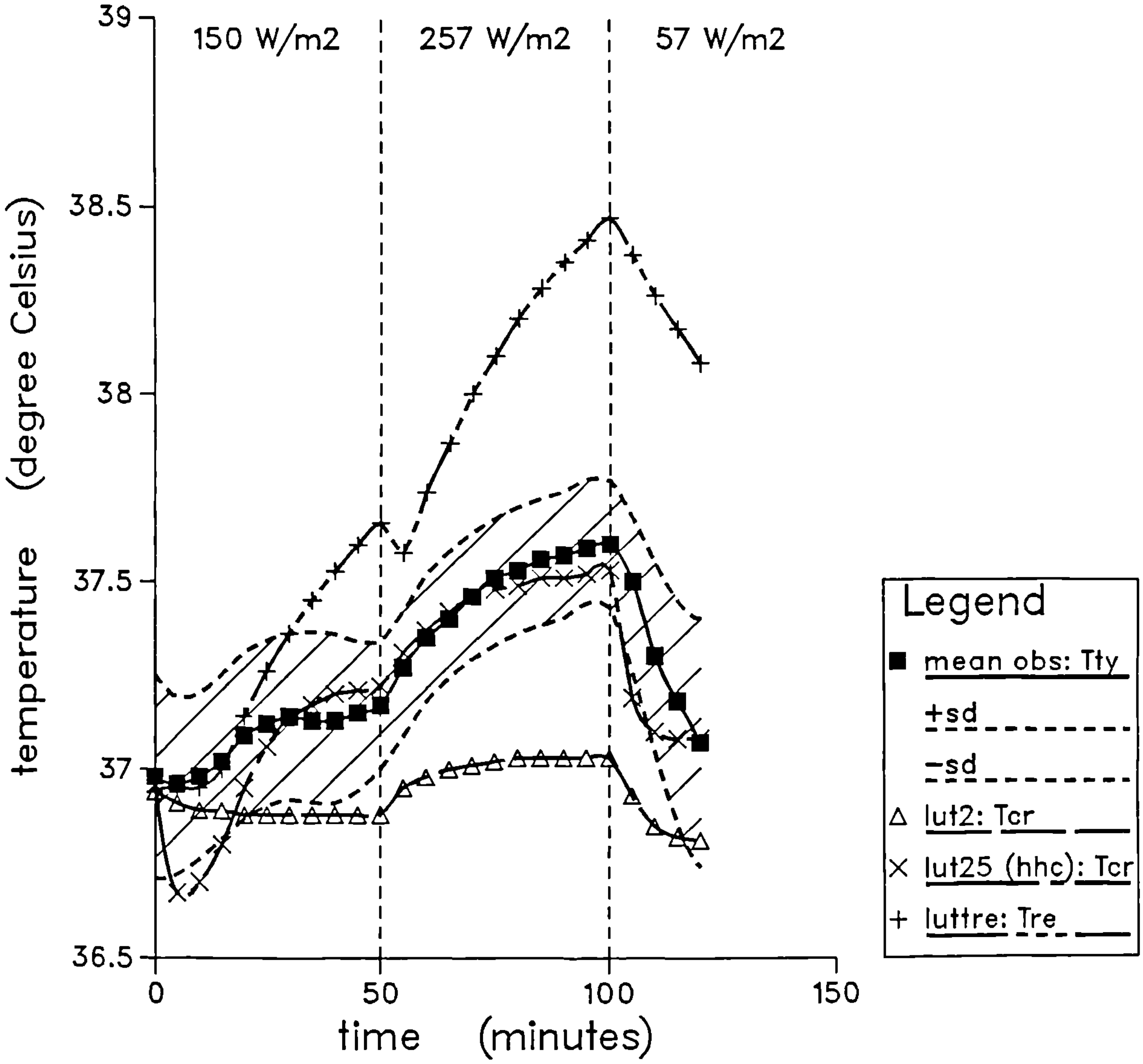
C+R from Chappuis et al (1976) (n=9) (exp code: A)
Ta=Tr=20 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2



E from Chappuis et al (1976) (n=9) (exp code: A)
Ta=Tr=20 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2

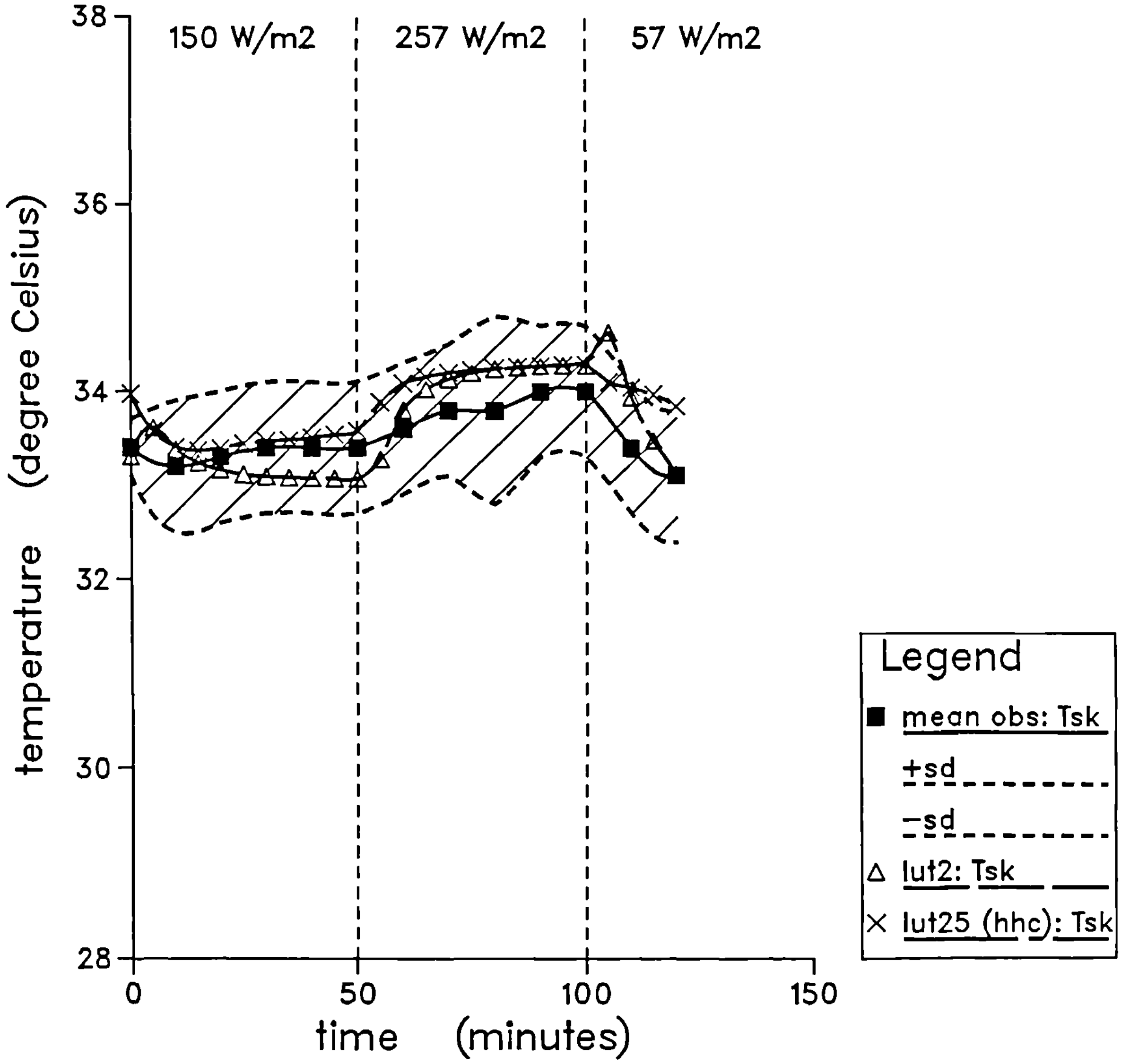


Tty from Chappuis et al (1976) (n=11) (exp code: B)
Ta=Tr=25 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2

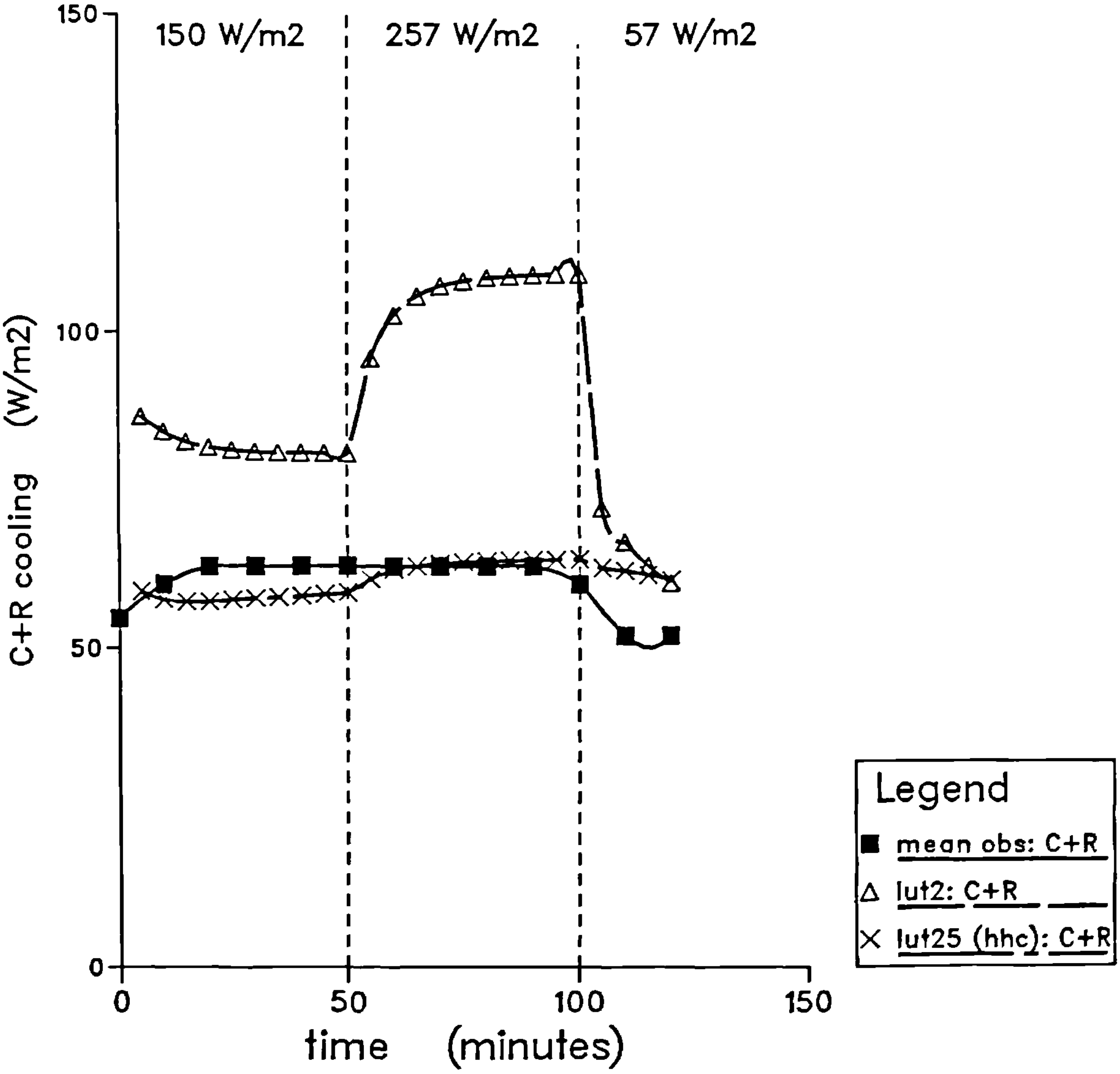


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

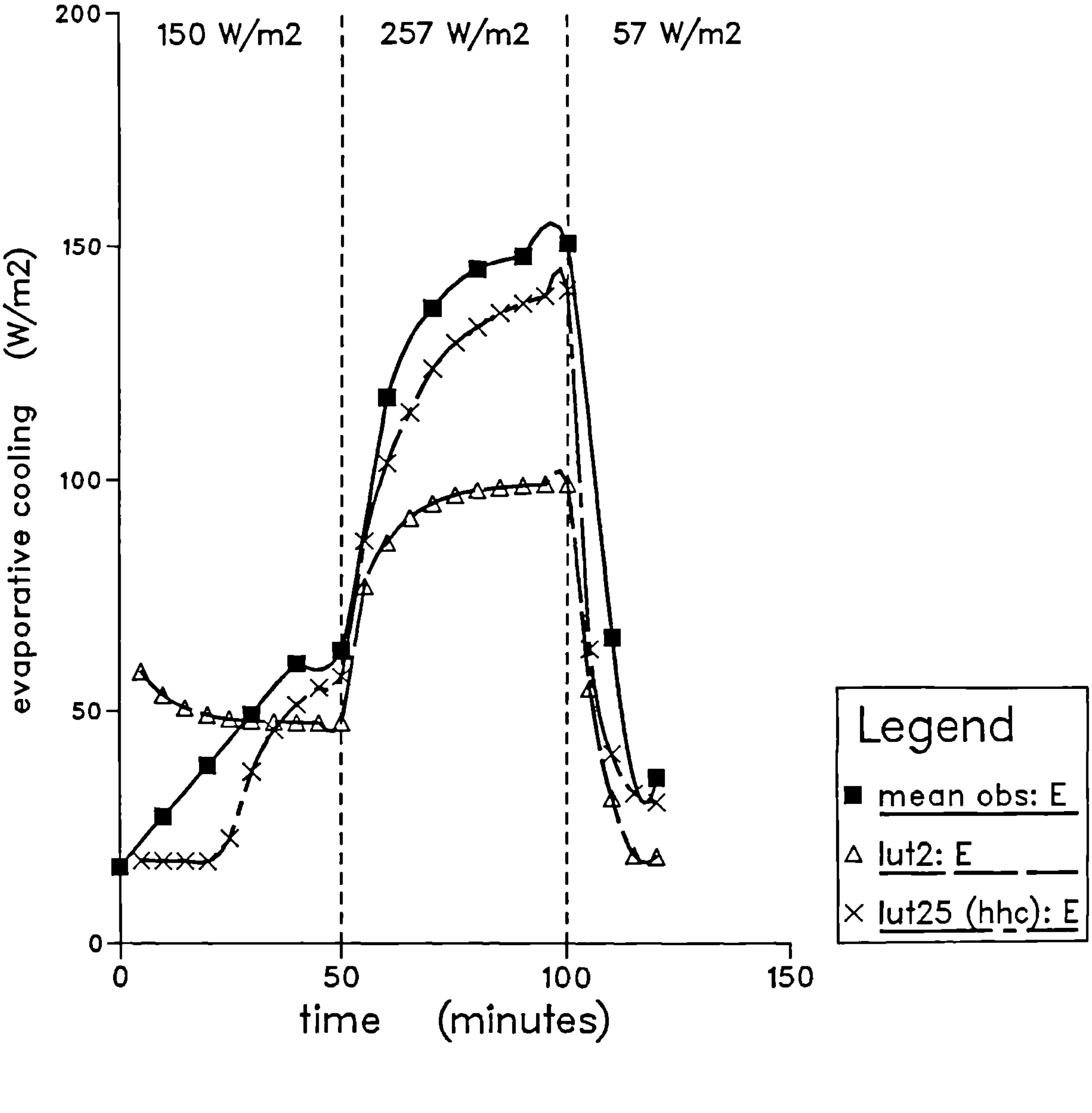
Tsk from Chappuis et al (1976) (n=11) (exp code: B)
Ta=Tr=25 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2



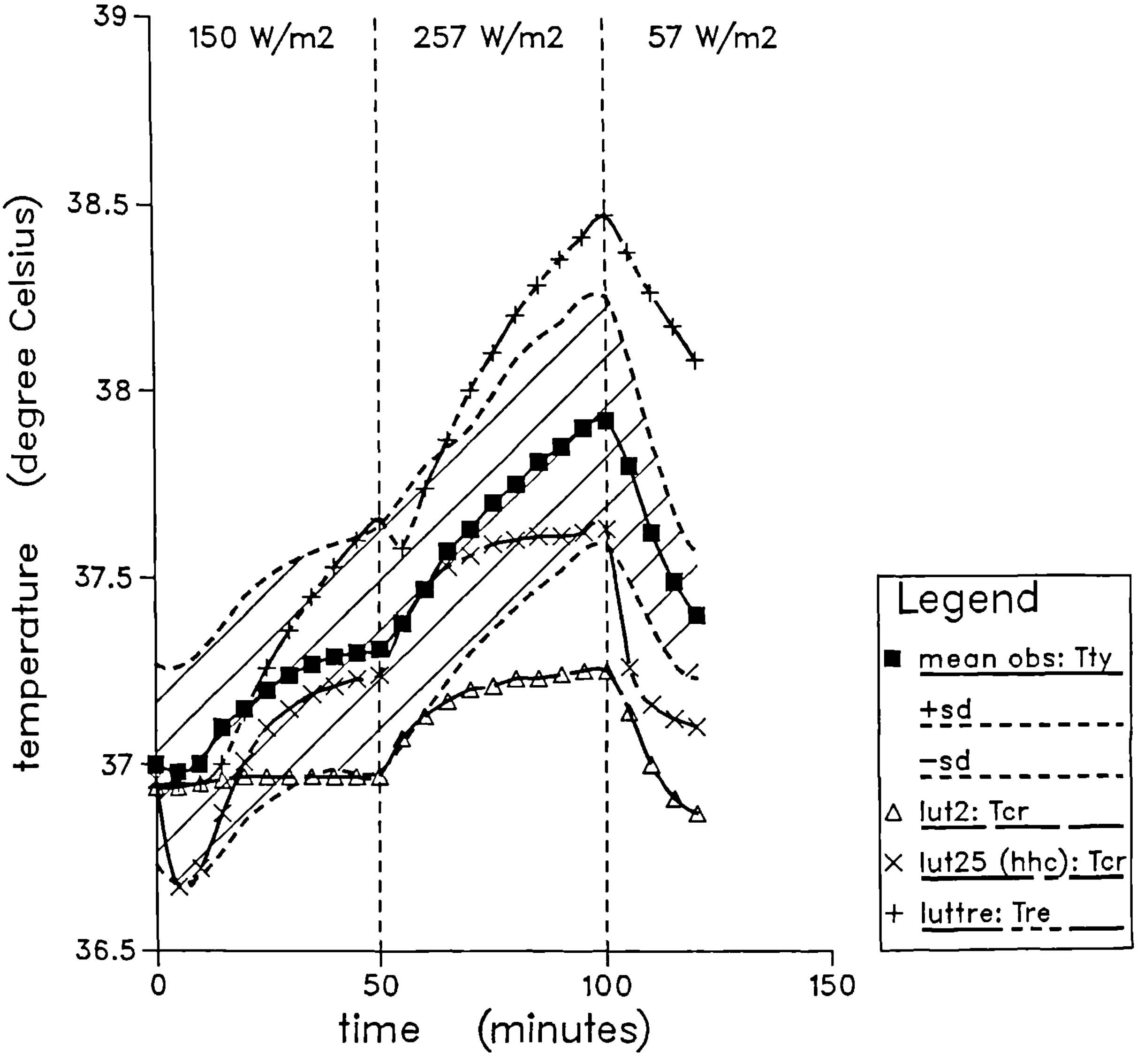
C+R from Chappuis et al (1976) (n=11) (exp code: B)
Ta=Tr=25 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2



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

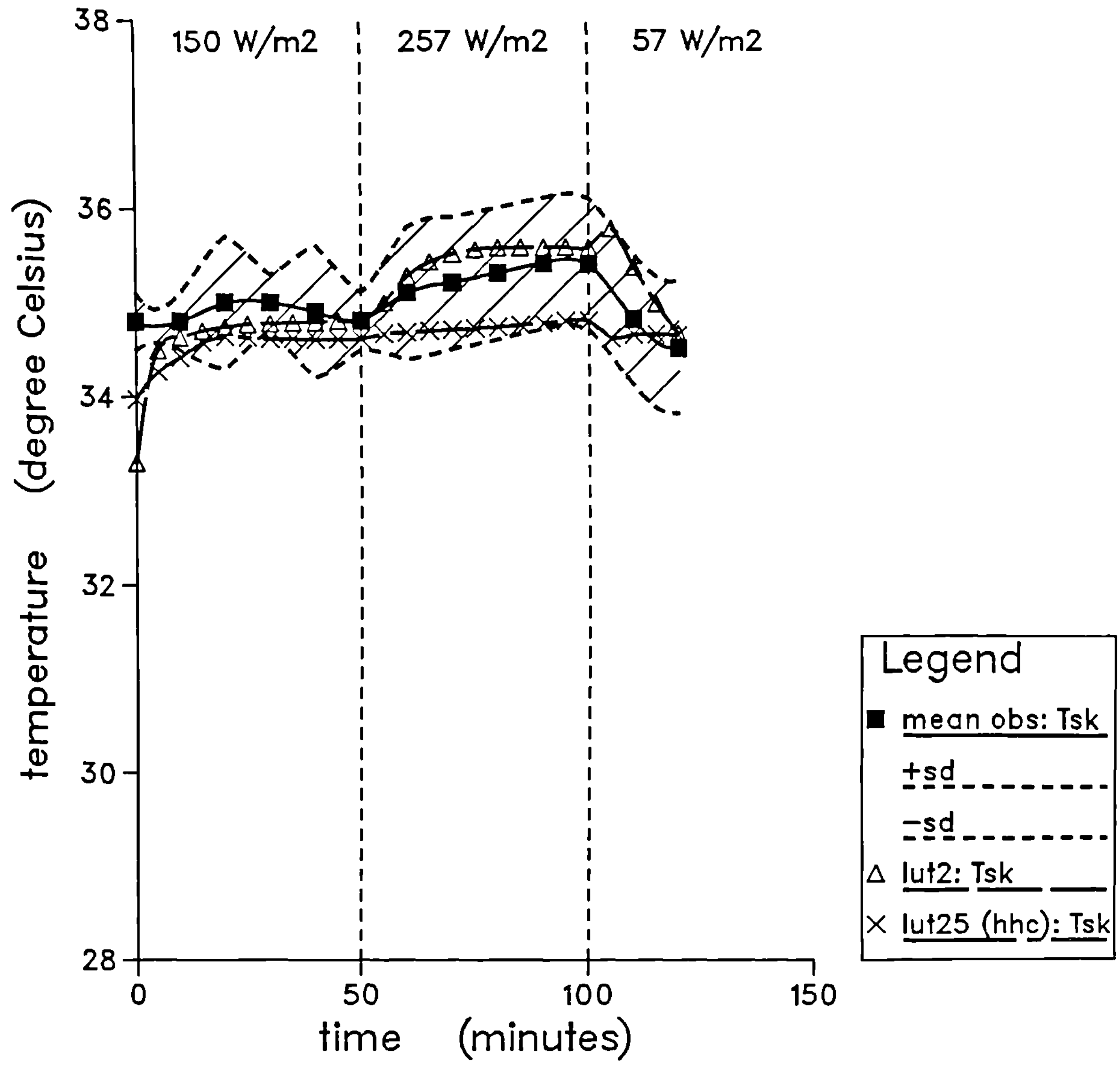


Tty from Chappuis et al (1976) (n=11) (exp code: C)
Ta=Tr=30 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2

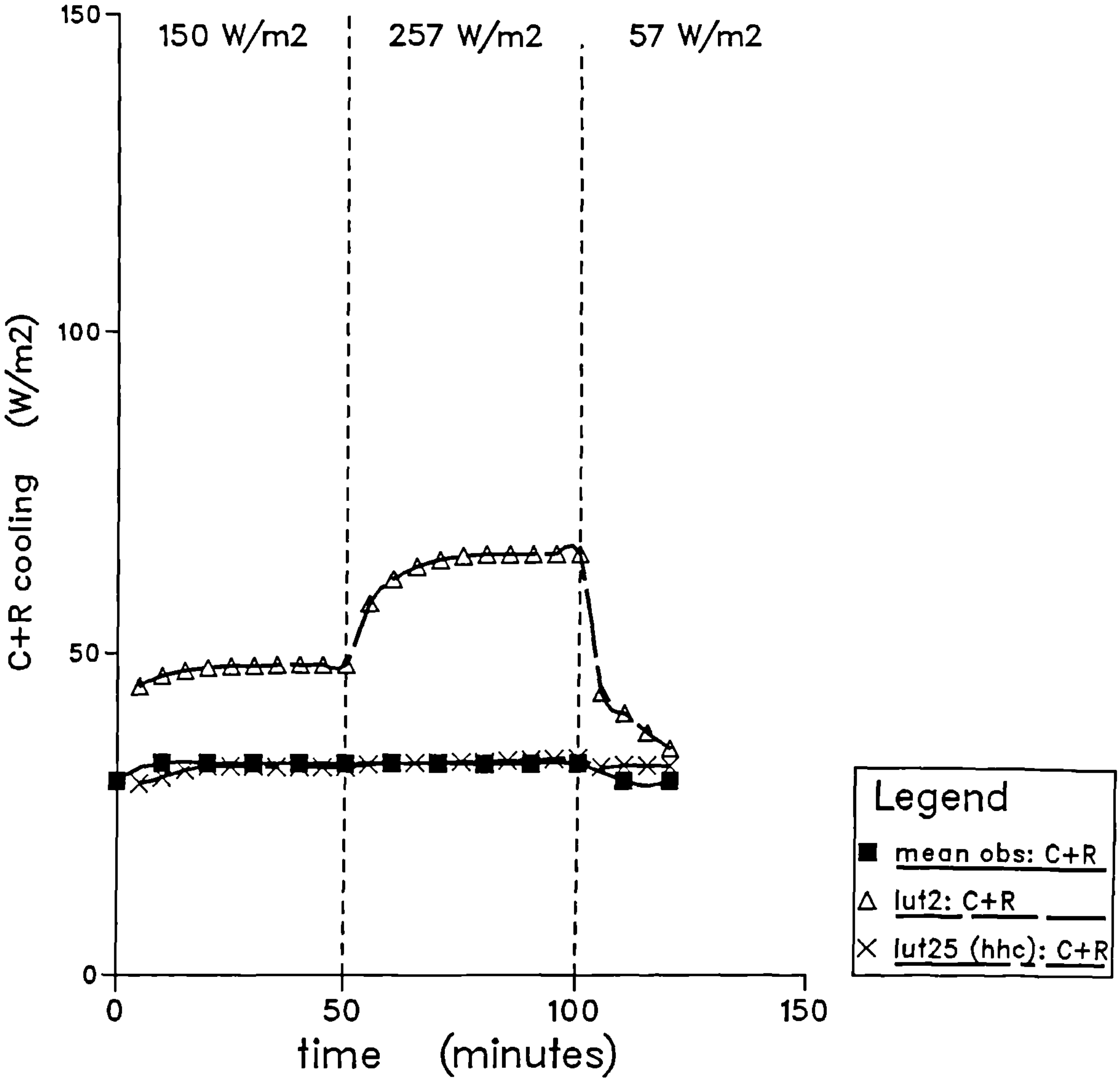


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

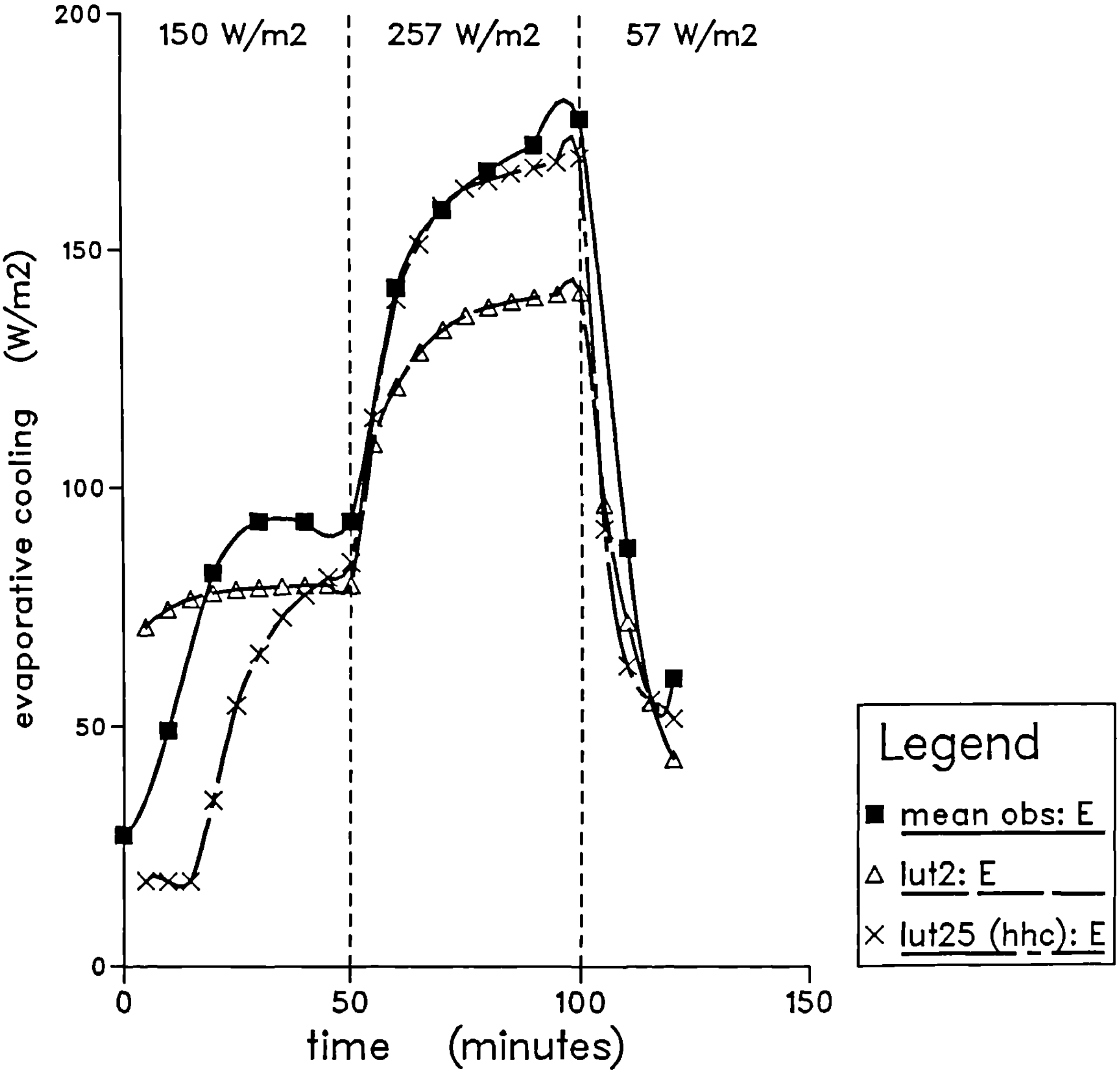
Tsk from Chappuis et al (1976) (n=11) (exp code: C)
Ta=Tr=30 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2



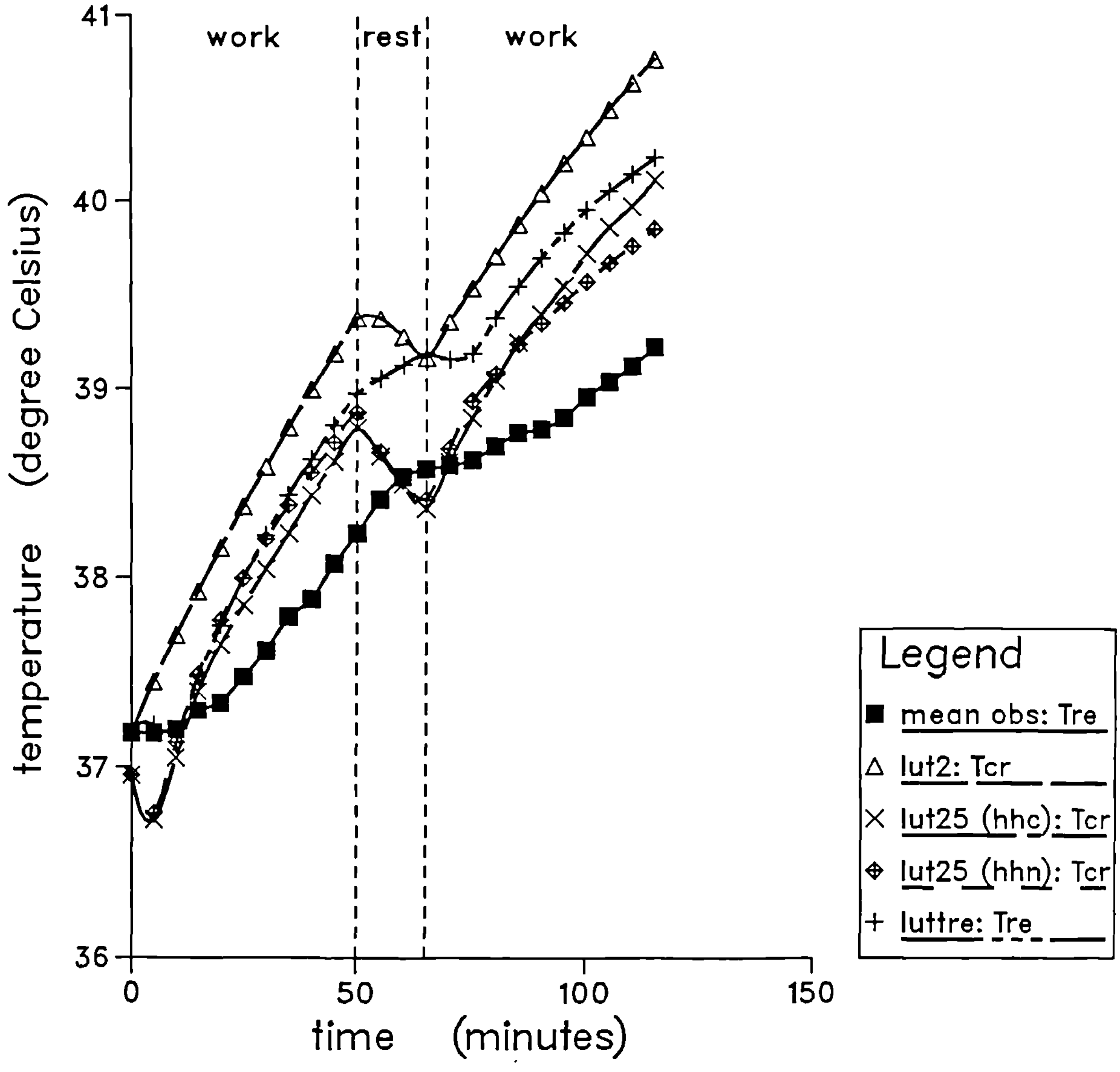
C+R from Chappuis et al (1976) (n=11) (exp code: C)
Ta=Tr=30 C, v=0.2 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND),
im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0 W/m2



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

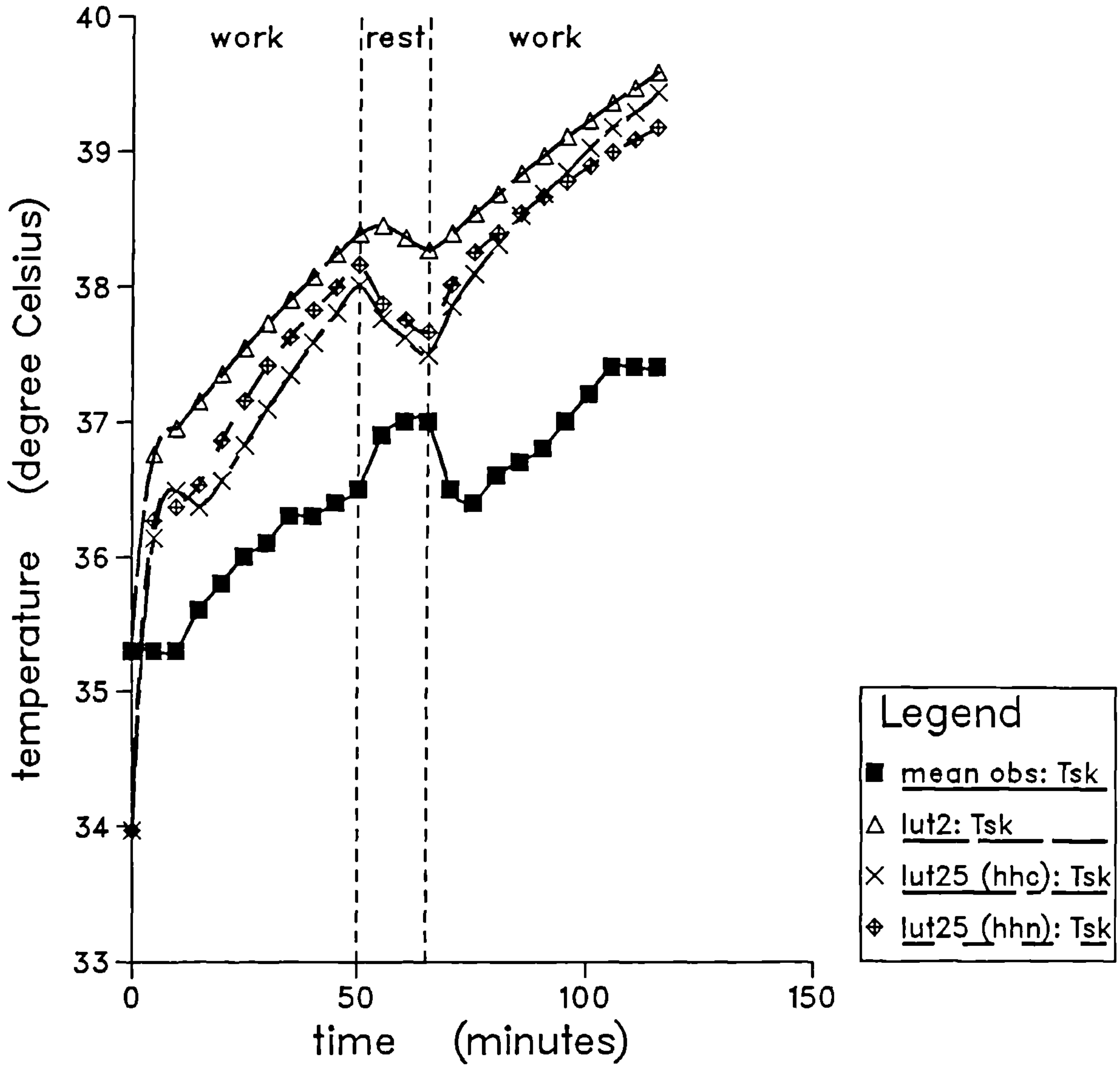


Tre from Haisman and Goldman (1974)
(n=7 reducing to 4, accl) (exp. code: ds)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=193, 58, 193 W/m2, W=0 W/m2

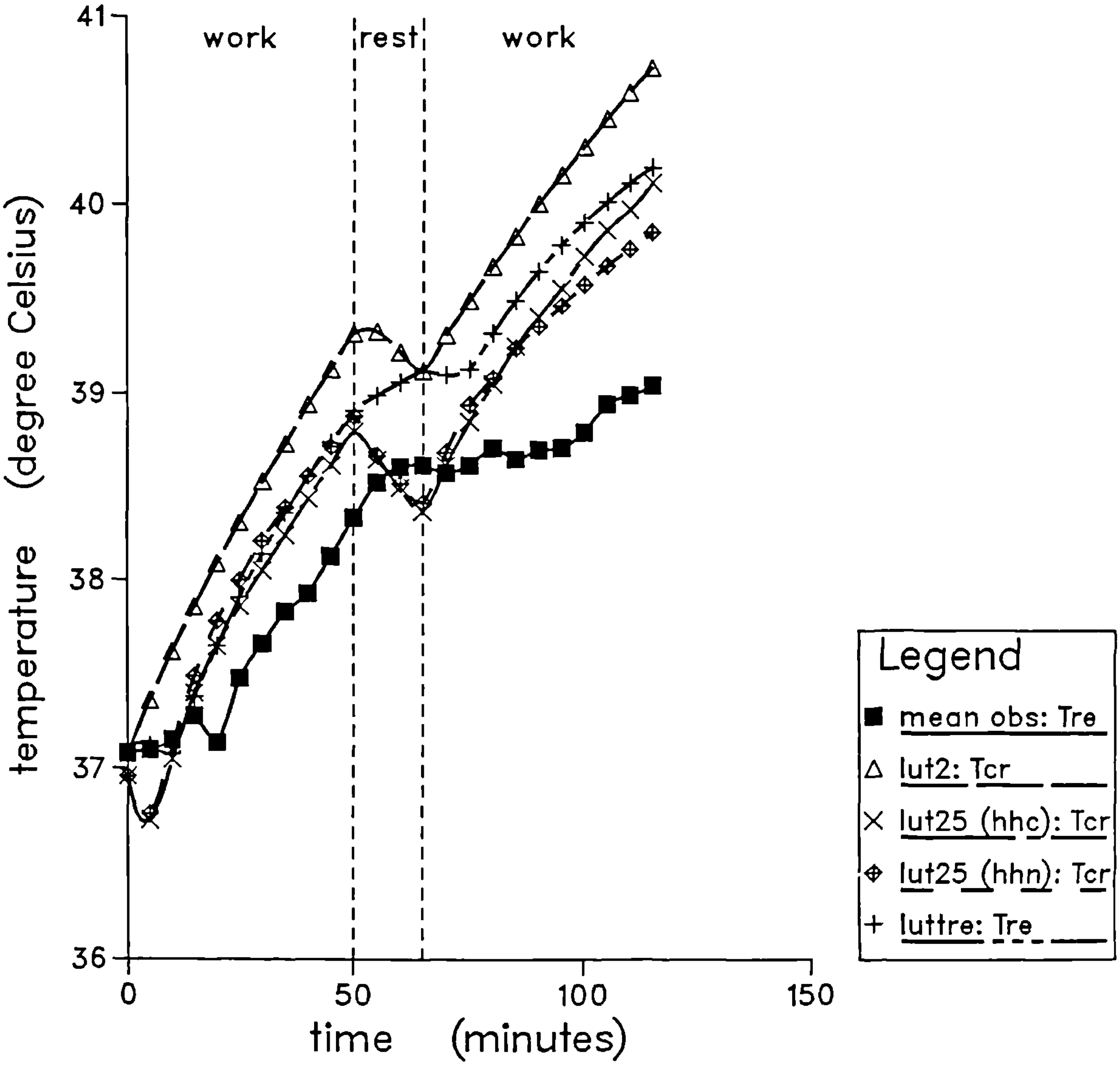


lutiso Allowable Exposure Times
(to work):
warning non accl: 14 min; body temperature increase
danger non accl : 19 min; body temperature increase
warning accl : 17 min; body temperature increase
danger accl : 25 min; body temperature increase

Tsk from Haisman and Goldman (1974)
(n=7 reducing to 4, accl) (exp. code: ds)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=193, 58, 193 W/m2, W=0 W/m2

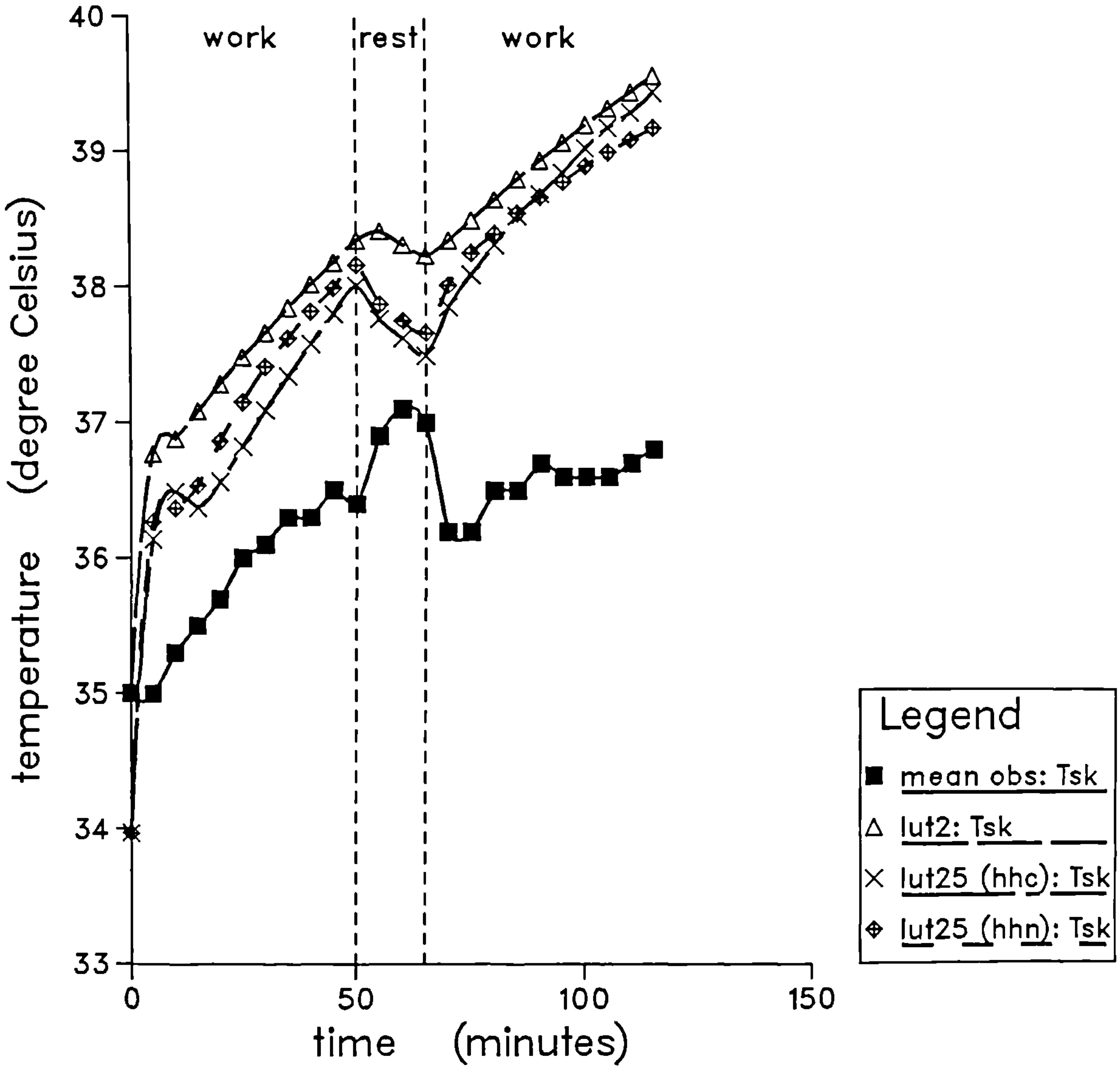


Tre from Haisman and Goldman (1974)
(n=7 reducing to 3, accl) (exp. code: dl)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=193, 58, 193 W/m2, W=0 W/m2

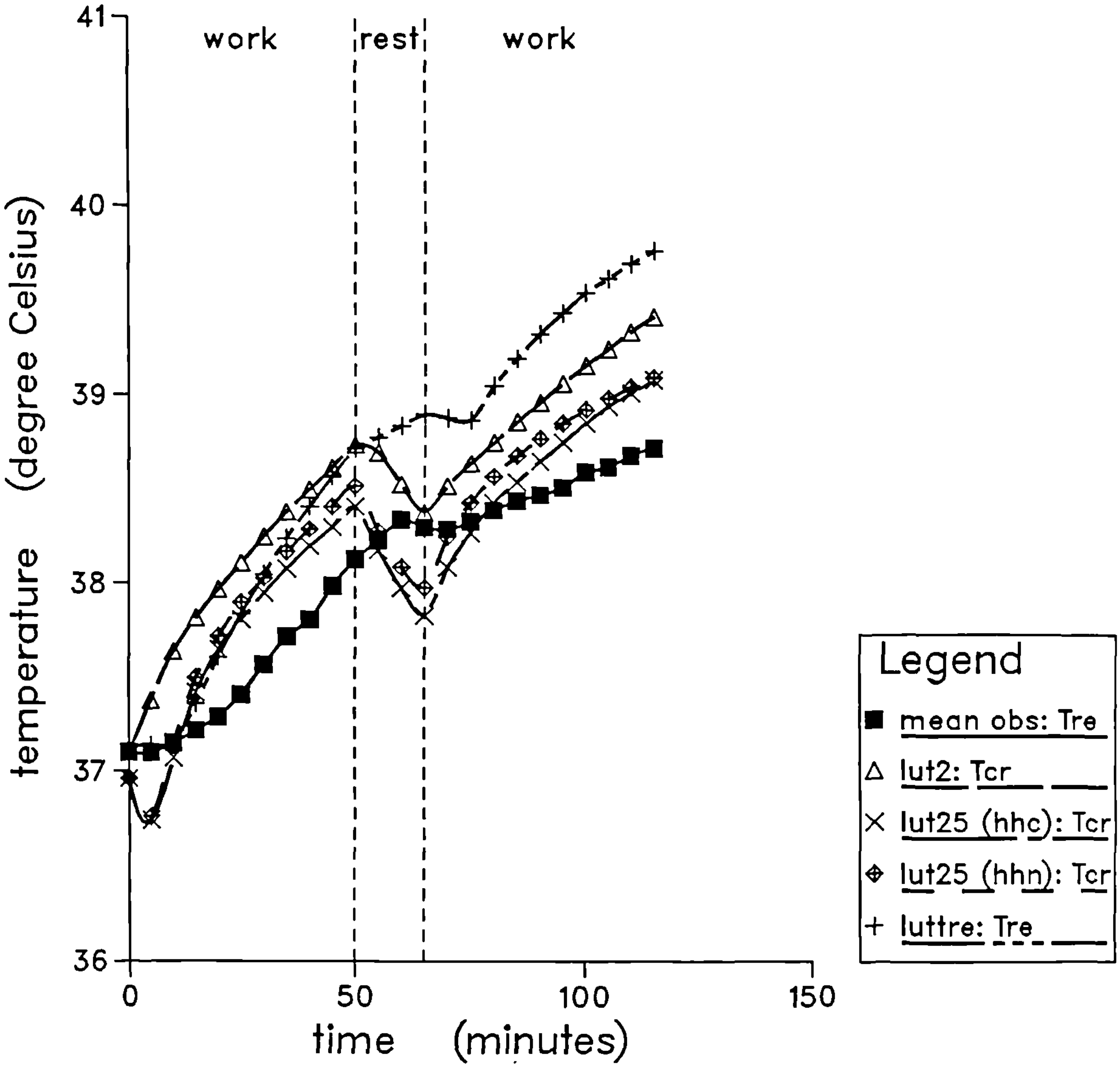


lutiso Allowable Exposure Times
(to work):
warning non accl: 14 min; body temperature increase
danger non accl : 19 min; body temperature increase
warning accl : 17 min; body temperature increase
danger accl : 25 min; body temperature increase

Tsk from Haisman and Goldman (1974)
(n=7 reducing to 3, accl) (exp. code: dl)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=193, 58, 193 W/m2, W=0 W/m2

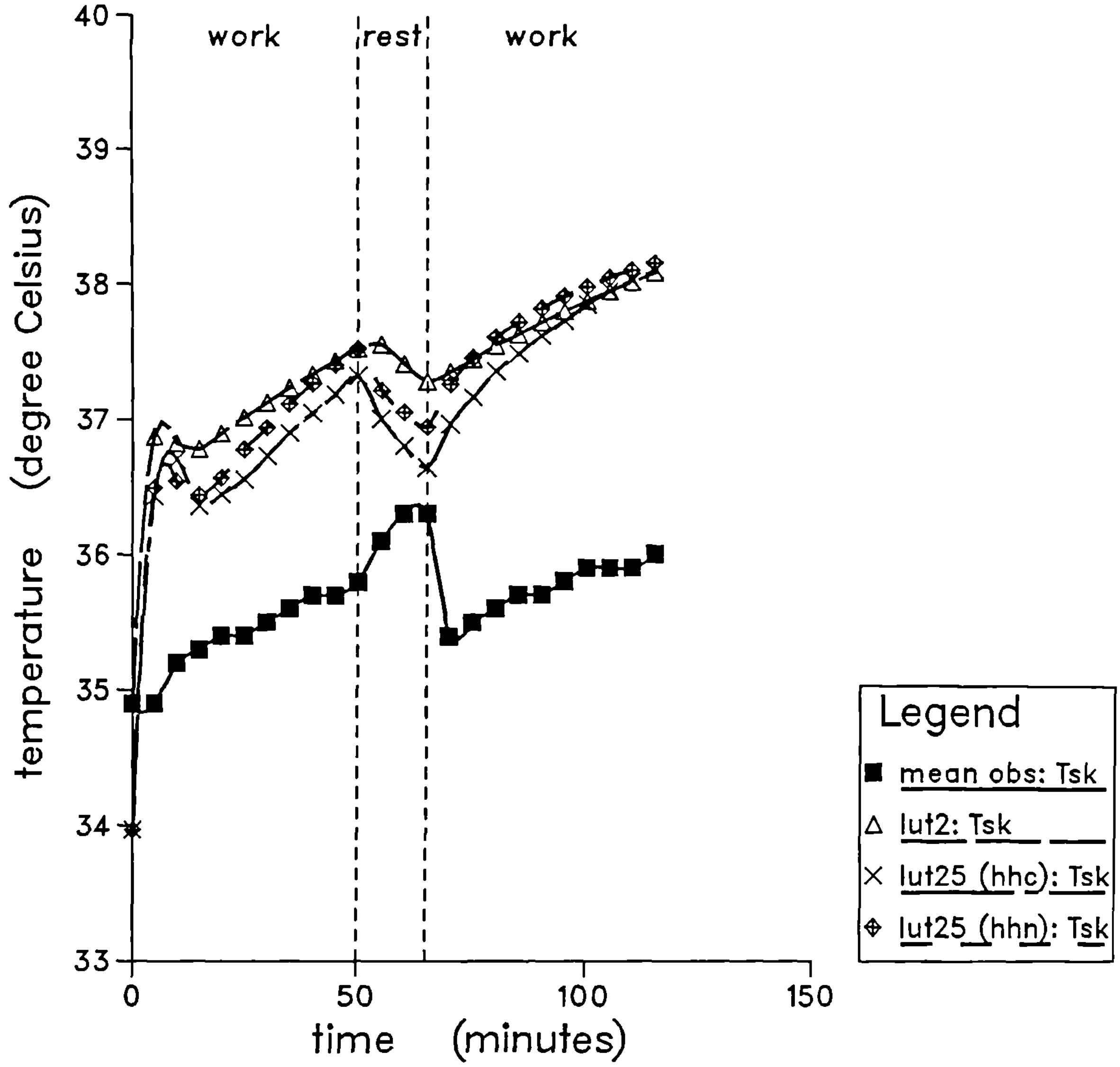


Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: dn)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, Icl=0.55 clo, fcl=1.19 (ND),
im=0.44 (ND), M=188, 58, 188 W/m2, W=0 W/m2

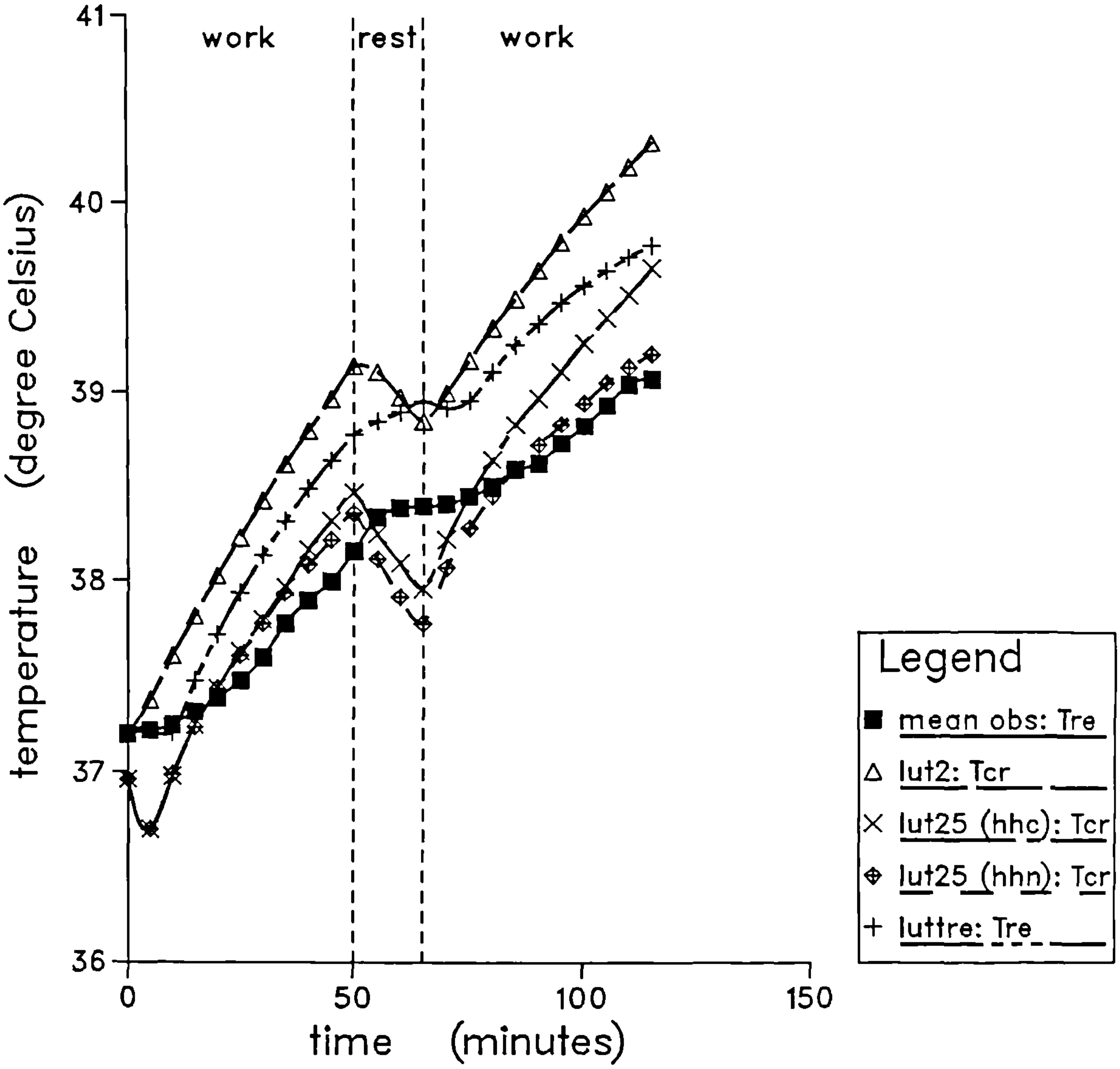


lutiso Allowable Exposure Times
(to work):
warning non accl: 19 min; body temperature increase
danger non accl : 31 min; body temperature increase
warning accl : 32 min; body temperature increase
danger accl : 43 min; body temperature increase

Tsk from Haisman and Goldman (1974)
(n=8, accl) (exp. code: dn)
Ta=Tr=48.9 C, v=0.8 m/s, rh=21 %, Icl=0.55 clo, fcl=1.19 (ND),
im=0.44 (ND), M=188, 58, 188 W/m2, W=0 W/m2

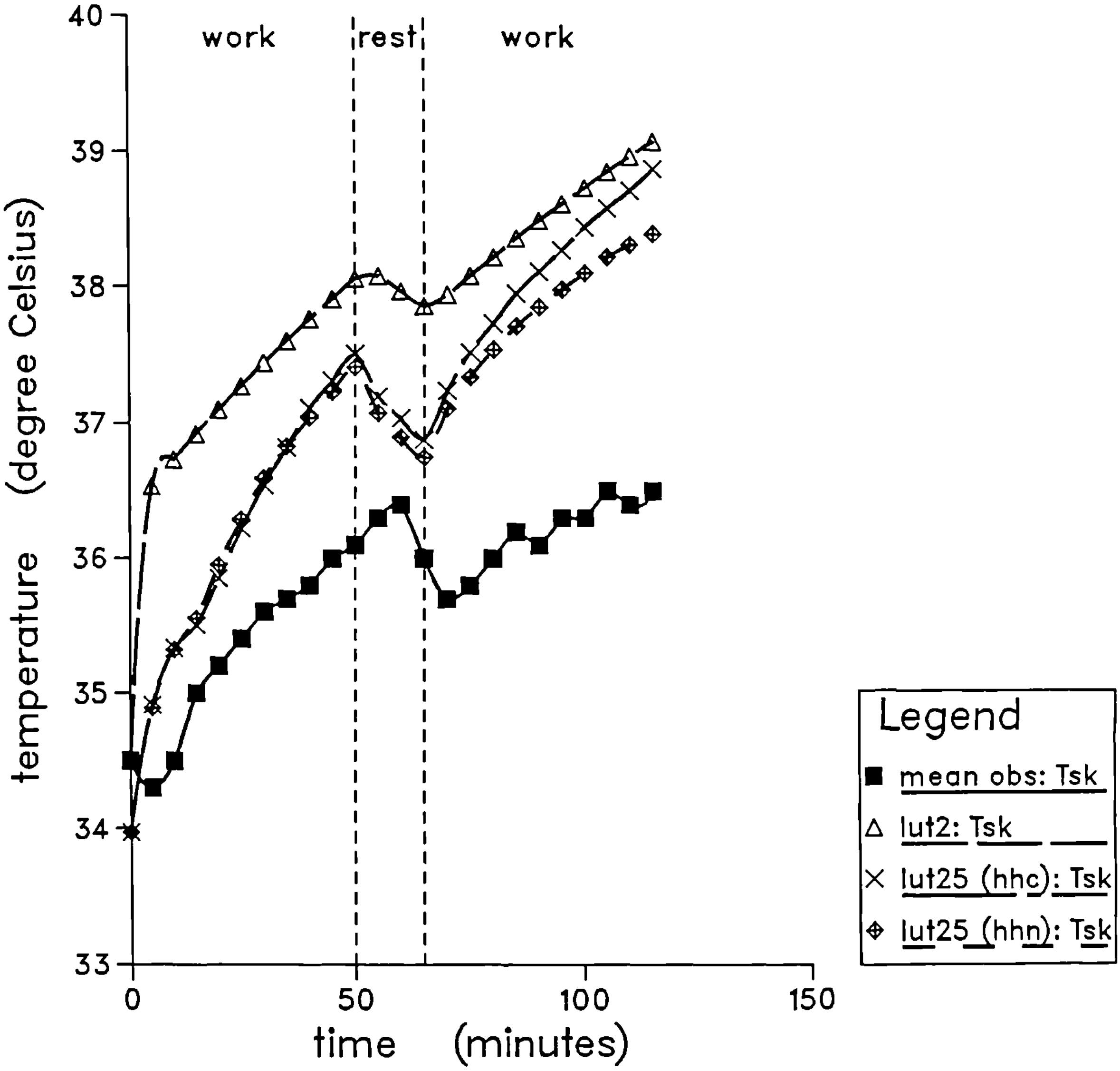


Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: ws)
Ta=Tr=35.0 C, v=0.8 m/s, rh=70 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=197, 58, 197 W/m2, W=0 W/m2

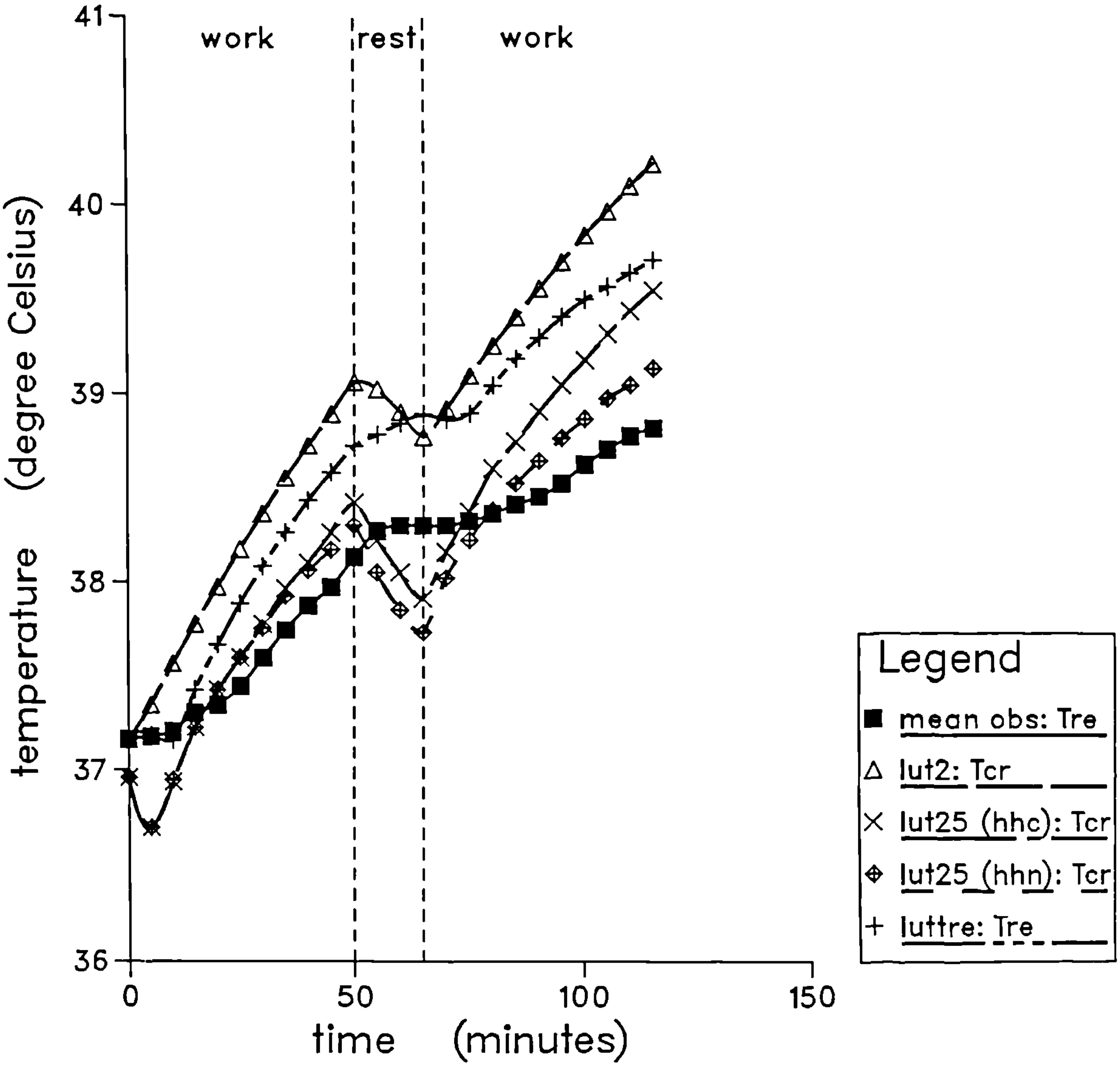


lutiso Allowable Exposure Times
(to work):
warning non accl: 20 min; body temperature increase
danger non accl : 28 min; body temperature increase
warning accl : 23 min; body temperature increase
danger accl : 31 min; body temperature increase

Tsk from Haisman and Goldman (1974)
(n=8, accl) (exp. code: ws)
Ta=Tr=35.0 C, v=0.8 m/s, rh=70 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=197, 58, 197 W/m2, W=0 W/m2

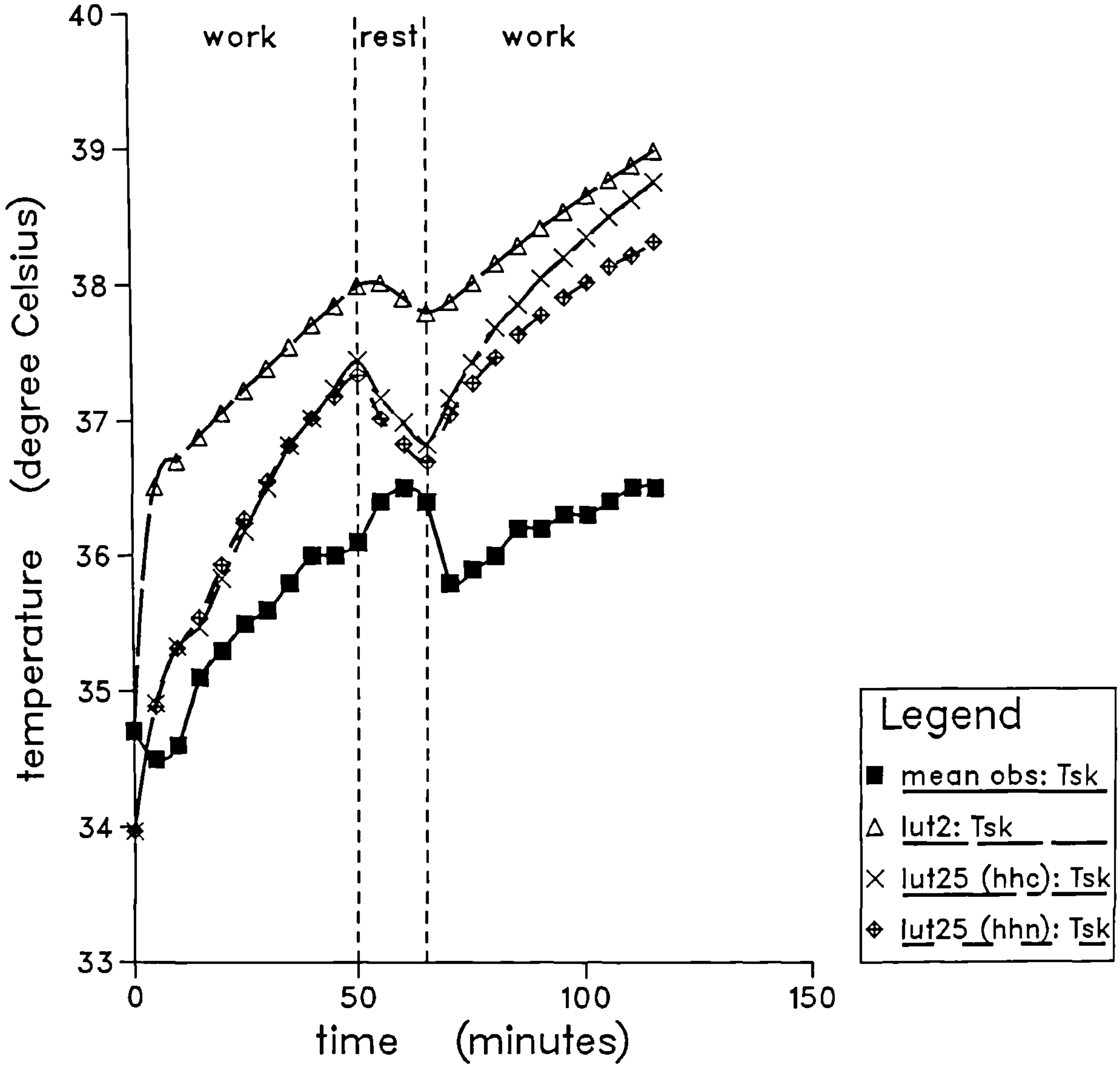


Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: wl)
Ta=Tr=35.0 C, v=0.8 m/s, rh=70 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=194, 58, 194 W/m2, W=0 W/m2

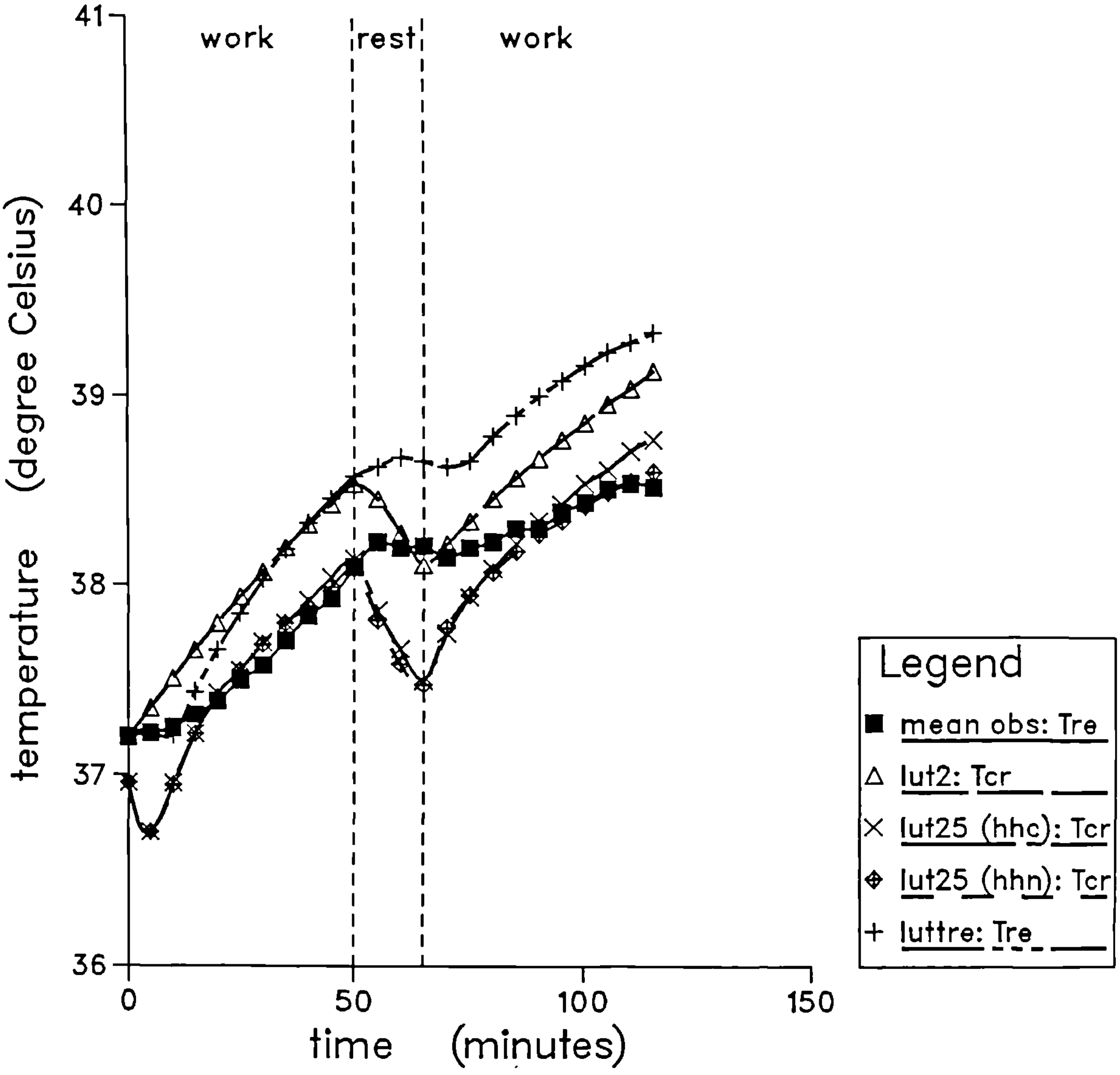


lutiso Allowable Exposure Times
(to work):
warning non accl : 21 min; body temperature increase
danger non accl : 29 min; body temperature increase
warning accl : 24 min; body temperature increase
danger accl : 32 min; body temperature increase

Tsk from Haisman and Goldman (1974)
(n=8, accl) (exp. code: wl)
Ta=Tr=35.0 C, v=0.8 m/s, rh=70 %, Icl=0.83 clo, fcl=1.25 (ND),
im=0.41 (ND), M=194, 58, 194 W/m2, W=0 W/m2

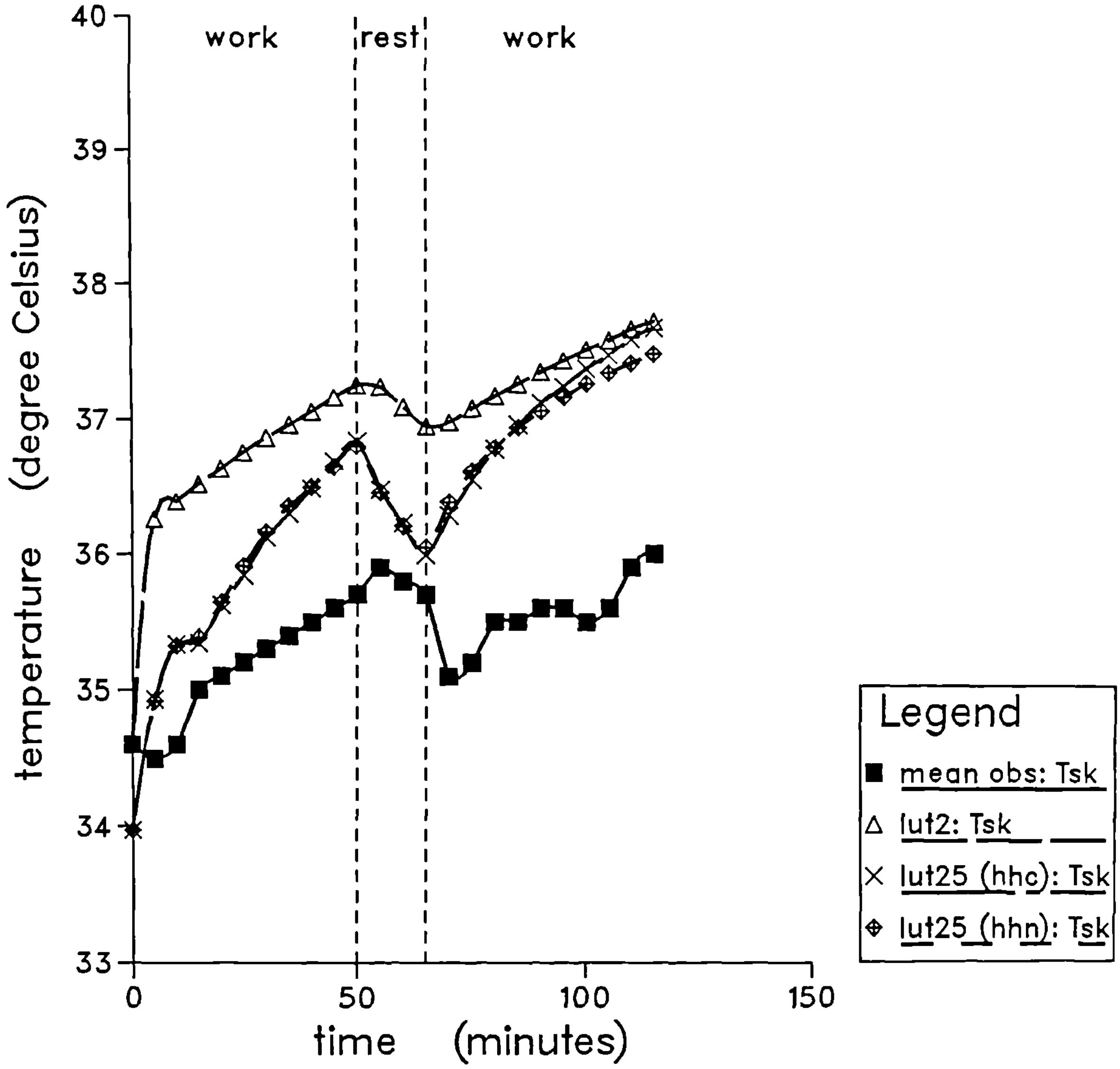


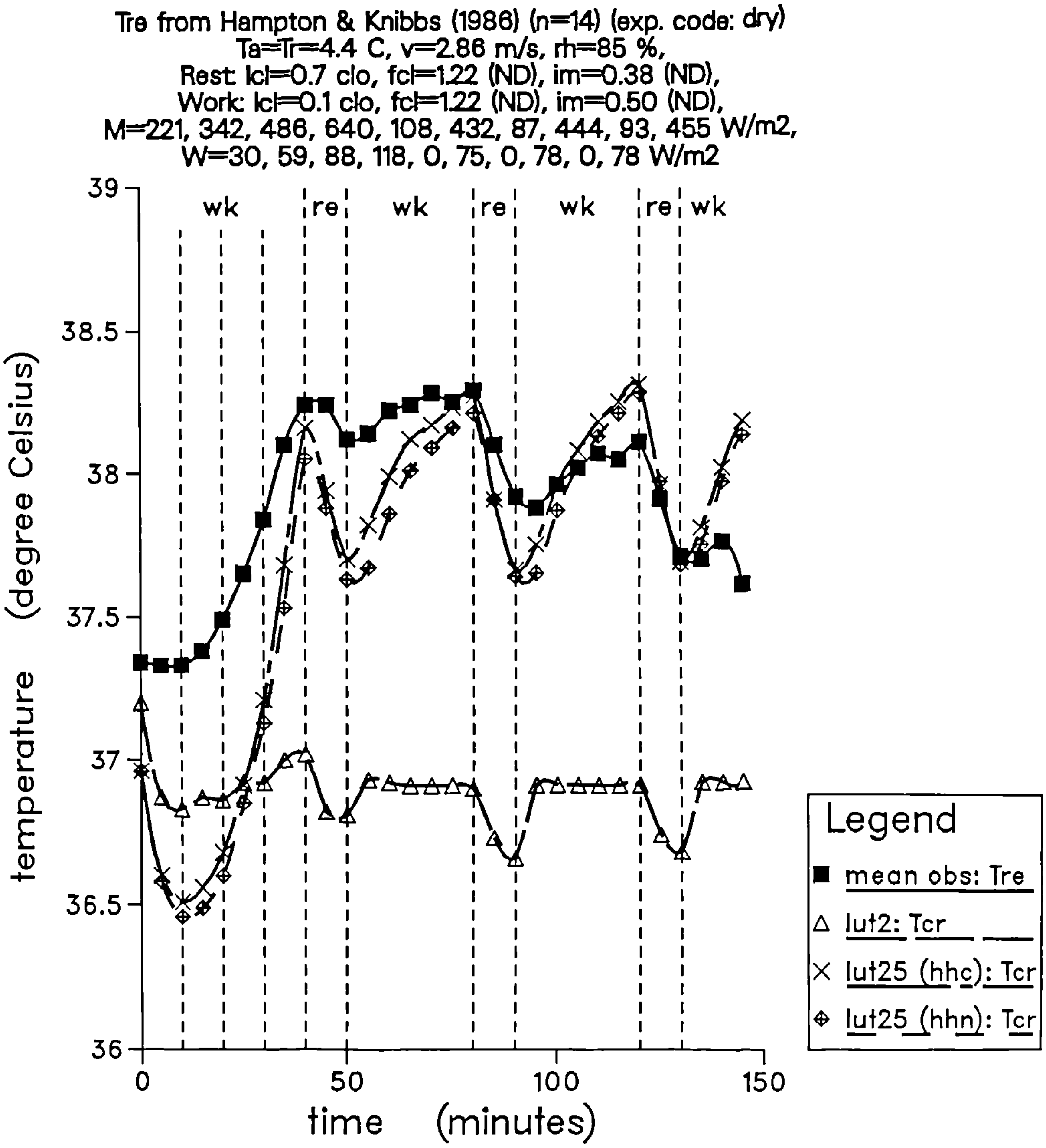
Tre from Haisman and Goldman (1974)
(n=8, accl) (exp. code: wn)
Ta=Tr=35.0 C, v=0.8 m/s, rh=70 %, Icl=0.55 clo, fcl=1.19 (ND),
im=0.44 (ND), M=195, 58, 195 W/m2, W=0 W/m2



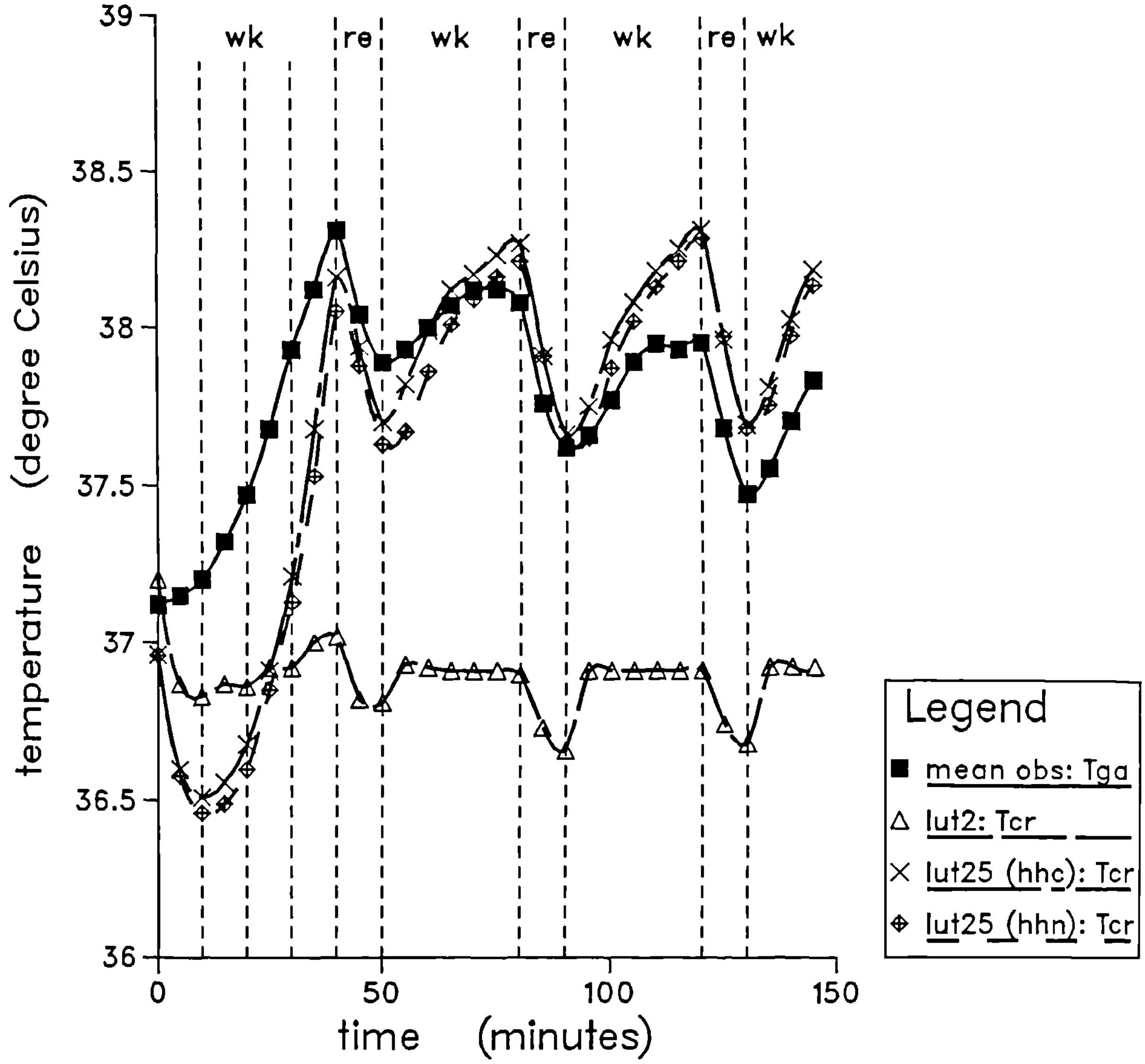
lutiso Allowable Exposure Times
(to work):
warning non accl: 32 min; body temperature increase
danger non accl : 39 min; body temperature increase
warning accl : 40 min; body temperature increase
danger accl : 48 min; body temperature increase

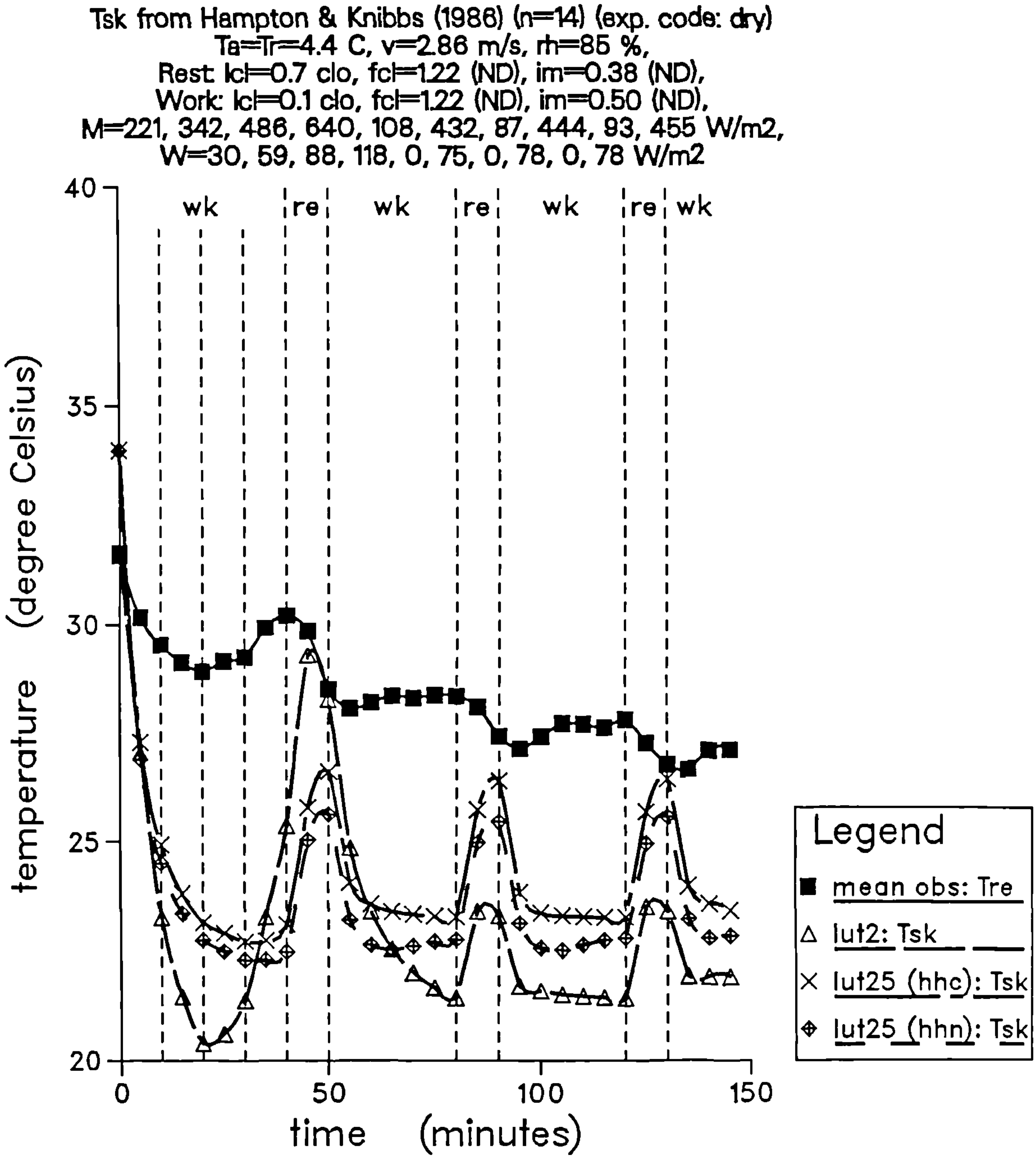
Tsk from Haisman and Goldman (1974)
(n=8, accl) (exp. code: wn)
Ta=Tr=35.0 C, v=0.8 m/s, rh=70 %, Icl=0.55 clo, fcl=1.19 (ND),
im=0.44 (ND), M=195, 58, 195 W/m2, W=0 W/m2



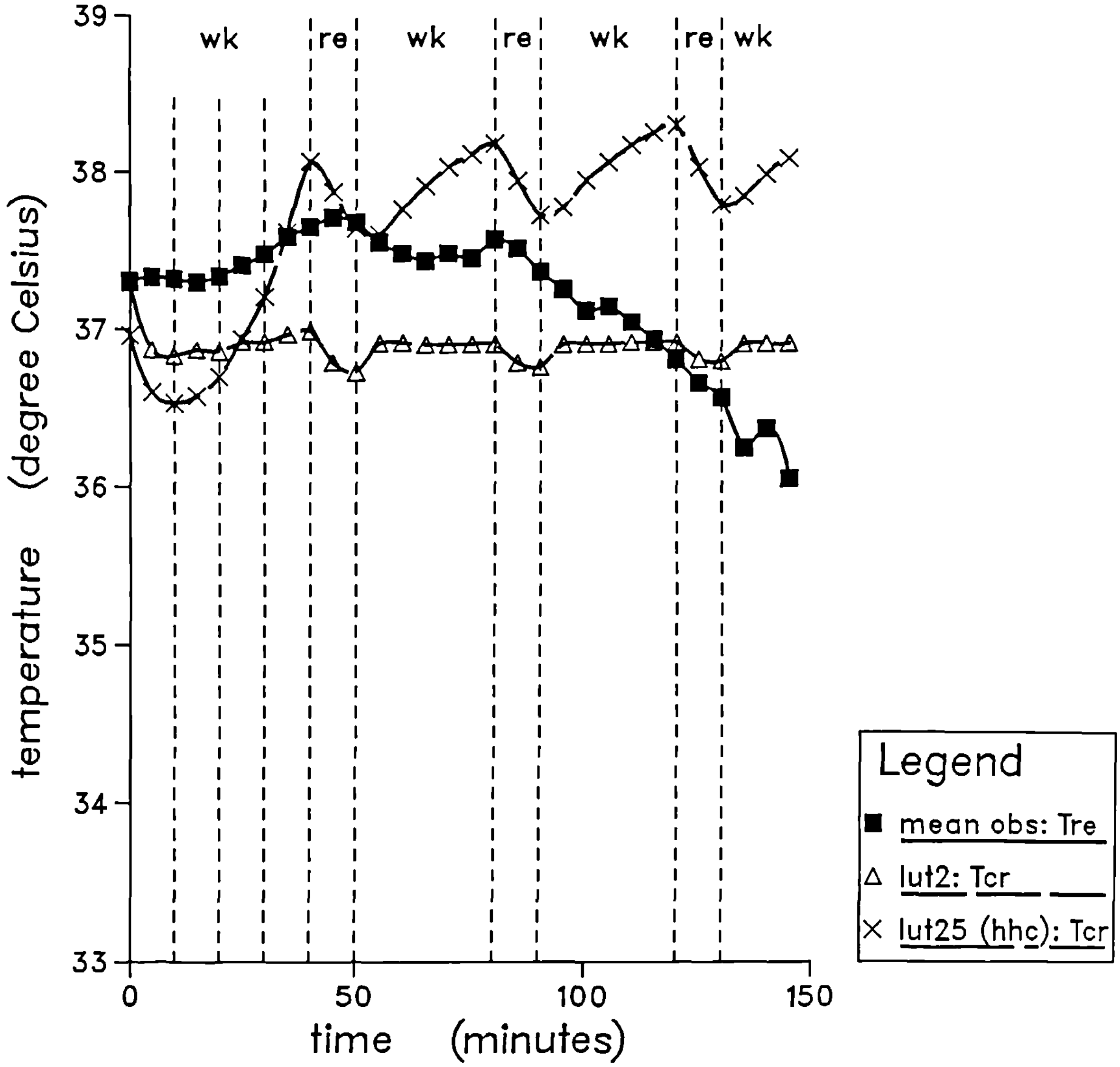

Tre from Hampton & Knibbs (1986) (n=14) (exp. code: dry)
Ta=Tr=4.4 C, v=2.86 m/s, rh=85 %,
Rest: Icl=0.7 clo, fcl=1.22 (ND), im=0.38 (ND),
Work: Icl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=221, 342, 486, 640, 108, 432, 87, 444, 93, 455 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2
wk
re
wk
re
wk
re
wk
temperature (degree Celsius)
39
38.5
38
37.5
37
36.5
36
0
50
100
150
time (minutes)
Legend
mean obs: Tre
lut2: Tcr
lut25 (hhc): Tcr
lut25 (hhn): Tcr

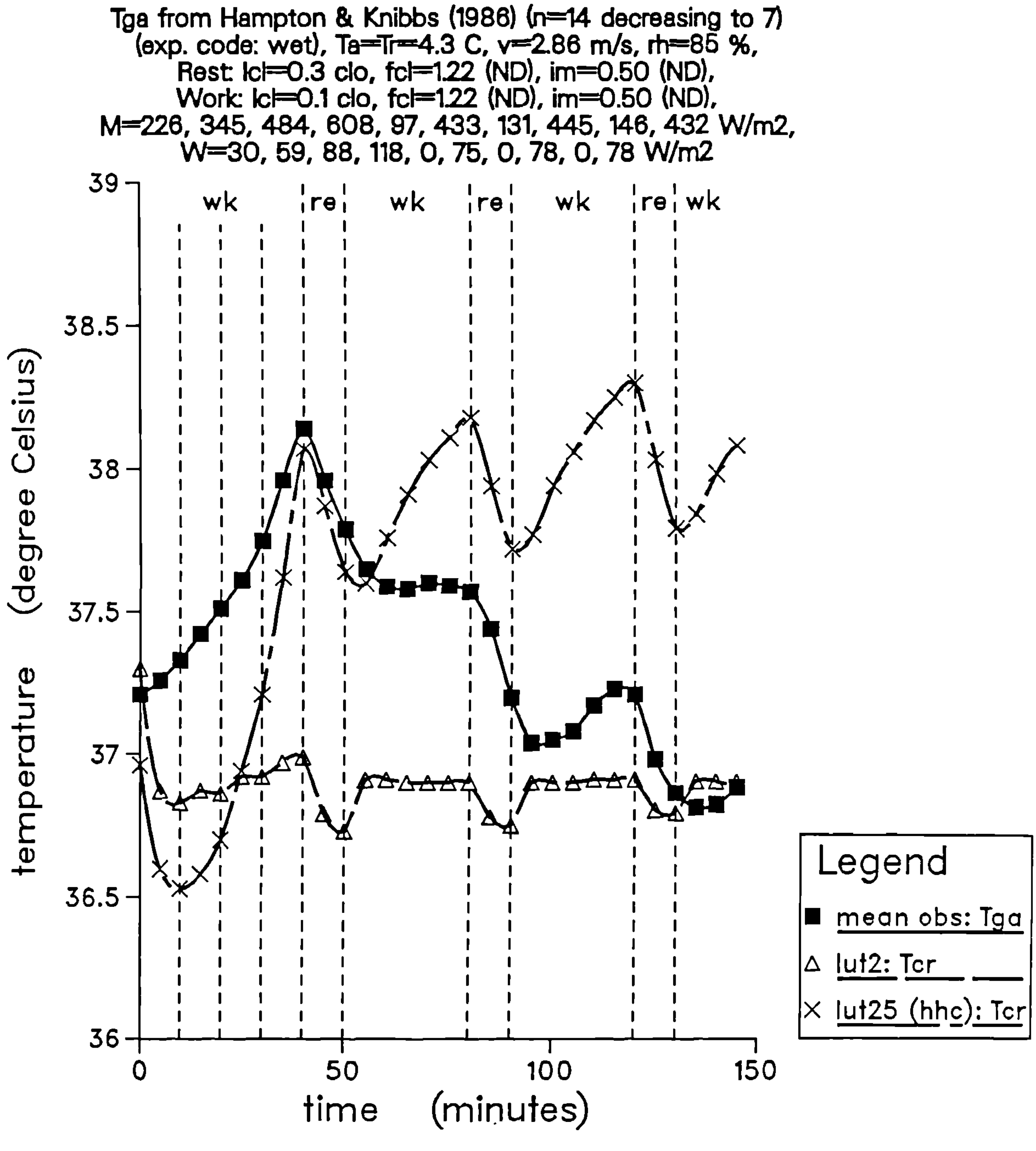
Tga from Hampton & Knibbs (1986) (n=14) (exp. code: dry)
Ta=Tr=4.4 C, v=2.86 m/s, rh=85 %,
Rest: Icl=0.7 clo, fcl=1.22 (ND), im=0.38 (ND),
Work: Icl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=221, 342, 486, 640, 108, 432, 87, 444, 93, 455 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2



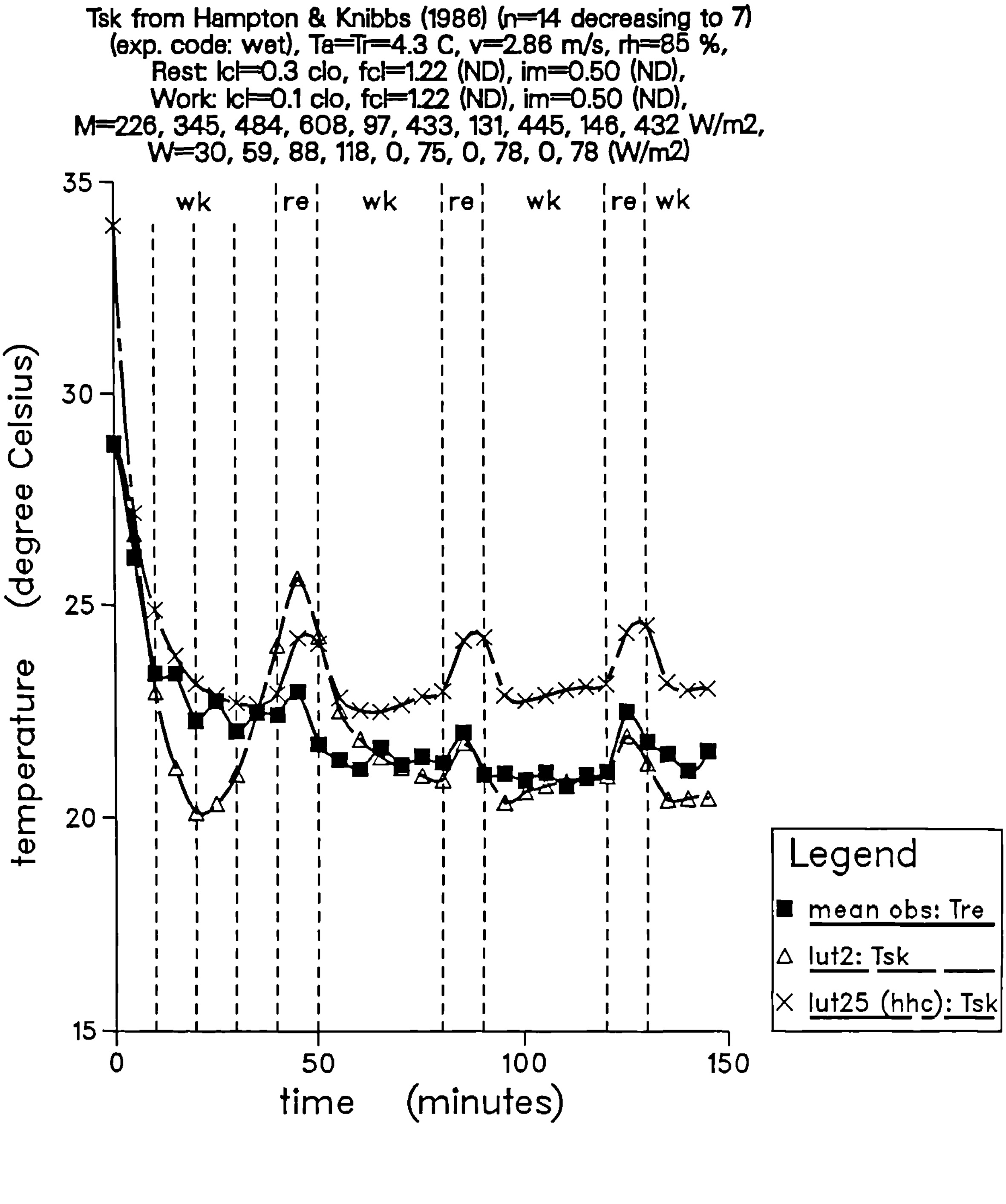

Tsk from Hampton & Knibbs (1986) (n=14) (exp. code: dry)
Ta=Tr=4.4 C, v=2.86 m/s, rh=85 %,
Rest: Icl=0.7 clo, fcl=1.22 (ND), im=0.38 (ND),
Work: Icl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=221, 342, 486, 640, 108, 432, 87, 444, 93, 455 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2
wk
re
wk
re
wk
re
wk
temperature (degree Celsius)
40
35
30
25
20
0
50
100
150
time (minutes)
Legend
mean obs: Tre
lut2: Tsk
lut25 (hhc): Tsk
lut25 (hhn): Tsk

Tre from Hampton & Knibbs (1986) (n=14 decreasing to 7)
(exp. code: wet), Ta=Tr=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, 131, 445, 146, 432 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2



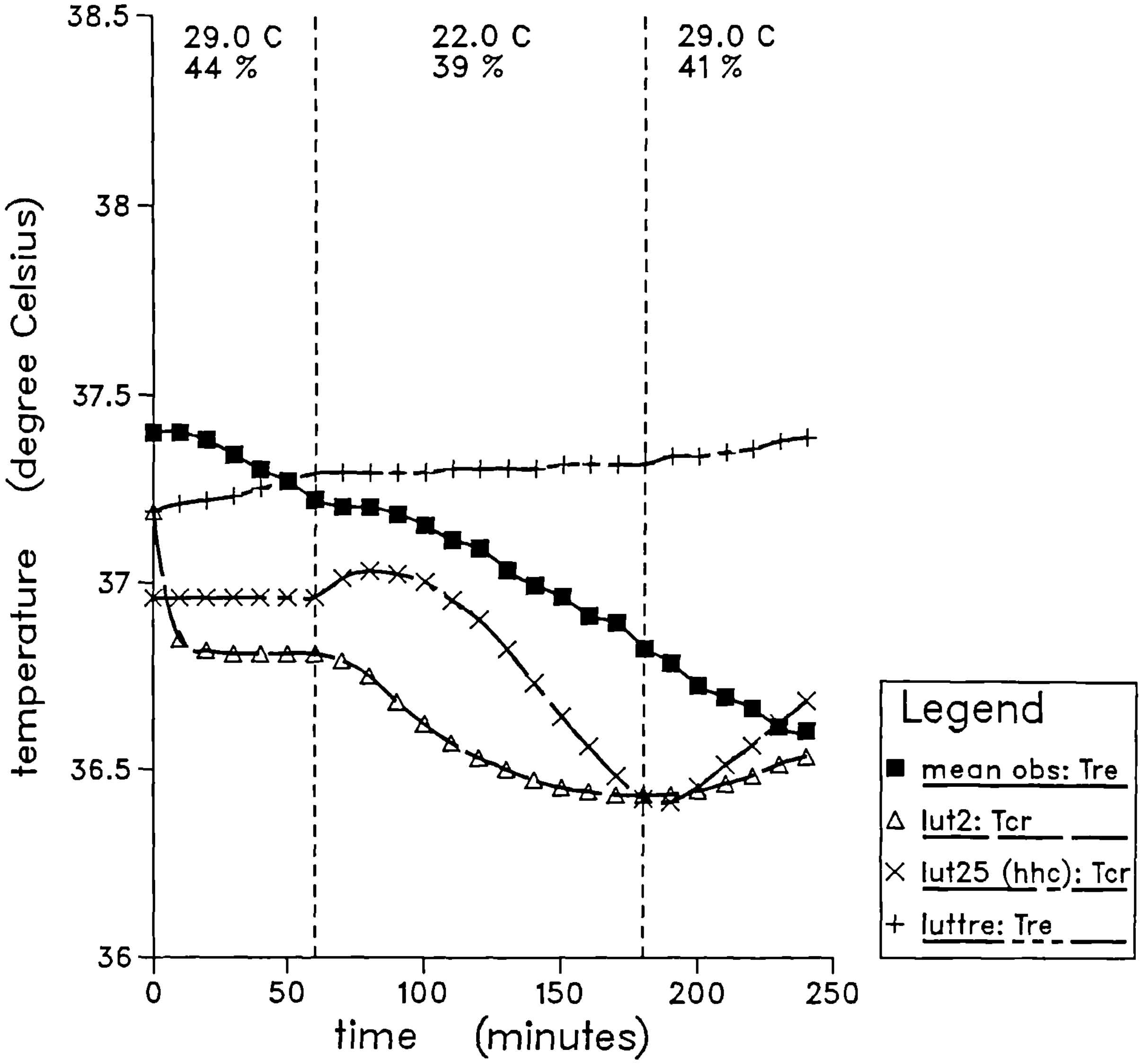


Tga from Hampton & Knibbs (1986) (n=14 decreasing to 7)
(exp. code: wet), Ta=Tr=4.3 C, v=2.86 m/s, rh=85 %,
Rest: Icl=0.3 clo, fcl=1.22 (ND), im=0.50 (ND),
Work: Icl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=226, 345, 484, 608, 97, 433, 131, 445, 146, 432 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 W/m2
wk
re
wk
re
wk
re
wk
temperature (degree Celsius)
39
38.5
38
37.5
37
36.5
36
0
50
100
150
time (minutes)
Legend
mean obs: Tga
lut2: Tcr
lut25 (hhc): Tcr

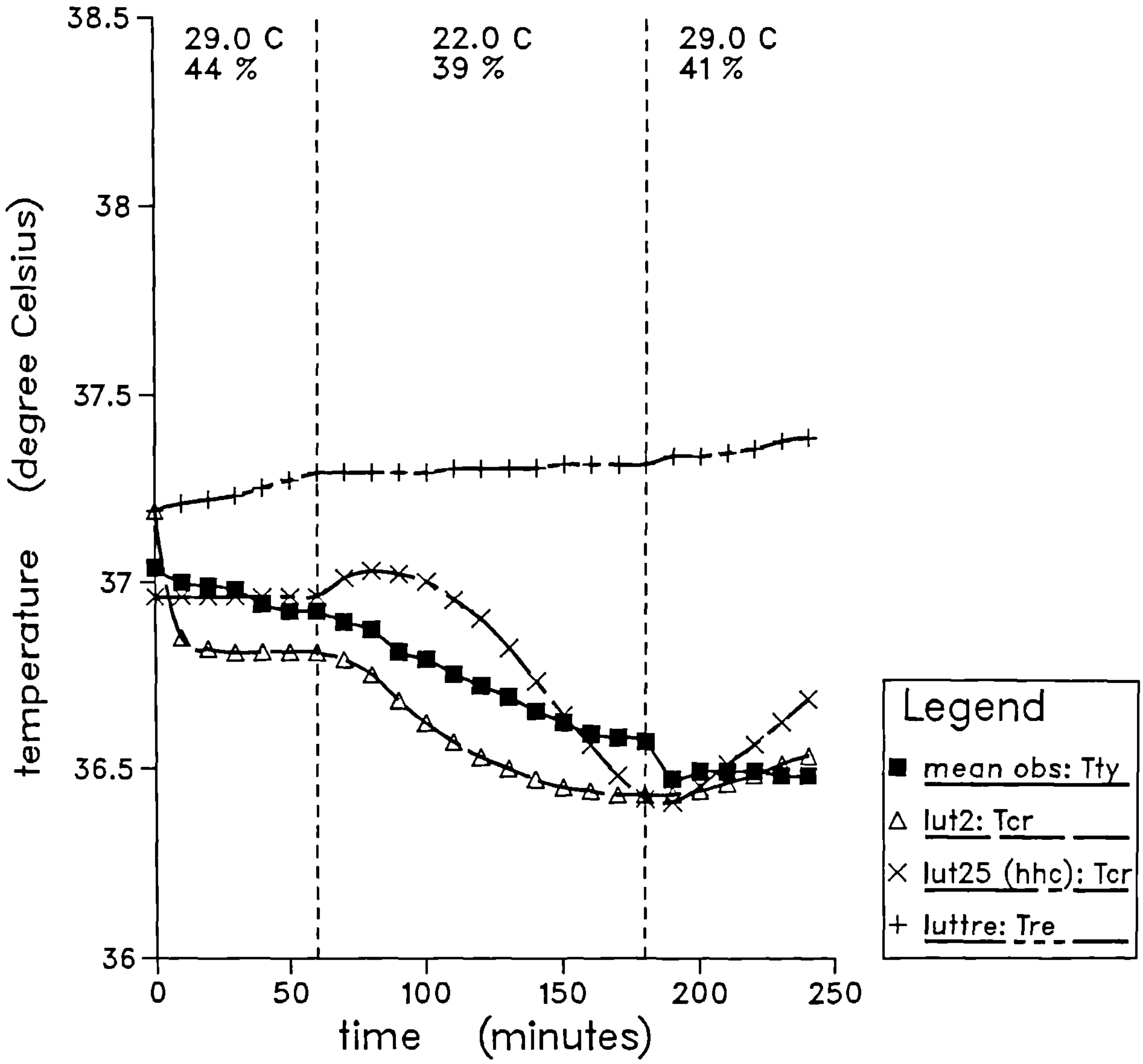


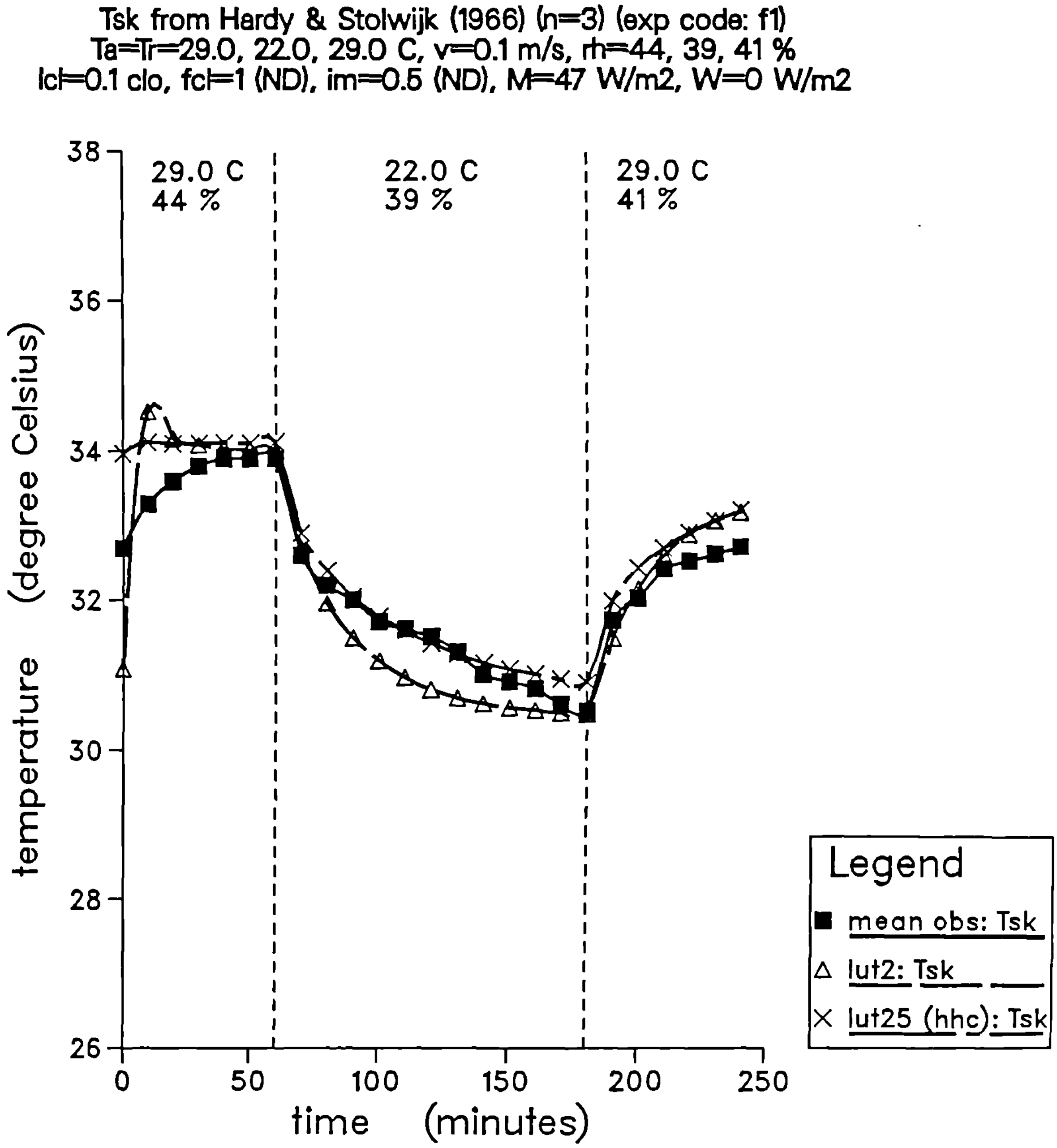
Tsk from Hampton & Knibbs (1986) (n=14 decreasing to 7)
(exp. code: wet), Ta=Tr=4.3 C, v=2.86 m/s, rh=85 %,
Rest: Icl=0.3 clo, fcl=1.22 (ND), im=0.50 (ND),
Work: Icl=0.1 clo, fcl=1.22 (ND), im=0.50 (ND),
M=226, 345, 484, 608, 97, 433, 131, 445, 146, 432 W/m2,
W=30, 59, 88, 118, 0, 75, 0, 78, 0, 78 (W/m2)
wk
re
wk
re
wk
re
wk
temperature (degree Celsius)
35
30
25
20
15
0
50
100
150
time (minutes)
Legend
mean obs: Tre
lut2: Tsk
lut25 (hhc): Tsk

Tre 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 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

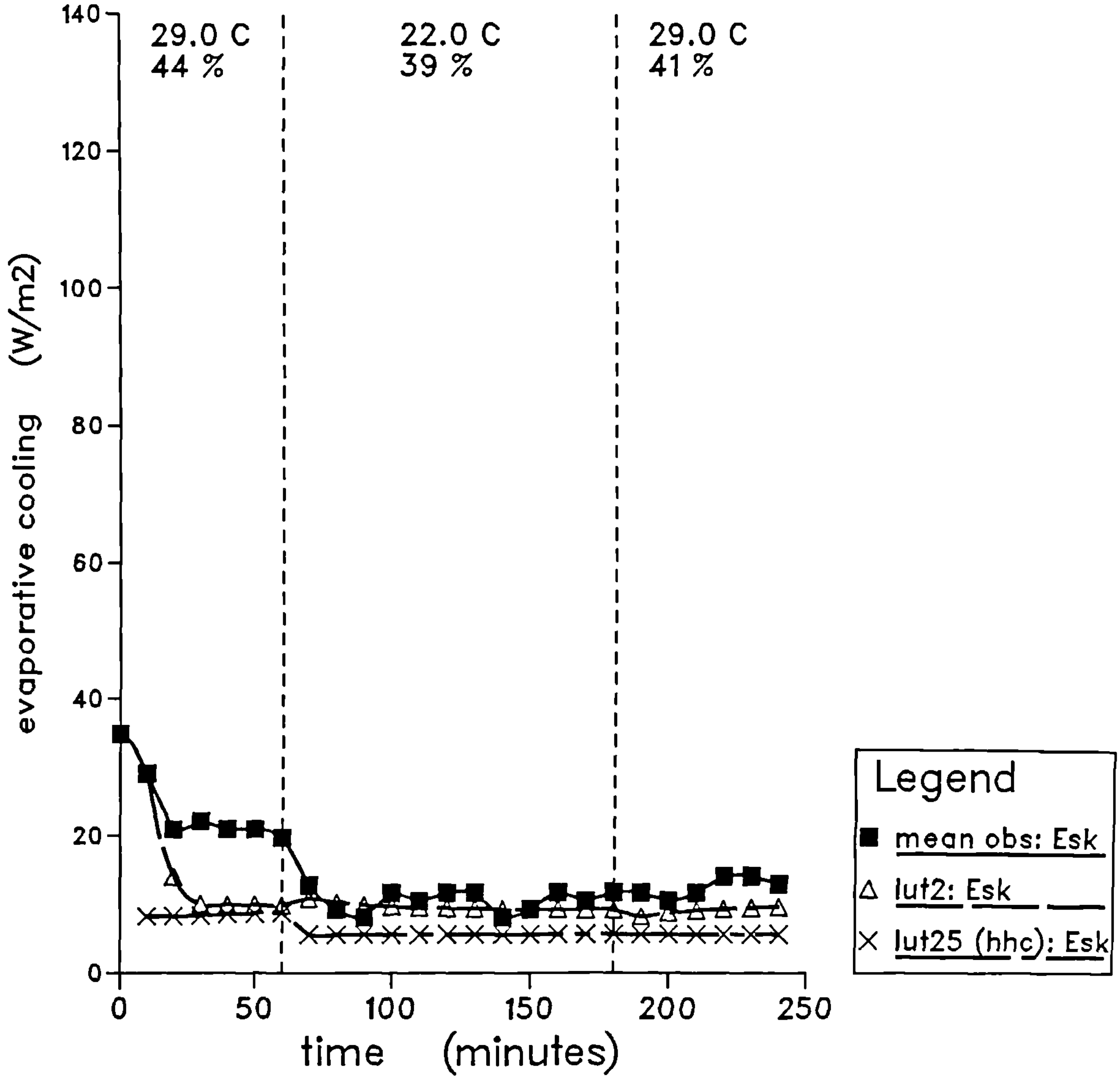


Tty from Hardy & Stolwijk (1966) (n=3) (exp code: f1)
Ta=Tr=29.0, 22.0, 29.0 C, v=0.1 m/s, rh=44, 39, 41 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

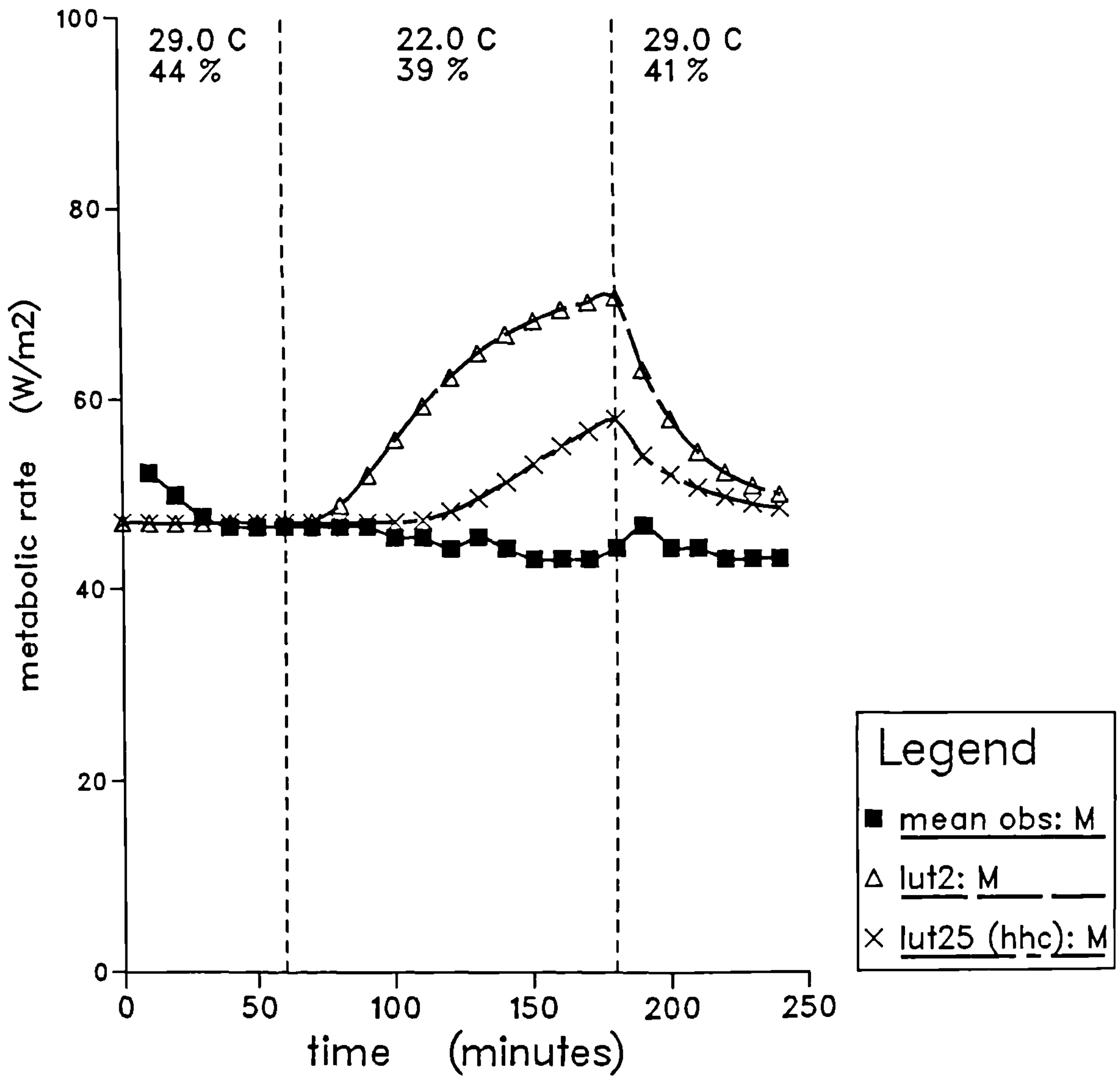



Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f1)
Ta=Tr=29.0, 22.0, 29.0 C, v=0.1 m/s, rh=44, 39, 41 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
29.0 C
44 %
22.0 C
39 %
29.0 C
41 %
38
36
34
32
30
28
26
temperature (degree Celsius)
0
50
100
150
200
250
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk

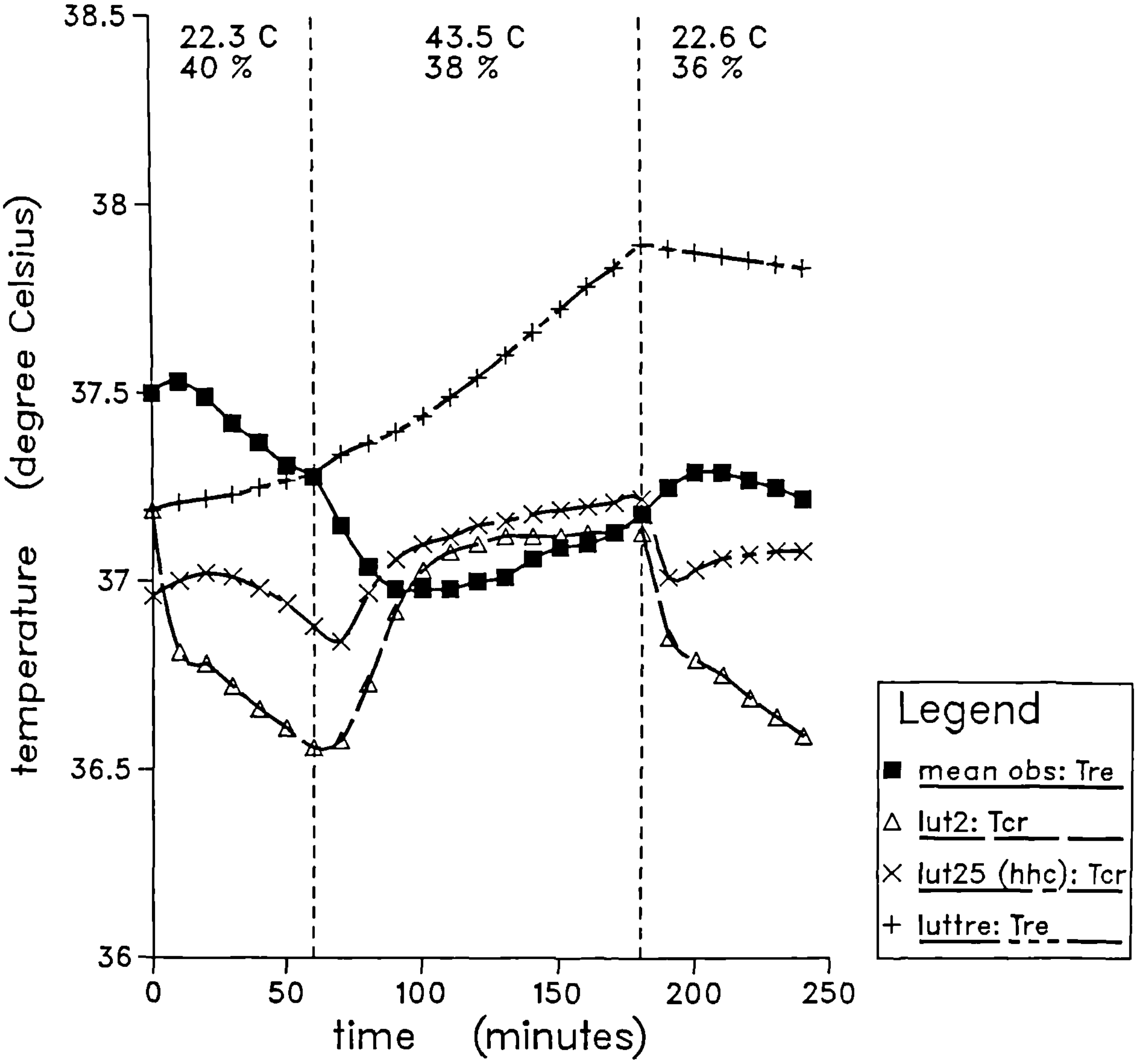
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f1)
Ta=Tr=29.0, 22.0, 29.0 C, v=0.1 m/s, rh=44, 39, 41 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



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

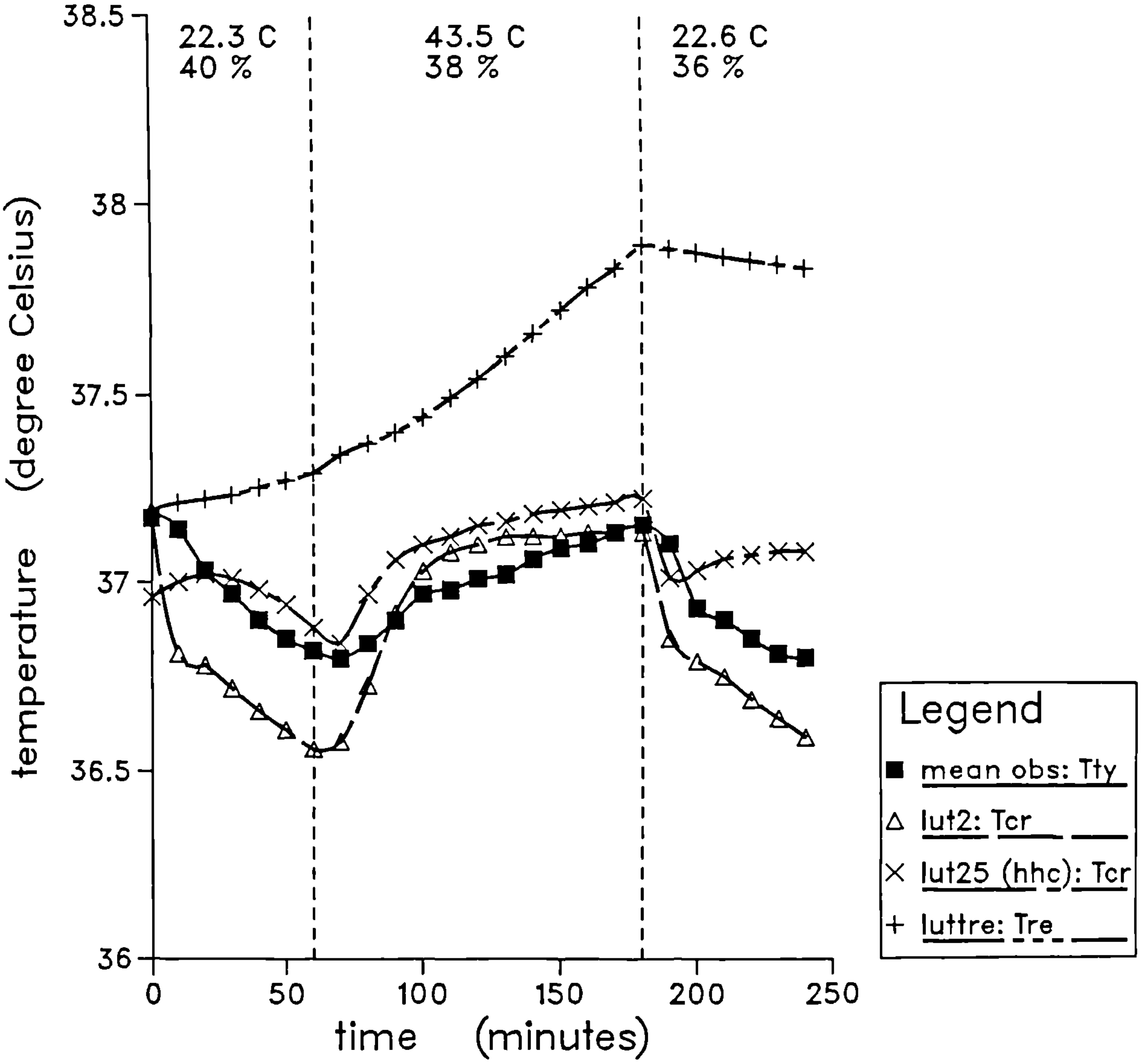


Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
Ta=Tr=22.3, 43.5, 22.6 C, v=0.1 m/s, rh=40, 38, 36 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



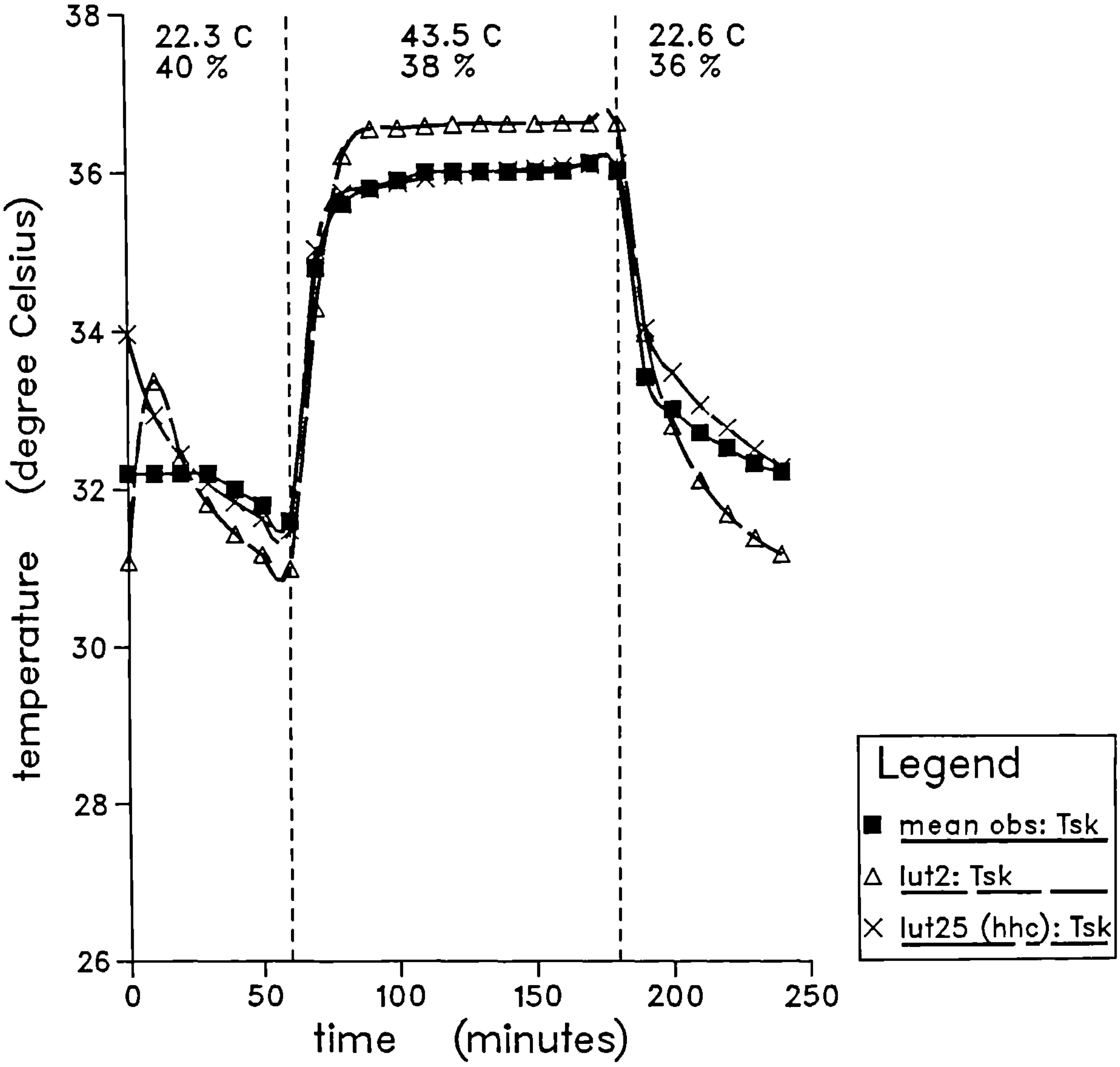
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tty from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
Ta=Tr=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

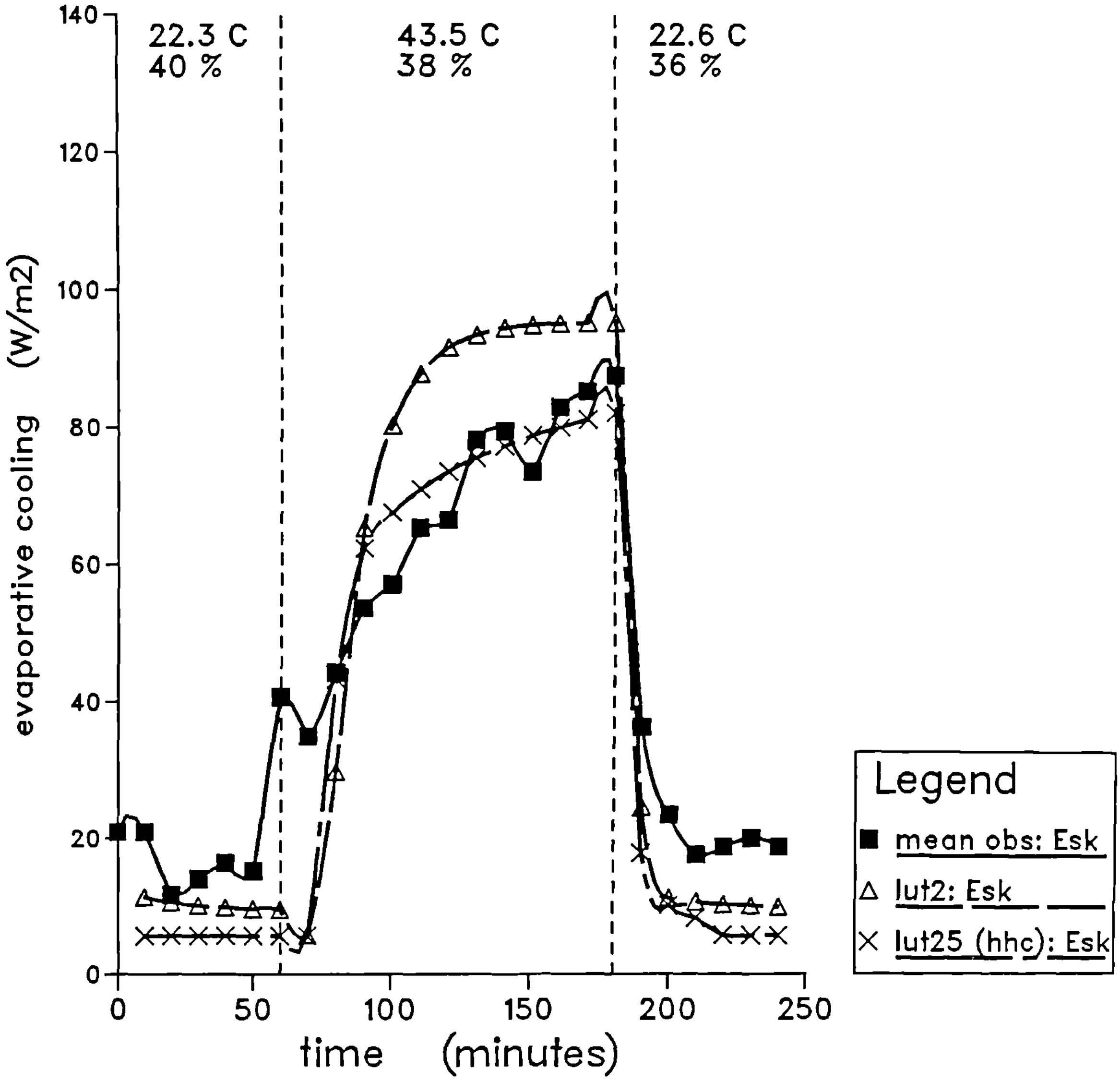


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

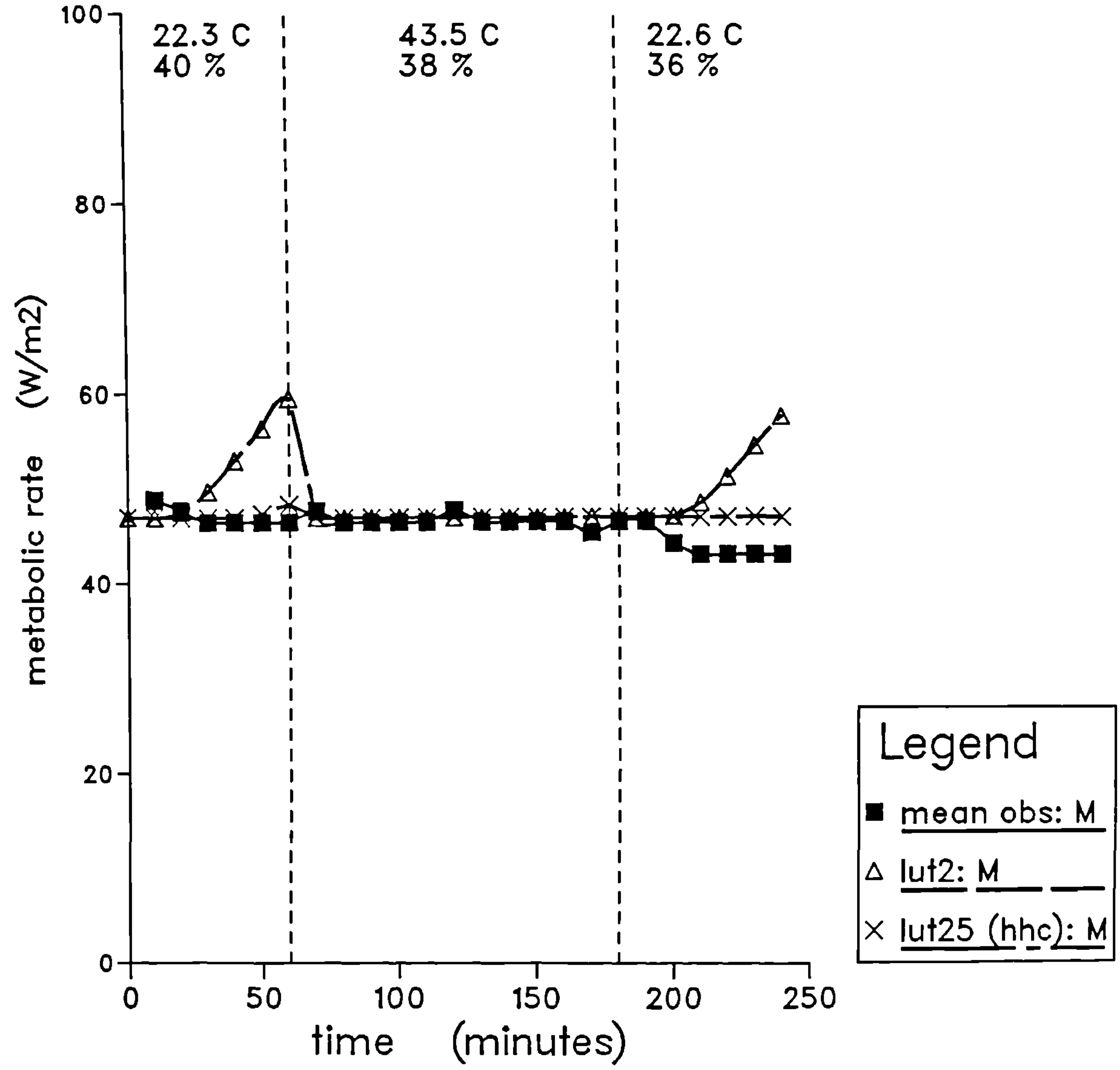
Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
Ta=Tr=22.3, 43.5, 22.6 C, v=0.1 m/s, rh=40, 38, 36 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



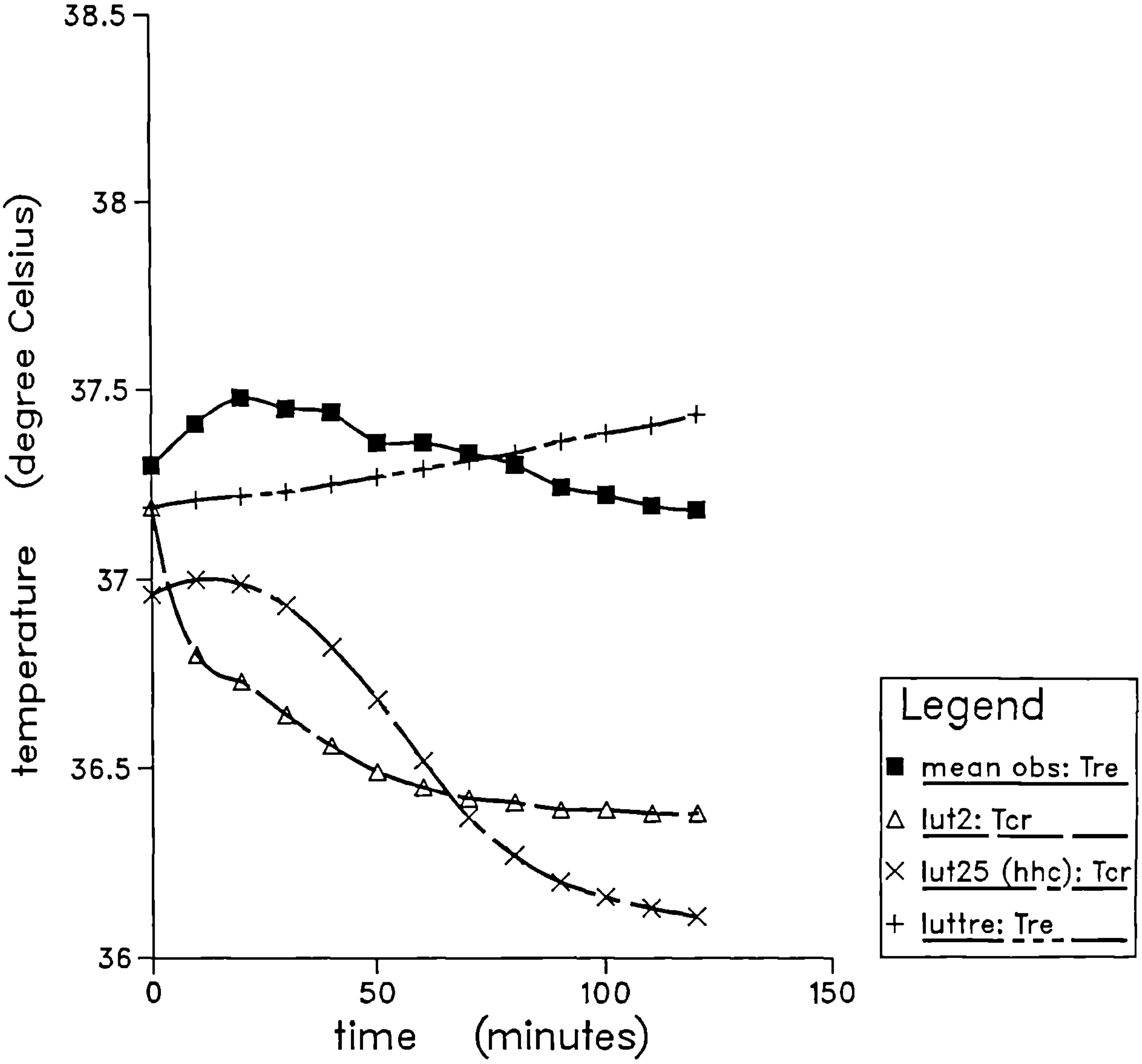
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
Ta=Tr=22.3, 43.5, 22.6 C, v=0.1 m/s, rh=40, 38, 36 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



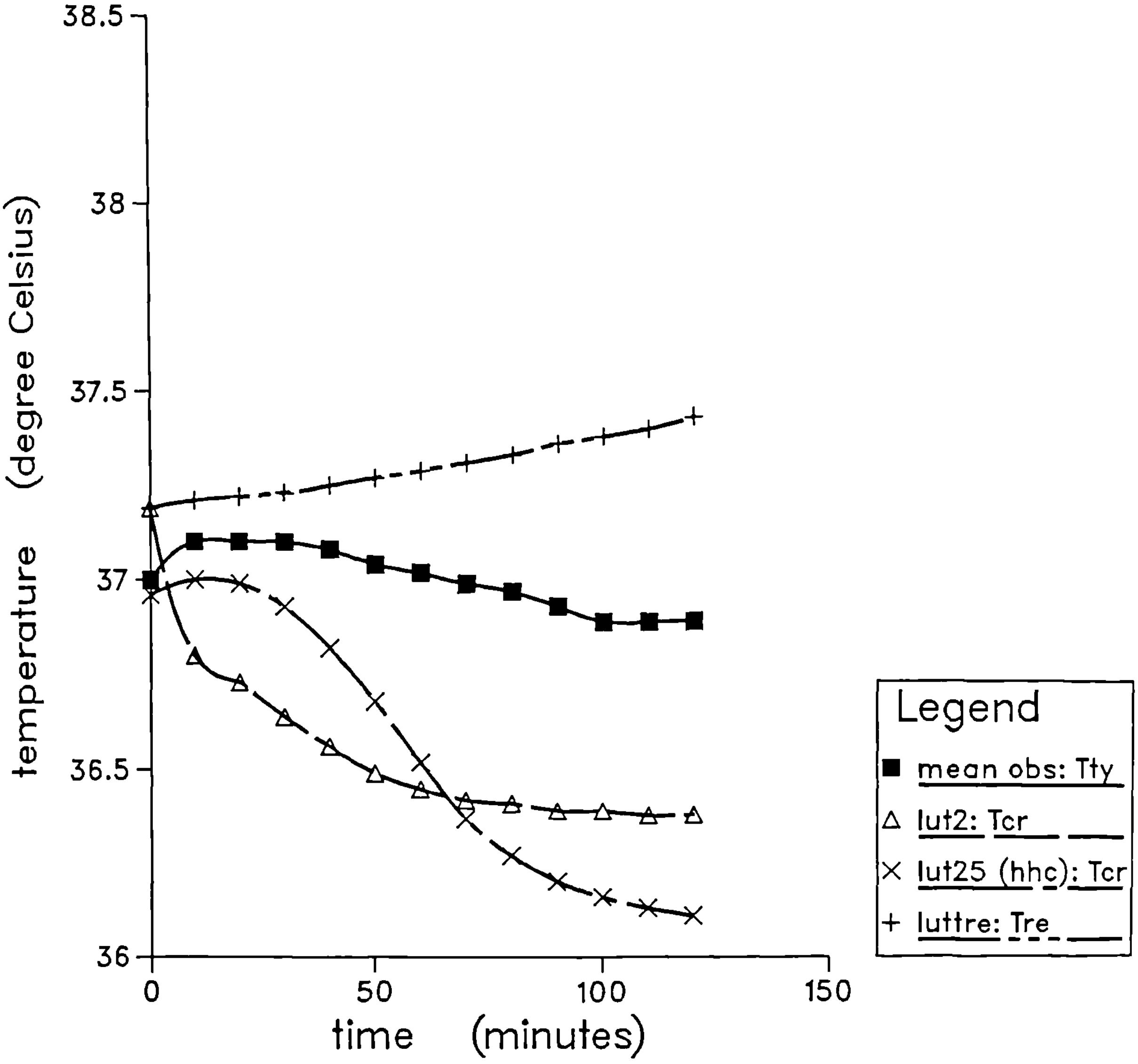
M from Hardy & Stolwijk (1966) (n=3) (exp code: f3)
Ta=Tr=22.3, 43.5, 22.6 C, v=0.1 m/s, rh=40, 38, 36 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



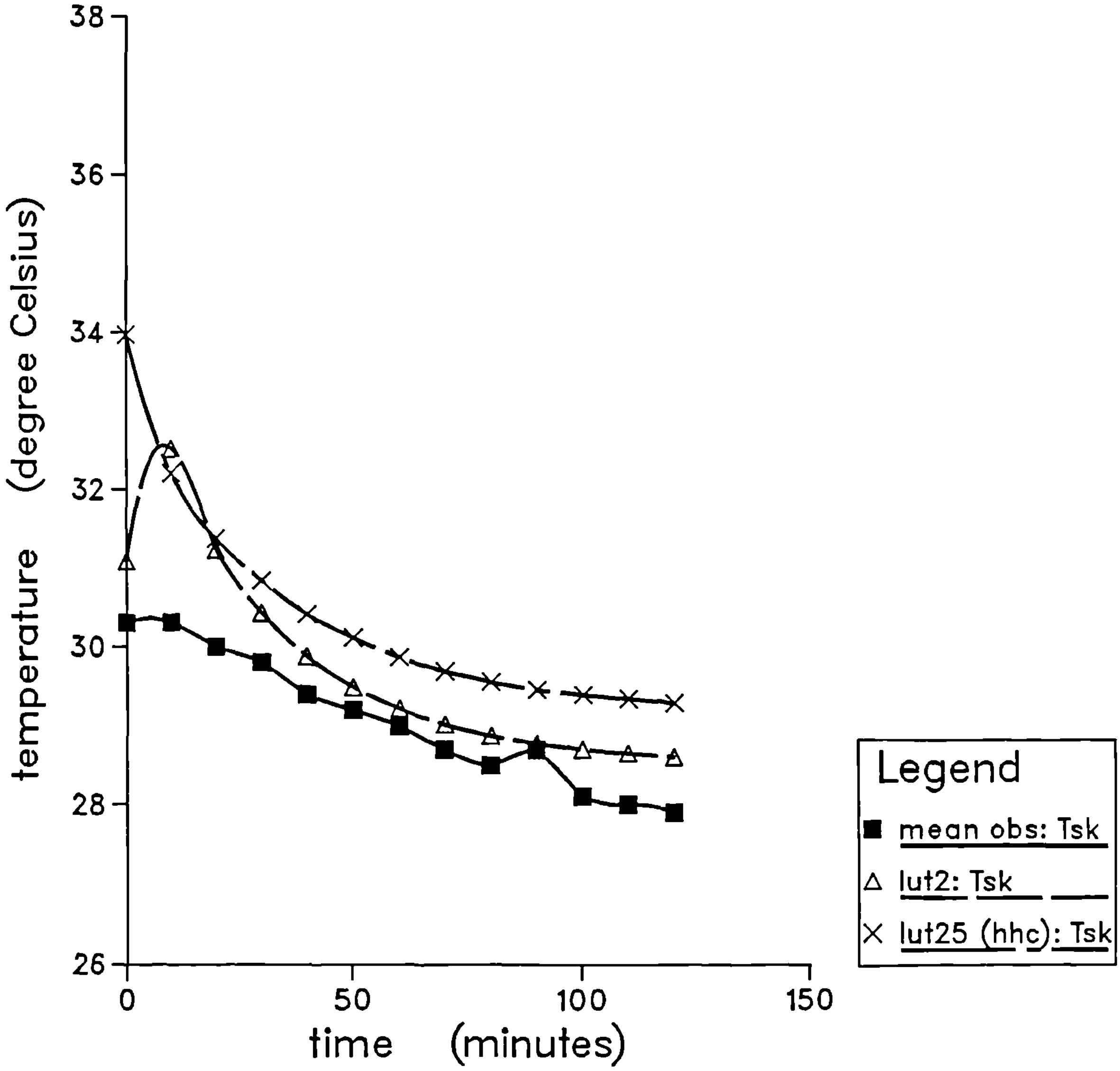
Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f6)
Ta=Tr=17.7 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



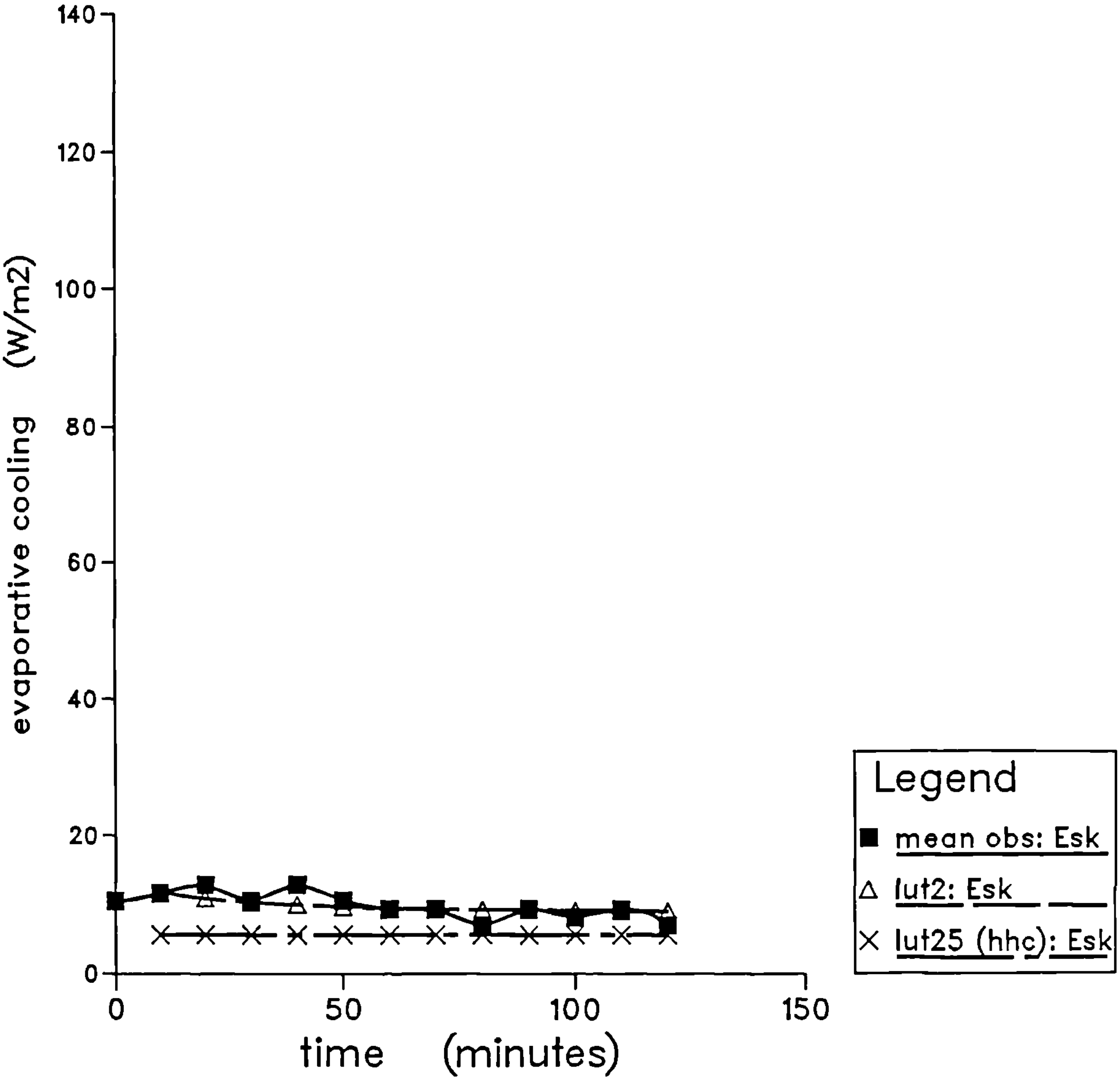
Tty from Hardy & Stolwijk (1966) (n=3) (exp code: f6)
Ta=Tr=17.7 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



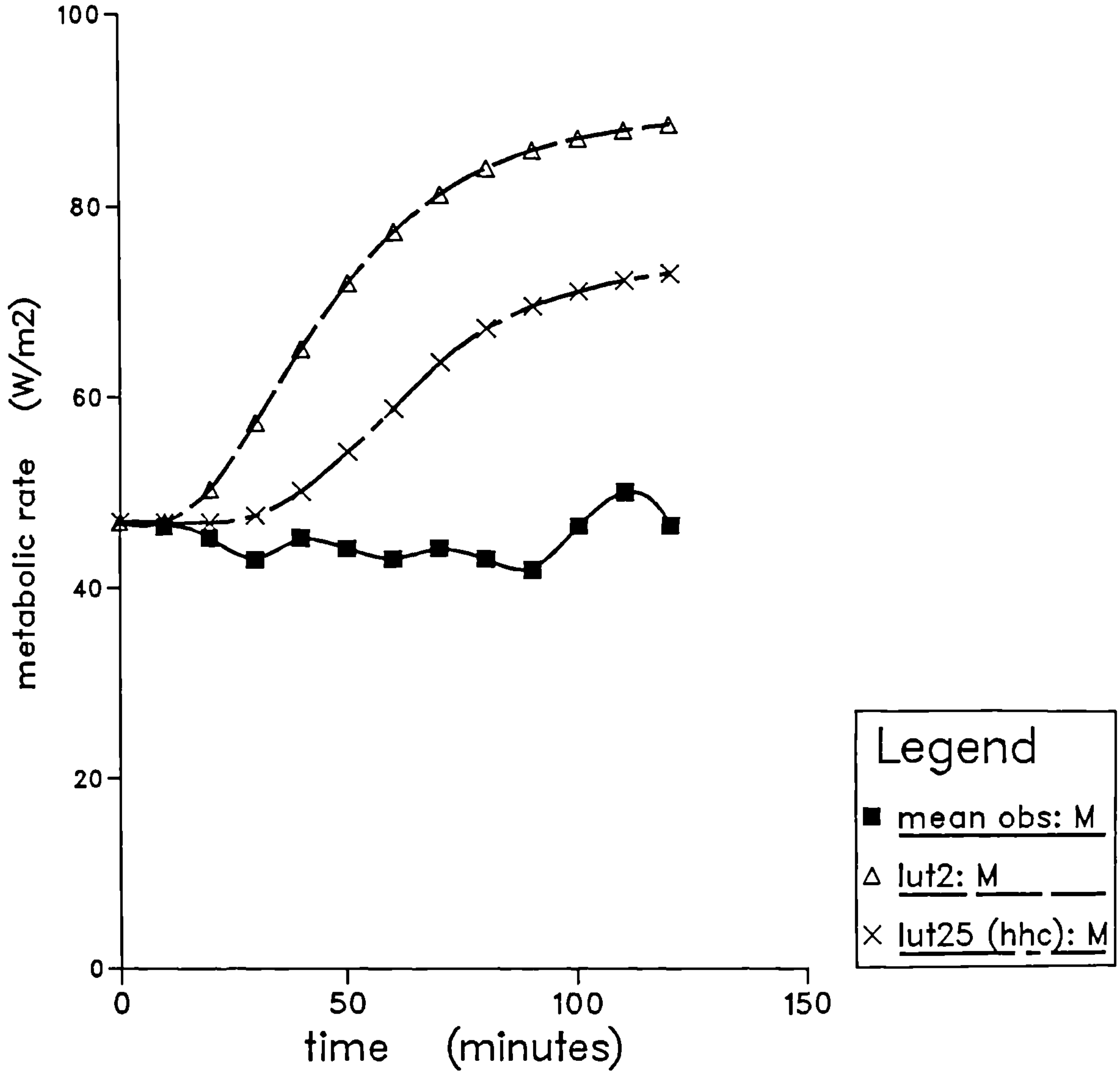
Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f6)
Ta=Tr=17.7 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



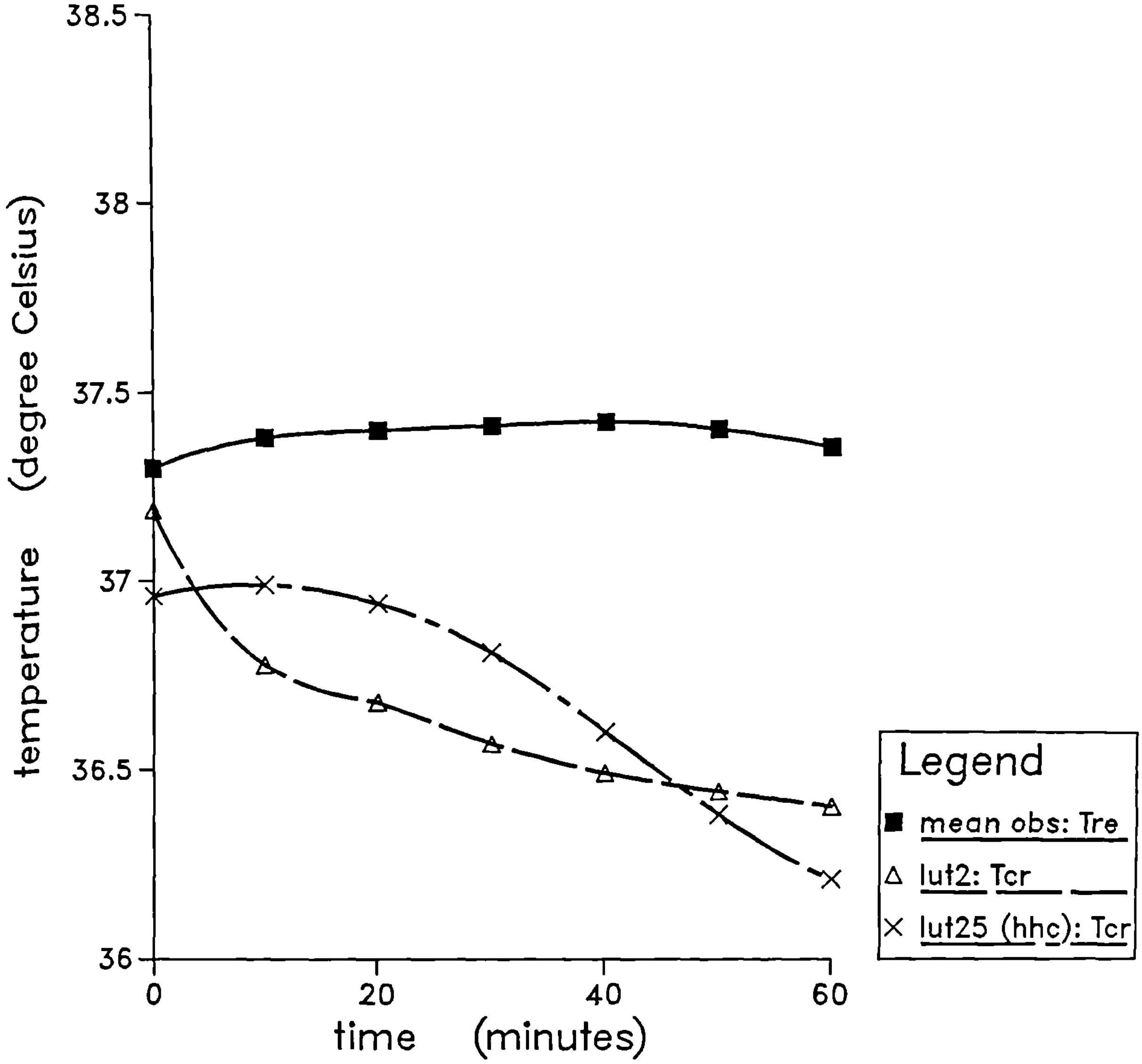
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f6)
Ta=Tr=17.7 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



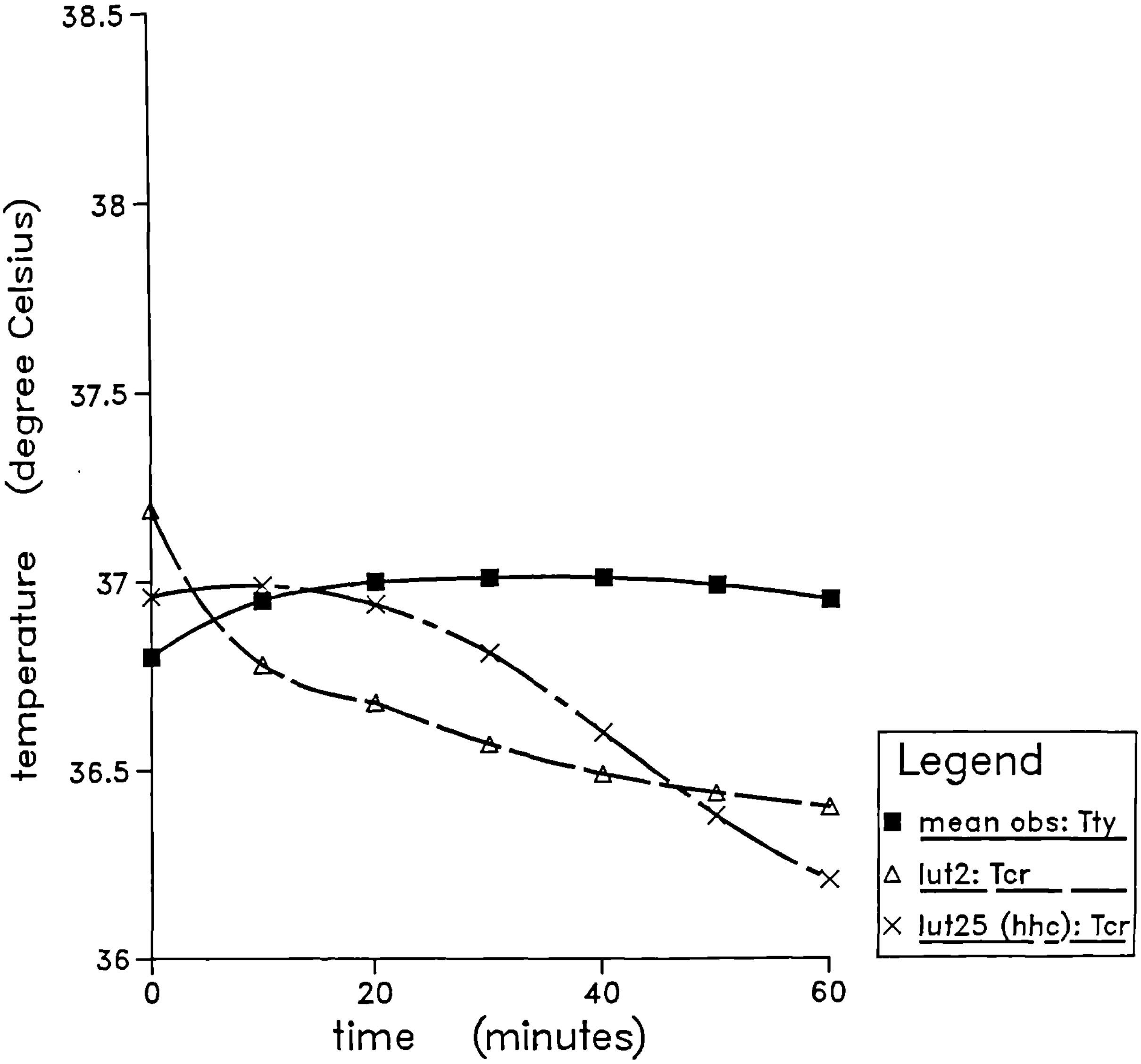
M from Hardy & Stolwijk (1966) (n=3) (exp code: f6)
Ta=Tr=17.7 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

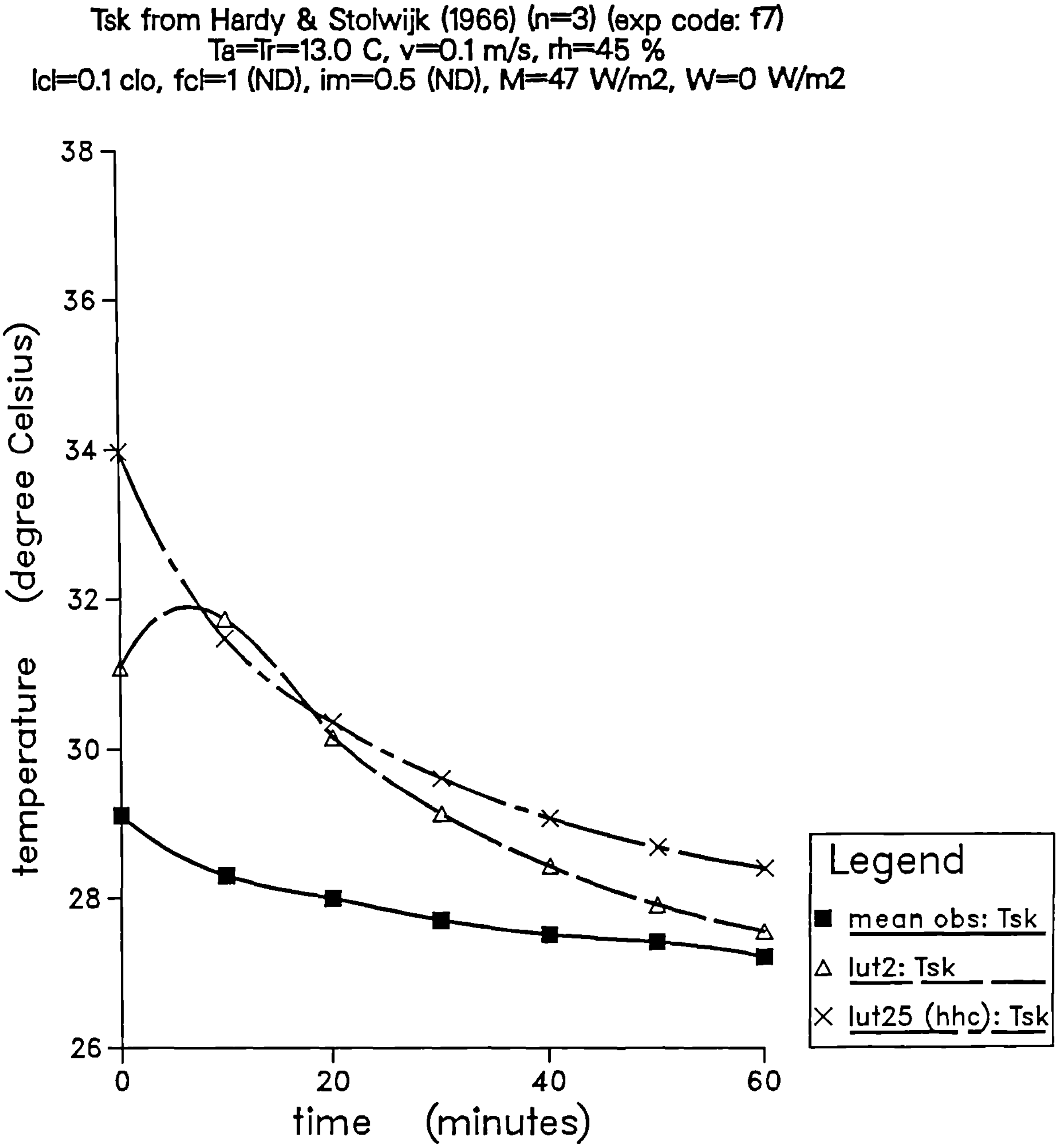


Tre from Hardy & Stolwijk (1966) (n=3) (exp code: f7)
Ta=Tr=13.0 C, v=0.1 m/s, rh=45 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

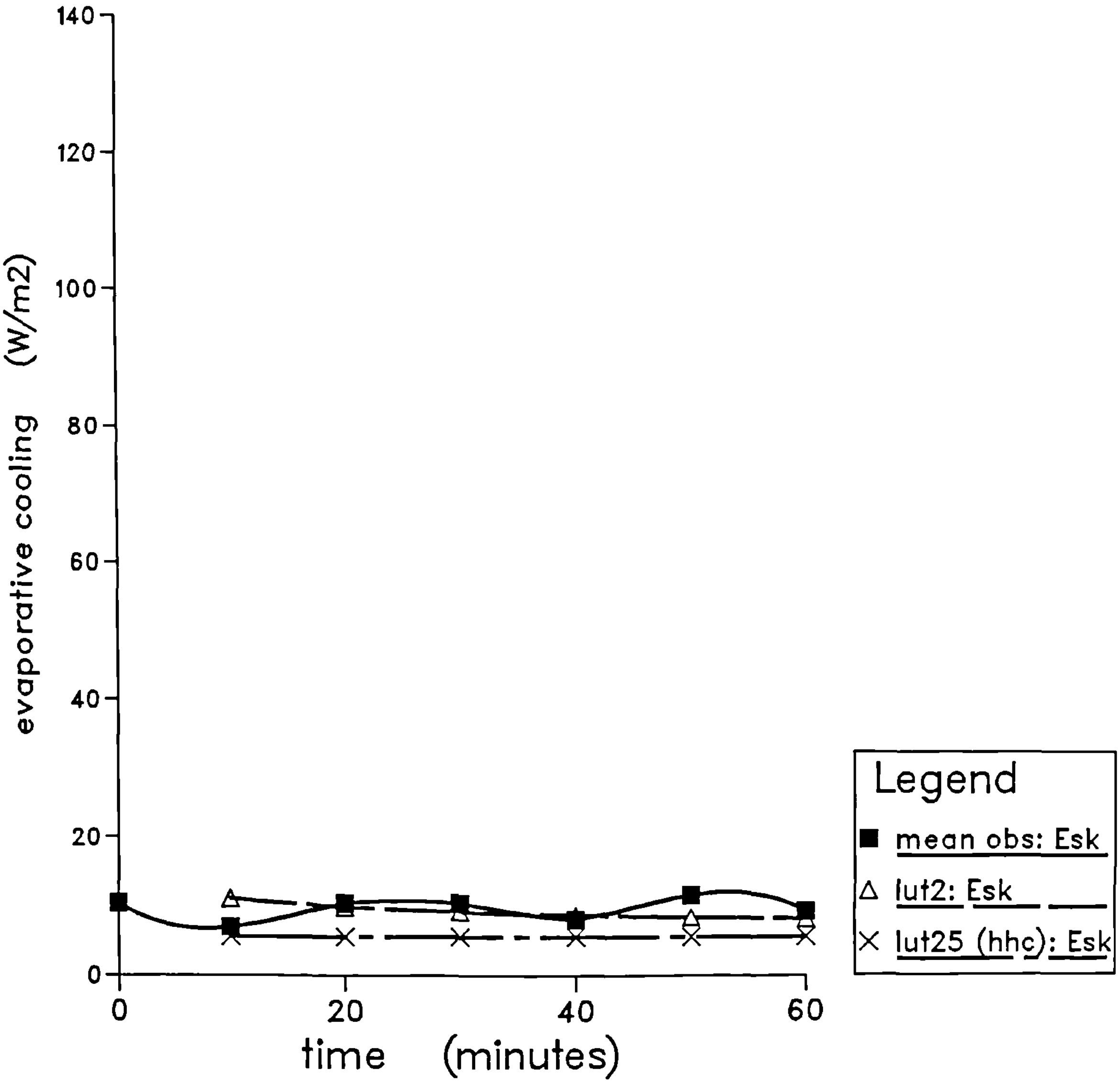


Tty from Hardy & Stolwijk (1966) (n=3) (exp code: f7)
Ta=Tr=13.0 C, v=0.1 m/s, rh=45 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

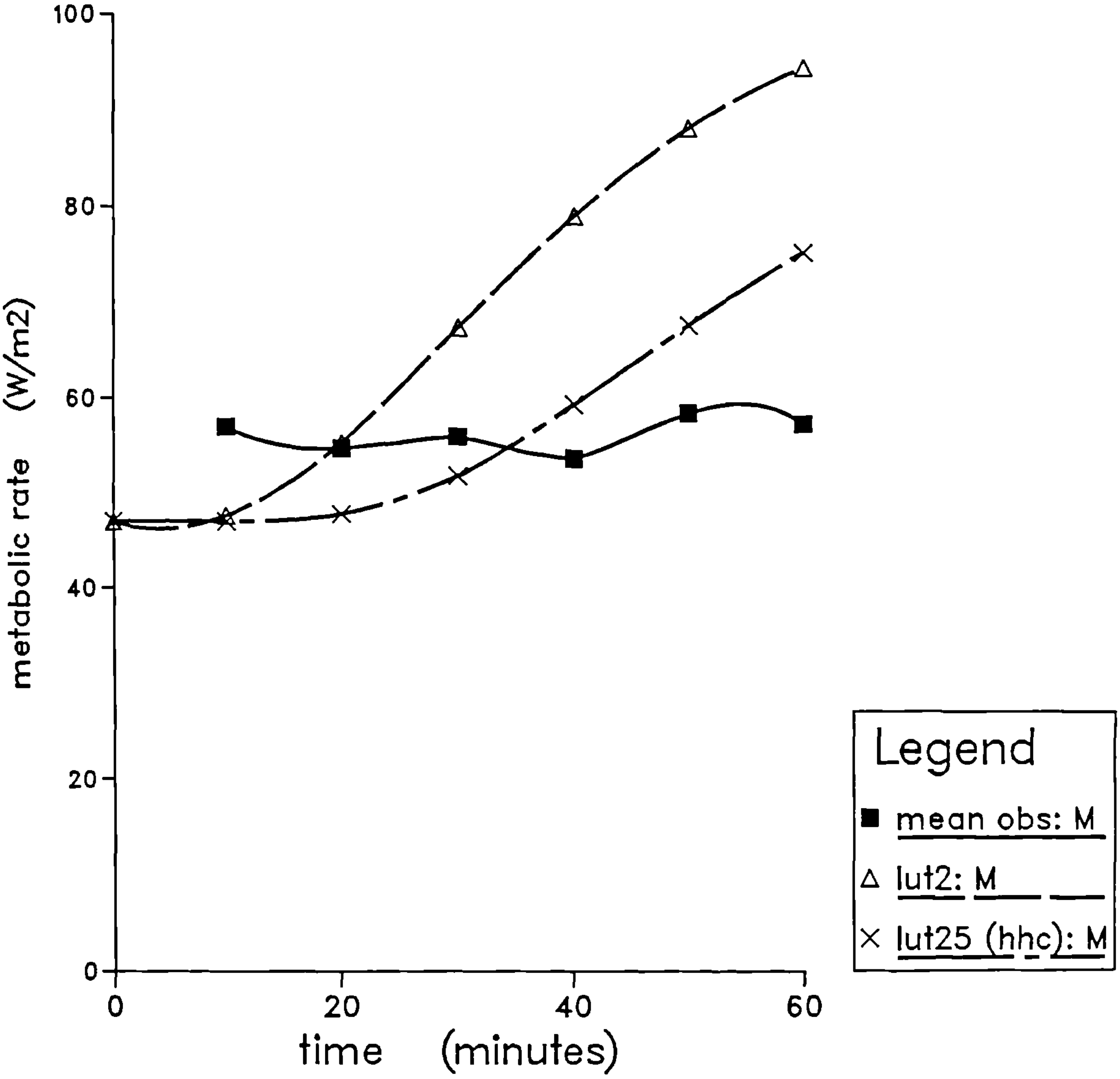



Tsk from Hardy & Stolwijk (1966) (n=3) (exp code: f7)
Ta=Tr=13.0 C, v=0.1 m/s, rh=45 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
temperature (degree Celsius)
38
36
34
32
30
28
26
0
20
40
60
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk

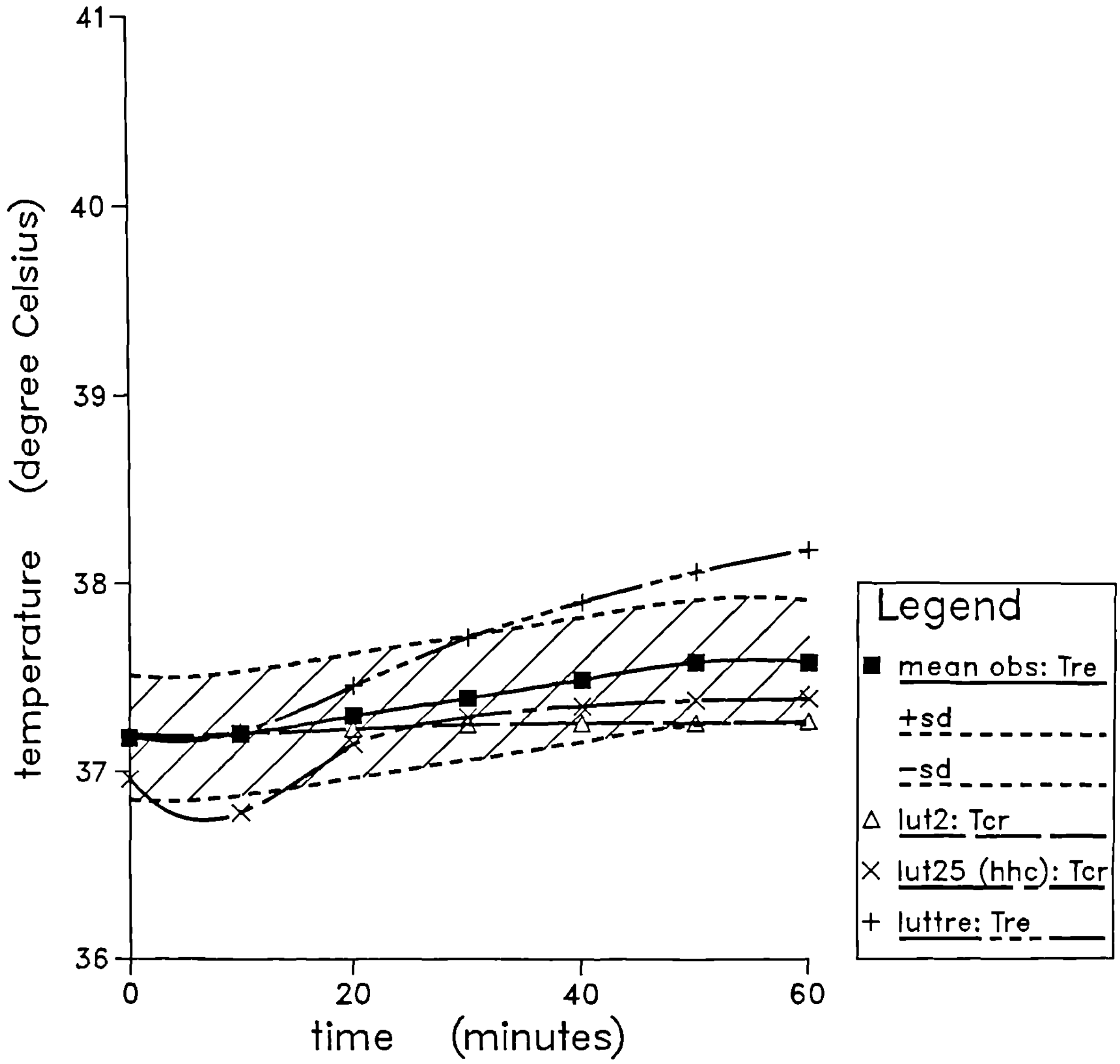
Esk from Hardy & Stolwijk (1966) (n=3) (exp code: f7)
Ta=Tr=13.0 C, v=0.1 m/s, rh=45 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



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

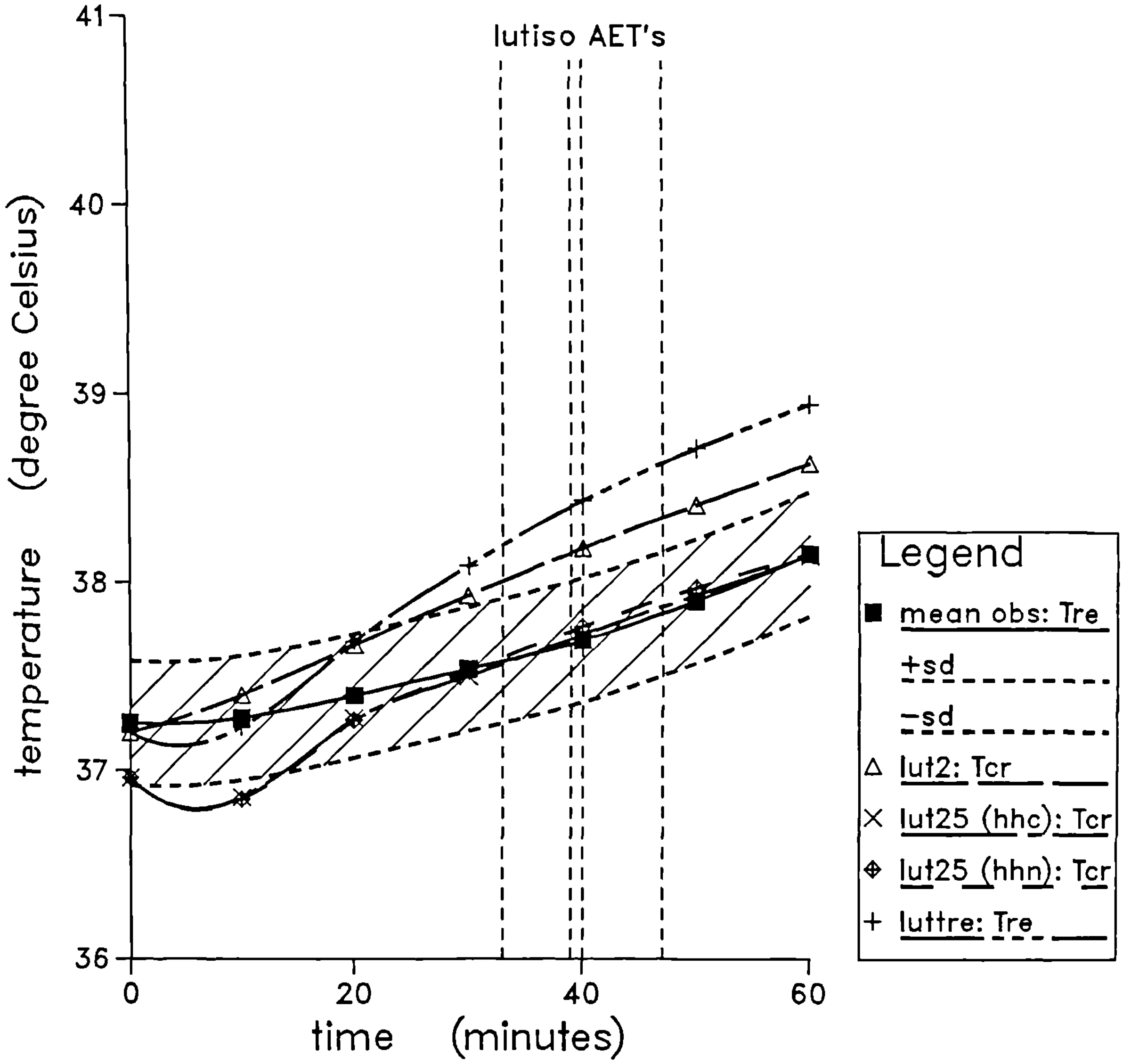


Tre from Henane et al (1979) (n=11) (exp. code: nude)
Ta=Tr=35 C, v=1 m/s, rh=54 %,
Icl=0.1 clo, fcl=1.00 (ND), im=0.50 (ND), M=165 W/m2, W=0 W/m2



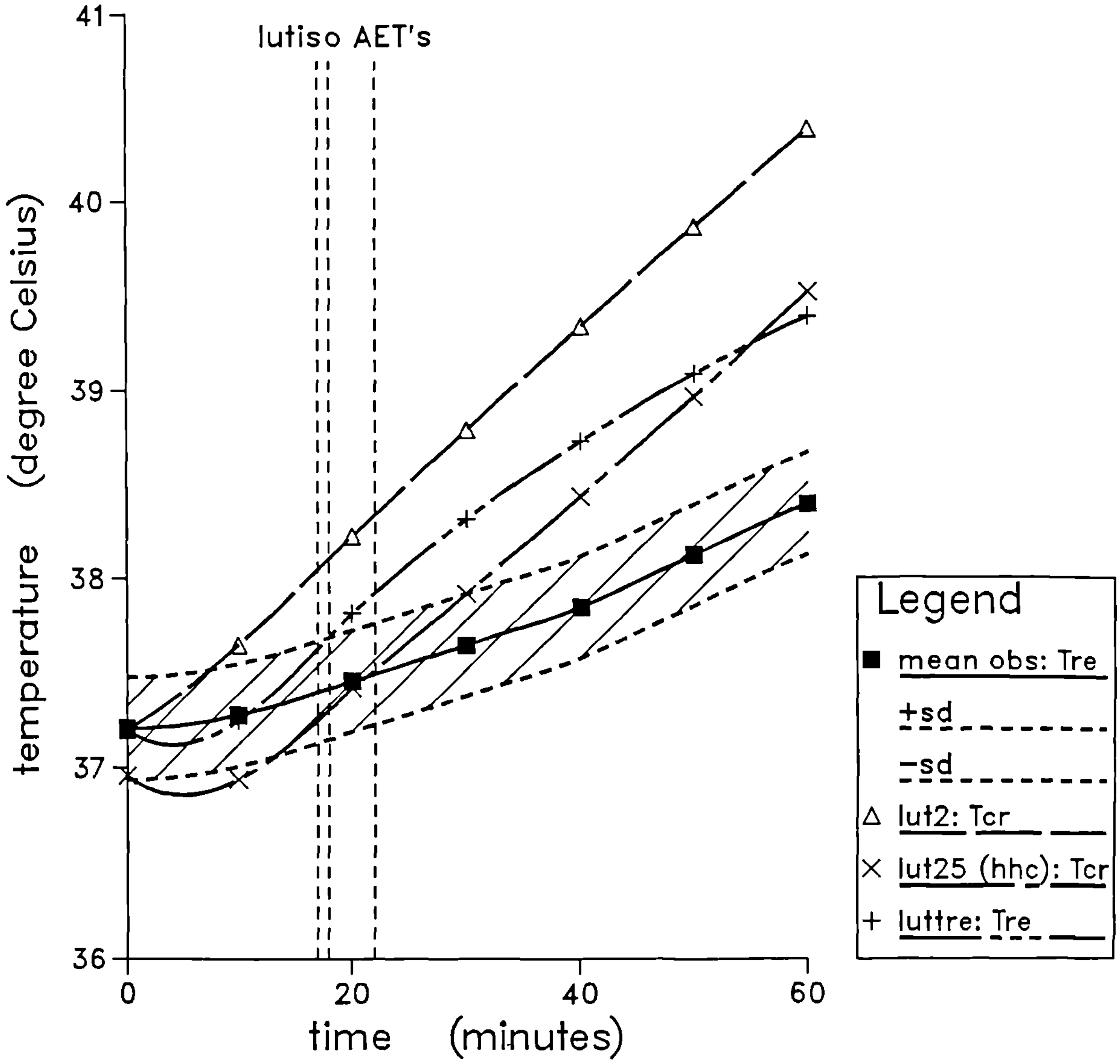
lutiso Allowable Exposure Times:
warning non-accl: 476 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

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



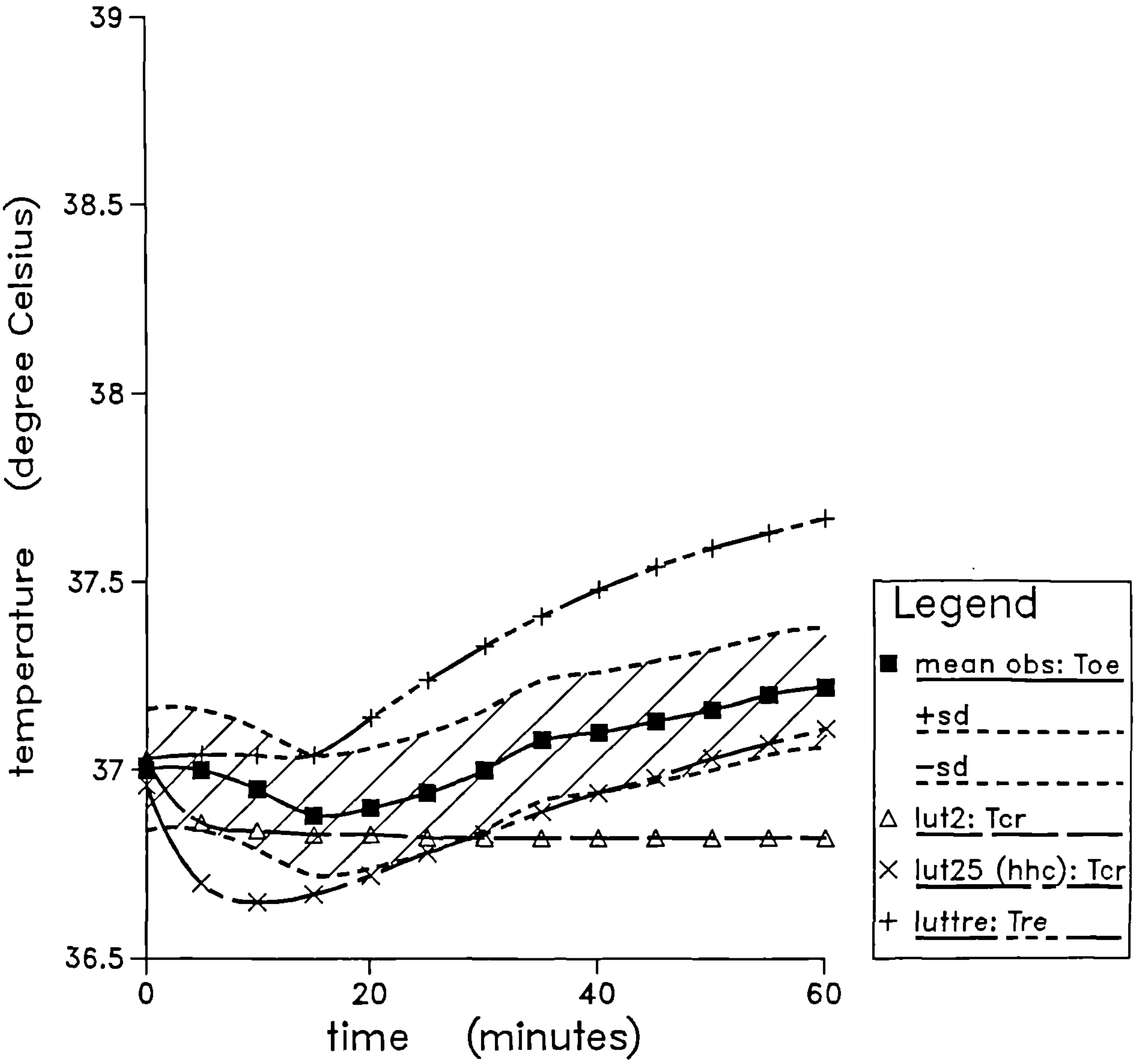
lutiso Allowable Exposure Times:
warning non-accl: 33 min; body temperature increase
danger non-accl : 40 min; body temperature increase
warning accl : 39 min; body temperature increase
danger accl : 47 min; body temperature increase

Tre from Henane et al (1979) (n=11) (exp. code: A2)
Ta=Tr=35 C, v=1 m/s, rh=54 %,
Icl=2.6 clo, fcl=1.40 (ND), im=0.30 (ND), M=209 W/m2, W=0 W/m2



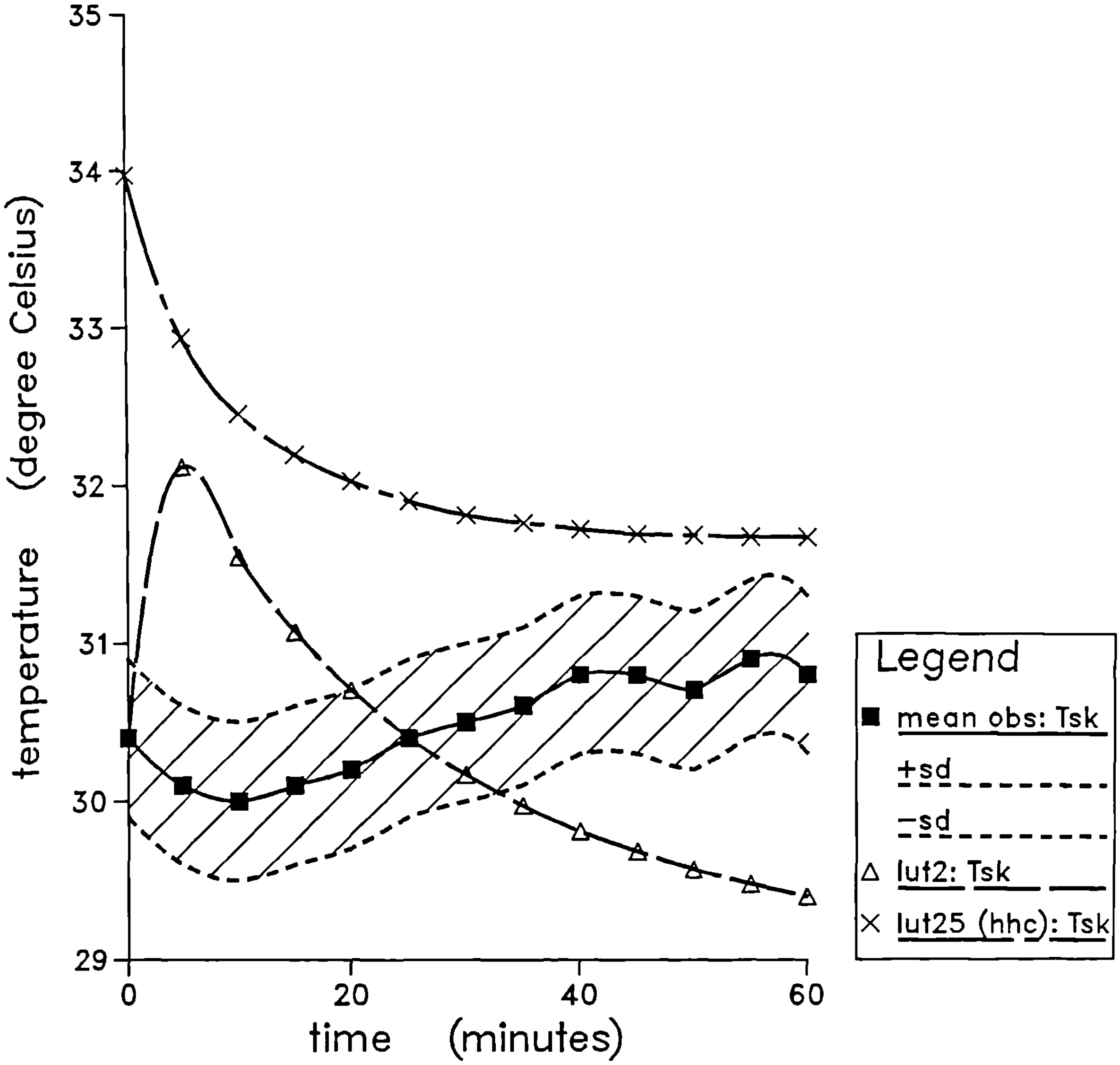
lutiso Allowable Exposure Times:
warning non-accl: 17 min; body temperature increase
danger non-accl : 22 min; body temperature increase
warning accl : 18 min; body temperature increase
danger accl : 22 min; body temperature increase

Toe from Hirata et al (1983) (n=4) (exp code: 20)
Ta=Tr=20 C, v=0.2 m/s, rh=60 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=126 W/m2, W=17 W/m2

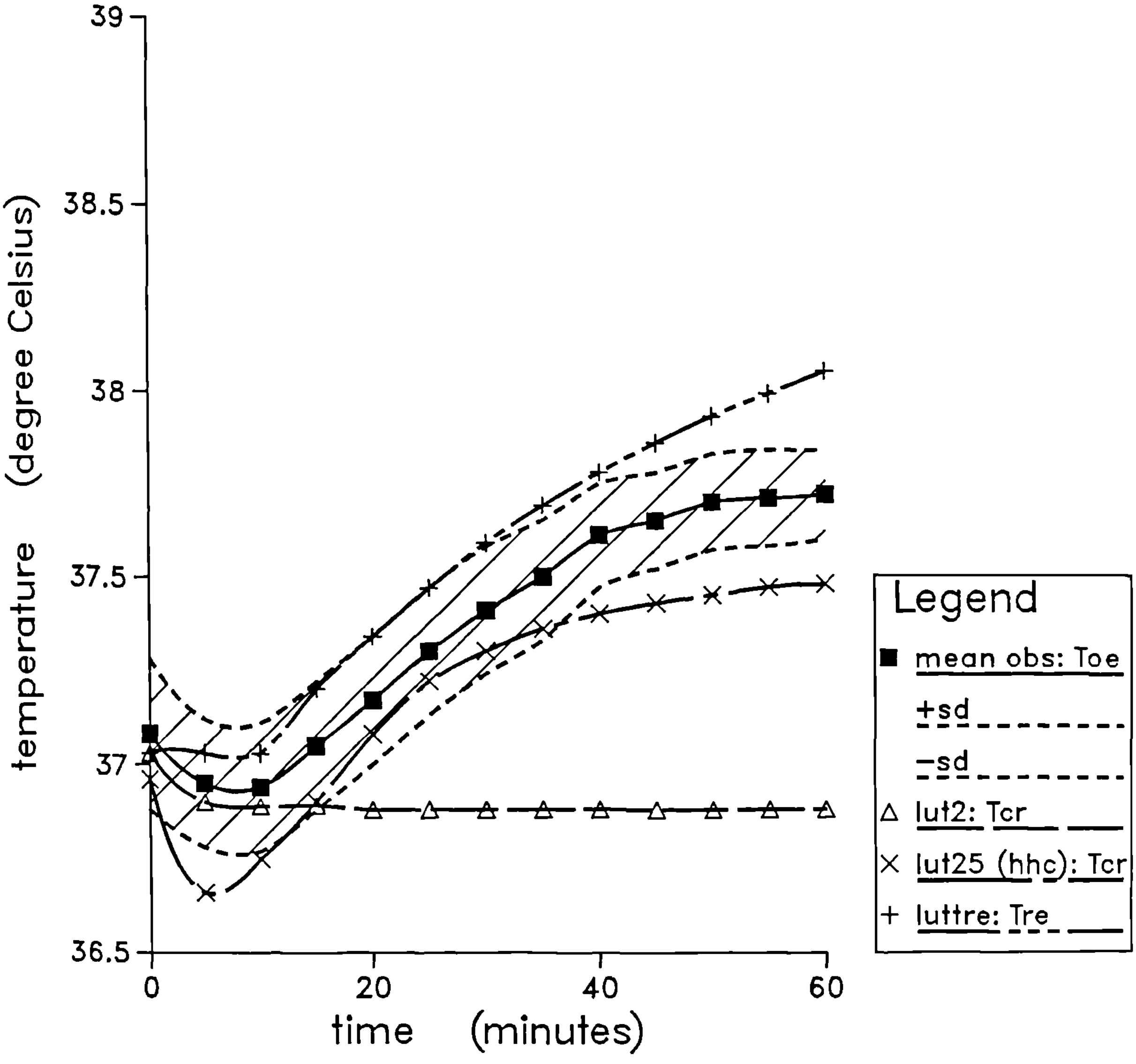


lutiso Allowable Exposure Times:
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tsk from Hirata et al (1983) (n=4) (exp code: 20)
Ta=Tr=20 C, v=0.2 m/s, rh=50 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=126 W/m2, W=17 W/m2

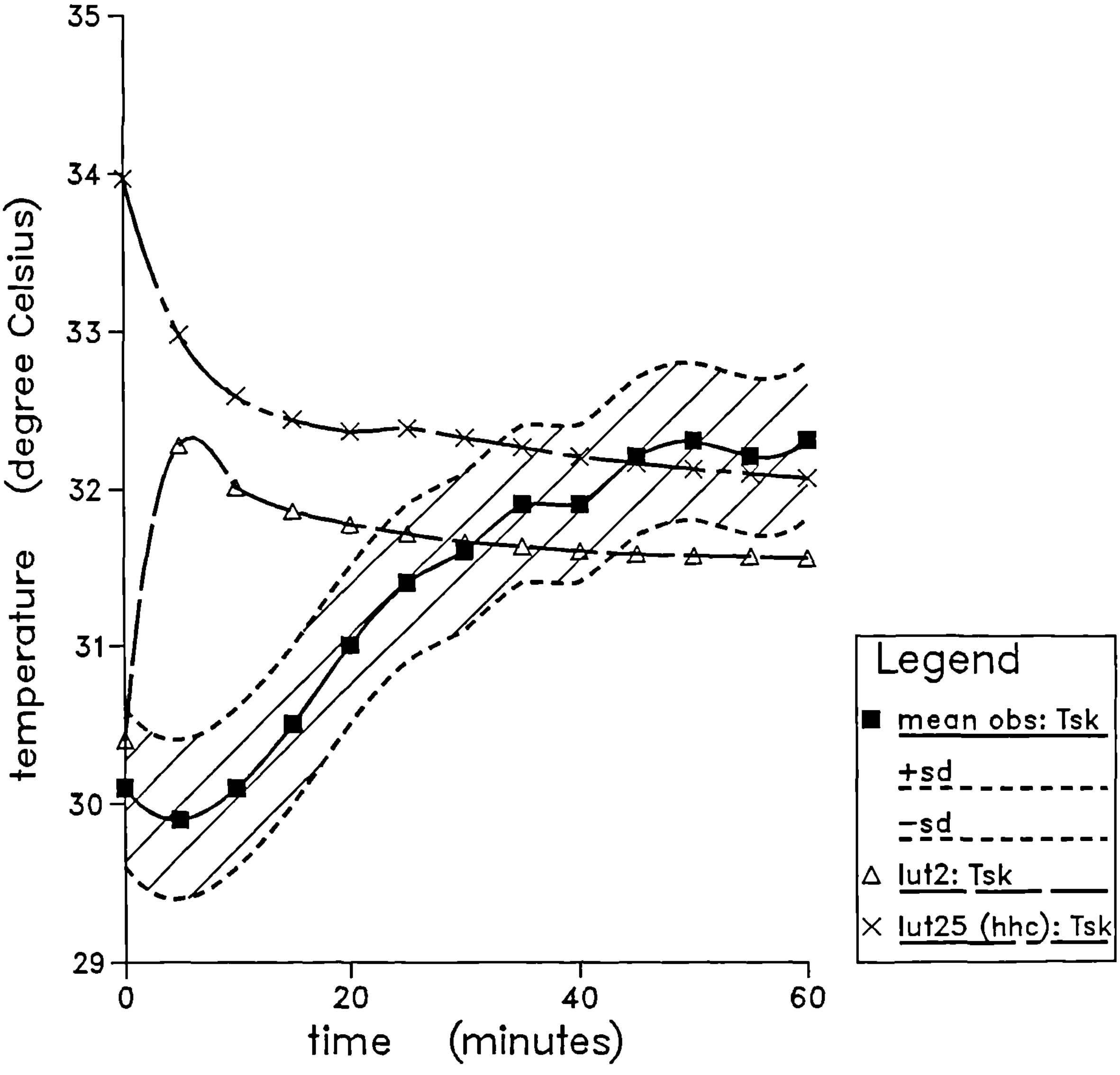


Toe from Hirata et al (1983) (n=4) (exp code: 35)
Ta=Tr=20 C, v=0.2 m/s, rh=50 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=194 W/m2, W=32 W/m2

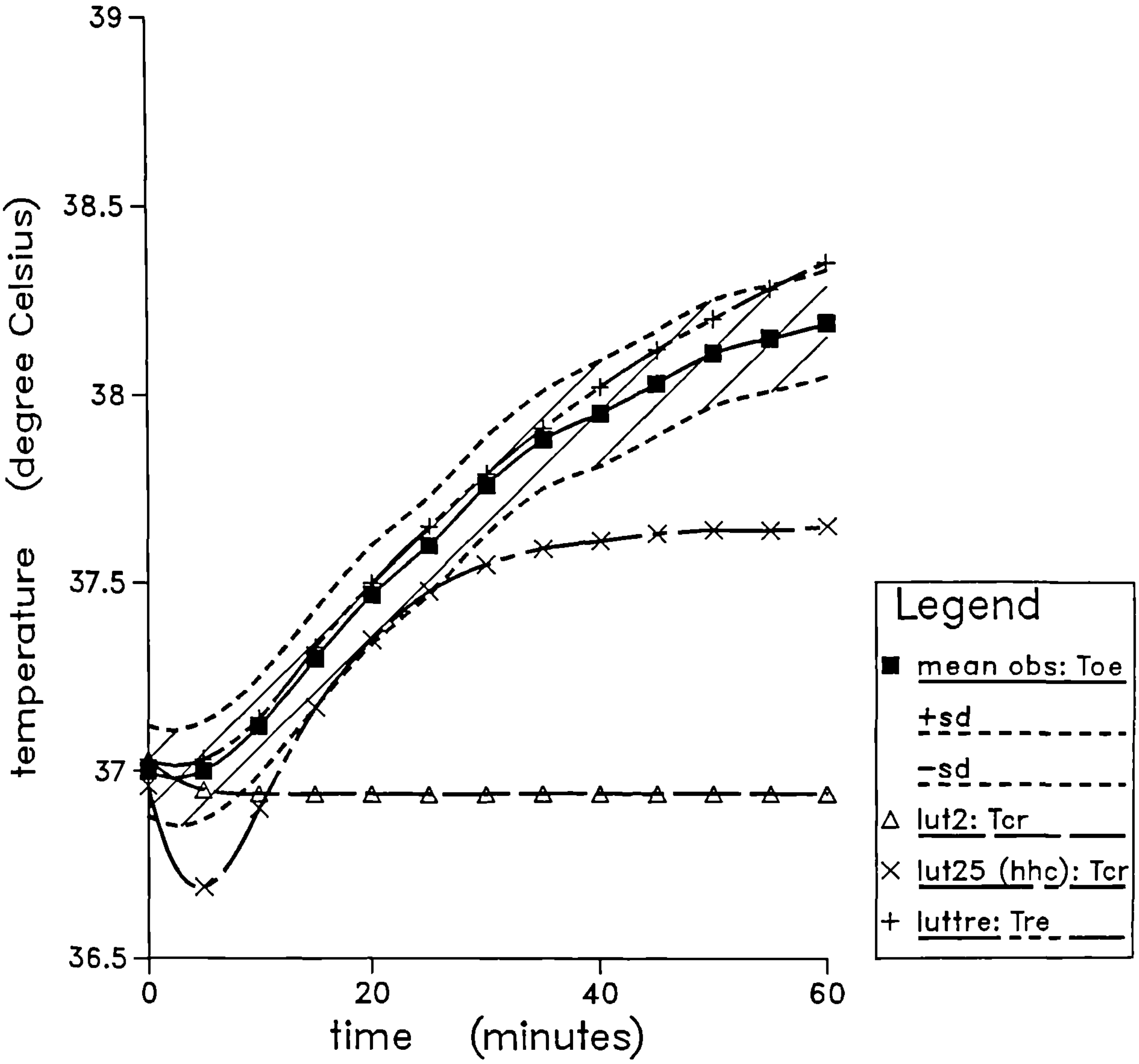


lutiso Allowable Exposure Times:
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tsk from Hirata et al (1983) (n=4) (exp code: 35)
Ta=Tr=20 C, v=0.2 m/s, rh=50 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=194 W/m2, W=32 W/m2

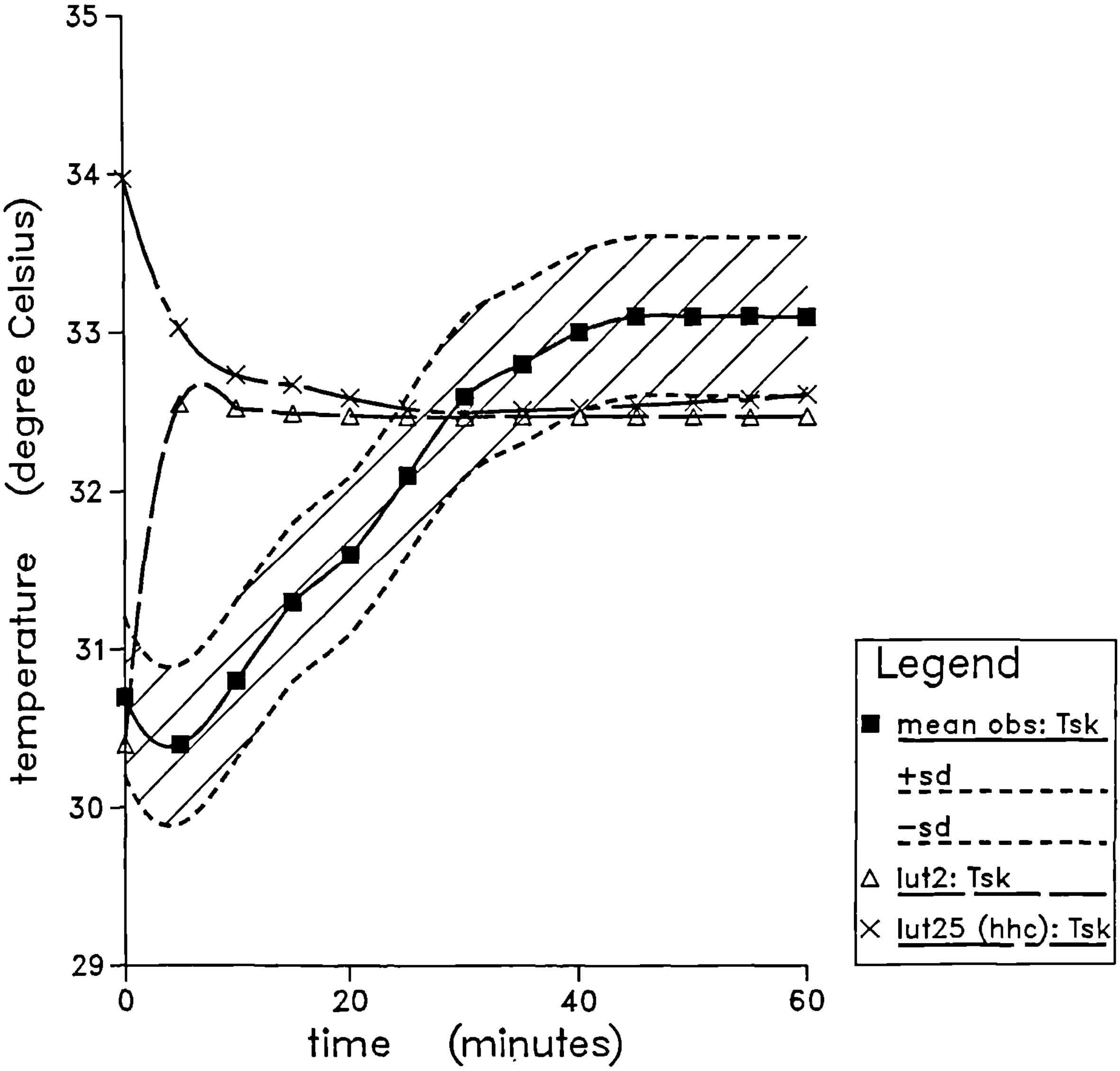


Toe from Hirata et al (1983) (n=4) (exp code: 45)
Ta=Tr=20 C, v=0.2 m/s, rh=50 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=258 W/m2, W=47 W/m2

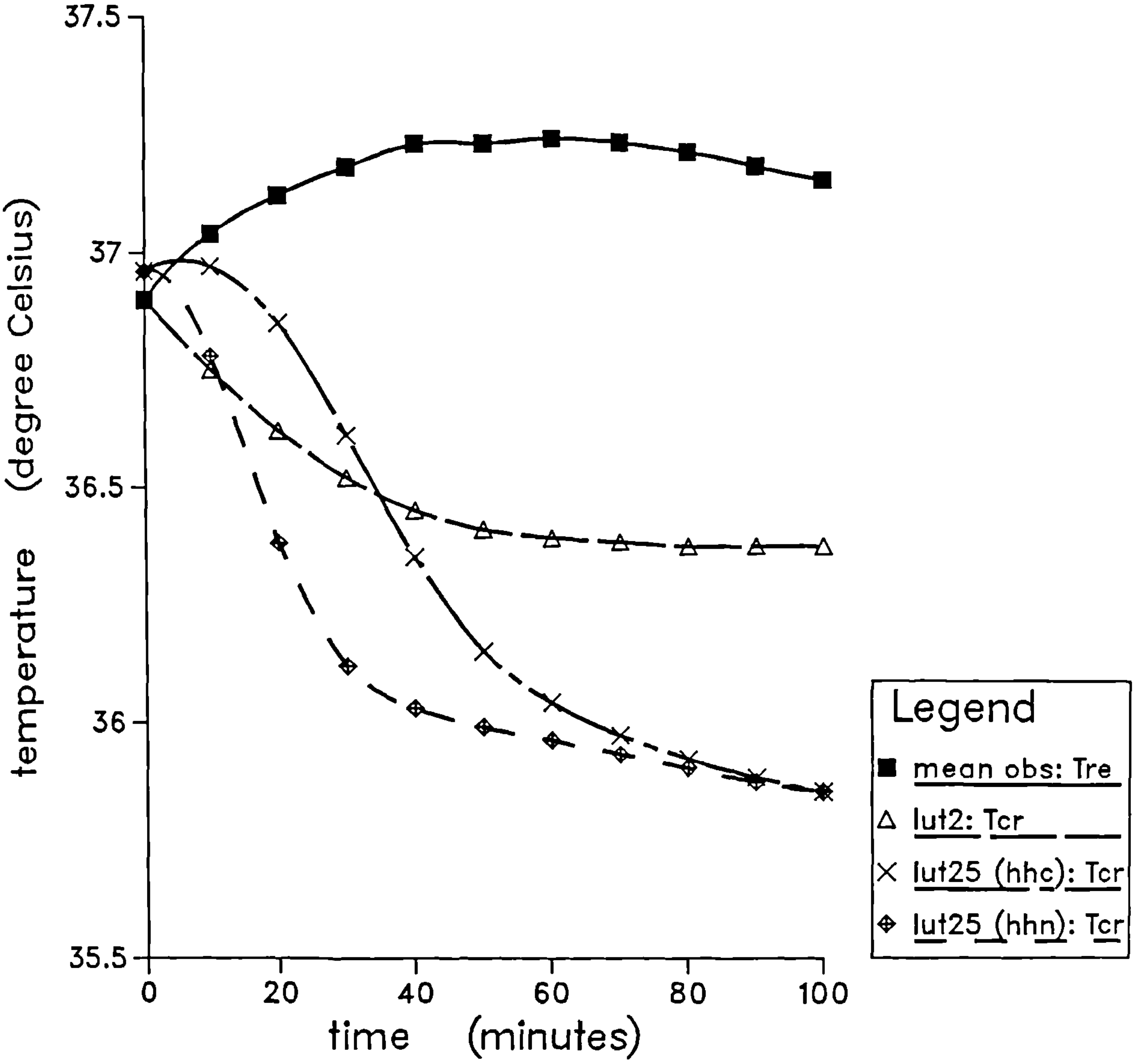


lutiso Allowable Exposure Times:
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

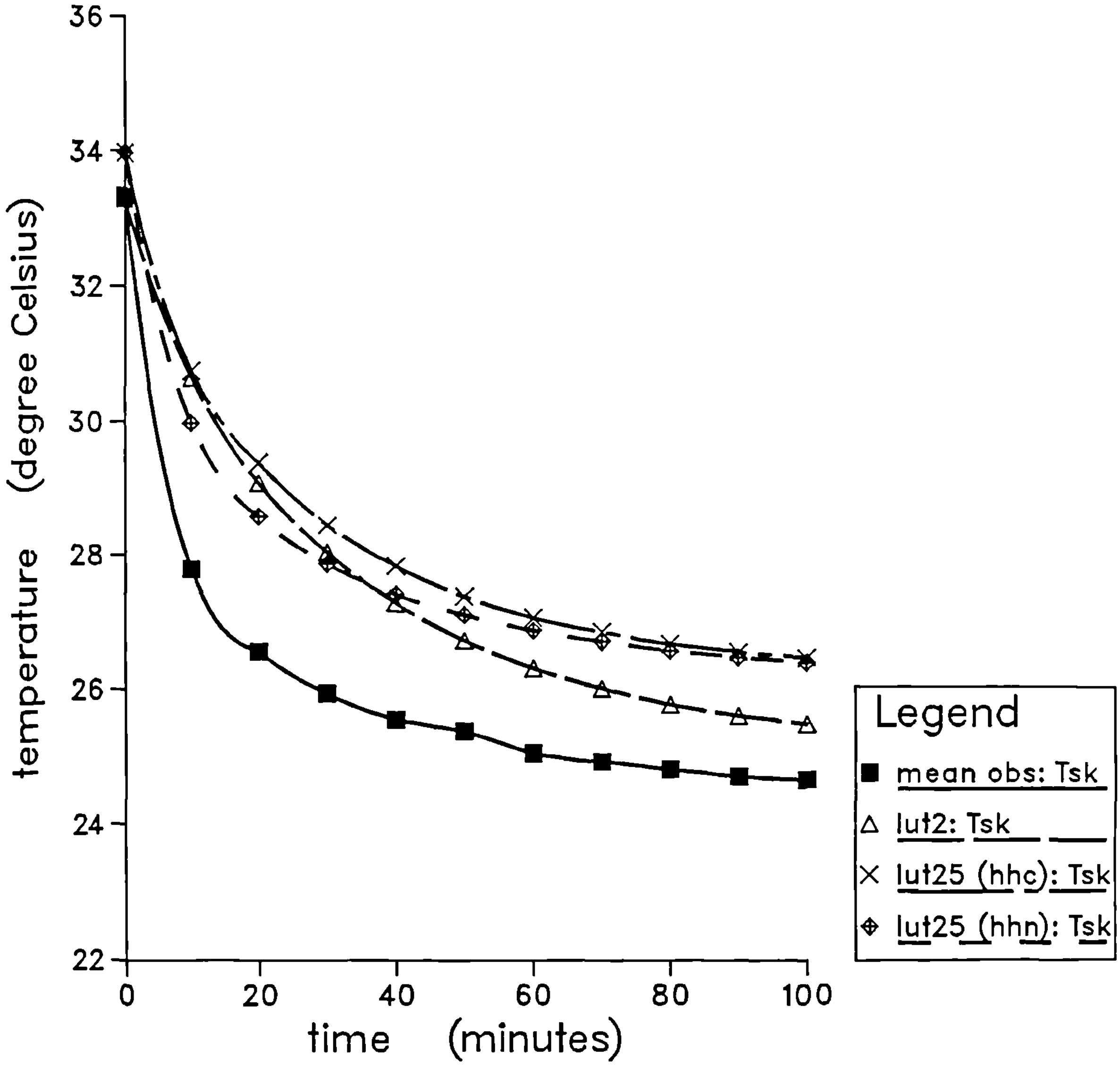
Tsk from Hirata et al (1983) (n=4) (exp code: 45)
Ta=Tr=20 C, v=0.2 m/s, rh=60 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=258 W/m2, W=47 W/m2



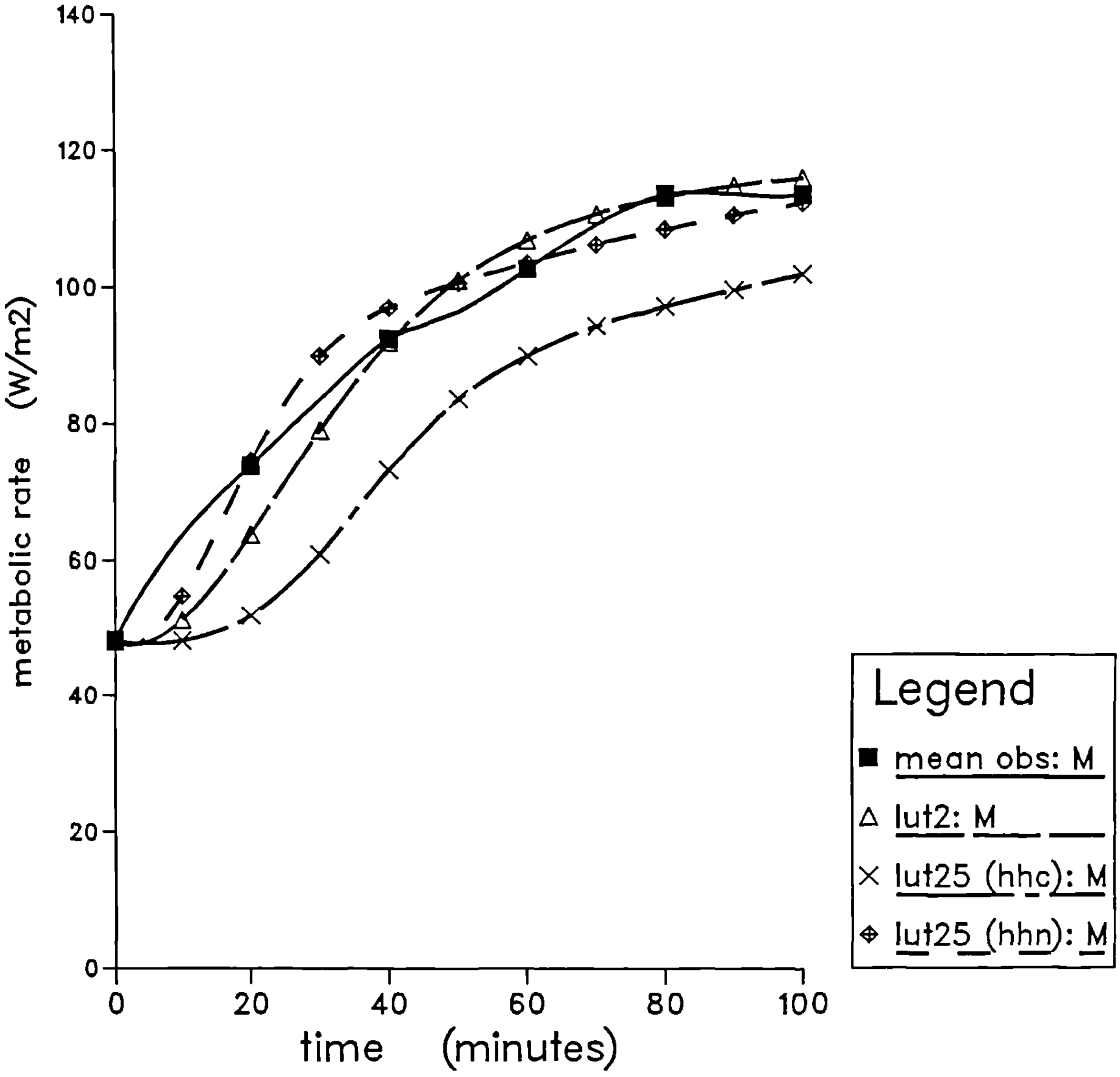
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e1)
Ta=Tr=10.0 C, v=4.5 m/s, rh=32 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



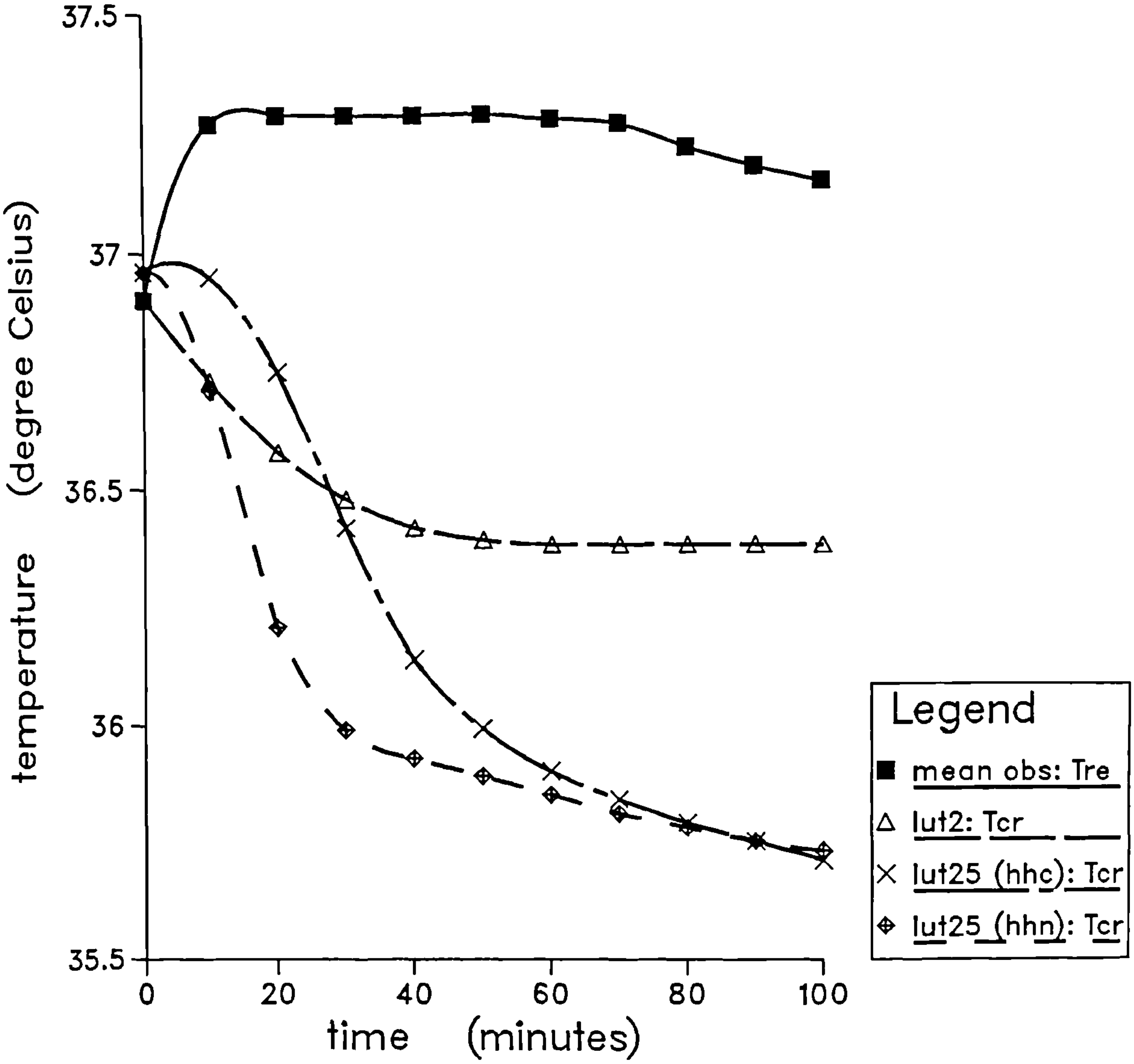
Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e1)
Ta=Tr=10.0 C, v=4.5 m/s, rh=32 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



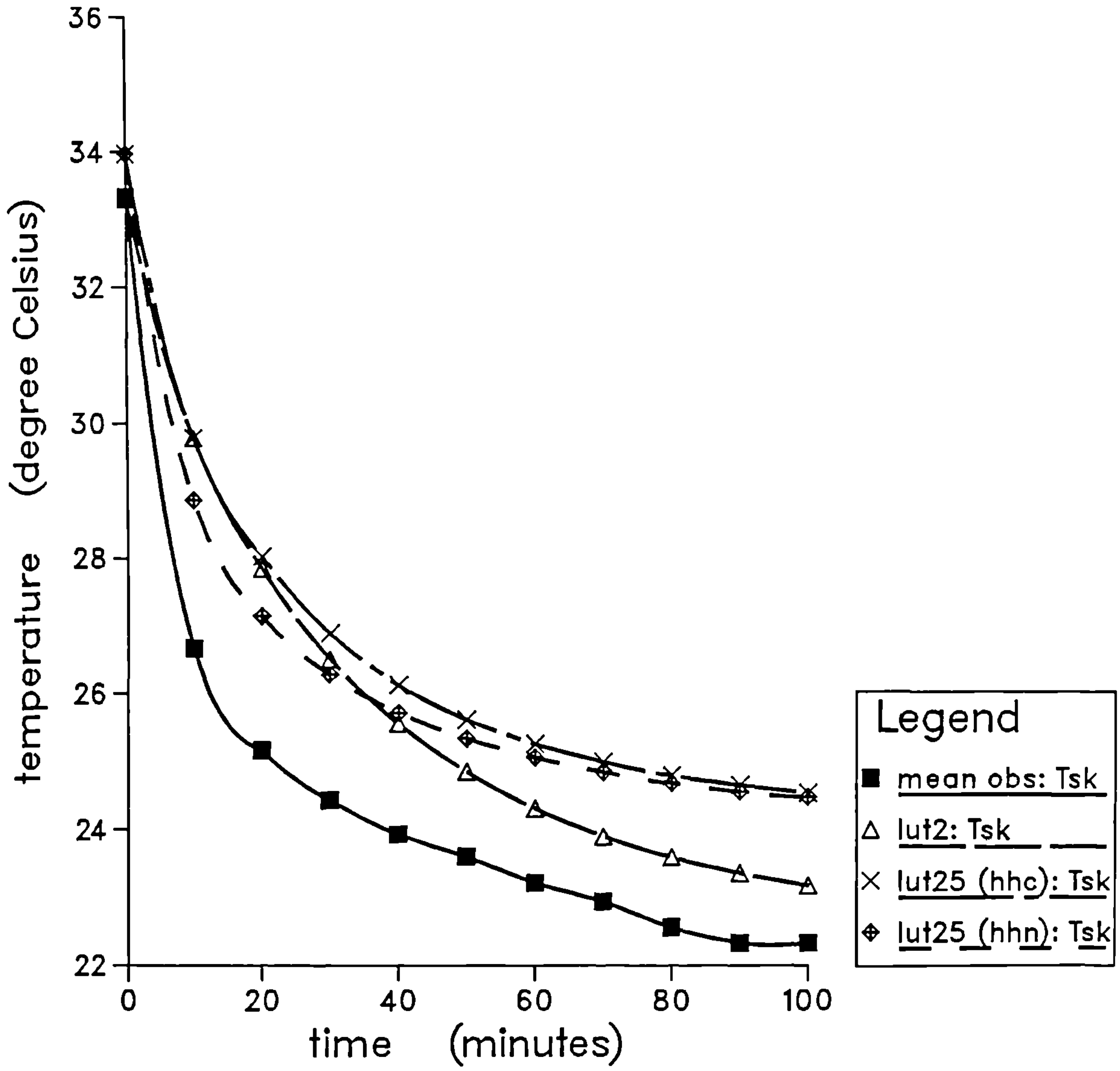
M from Iampietro and Buskirk (1960) (n=6) (exp. code: e1)
Ta=Tr=10.0 C, v=4.5 m/s, rh=32 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



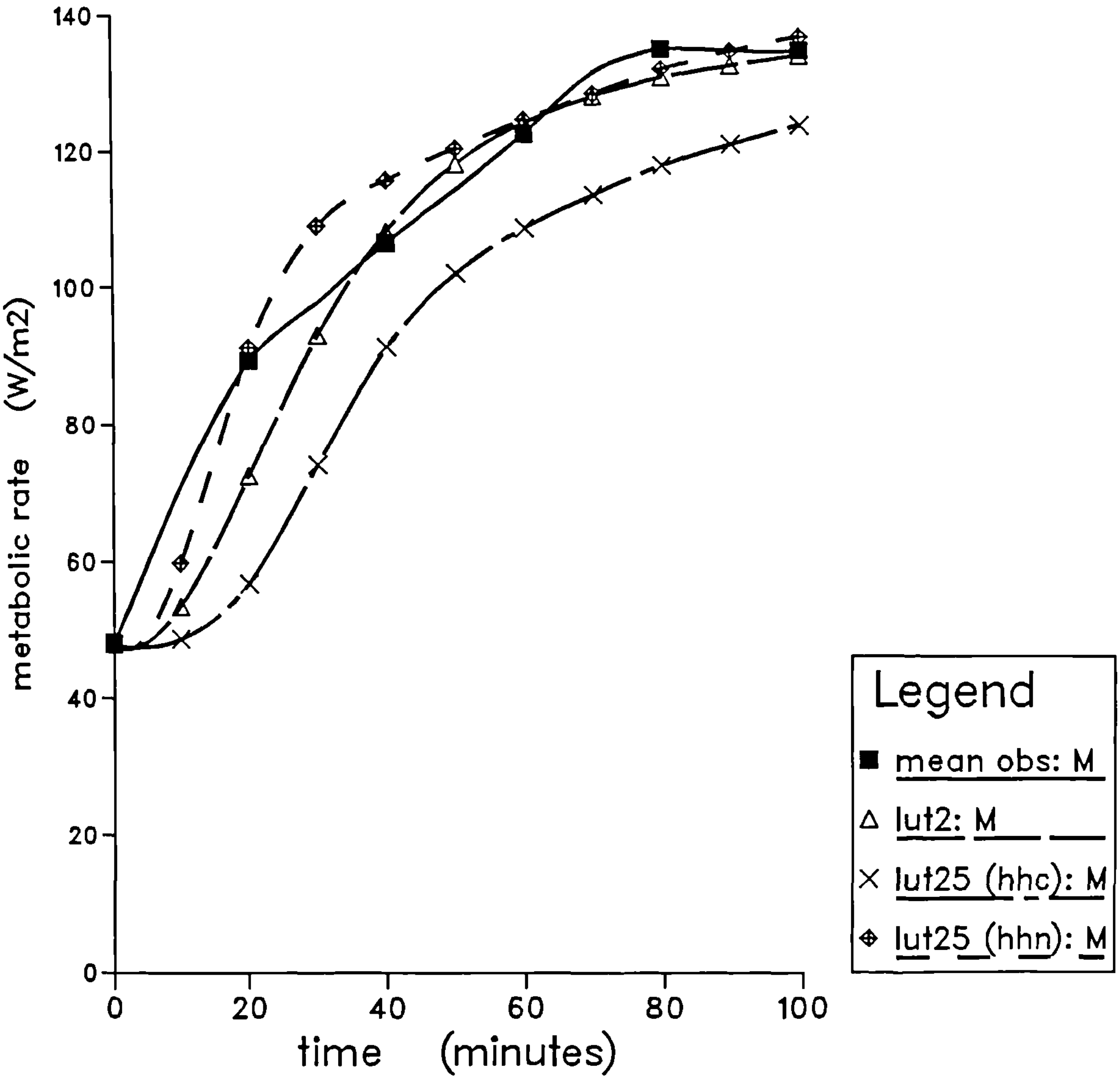
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e2)
Ta=Tr=4.4 C, v=4.5 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

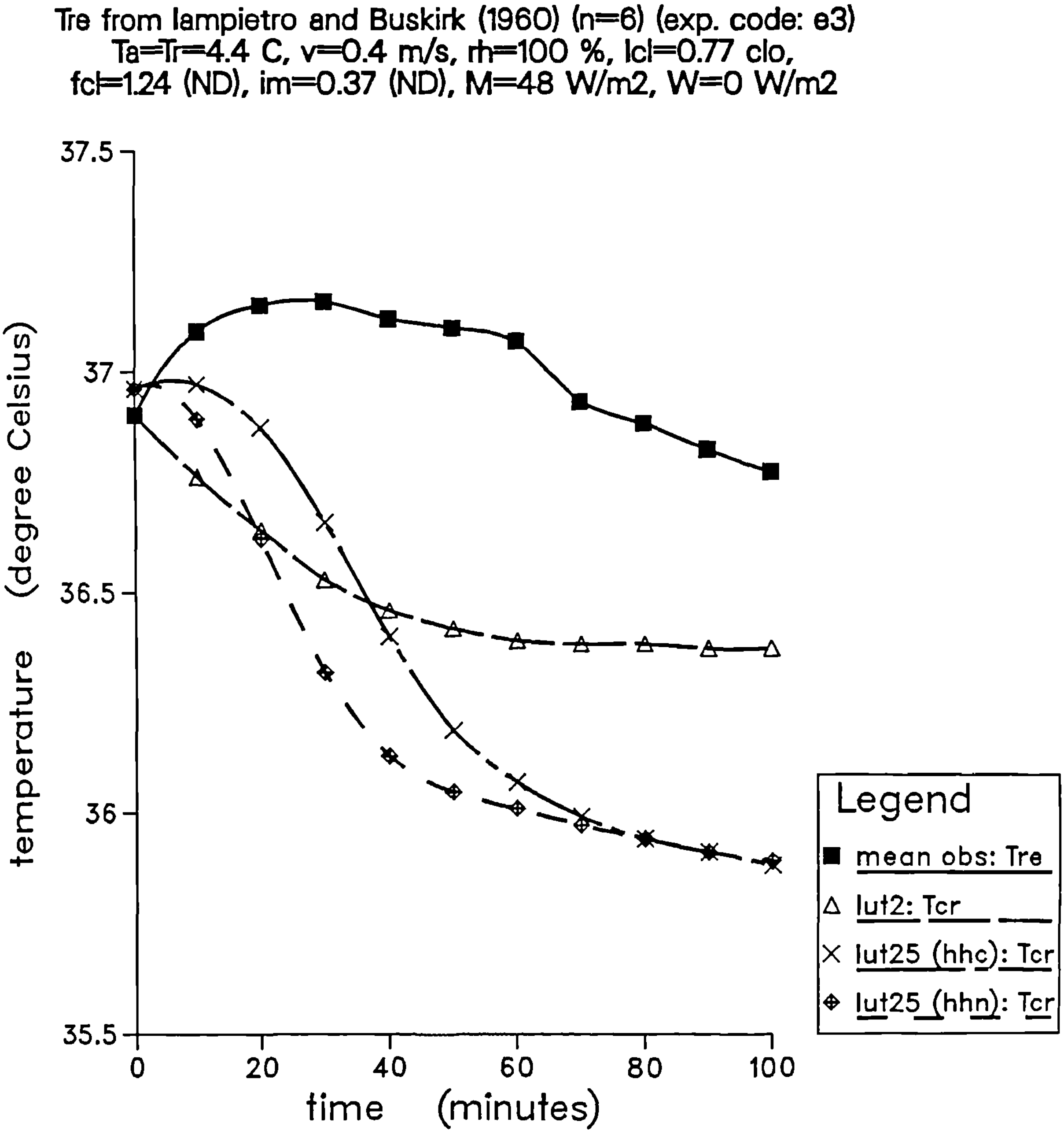


Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e2)
Ta=Tr=4.4 C, v=4.5 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

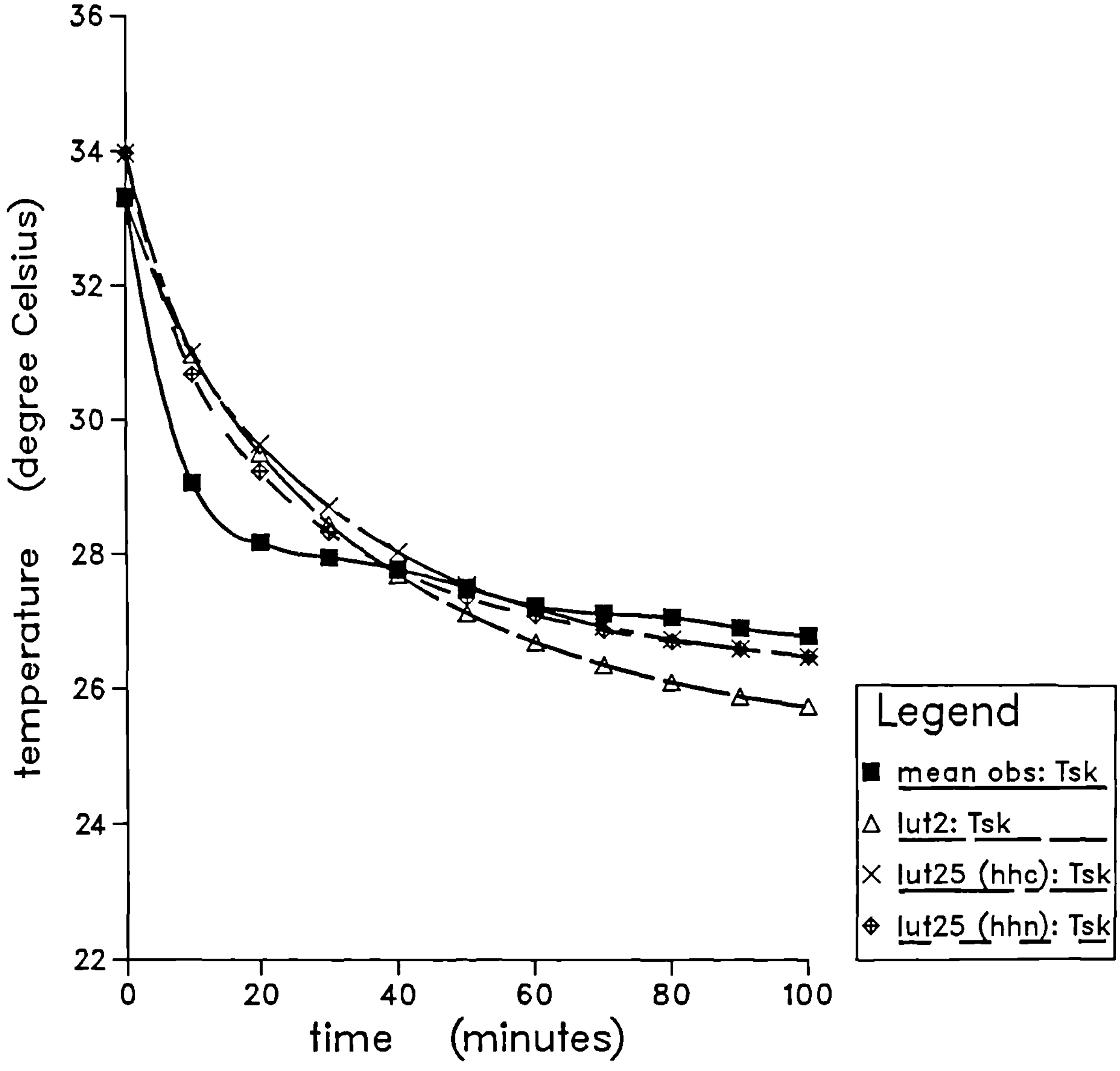


M from Iampietro and Buskirk (1960) (n=6) (exp. code: e2)
Ta=Tr=4.4 C, v=4.5 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

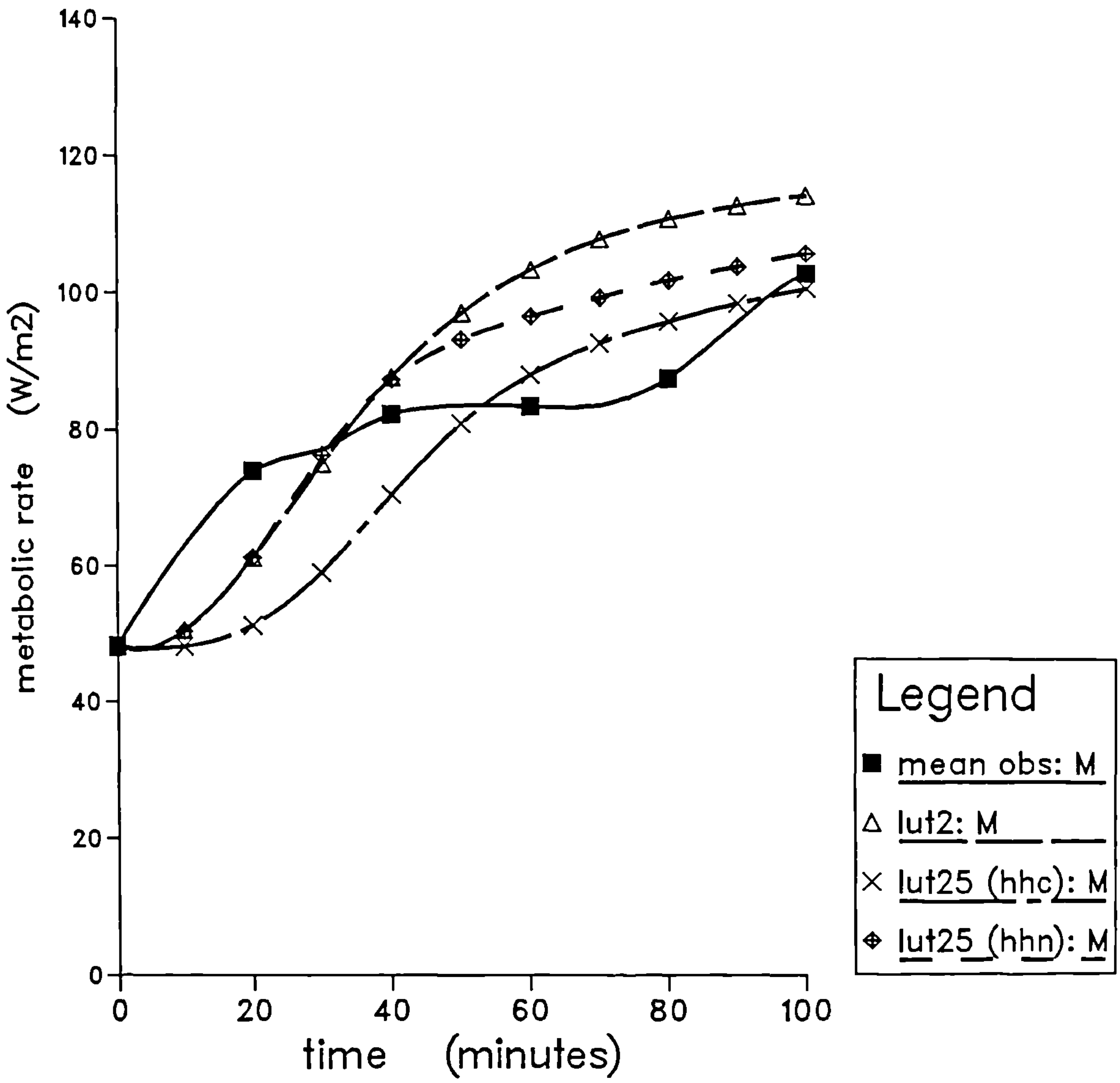



Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e3)
Ta=Tr=4.4 C, v=0.4 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
37.5
37
36.5
36
35.5
temperature (degree Celsius)
0
20
40
60
80
100
time (minutes)
Legend
mean obs: Tre
lut2: Tcr
lut25 (hhc): Tcr
lut25 (hhn): Tcr

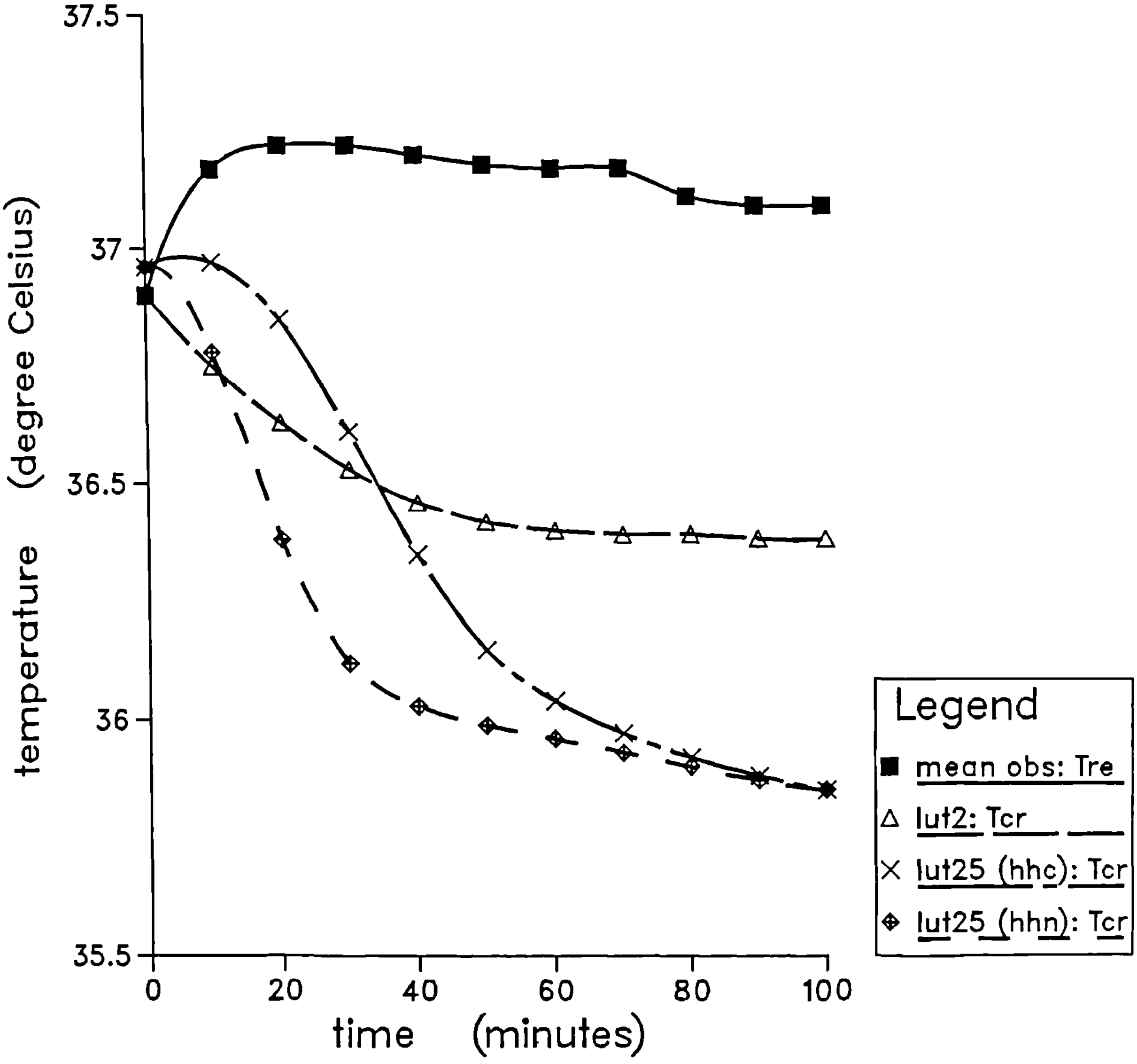
Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e3)
Ta=Tr=4.4 C, v=0.4 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



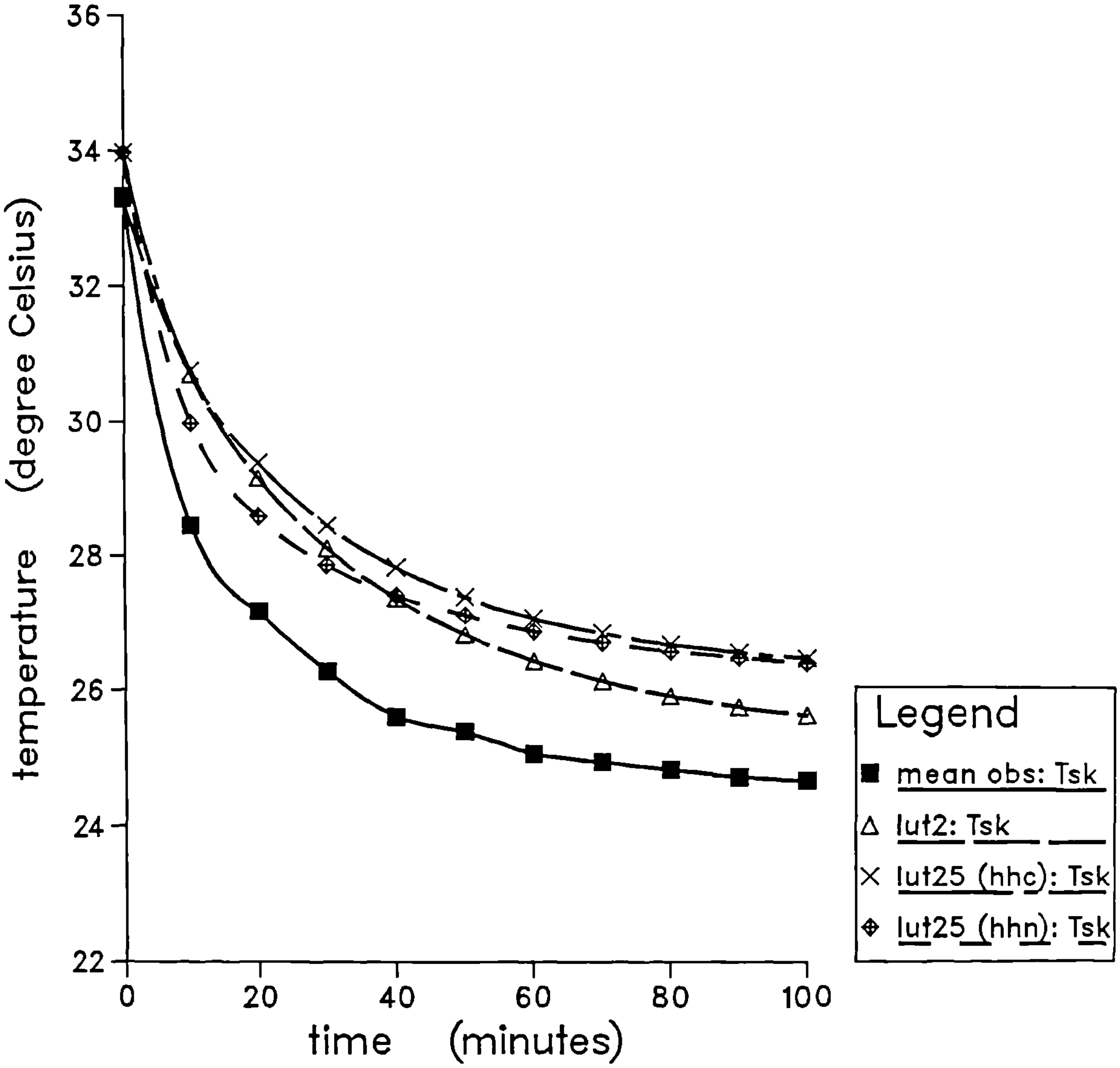
M from Iampietro and Buskirk (1960) (n=6) (exp. code: e3)
Ta=Tr=4.4 C, v=0.4 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



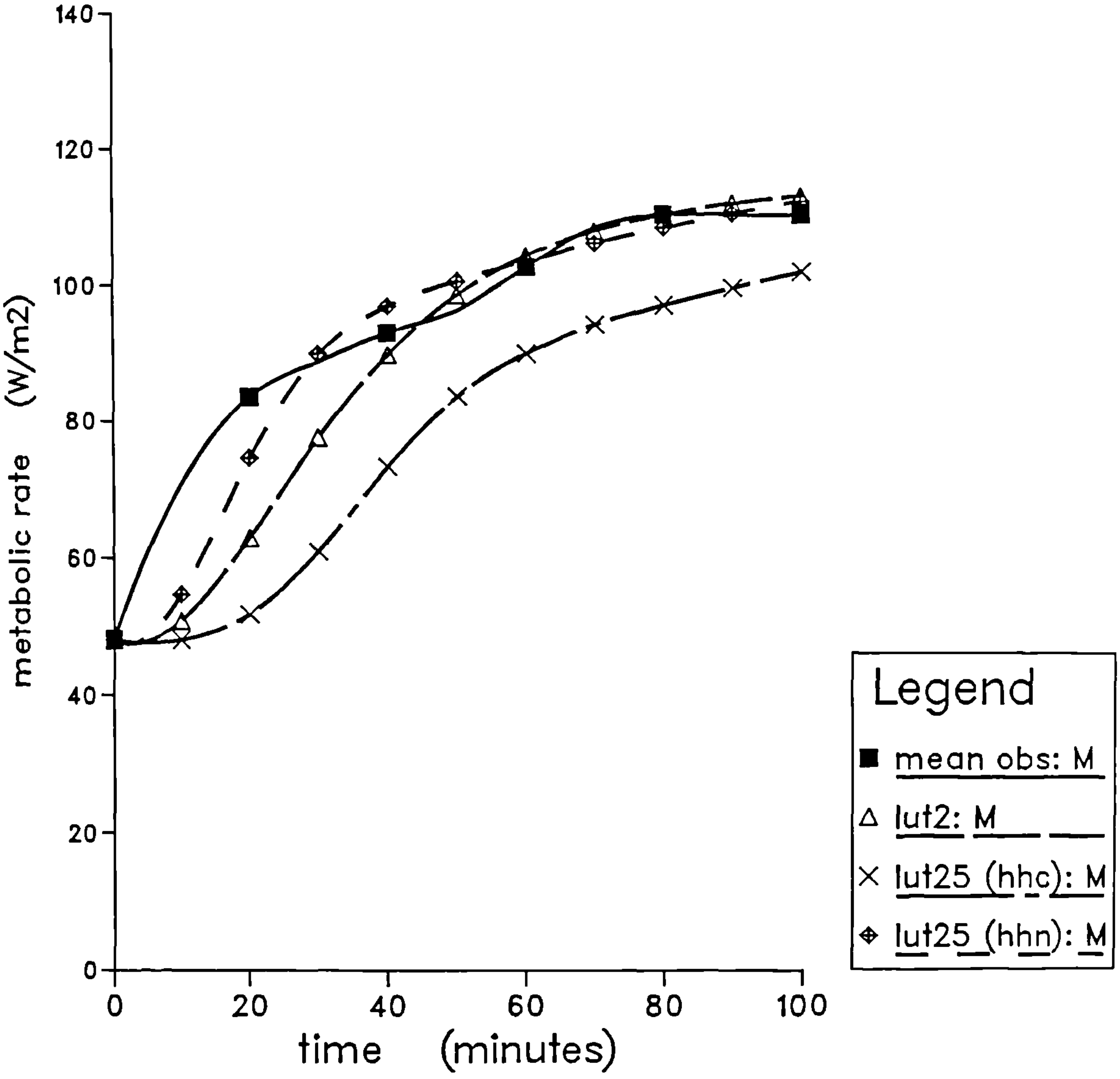
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e4)
Ta=Tr=10.0 C, v=4.5 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



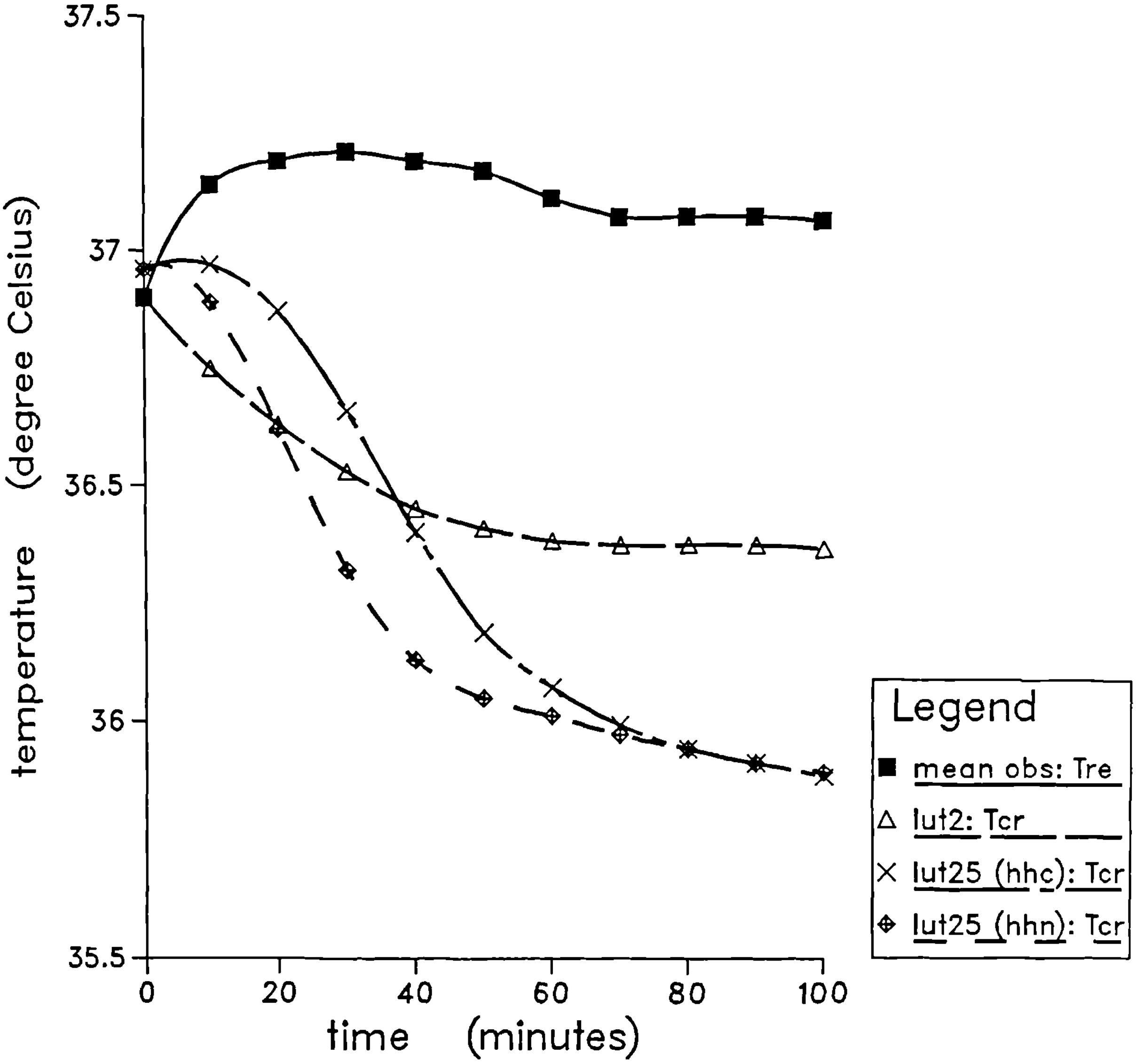
Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e4)
Ta=Tr=10.0 C, v=4.5 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



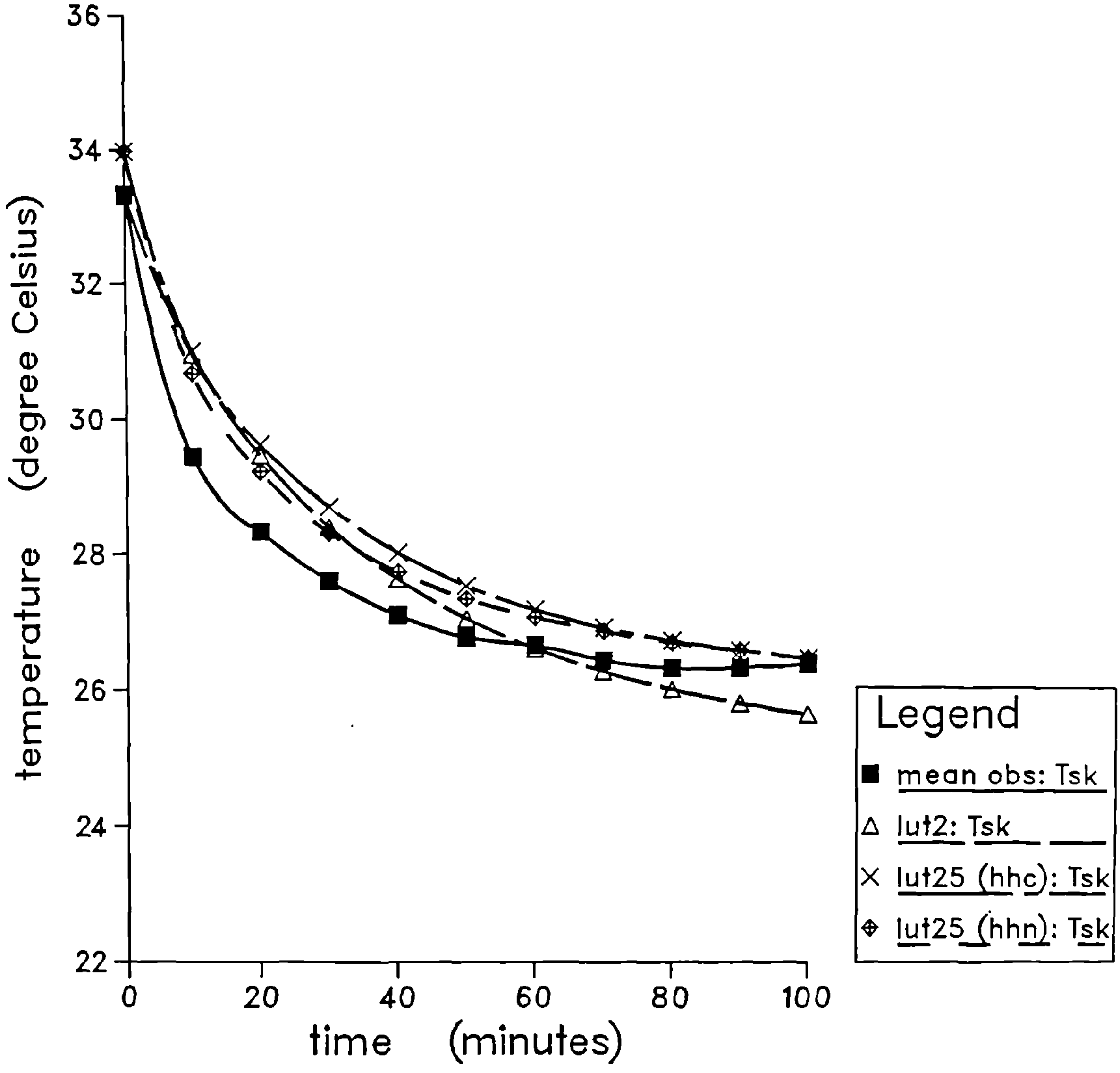
M from Iampietro and Buskirk (1960) (n=6) (exp. code: e4)
Ta=Tr=10.0 C, v=4.5 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



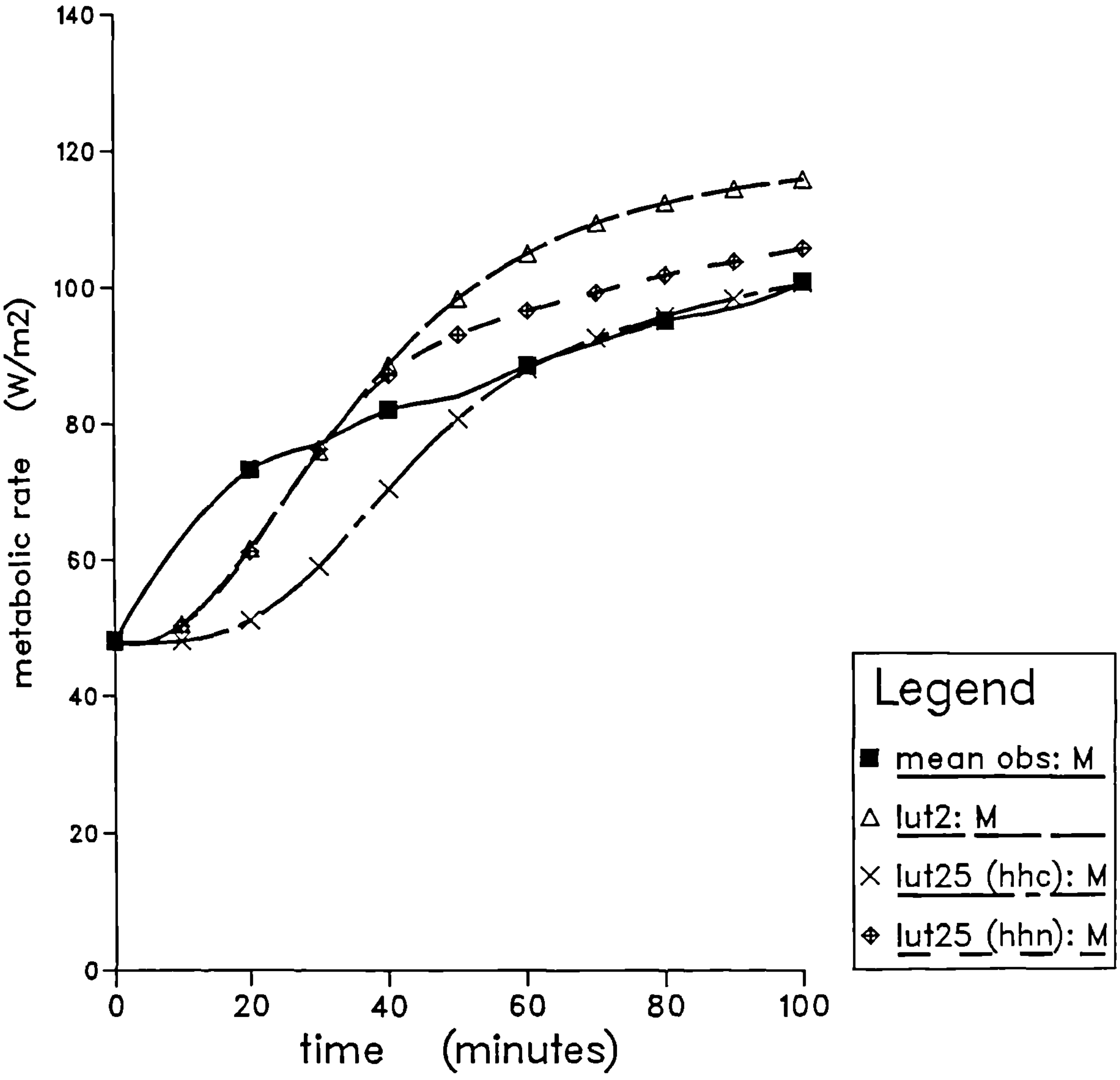
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e5)
Ta=Tr=4.4 C, v=0.4 m/s, rh=37 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



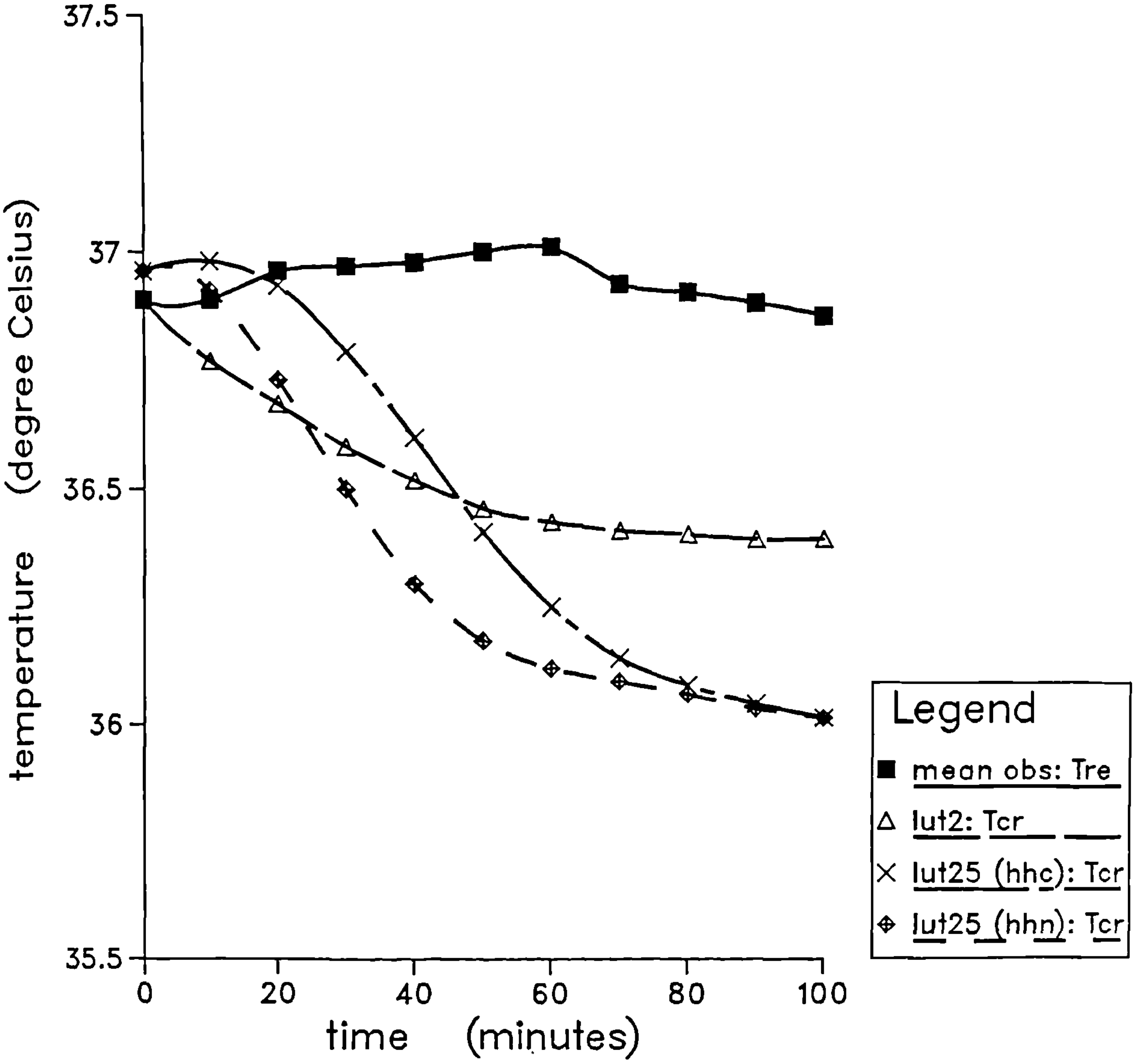
Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e5)
Ta=Tr=4.4 C, v=0.4 m/s, rh=37 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



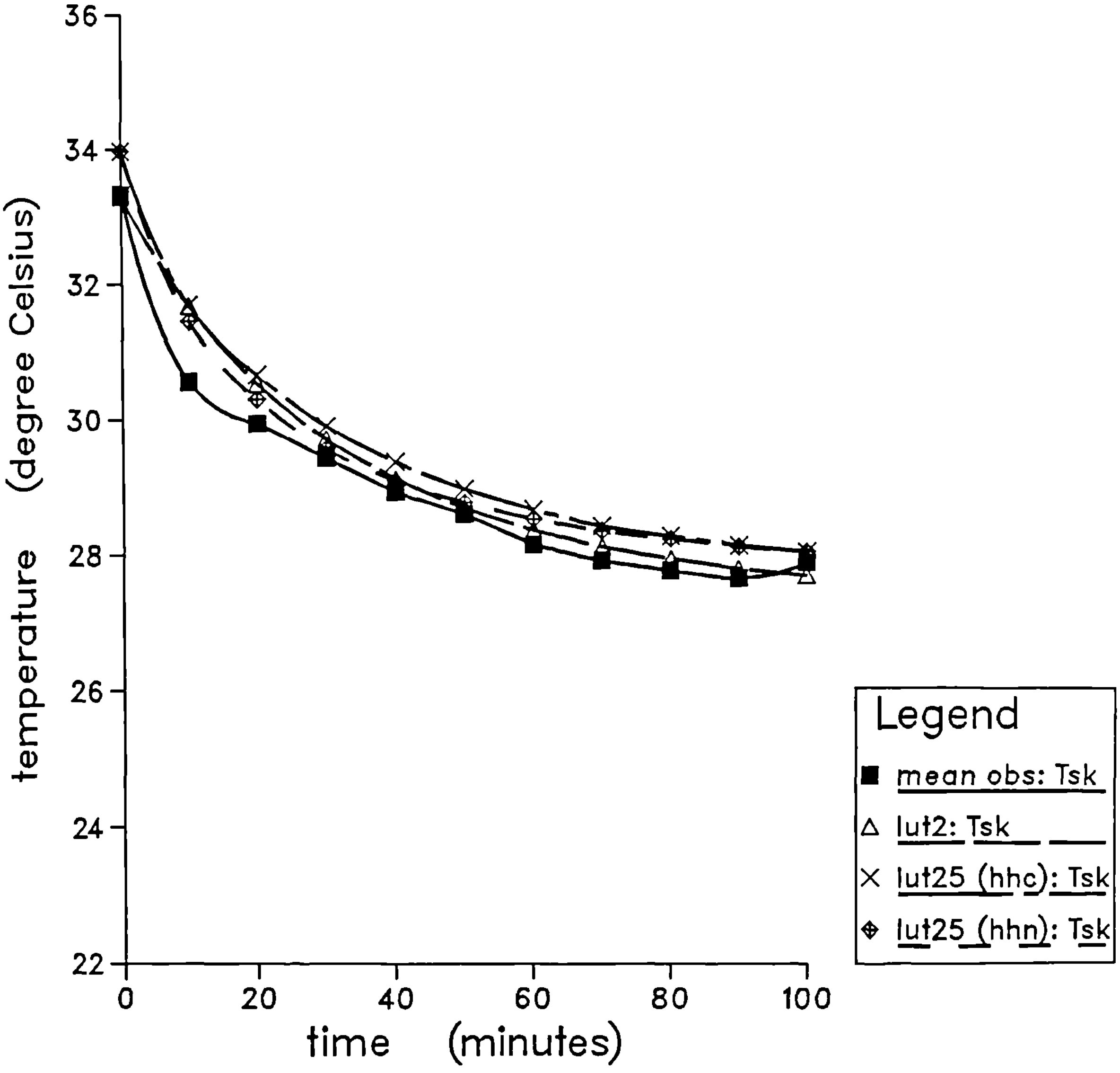
M from Iampietro and Buskirk (1960) (n=6) (exp. code: e5)
Ta=Tr=4.4 C, v=0.4 m/s, rh=37 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



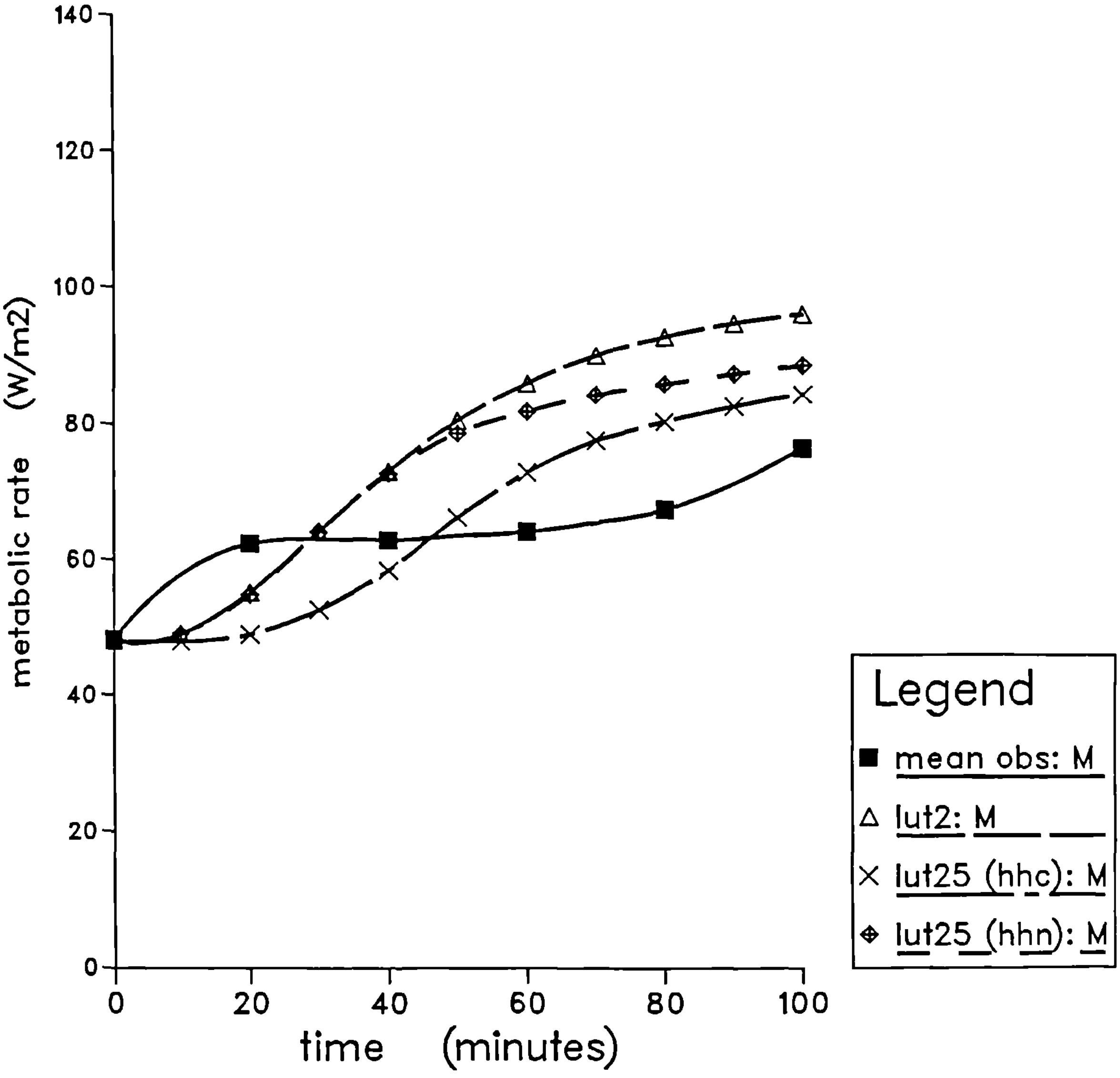
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e6)
Ta=Tr=10.0 C, v=0.4 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



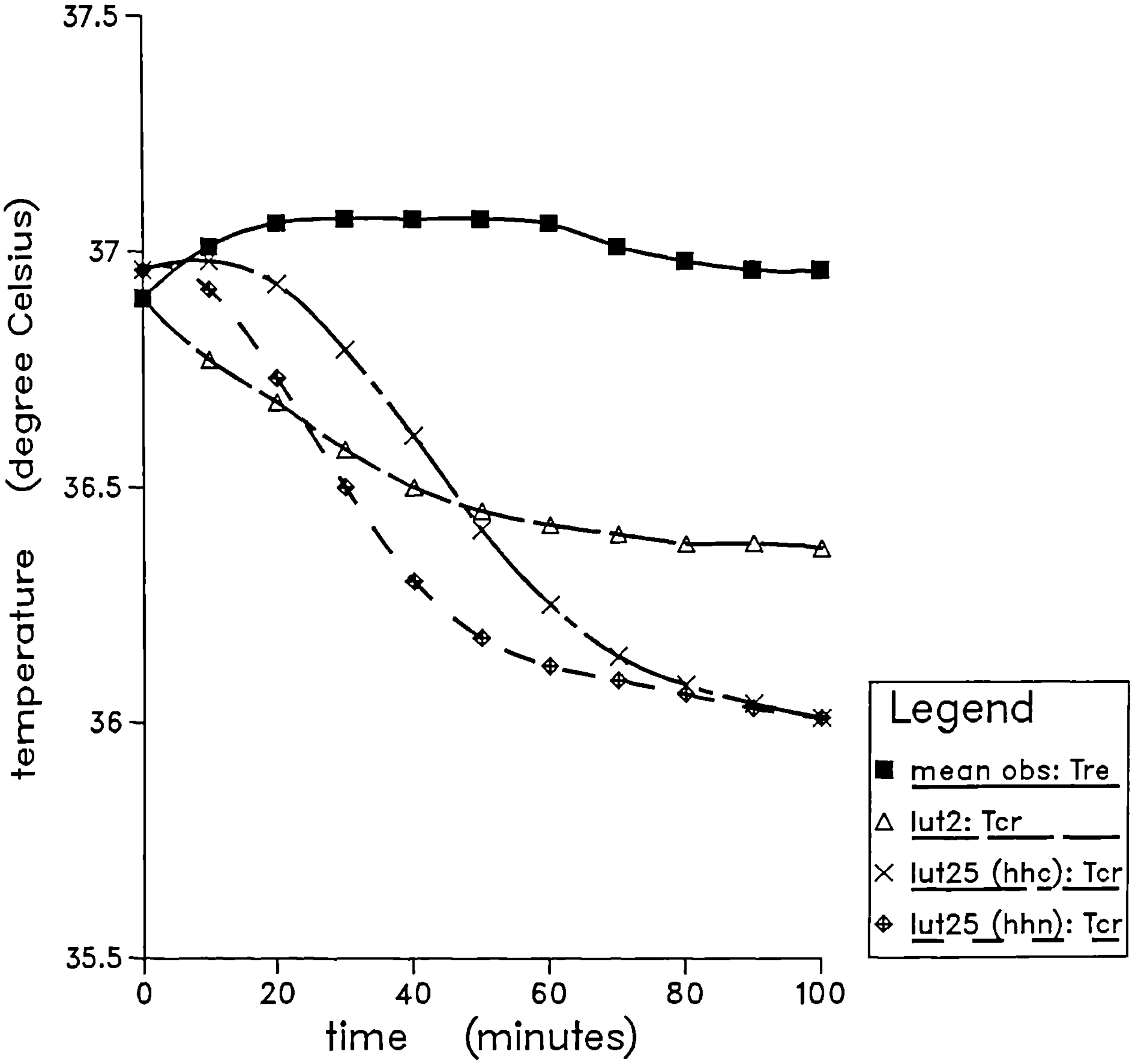
Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e6)
Ta=Tr=10.0 C, v=0.4 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

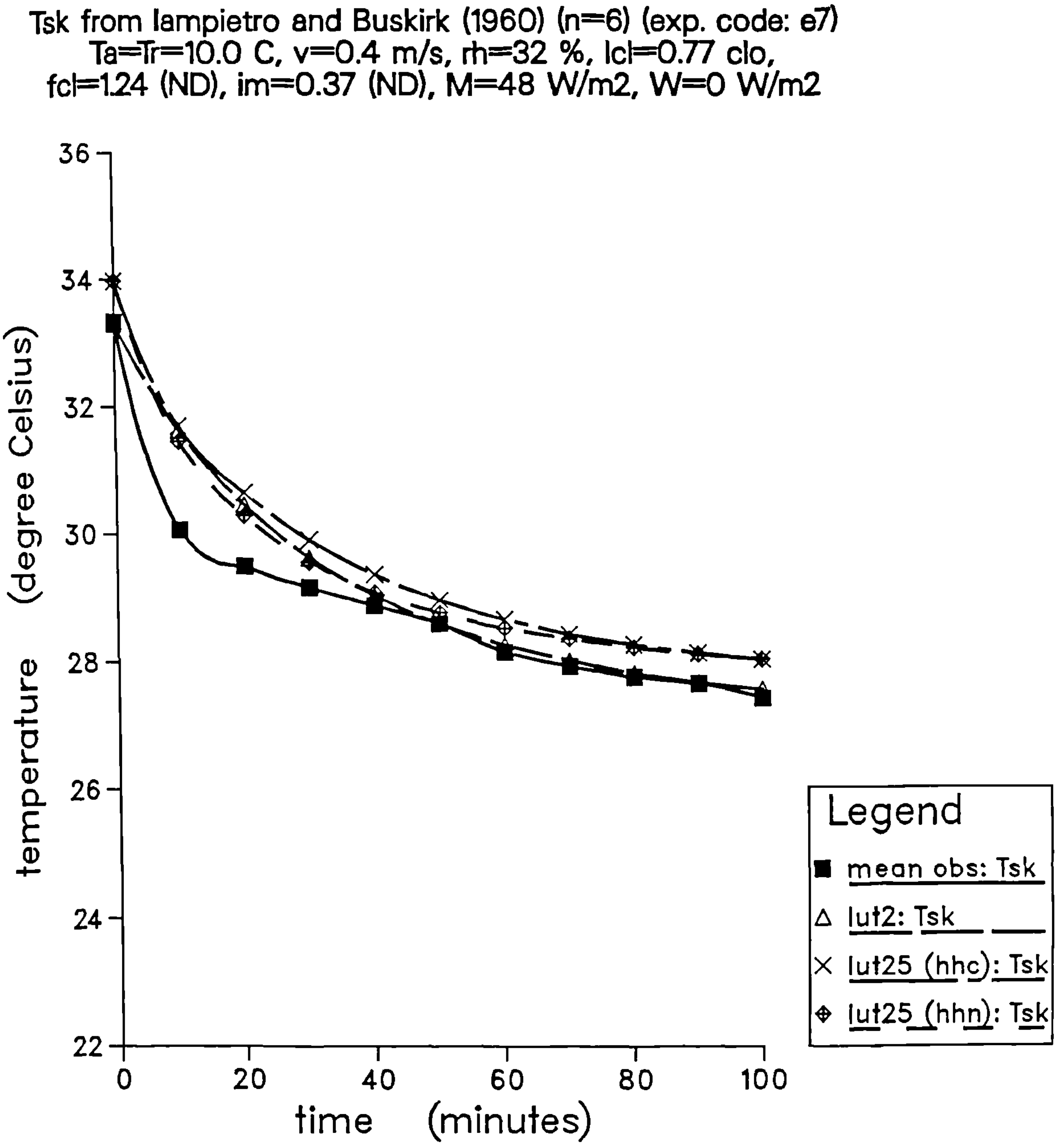


M from Iampietro and Buskirk (1960) (n=6) (exp. code: e6)
Ta=Tr=10.0 C, v=0.4 m/s, rh=100 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

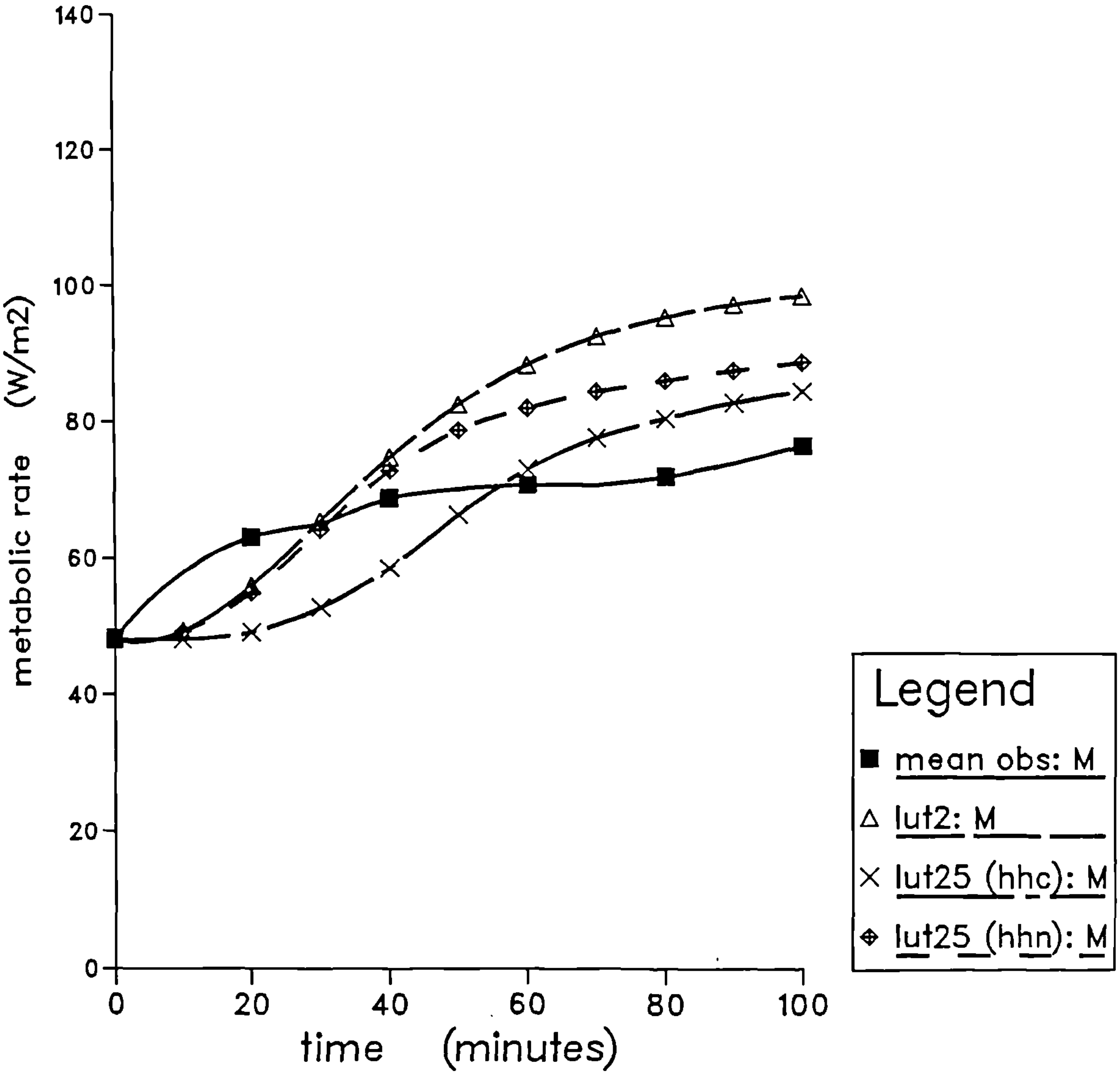


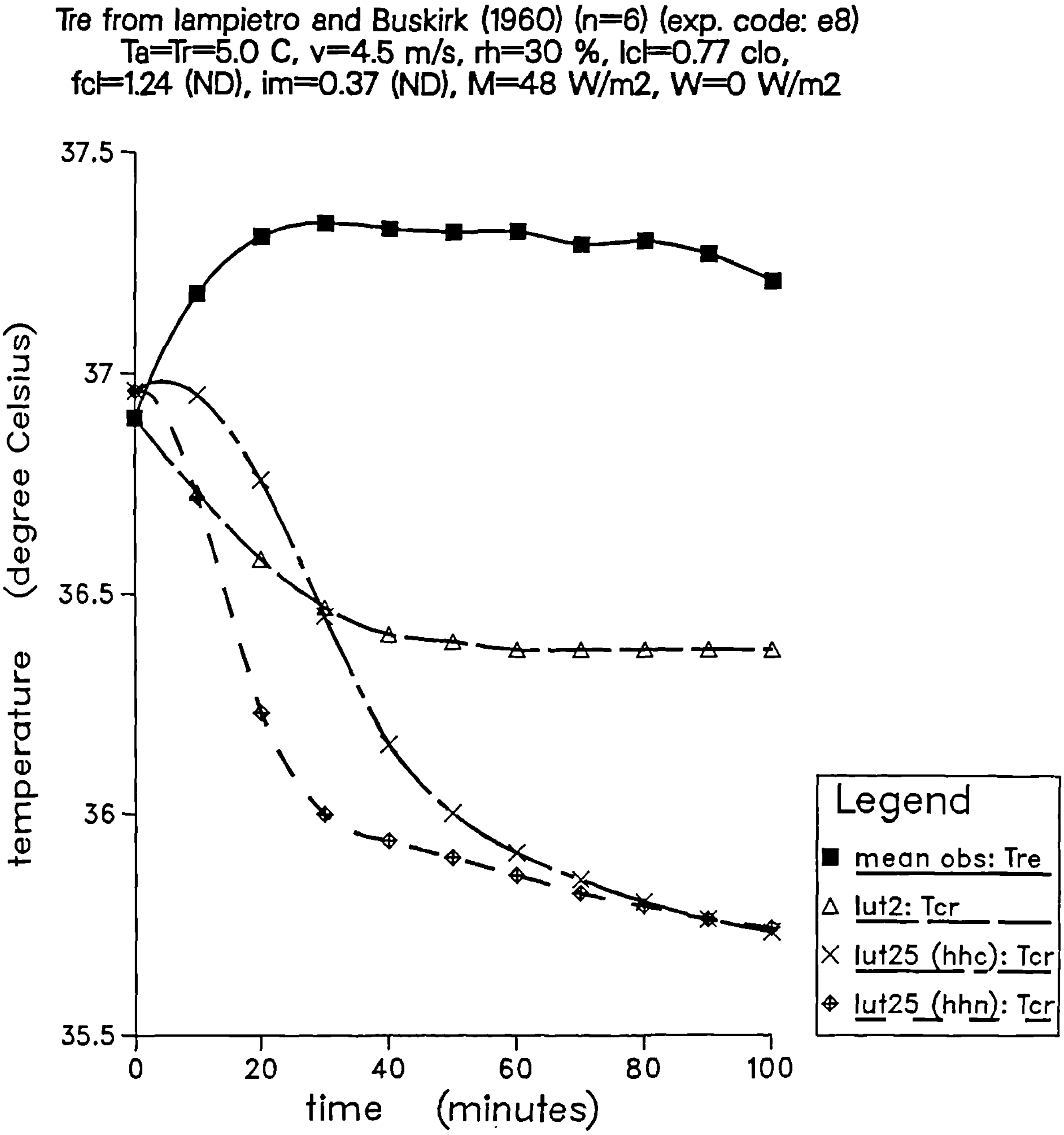
Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e7)
Ta=Tr=10.0 C, v=0.4 m/s, rh=32 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2

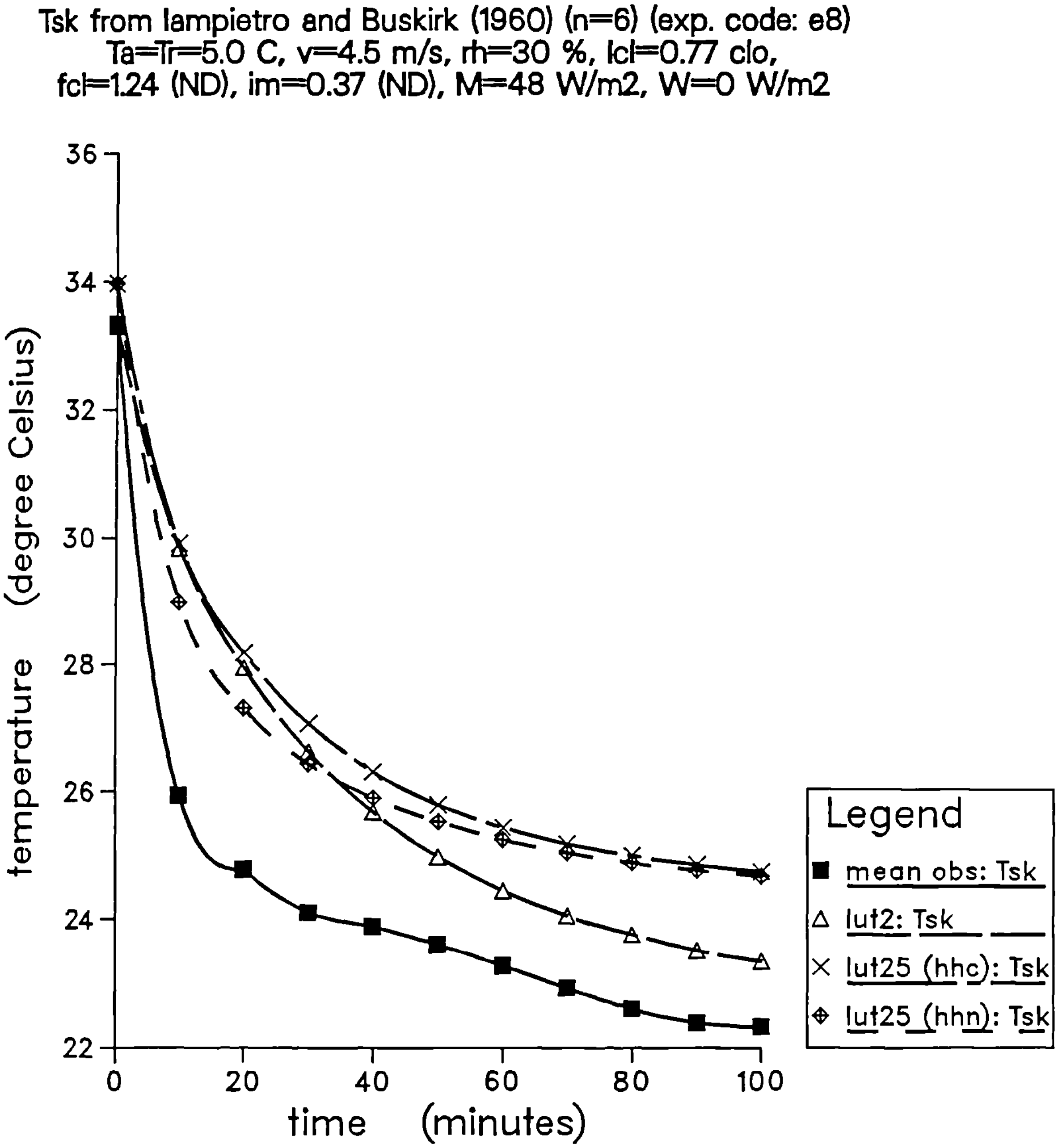



Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e7)
Ta=Tr=10.0 C, v=0.4 m/s, rh=32 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
temperature (degree Celsius)
36
34
32
30
28
26
24
22
0
20
40
60
80
100
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk
lut25 (hhn): Tsk

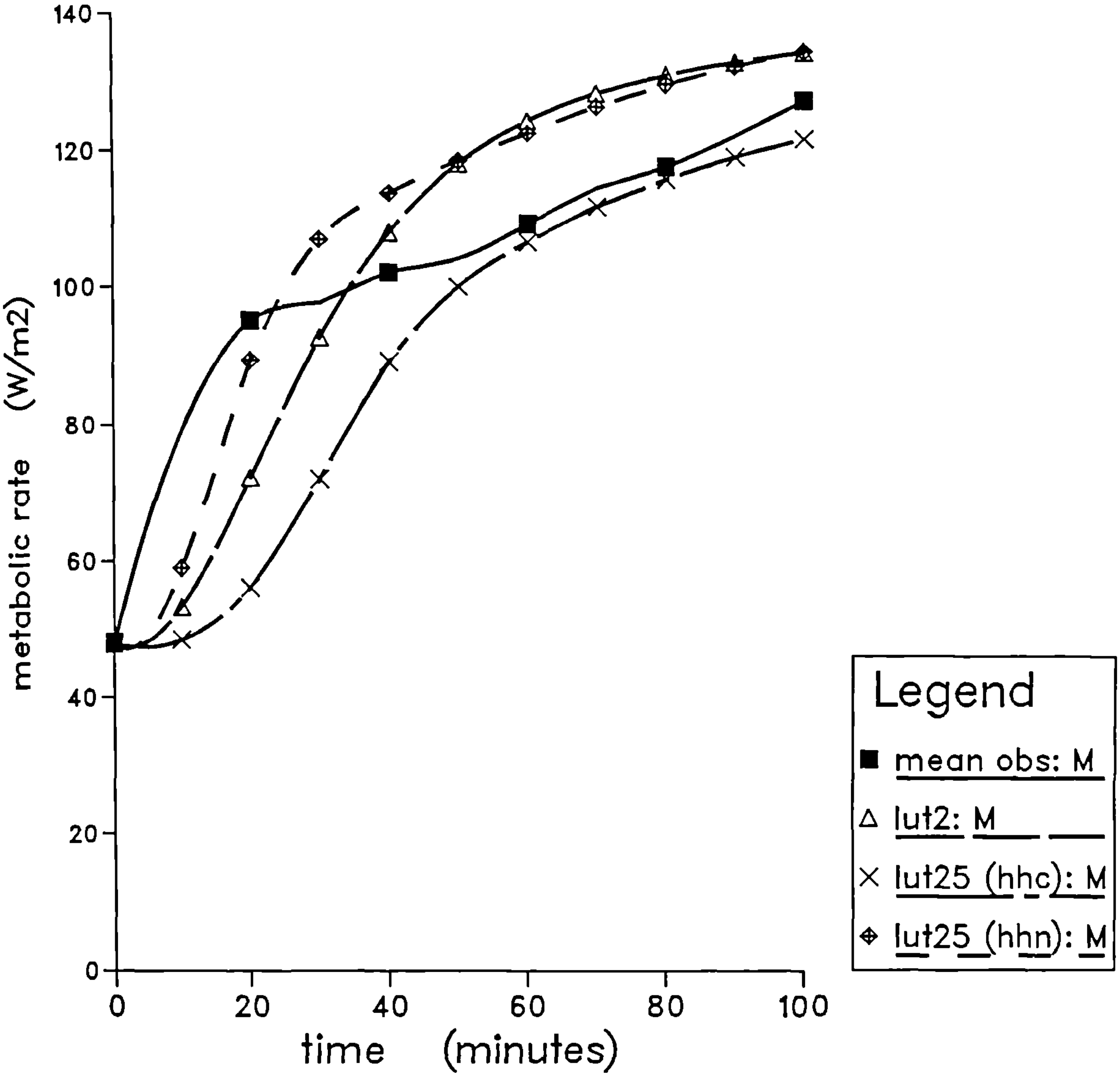
M from Iampietro and Buskirk (1960) (n=6) (exp. code: e7)
Ta=Tr=10.0 C, v=0.4 m/s, rh=32 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



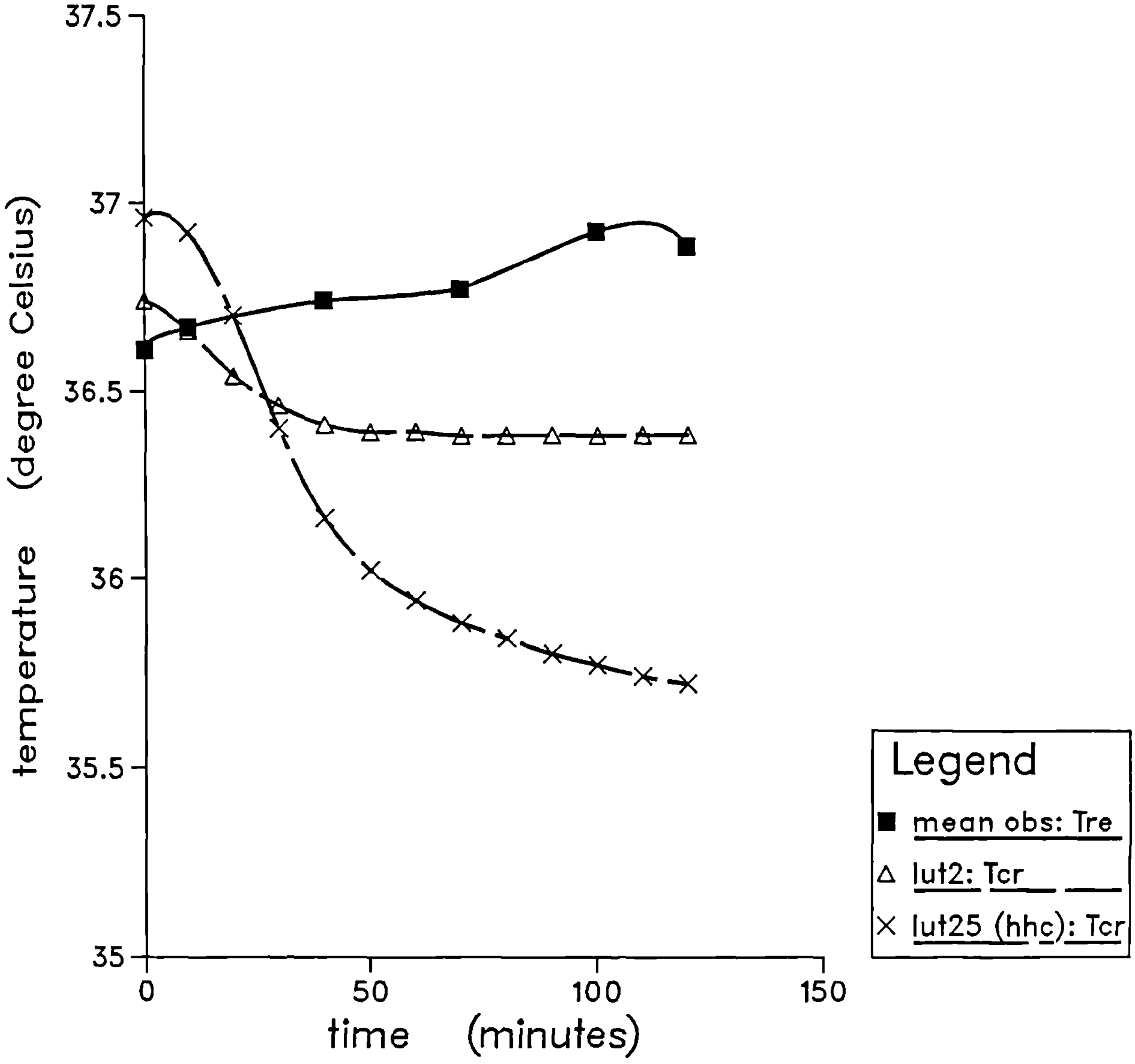

Tre from Iampietro and Buskirk (1960) (n=6) (exp. code: e8)
Ta=Tr=5.0 C, v=4.5 m/s, rh=30 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
37.5
37
36.5
36
35.5
temperature (degree Celsius)
0
20
40
60
80
100
time (minutes)
Legend
mean obs: Tre
lut2: Tcr
lut25 (hhc): Tcr
lut25 (hhn): Tcr


Tsk from Iampietro and Buskirk (1960) (n=6) (exp. code: e8)
Ta=Tr=5.0 C, v=4.5 m/s, rh=30 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2
temperature (degree Celsius)
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk
lut25 (hhn): Tsk

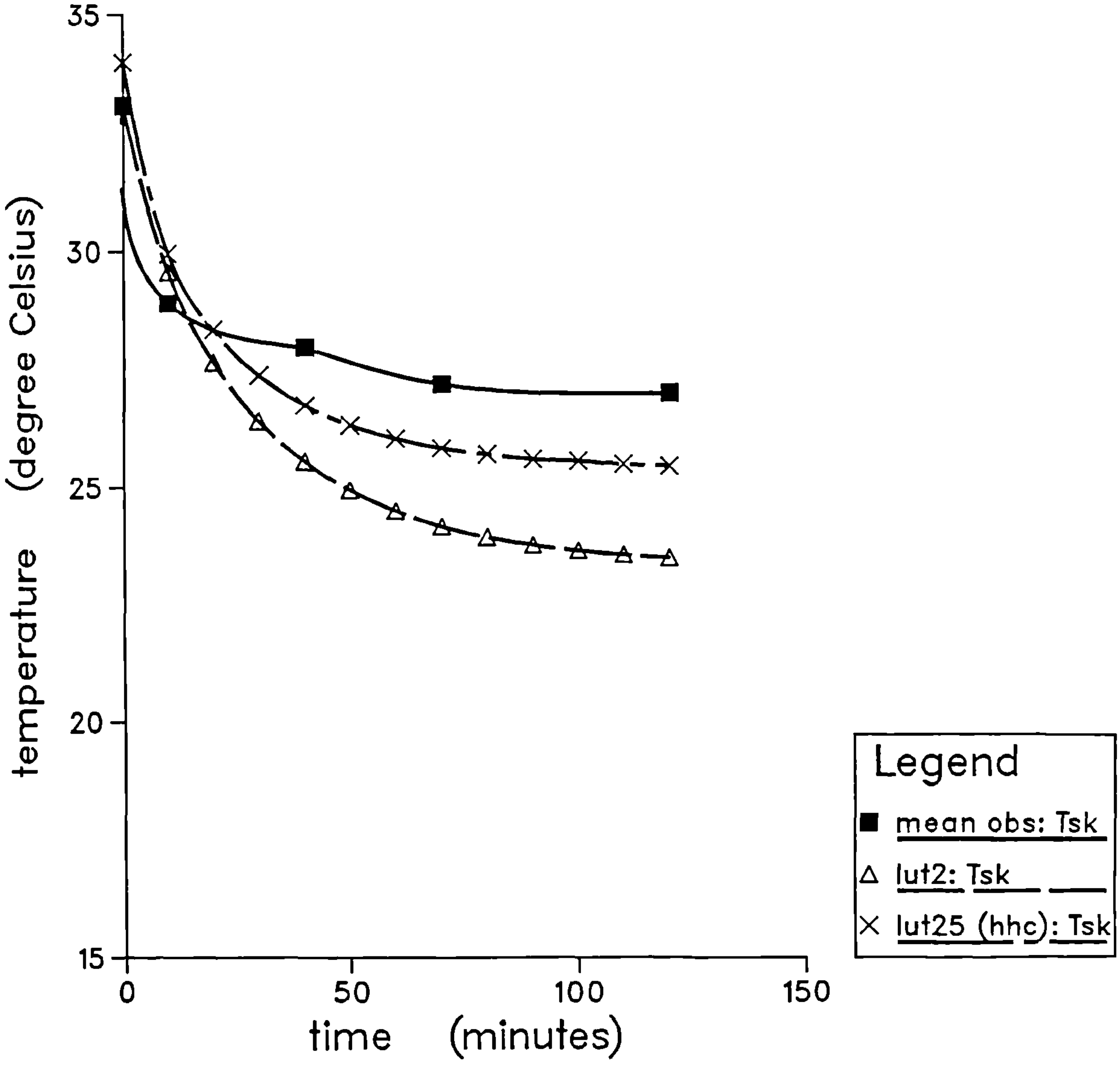
M from Iampietro and Buskirk (1960) (n=6) (exp. code: e8)
Ta=Tr=5.0 C, v=4.5 m/s, rh=30 %, Icl=0.77 clo,
fcl=1.24 (ND), im=0.37 (ND), M=48 W/m2, W=0 W/m2



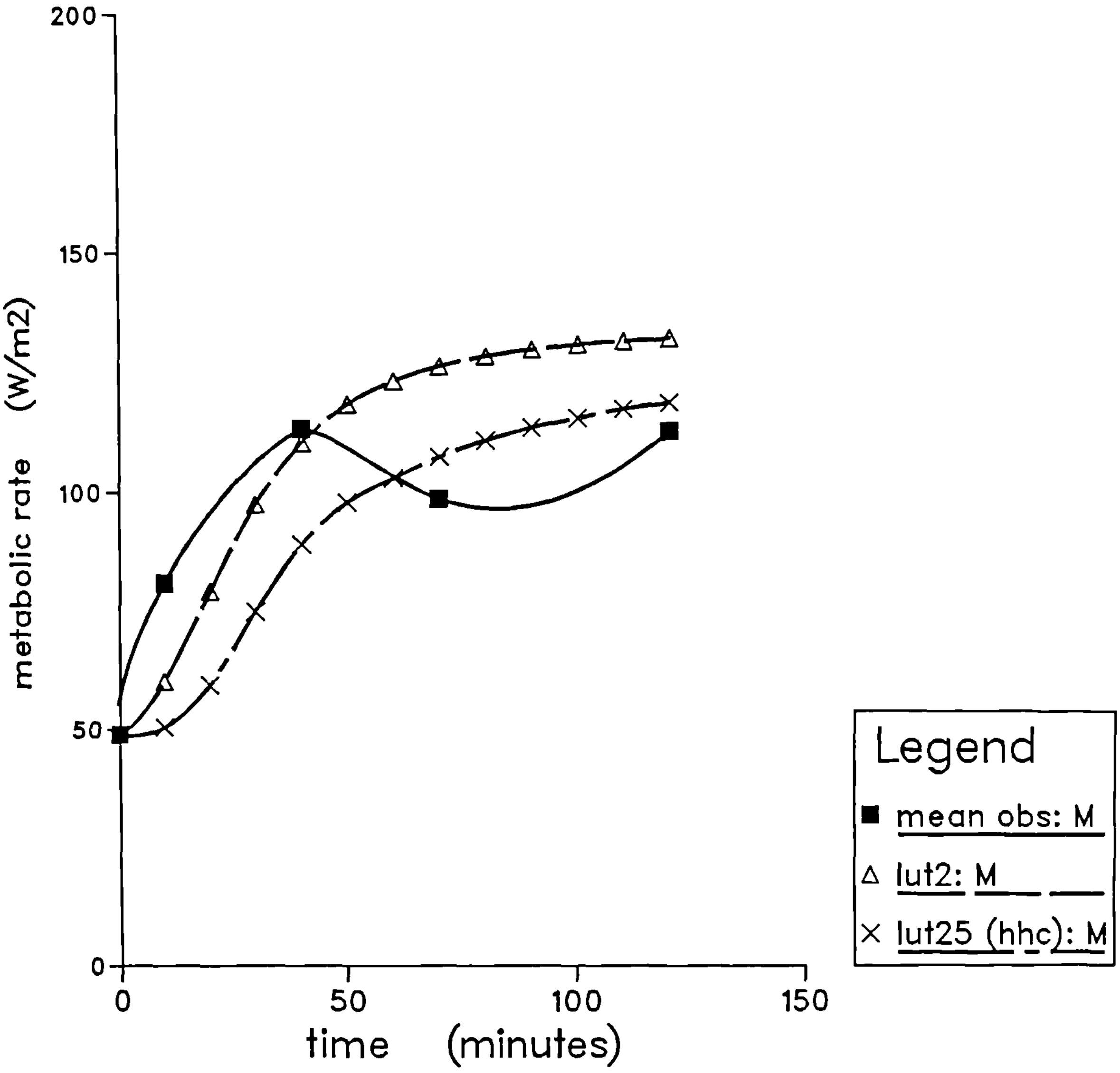
Tre from Iampietro et al (1958) (n=6) (exp code: 1)
Ta=Tr=10.2 C, v=0.4 m/s, rh=34 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



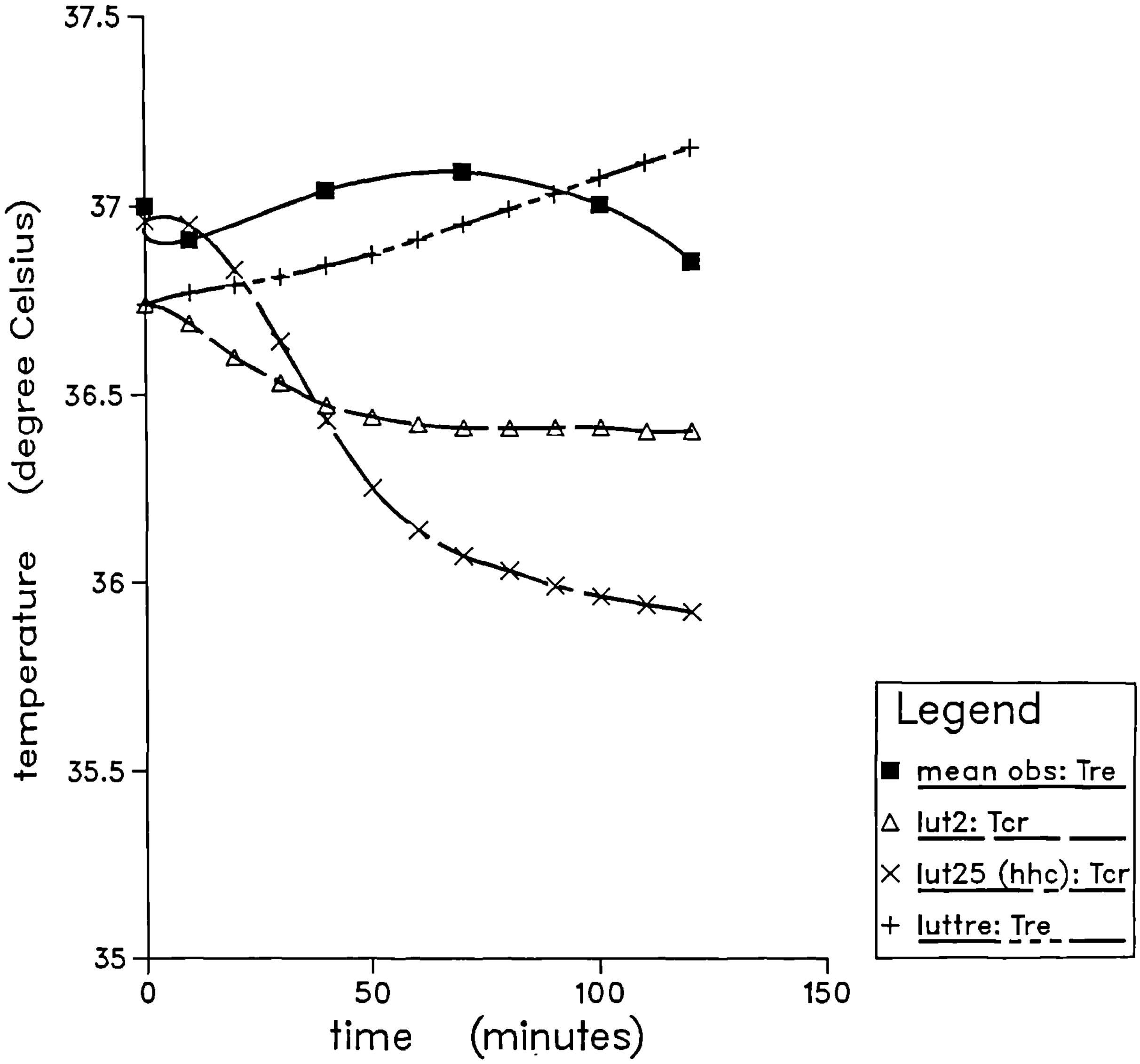
Tsk from Iampietro et al (1958) (n=6) (exp code: 1)
Ta=Tr=10.2 C, v=0.4 m/s, rh=34 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



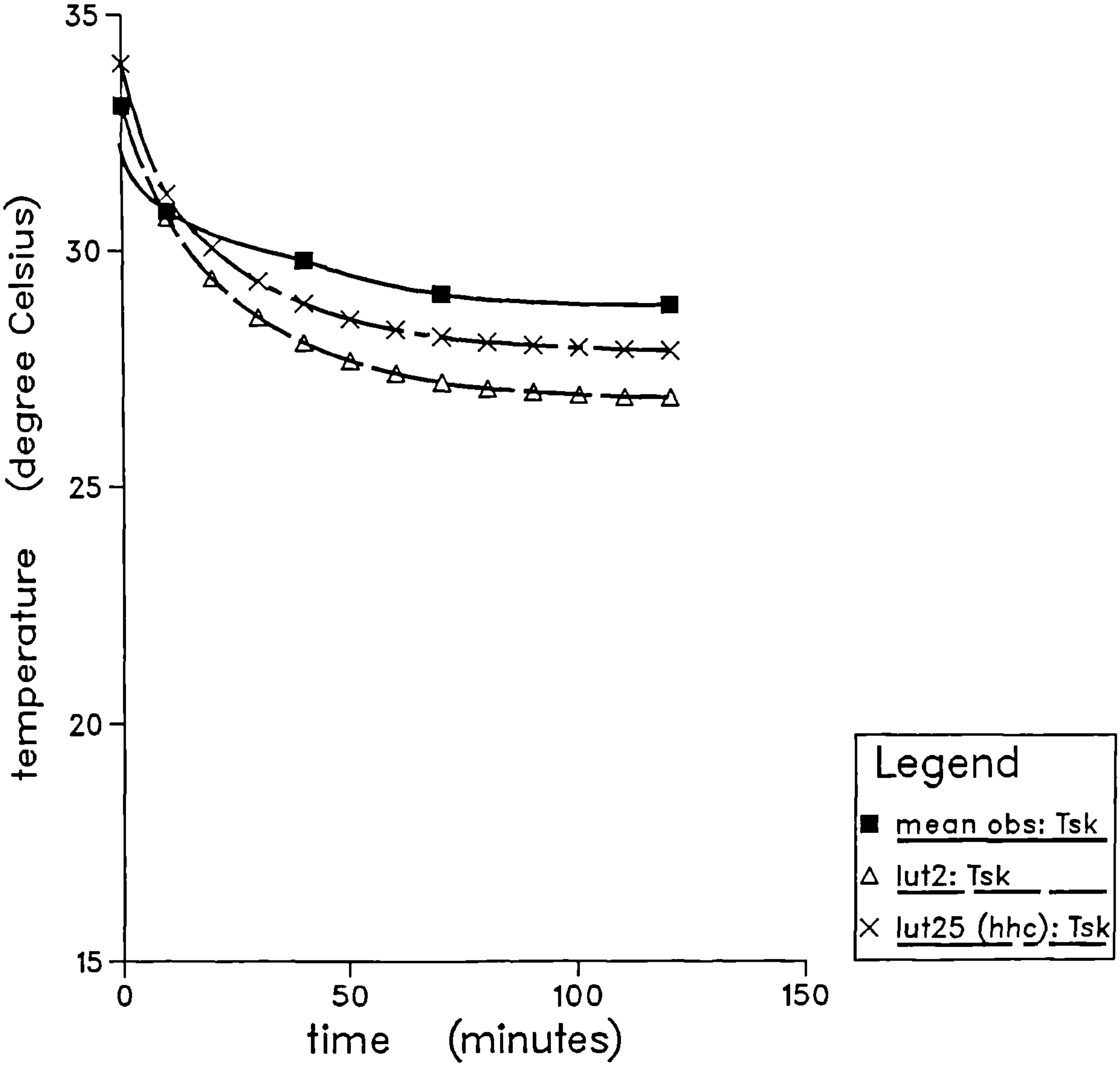
M from Iampietro et al (1958) (n=6) (exp code: 1)
Ta=Tr=10.2 C, v=0.4 m/s, rh=34 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



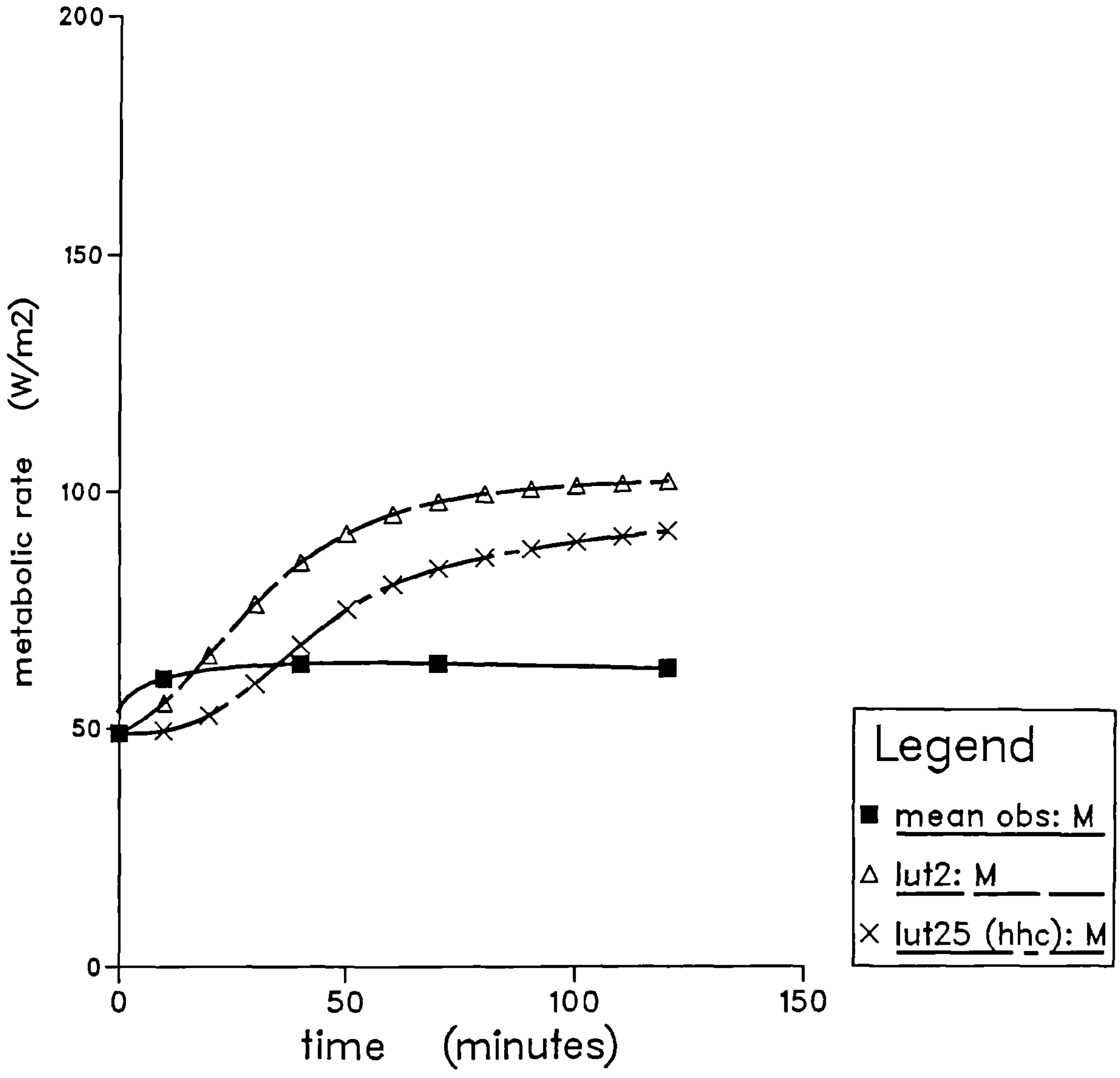
Tre from Iampietro et al (1958) (n=6) (exp code: 2)
Ta=Tr=16.5 C, v=0.4 m/s, rh=95 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



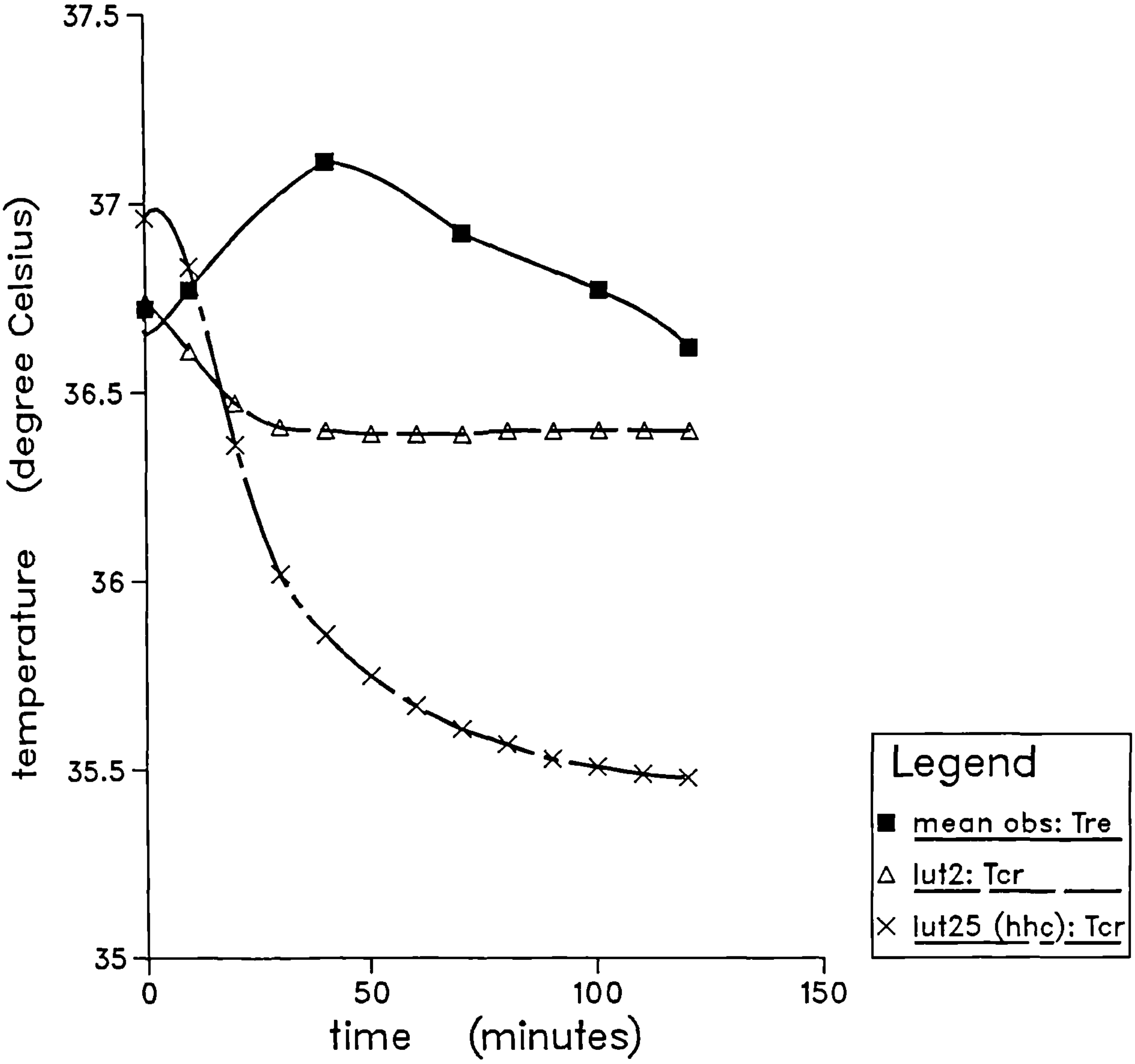
Tsk from Iampietro et al (1958) (n=6) (exp code: 2)
Ta=Tr=16.5 C, v=0.4 m/s, rh=95 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2

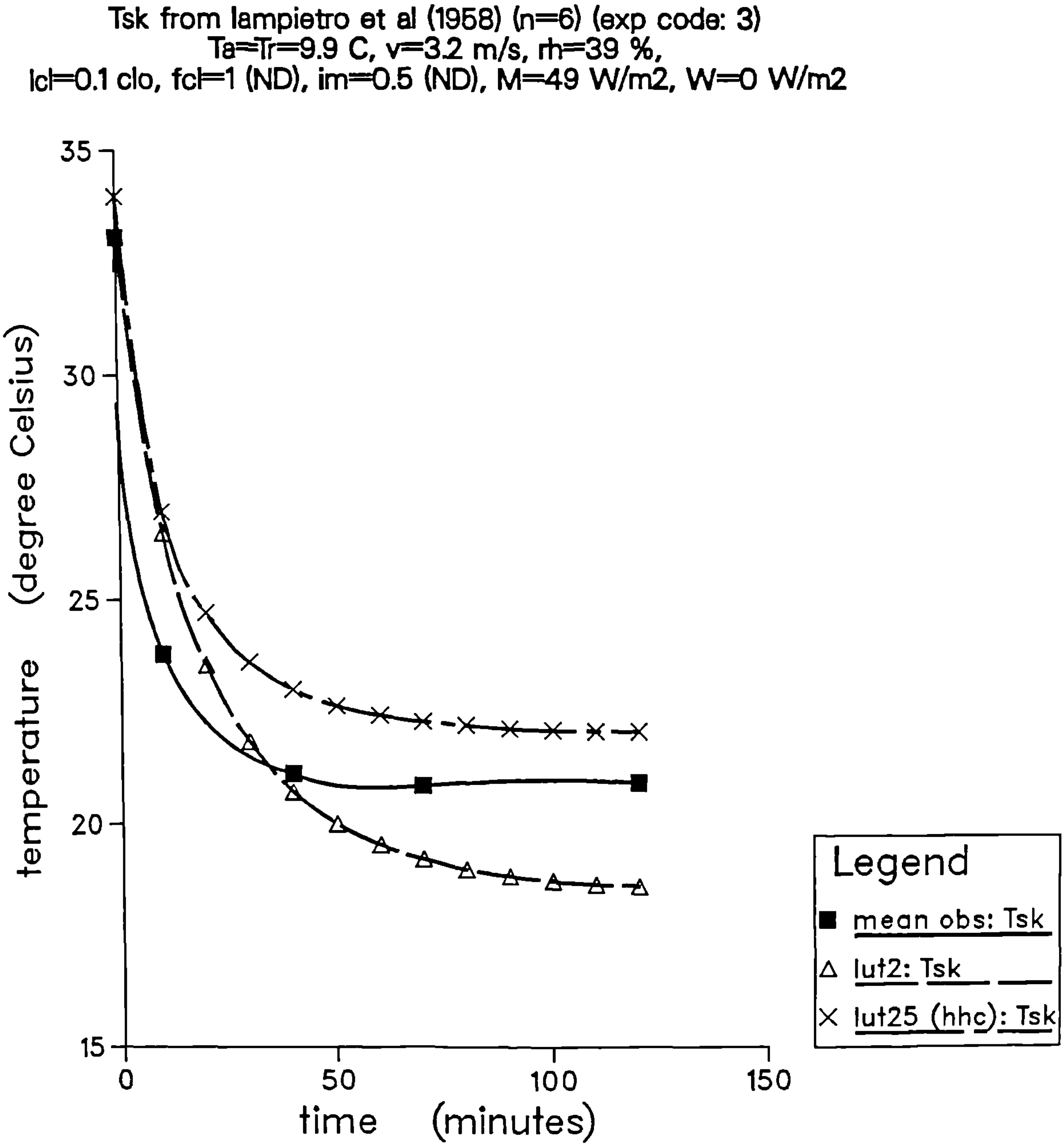


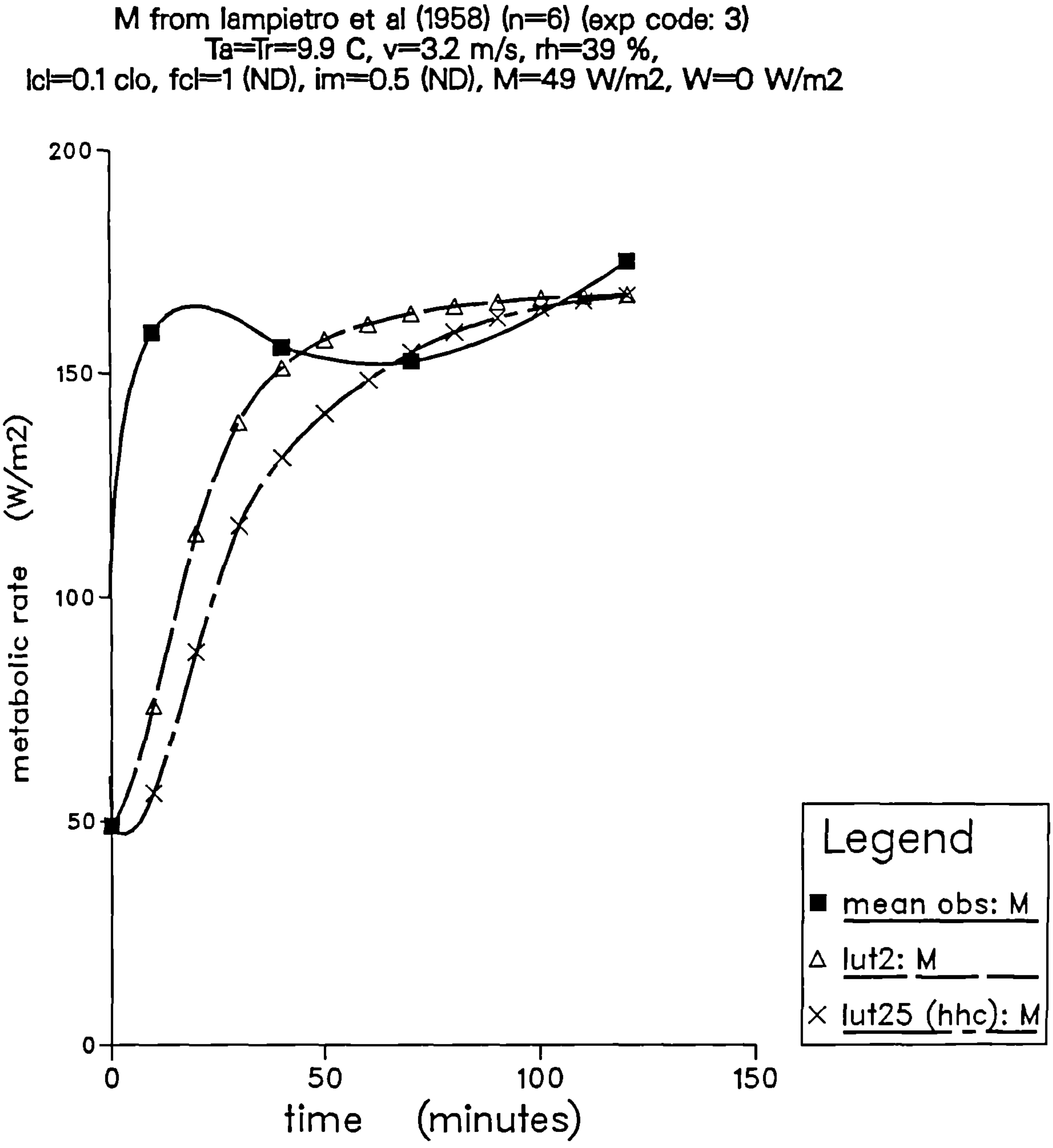
M from Iampietro et al (1958) (n=6) (exp code: 2)
Ta=Tr=16.5 C, v=0.4 m/s, rh=95 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



Tre from Iampietro et al (1958) (n=6) (exp code: 3)
Ta=Tr=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

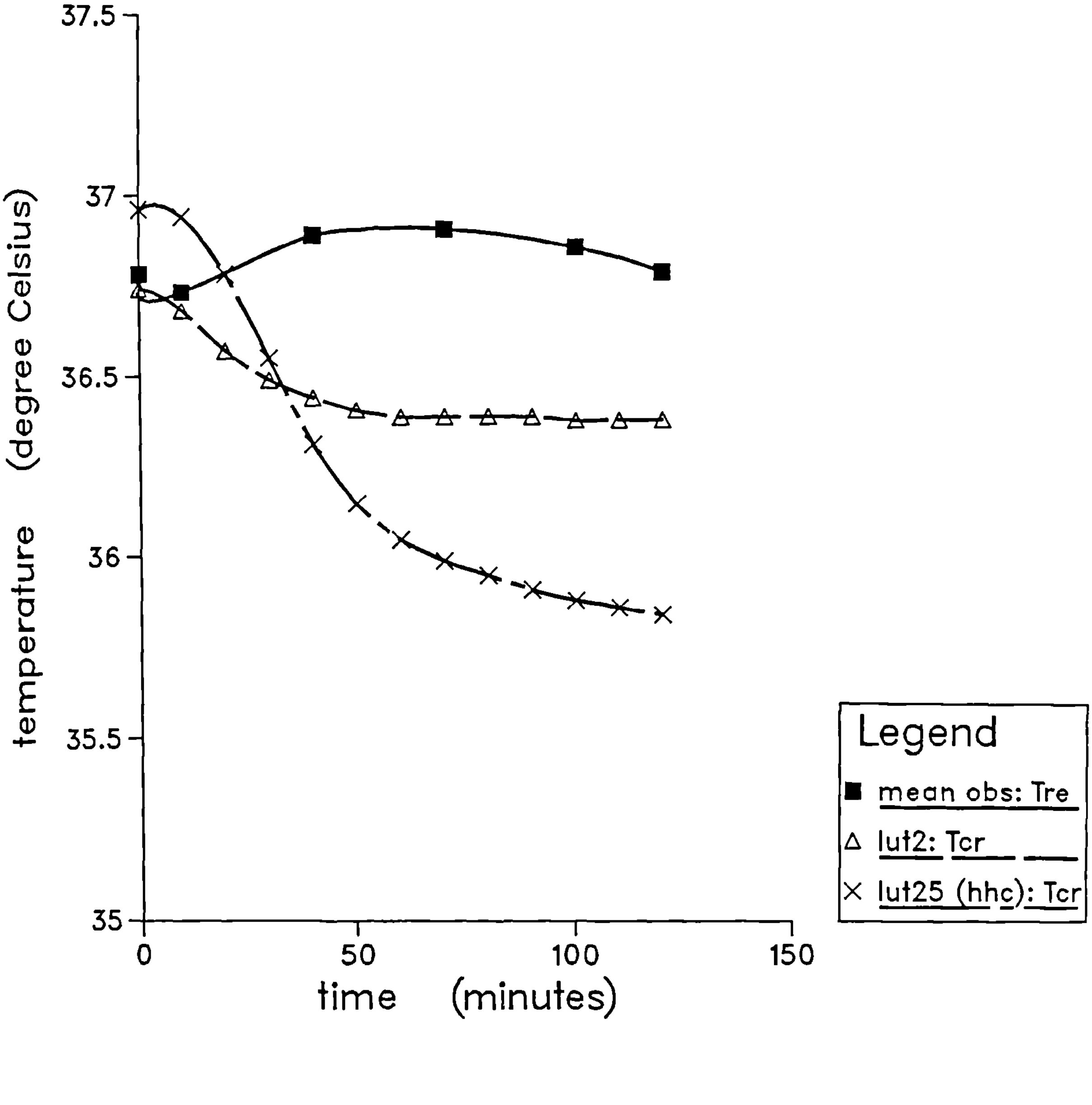


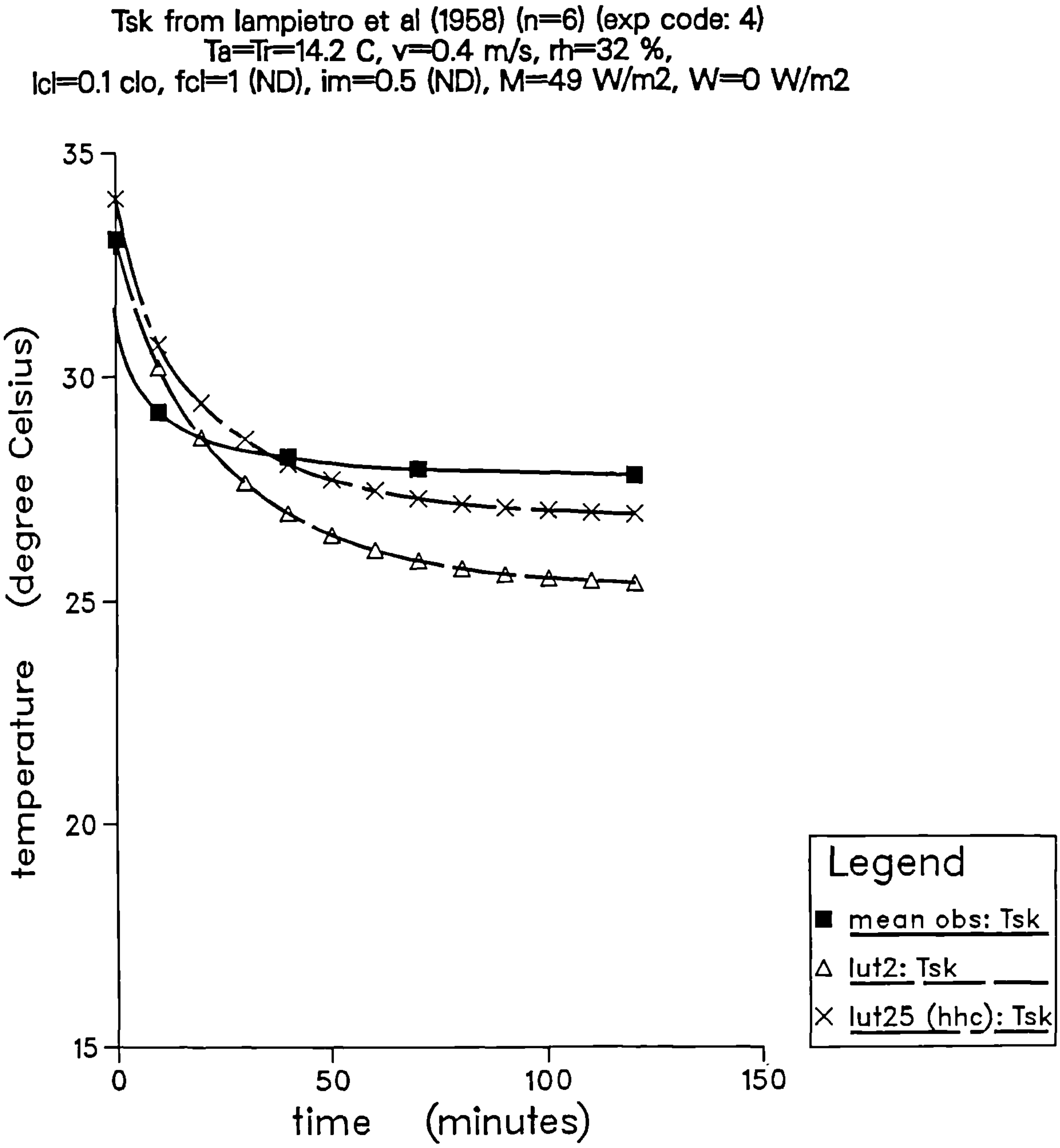

Tsk from Iampietro et al (1958) (n=6) (exp code: 3)
Ta=Tr=9.9 C, v=3.2 m/s, rh=39 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
temperature (degree Celsius)
35
30
25
20
15
0
50
100
150
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk

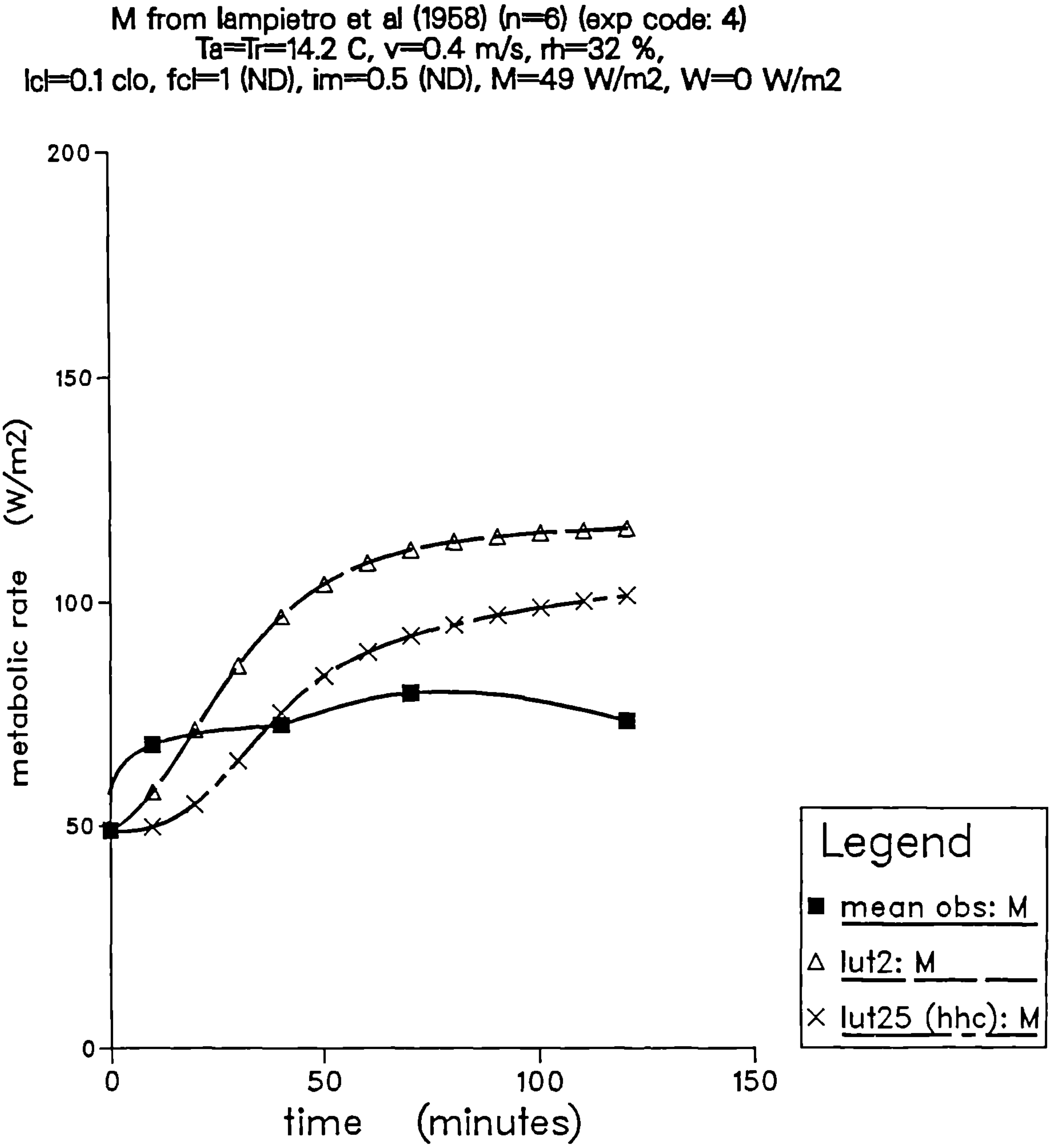


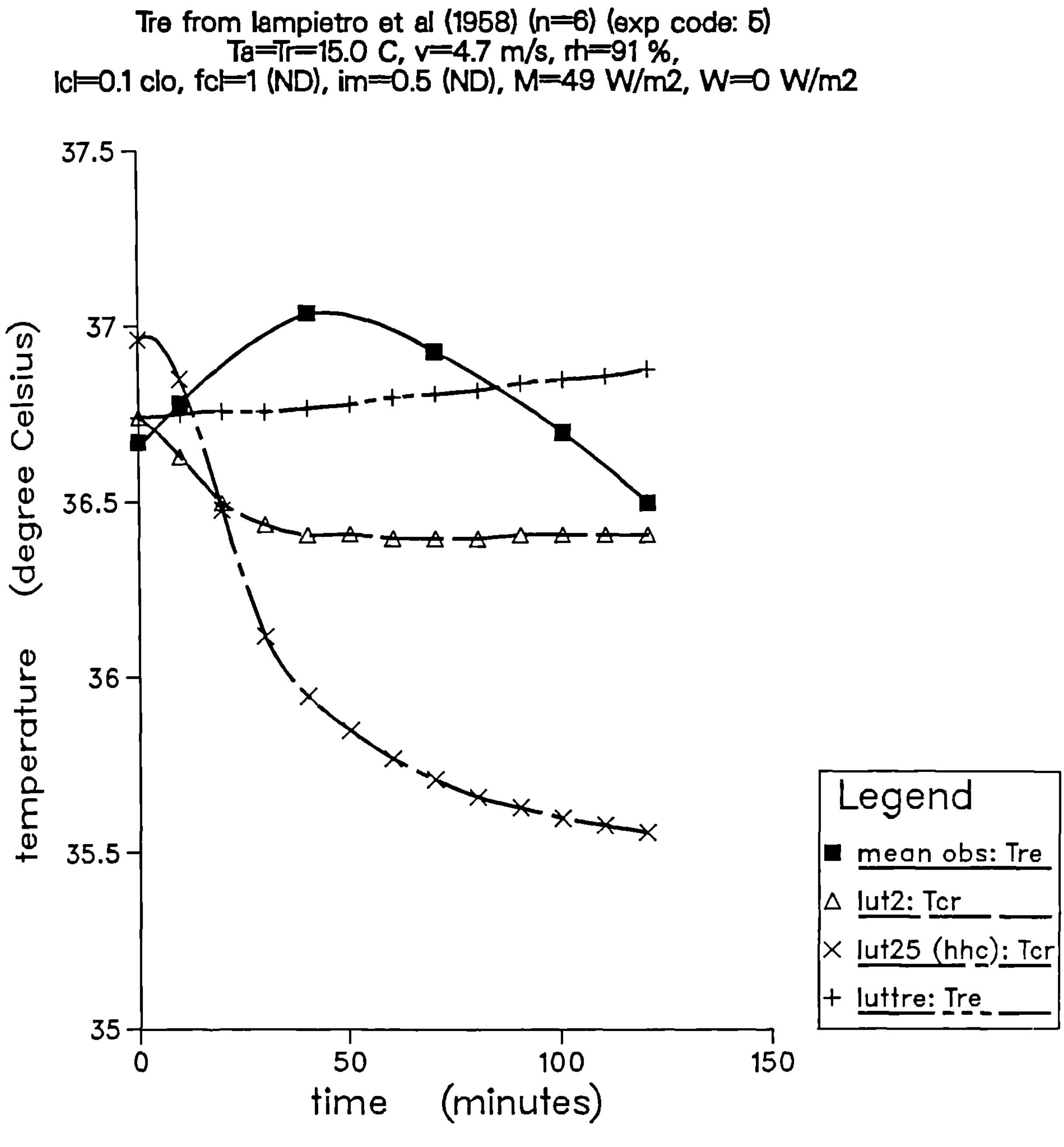
M from Iampietro et al (1958) (n=6) (exp code: 3)
Ta=Tr=9.9 C, v=3.2 m/s, rh=39 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
200
150
100
50
0
metabolic rate (W/m2)
0
50
100
150
time (minutes)
Legend
mean obs: M
lut2: M
lut25 (hhc): M

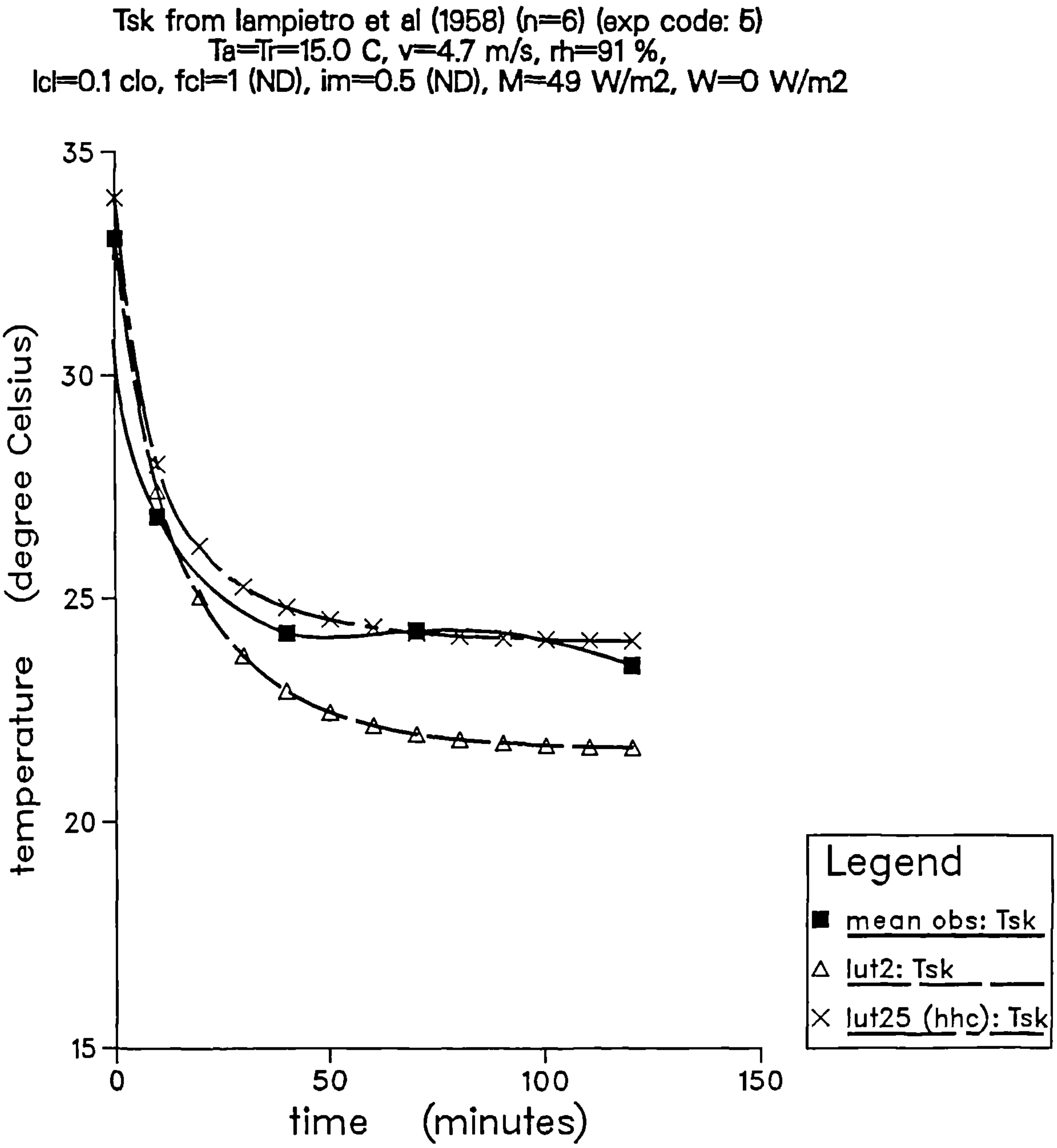
Tre from Iampietro et al (1958) (n=6) (exp code: 4)
Ta=Tr=14.2 C, v=0.4 m/s, rh=32 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



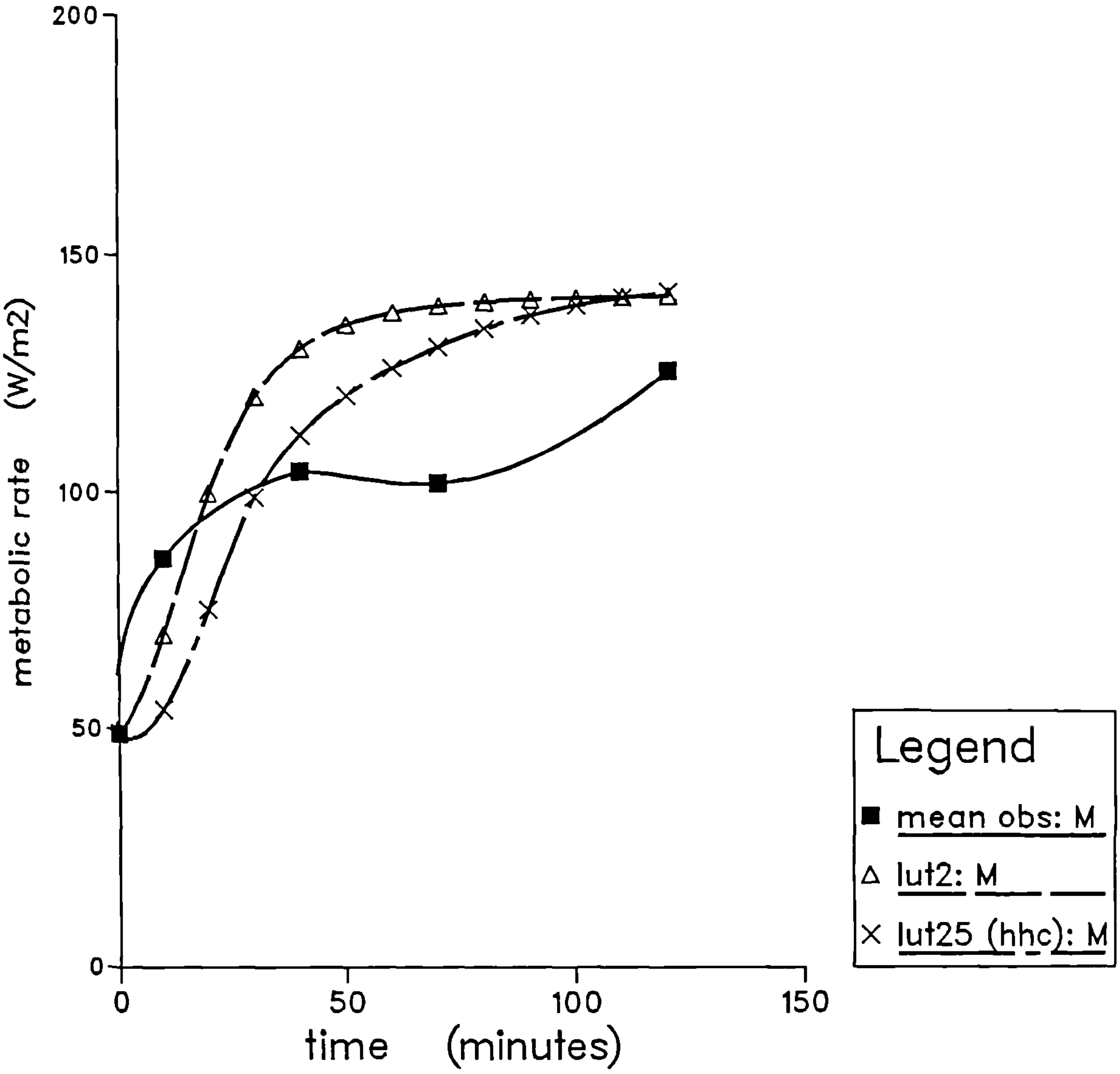

Tsk from Iampietro et al (1958) (n=6) (exp code: 4)
Ta=Tr=14.2 C, v=0.4 m/s, rh=32 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
temperature (degree Celsius)
35
30
25
20
15
0
50
100
150
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk


M from Iampietro et al (1958) (n=6) (exp code: 4)
Ta=Tr=14.2 C, v=0.4 m/s, rh=32 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
metabolic rate (W/m2)
200
150
100
50
0
0
50
100
150
time (minutes)
Legend
mean obs: M
lut2: M
lut25 (hhc): M

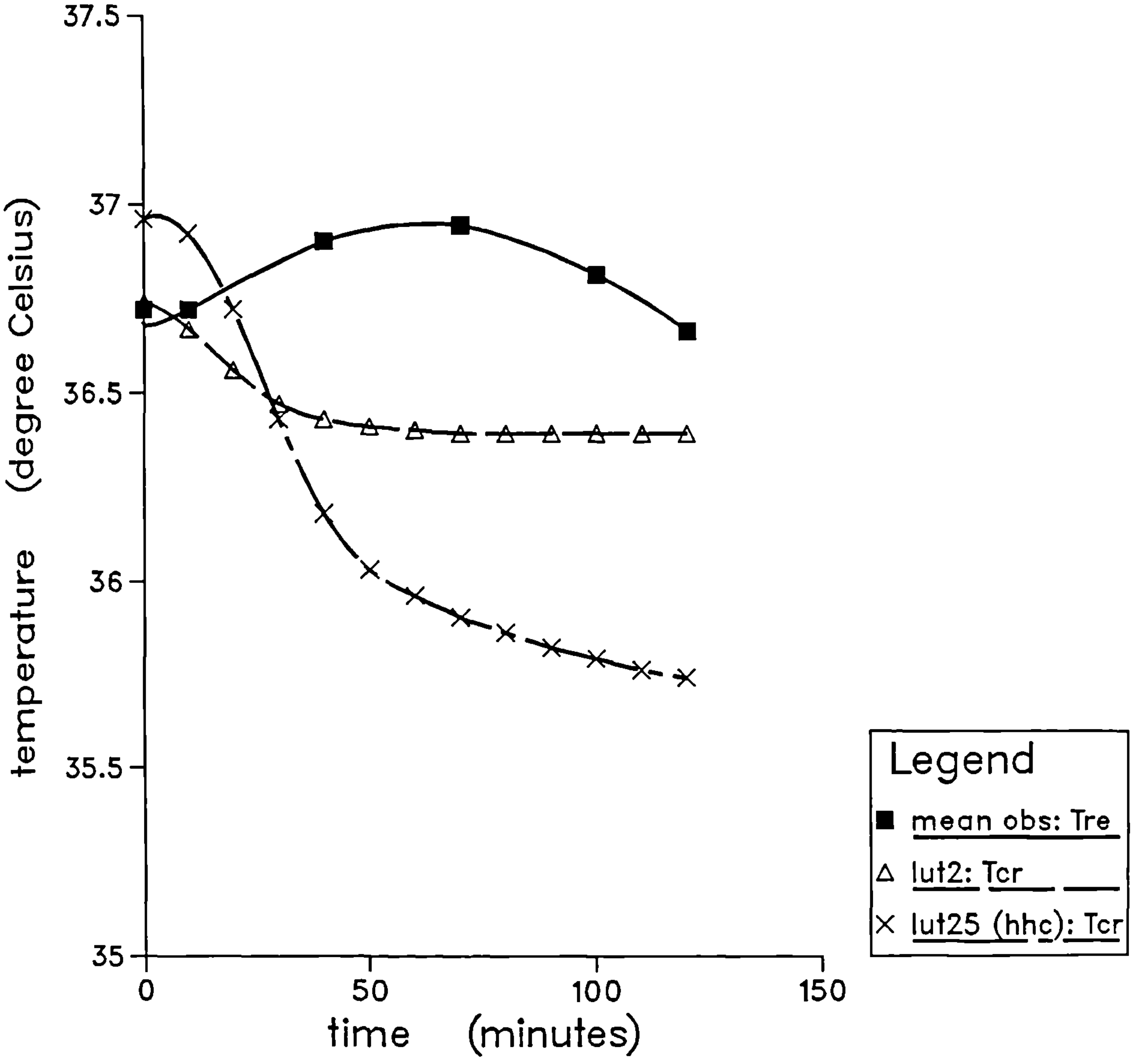

Tre from Iampietro et al (1958) (n=6) (exp code: 5)
Ta=Tr=15.0 C, v=4.7 m/s, rh=91 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
temperature (degree Celsius)
37.5
37
36.5
36
35.5
35
0
50
100
150
time (minutes)
Legend
mean obs: Tre
lut2: Tcr
lut25 (hhc): Tcr
luttre: Tre


Tsk from Iampietro et al (1958) (n=6) (exp code: 5)
Ta=Tr=15.0 C, v=4.7 m/s, rh=91 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2
temperature (degree Celsius)
35
30
25
20
15
0
50
100
150
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk

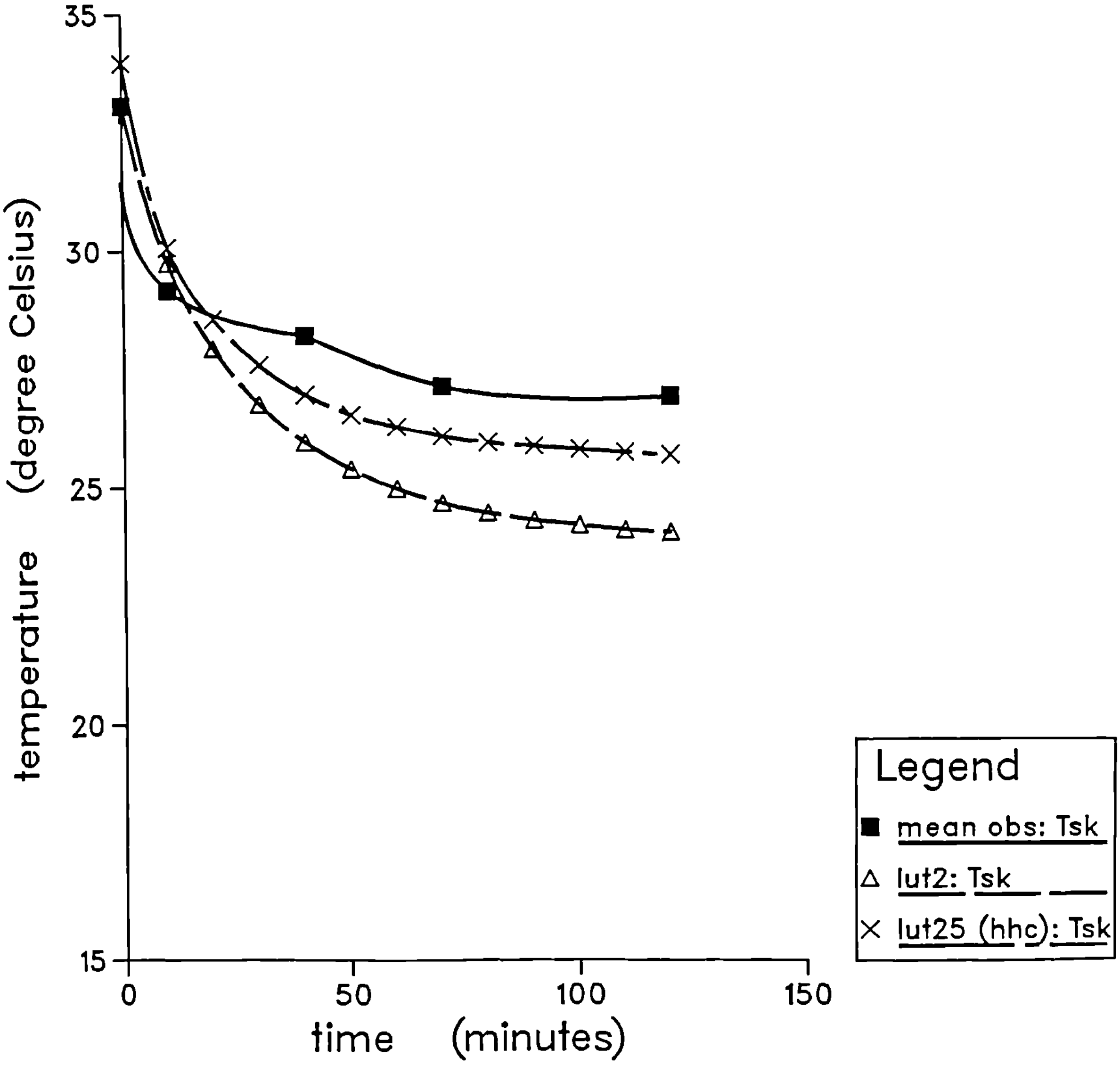
M from Iampietro et al (1958) (n=6) (exp code: 5)
Ta=Tr=15.0 C, v=4.7 m/s, rh=91 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



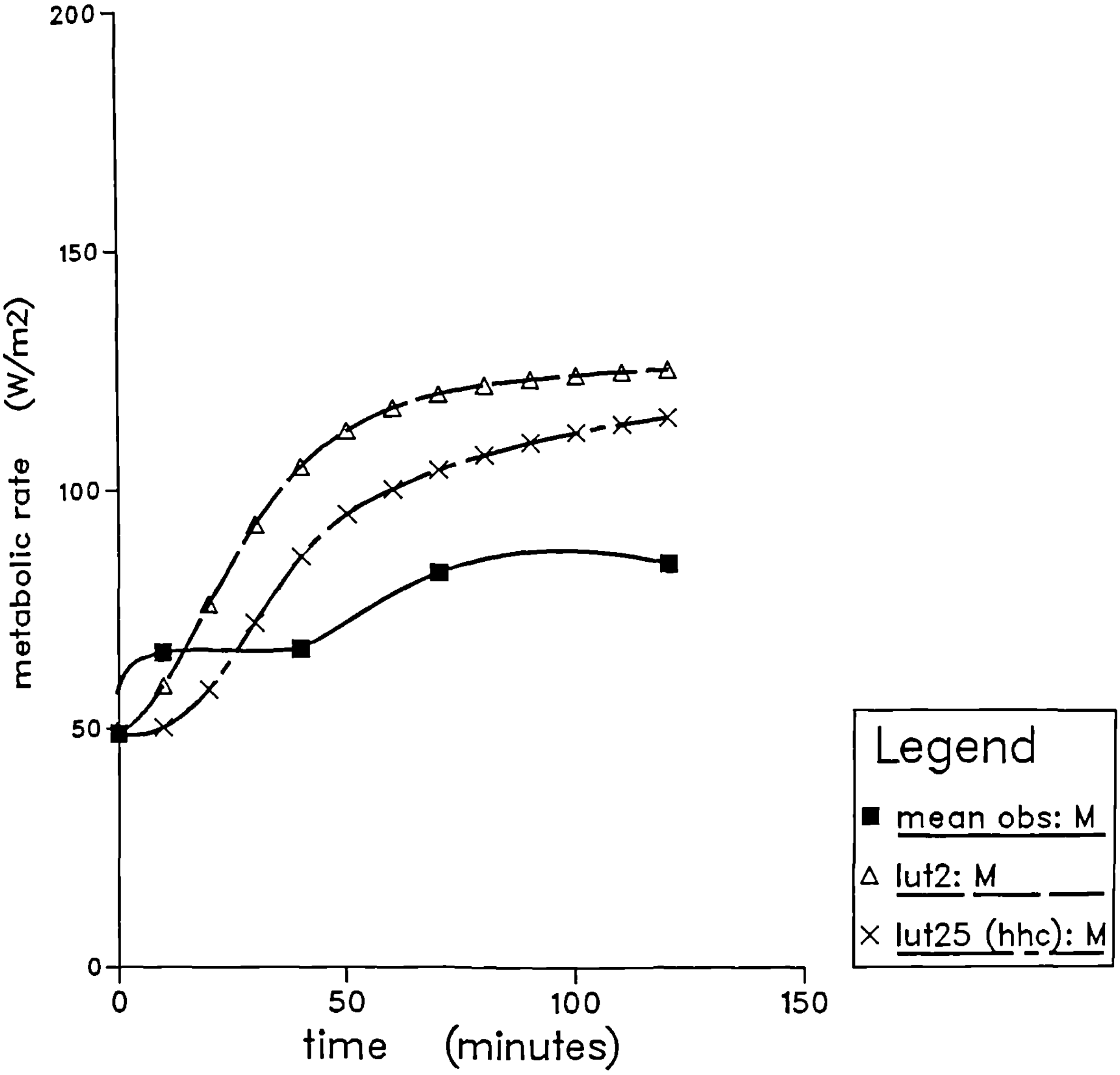
Tre from Iampietro et al (1958) (n=6) (exp code: 6)
Ta=Tr=11.0 C, v=0.4 m/s, rh=94 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



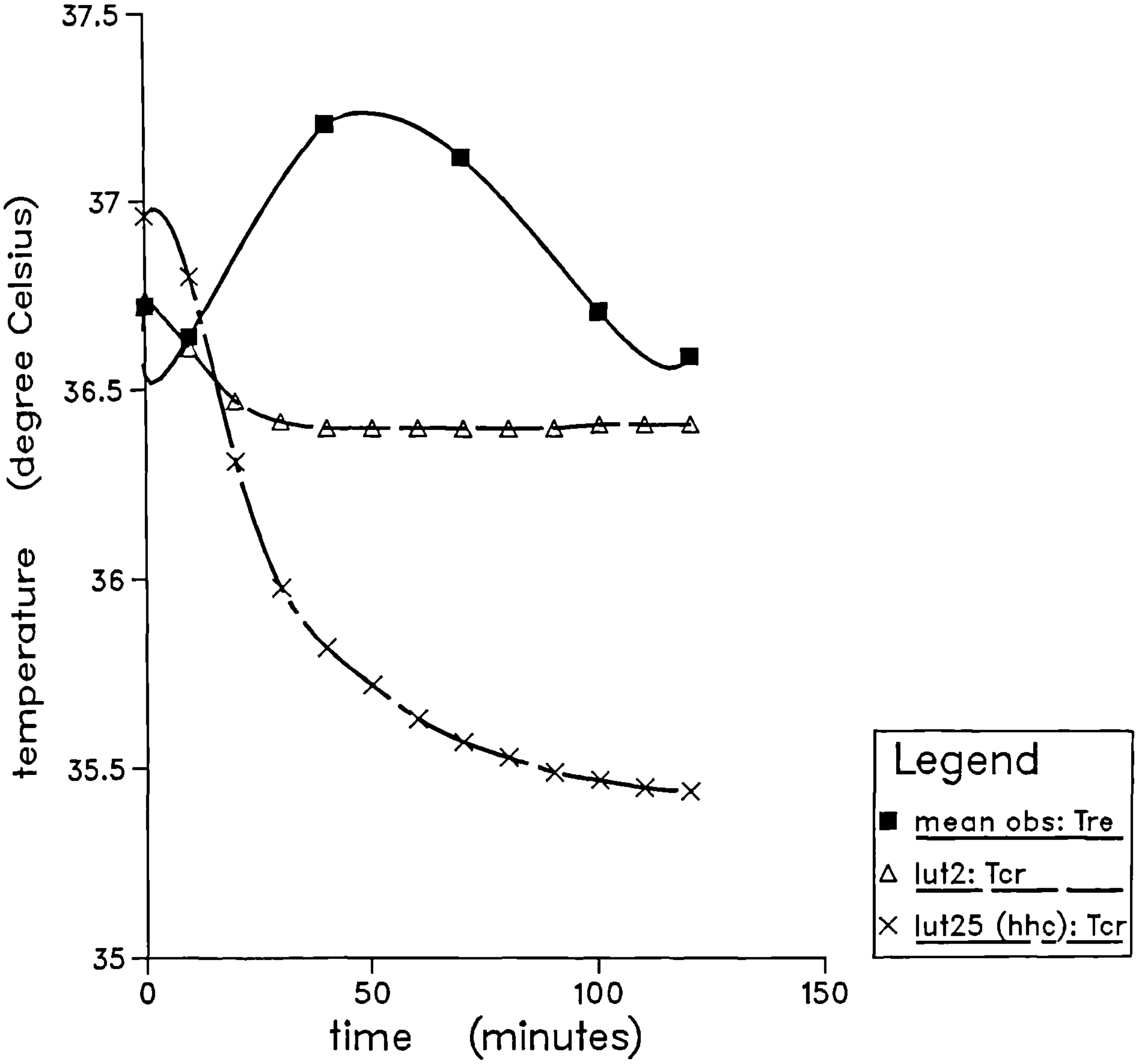
Tsk from Iampietro et al (1958) (n=6) (exp code: 6)
Ta=Tr=11.0 C, v=0.4 m/s, rh=94 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



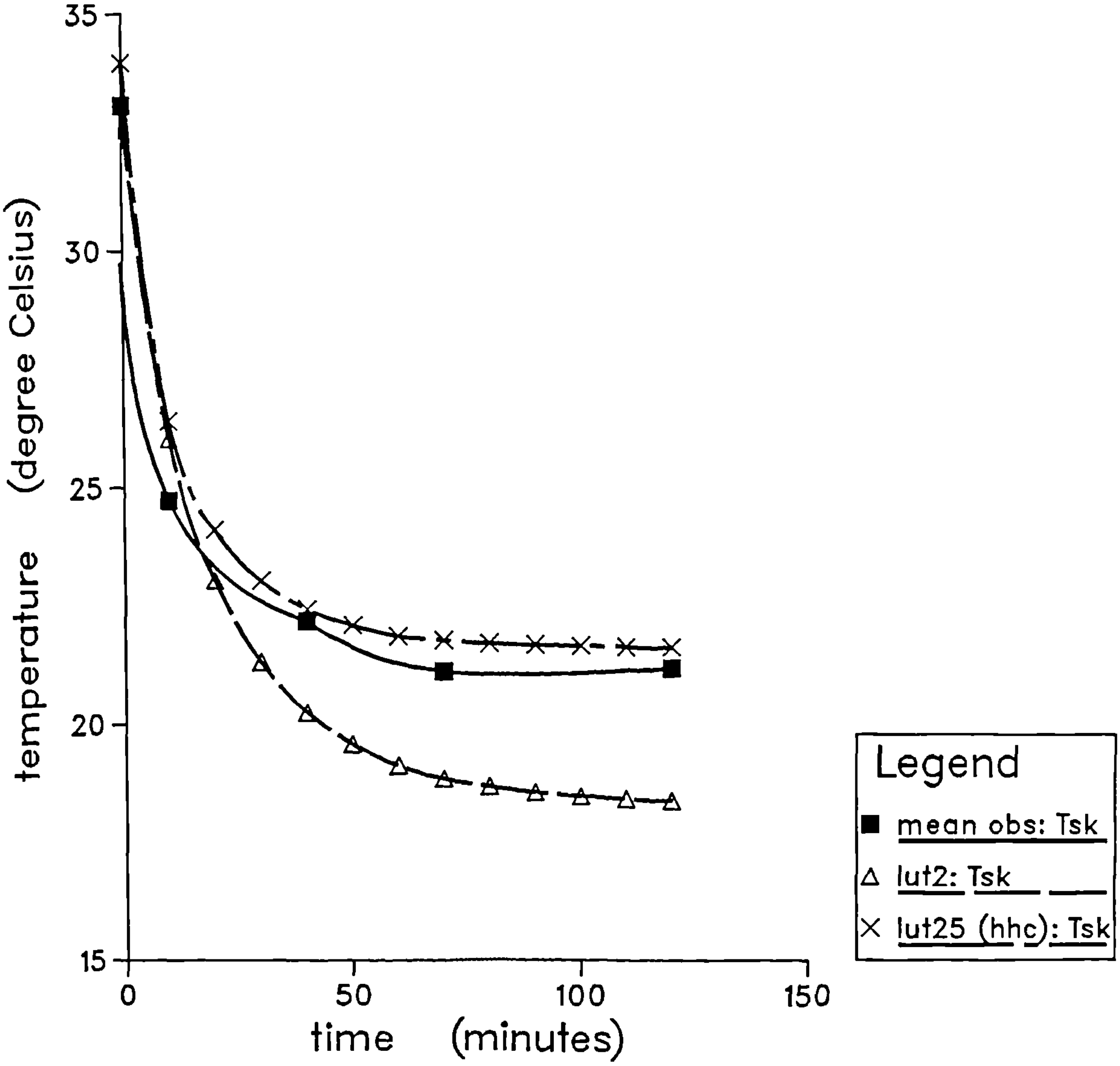
M from Iampietro et al (1958) (n=6) (exp code: 6)
Ta=Tr=11.0 C, v=0.4 m/s, rh=94 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



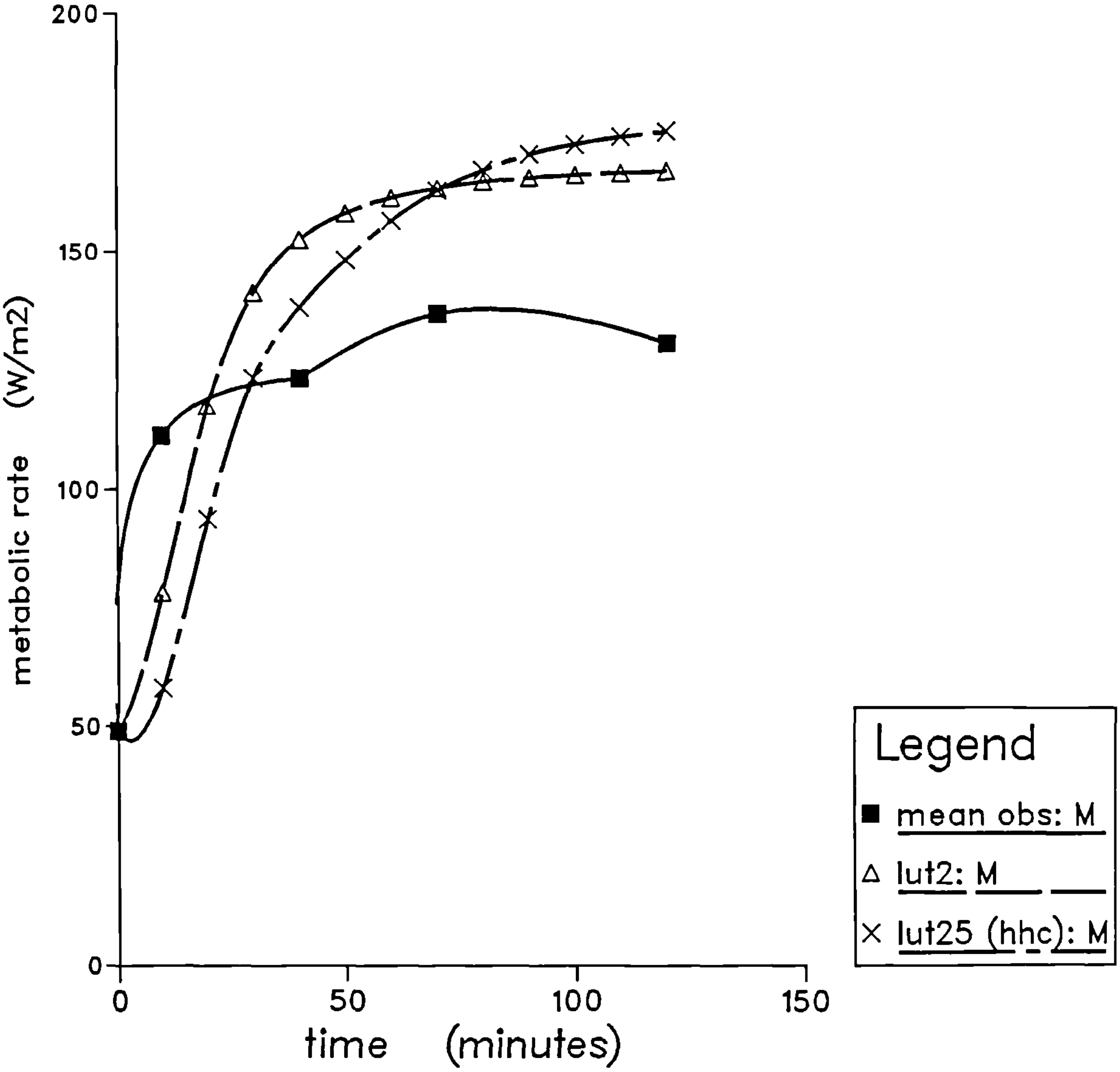
Tre from Iampietro et al (1958) (n=6) (exp code: 7)
Ta=Tr=10.1 C, v=4.5 m/s, rh=98 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



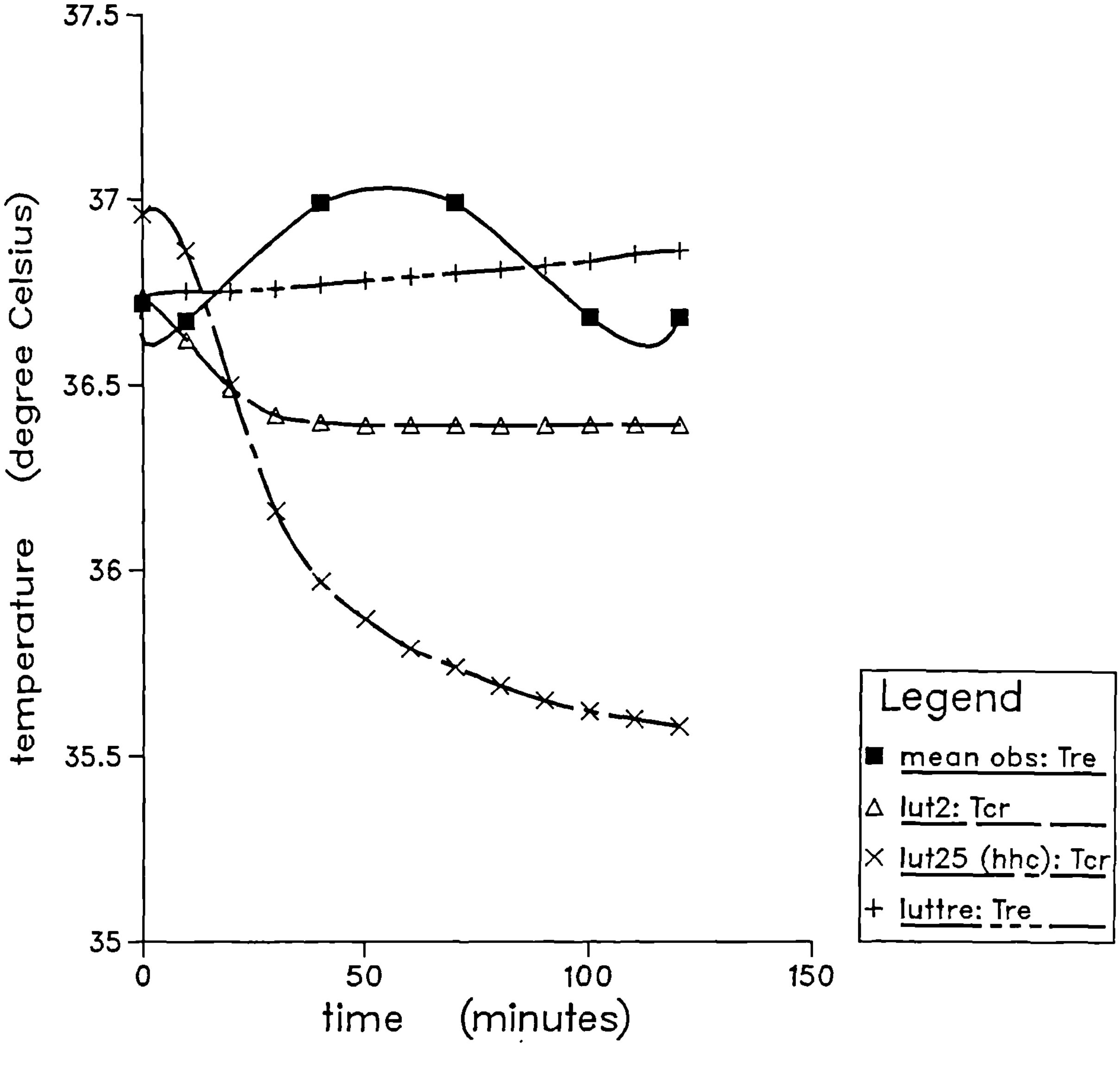
Tsk from Iampietro et al (1958) (n=6) (exp code: 7)
Ta=Tr=10.1 C, v=4.5 m/s, rh=98 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



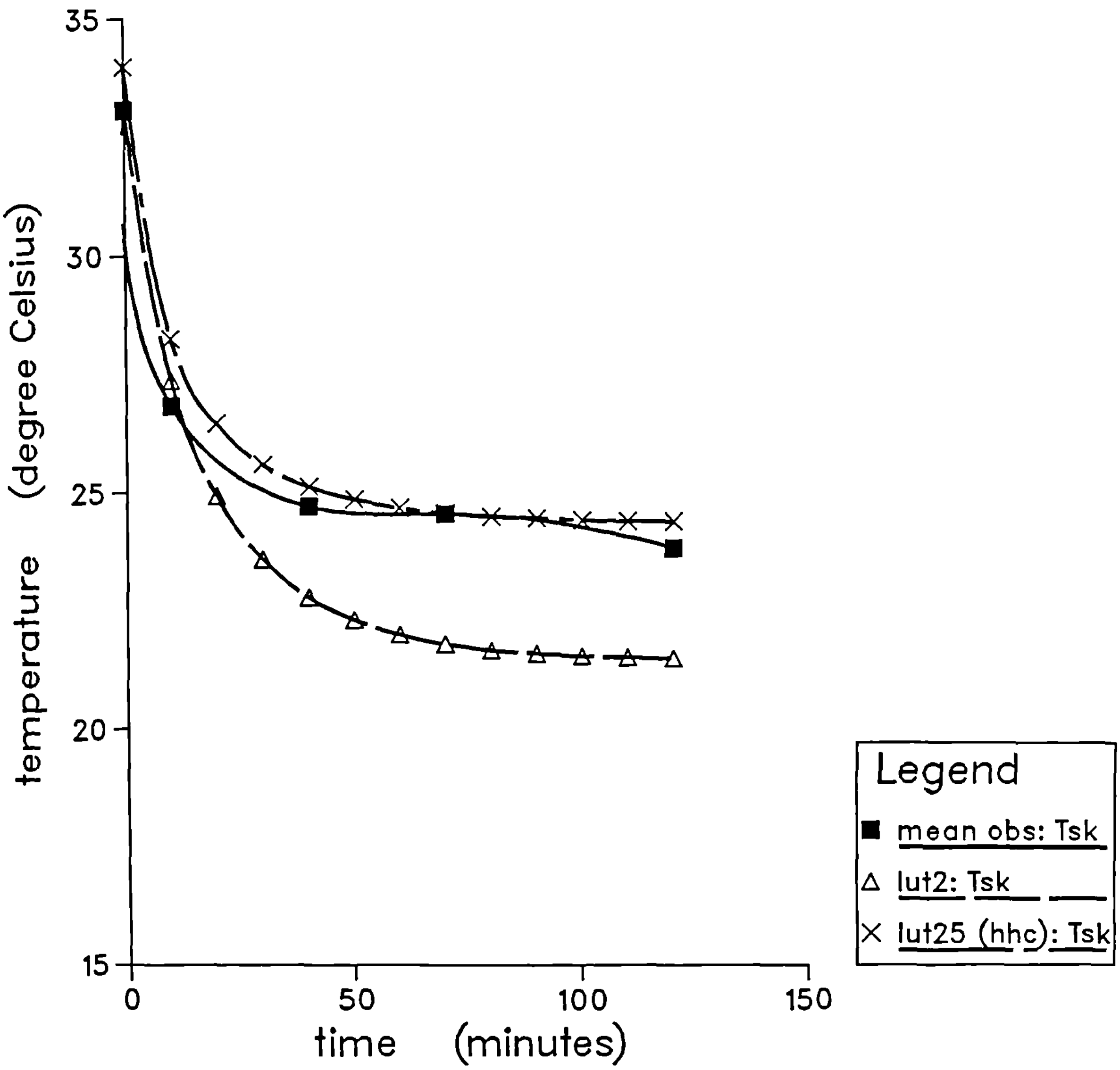
M from Iampietro et al (1958) (n=6) (exp code: 7)
Ta=Tr=10.1 C, v=4.5 m/s, rh=98 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



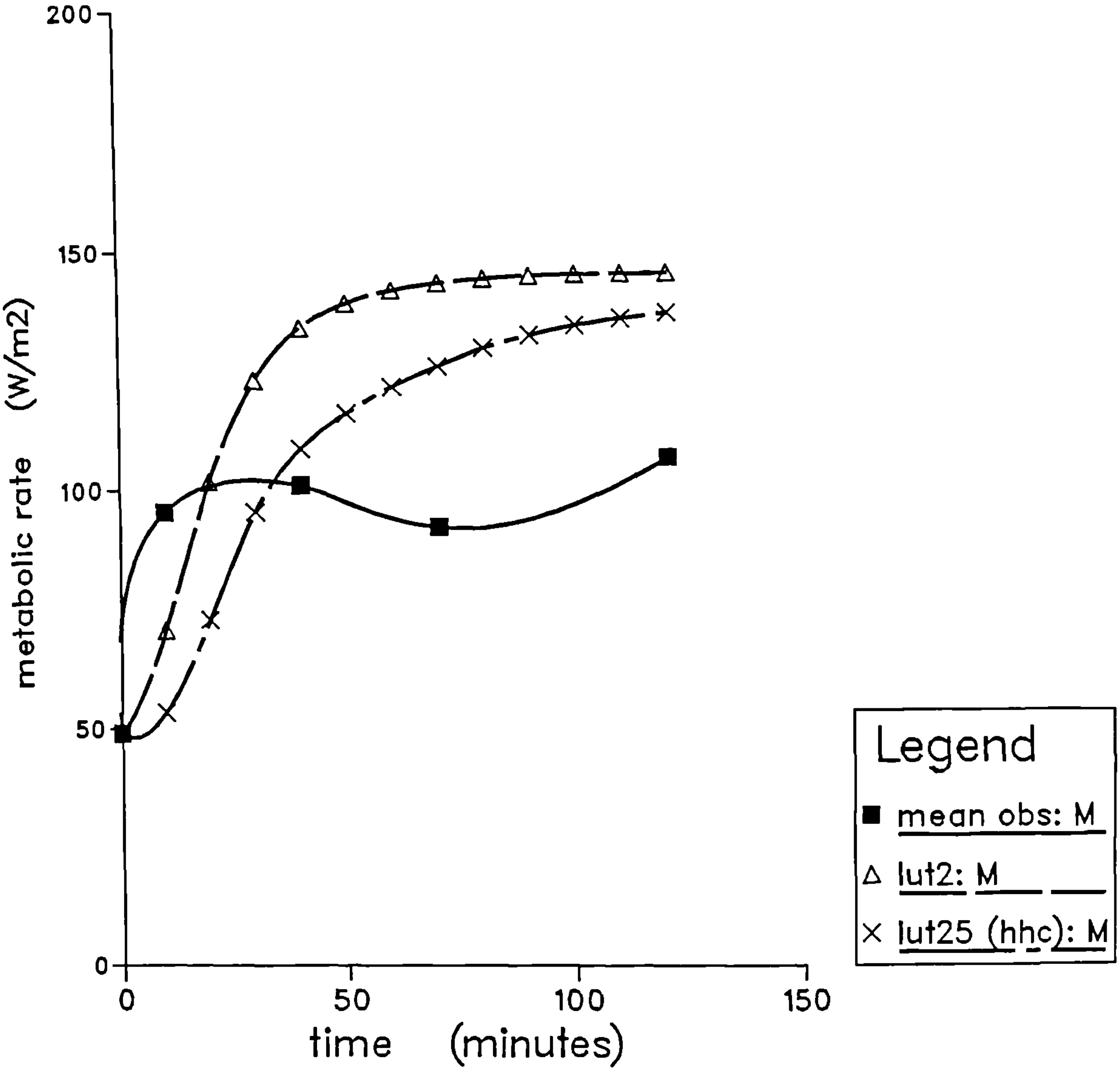
Tre from Iampietro et al (1958) (n=6) (exp code: 8)
Ta=Tr=15.6 C, v=4.6 m/s, rh=14 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



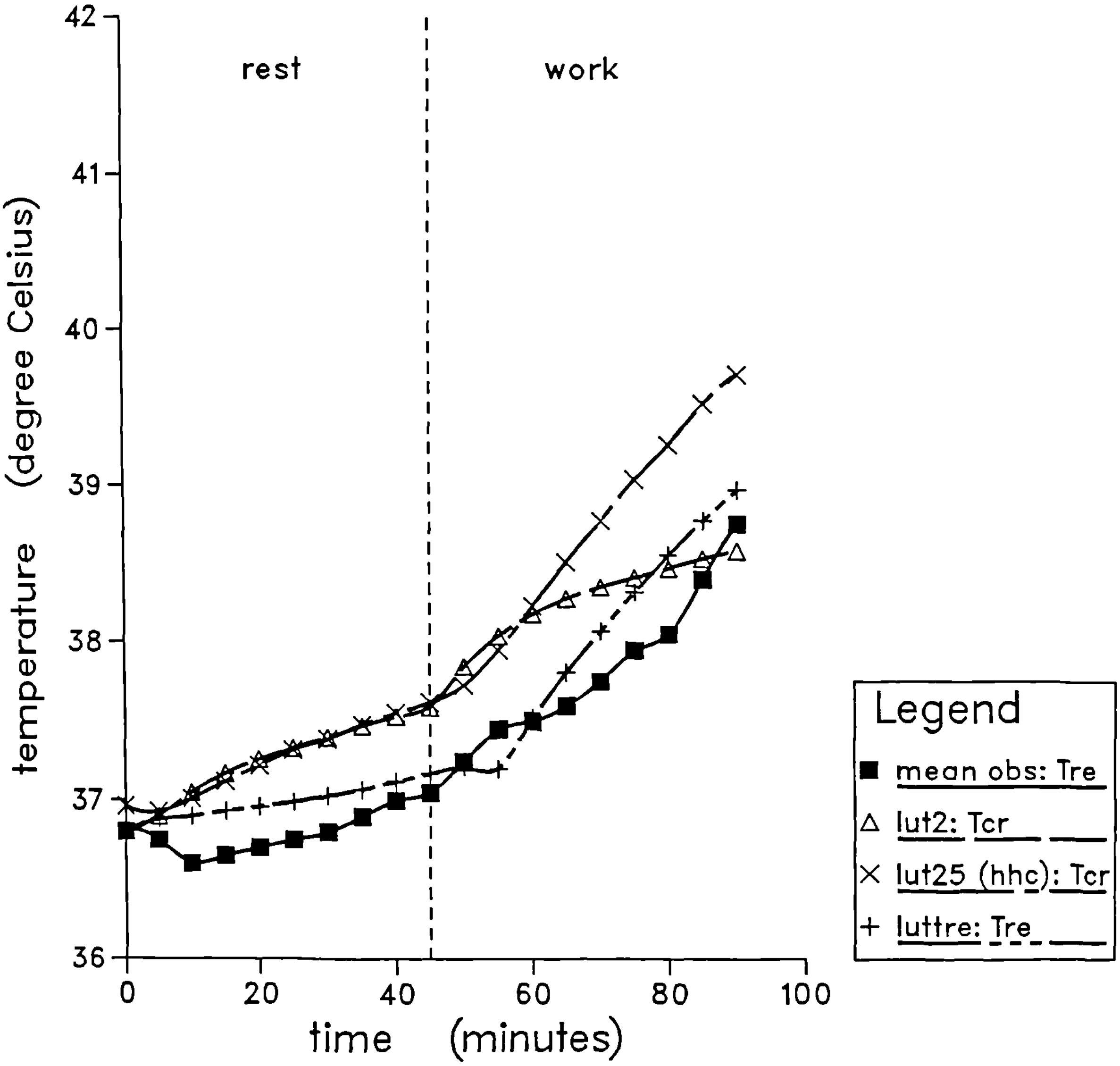
Tsk from Iampietro et al (1958) (n=6) (exp code: 8)
Ta=Tr=15.6 C, v=4.6 m/s, rh=14 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=49 W/m2, W=0 W/m2



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

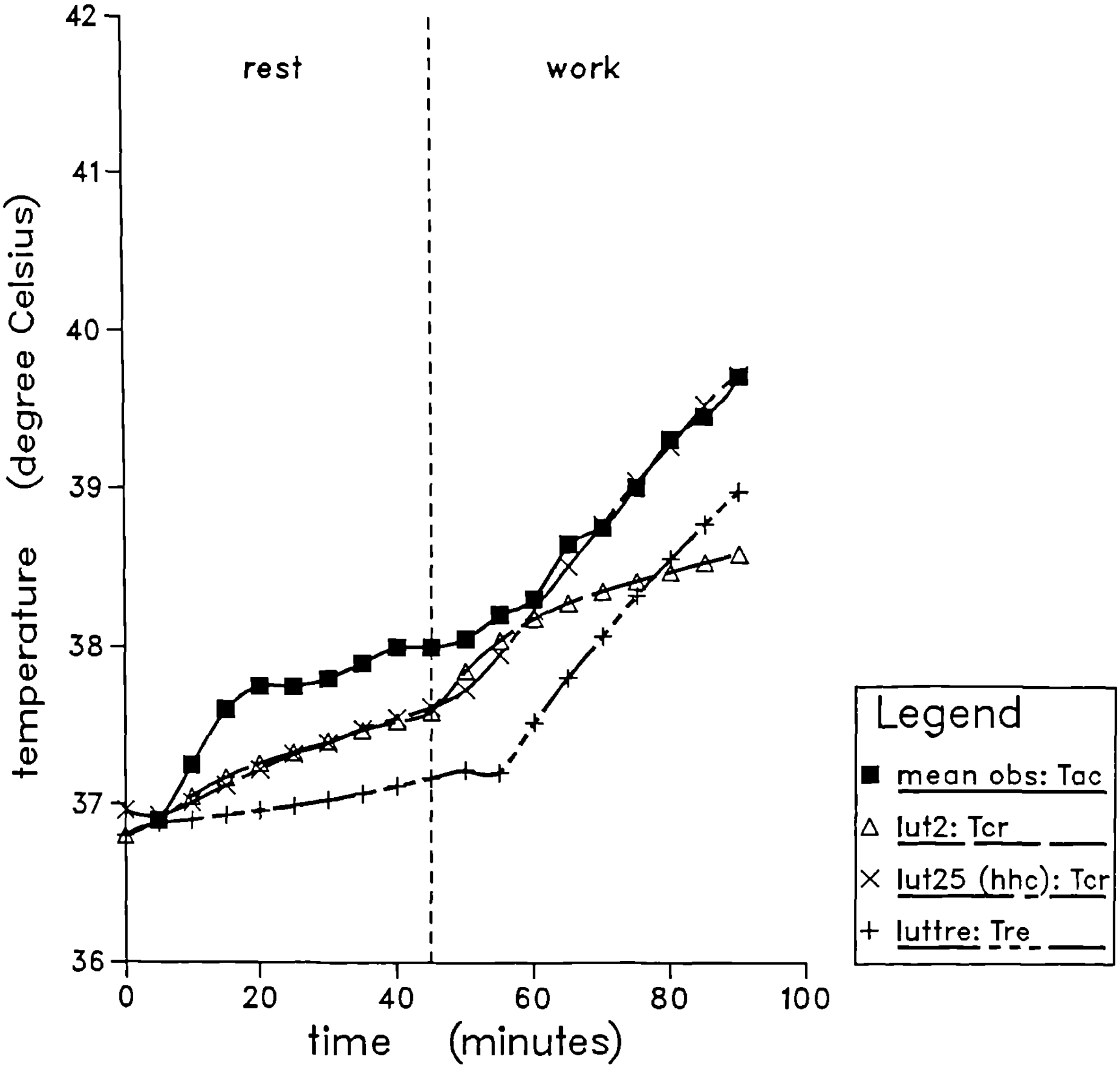


Tre from Kobayashi et al. (1980) (n=5) (moderate work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=204 W/m2, W=28 W/m2 (work)



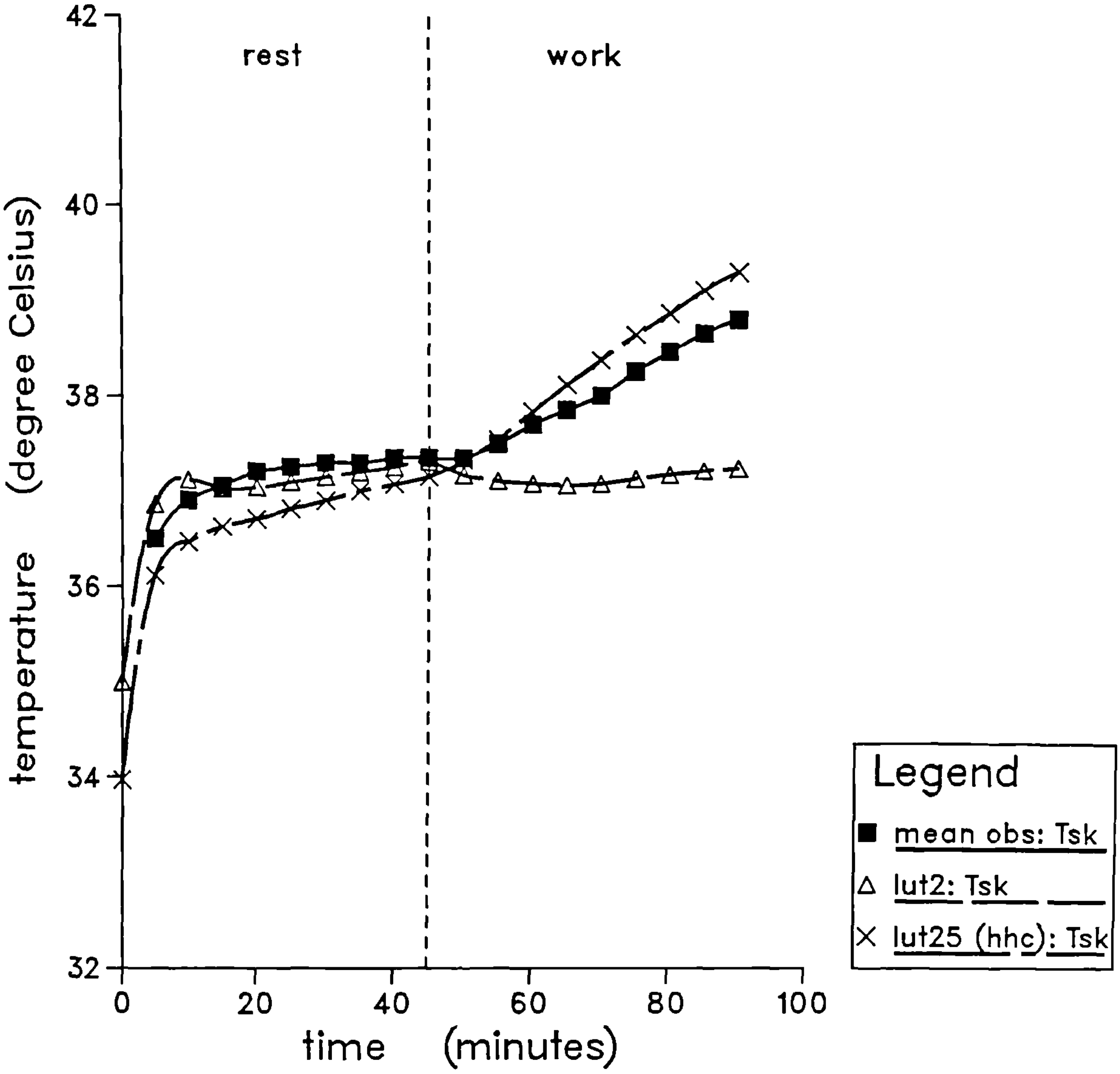
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 34 min; body temperature increase
danger non-accl : 41 min; body temperature increase
warning accl : 45 min; body temperature increase
danger accl : 59 min; body temperature increase

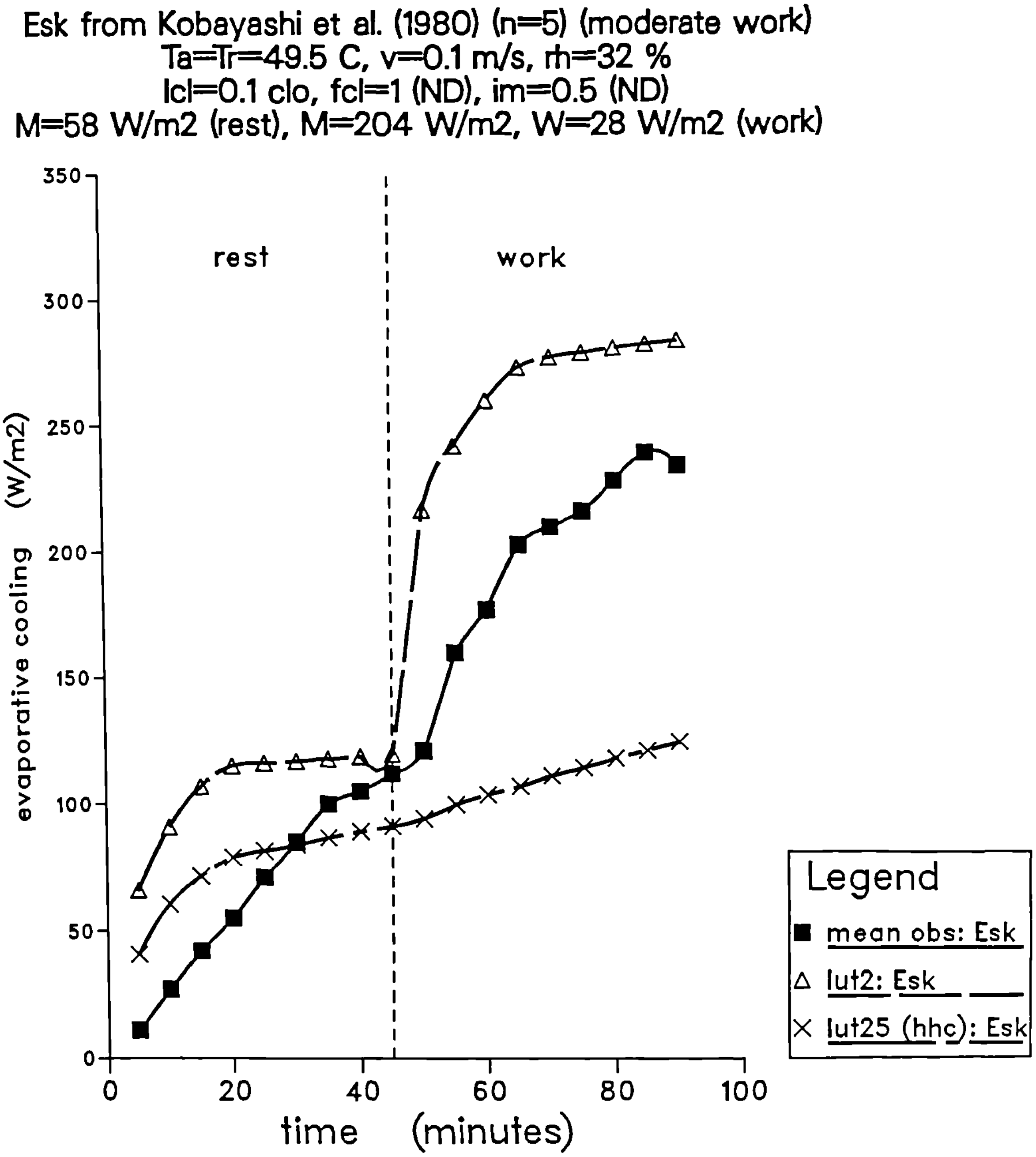
Tac from Kobayashi et al. (1980) (n=5) (moderate work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=204 W/m2, W=28 W/m2 (work)



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

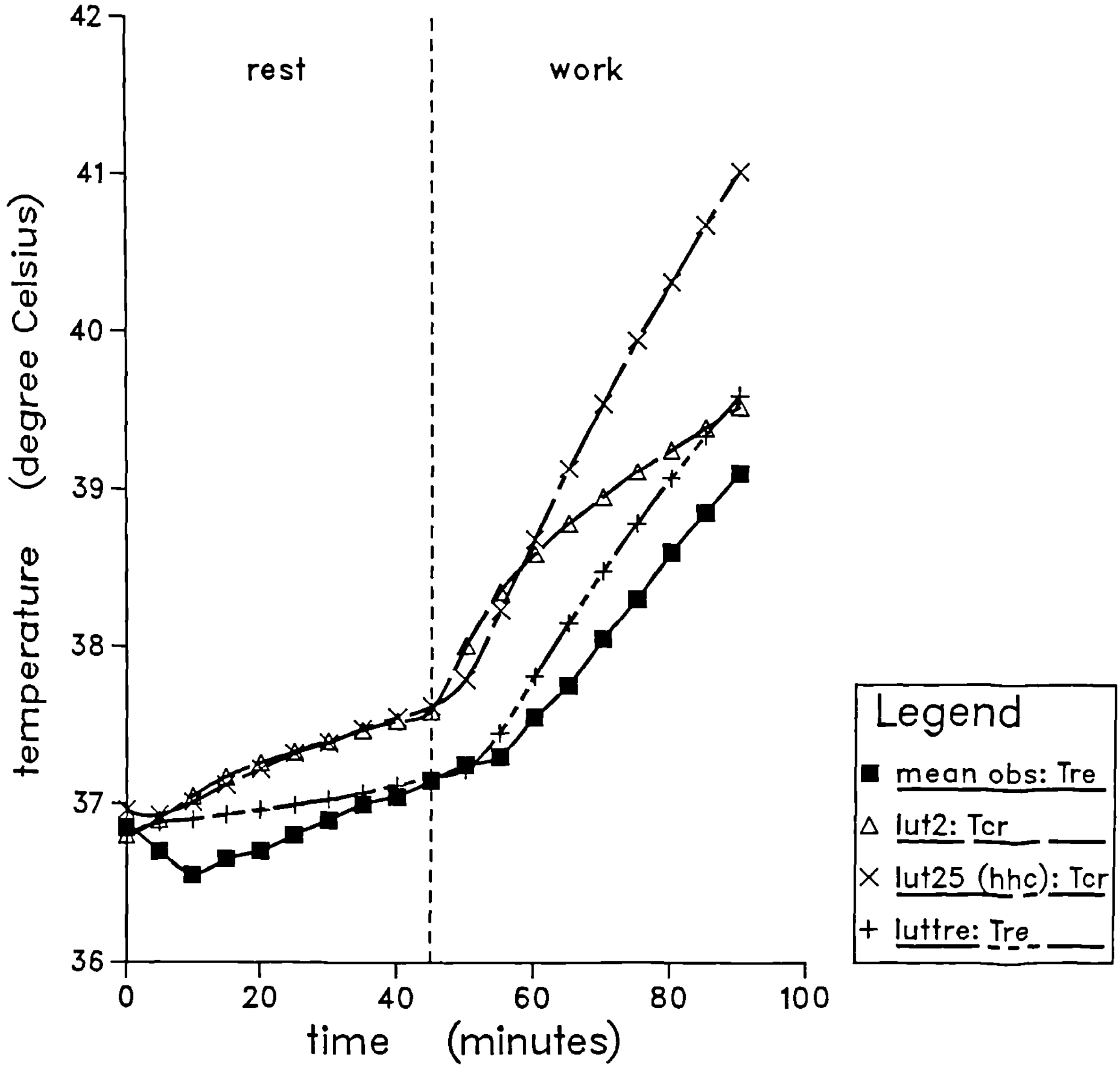
Tsk from Kobayashi et al. (1980) (n=5) (moderate work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=204 W/m2, W=28 W/m2 (work)





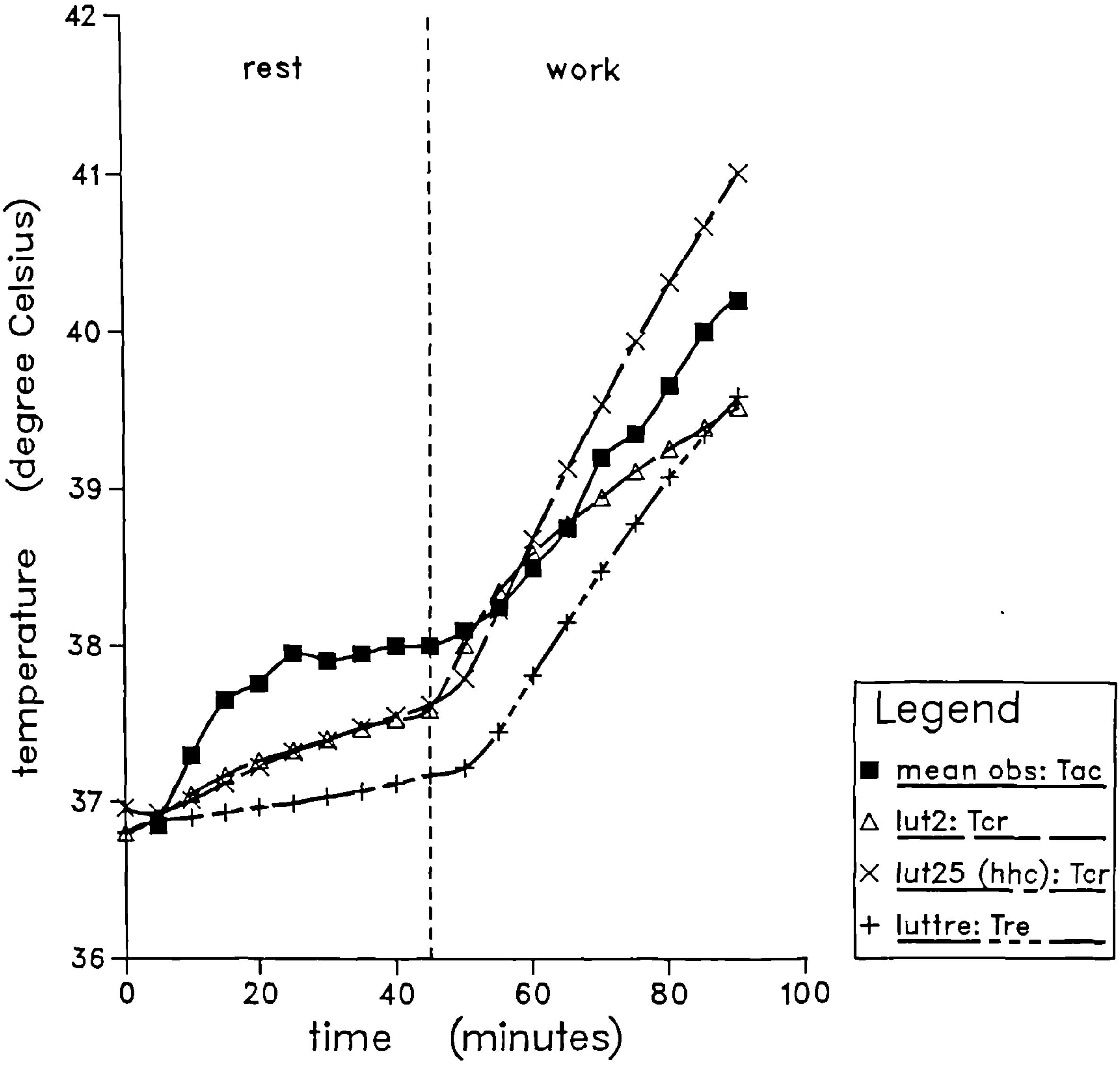
Esk from Kobayashi et al. (1980) (n=5) (moderate work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=204 W/m2, W=28 W/m2 (work)
rest
work
evaporative cooling (W/m2)
0
50
100
150
200
250
300
350
0
20
40
60
80
100
time (minutes)
Legend
mean obs: Esk
lut2: Esk
lut25 (hhc): Esk

Tre from Kobayashi et al. (1980) (n=5) (heavy work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)



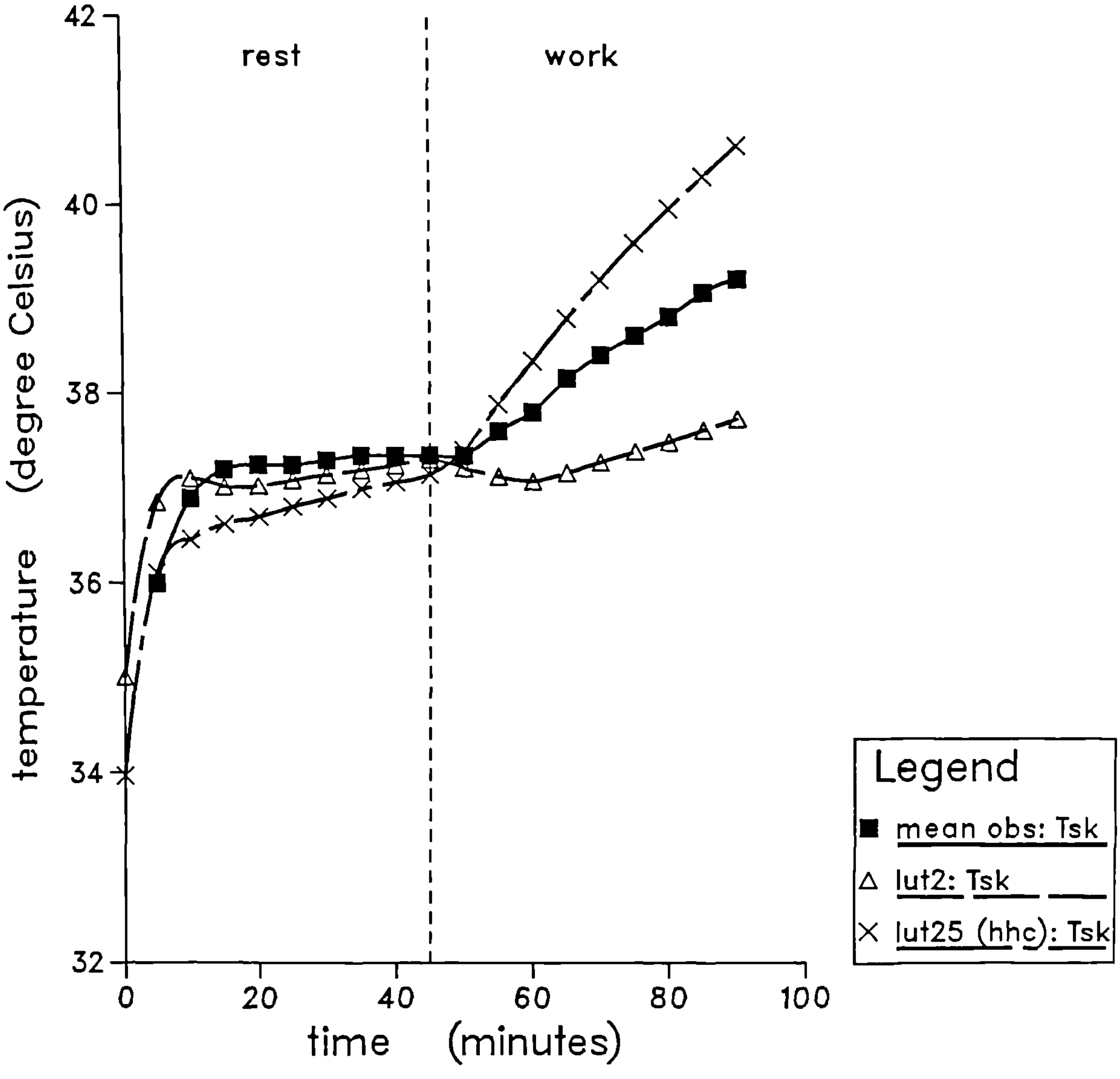
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 16 min; body temperature increase
danger non-accl : 24 min; body temperature increase
warning accl : 23 min; body temperature increase
danger accl : 34 min; body temperature increase

Tac from Kobayashi et al. (1980) (n=5) (heavy work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)

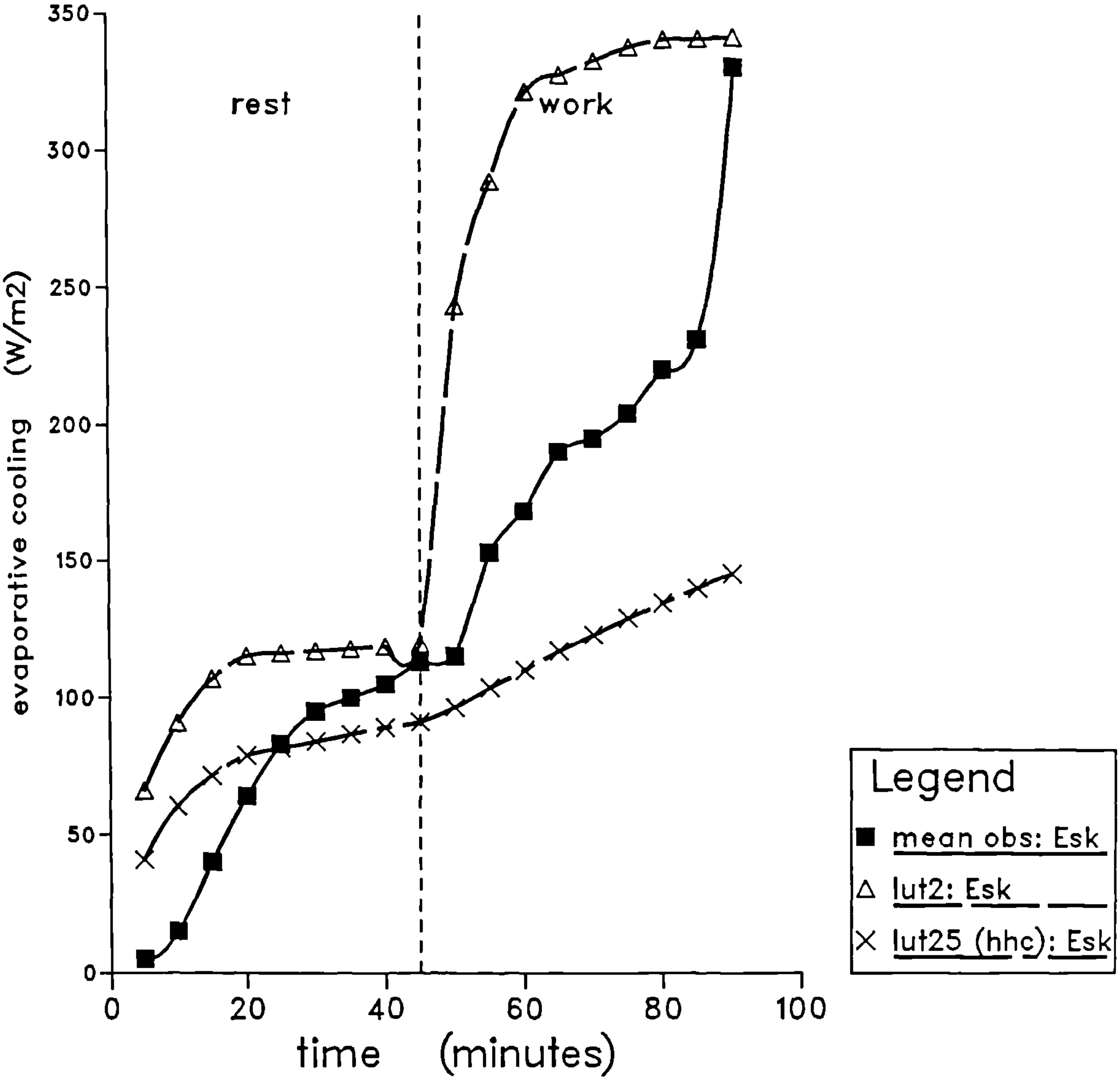


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 16 min; body temperature increase
danger non-accl : 24 min; body temperature increase
warning accl : 23 min; body temperature increase
danger accl : 34 min; body temperature increase

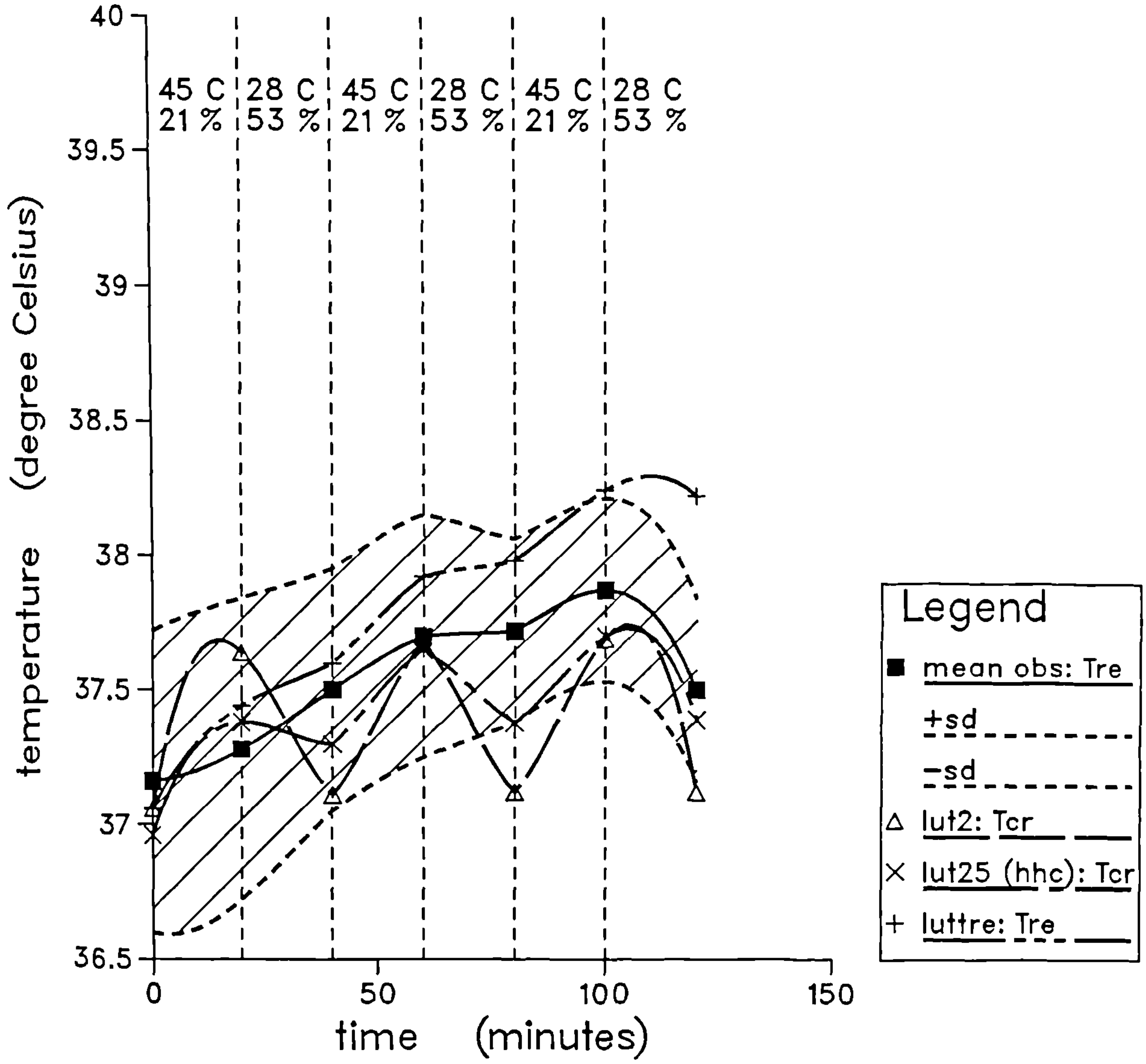
Tsk from Kobayashi et al. (1980) (n=5) (heavy work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)



Esk from Kobayashi et al. (1980) (n=5) (heavy work)
Ta=Tr=49.5 C, v=0.1 m/s, rh=32 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND)
M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)

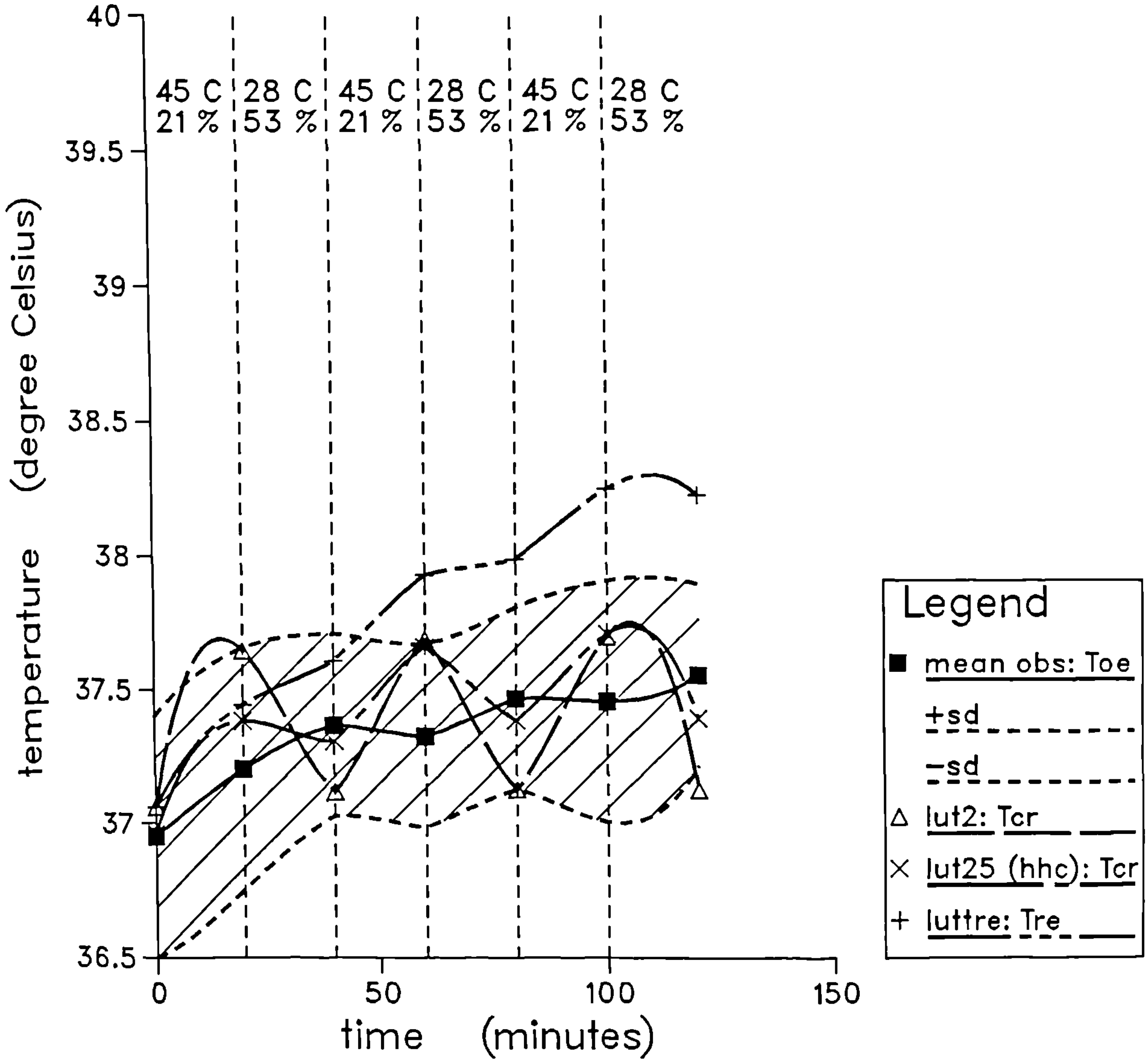


Tre from Mairiaux et al. (1986) (n=5) (exp. code: WD-1)
Ta=Tr=45-28 C, v=0.2 m/s, rh=21-53 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



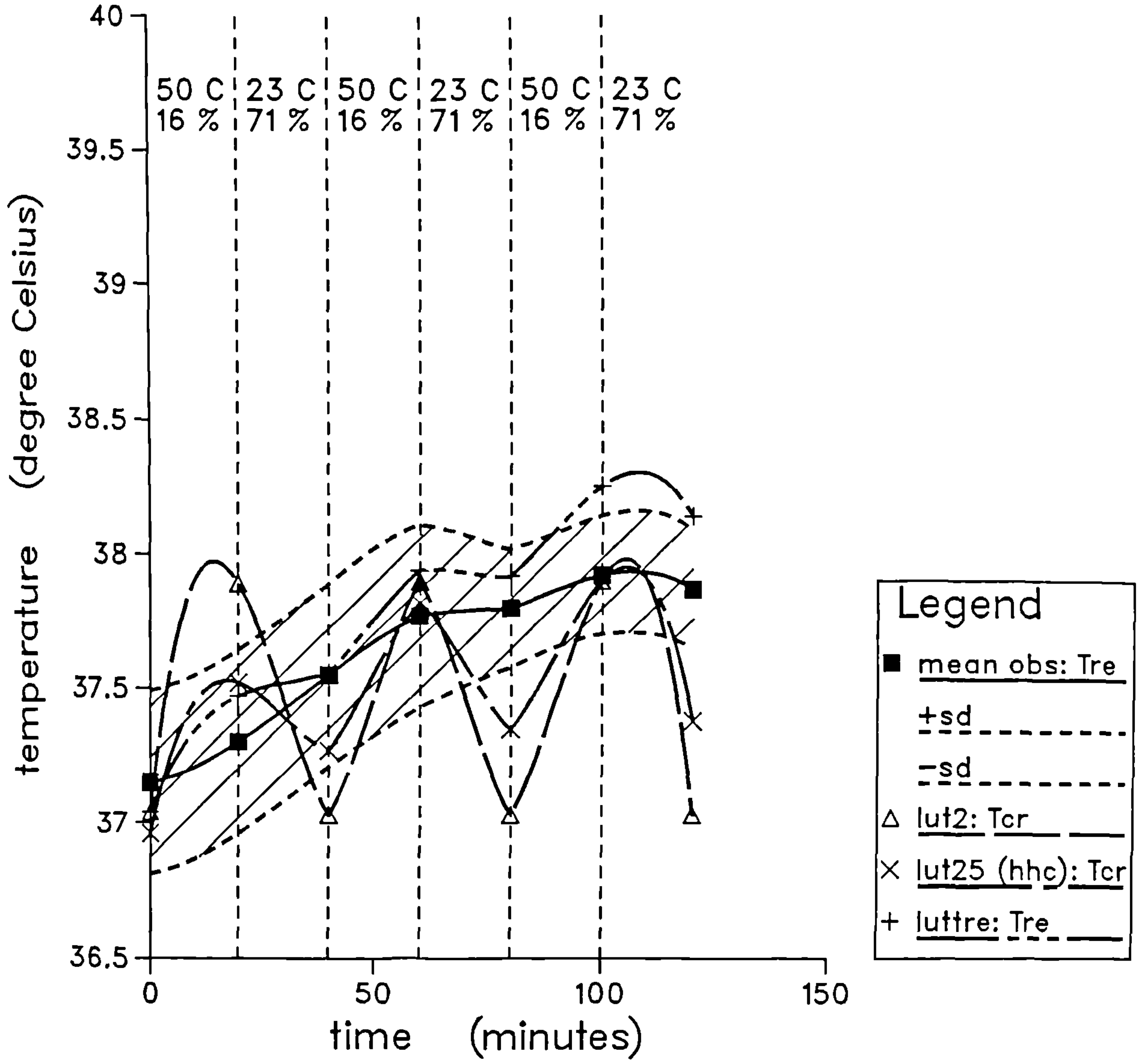
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Toe from Mairiaux et al. (1986) (n=5) (exp. code: WD-1)
Ta=Tr=45-28 C, v=0.2 m/s, rh=21-53 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



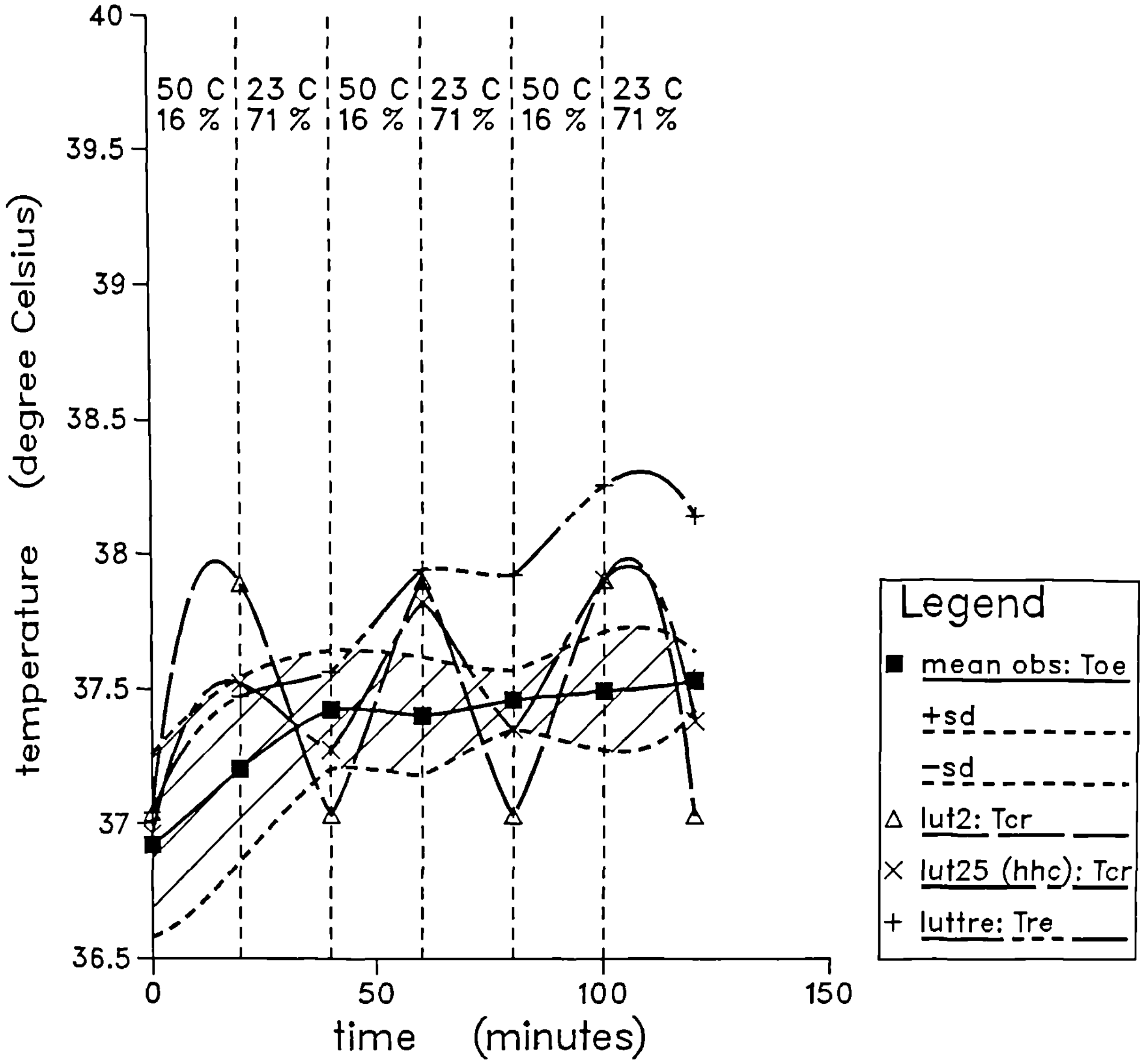
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

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 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



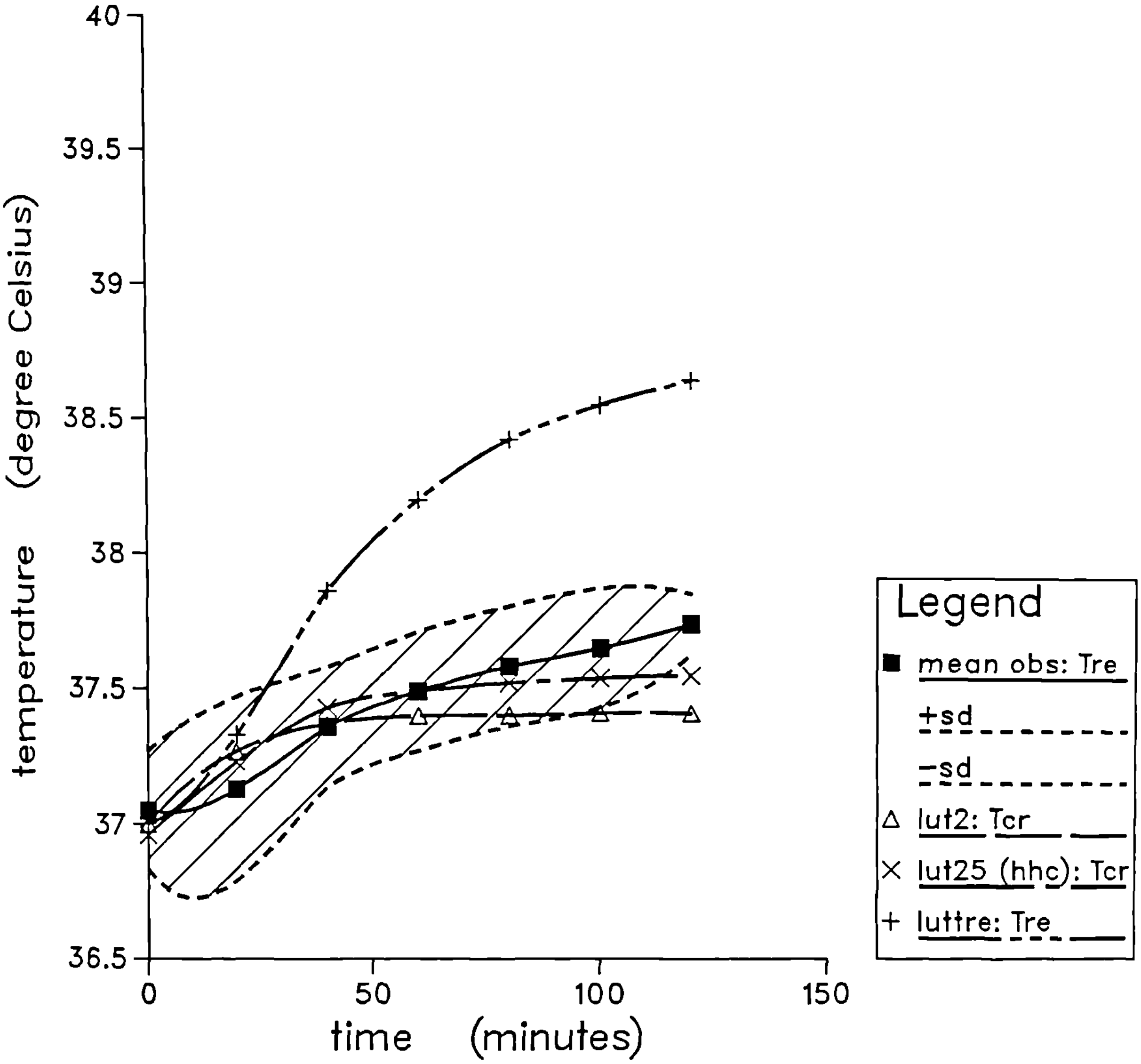
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 390 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

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 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



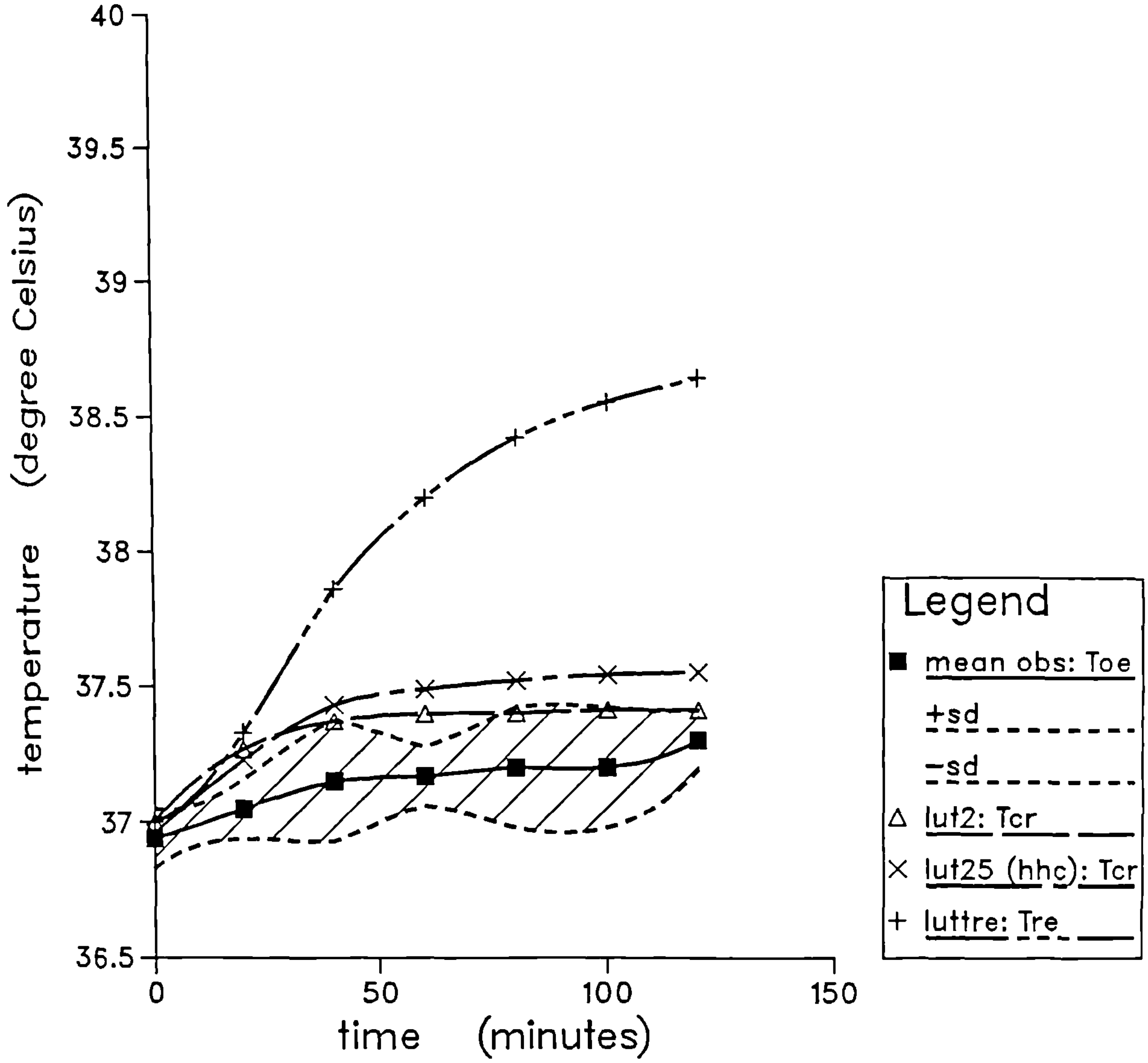
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl : 390 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tre from Mairiaux et al. (1986) (n=5) (exp. code: WD-3)
Ta=Tr=36.5 C, v=0.2 m/s, rh=33 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



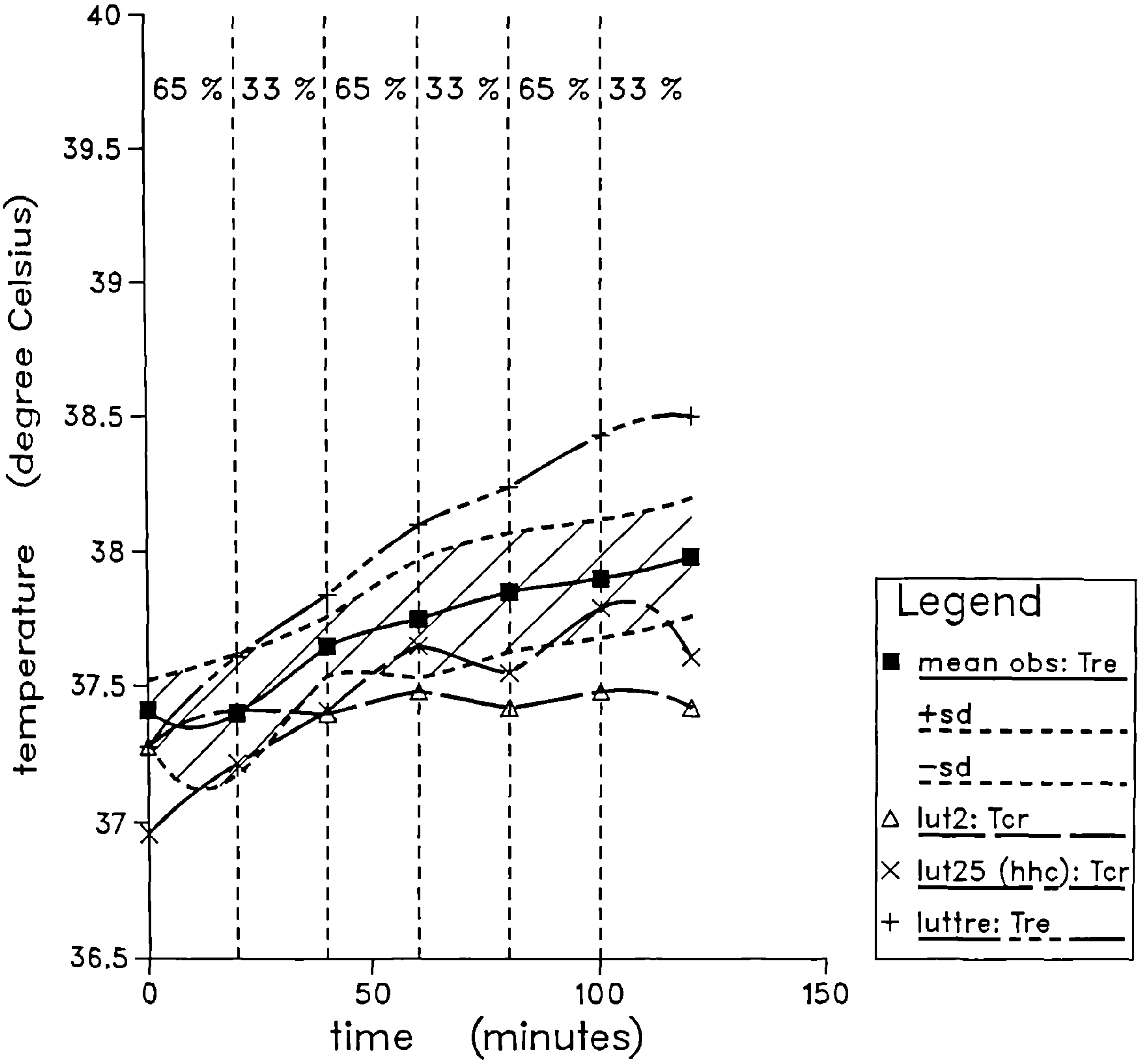
lutiso Allowable Exposure Times
warning non−accl: 399 min; excessive dehydration
danger non−accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Toe from Mairiaux et al. (1986) (n=5) (exp. code: WD-3)
Ta=Tr=36.5 C, v=0.2 m/s, rh=33 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



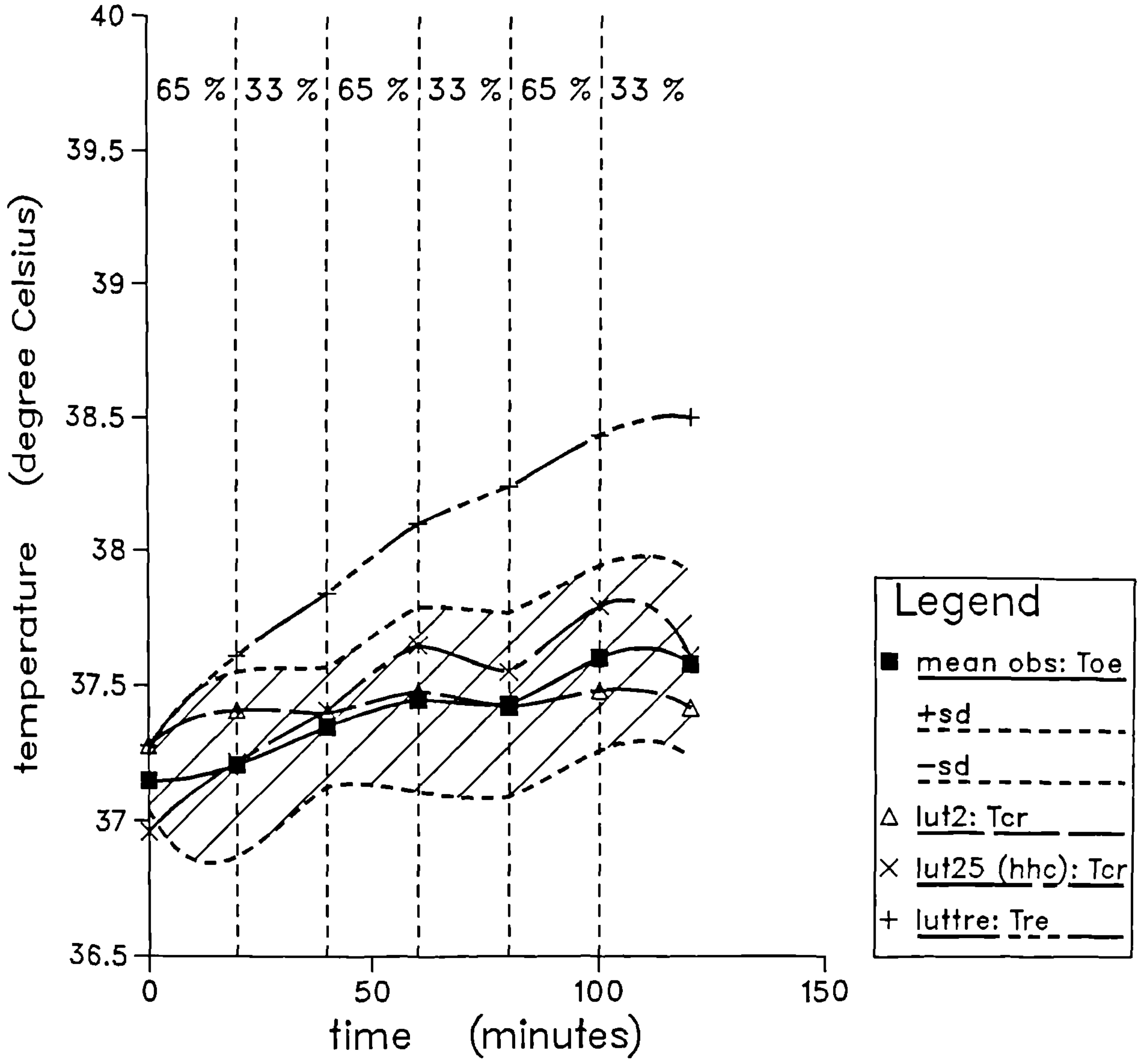
lutiso Allowable Exposure Times
warning non-accl: 399 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tre from Mairiaux et al. (1986) (n=5) (exp. code: WH-1)
Ta=Tr=36.5 C, v=0.2 m/s, rh=65-33 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



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

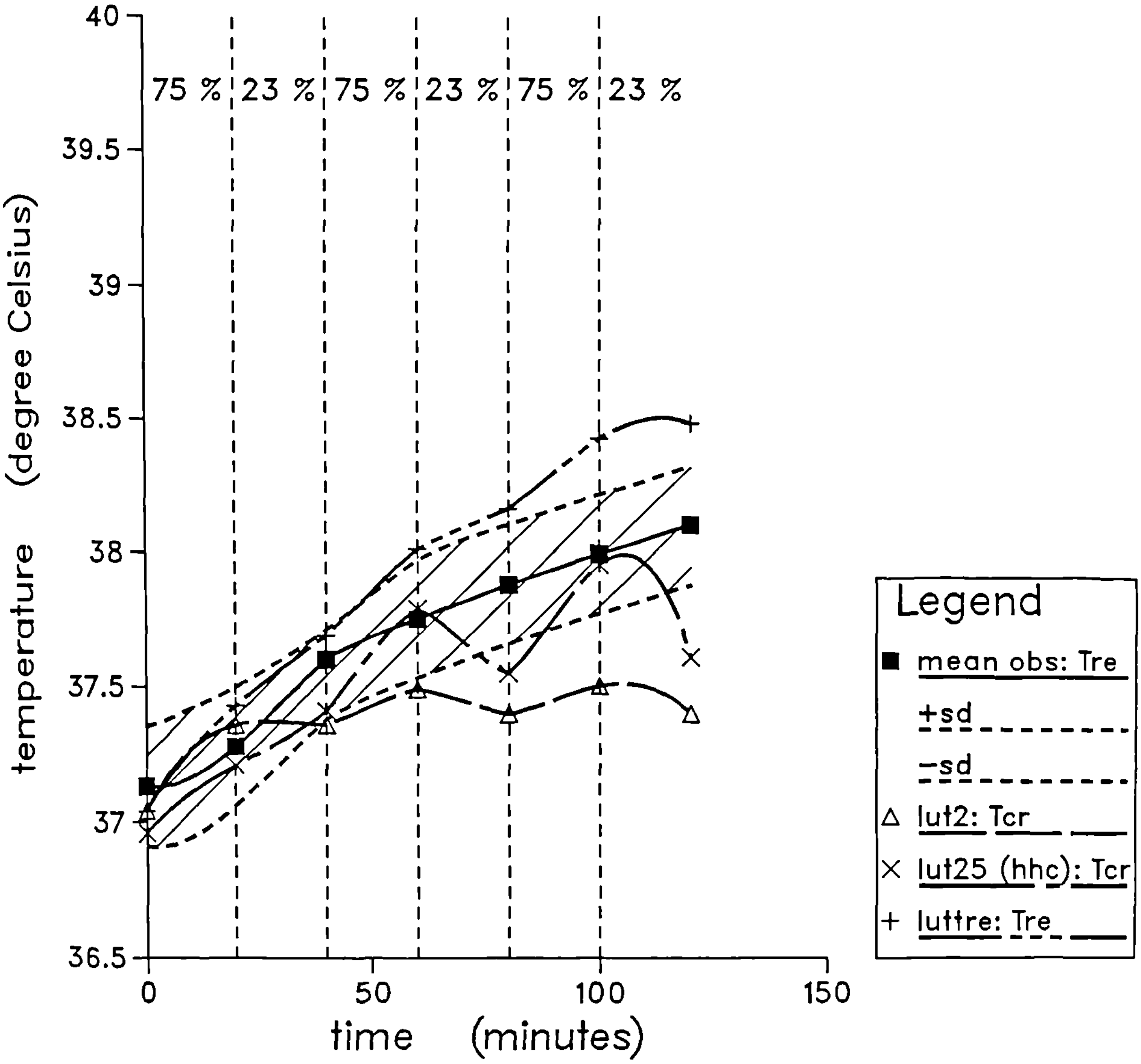
Toe from Mairiaux et al. (1986) (n=5) (exp. code: WH-1)
Ta=Tr=36.5 C, v=0.2 m/s, rh=65-33 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



lutiso Allowable Exposure Times
(time weighted averages):

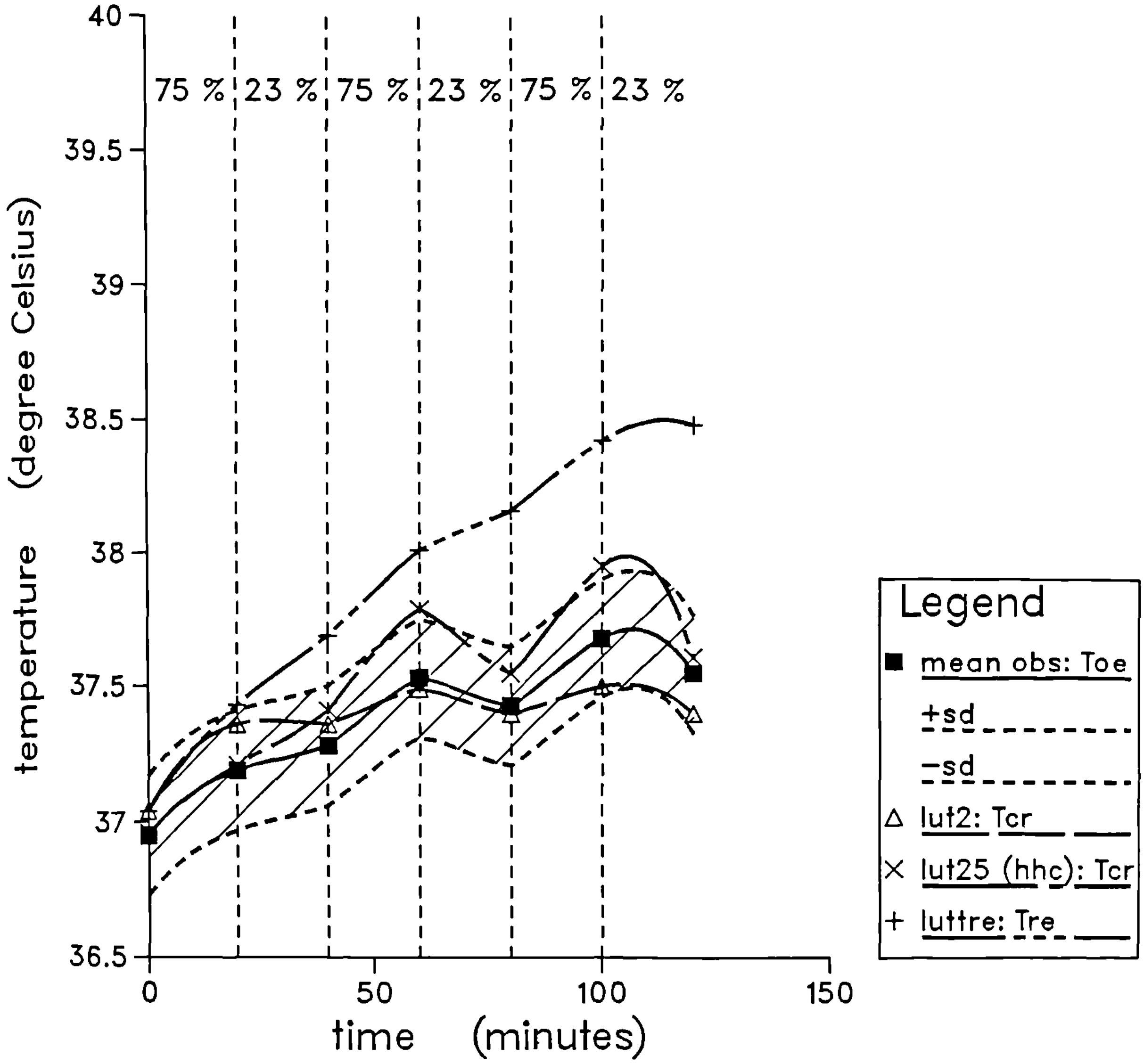
```
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl    : 480 min; unlimited duration
danger accl     : 480 min; unlimited duration
```

Tre from Mairiaux et al. (1986) (n=5) (exp. code: WH-2)
Ta=Tr=36.5 C, v=0.2 m/s, rh=75-23 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



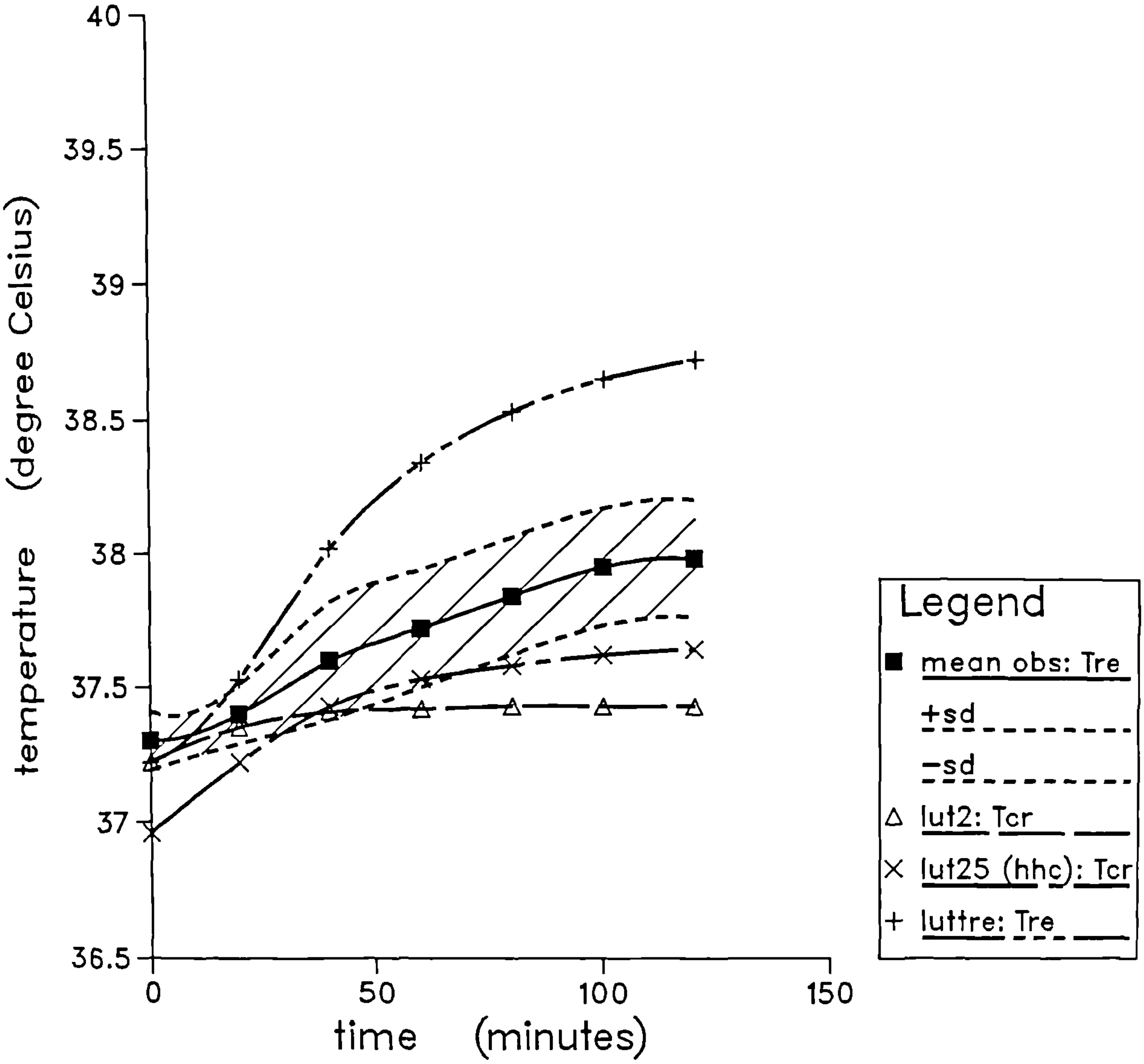
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Toe from Mairiaux et al. (1986) (n=5) (exp. code: WH-2)
Ta=Tr=36.5 C, v=0.2 m/s, rh=75-23 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



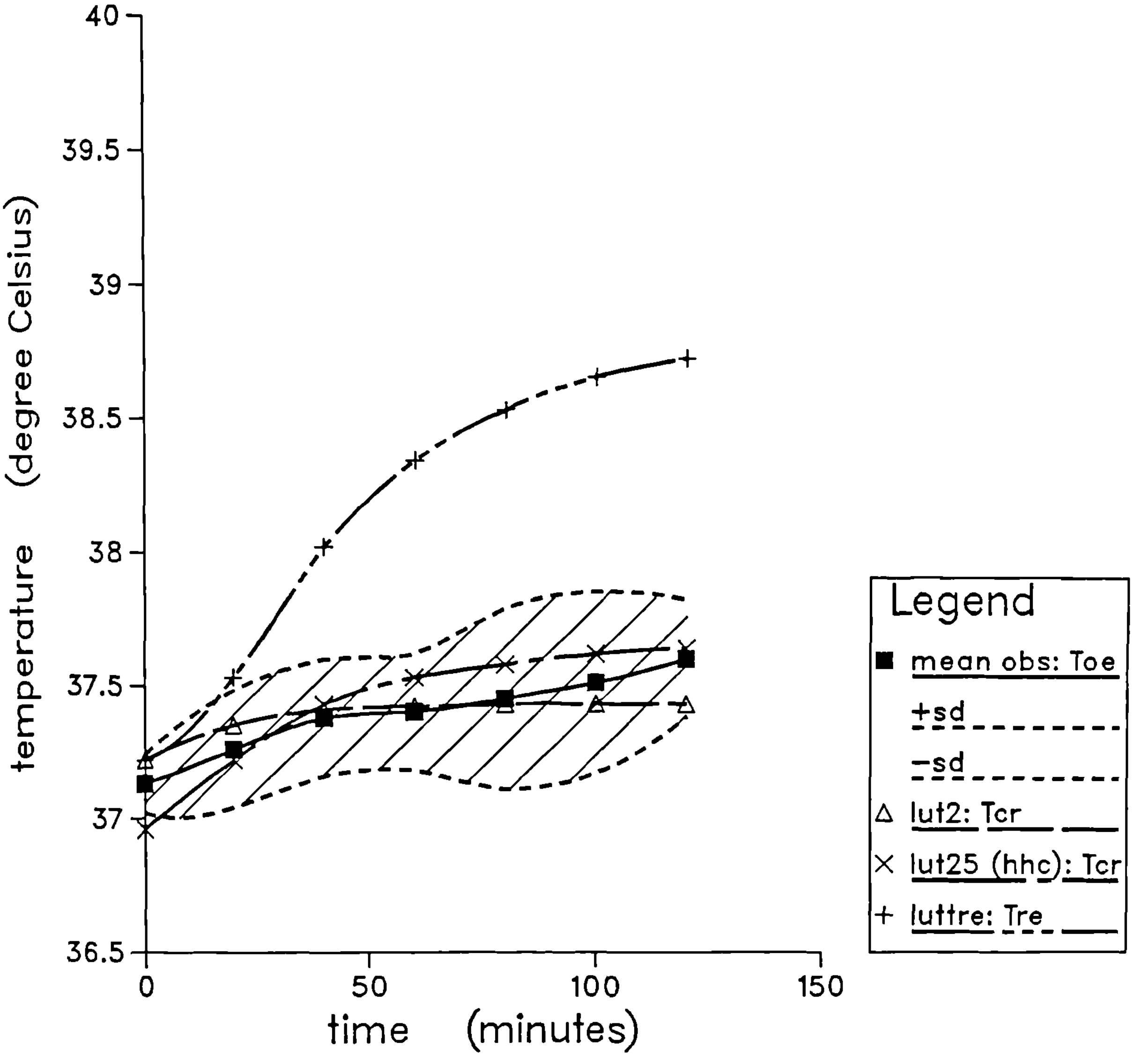
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tre from Mairiaux et al. (1986) (n=5) (exp. code: WH-3)
Ta=Tr=36.5 C, v=0.2 m/s, rh=49 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2



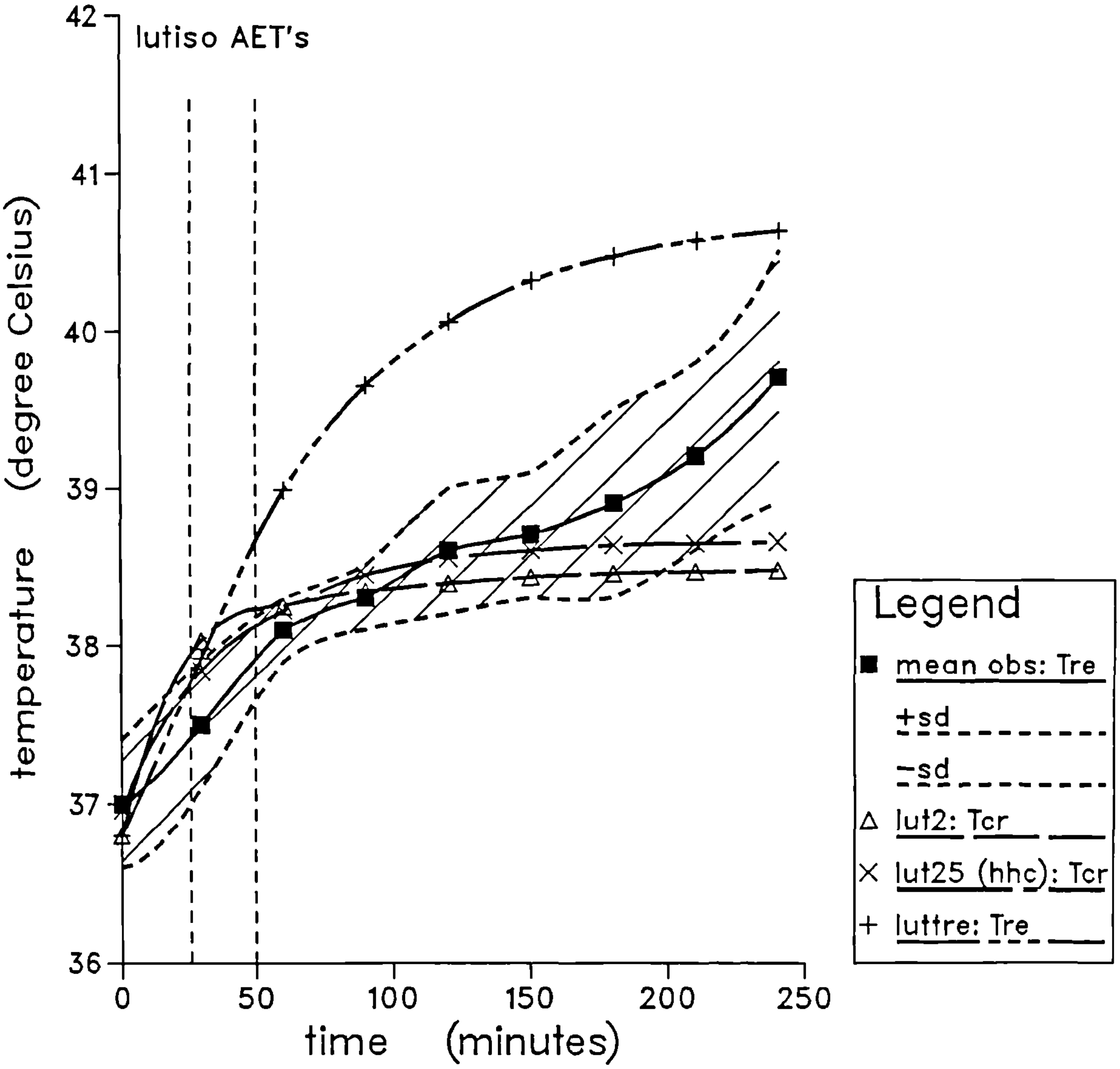
lutiso Allowable Exposure Times
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Toe from Mairiaux et al. (1986) (n=5) (exp. code: WH-3)
Ta=Tr=36.5 C, v=0.2 m/s, rh=49 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=172 W/m2, W=28 W/m2

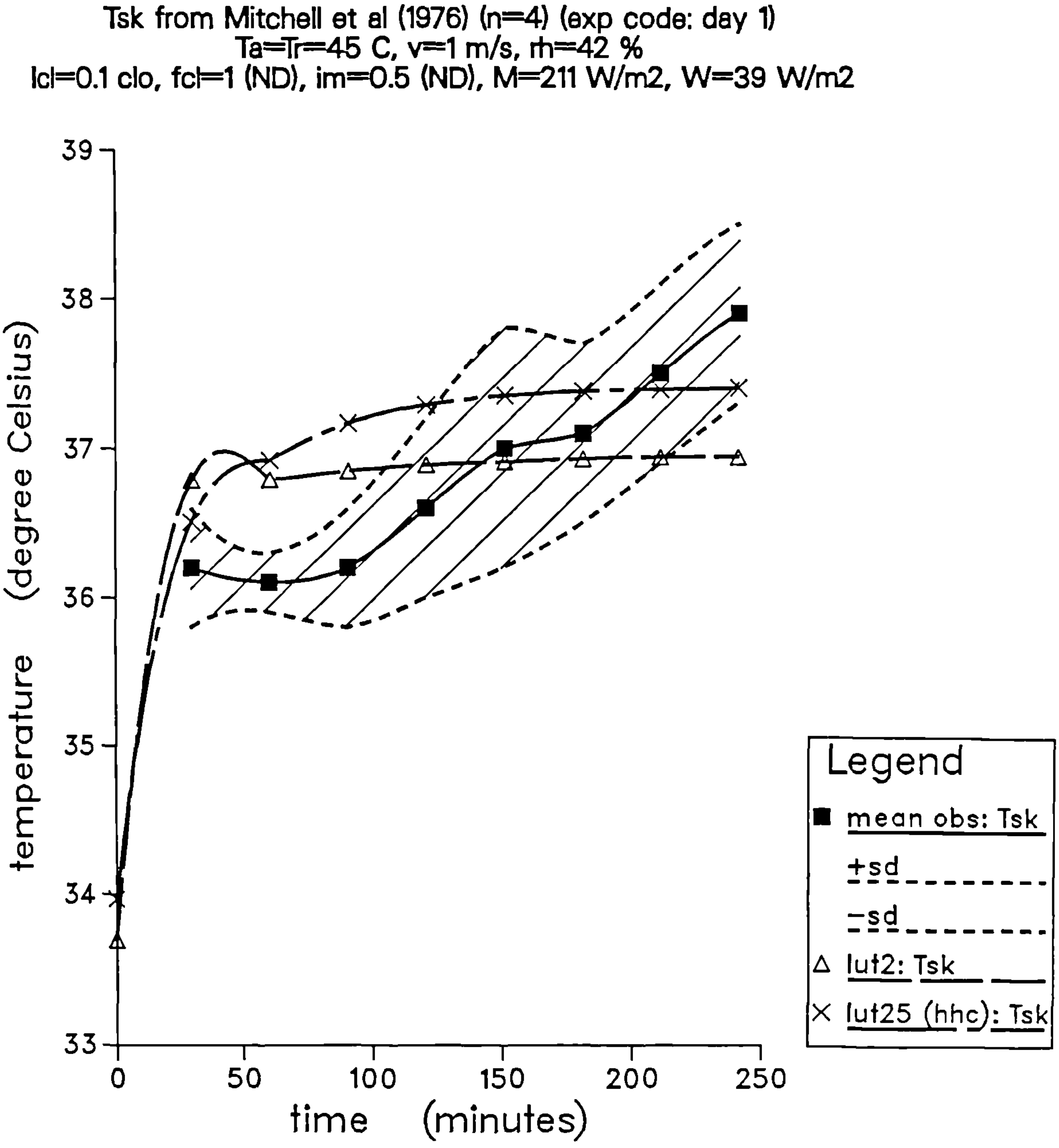


lutiso Allowable Exposure Times
warning non-accl: 395 min; excessive dehydration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

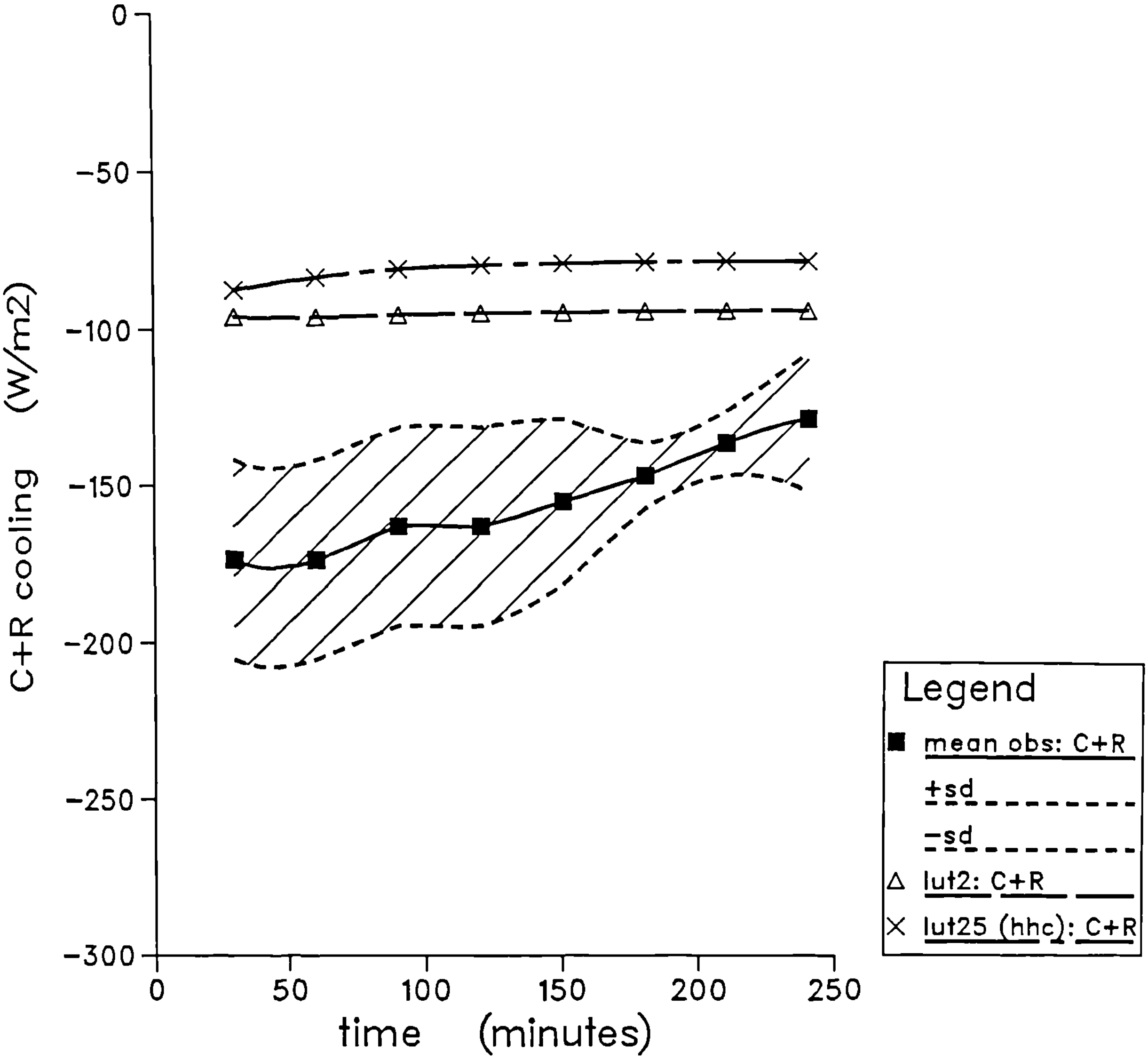
Tre from Mitchell et al (1976) (n=4) (exp code: day 1)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2



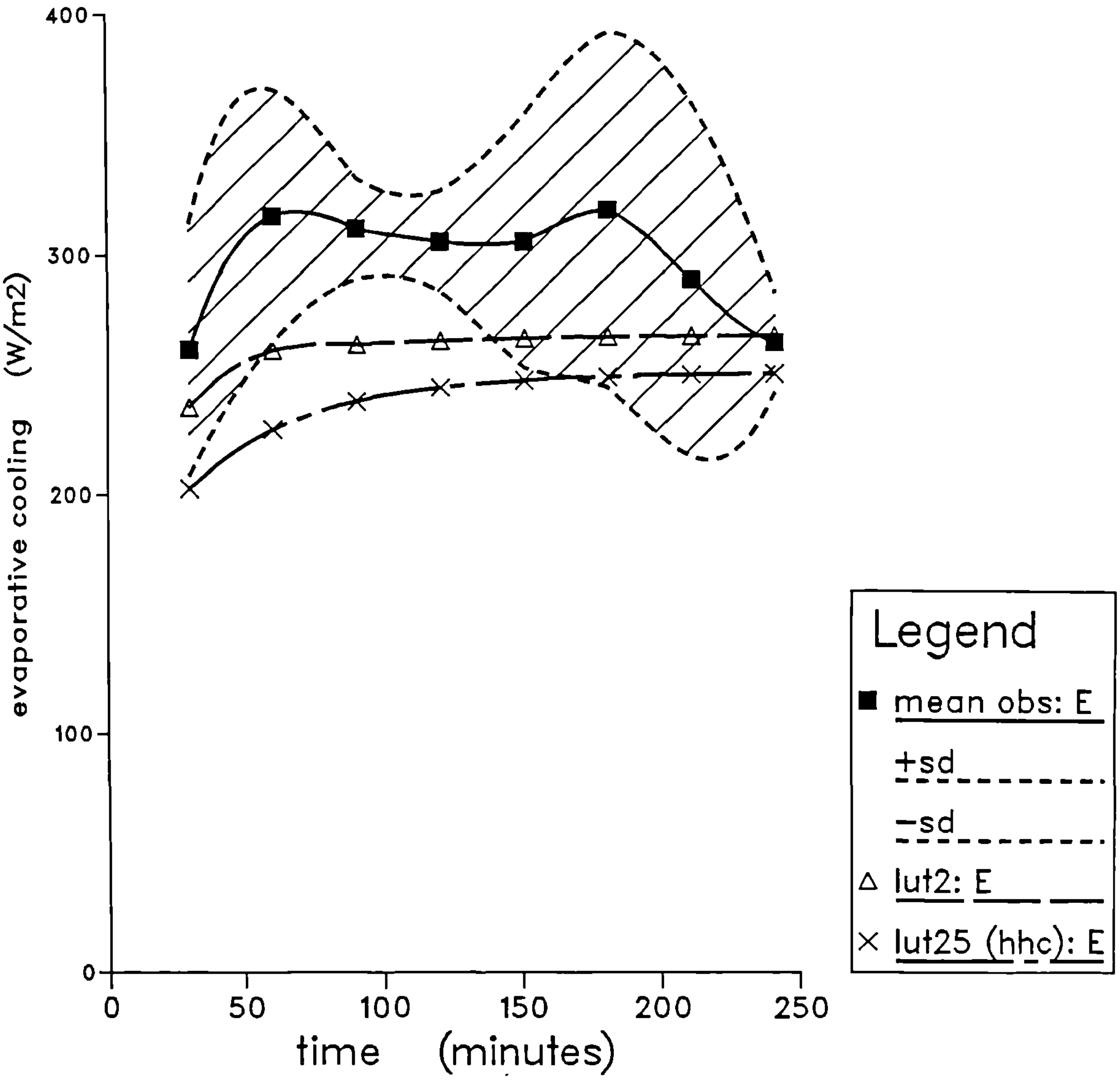
lutiso Allowable Exposure Times
warning non-accl: 26 min; body temperature increase
danger non-accl : 50 min; body temperature increase
warning accl : 60 min; body temperature increase
danger accl : 142 min; body temperature increase


Tsk from Mitchell et al (1976) (n=4) (exp code: day 1)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2
temperature (degree Celsius)
time (minutes)
Legend
mean obs: Tsk
+sd
−sd
lut2: Tsk
lut25 (hhc): Tsk

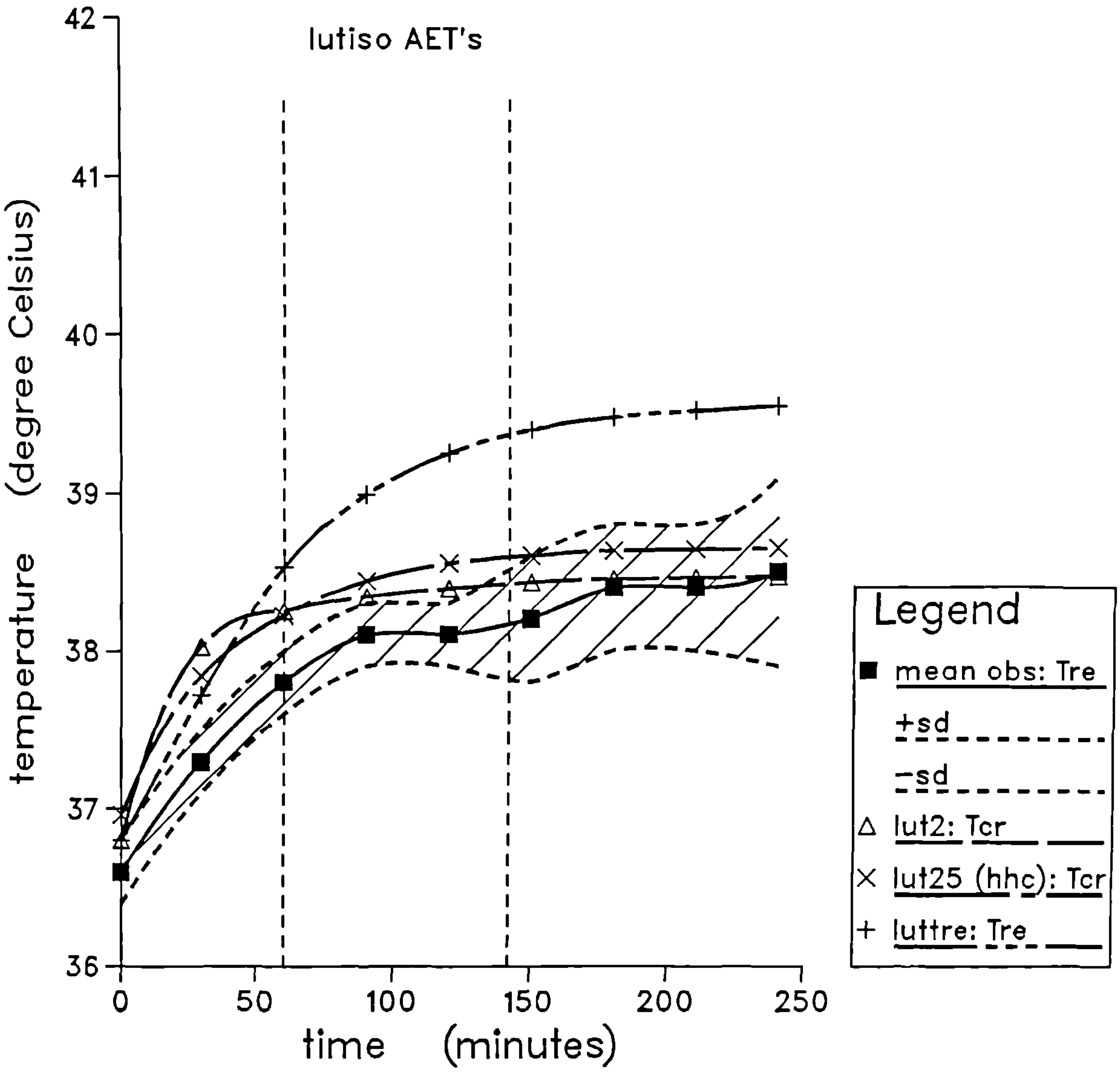
C+R from Mitchell et al (1976) (n=4) (exp code: day 1)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2



E from Mitchell et al (1976) (n=4) (exp code: day 1)
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

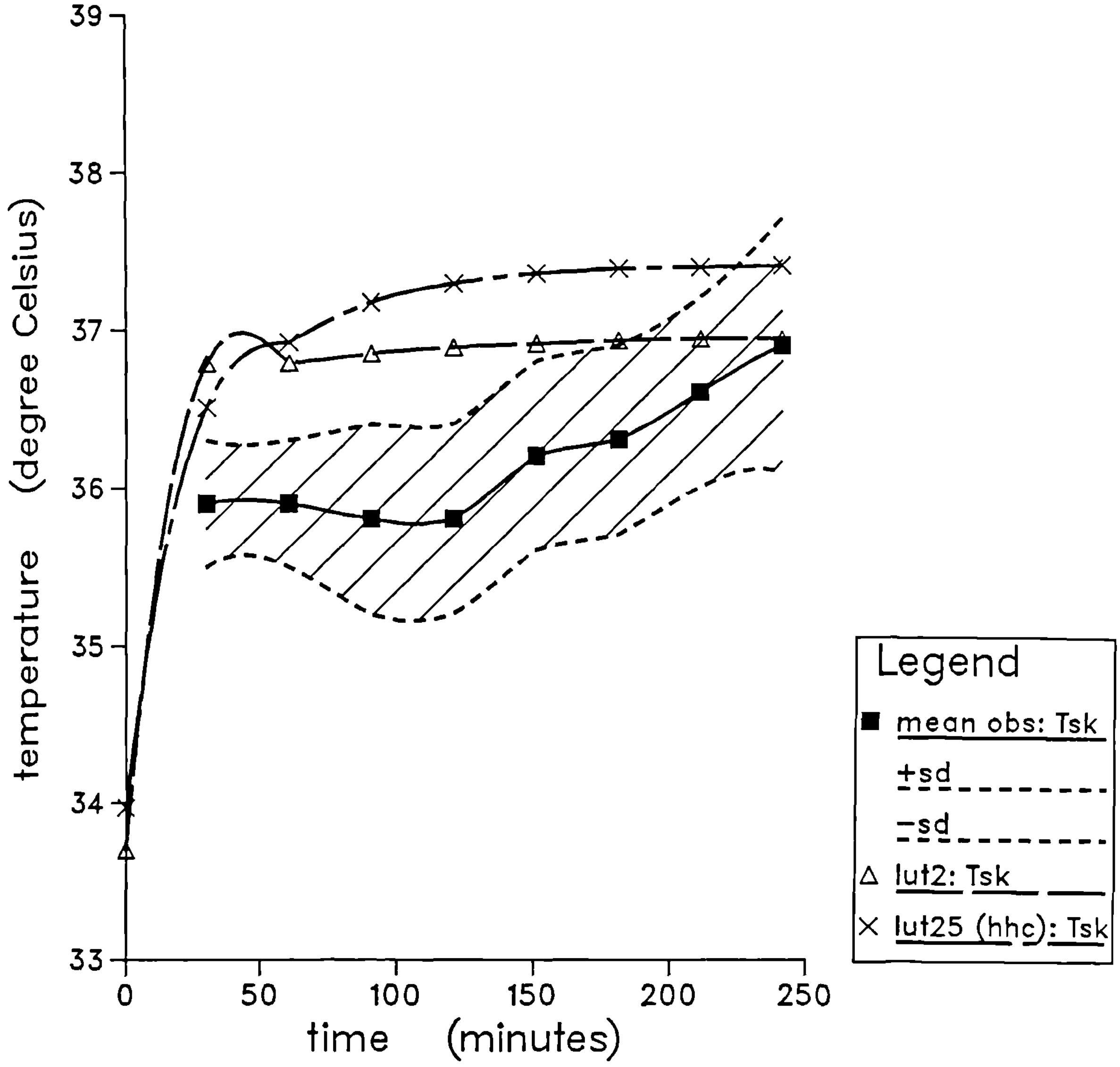


Tre from Mitchell et al (1976) (n=4) (exp code: day 10)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2

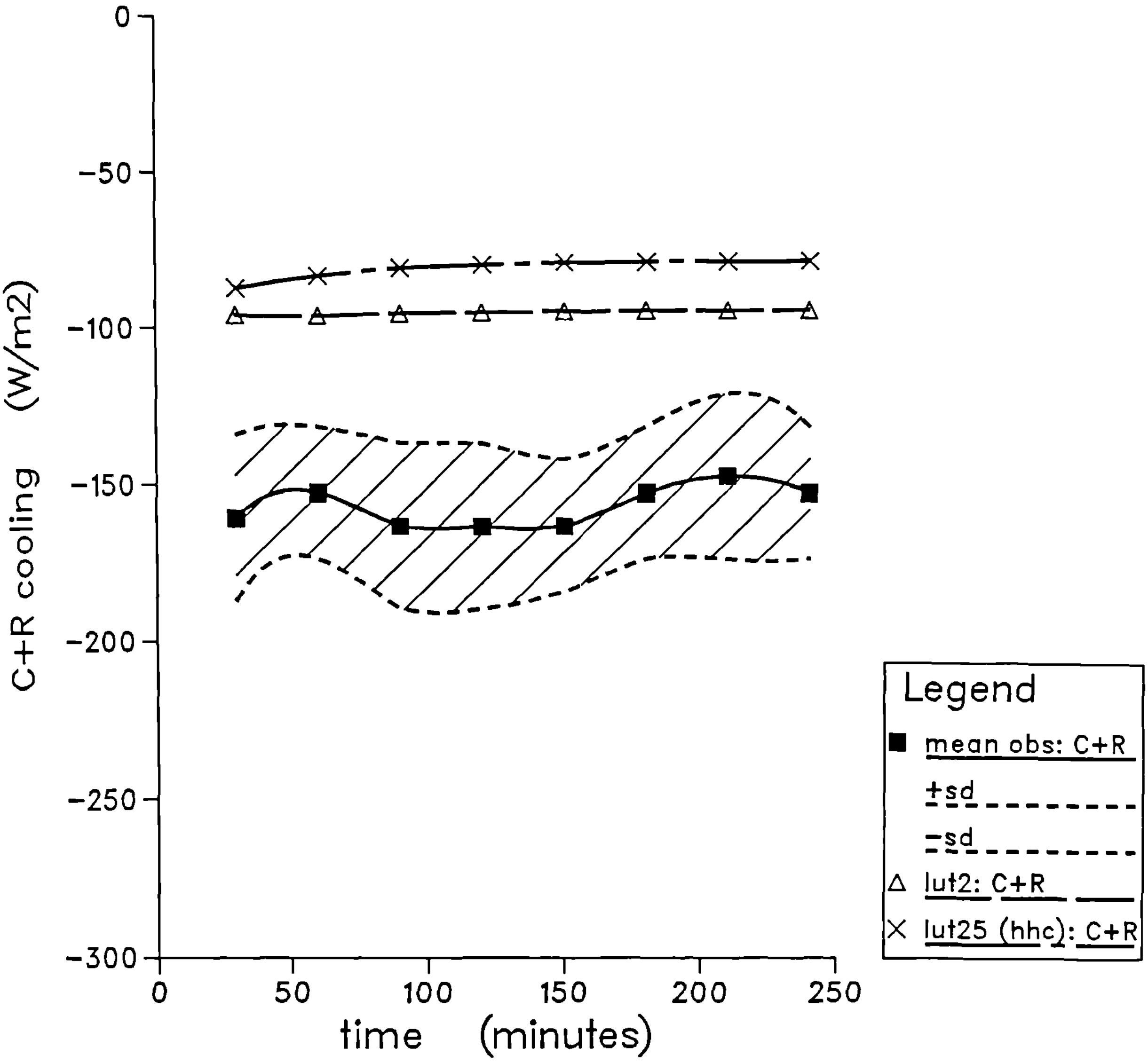


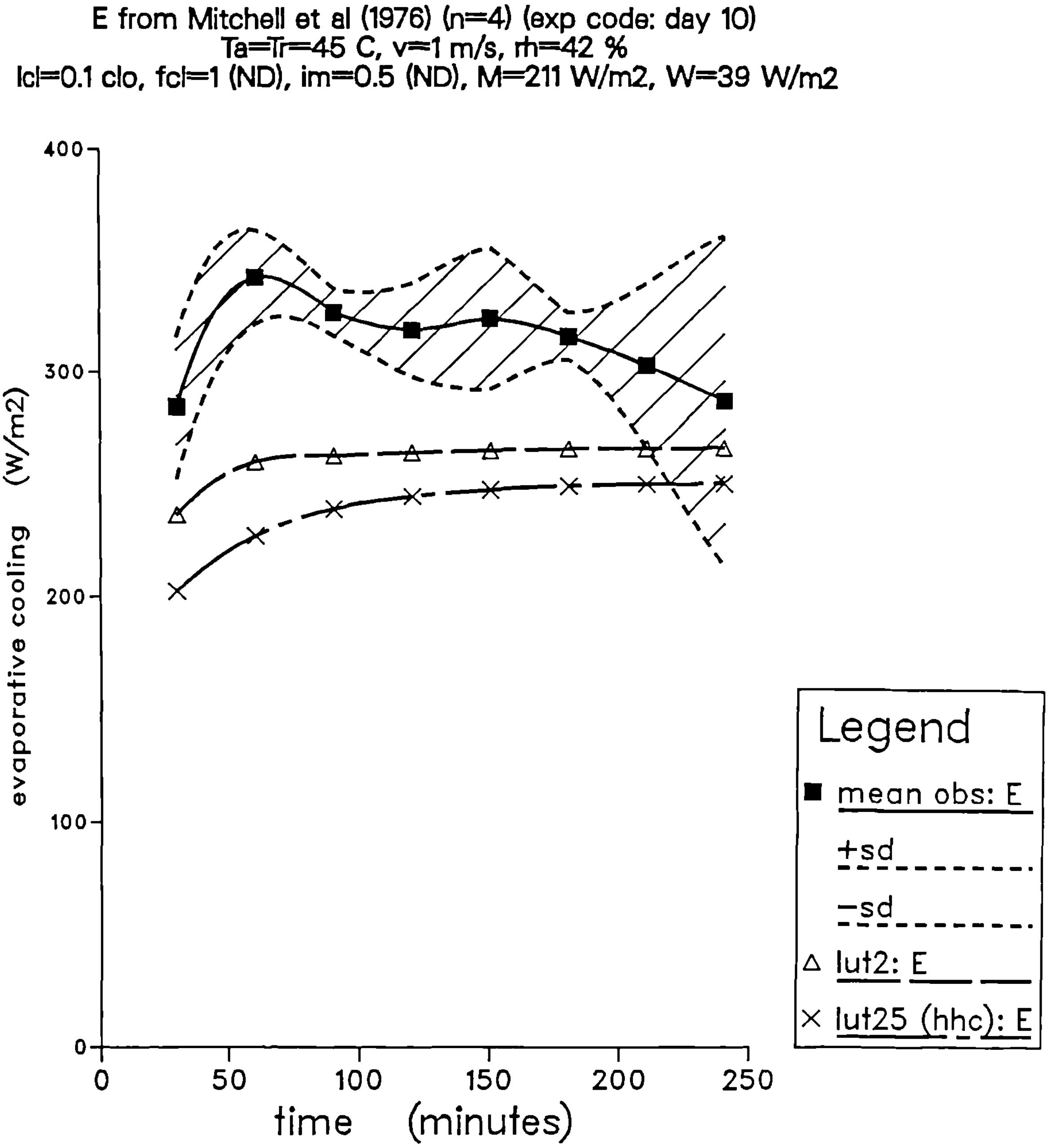
lutiso Allowable Exposure Times
warning non-accl: 26 min; body temperature increase
danger non-accl : 50 min; body temperature increase
warning accl : 60 min; body temperature increase
danger accl : 142 min; body temperature increase

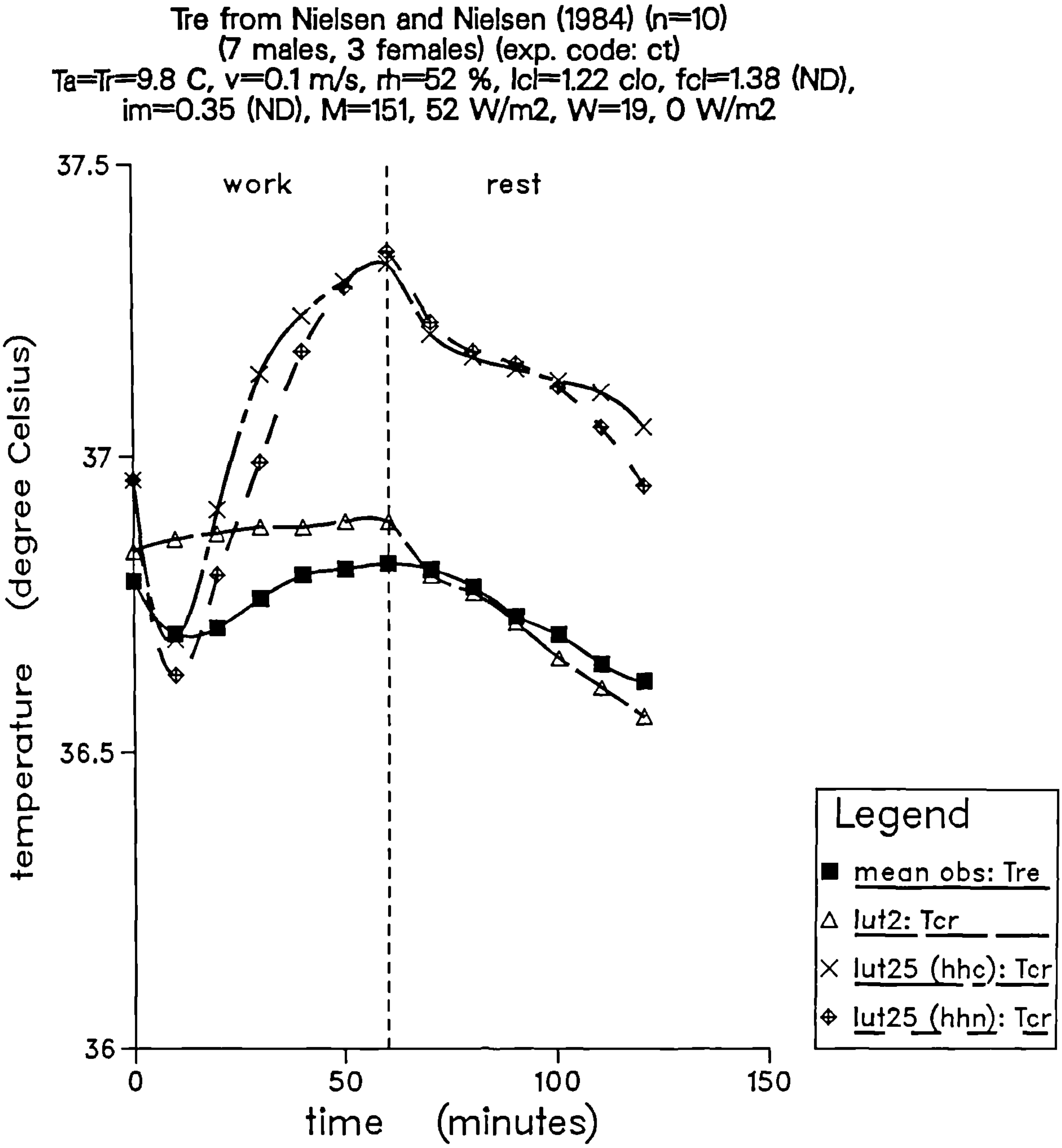
Tsk from Mitchell et al (1976) (n=4) (exp code: day 10)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2



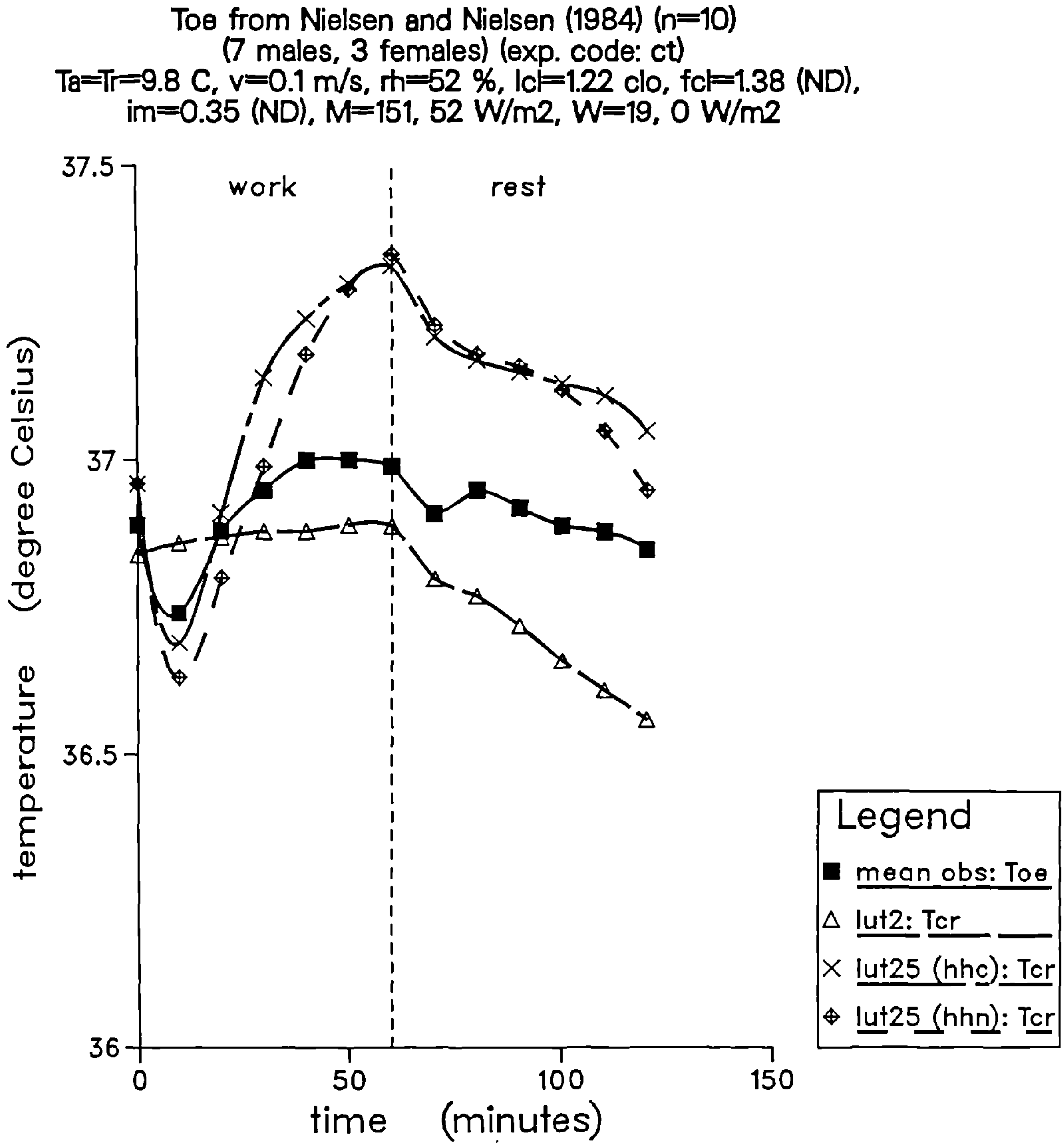
C+R from Mitchell et al (1976) (n=4) (exp code: day 10)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2

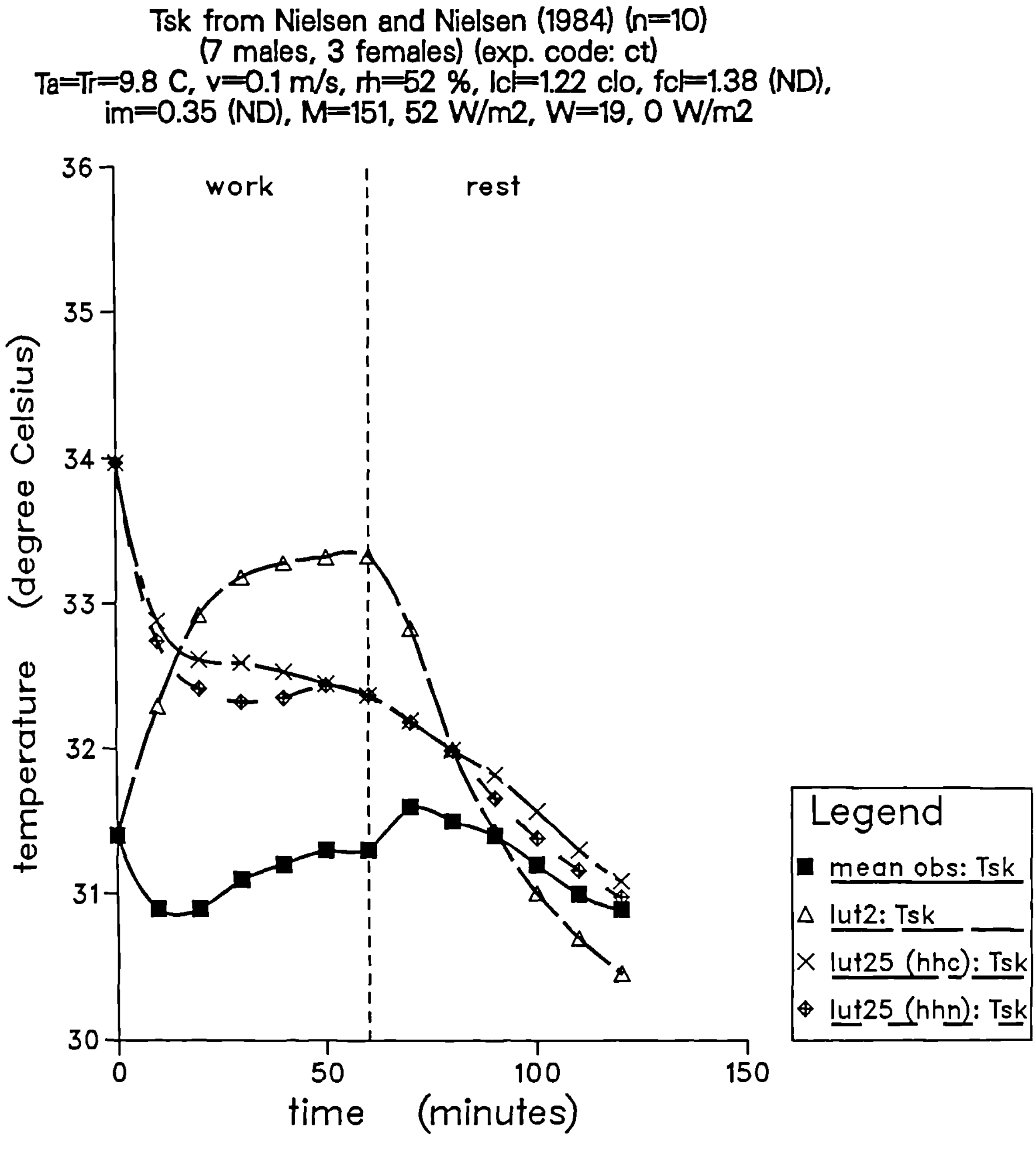



E from Mitchell et al (1976) (n=4) (exp code: day 10)
Ta=Tr=45 C, v=1 m/s, rh=42 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=211 W/m2, W=39 W/m2
400
300
200
100
0
evaporative cooling (W/m2)
0
50
100
150
200
250
time (minutes)
Legend
mean obs: E
+sd
−sd
lut2: E
lut25 (hhc): E

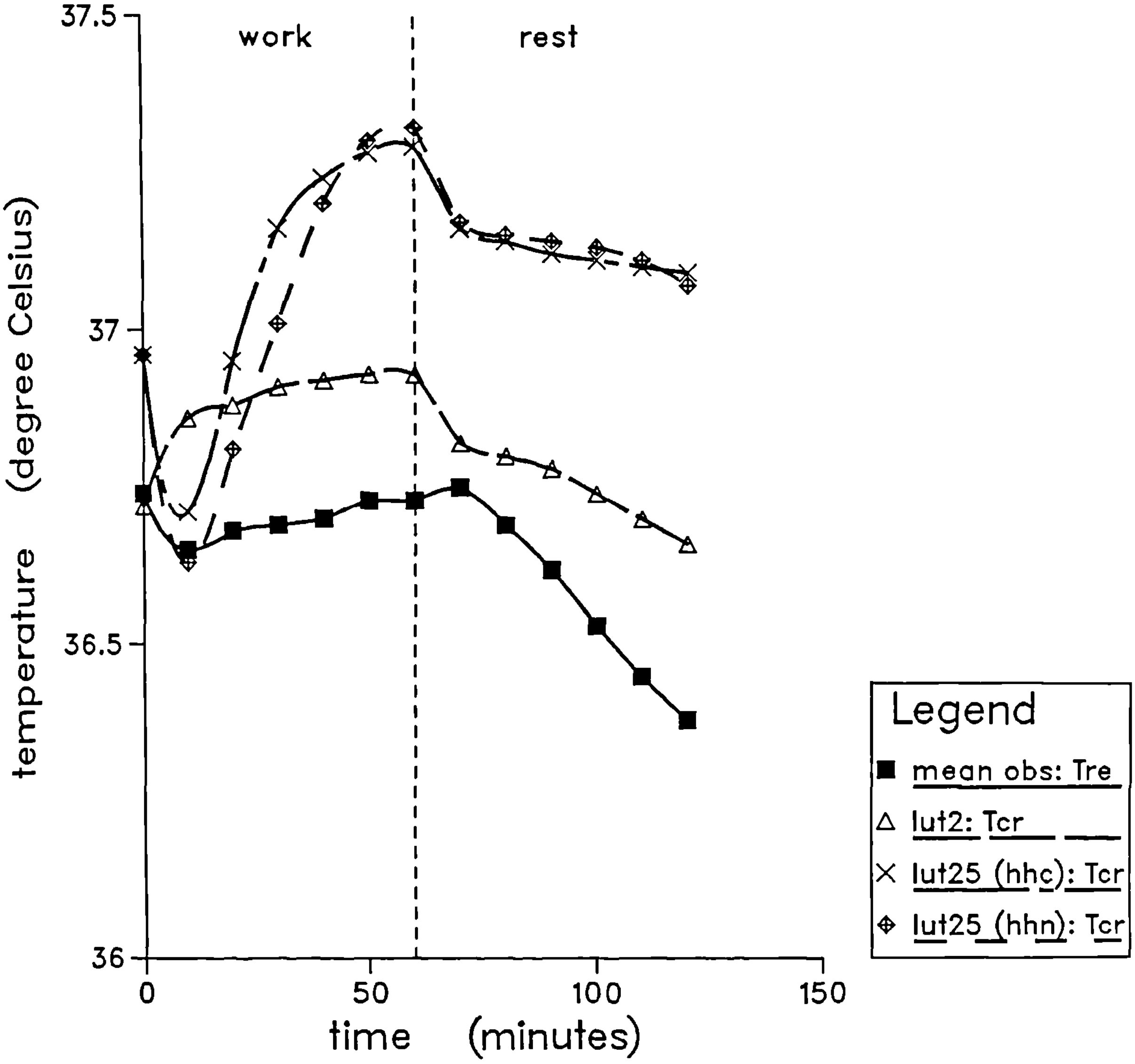


Tre from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: ct)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Icl=1.22 clo, fcl=1.38 (ND),
im=0.35 (ND), M=151, 52 W/m2, W=19, 0 W/m2
37.5
37
36.5
36
work
rest
temperature (degree Celsius)
0
50
100
150
time (minutes)
Legend
mean obs: Tre
lut2: Tcr
lut25 (hhc): Tcr
lut25 (hhn): Tcr

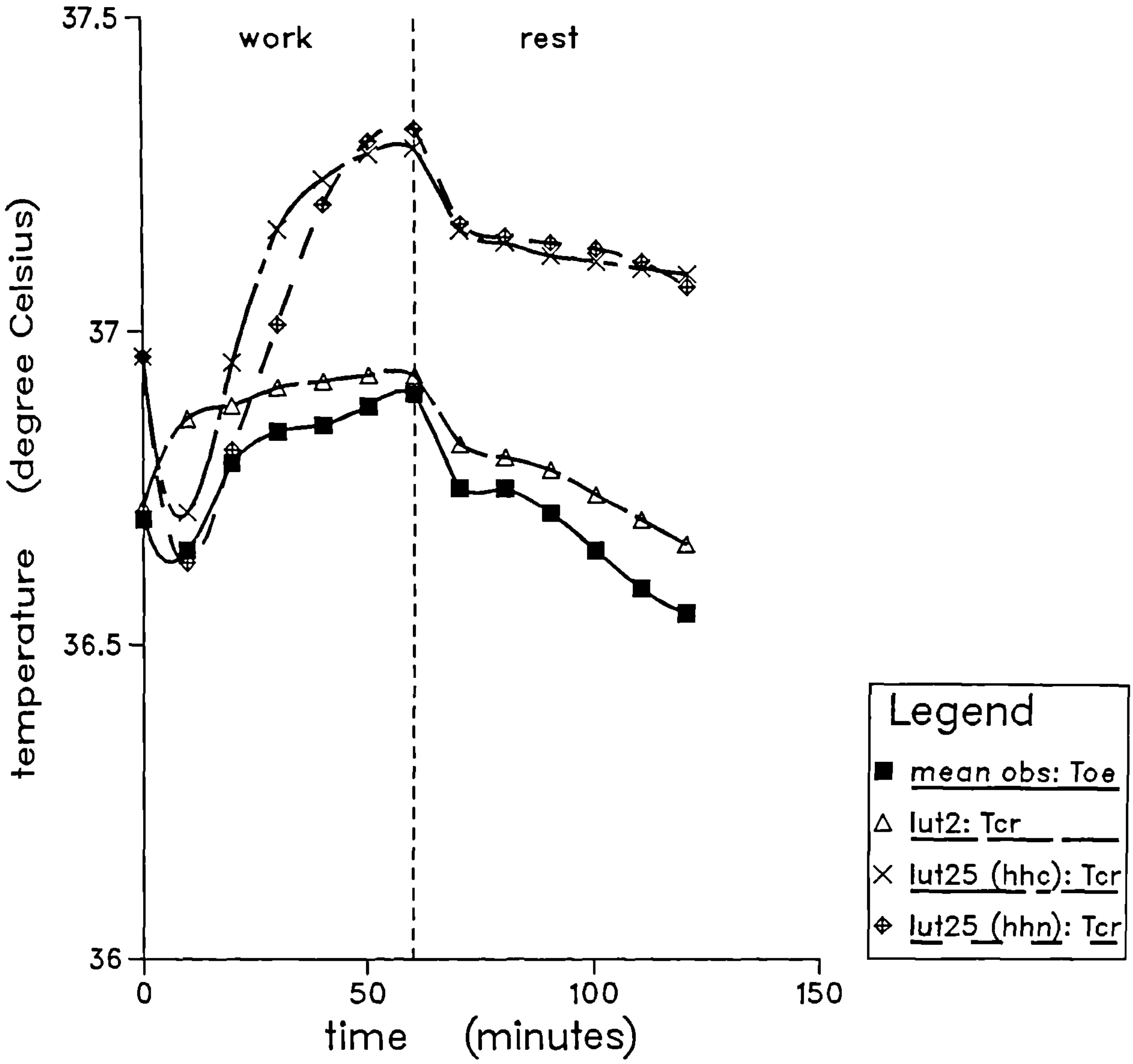

Toe from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: ct)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Icl=1.22 clo, fcl=1.38 (ND),
im=0.35 (ND), M=151, 52 W/m2, W=19, 0 W/m2
37.5
37
36.5
36
work
rest
temperature (degree Celsius)
0
50
100
150
time (minutes)
Legend
mean obs: Toe
lut2: Tcr
lut25 (hhc): Tcr
lut25 (hhn): Tcr

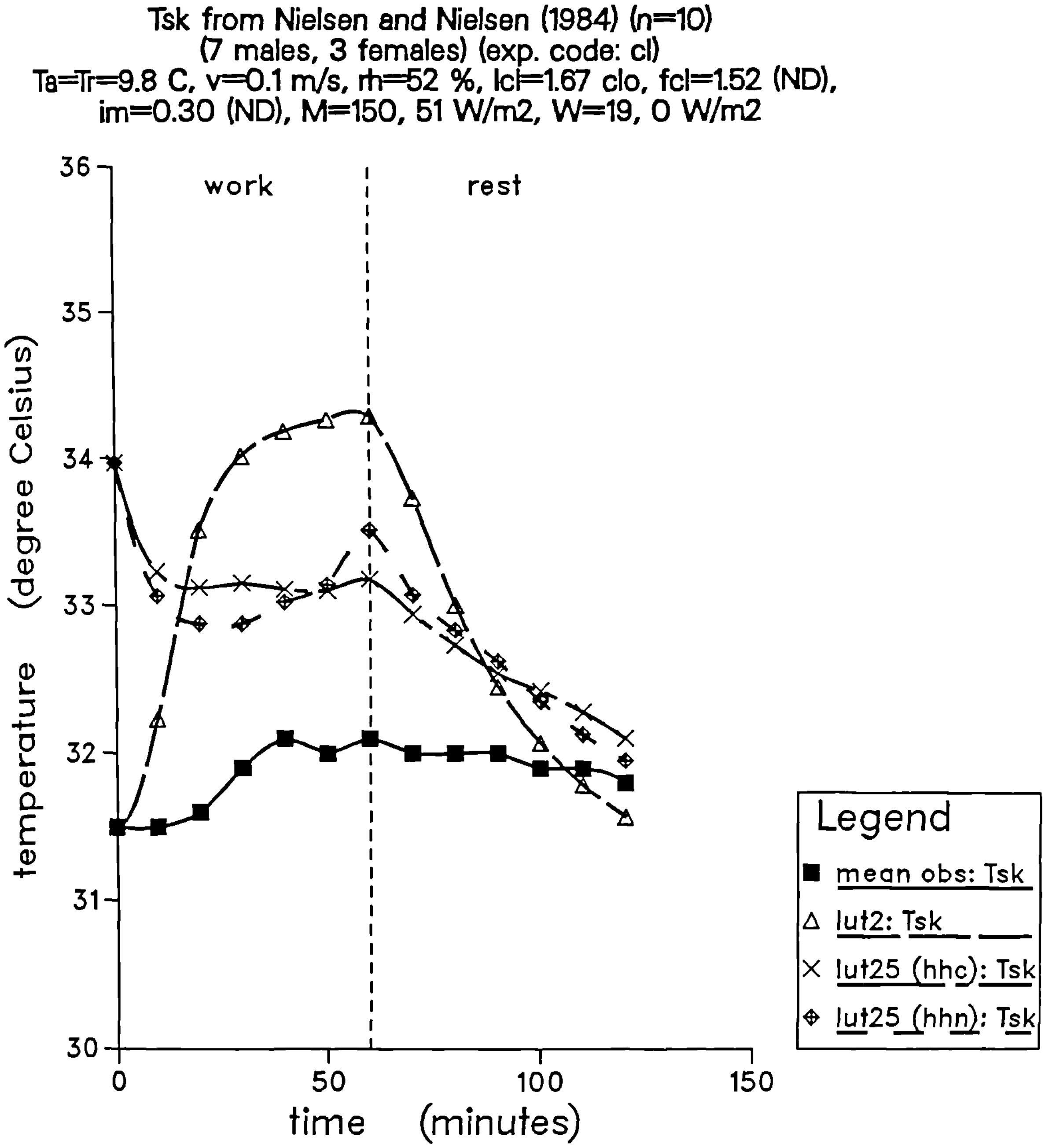

Tsk from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: ct)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Icl=1.22 clo, fcl=1.38 (ND),
im=0.35 (ND), M=151, 52 W/m2, W=19, 0 W/m2
work
rest
temperature (degree Celsius)
time (minutes)
36
35
34
33
32
31
30
0
50
100
150
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk
lut25 (hhn): Tsk

Tre from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: cl)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Icl=1.67 clo, fcl=1.52 (ND),
im=0.30 (ND), M=150, 51 W/m2, W=19, 0 W/m2

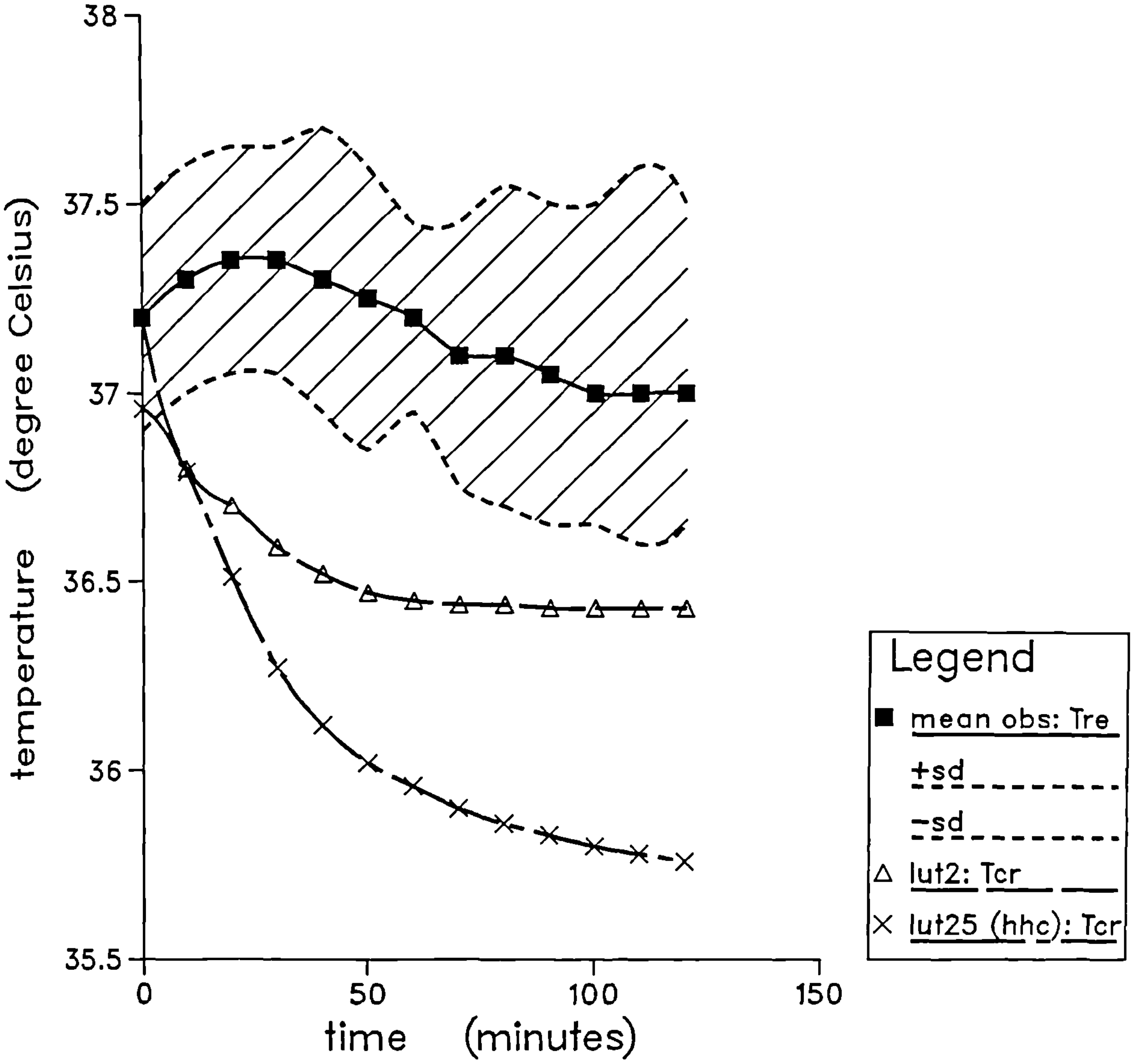


Toe from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: cl)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Icl=1.67 clo, fcl=1.52 (ND),
im=0.30 (ND), M=150, 51 W/m2, W=19, 0 W/m2

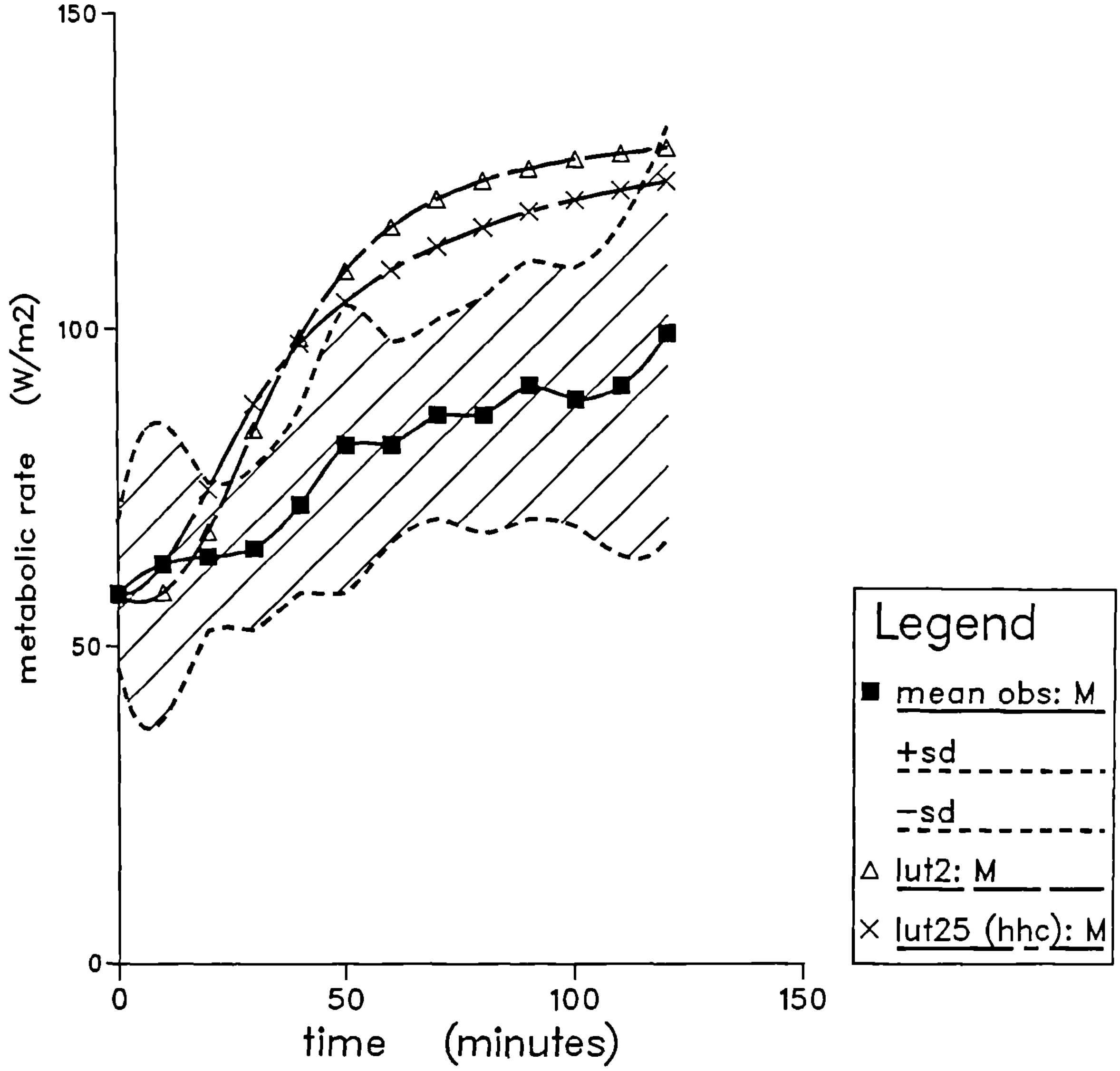


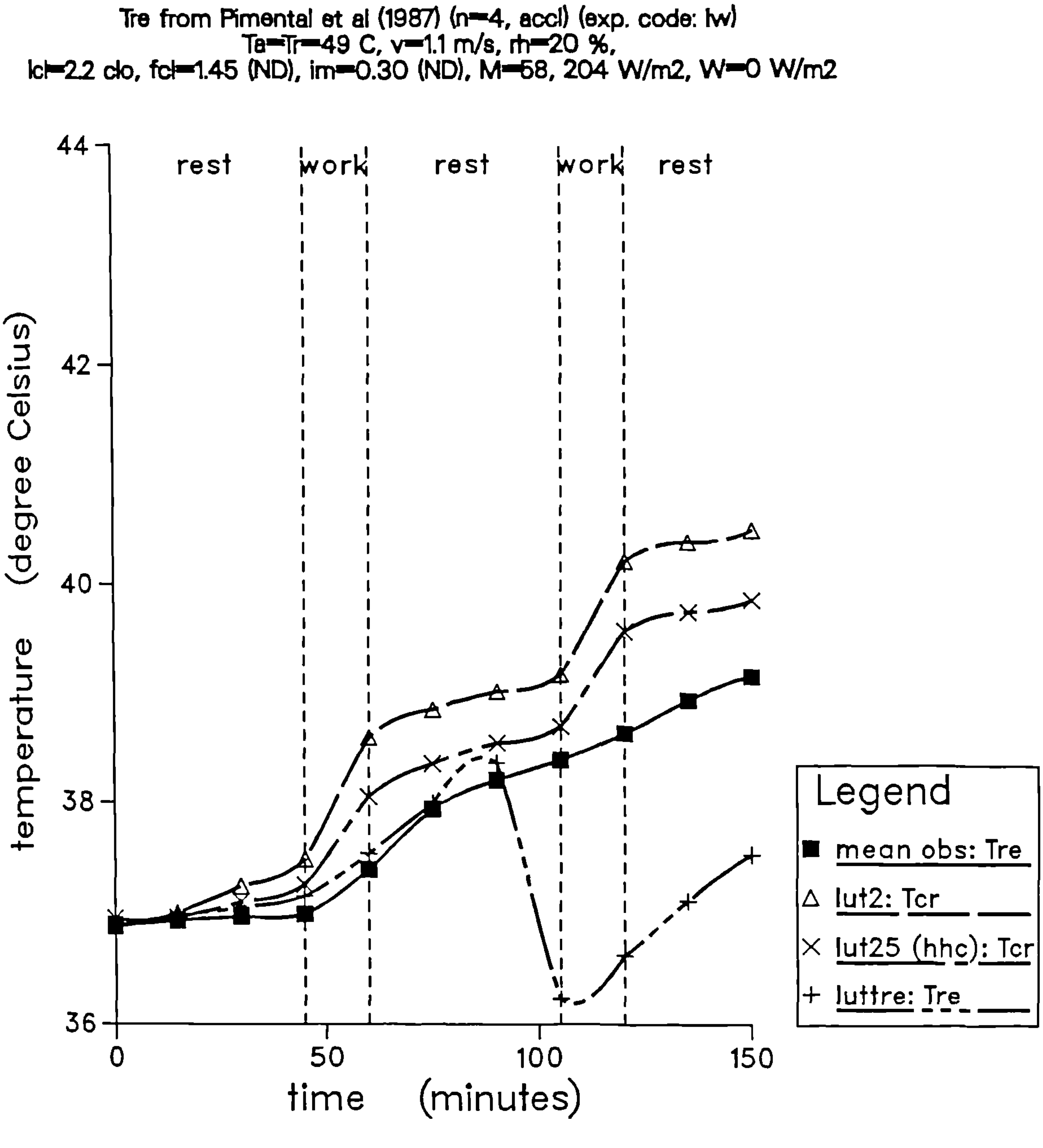

Tsk from Nielsen and Nielsen (1984) (n=10)
(7 males, 3 females) (exp. code: cl)
Ta=Tr=9.8 C, v=0.1 m/s, rh=52 %, Icl=1.67 clo, fcl=1.52 (ND),
im=0.30 (ND), M=150, 51 W/m2, W=19, 0 W/m2
work
rest
temperature (degree Celsius)
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk
lut25 (hhn): Tsk

Tre 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



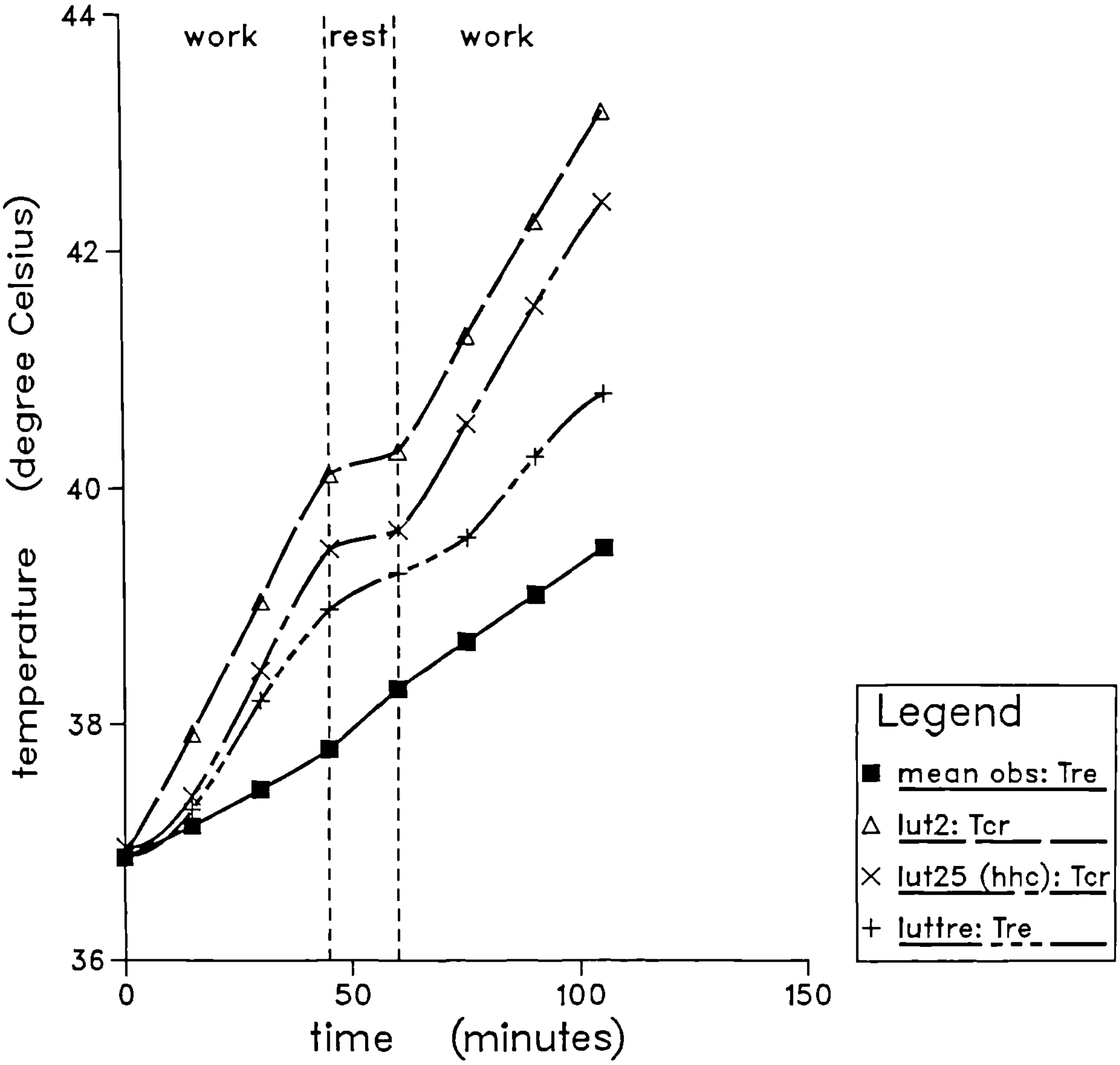
M from O'Hanlon and Horvath (1970) (n=34)
Ta=Tr=7.7 C, v=0.2 m/s, rh=85 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=58 W/m2, W=0 W/m2





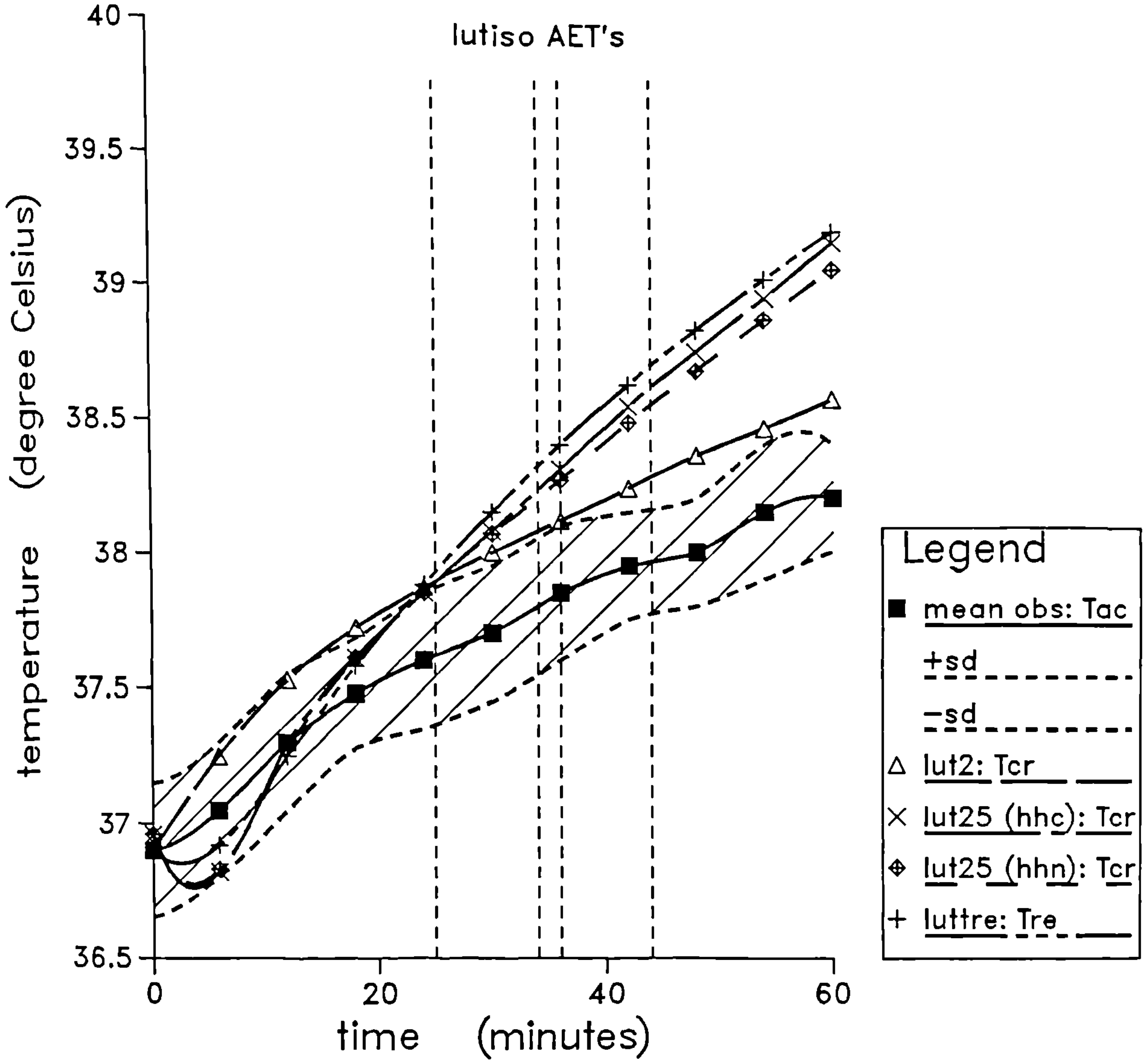
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 33 min; body temperature increase
danger non-accl : 40 min; body temperature increase
warning accl : 36 min; body temperature increase
danger accl : 43 min; body temperature increase

Tre from Pimental et al (1987) (n=4, accl) (exp. code: hw)
Ta=Tr=49 C, v=1.1 m/s, rh=20 %,
Icl=2.2 clo, fcl=1.45 (ND), im=0.30 (ND), M=204, 58 W/m2, W=0 W/m2



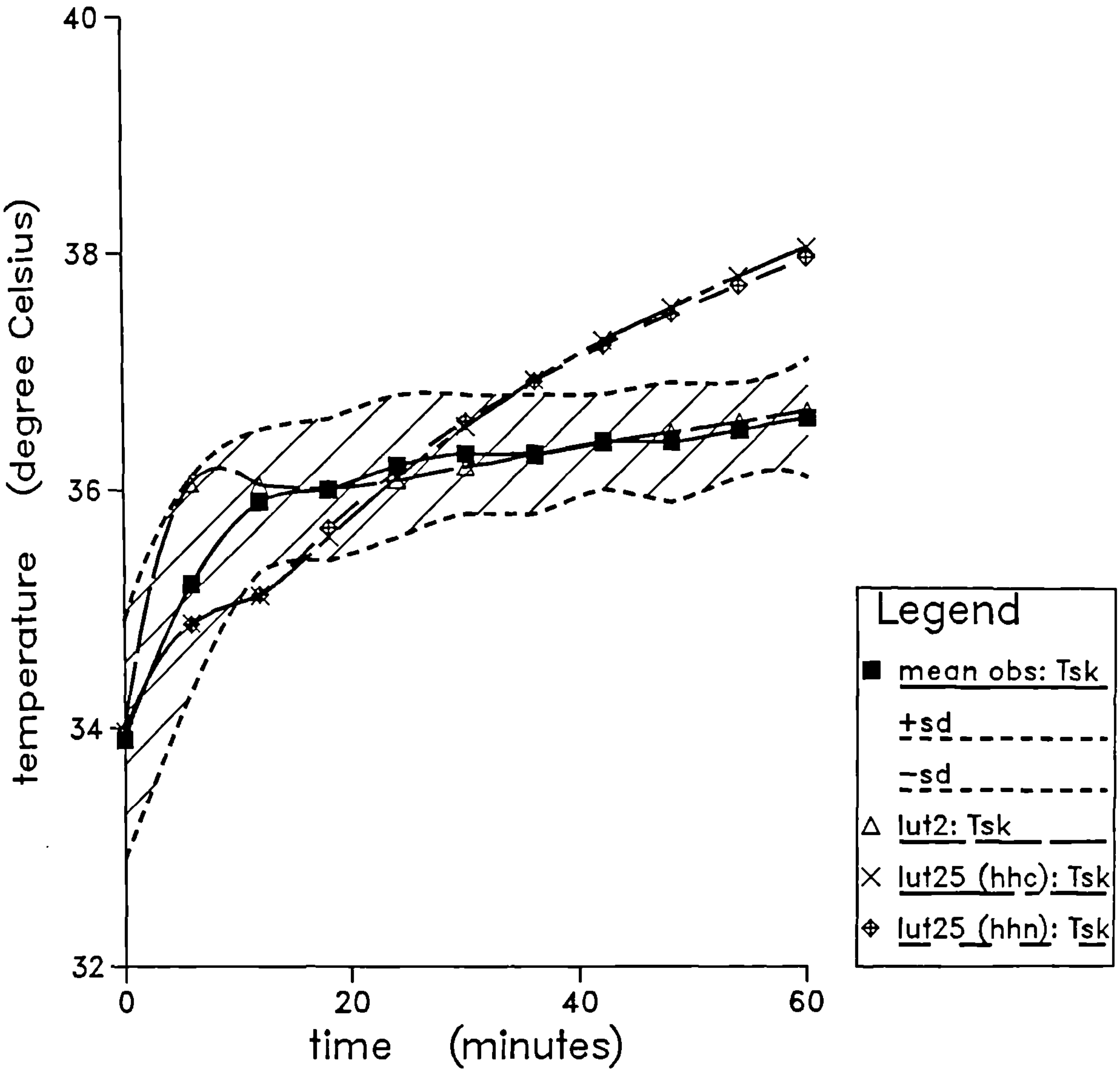
lutiso Allowable Exposure Times
(to work):
warning non-accl: 13 min; body temperature increase
danger non-accl : 16 min; body temperature increase
warning accl : 13 min; body temperature increase
danger accl : 16 min; body temperature increase

Tac from Randle and Legg (1985) (n=8) (exp. code: wk)
Ta=Tr=32.8 C, v=0.2 m/s, rh=52 %,
Icl=0.5 clo, fcl=1.2 (ND), im=0.39 (ND), M=310 W/m2, W=47 W/m2

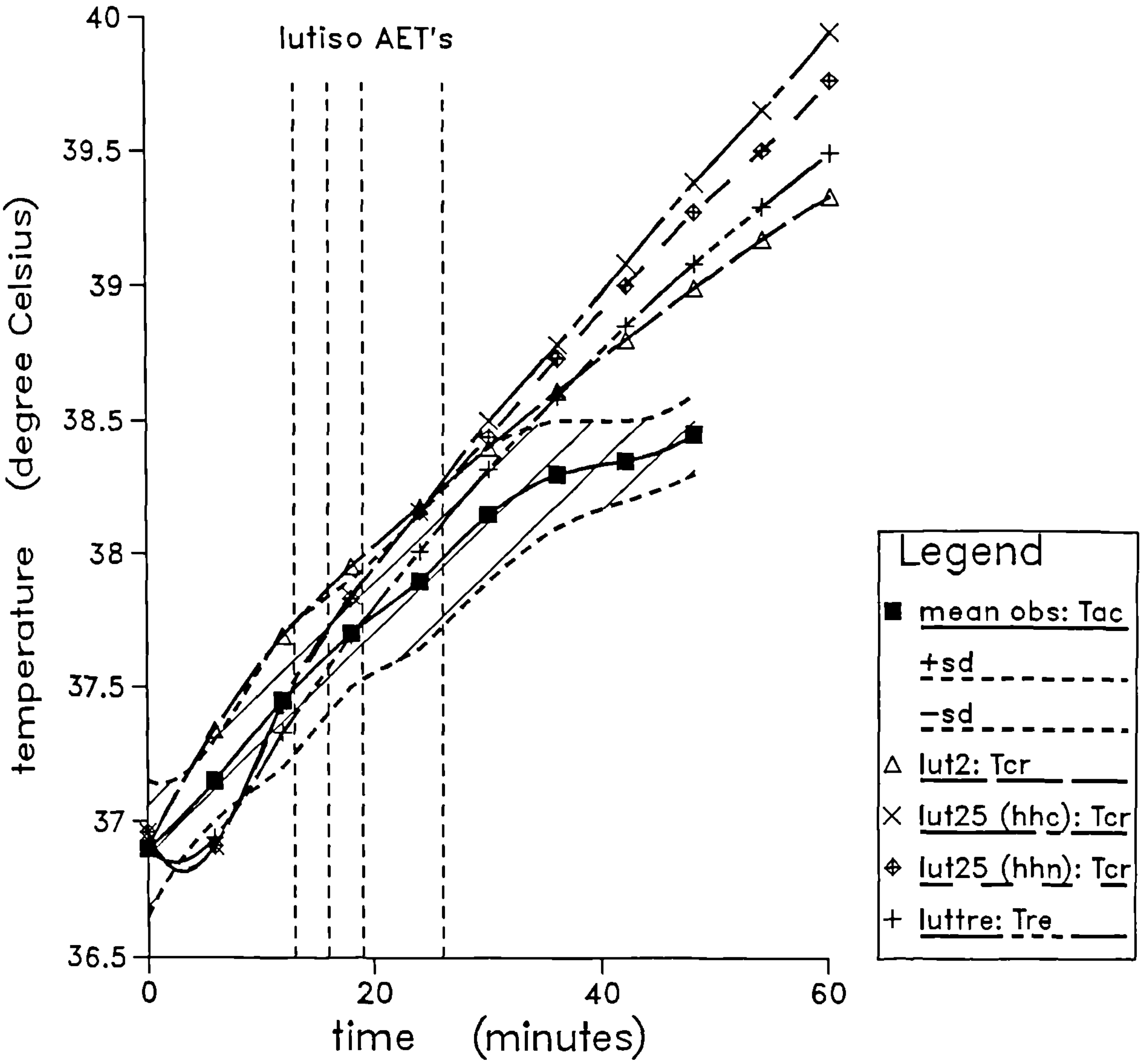


lutiso Allowable Exposure Times:
warning non-accl: 25 min; body temperature increase
danger non-accl : 34 min; body temperature increase
warning accl : 36 min; body temperature increase
danger accl : 44 min; body temperature increase

Tsk from Randle and Legg (1985) (n=8) (exp. code: wk)
Ta=Tr=32.8 C, v=0.2 m/s, rh=52 %,
Icl=0.5 clo, fcl=1.2 (ND), im=0.39 (ND), M=310 W/m2, W=47 W/m2

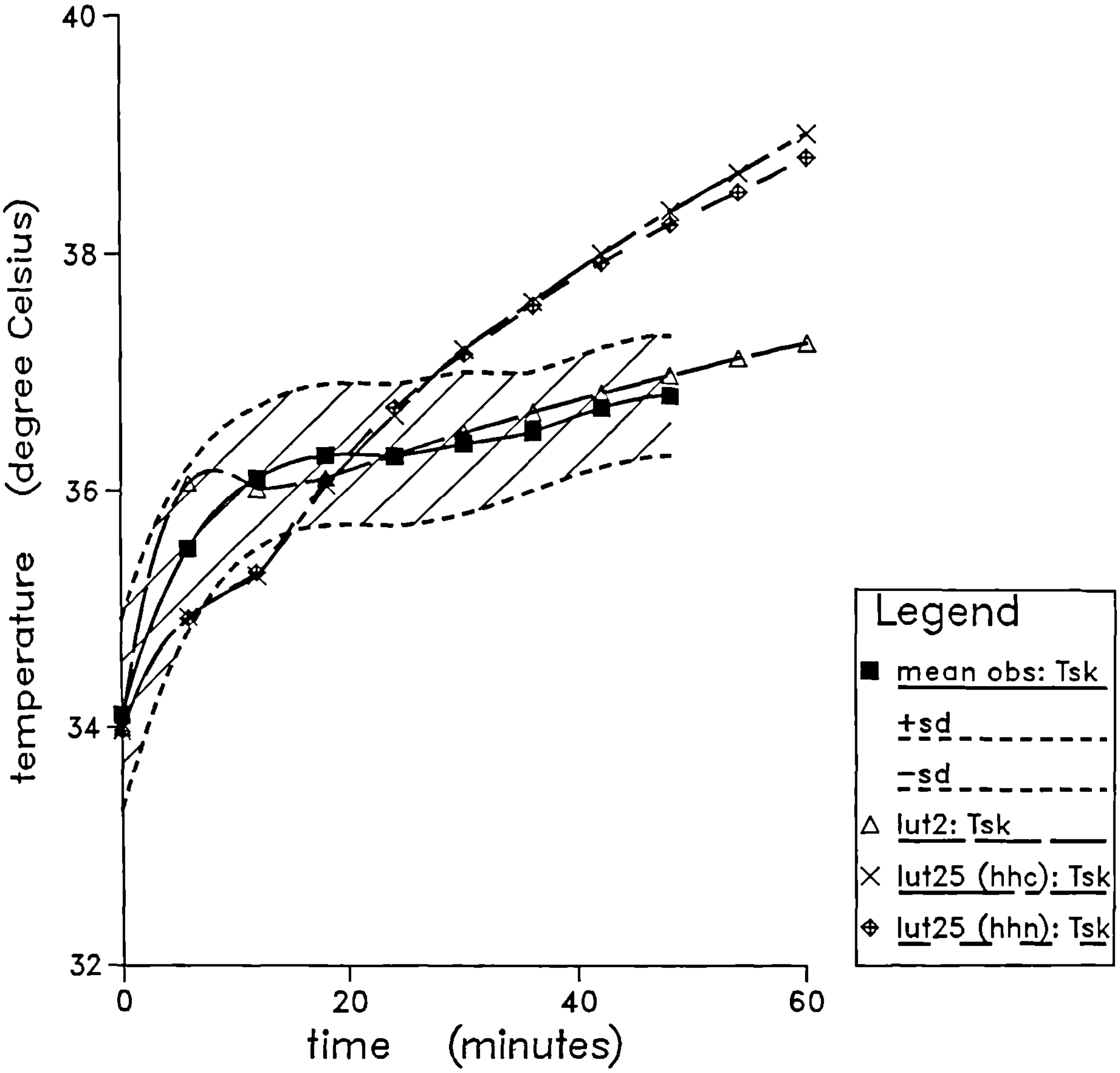


Tac from Randle and Legg (1985)
(n=8, decreasing to 2) (exp. code: cy)
Ta=Tr=32.8 C, v=0.2 m/s, rh=52 %,
Icl=0.5 clo, fcl=1.2 (ND), im=0.39 (ND), M=353 W/m2, W=46 W/m2

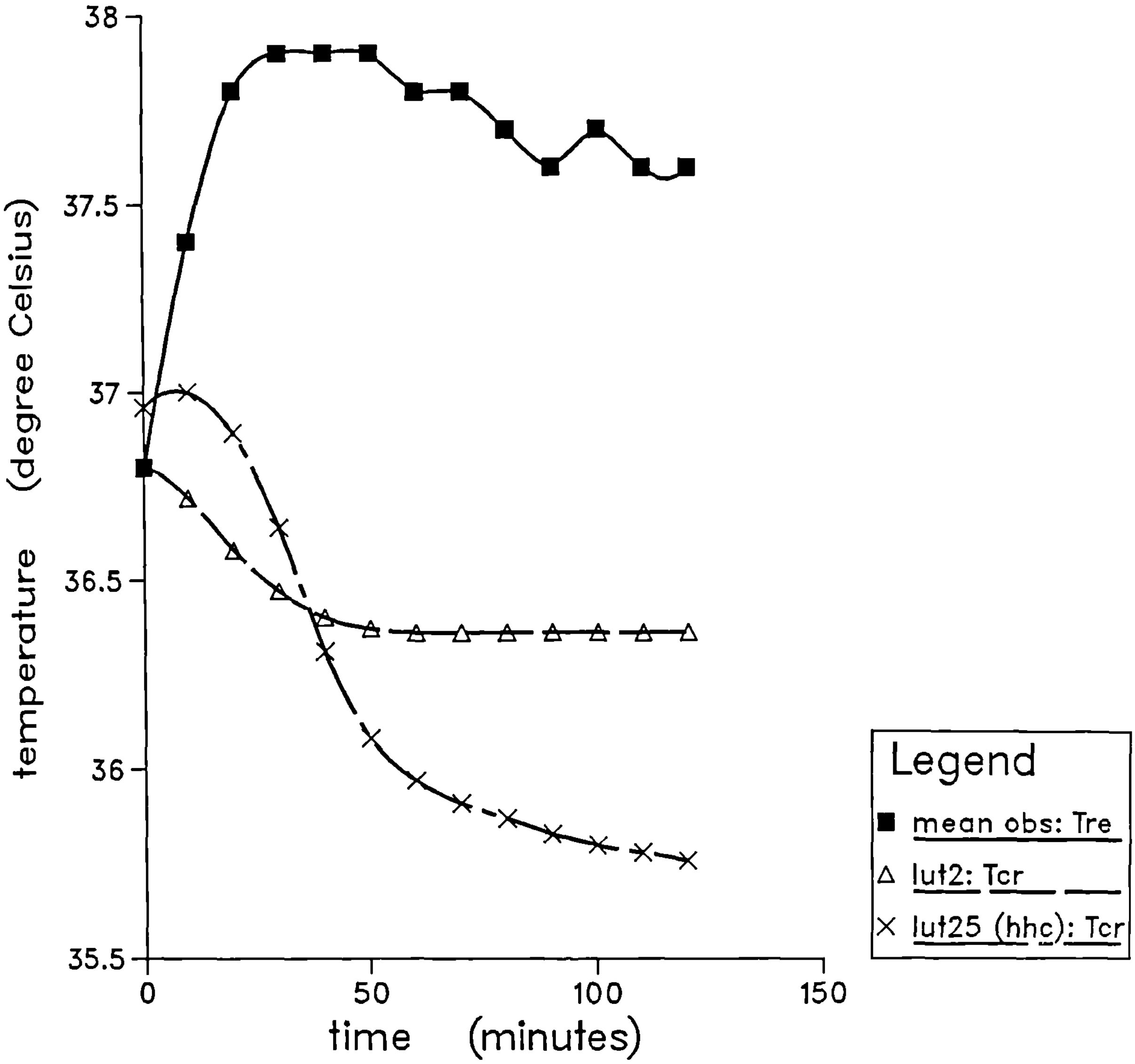


lutiso Allowable Exposure Times:
warning non-accl: 13 min; body temperature increase
danger non-accl : 19 min; body temperature increase
warning accl : 16 min; body temperature increase
danger accl : 26 min; body temperature increase

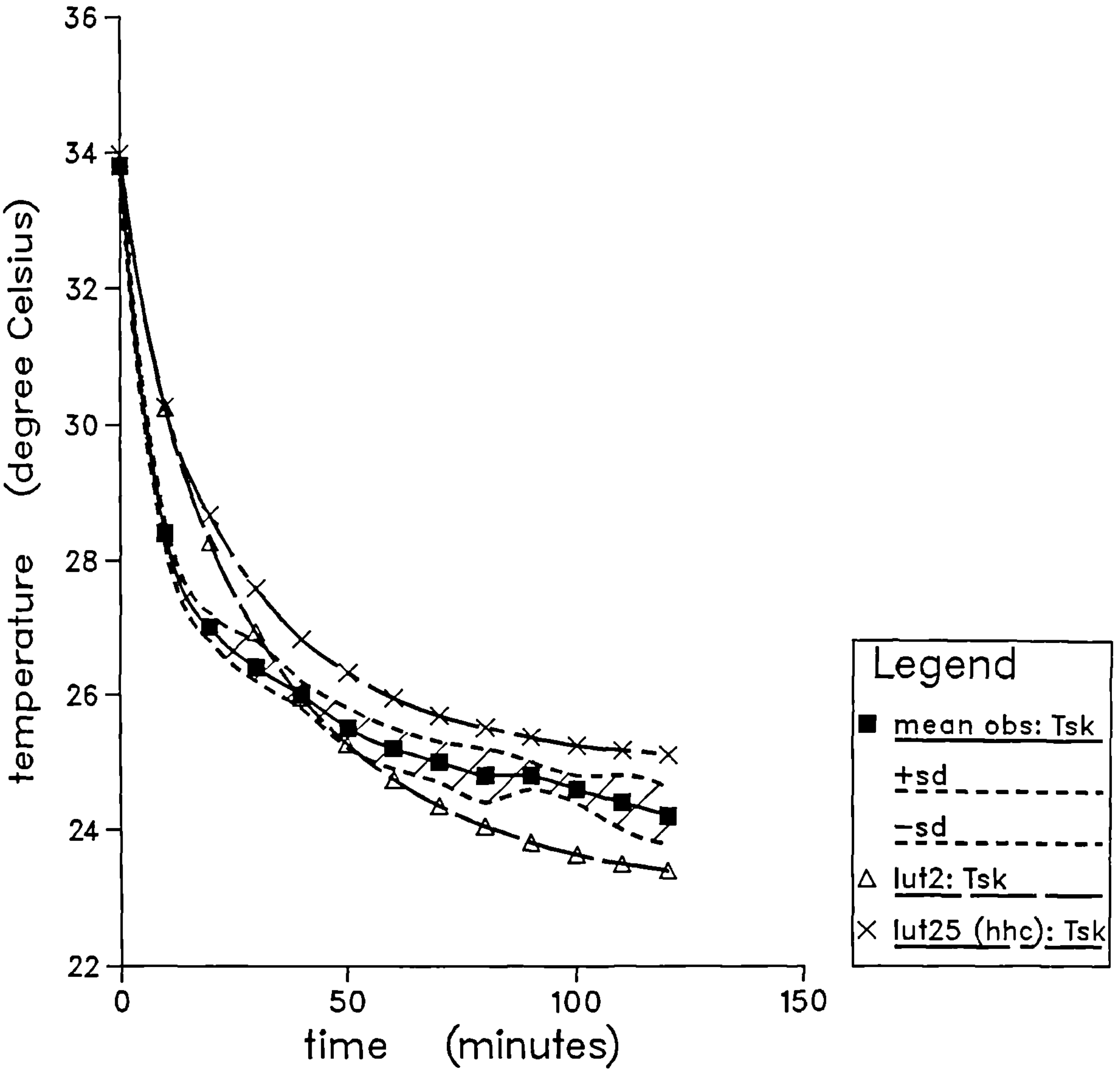
Tsk from Randle and Legg (1985)
(n=8, decreasing to 2) (exp. code: cy)
Ta=Tr=32.8 C, v=0.2 m/s, rh=52 %,
Icl=0.5 clo, fcl=1.2 (ND), im=0.39 (ND), M=353 W/m2, W=46 W/m2

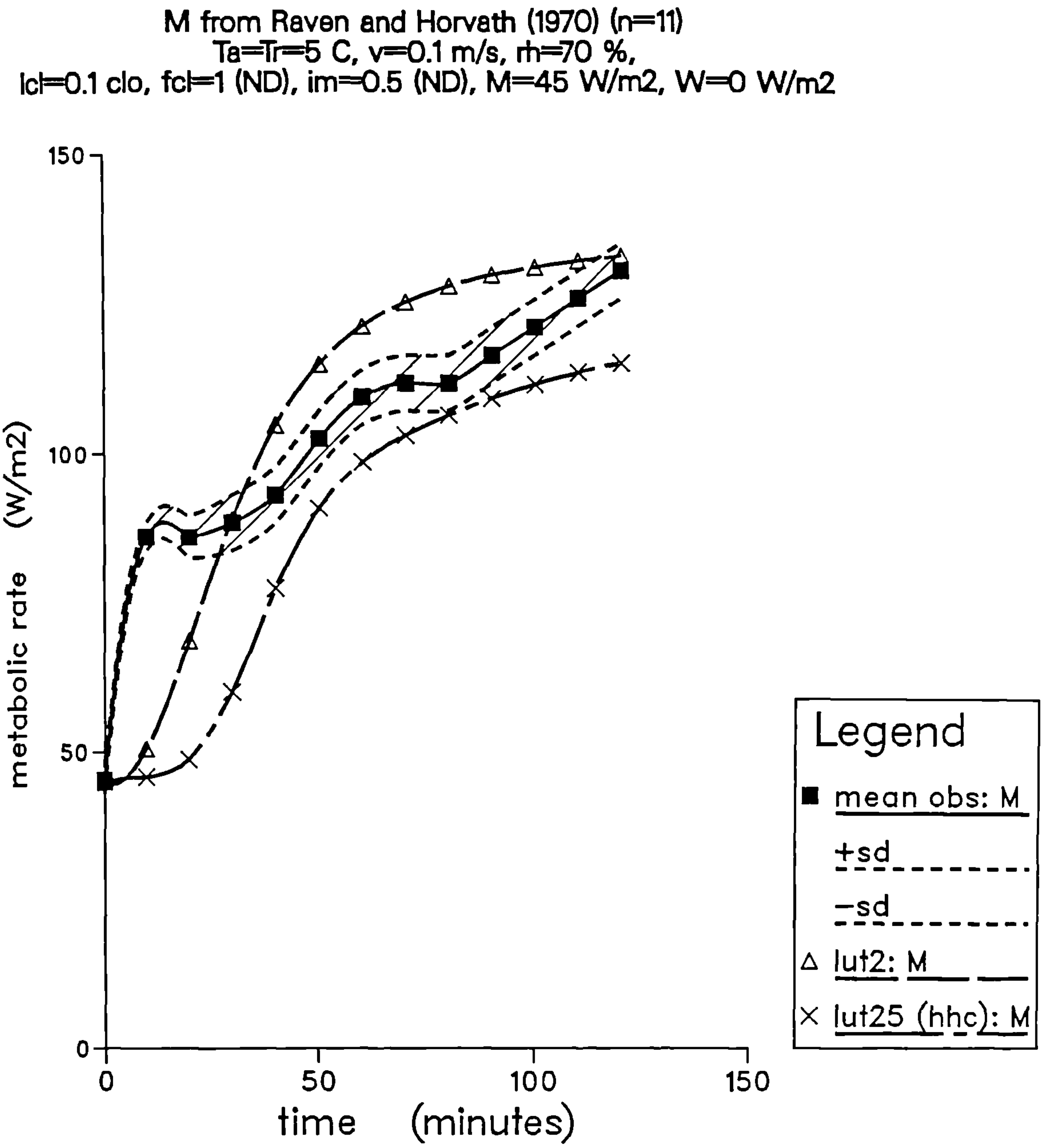


Tre from Raven and Horvath (1970) (n=11)
Ta=Tr=5 C, v=0.1 m/s, rh=70 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=45 W/m2, W=0 W/m2

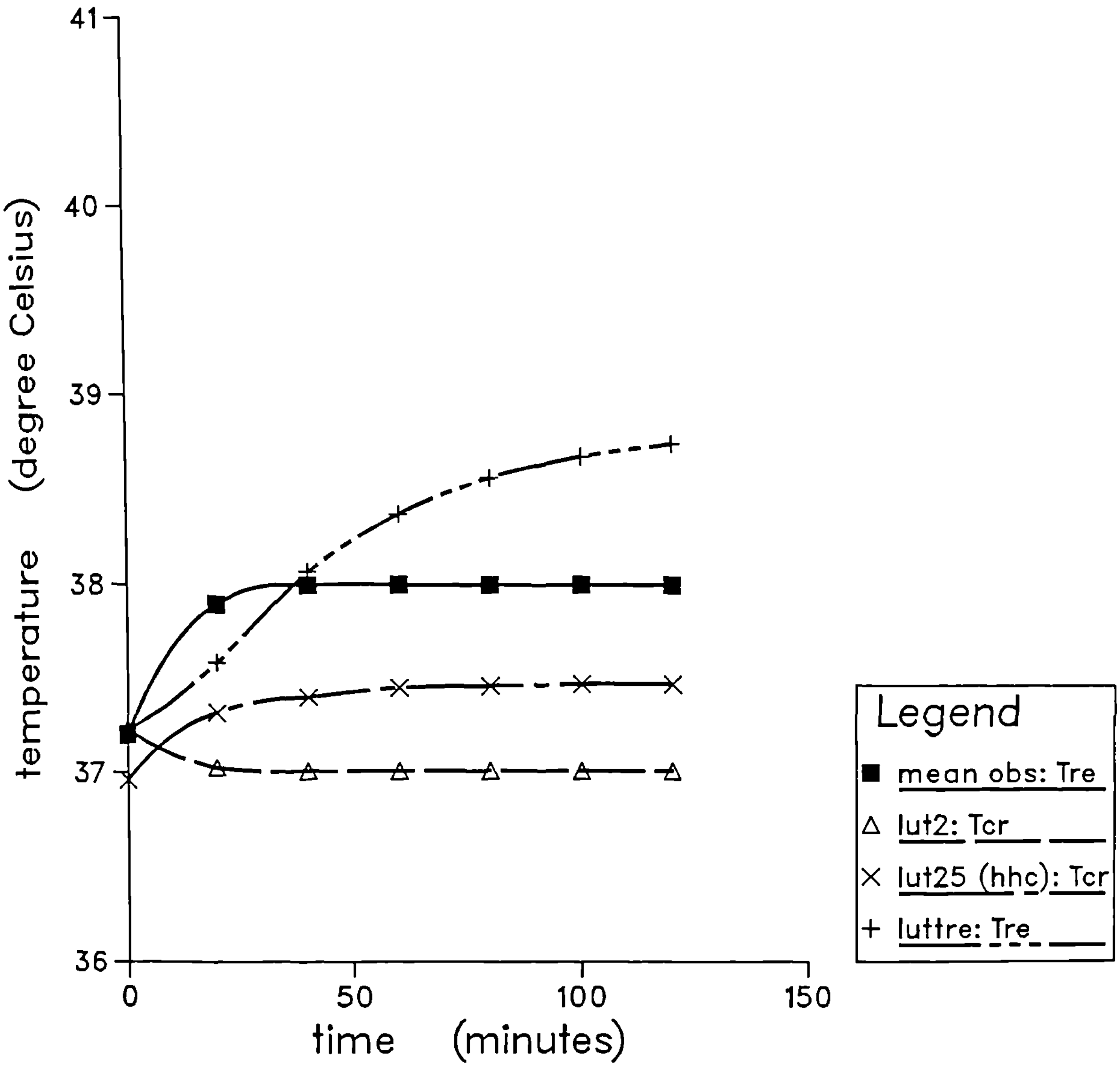


Tsk from Raven and Horvath (1970) (n=11)
Ta=Tr=5 C, v=0.1 m/s, rh=70 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=45 W/m2, W=0 W/m2

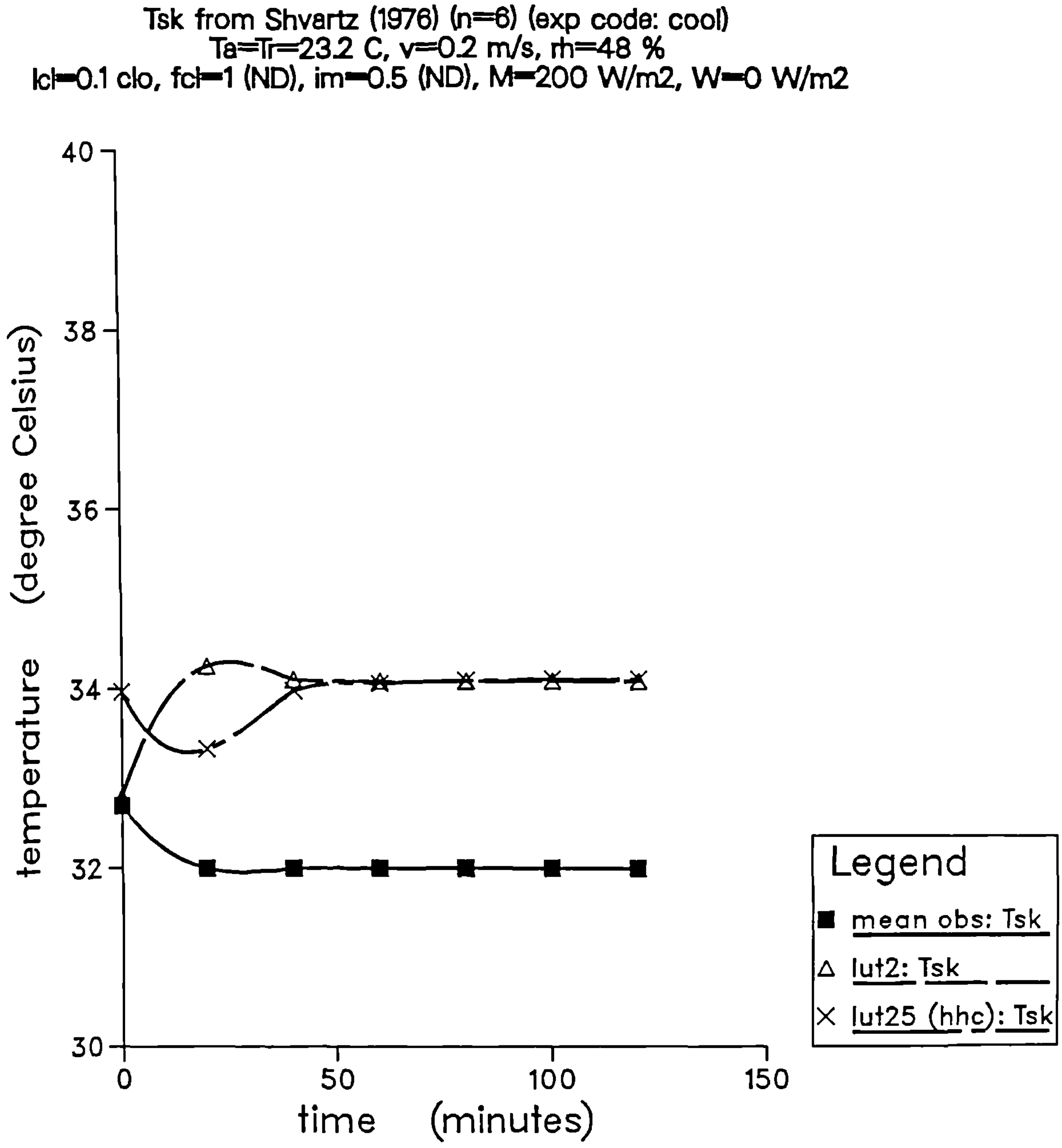



M from Raven and Horvath (1970) (n=11)
Ta=Tr=5 C, v=0.1 m/s, rh=70 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=45 W/m2, W=0 W/m2
metabolic rate (W/m2)
150
100
50
0
0
50
100
150
time (minutes)
Legend
mean obs: M
+sd
-sd
lut2: M
lut25 (hhc): M

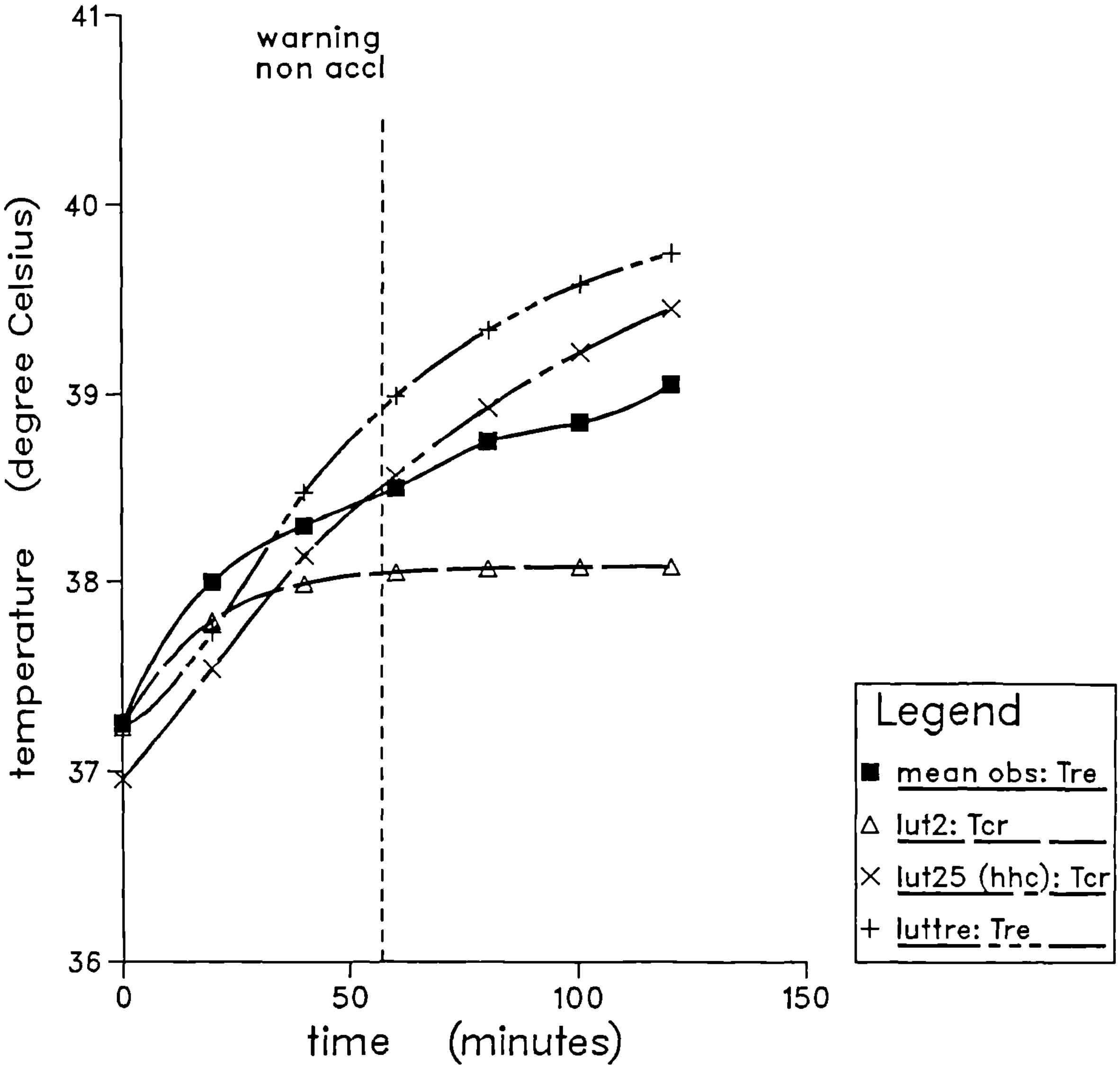
Tre from Shvartz (1976) (n=6) (exp code: cool)
Ta=Tr=23.2 C, v=0.2 m/s, rh=48 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=200 W/m2, W=0 W/m2



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

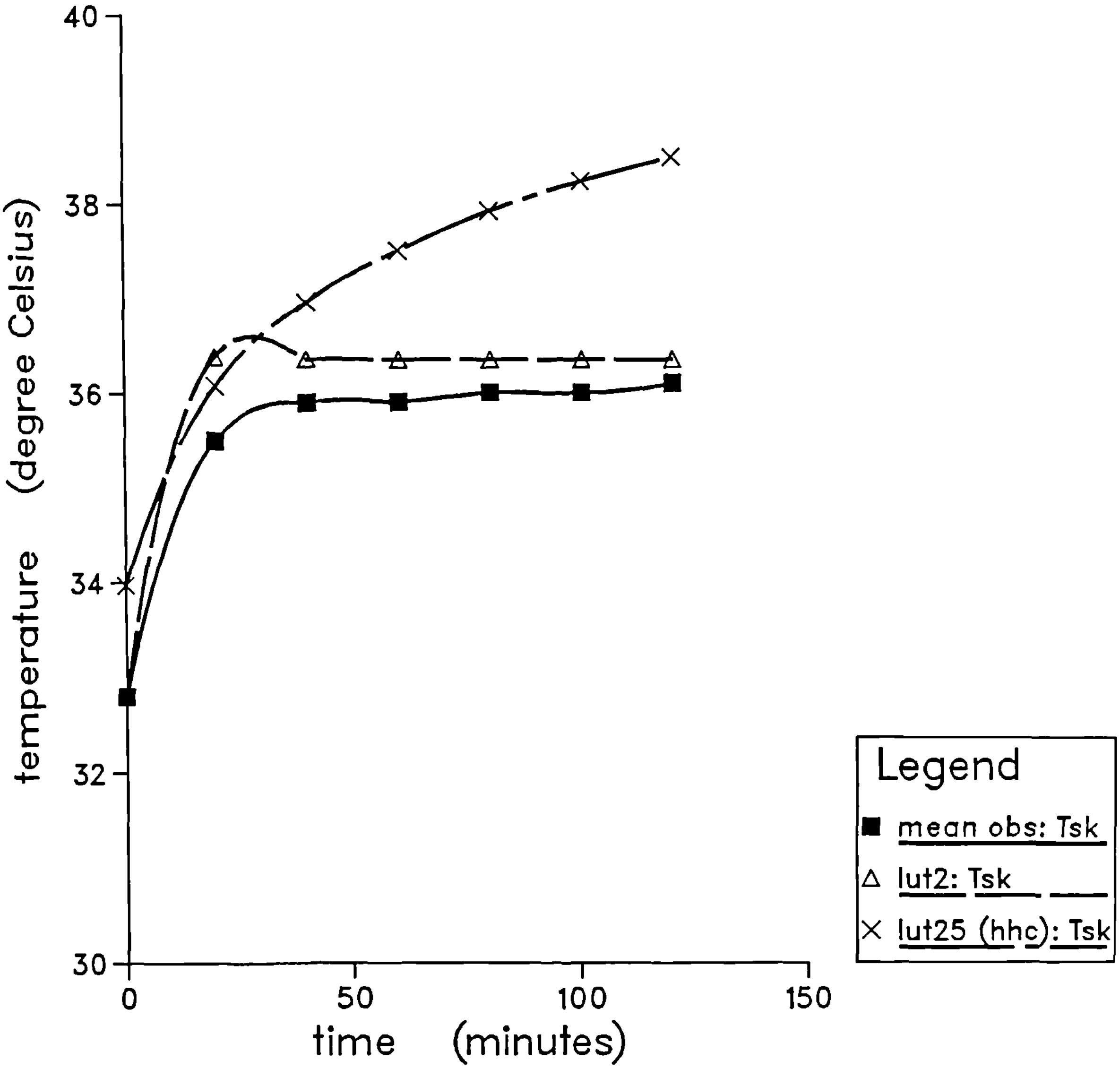

Tsk from Shvartz (1976) (n=6) (exp code: cool)
Ta=Tr=23.2 C, v=0.2 m/s, rh=48 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=200 W/m2, W=0 W/m2
40
38
36
34
32
30
temperature (degree Celsius)
0
50
100
150
time (minutes)
Legend
mean obs: Tsk
lut2: Tsk
lut25 (hhc): Tsk

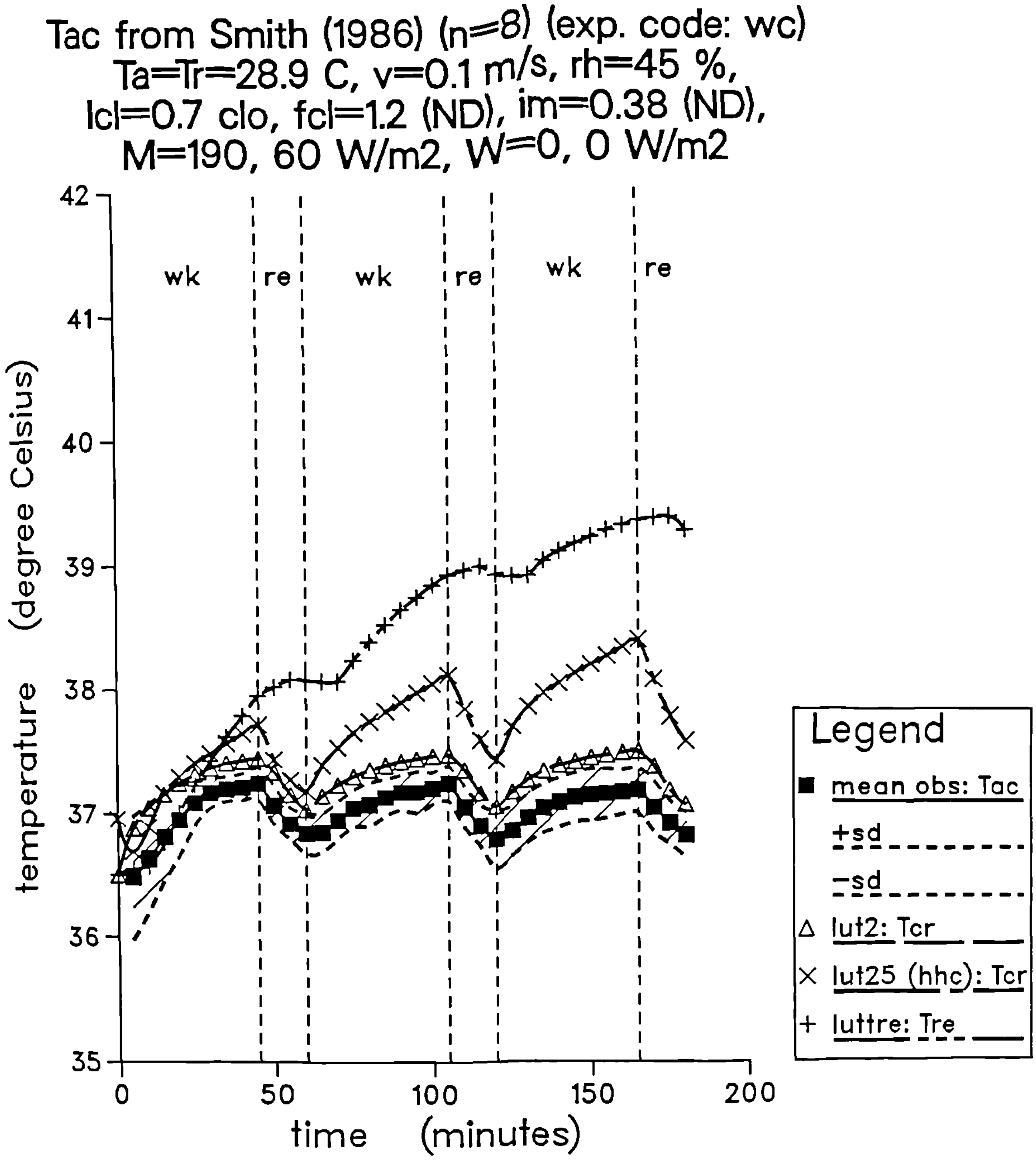
Tre from Shvartz (1976) (n=6) (exp code: hot)
Ta=Tr=39.5 C, v=0.2 m/s, rh=52 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=196 W/m2, W=0 W/m2



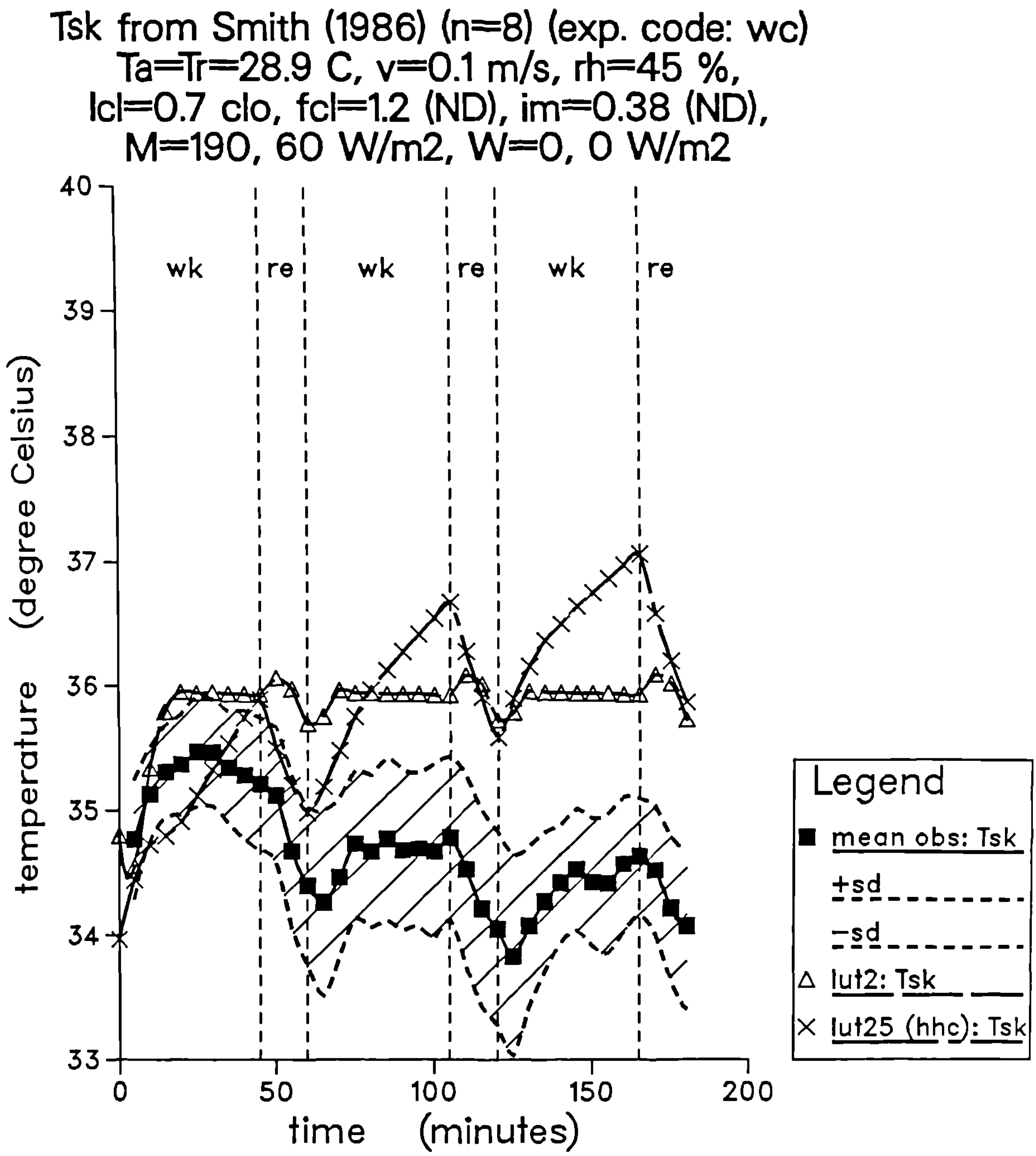
lutiso Allowable Exposure Times
warning non-accl: 57 min; body temperature increase
danger non-accl : 131 min; body temperature increase
warning accl : 242 min; body temperature increase
danger accl : 325 min; excessive dehydration

Tsk from Shvartz (1976) (n=6) (exp code: hot)
Ta=Tr=39.5 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

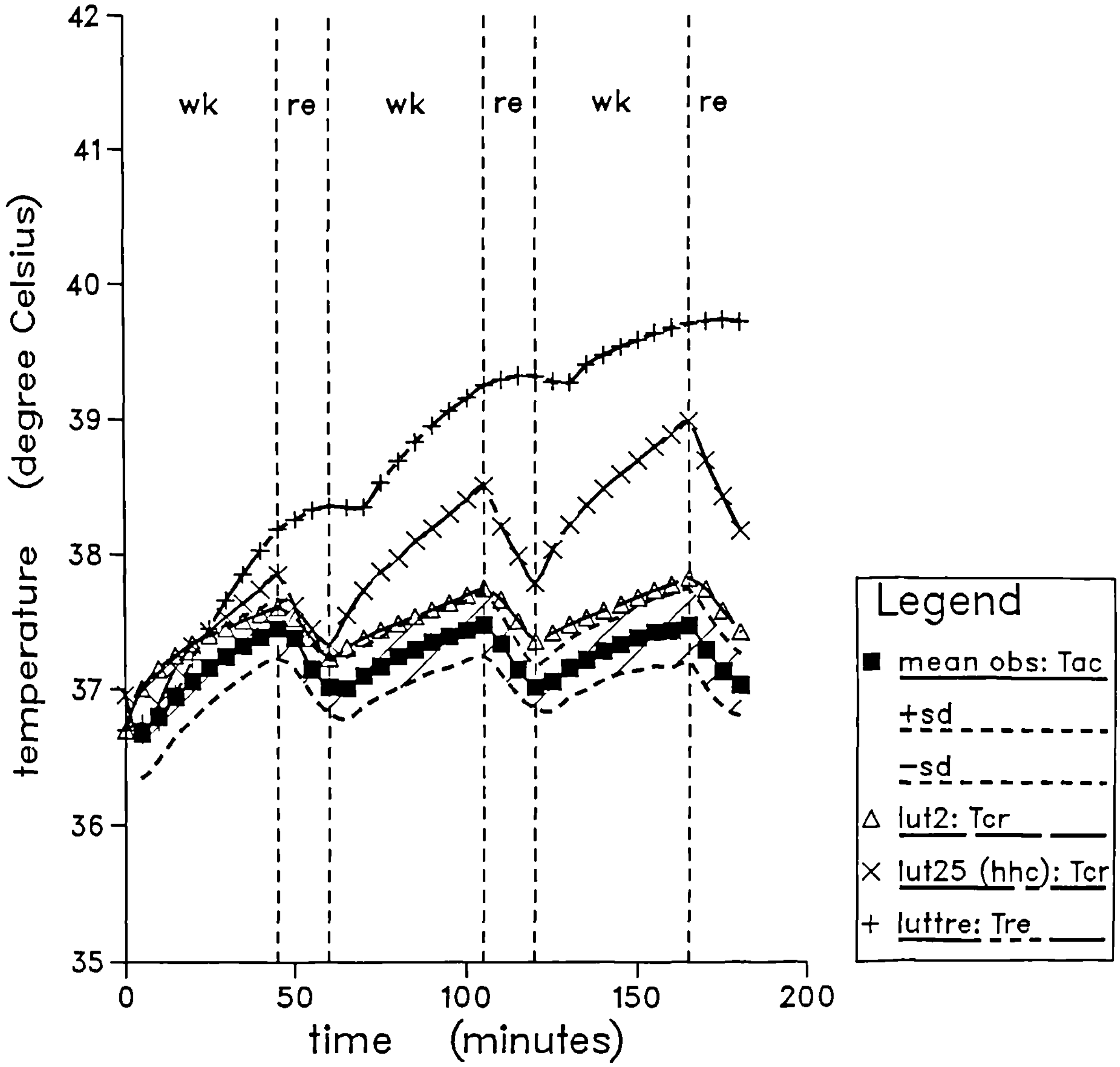




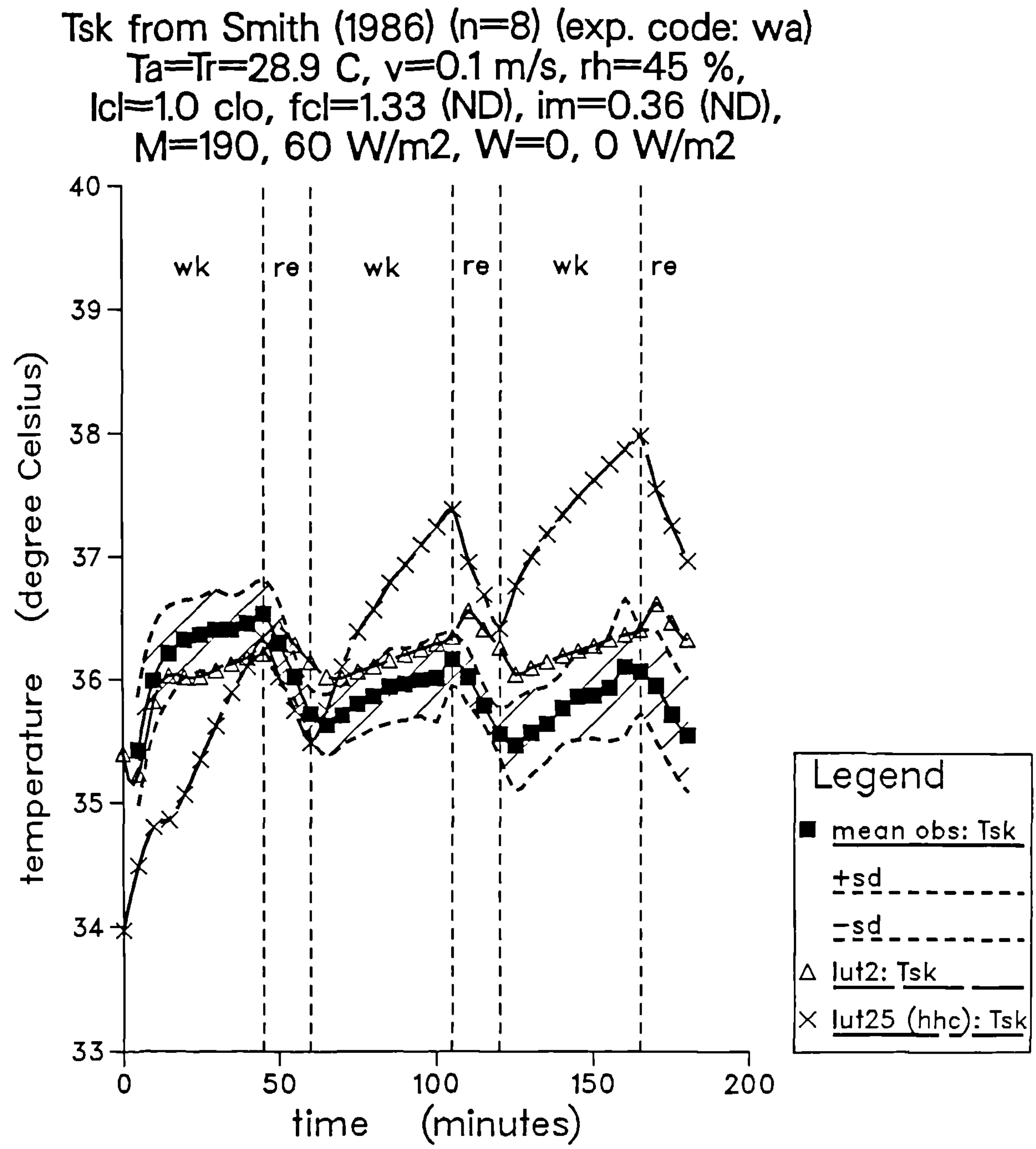
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 190 min; excessive wettedness
danger non-accl : 228 min; excessive wettedness
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration


Tsk from Smith (1986) (n=8) (exp. code: wc)
Ta=Tr=28.9 C, v=0.1 m/s, rh=45 %,
Icl=0.7 clo, fcl=1.2 (ND), im=0.38 (ND),
M=190, 60 W/m2, W=0, 0 W/m2
wk
re
wk
re
wk
re
temperature (degree Celsius)
time (minutes)
Legend
mean obs: Tsk
+sd
−sd
lut2: Tsk
lut25 (hhc): Tsk

Tac from Smith (1986) (n=8) (exp. code: wa)
Ta=Tr=28.9 C, v=0.1 m/s, rh=45 %,
Icl=1.0 clo, fcl=1.33 (ND), im=0.36 (ND),
M=190, 60 W/m2, W=0, 0 W/m2

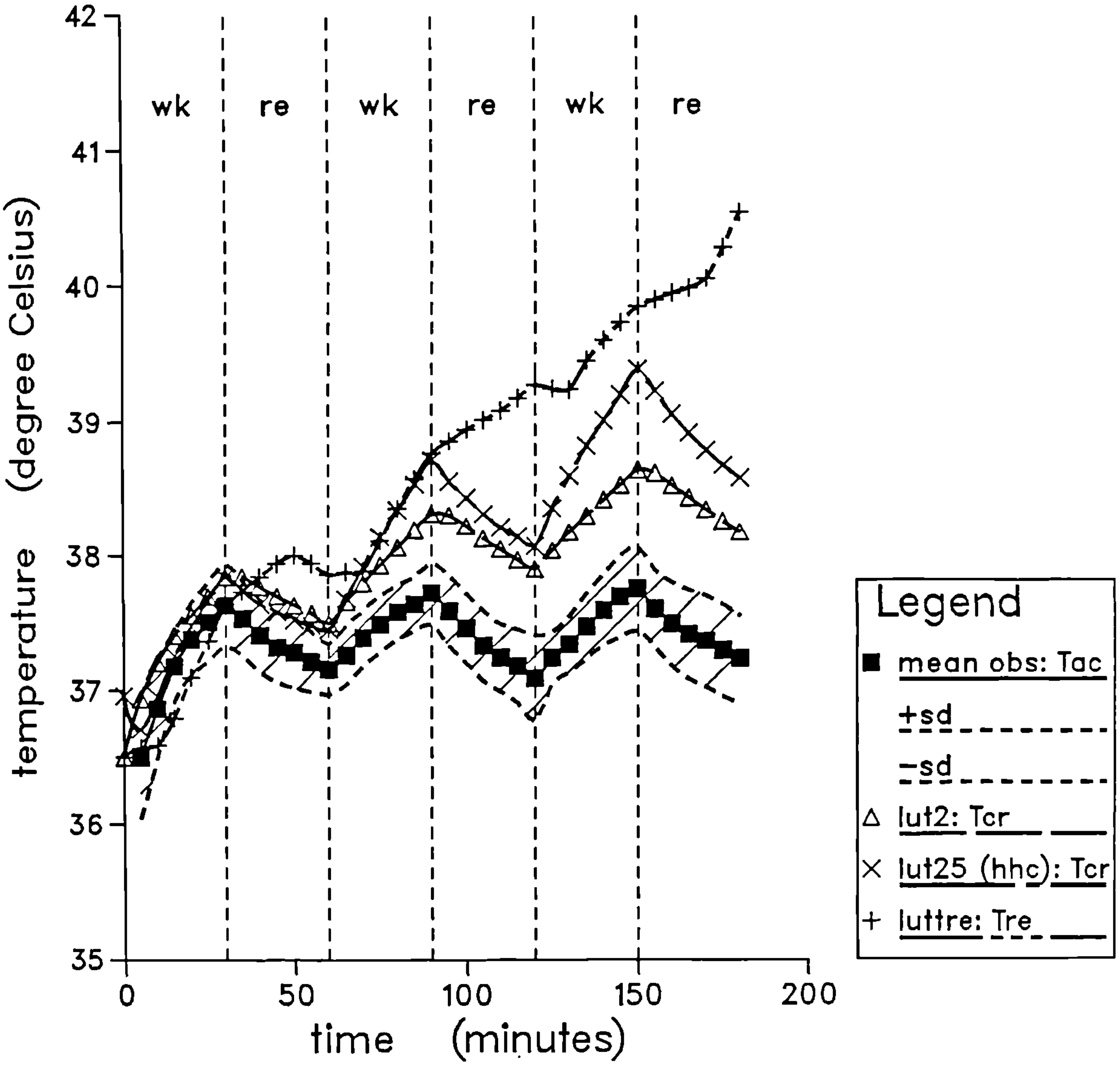


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 96 min; excessive wettedness
danger non-accl : 116 min; excessive wettedness
warning accl : 222 min; excessive wettedness
danger accl : 267 min; excessive wettedness

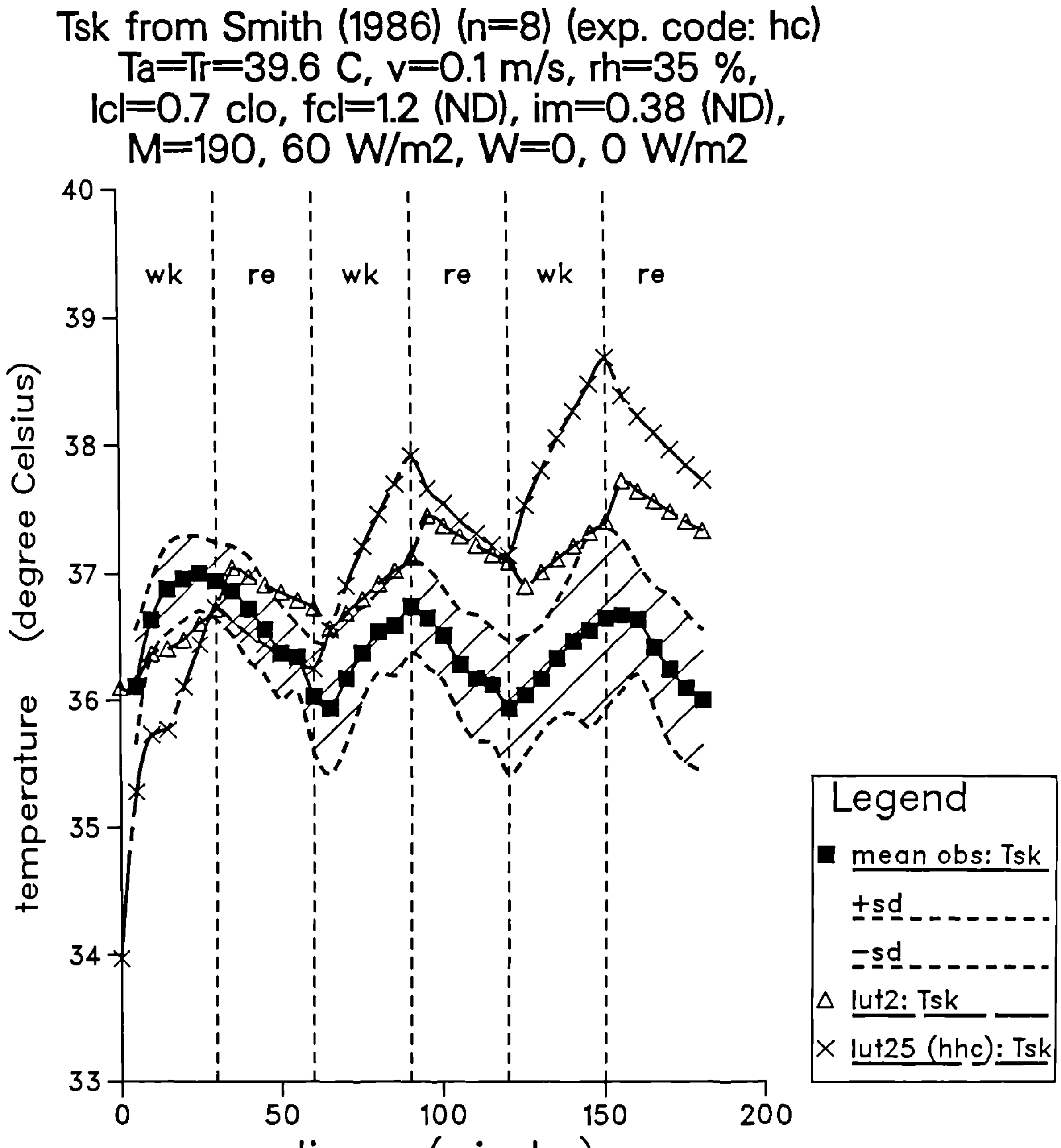


Tsk from Smith (1986) (n=8) (exp. code: wa)
Ta=Tr=28.9 C, v=0.1 m/s, rh=45 %,
Icl=1.0 clo, fcl=1.33 (ND), im=0.36 (ND),
M=190, 60 W/m2, W=0, 0 W/m2
wk
re
wk
re
wk
re
40
39
38
37
36
35
34
33
temperature (degree Celsius)
0
50
100
150
200
time (minutes)
Legend
mean obs: Tsk
+sd
-sd
lut2: Tsk
lut25 (hhc): Tsk

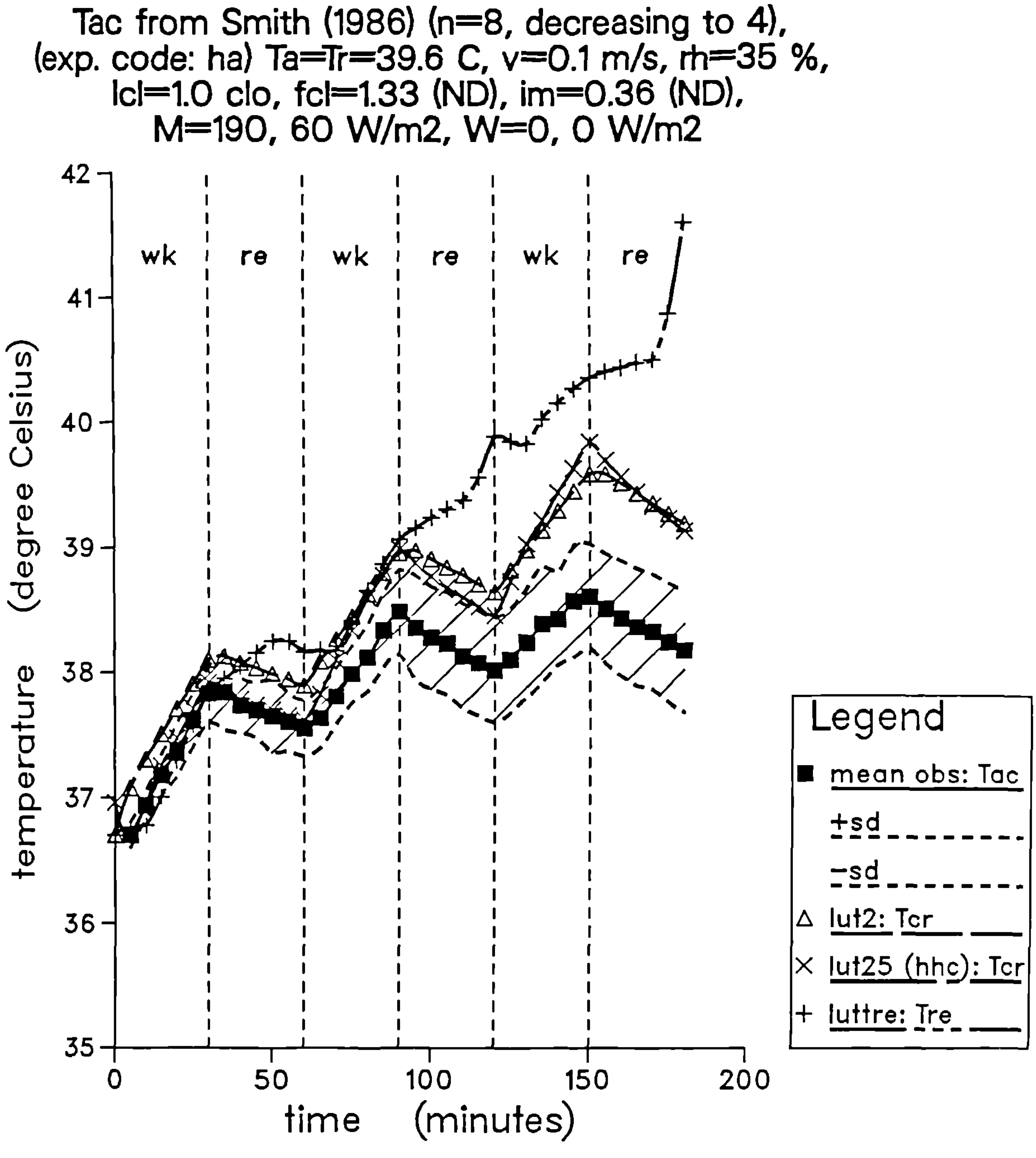
Tac from Smith (1986) (n=8) (exp. code: hc)
Ta=Tr=39.6 C, v=0.1 m/s, rh=35 %,
Icl=0.7 clo, fcl=1.2 (ND), im=0.38 (ND),
M=190, 60 W/m2, W=0, 0 W/m2



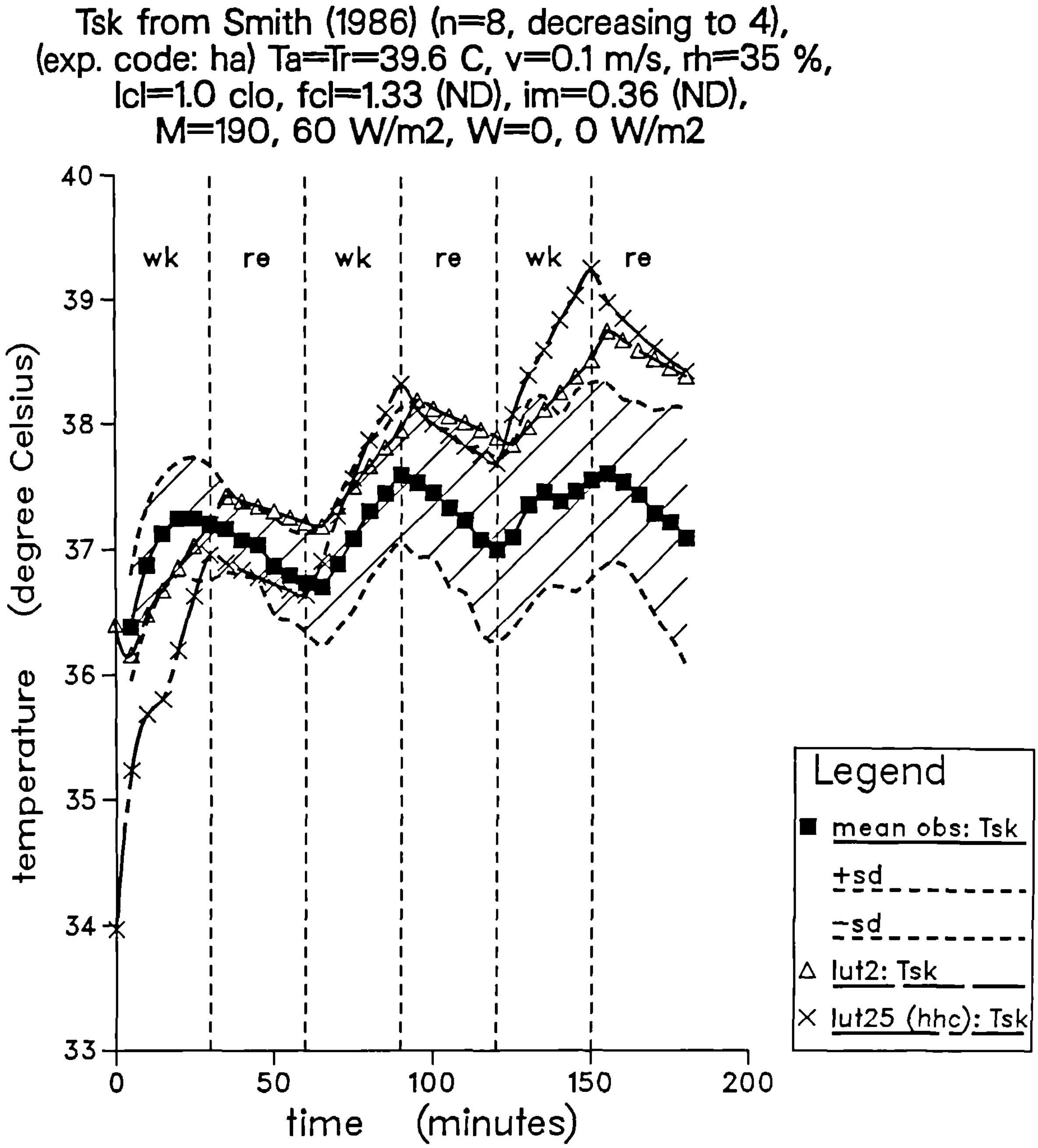
lutIso Allowable Exposure Times
(time weighted averages):
warning non-accl: 65 min; body temperature increase
danger non-accl : 78 min; body temperature increase
warning accl : 104 min; body temperature increase
danger accl : 124 min; body temperature increase



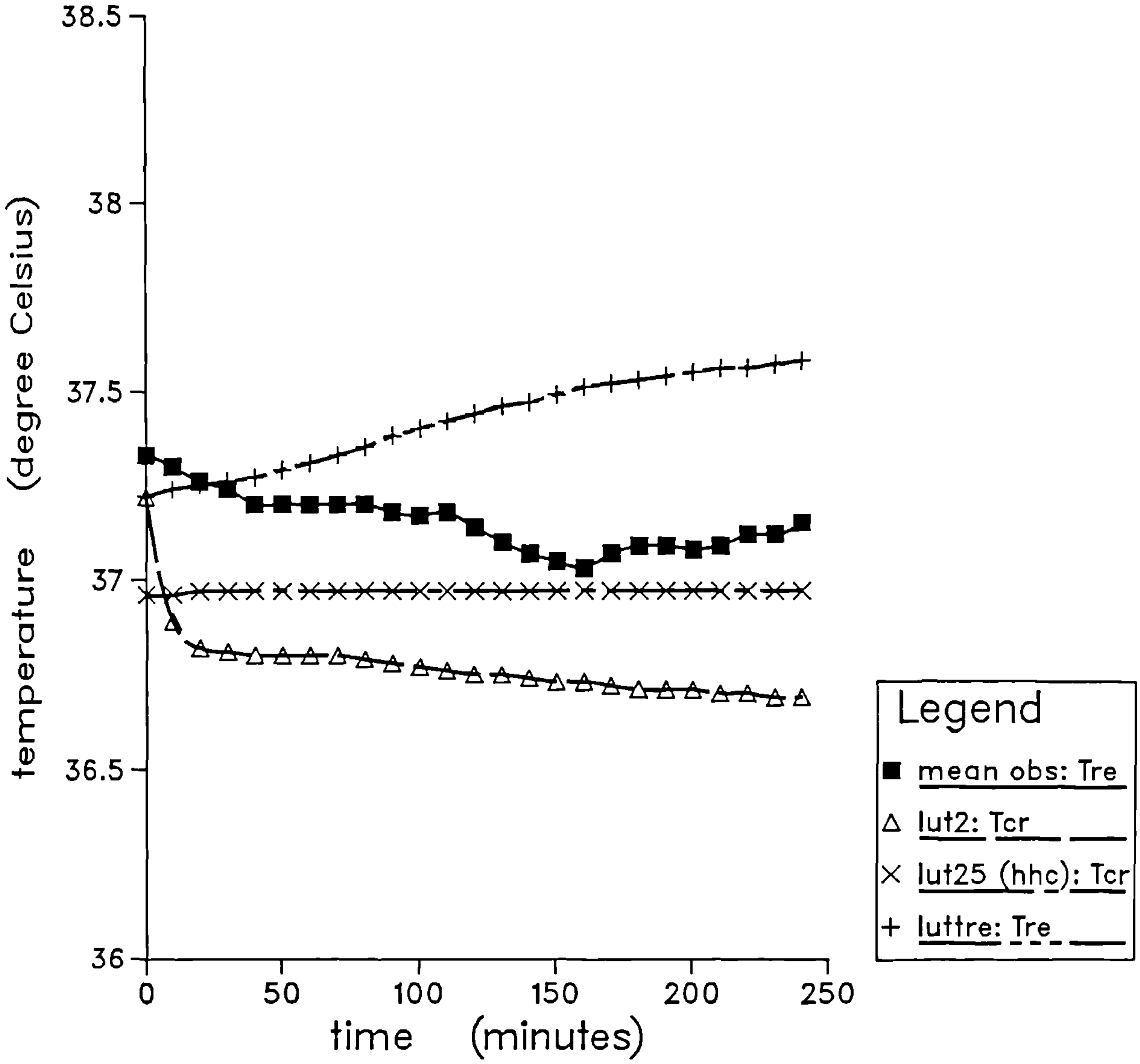
Tsk from Smith (1986) (n=8) (exp. code: hc)
Ta=Tr=39.6 C, v=0.1 m/s, rh=35 %,
Icl=0.7 clo, fcl=1.2 (ND), im=0.38 (ND),
M=190, 60 W/m2, W=0, 0 W/m2
wk
re
wk
re
wk
re
temperature (degree Celsius)
time (minutes)
40
39
38
37
36
35
34
33
0
50
100
150
200
Legend
mean obs: Tsk
+sd
−sd
lut2: Tsk
lut25 (hhc): Tsk

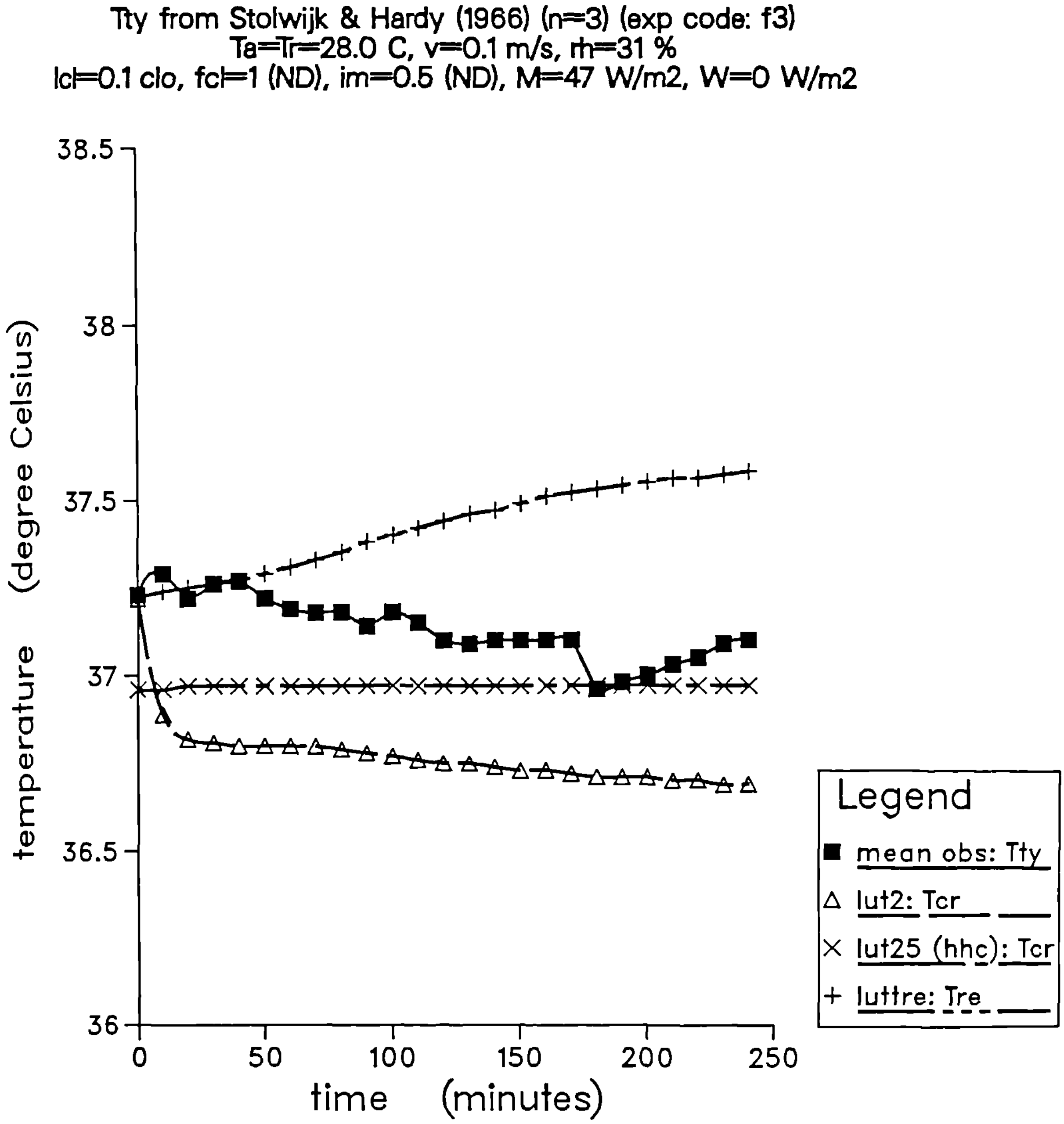


lutIso Allowable Exposure Times
(time weighted averages):
warning non-accl: 46 min; body temperature increase
danger non-accl : 55 min; body temperature increase
warning accl : 58 min; body temperature increase
danger accl : 70 min; body temperature increase


Tsk from Smith (1986) (n=8, decreasing to 4),
(exp. code: ha) Ta=Tr=39.6 C, v=0.1 m/s, rh=35 %,
Icl=1.0 clo, fcl=1.33 (ND), im=0.36 (ND),
M=190, 60 W/m2, W=0, 0 W/m2
wk
re
wk
re
wk
re
temperature (degree Celsius)
40
39
38
37
36
35
34
33
0
50
100
150
200
time (minutes)
Legend
mean obs: Tsk
+sd
-sd
lut2: Tsk
lut25 (hhc): Tsk

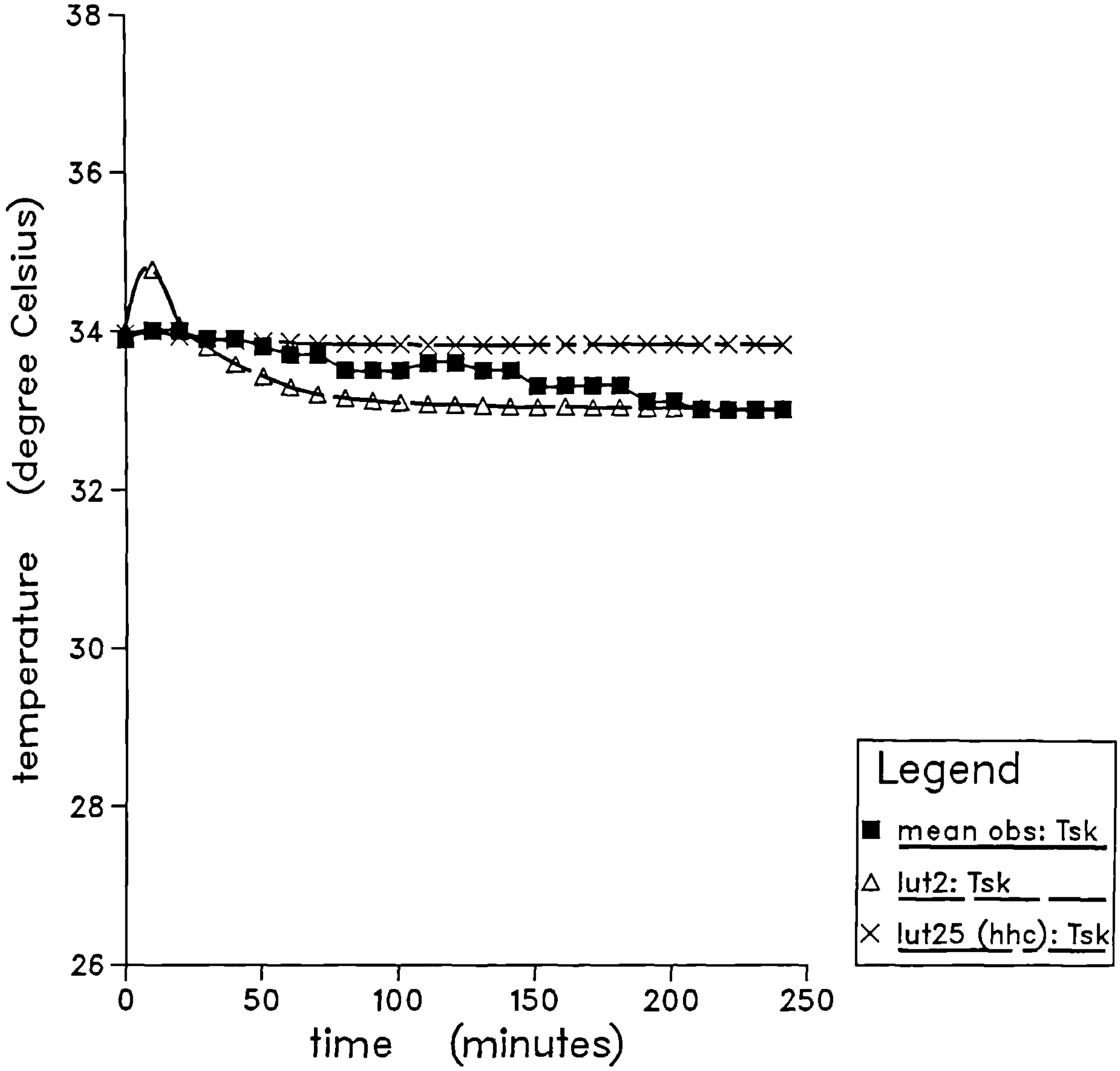
Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f3)
Ta=Tr=28.0 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



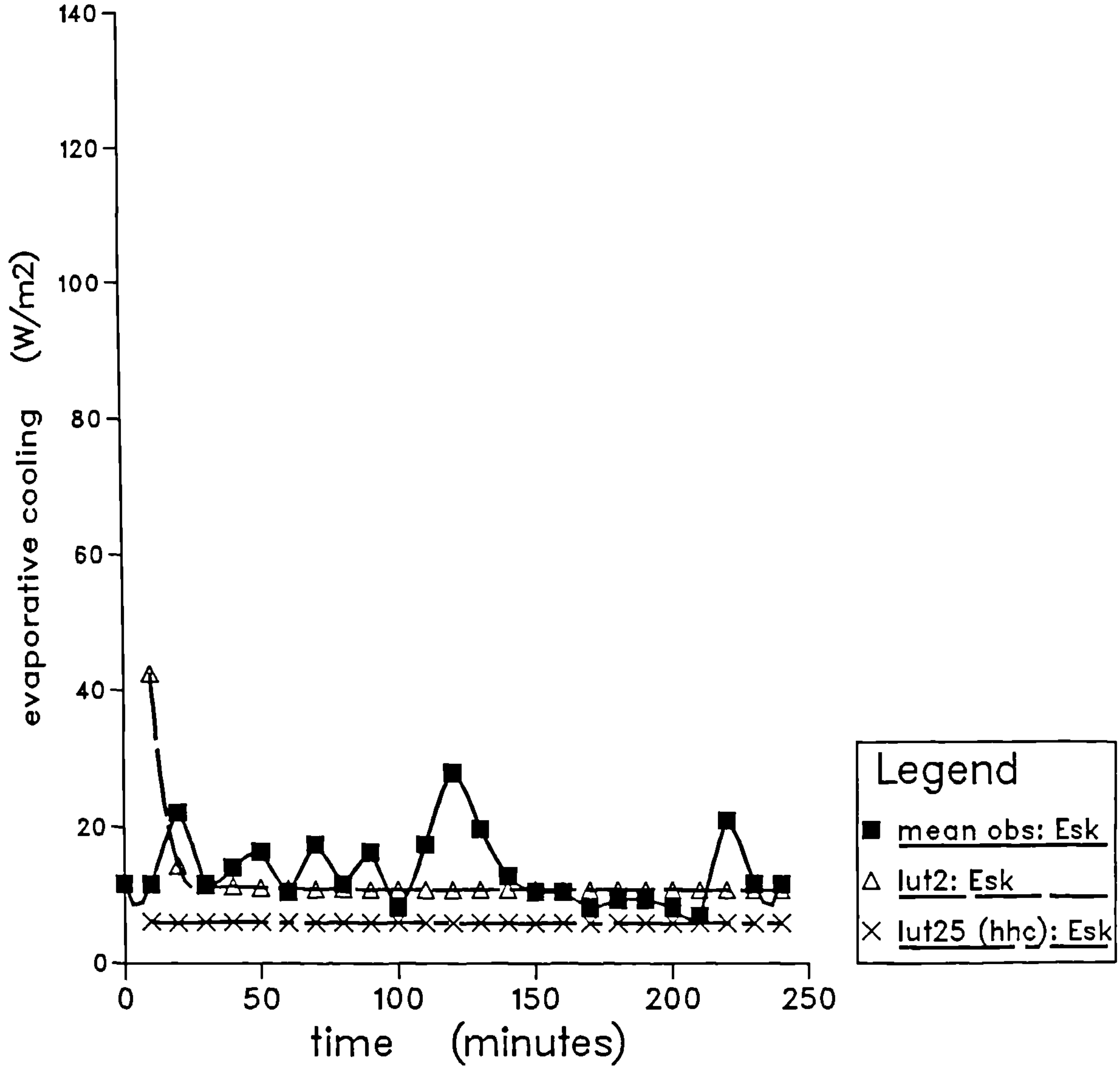


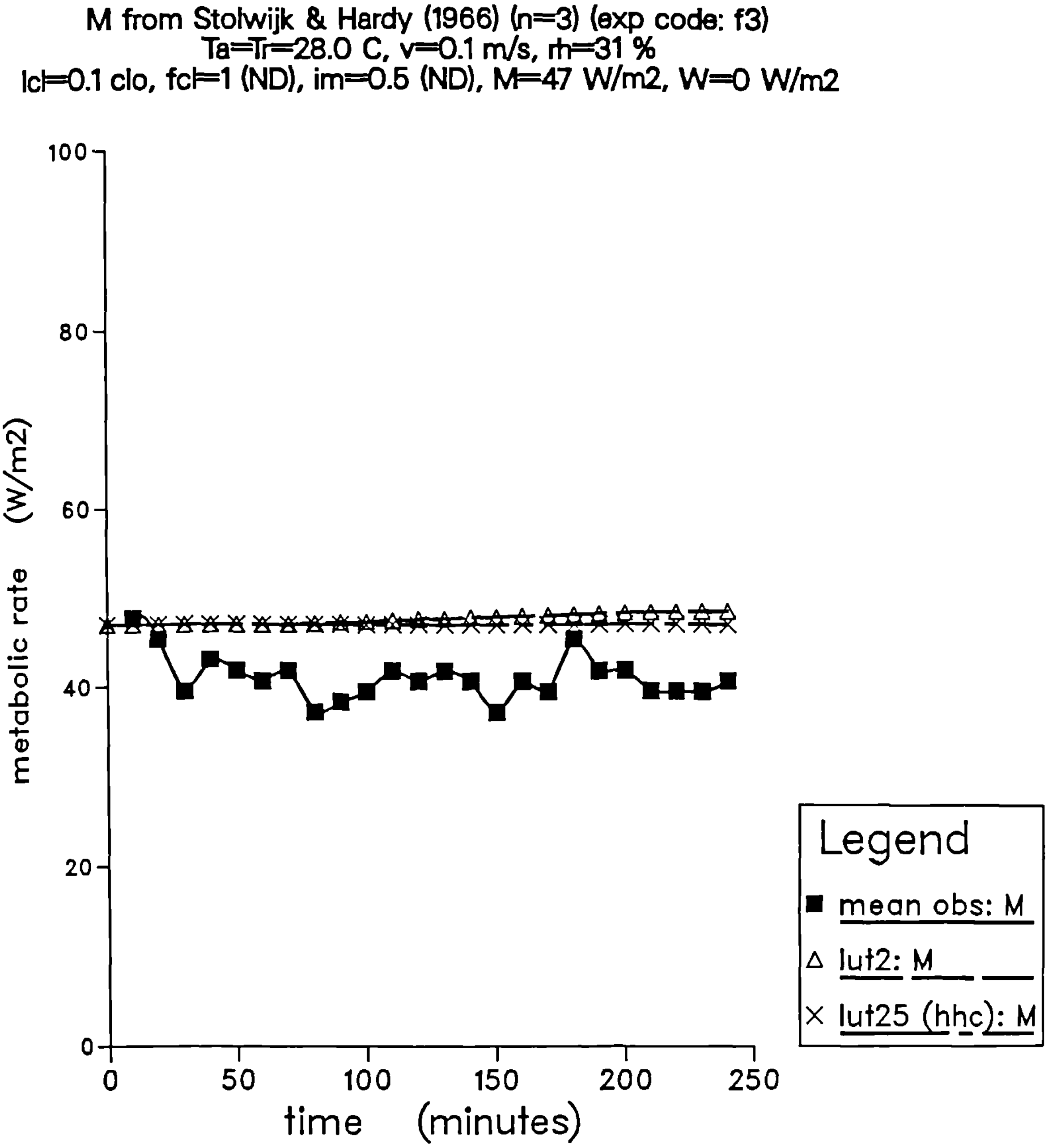
Tty from Stolwijk & Hardy (1966) (n=3) (exp code: f3)
Ta=Tr=28.0 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
38.5
38
37.5
37
36.5
36
temperature (degree Celsius)
0
50
100
150
200
250
time (minutes)
Legend
mean obs: Tty
lut2: Tcr
lut25 (hhc): Tcr
luttre: Tre

Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f3)
Ta=Tr=28.0 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

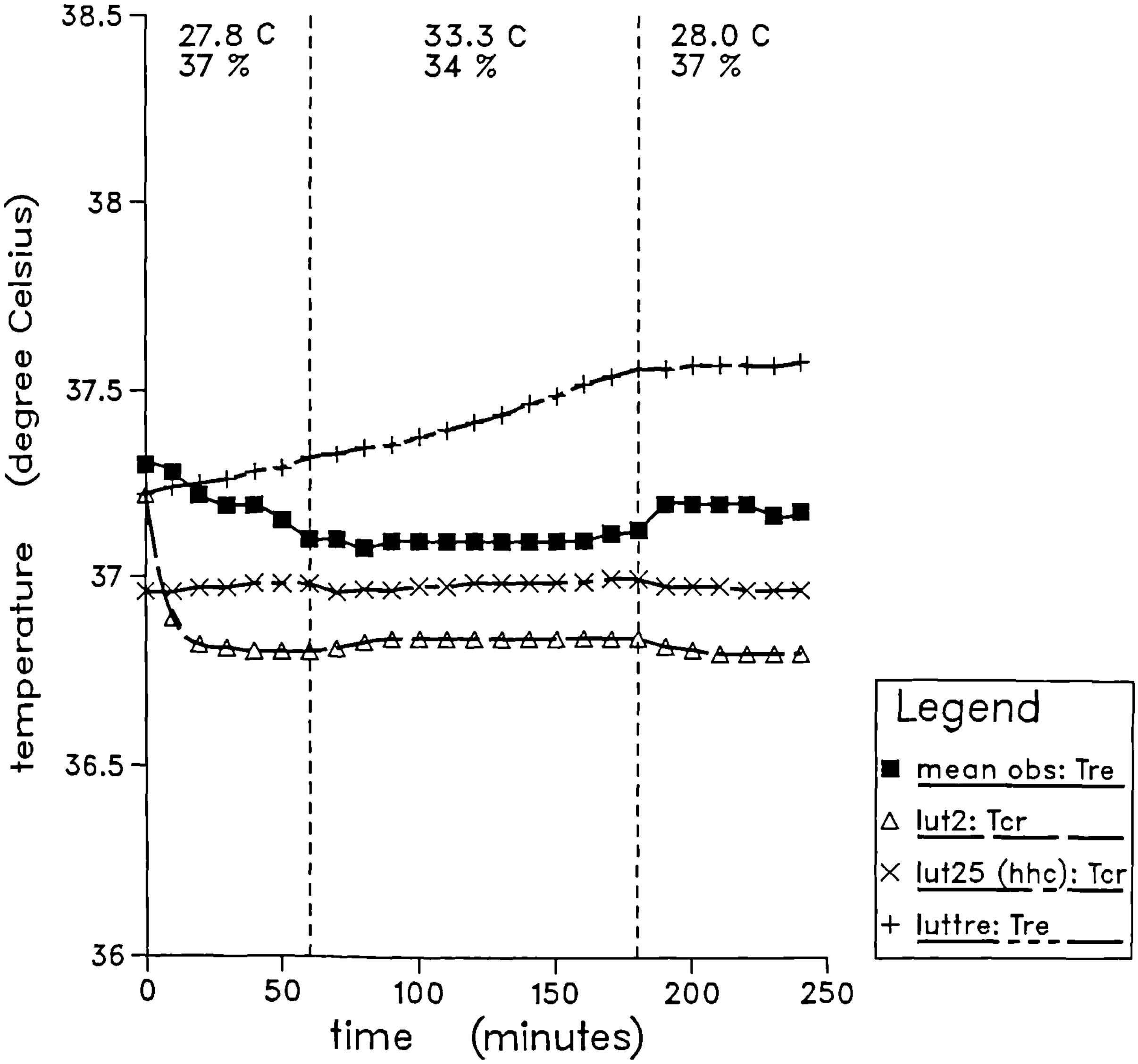


Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f3)
Ta=Tr=28.0 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



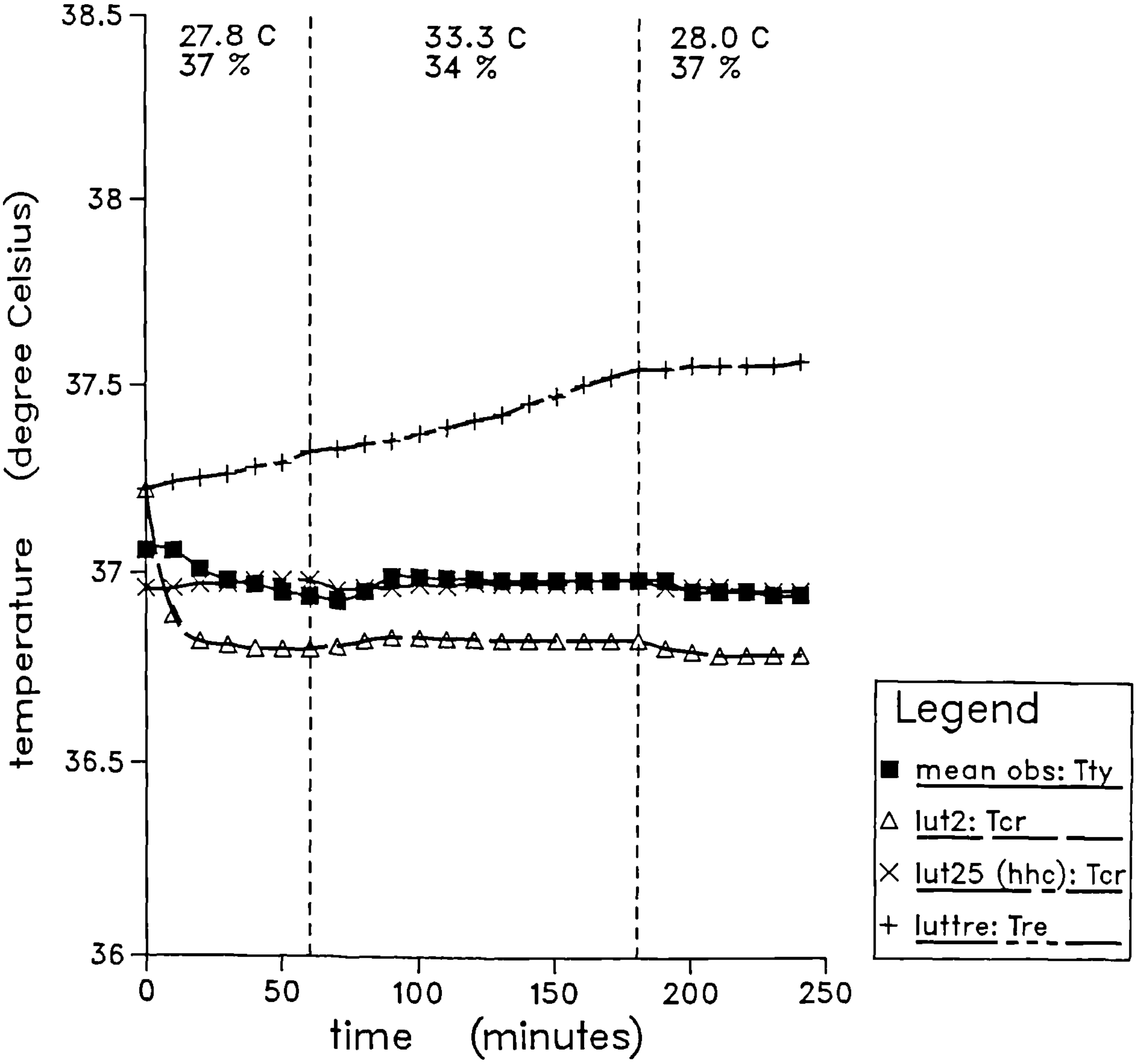

M from Stolwijk & Hardy (1966) (n=3) (exp code: f3)
Ta=Tr=28.0 C, v=0.1 m/s, rh=31 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
metabolic rate (W/m2)
100
80
60
40
20
0
0
50
100
150
200
250
time (minutes)
Legend
mean obs: M
lut2: M
lut25 (hhc): M

Tre 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 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



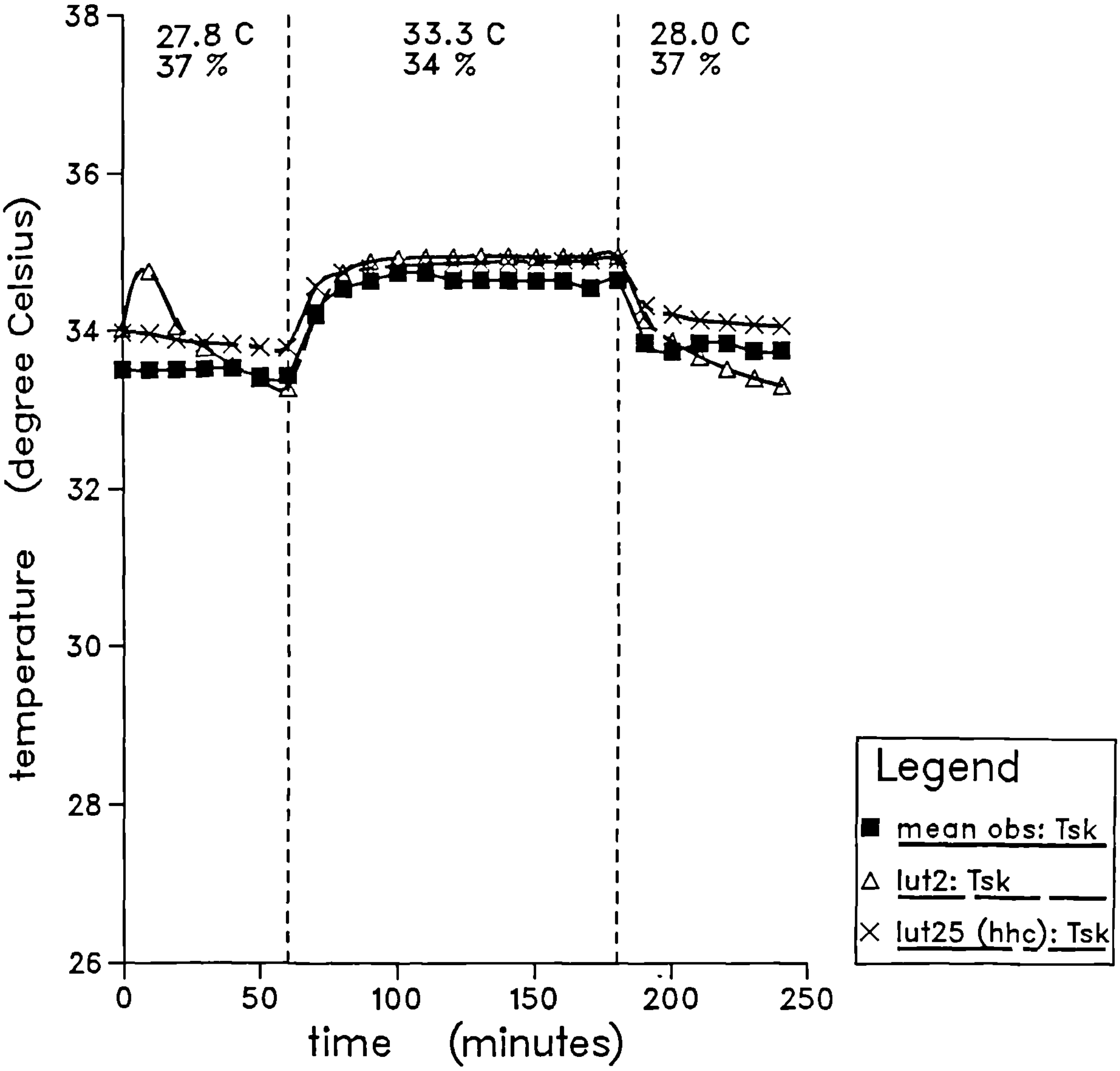
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tty from Stolwijk & Hardy (1966) (n=3) (exp code: f4)
Ta=Tr=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

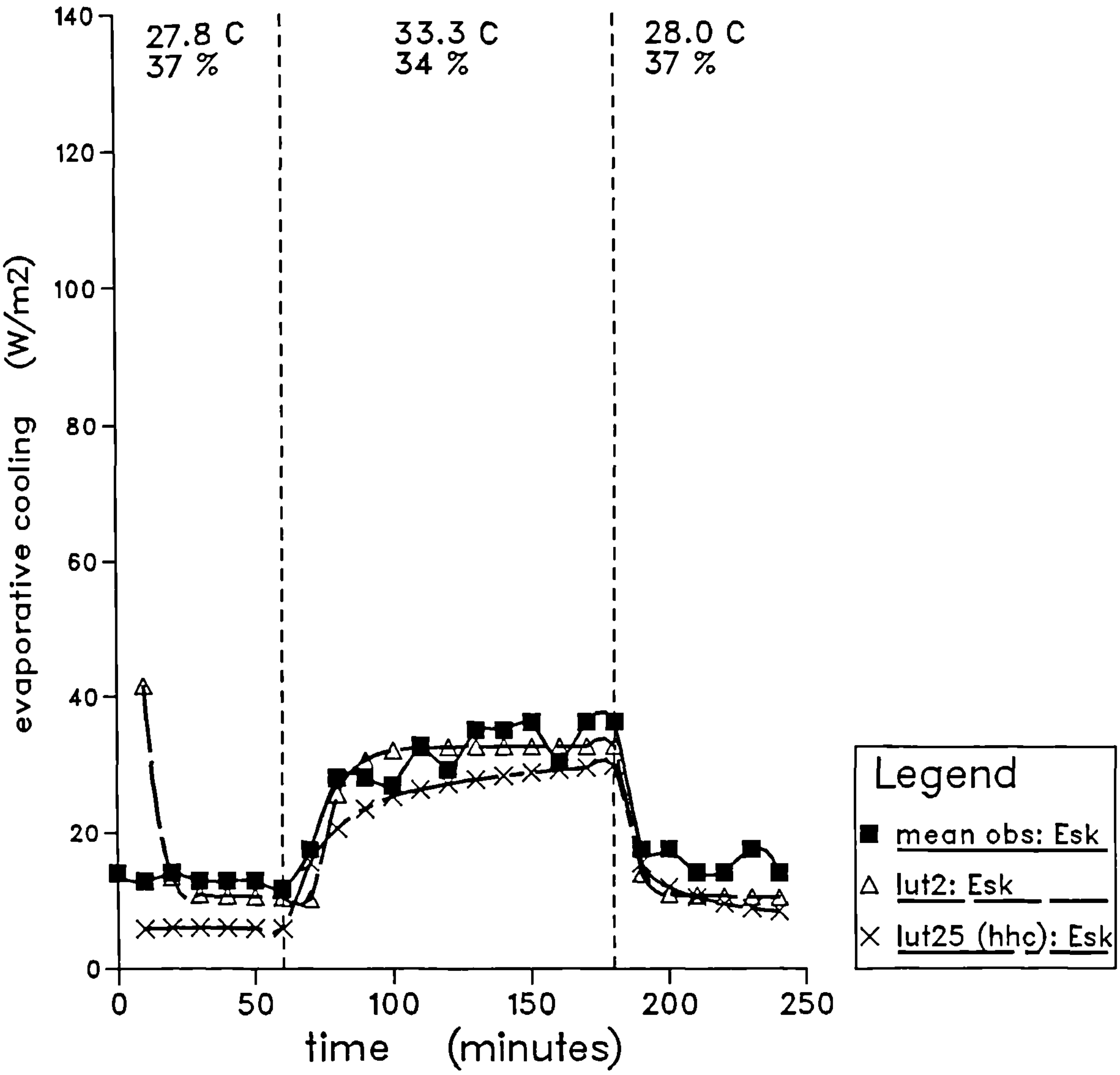


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl : 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

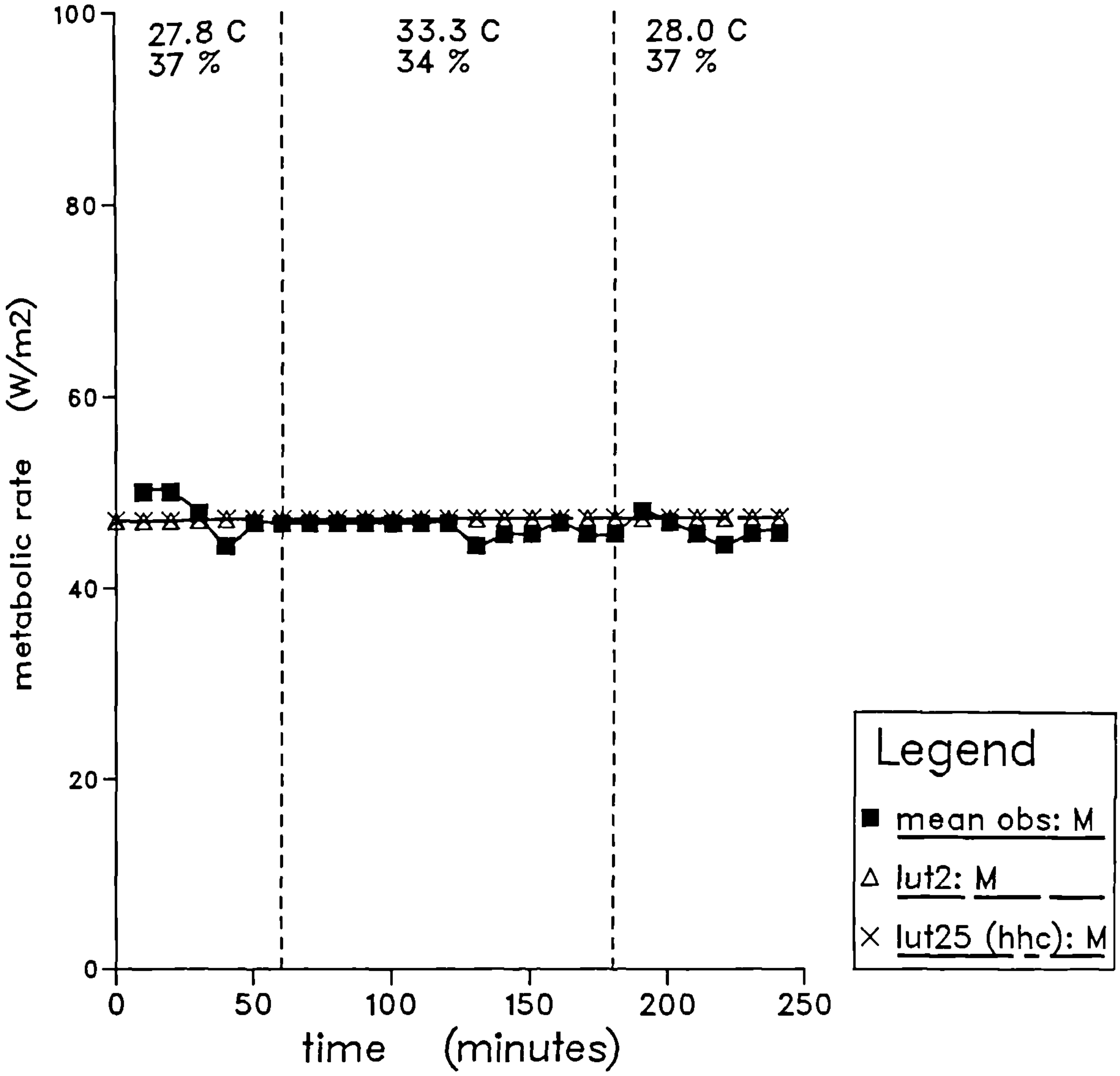
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f4)
Ta=Tr=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



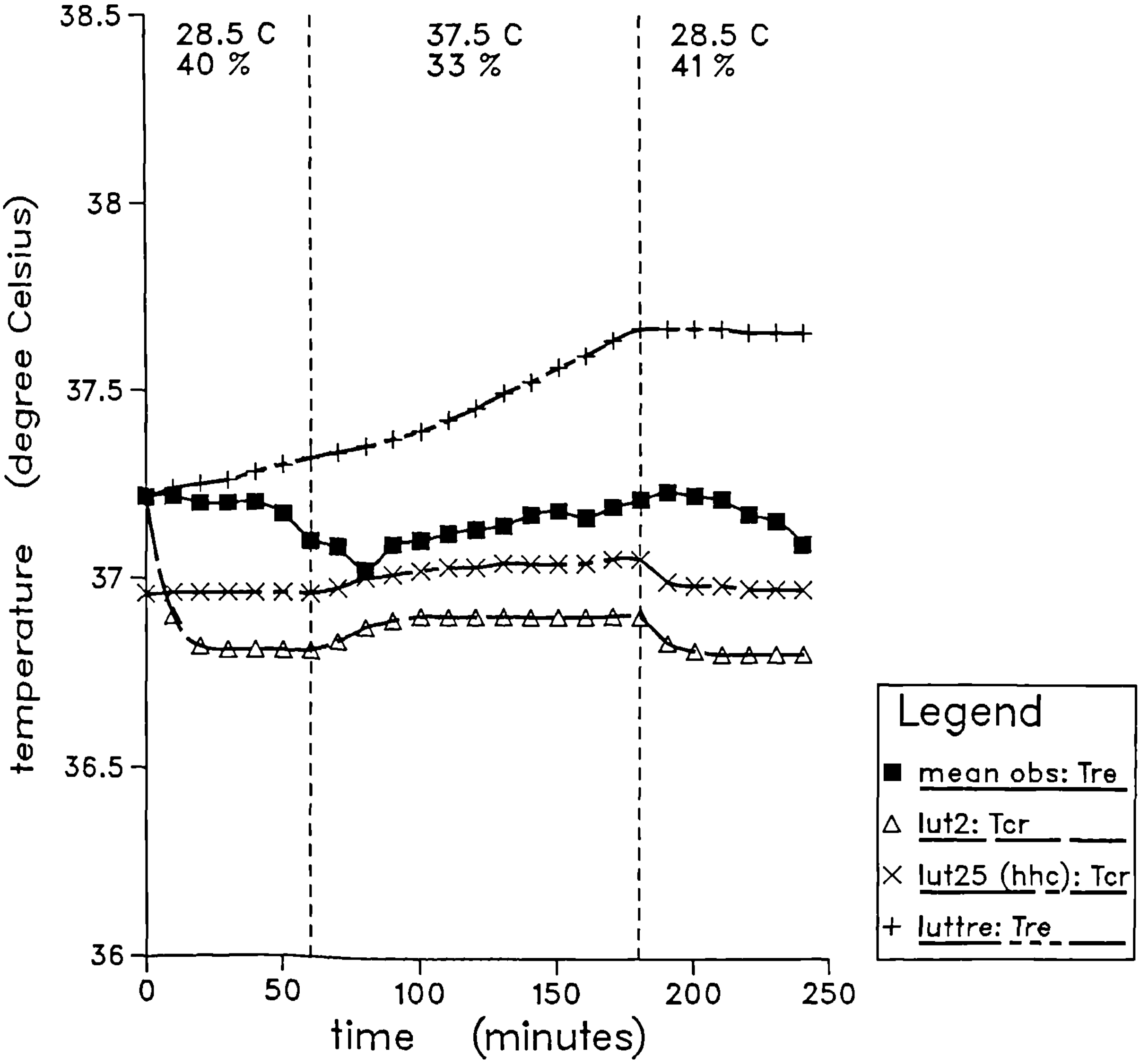
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f4)
Ta=Tr=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



M from Stolwijk & Hardy (1966) (n=3) (exp code: f4)
Ta=Tr=27.8, 33.3, 28.0 C, v=0.1 m/s, rh=37, 34, 37 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

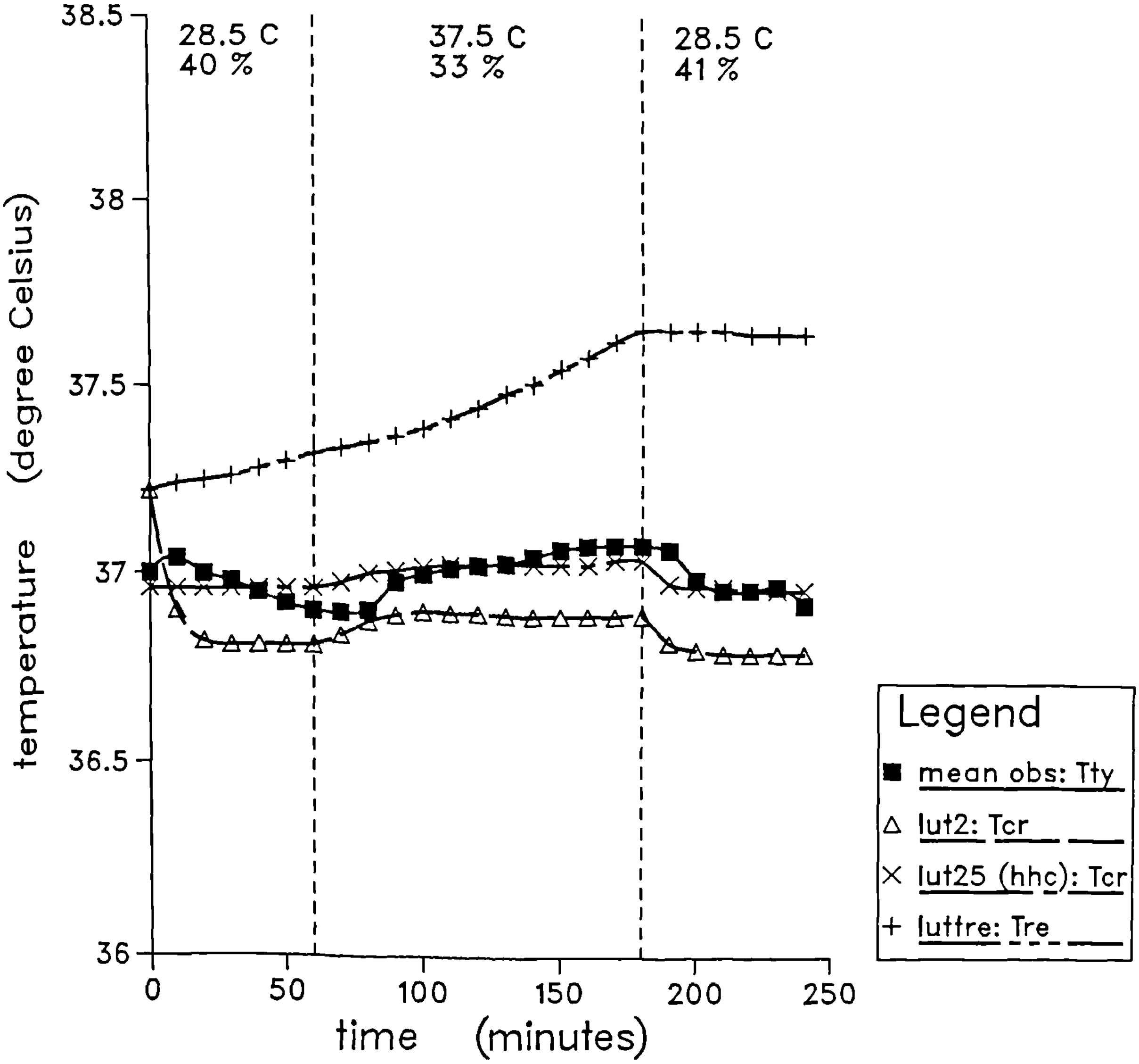


Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f5)
Ta≈Tr=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



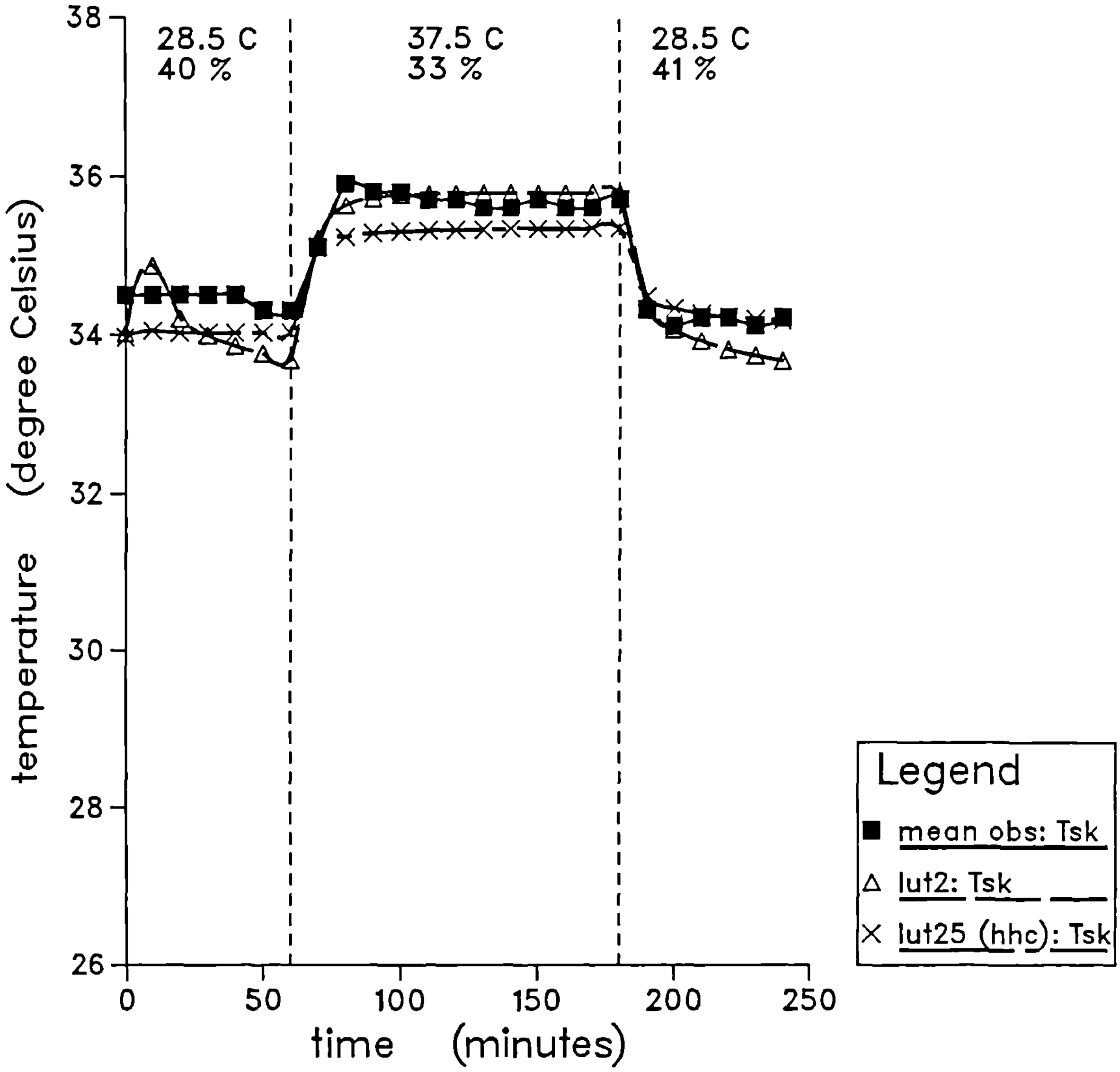
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

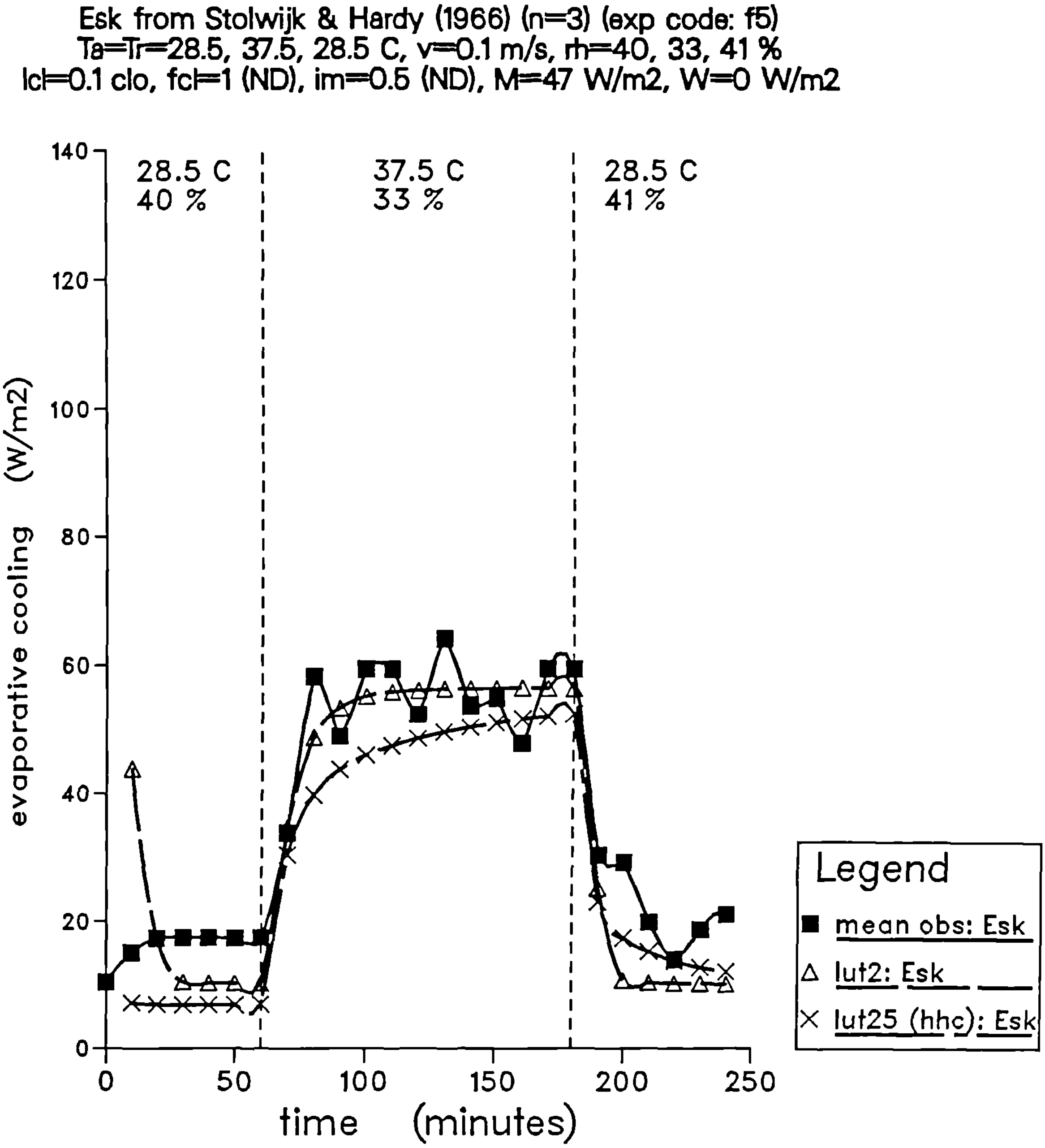
Tty from Stolwijk & Hardy (1966) (n=3) (exp code: f5)
Ta=Tr=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



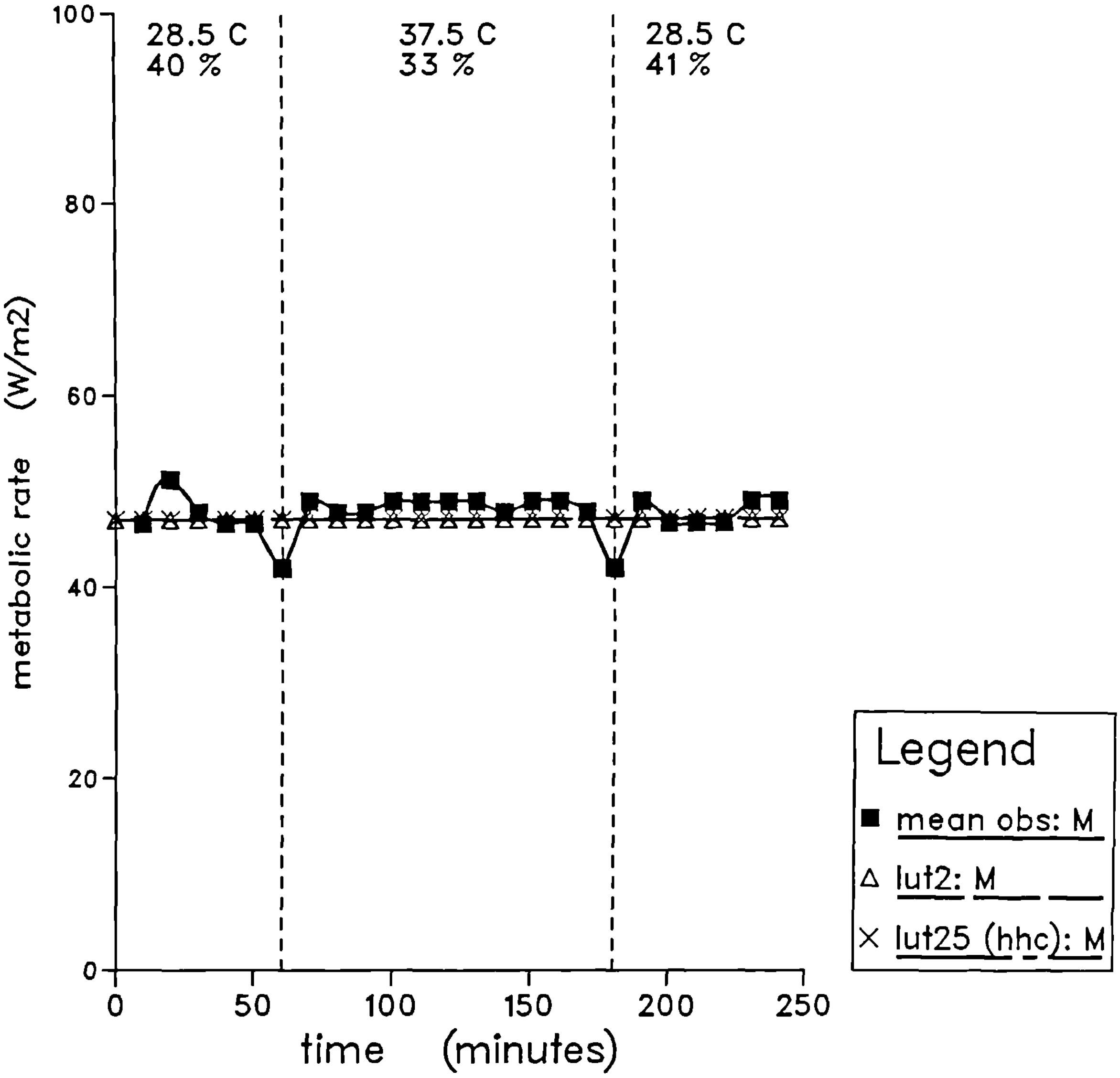
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

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 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

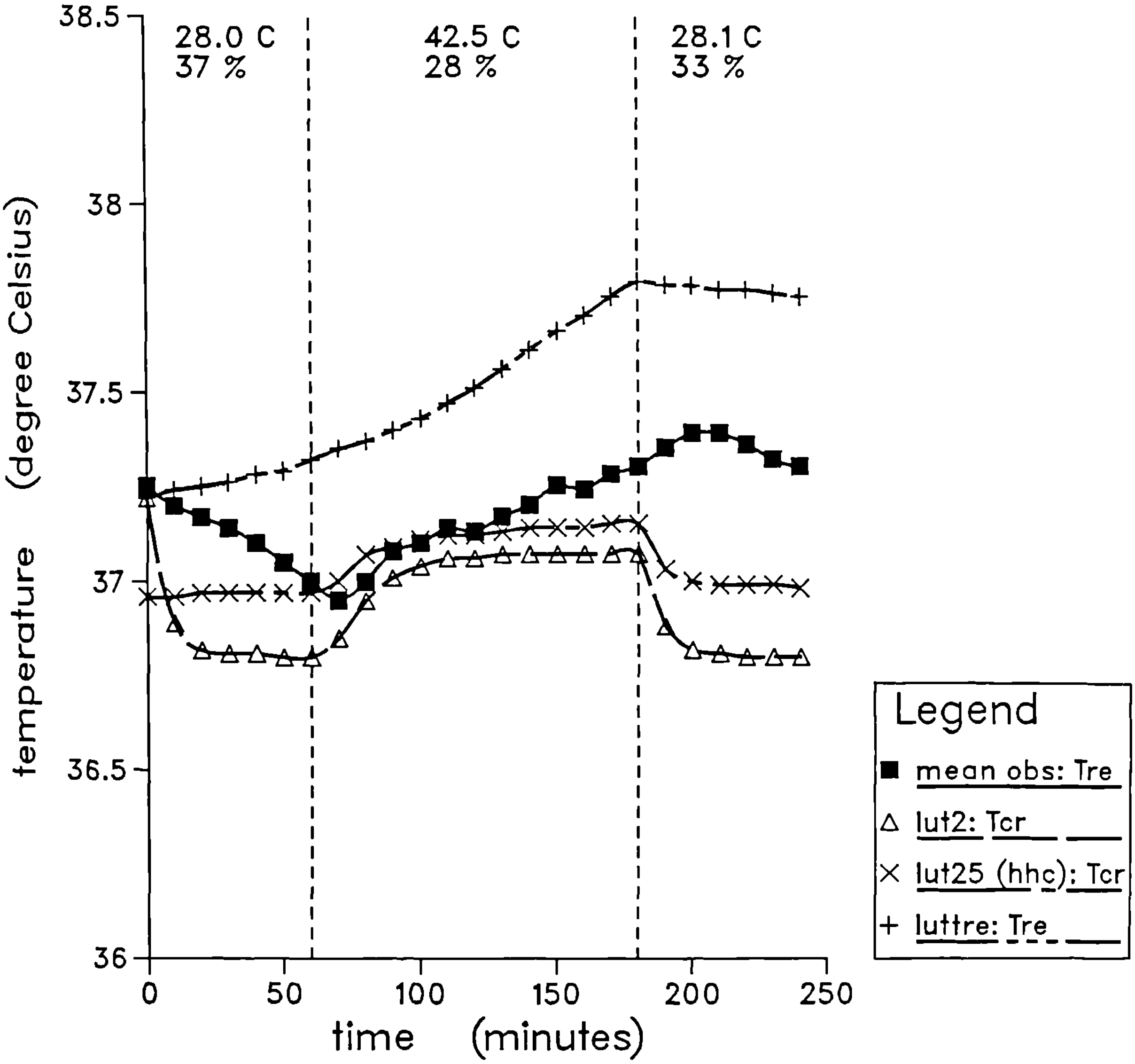



Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f5)
Ta=Tr=28.5, 37.5, 28.5 C, v=0.1 m/s, rh=40, 33, 41 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2
28.5 C
40 %
37.5 C
33 %
28.5 C
41 %
evaporative cooling (W/m2)
time (minutes)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
Legend
mean obs: Esk
lut2: Esk
lut25 (hhc): Esk

M 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 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

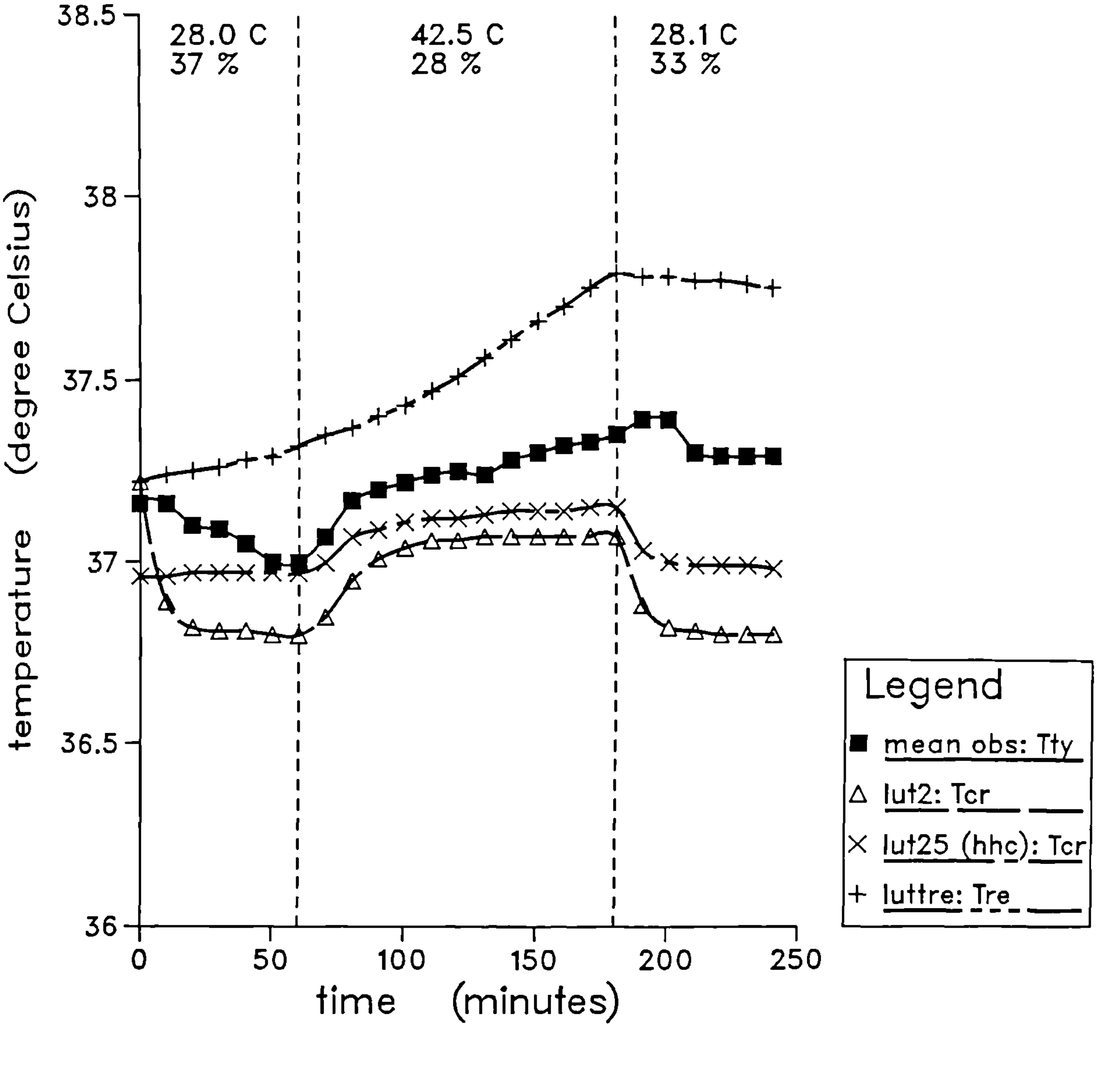


Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
Ta=Tr=28.0, 42.5, 28.1 C, v=0.1 m/s, rh=37, 28, 33 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



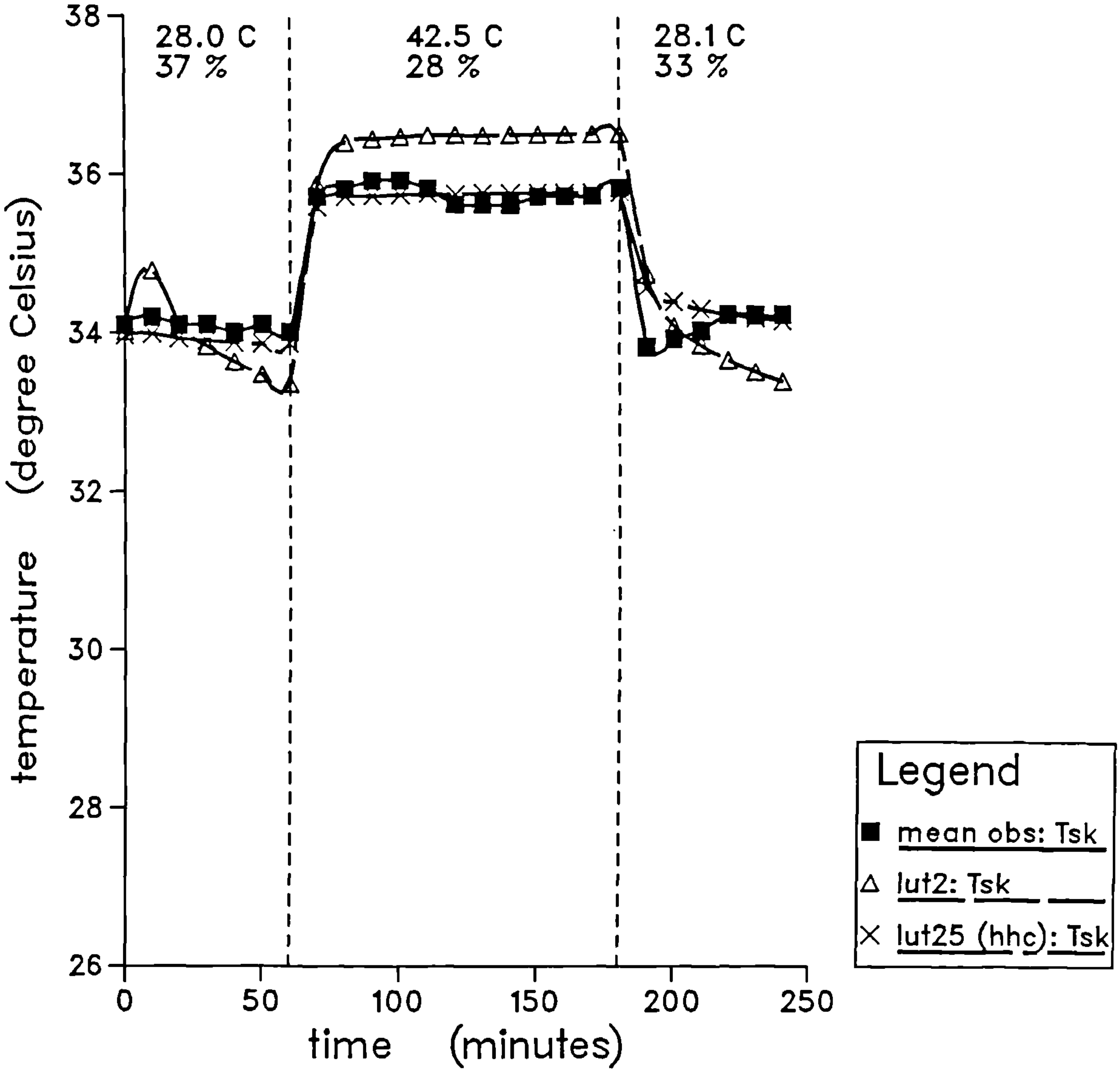
lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 450 min; excessive dehydration
danger accl : 400 min; excessive dehydration

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 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

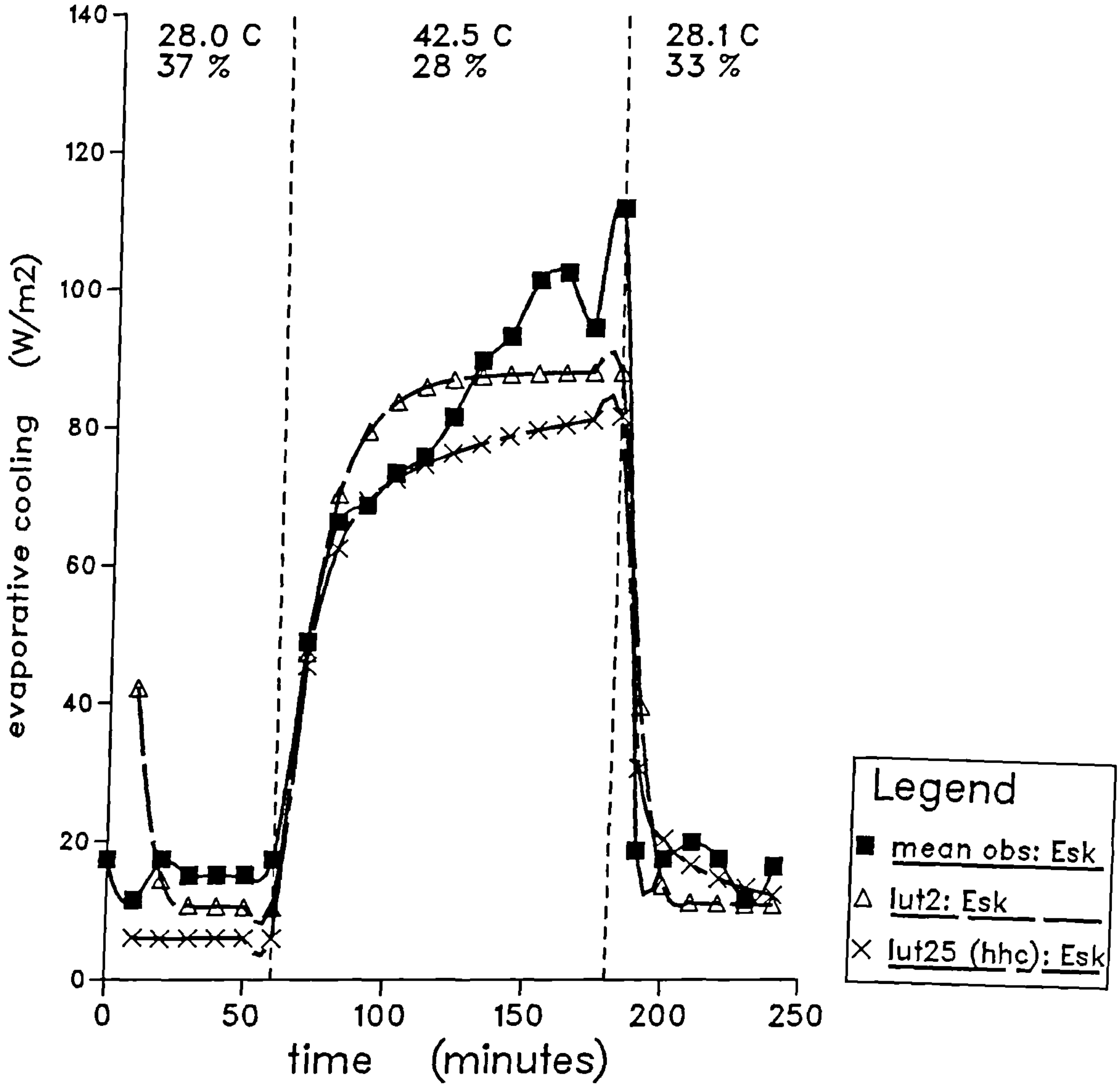


lutiso Allowable Exposure Times
(time weighted averages):
warning non-accl: 480 min; unlimited duration
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

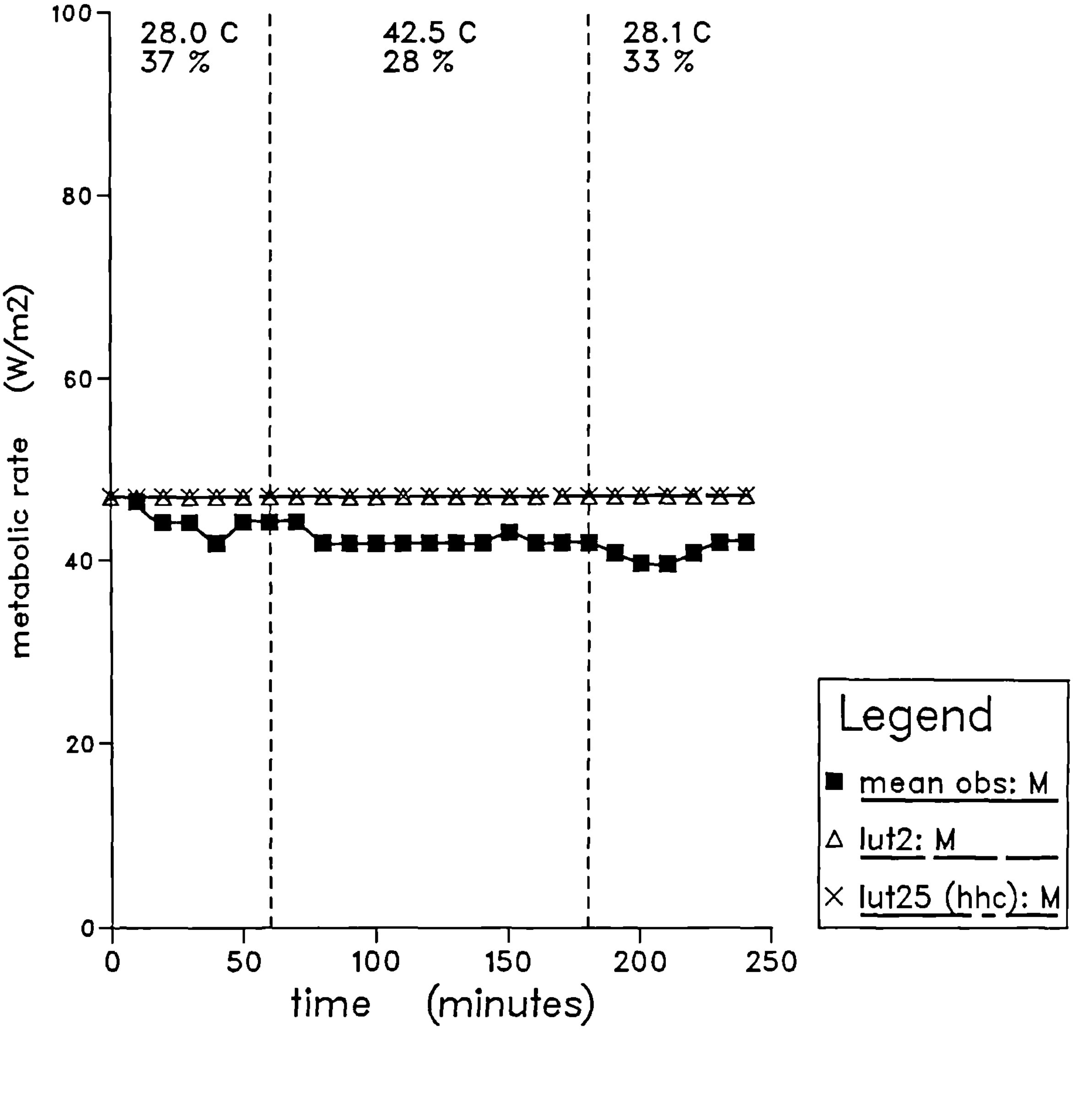
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
Ta=Tr=28.0, 42.5, 28.1 C, v=0.1 m/s, rh=37, 28, 33 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



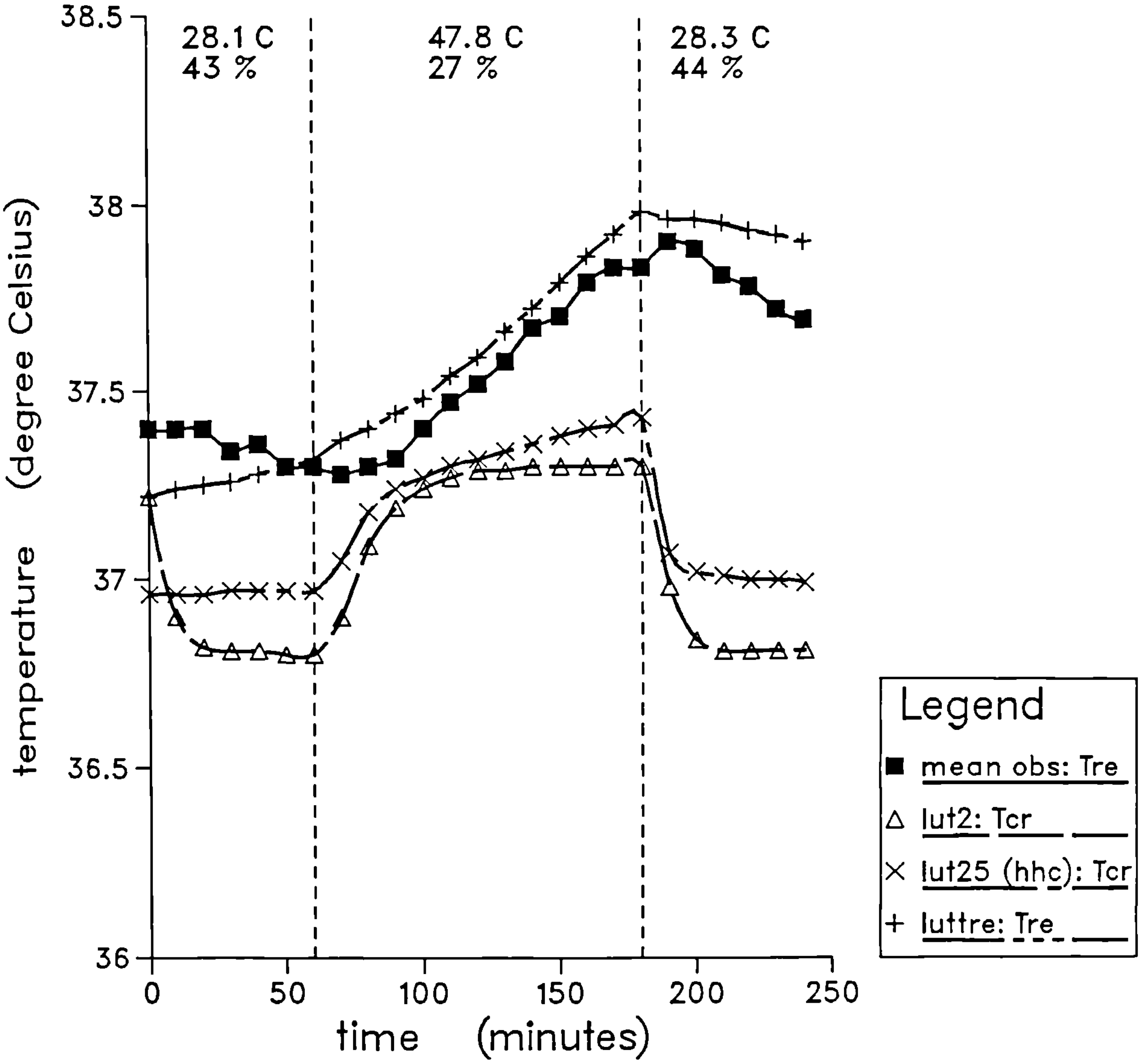
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
Ta=Tr=28.0, 42.5, 28.1 C, v=0.1 m/s, rh=37, 28, 33 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



M from Stolwijk & Hardy (1966) (n=3) (exp code: f6)
Ta=Tr=28.0, 42.5, 28.1 C, v=0.1 m/s, rh=37, 28, 33 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

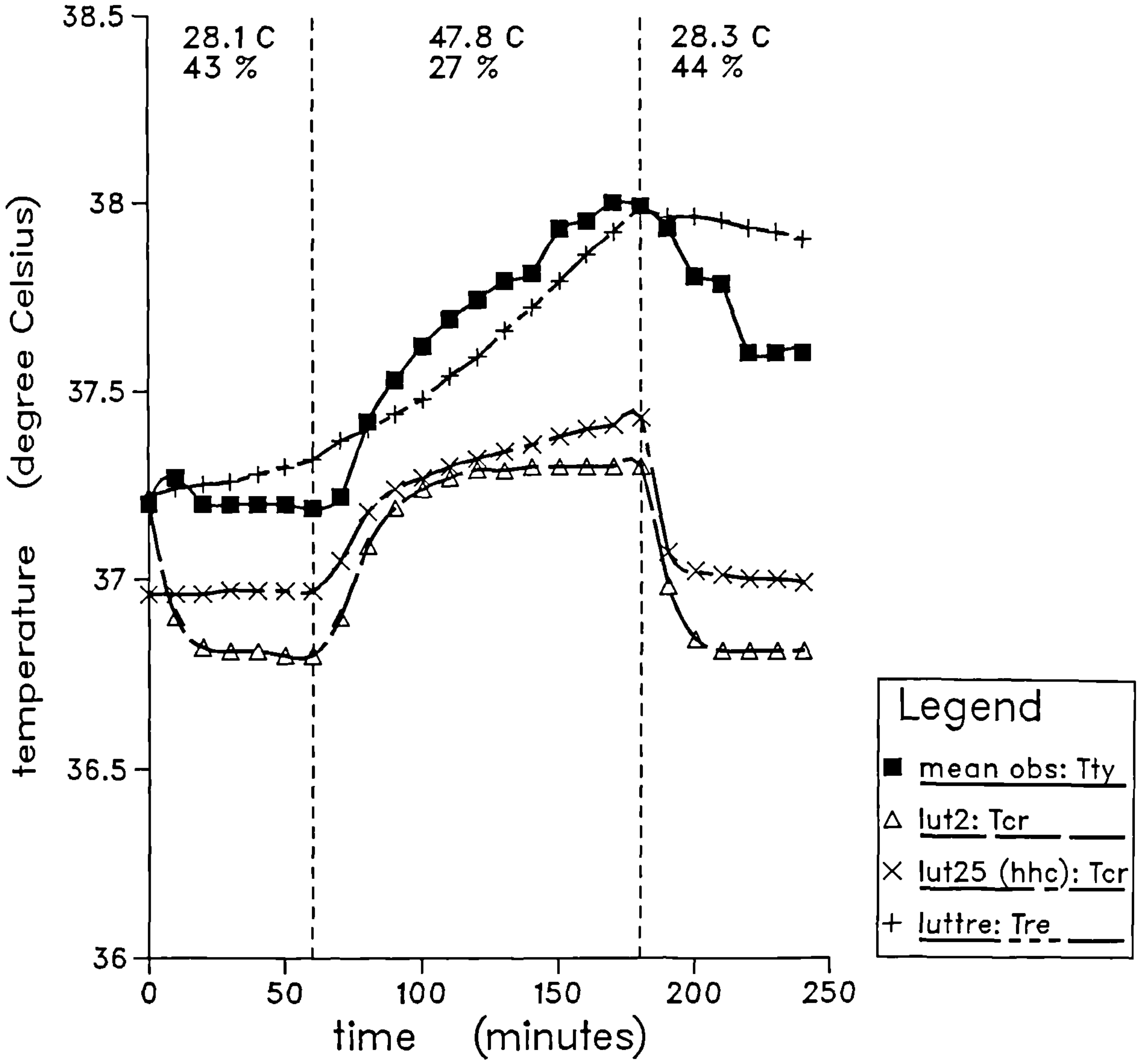


Tre from Stolwijk & Hardy (1966) (n=3) (exp code: f7)
Ta=Tr=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



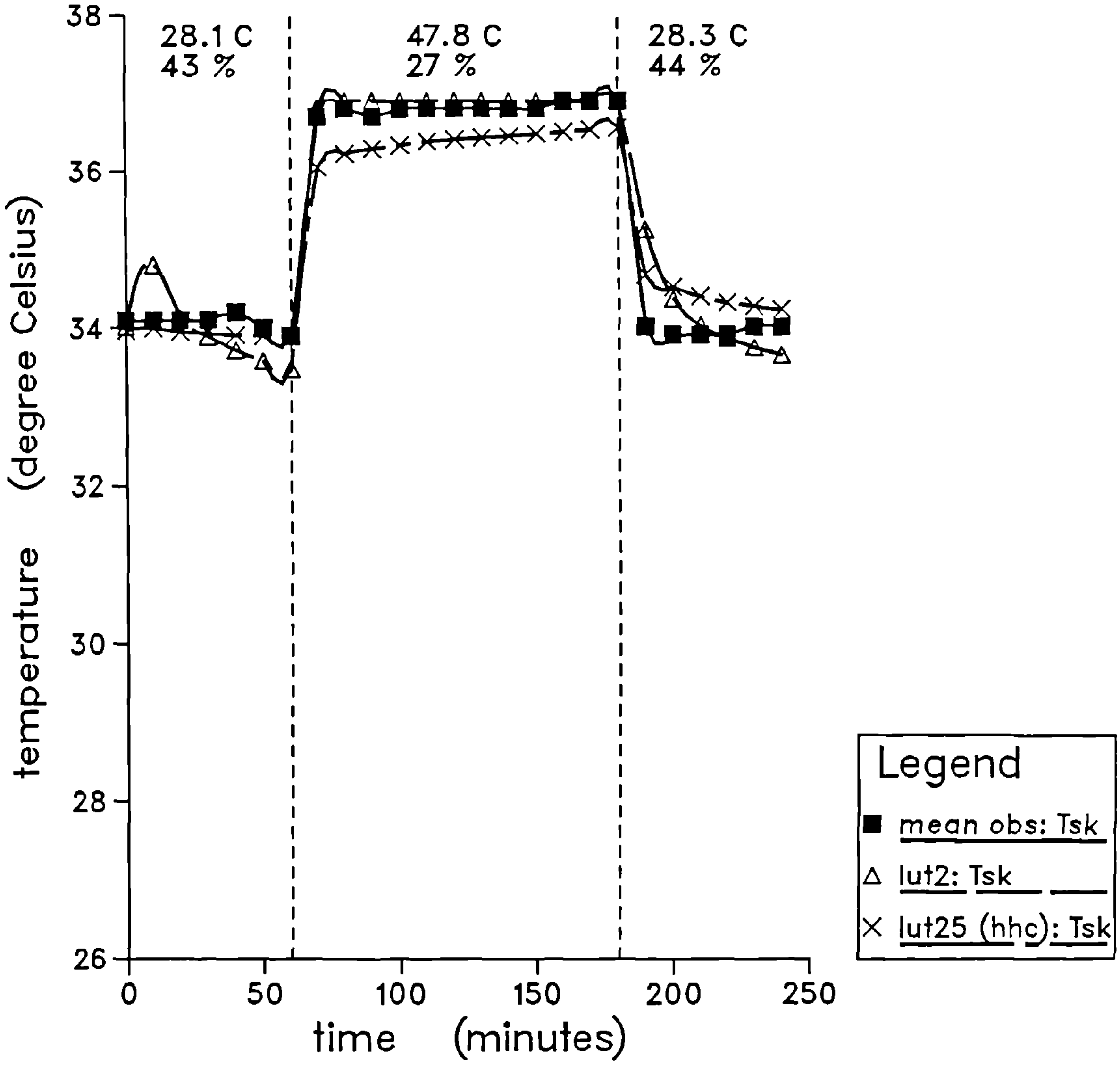
lutiso Allowable Exposure Times
(to 47 C, 27 %):
warning non-accl: 65 min; body temperature increase
(time weighted averages):
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

Tty 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 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2

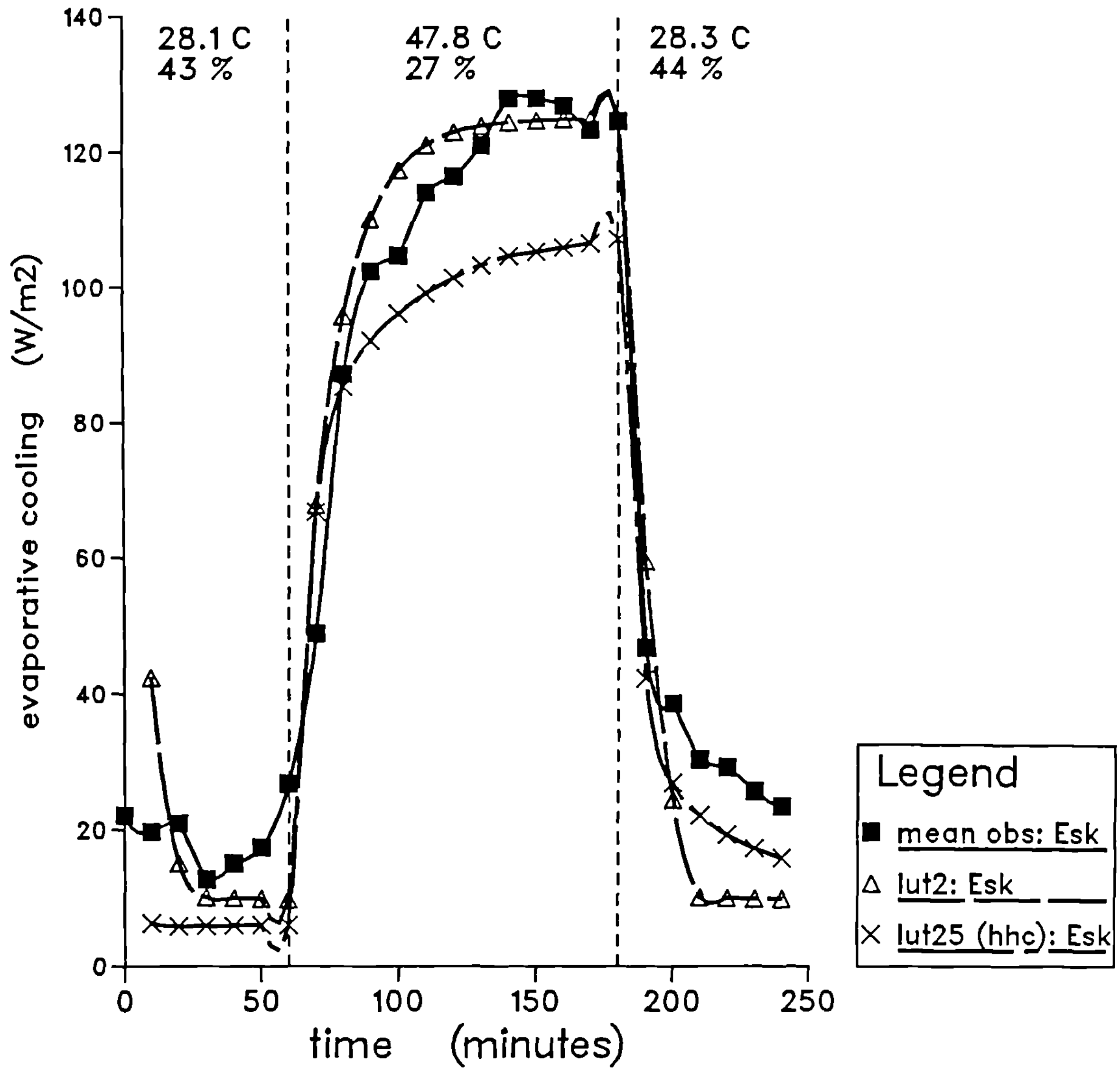


lutiso Allowable Exposure Times
(to 47 C, 27 %):
warning non-accl: 65 min; body temperature increase
(time weighted averages):
danger non-accl : 480 min; unlimited duration
warning accl : 480 min; unlimited duration
danger accl : 480 min; unlimited duration

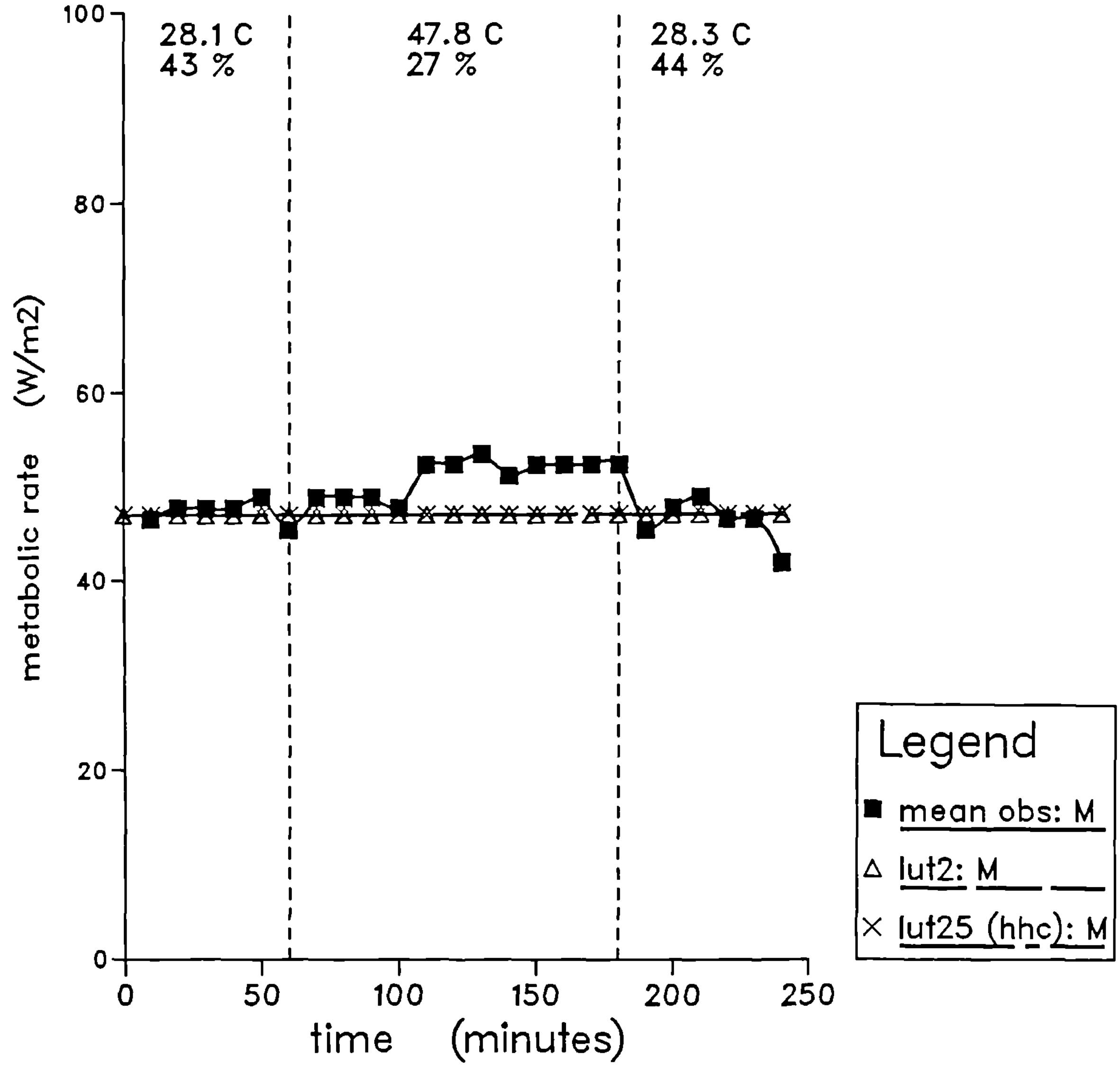
Tsk from Stolwijk & Hardy (1966) (n=3) (exp code: f7)
Ta=Tr=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



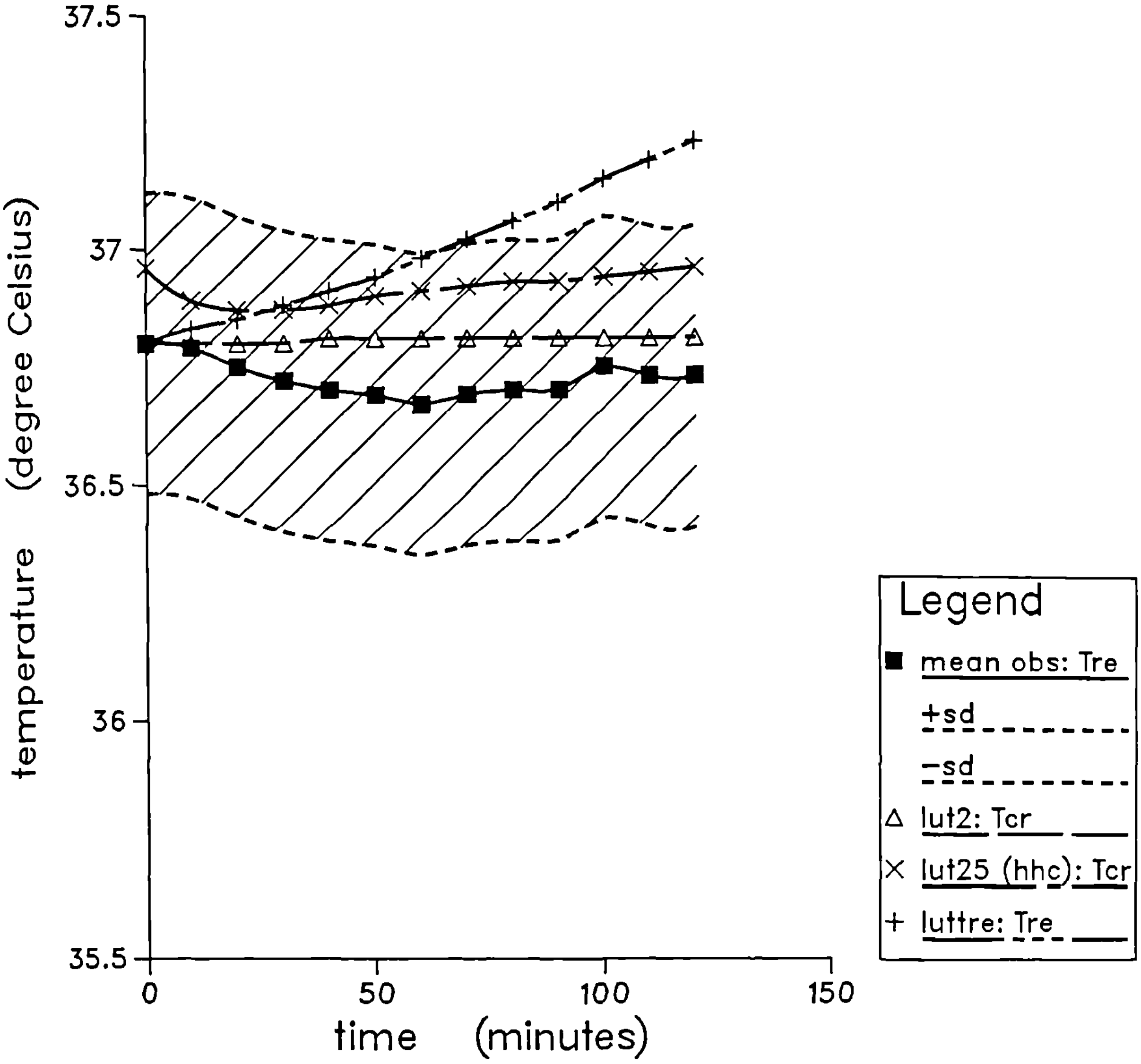
Esk from Stolwijk & Hardy (1966) (n=3) (exp code: f7)
Ta=Tr=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



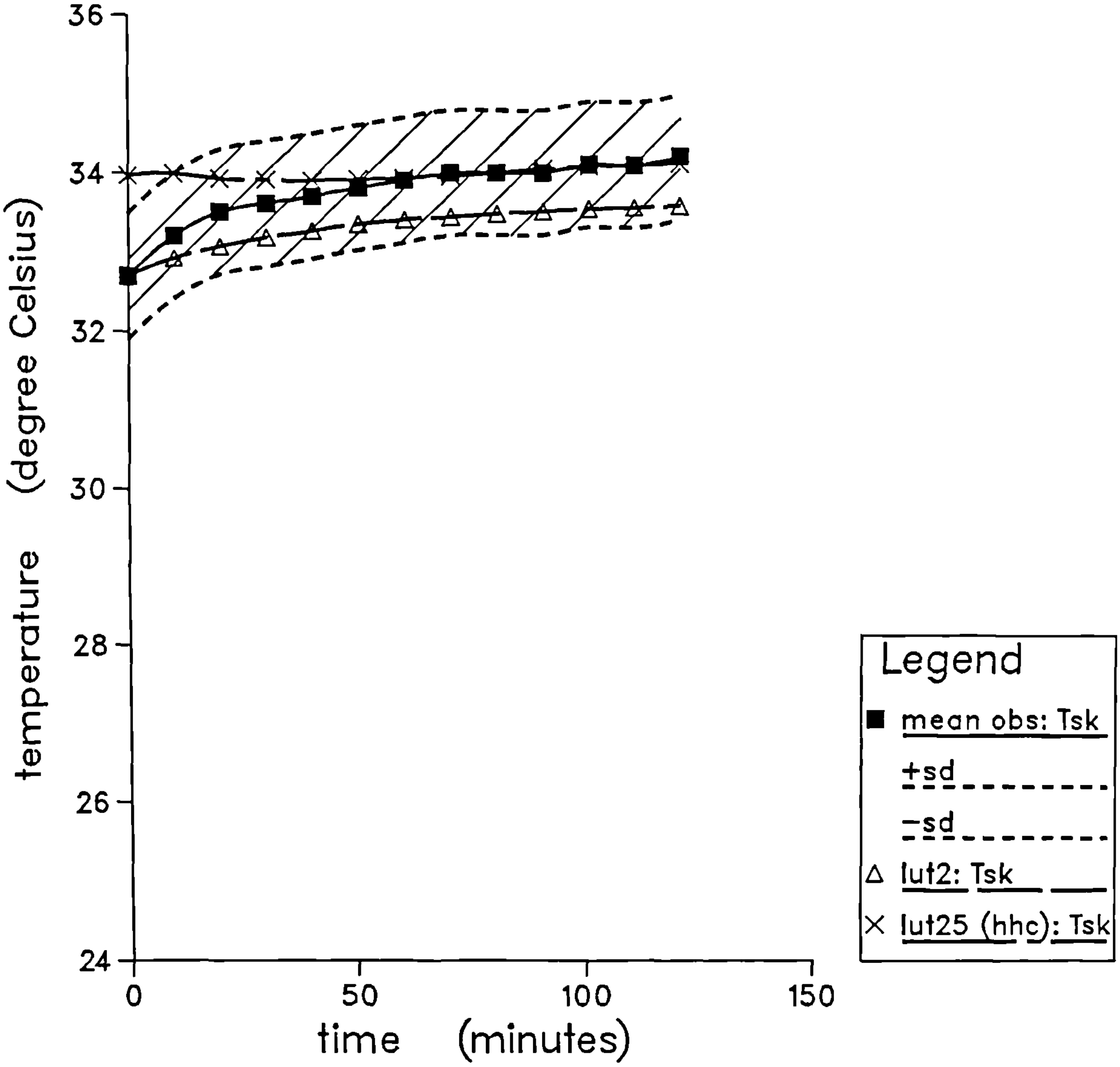
M from Stolwijk & Hardy (1966) (n=3) (exp code: f7)
Ta=Tr=28.1, 47.8, 28.3 C, v=0.1 m/s, rh=43, 27, 44 %
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=47 W/m2, W=0 W/m2



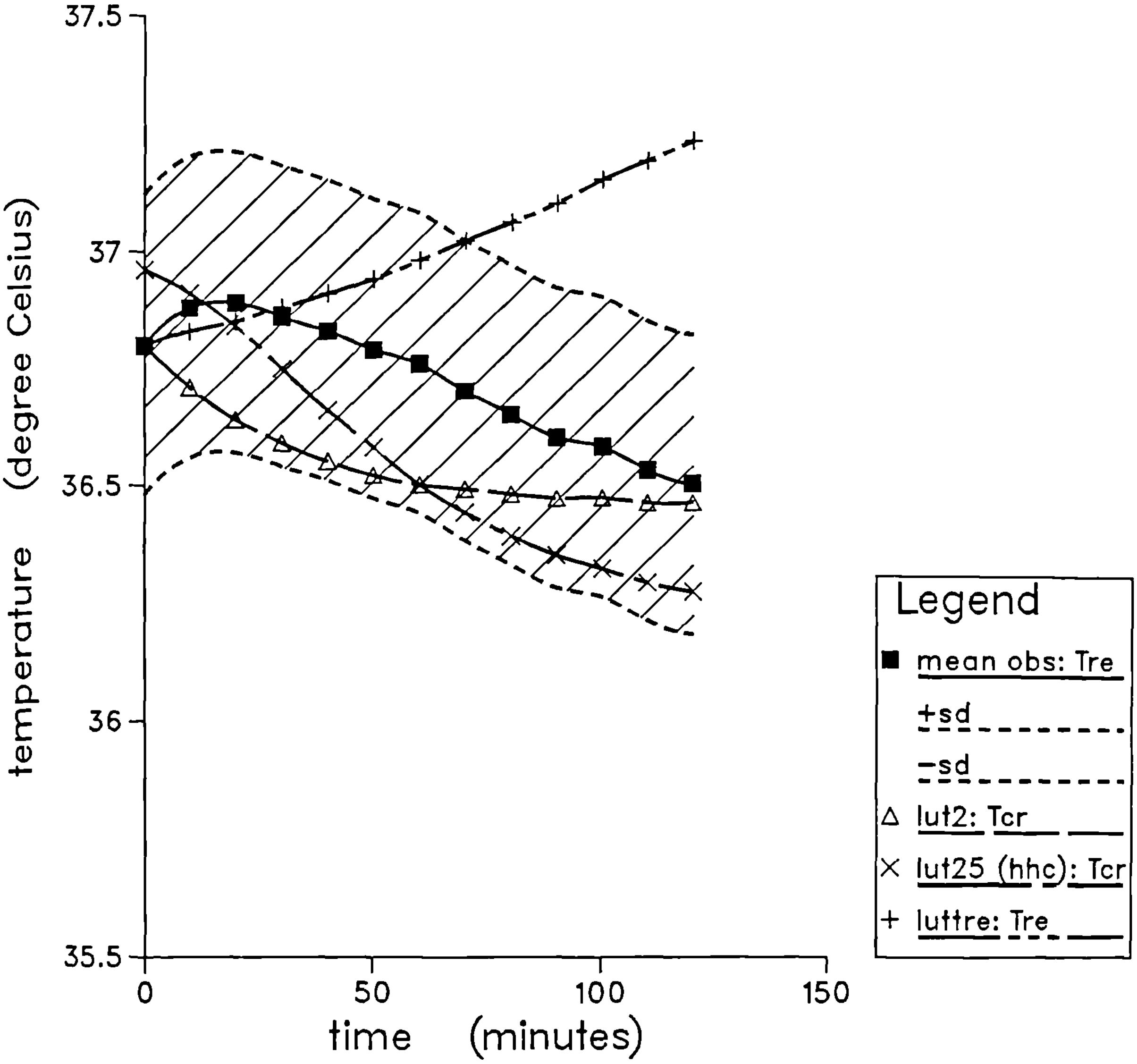
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 28)
Ta=28 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2

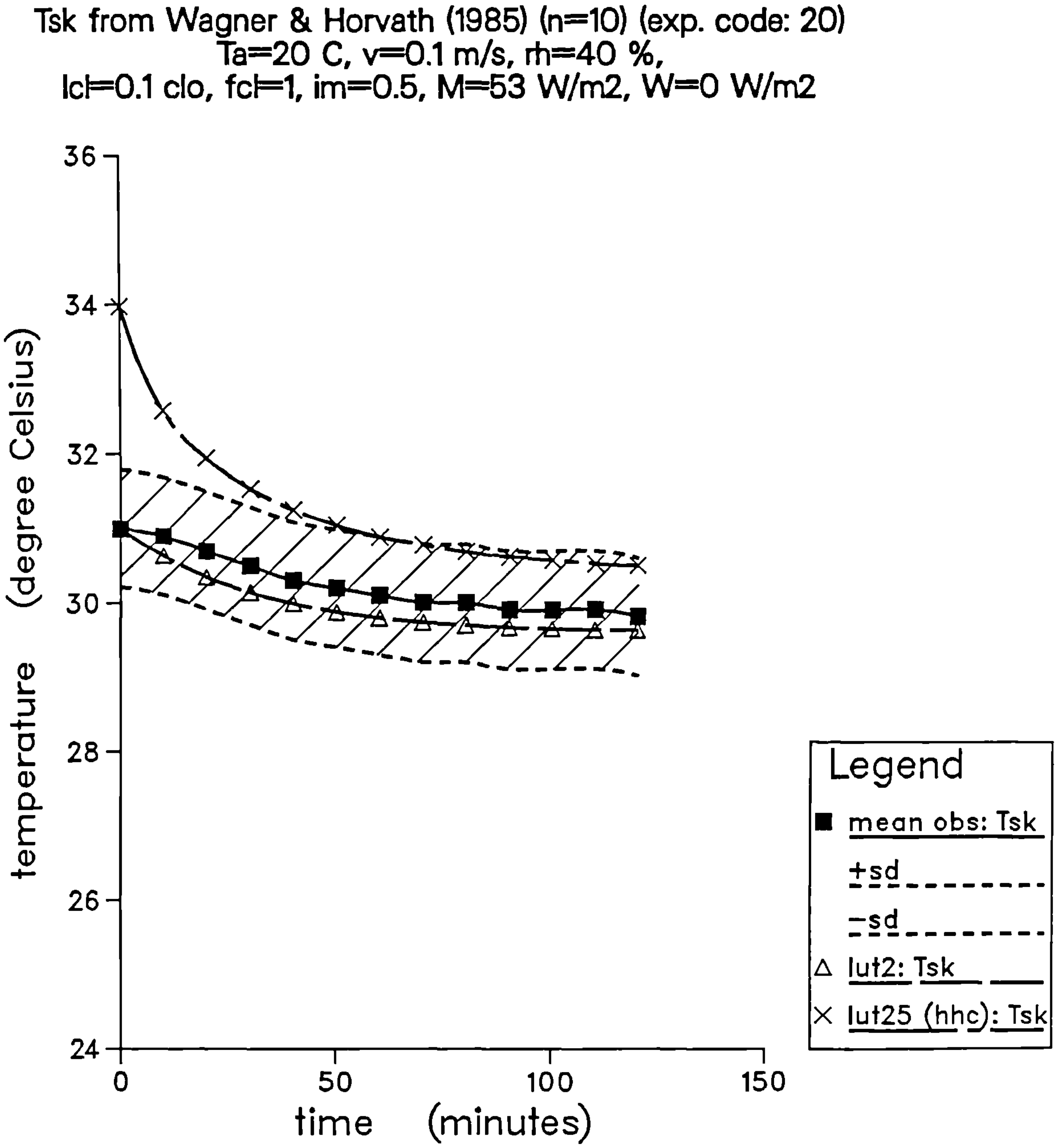


Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 28)
Ta=28 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2



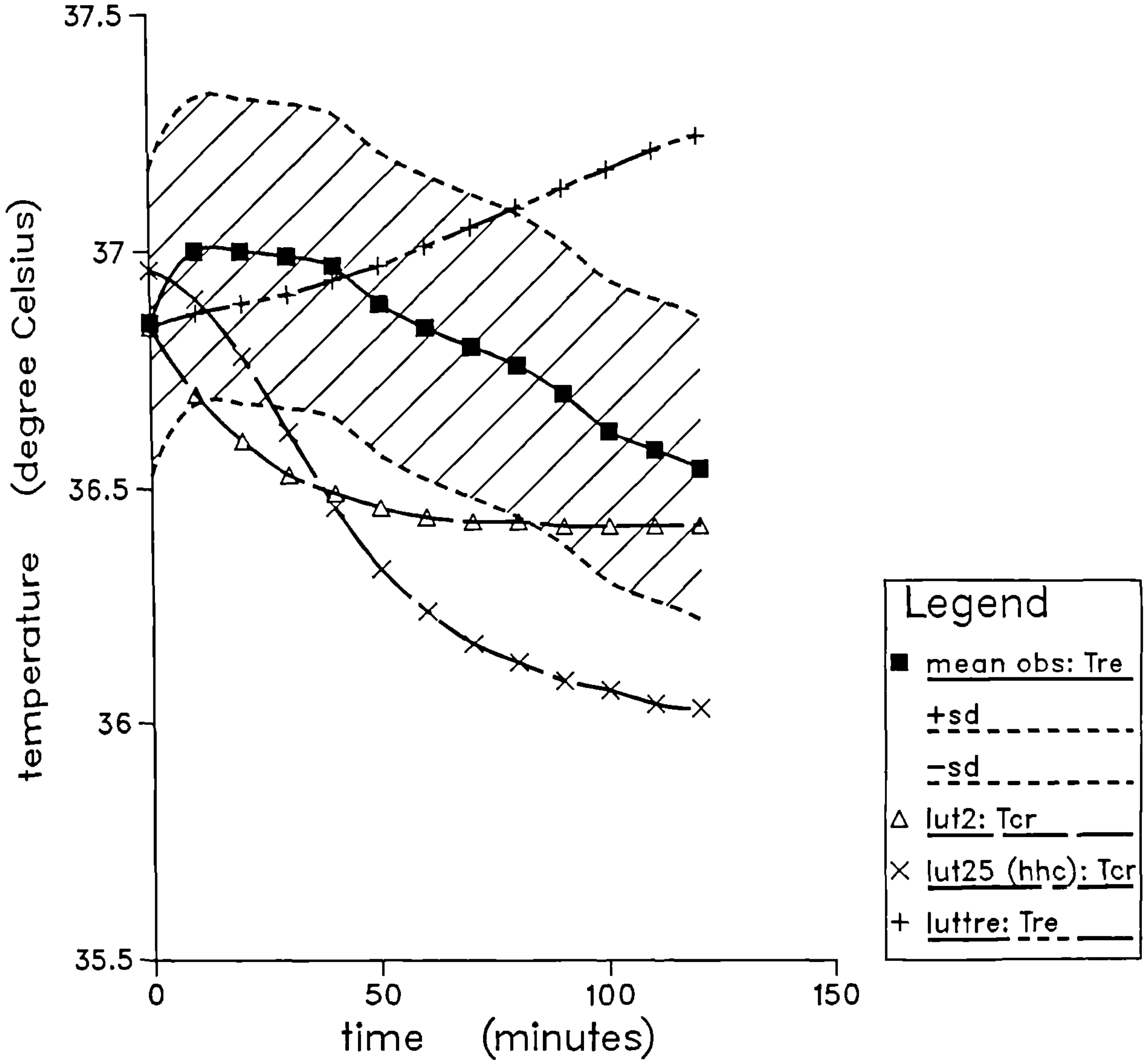
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 20)
Ta=20 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2

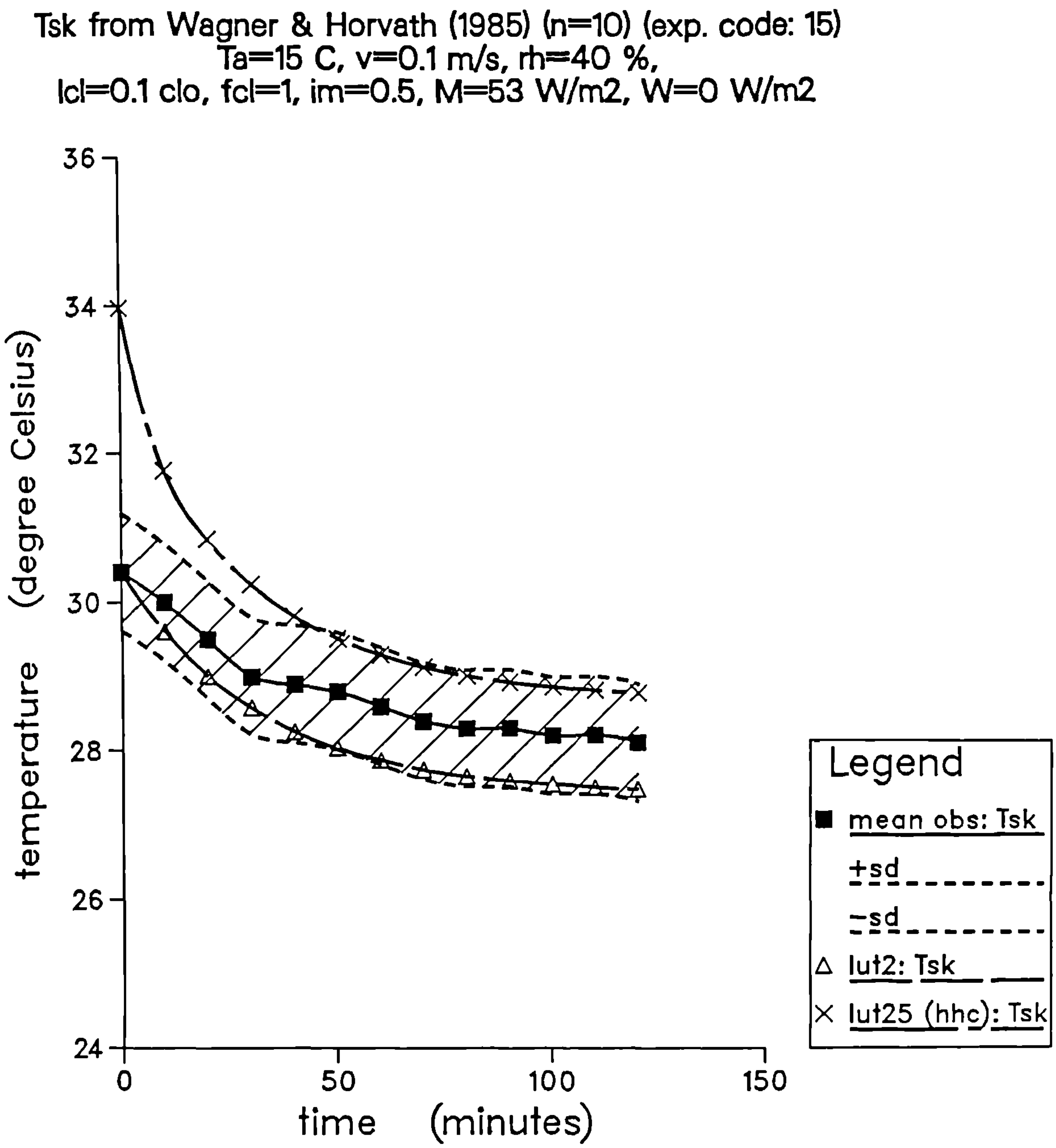




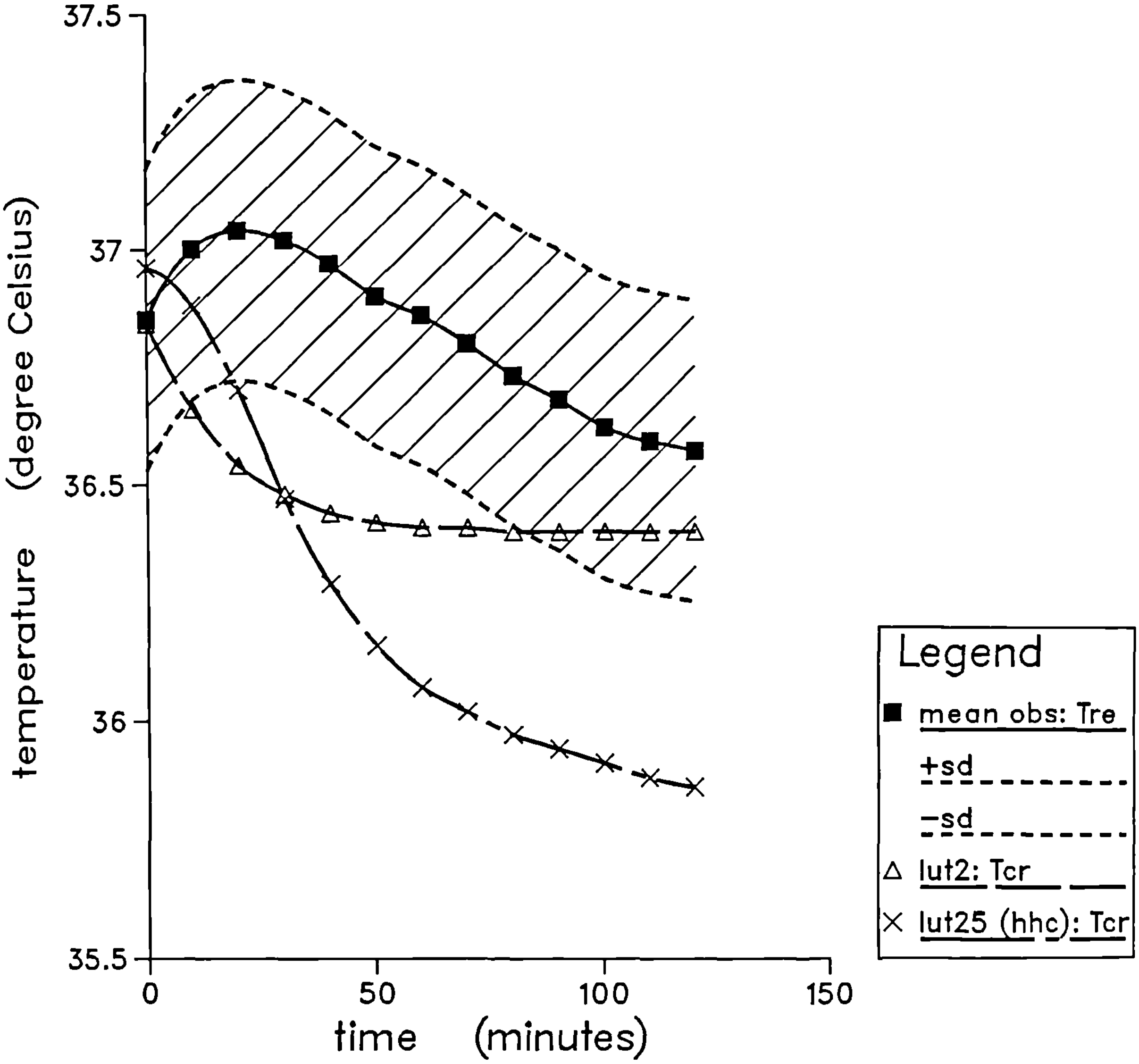
Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 20)
Ta=20 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2
36
34
32
30
28
26
24
temperature (degree Celsius)
0
50
100
150
time (minutes)
Legend
mean obs: Tsk
+sd
-sd
lut2: Tsk
lut25 (hhc): Tsk

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

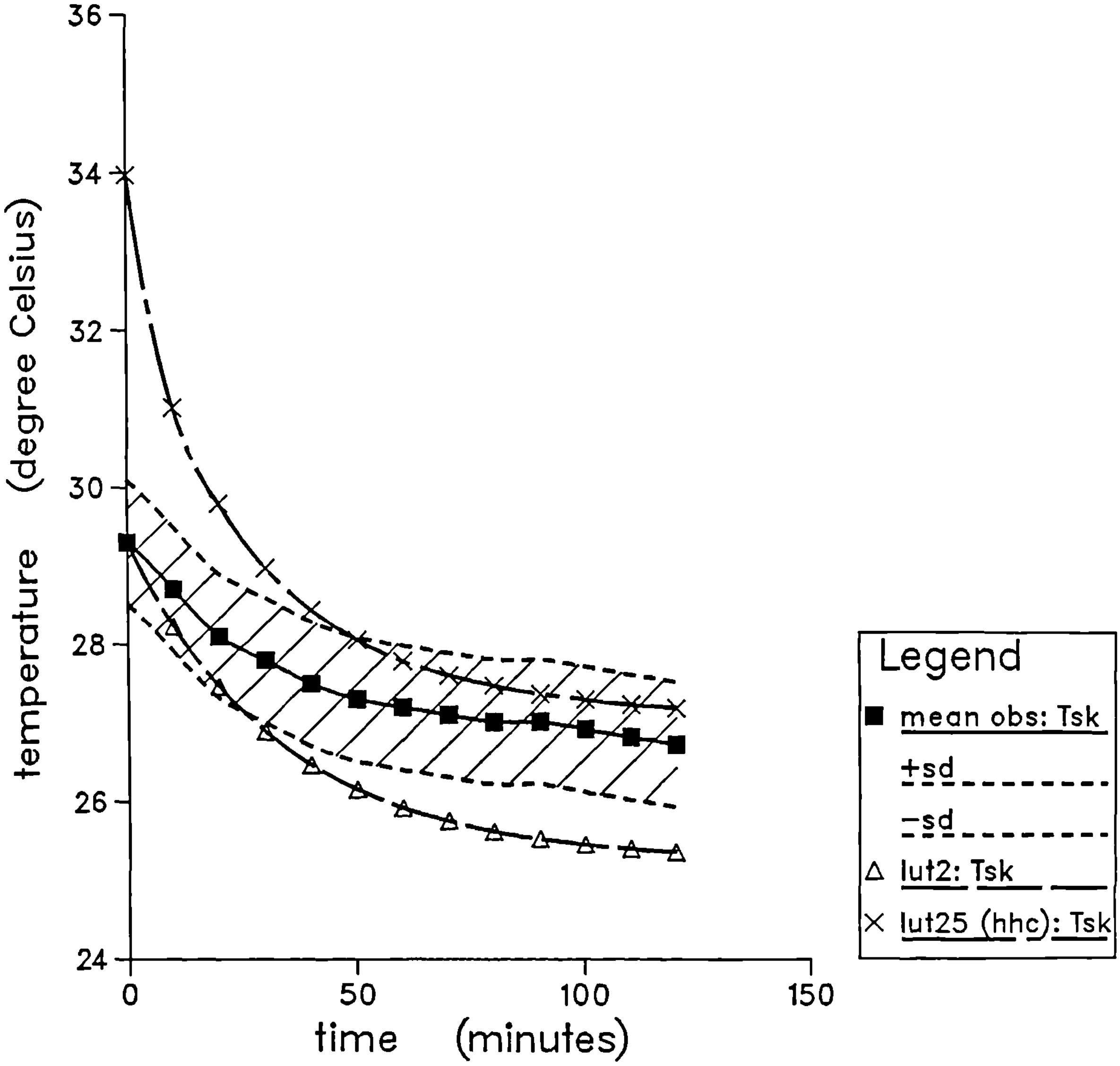



Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 15)
Ta=15 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2
temperature (degree Celsius)
36
34
32
30
28
26
24
0
50
100
150
time (minutes)
Legend
mean obs: Tsk
+sd
-sd
lut2: Tsk
lut25 (hhc): Tsk

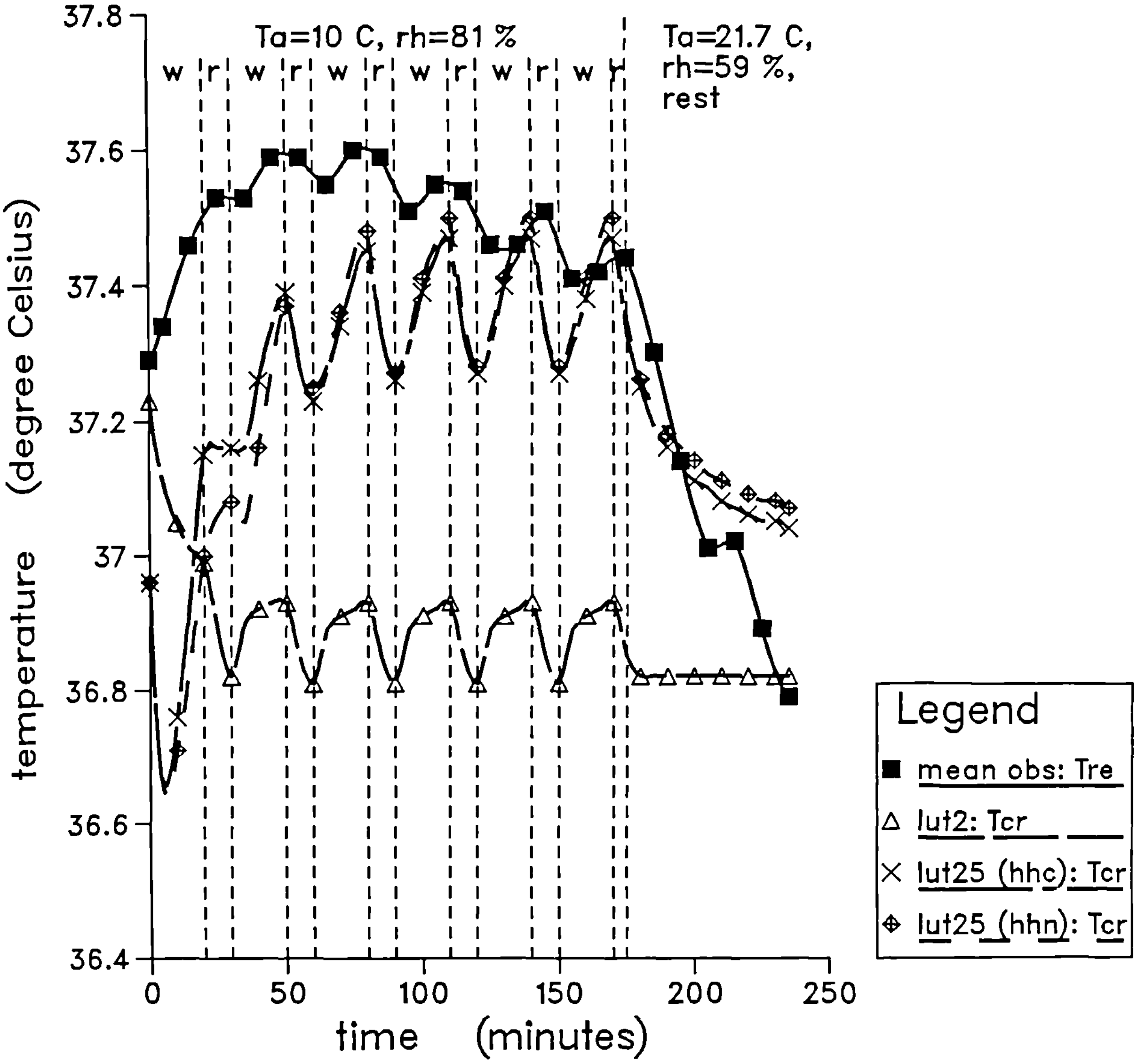
Tre from Wagner & Horvath (1985) (n=10) (exp. code: 10)
Ta=10 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2



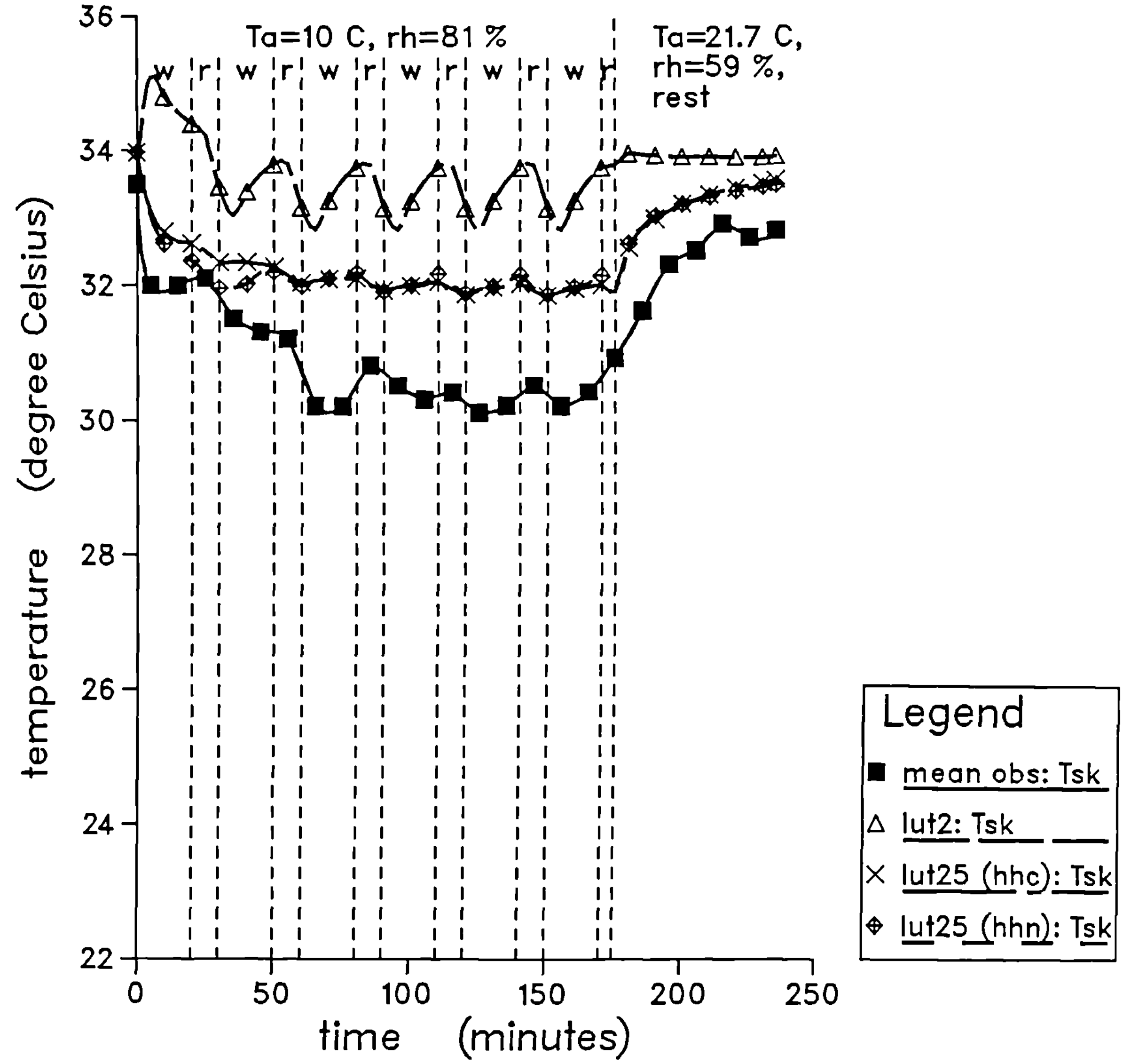
Tsk from Wagner & Horvath (1985) (n=10) (exp. code: 10)
Ta=10 C, v=0.1 m/s, rh=40 %,
Icl=0.1 clo, fcl=1, im=0.5, M=53 W/m2, W=0 W/m2



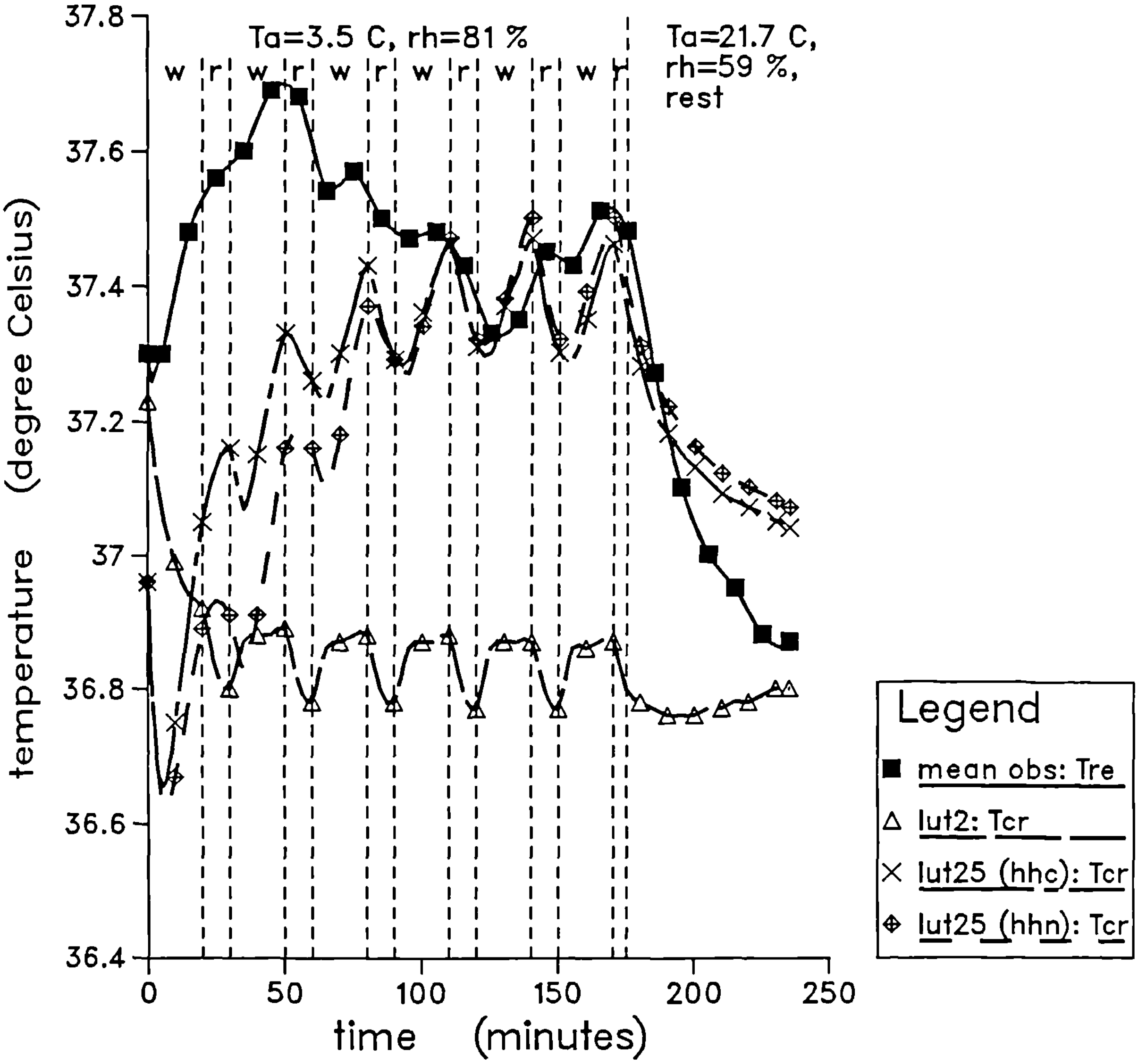
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e1)
Ta=Tr=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



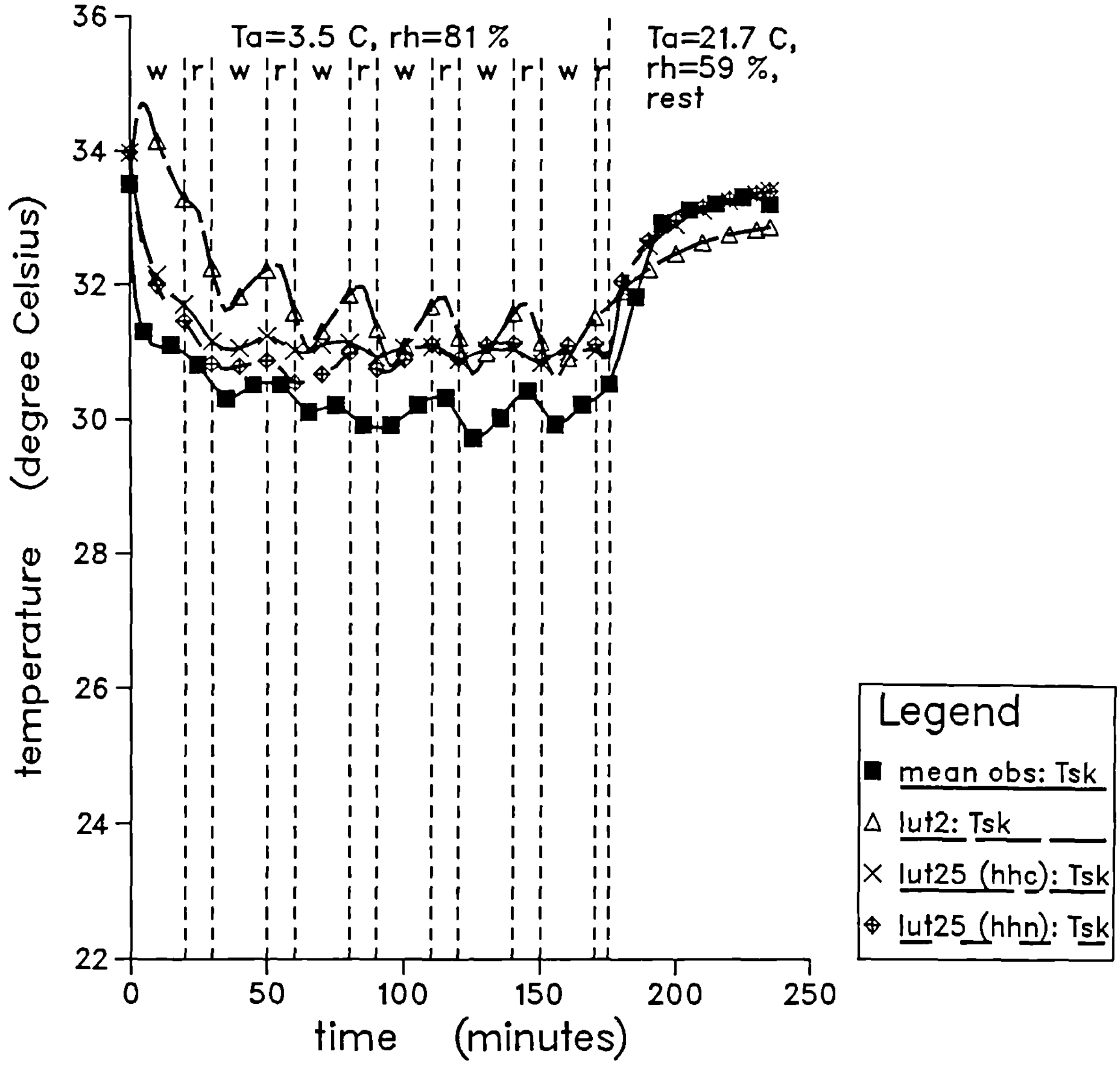
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e1)
Ta=Tr=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



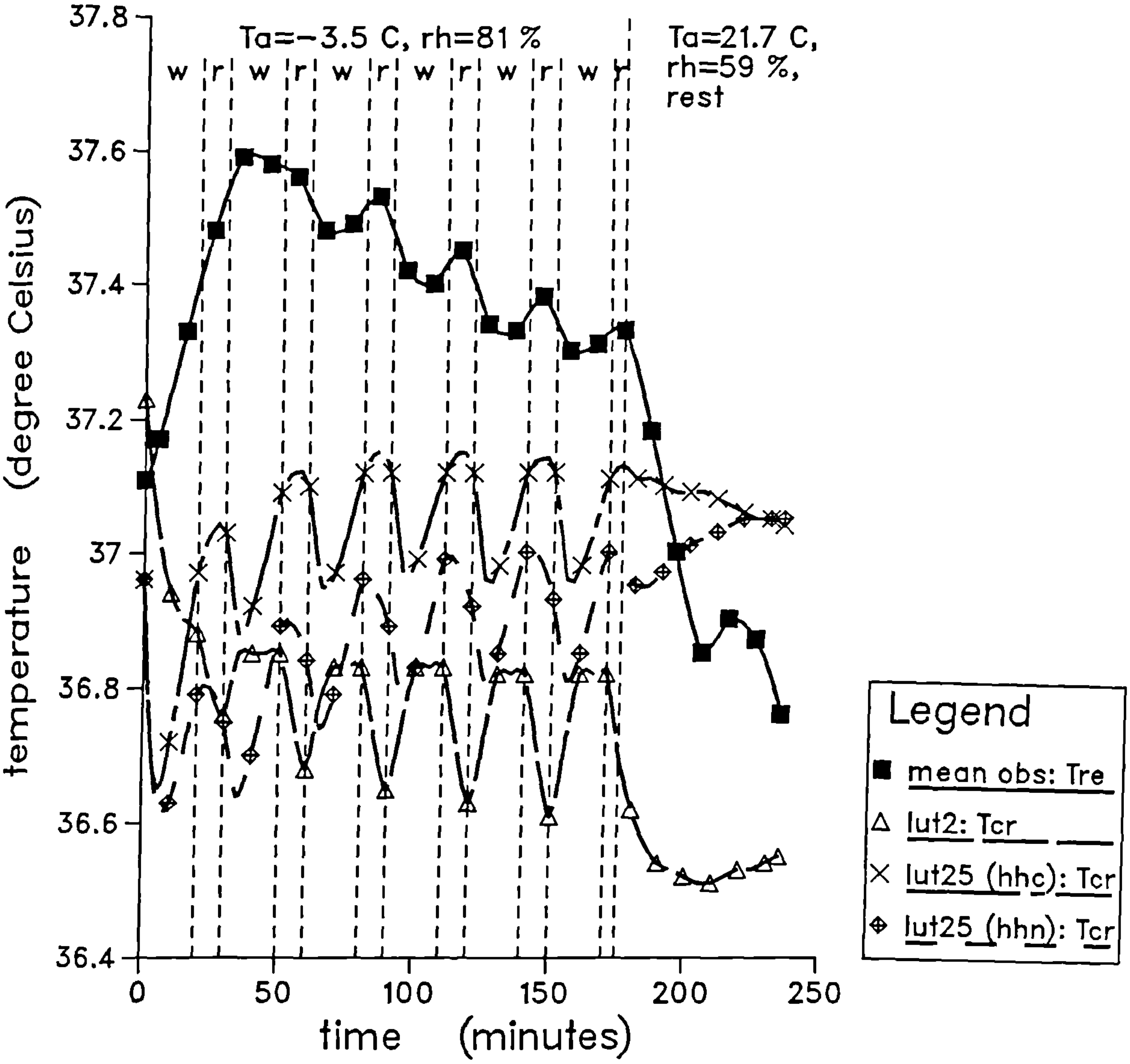
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e2)
Ta=Tr=3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



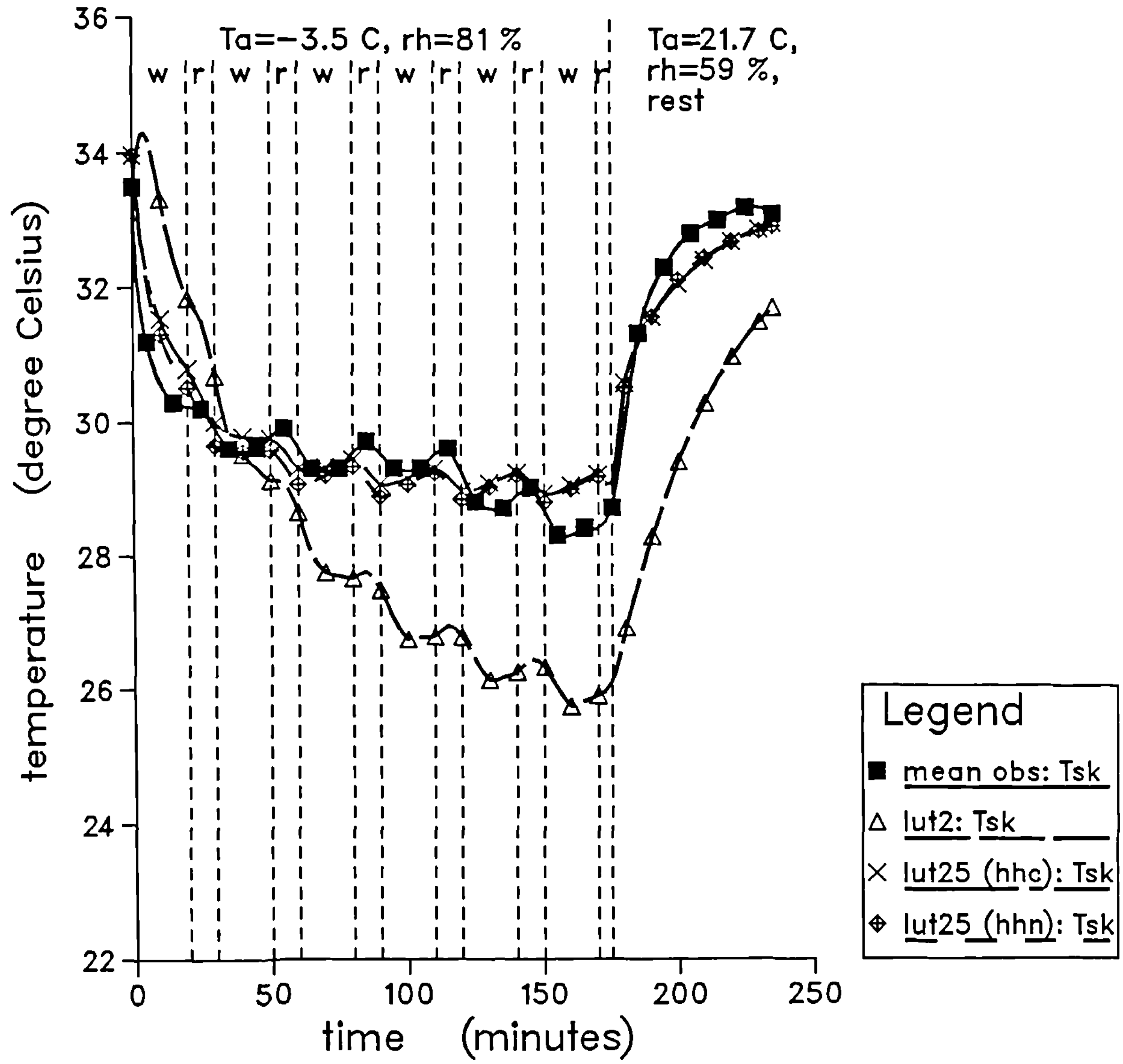
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e2)
Ta=Tr=3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



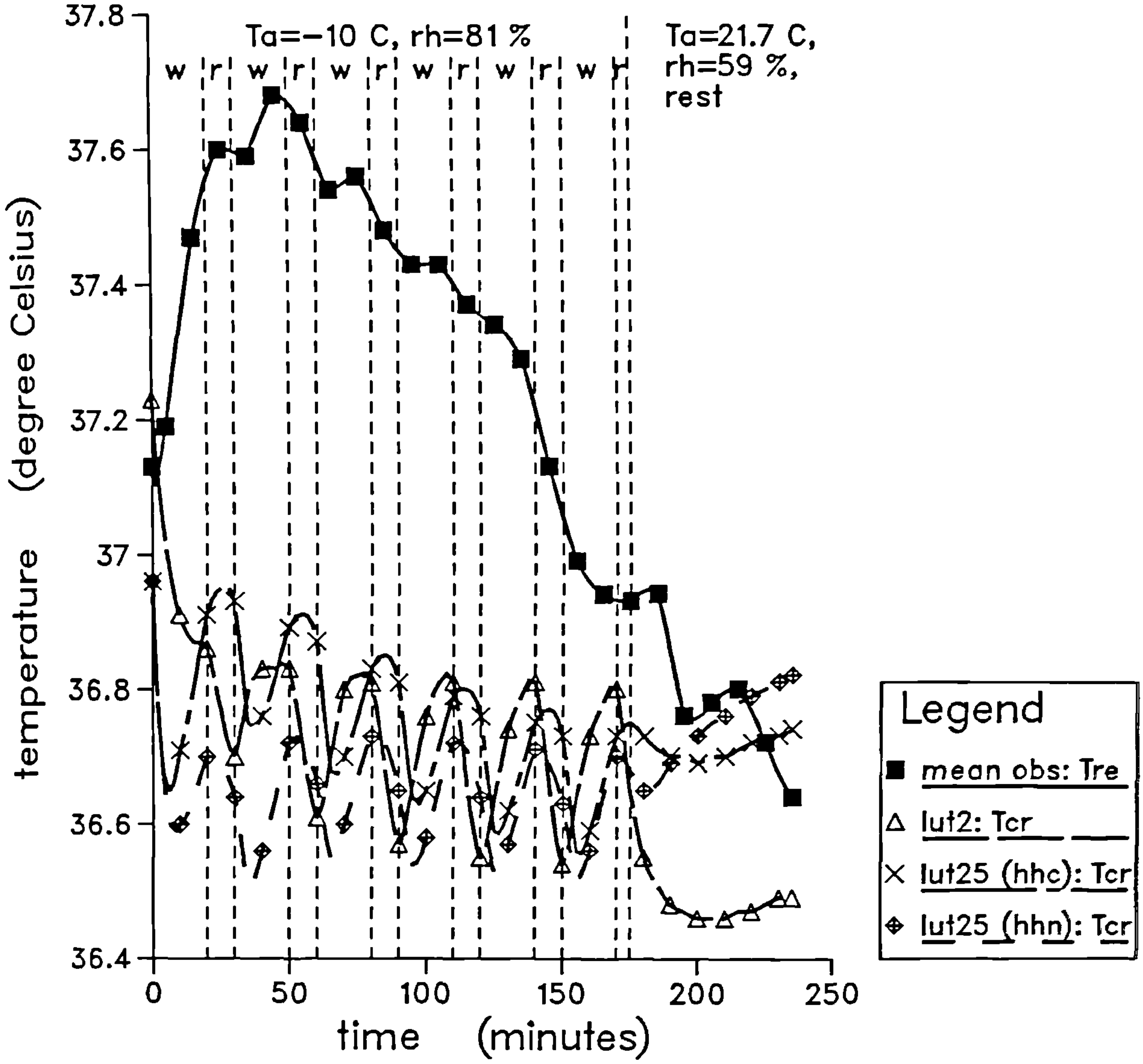
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e3)
Ta=Tr=-3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



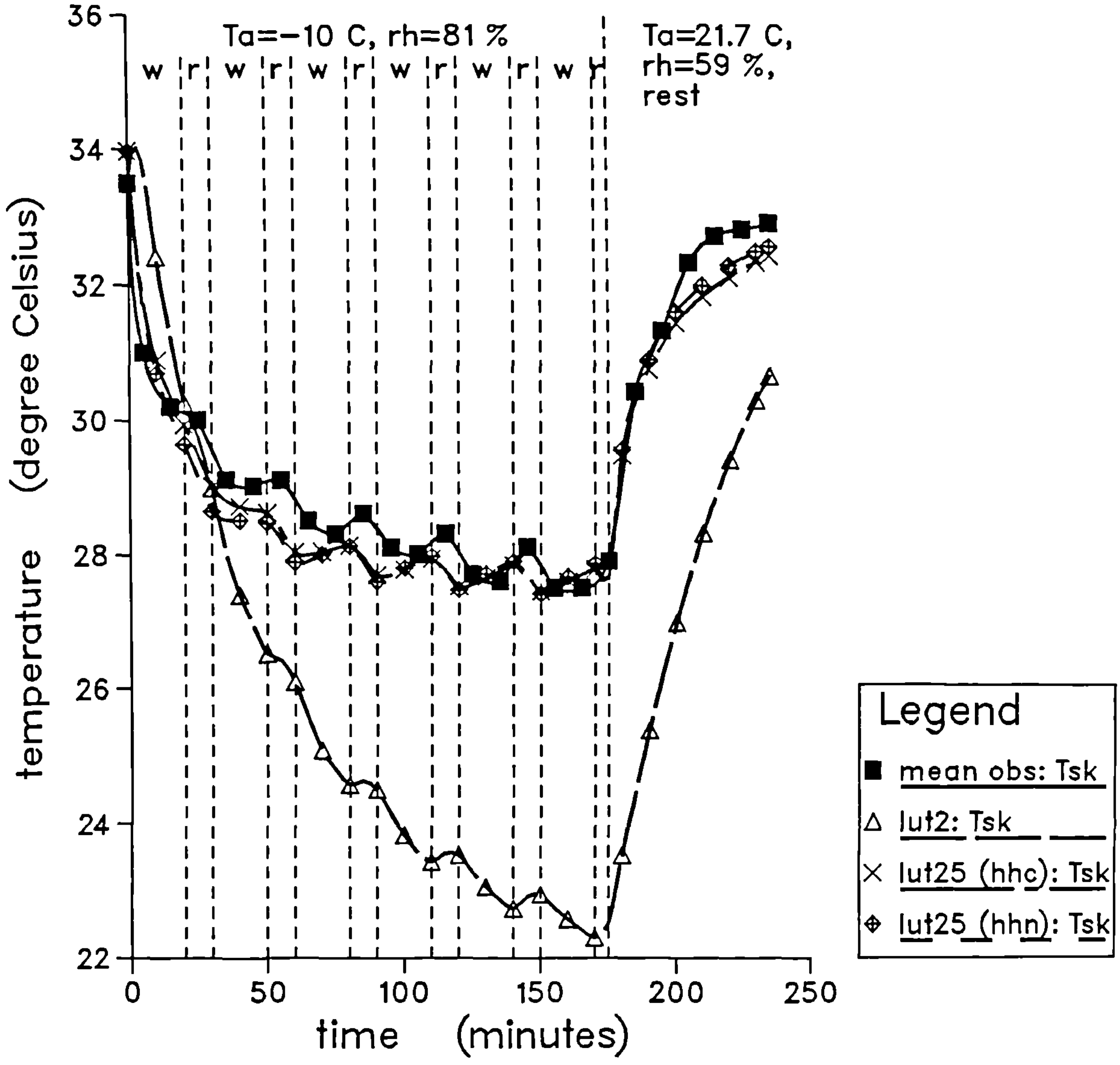
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e3)
Ta=Tr=-3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



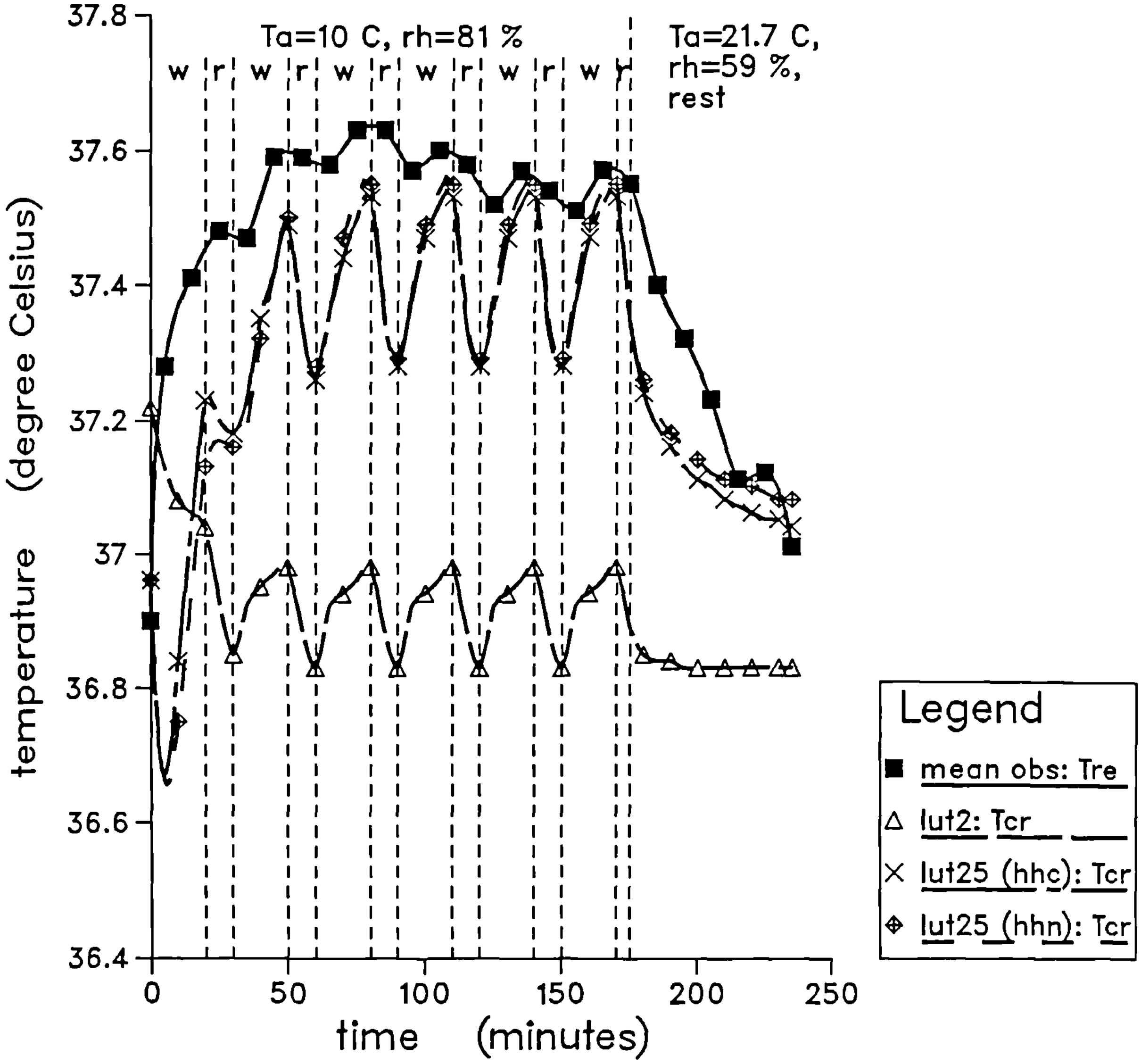
Tre from Walsh and Graham (1986) (n=8, males) (exp. code: e4)
Ta=Tr=-10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



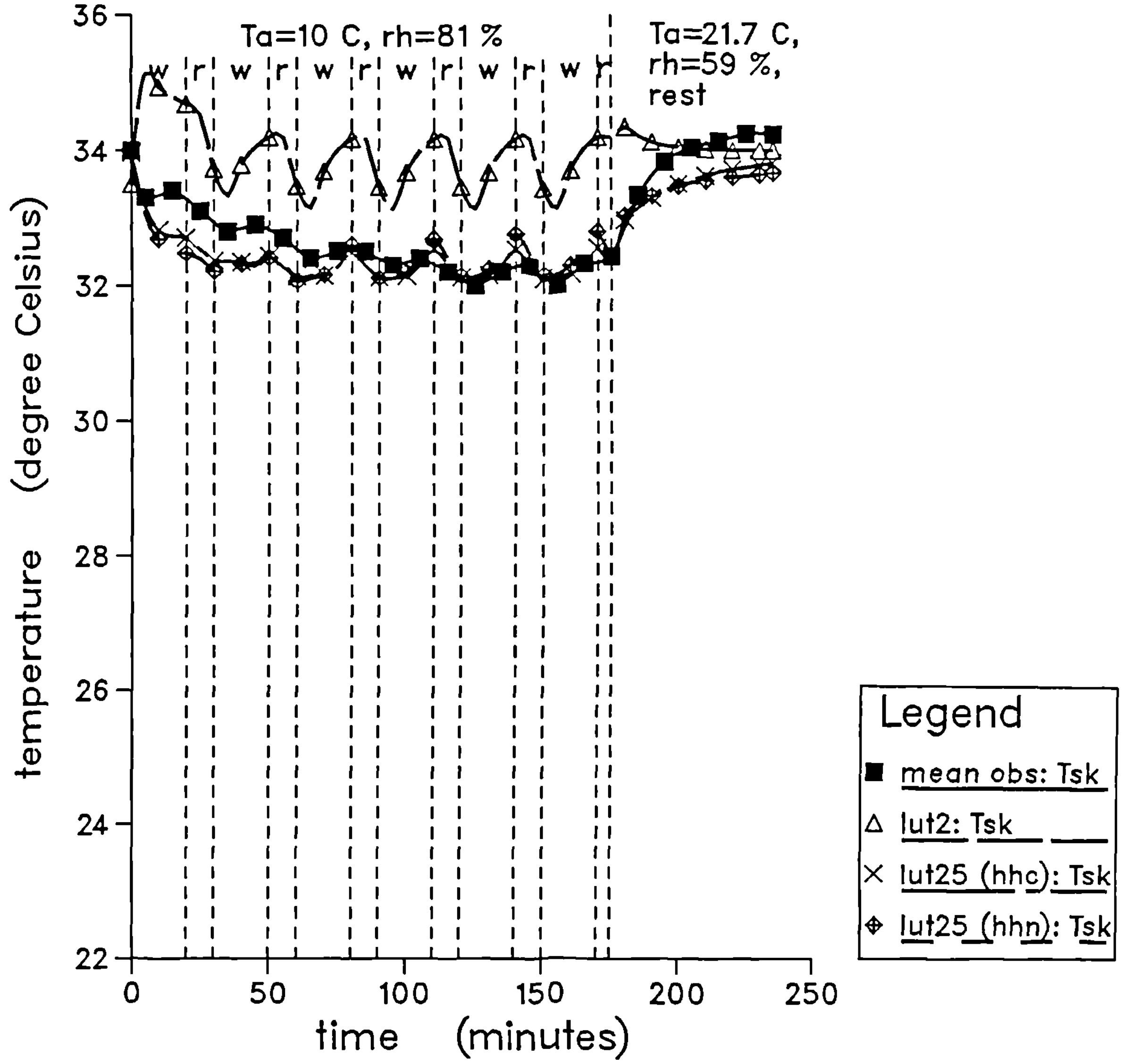
Tsk from Walsh and Graham (1986) (n=8, males) (exp. code: e4)
Ta=Tr=-10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=196, 56 W/m2, W=32, 0 W/m2



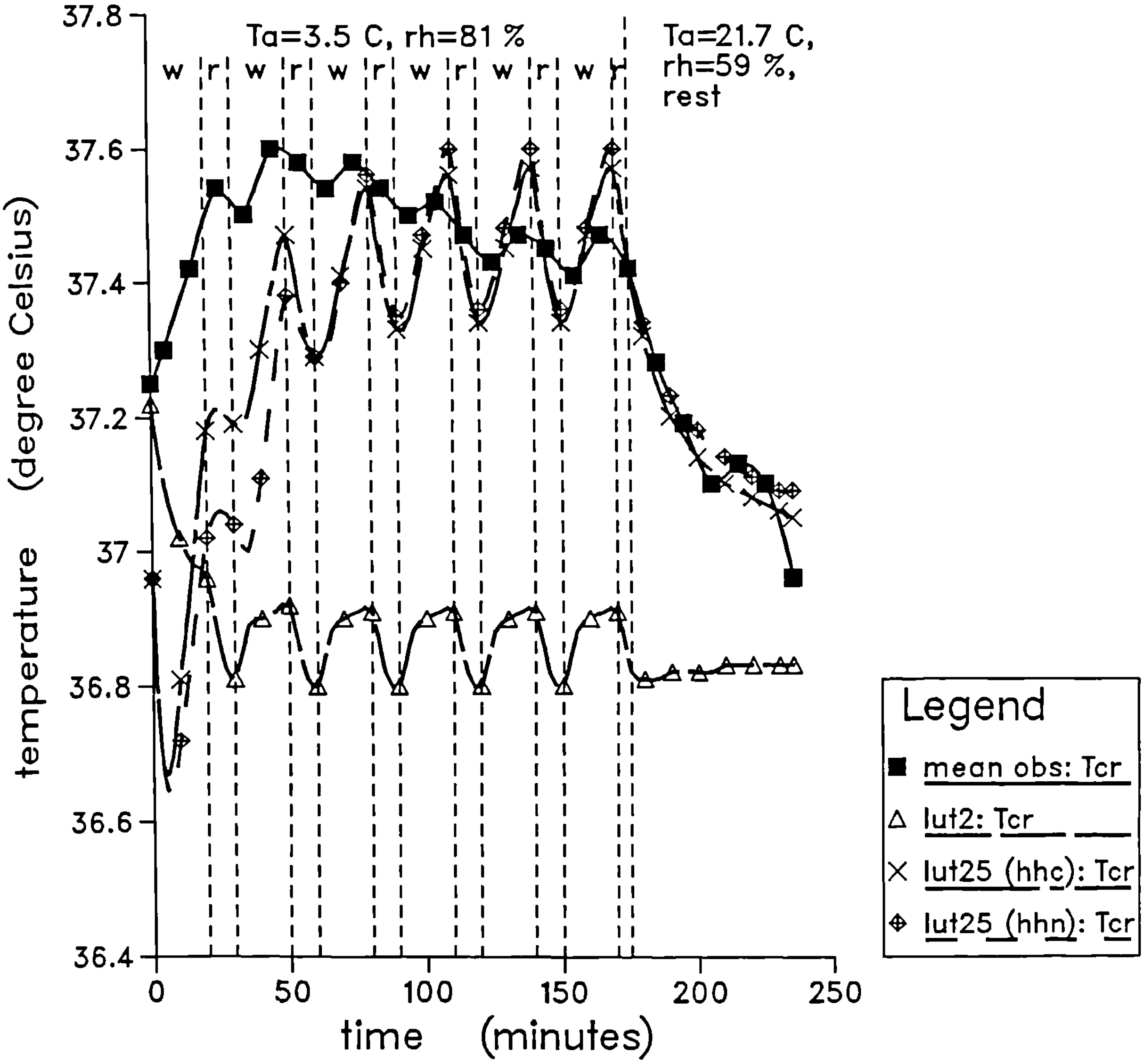
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e1)
Ta=Tr=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2



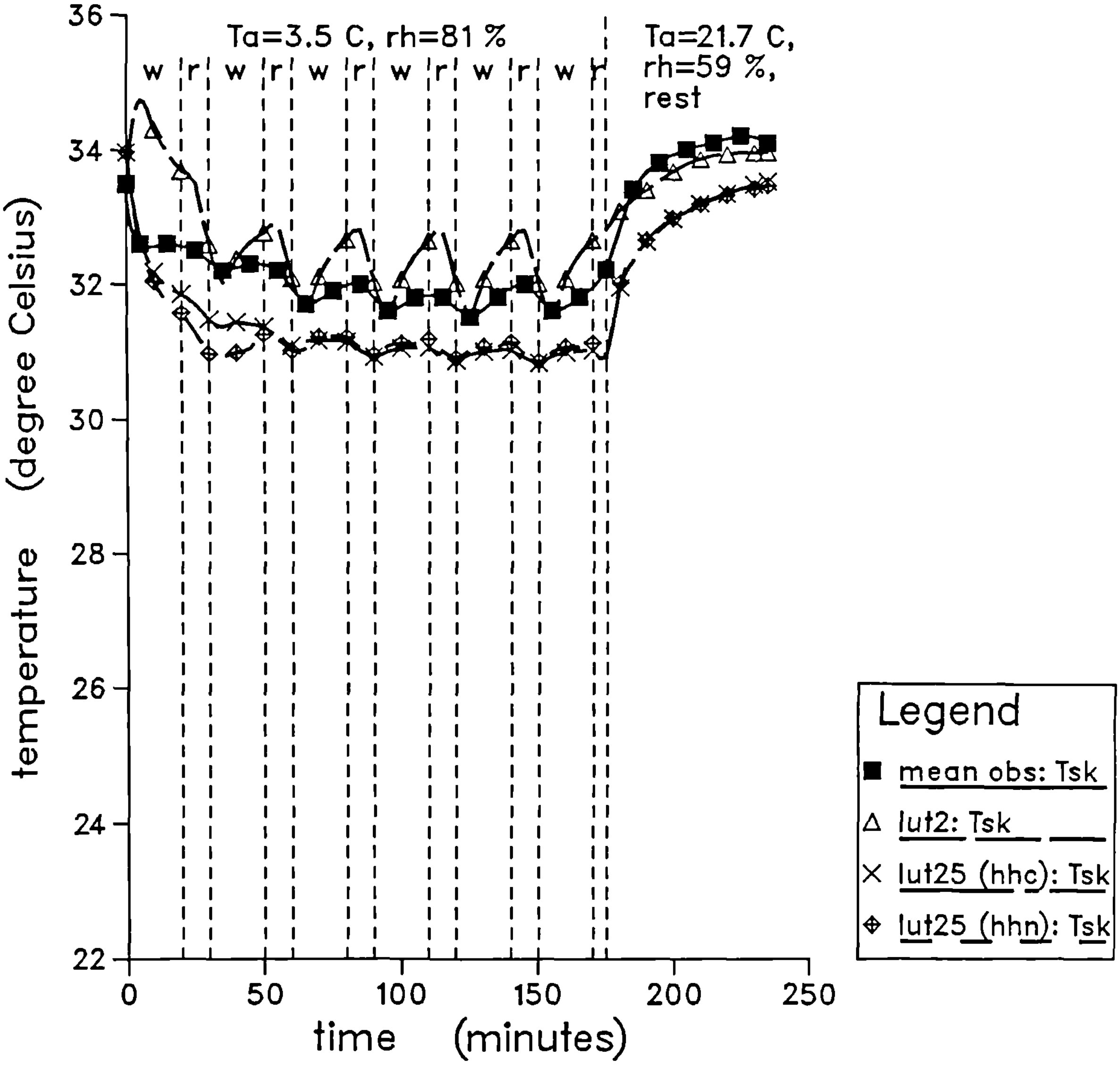
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e1)
Ta=Tr=10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2



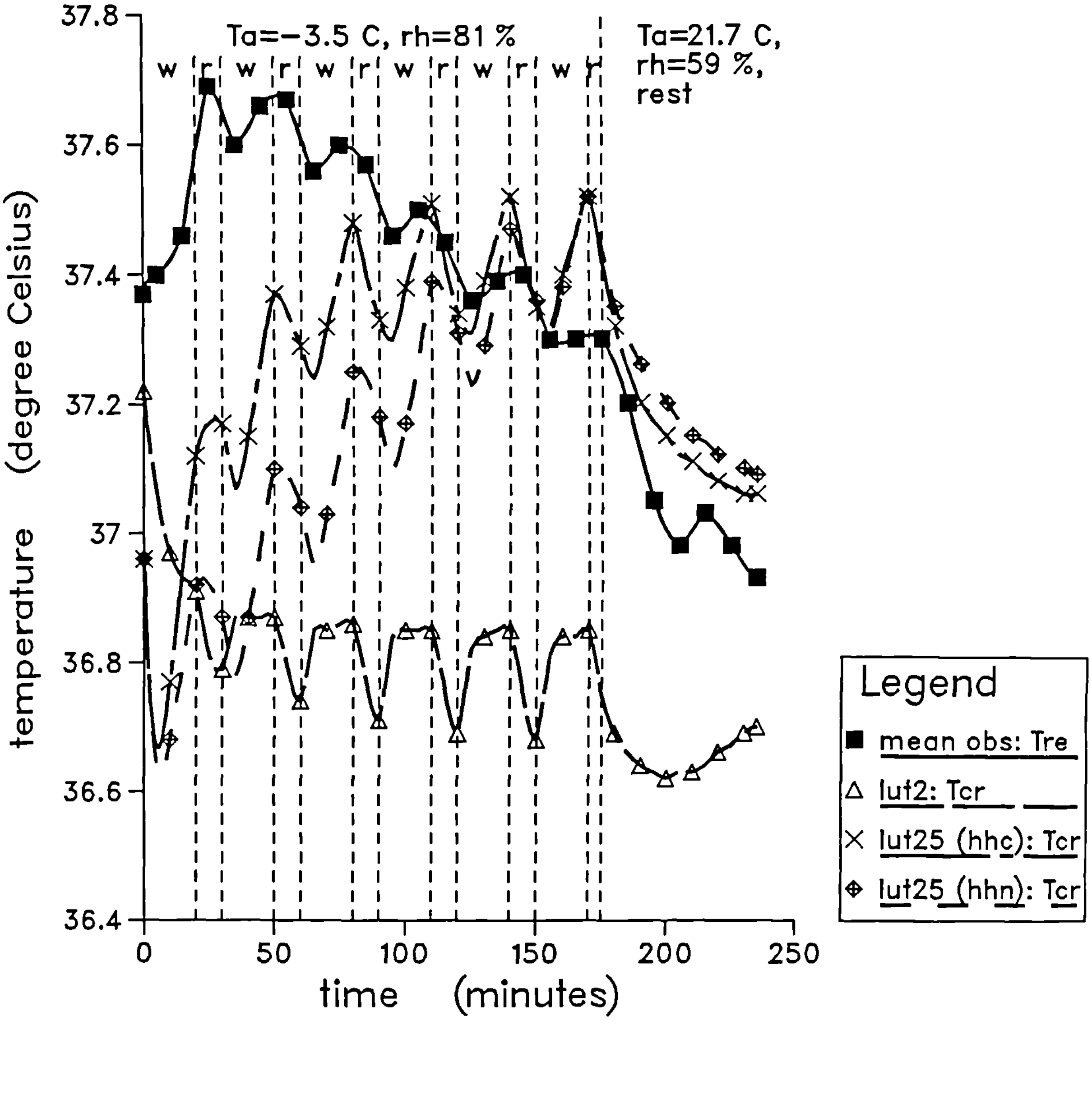
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e2)
Ta=Tr=3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2



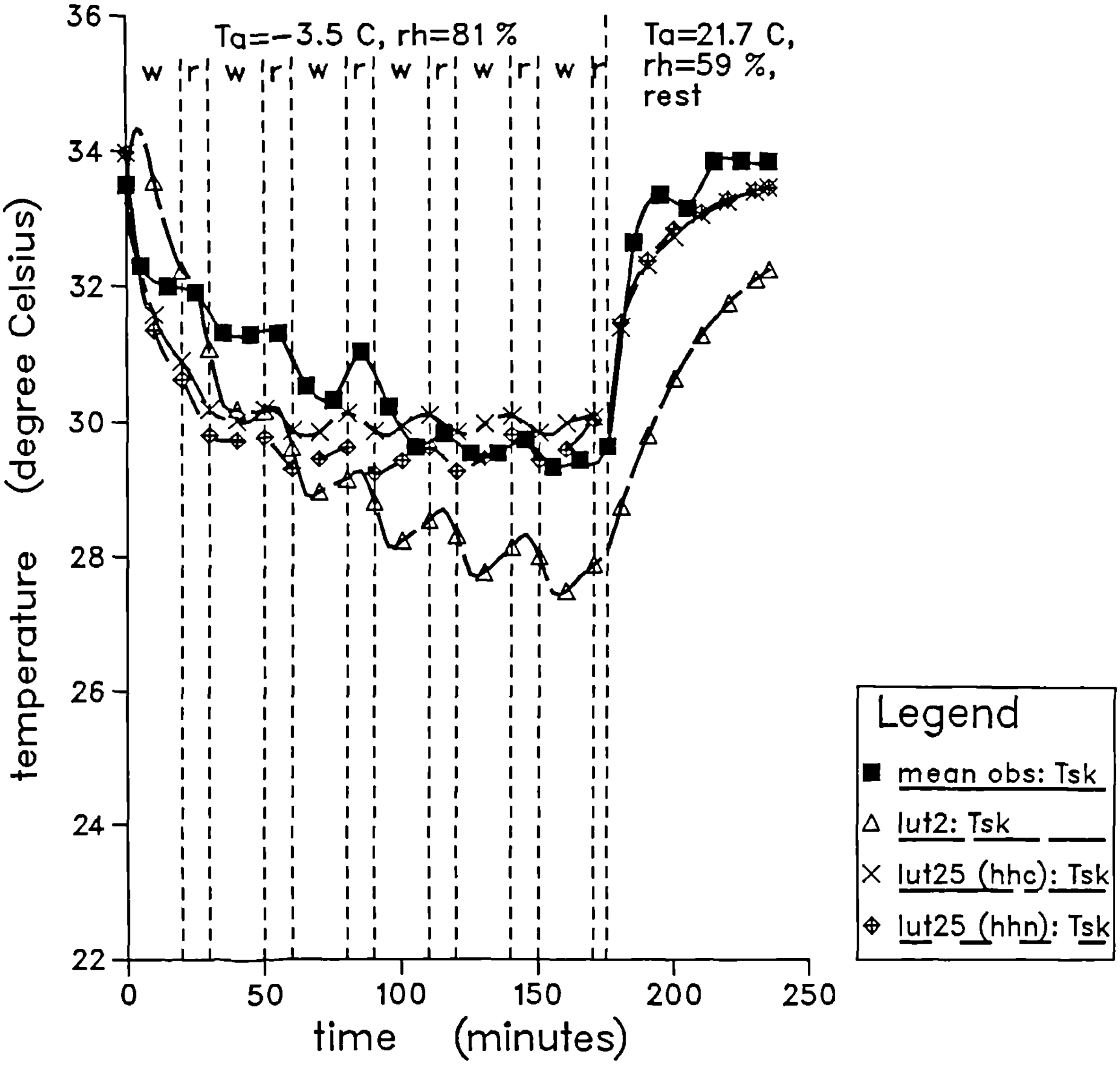
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e2)
Ta=Tr=3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2



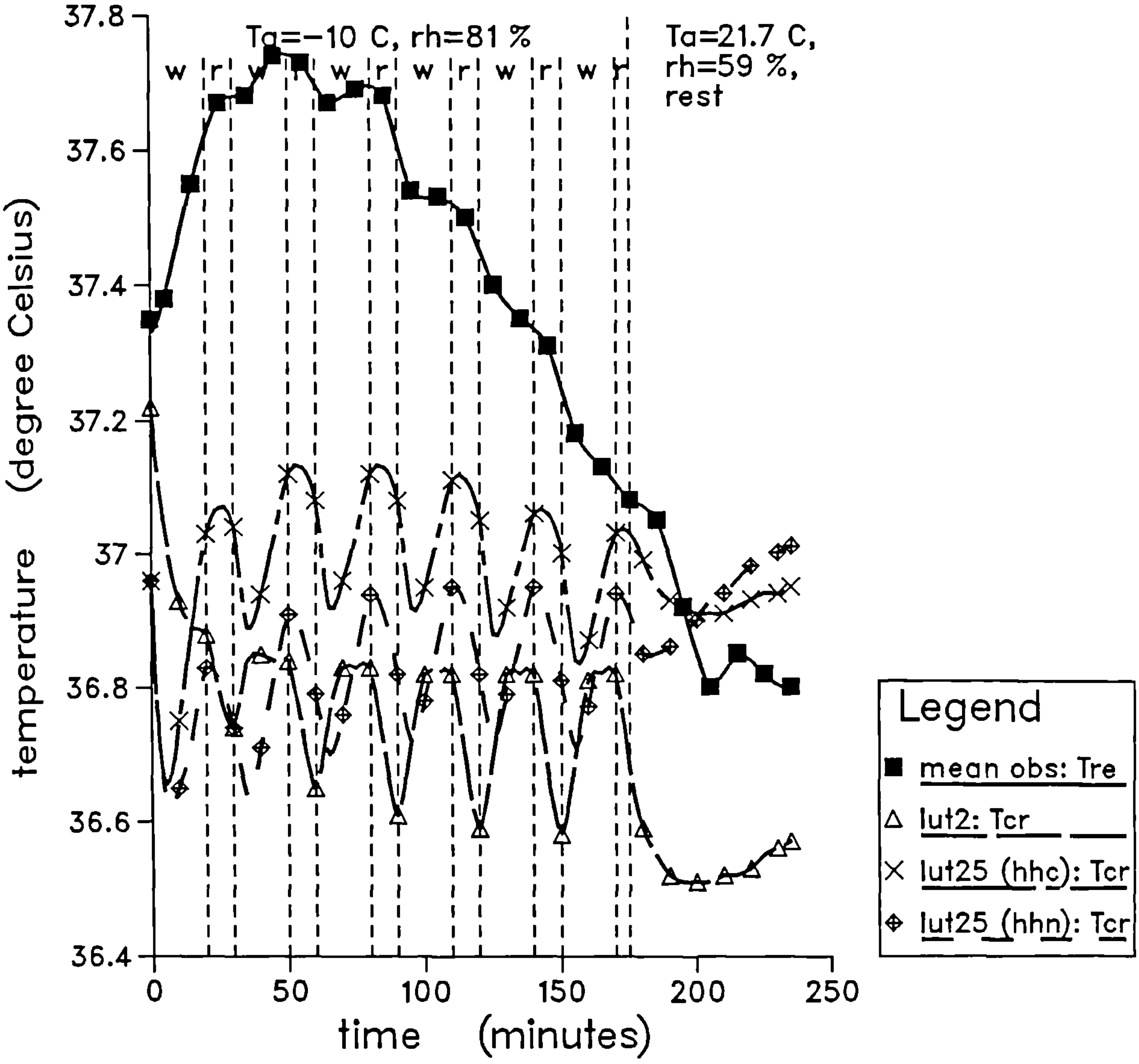
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e3)
Ta=Tr=-3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2



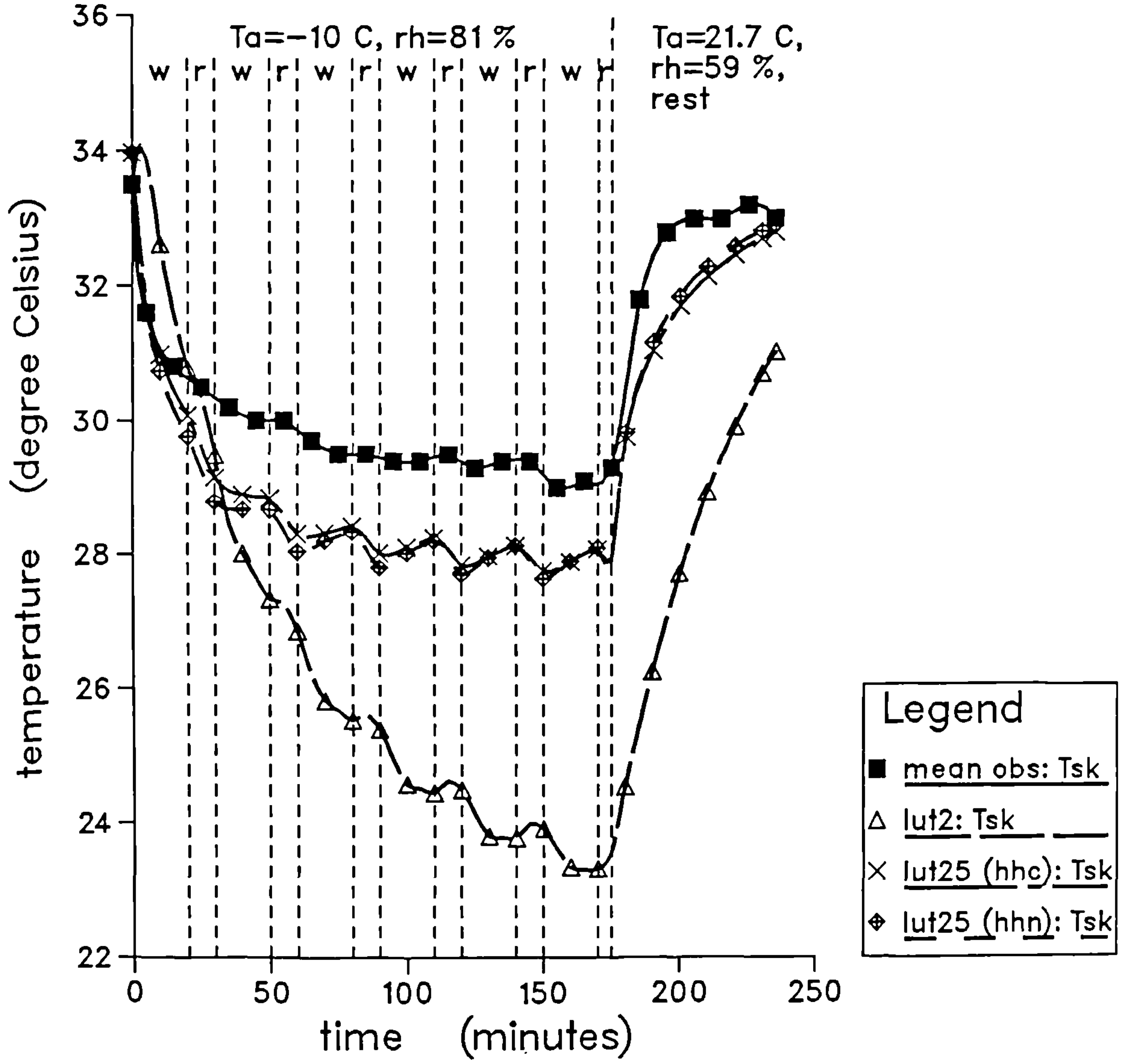
Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e3)
Ta=Tr=-3.5, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2



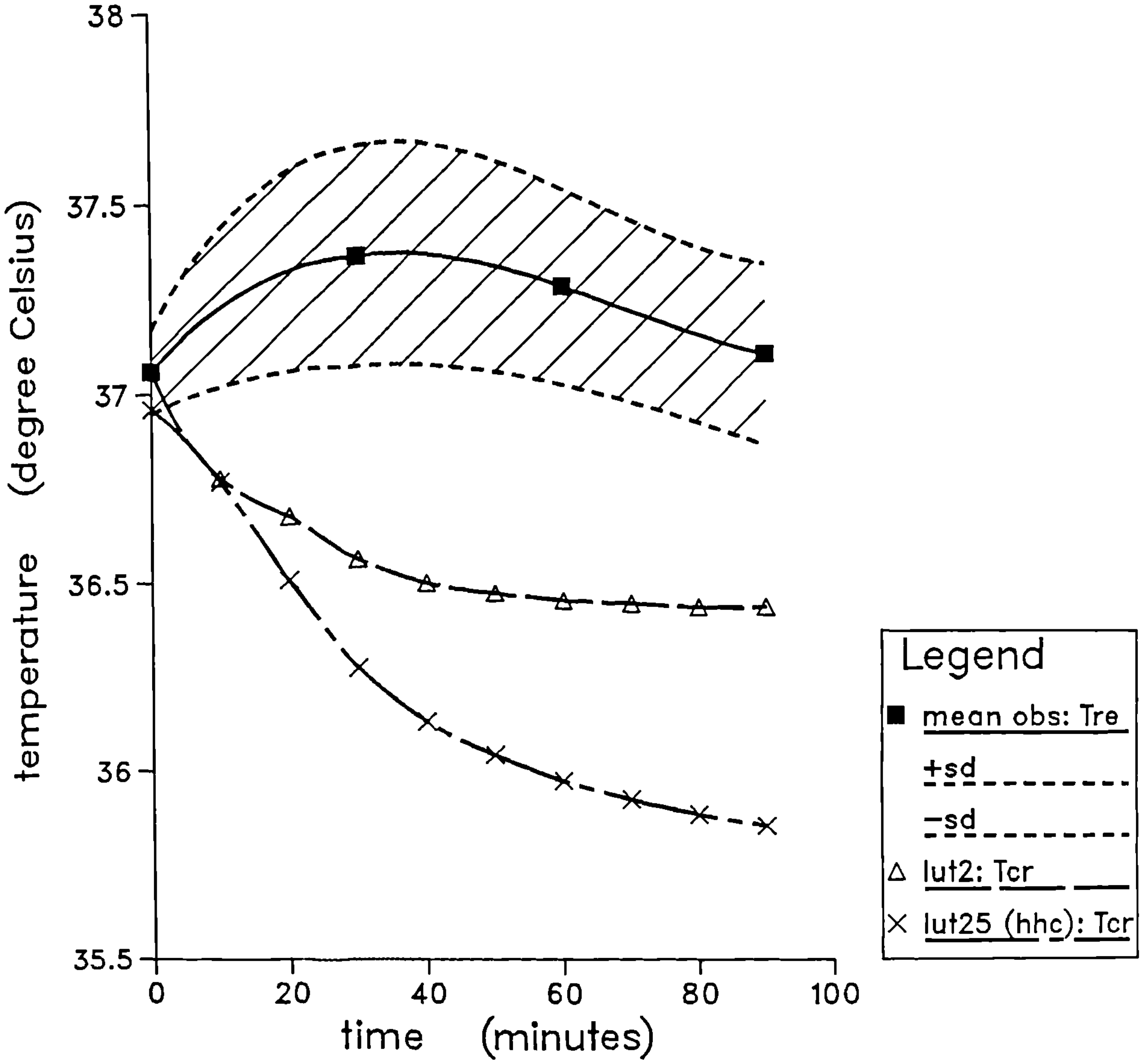
Tre from Walsh and Graham (1986) (n=8, females) (exp. code: e4)
Ta=Tr=-10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2

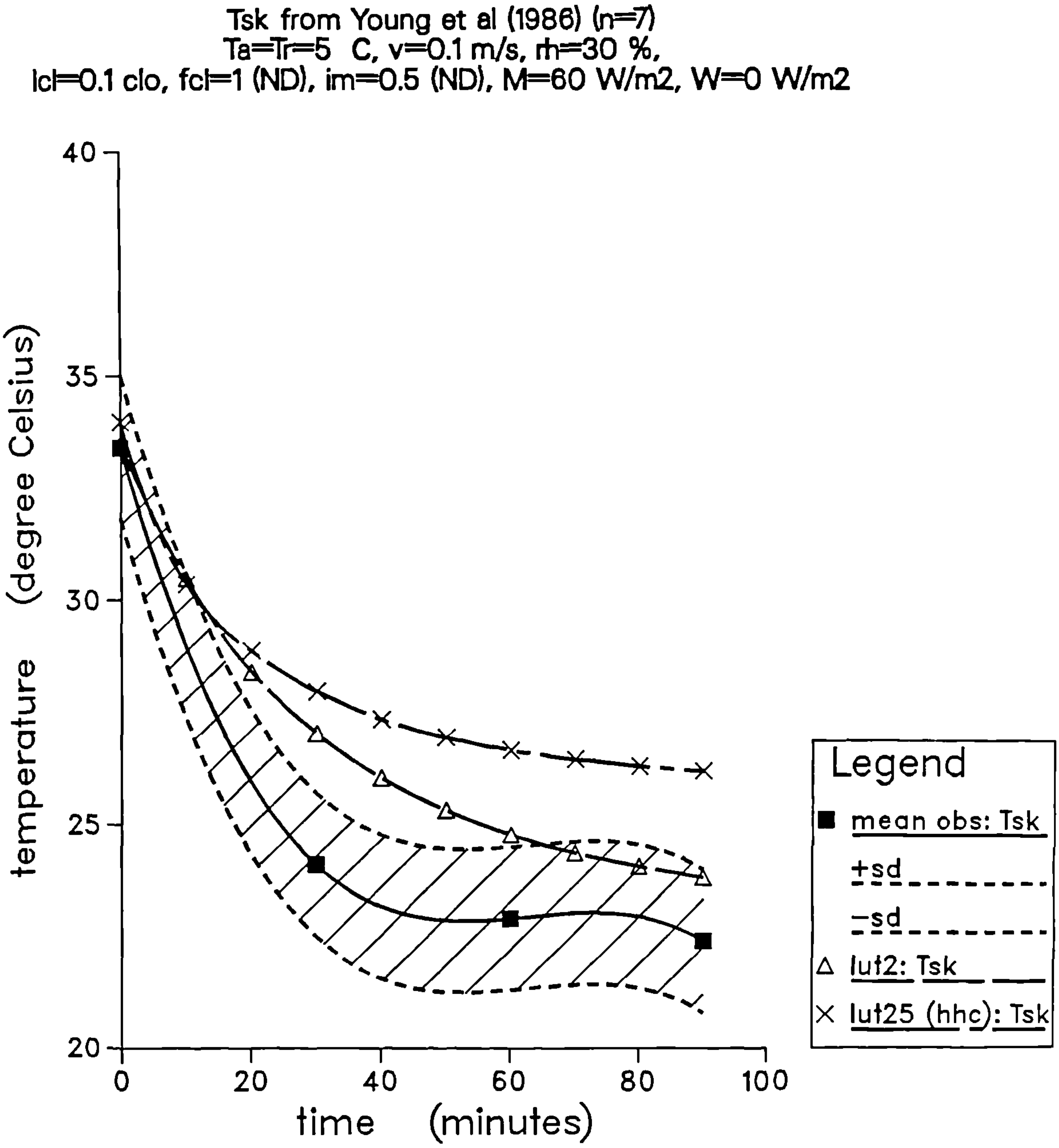


Tsk from Walsh and Graham (1986) (n=8, females) (exp. code: e4)
Ta=Tr=-10.0, 21.7 C, v=0.15 m/s, rh=81, 59 %, Icl=1.1 clo,
fcl=1.34 (ND), im=0.35 (ND), M=218, 62 W/m2, W=36, 0 W/m2

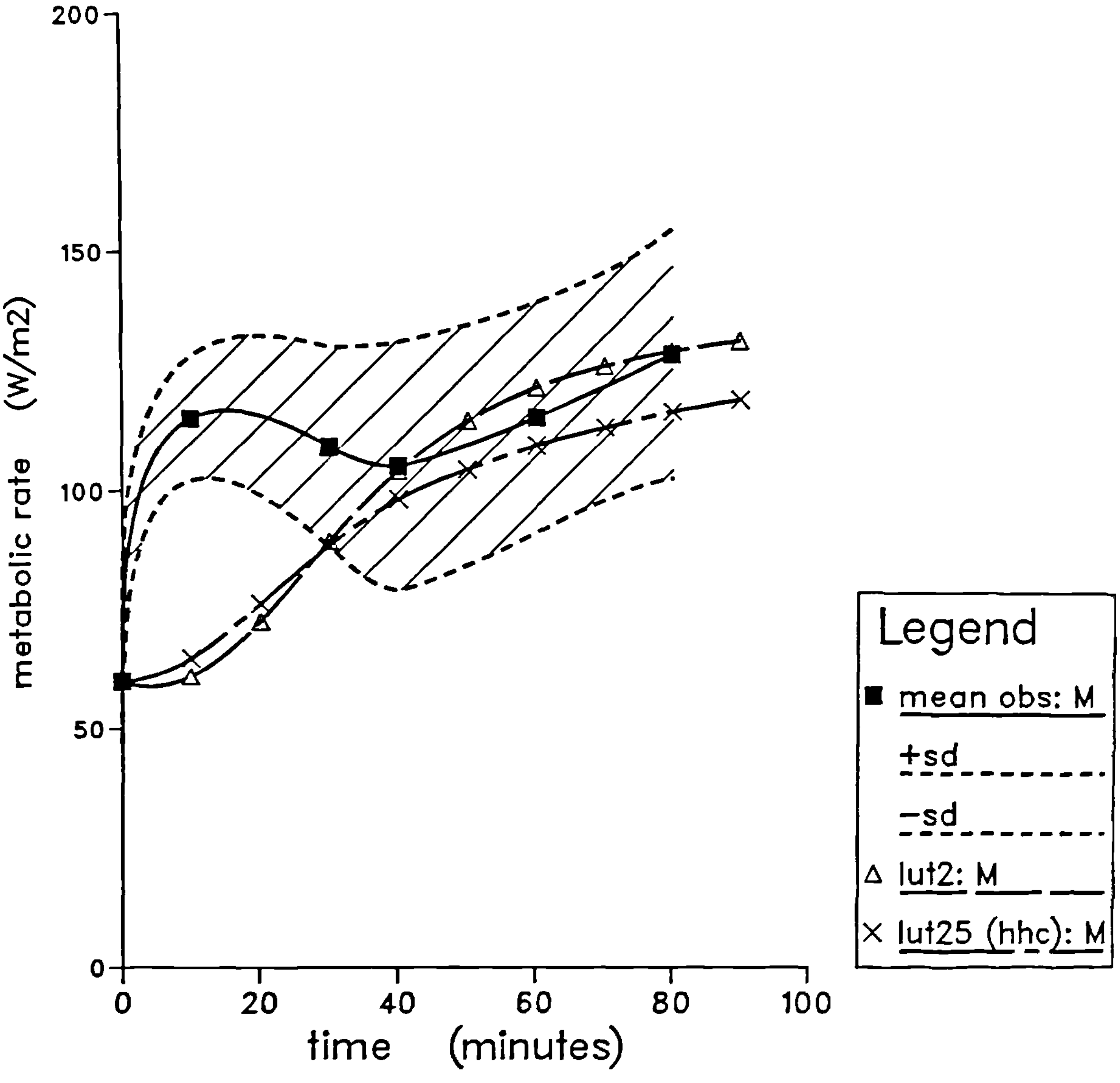


Tre from Young et al (1986) (n=7)
Ta=Tr=5 C, v=0.1 m/s, rh=30 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m2, W=0 W/m2




Tsk from Young et al (1986) (n=7)
Ta=Tr=5 C, v=0.1 m/s, rh=30 %,
Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m2, W=0 W/m2
temperature (degree Celsius)
40
35
30
25
20
0
20
40
60
80
100
time (minutes)
Legend
mean obs: Tsk
+sd
−sd
lut2: Tsk
lut25 (hhc): Tsk

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



APPENDIX D

TABLES OF RMSDS BETWEEN OBSERVED AND PREDICTED RESPONSES FOR EACH EXPERIMENTAL DATA SET

model	males Tcr	males Tsk	females Tcr	females Tsk
sd (obs)	0.25	0.73	0.19	0.54
lut2	0.61	1.00	0.23	0.39
lut25 (hhc)	0.62	1.65	0.22	1.27
lut25 (hhn)	0.69	1.76	0.31	1.33
luttre	1.45	/	1.01	/

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.

model	Tcr
lut2	0.35
lut25 (hhc)	0.78
lut25 (hhn)	0.79

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

	environment					
	A		B		C	
model	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
sd (obs)	0.16	0.37	0.22	0.71	0.30	0.61
lut2	0.23	0.78	0.37	0.30	0.43	0.48
lut25	0.29	0.84	0.13	0.41	0.23	0.46
luttre	0.81	/	0.59	/	0.39	/

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.

	environment					
	A		B		C	
model	C+R	E	C+R	E	C+R	E
lut2	37	35	32	33	23	22
lut25	5	6	5	13	1	21

Table D-4. Rmsd's (W/m^2) between observed and predicted responses for Chappuis et al. (1976) dry cooling (C+R) and total evaporative cooling (E) data.

model	experiment code ws Tcr	Tsk	wl Tcr	Tsk	wn Tcr	Tsk
lut2	0.83	2.08	0.87	1.95	0.37	1.63
lut25 (hhc)	0.32	1.46	0.37	1.36	0.27	1.16
lut25 (hhn)	0.25	1.29	0.26	1.19	0.27	1.12
luttre	0.55	/	0.61	/	0.51	/

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.

model	experiment code ds Tcr	Tsk	dl Tcr	Tsk	dn Tcr	Tsk
lut2	1.03	1.78	1.03	1.96	0.53	1.73
lut25 (hhc)	0.50	1.40	0.55	1.63	0.29	1.52
lut25 (hhn)	0.48	1.45	0.52	1.66	0.33	1.67
luttre	0.69	/	0.69	/	0.64	/

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.

model	clothing dry Tga	Tre	Tsk	clothing wet Tga	Tre	Tsk
sd (obs)	0.33	0.42	1.27	0.35	1.10	2.09
lut2	0.65	0.79	5.59	0.56	0.51	5.74
lut25 (hhc)	0.30	0.36	2.89	0.86	1.05	4.34
lut25 (hhn)	0.40	0.38	1.49	/	/	/

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.

model	clothing dry Tga	Tre	Tsk	clothing wet Tga	Tre	Tsk
sd (obs)	0.33	0.42	1.27	0.35	1.11	2.09
lut2	0.94	1.07	5.60	0.61	0.54	1.15
lut25 (hhc)	0.38	0.40	4.42	0.74	0.90	1.90
lut25 (hhn)	0.40	0.44	4.99	/	/	/

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.

	environment							
	f1		f3		f6		f7	
model	Tty	Tre	Tty	Tre	Tty	Tre	Tty	Tre
lut2	0.13	0.44	0.17	0.46	0.49	0.80	0.44	0.78
lu 25	0.12	0.29	0.14	0.28	0.53	0.82	0.41	0.74
luttre	0.84	0.61	0.70	0.54	0.38	0.21	/	/

Table D-9. Rmsd's (°C) between observed and predicted responses for Hardy and Stolwijk (1966) tympanic (Tty) and rectal (Tre) temperature data.

	environment			
model	f1	f3	f6	f7
lut2	0.55	0.68	0.85	1.83
lut25	0.41	0.44	1.54	2.63

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

	environment							
	f1		f3		f6		f7	
model	M	Esk	M	Esk	M	Esk	M	Esk
lut2	15	5	6	16	32	1	23	2
lut25	6	9	2	13	18	5	10	4

Table D-11. Rmsd's (W/m^2) between observed and predicted responses for Hardy and Stolwijk (1966) metabolic rate (M) and evaporative cooling from the skin (Esk) data.

model	clothing nude	A1	A2
sd (obs)	0.33	0.33	0.27
lut2	0.20	0.37	1.27
lut25 (hhc)	0.22	0.20	0.60
lut25 (hhn)	/	0.21	/
luttre	0.36	0.56	0.68

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

	experiment code					
	20		35		45	
model	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
sd (obs)	0.16	0.50	0.16	0.50	0.13	0.50
lut2	0.24	1.10	0.57	1.04	0.83	0.96
lut25	0.18	1.83	0.19	1.71	0.32	1.41
luttre	0.31	/	0.19	/	0.07	/

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.

model	environment 1	2	3	4	5	6	7	8
lut2	0.37	0.49	0.41	0.38	0.36	0.36	0.47	0.38
lut25	0.81	0.75	1.02	0.72	0.90	0.77	1.10	0.92
luttre	/	0.20	/	/	0.21	/	/	0.16

Table D-14. Rmsd's (°C) between observed and predicted responses for Iampietro et al. (1958) core (rectal) temperature data.

model	environment 1	2	3	4	5	6	7	8
lut2	2.34	1.44	1.76	1.58	1.47	1.99	1.91	1.85
lut25	1.23	0.84	1.89	0.92	0.75	1.08	0.93	0.81

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

model	environment 1	2	3	4	5	6	7	8
lut2	18	25	38	27	23	30	28	34
lut25	18	17	47	16	21	20	34	28

Table D-16. Rmsd's (W/m^2) between observed and predicted responses for Iampietro et al. (1958) metabolic rate data.

model	1	2	3	4	5	6	7	8
	environment							
lut2	0.70	0.77	0.53	0.66	0.64	0.43	0.52	0.82
lut25 (hhc)	0.97	1.14	0.74	0.93	0.87	0.59	0.65	1.17
lut25 (hhn)	1.09	1.25	0.83	1.06	0.95	0.68	0.75	1.28

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

model	1	2	3	4	5	6	7	8
	environment							
lut2	1.62	1.66	0.94	1.48	0.71	0.41	0.58	1.98
lut25 (hhc)	2.14	2.28	0.81	1.95	0.85	0.58	0.78	2.60
lut25 (hhn)	1.78	1.91	0.65	1.62	0.64	0.44	0.63	2.22

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

model	1	2	3	4	5	6	7	8
	environment							
lut2	5	8	15	9	13	17	16	14
lut25 (hhc)	16	18	11	18	10	9	9	17
lut25 (hhn)	4	6	10	6	8	13	10	12

Table D-19. Rmsd's (W/m^2) between observed and predicted responses for Iampietro and Buskirk (1960) metabolic rate (M) data.

	moderate work				heavy work			
model	Tac (°C)	Tre (°C)	Tsk (°C)	Esk (W/m²)	Tac (°C)	Tre (°C)	Tsk (°C)	Esk (W/m²)
lut2	0.52	0.50	0.73	59	0.40	0.66	0.79	94
lut25	0.30	0.73	0.36	67	0.48	1.05	0.69	66
luttre	0.75	0.25	/	/	0.72	0.30	/	/

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

	experiment code					
model	WD-1	WD-2	WD-3	WH-1	WH-2	WH-3
sd (obs)	0.39	0.24	0.17	0.30	0.22	0.25
lut2	0.33	0.46	0.19	0.12	0.12	0.09
lut25	0.18	0.27	0.27	0.14	0.16	0.11
luttre	0.51	0.47	0.98	0.66	0.59	0.85

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

	experiment code					
model	WD-1	WD-2	WD-3	WH-1	WH-2	WH-3
sd (obs)	0.44	0.29	0.23	0.20	0.21	0.20
lut2	0.34	0.53	0.18	0.34	0.40	0.35
lut25 (hhc)	0.19	0.29	0.10	0.28	0.25	0.27
luttre	0.34	0.20	0.67	0.36	0.27	0.55

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

model	day 1 Tcr (°C)	Tsk (°C)	C+R (W/m²)	E (W/m²)	day 10 Tcr (°C)	Tsk (°C)	C+R (W/m²)	E (W/m²)
sd (obs)	0.48	0.55	26	51	0.34	0.59	24	35
lut2	0.55	0.57	62	40	0.33	0.78	62	55
lut25	0.43	0.58	75	61	0.37	1.05	76	77
luttre	1.19	/	/	/	0.93	/	/	/

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.

model	clothing on trunk (ct) Tre	Toe	Tsk	clothing on limbs (cl) Tre	Toe	Tsk
lut2	0.08	0.16	1.39	0.19	0.09	1.45
lut25 (hhc)	0.39	0.22	1.27	0.49	0.38	1.20
lut25 (hhn)	0.36	0.21	1.18	0.48	0.38	1.17

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.

model	Tcr (°C)	M (W/m²)
sd (obs)	0.38	20
lut2	0.64	28
lut25	1.09	24

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

model	experiment code lw	hw
lut2	0.97	2.31
lut25 (hhc)	0.52	1.72
luttre	1.15	0.92

Table D-26. Rmsd's (°C) between observed and predicted respo ses for Pimental et al. (1987) core (Tcr, rectal) temp ature data.

model	Walk Tcr	Tsk	Carry Tcr	Tsk
sd (obs)	0.23	0.62	0.21	0.61
lut2	0.27	0.27	0.31	0.22
lut25 (hhc)	0.51	0.80	0.46	0.89
lut25 (hhn)	0.47	0.76	0.41	0.85
luttre	0.56	/	0.30	/

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.

model	Tcr (°C)	Tsk (°C)	M (W/m^2)
sd (obs)	/	0.29	4
lut2	1.27	0.87	15
lut25	1.57	0.98	20

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.

model	cool		hot	
	Tcr	Tsk	Tcr	Tsk
lut2	0.90	1.96	0.58	0.47
lut25	0.52	1.88	0.31	1.69
luttre	0.47	/	0.49	/

Table D-29. Rmsd's (°C) between observed and predicted responses for Shvartz (1976) core (Tcr, rectal) and mean skin temperature (Tsk) data.

	environment							
	wc		wa		hc		ha	
model	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
sd (obs)	0.21	0.59	0.24	0.33	0.28	0.46	0.35	0.62
lut2	0.28	1.30	0.30	0.41	0.67	0.77	0.66	0.72
lut25 (hhc)	0.73	1.54	0.88	1.16	0.97	1.21	0.63	0.94
luttre	1.59	/	1.70	/	1.61	/	1.35	/

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.

	environment									
	f3		f4		f5		f6		f7	
mode	Tty	Tre	Tty	Tre	Tty	Tre	Tty	Tre	Tty	Tre
lut2	0.37	0.39	0.16	0.32	0.16	0.31	0.32	0.31	0.59	0.59
lut2	0.19	0.20	0.03	0.19	0.05	0.18	0.20	0.21	0.48	0.48
luttre	0.35	0.33	0.45	0.31	0.49	0.34	0.33	0.36	0.15	0.12

able D-31. Rmsd's (°C) between observed and predicted esp nses for Stolwijk and Hardy (1966) tympanic (Tty) and ectal (Tre) temperature data.

	environment				
model	f3	f4	f5	f6	f7
lut2	0.34	0.39	0.33	0.62	0.36
lut25	0.47	0.32	0.36	0.22	0.39

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

	environment									
	f3		f4		f5		f6		f7	
model	M	Esk	M	Esk	M	Esk	M	Esk	M	Esk
lut2	7	8	1	7	2	9	5	11	3	12
lut25	6	9	1	6	2	9	5	12	3	14

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.

	environment							
	28		20		15		10	
model	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
sd obs)	0.32	0.79	0.32	0.79	0.32	0.79	0.32	0.79
lut2	0.09	0.48	0.19	0.28	0.33	0.61	0.37	1.16
lut 5	0.20	0.44	0.21	1.22	0.49	1.35	0.64	1.62
luttre	0.31	/	0.38	/	0.35	/	/	/

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.

	environment							
	e1		e2		e3		e4	
model	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
lut2	0.53	2.50	0.56	1.42	0.58	2.24	0.58	3.87
lut25 (hhc)	0.26	1.25	0.28	0.77	0.38	0.44	0.56	0.45
lut25 (hhn)	0.29	1.24	0.36	0.68	0.51	0.42	0.66	0.47

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.

	environment							
	e1		e2		e3		e4	
model	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
lut2	0.55	1.27	0.54	0.70	0.59	1.75	0.65	4.18
lut25 (hhc)	0.22	0.34	0.21	0.82	0.29	0.71	0.48	1.14
lut25 (hhn)	0.23	0.41	0.25	0.87	0.42	0.89	0.62	1.21

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.

model	Tcr (°C)	Tsk (°C)	M (W/m^2)
sd (obs)	0.24	1.60	21
lut2	0.67	1.88	24
lut25	1.06	3.31	23

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.

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).

		experiment code		warning unacclimatized subjects	danger unacclimatized subjects	warning acclimatized subjects	danger acclimatized subjects
nude/rest/no-wind							
25<Ta<=35 °C	Stolwijk and Hardy (1966)	f4	Tre	0.3[1,2]	0.3[1,2]	0.3[1,2]	0.3[1,2]
			Tty	0.1[1,2]	0.1[1,2]	0.1[1,2]	0.1[1,2]
			Tsk	1.1[1,2]	1.1[1,2]	1.1[1,2]	1.1[1,2]
35<Ta °C	Hardy and Stolwijk (1966)	f3	Tre	0.5[1,2]	0.5[1,2]	0.5[1,2]	0.5[1,2]
			Tty	0.2[1,2]	0.2[1,2]	0.2[1,2]	0.2[1,2]
			Tsk	2.6[1,2]	2.6[1,2]	2.6[1,2]	2.6[1,2]
	Stolwijk and Hardy (1966)	f5	Tre	0.2[1,2]	0.2[1,2]	0.2[1,2]	0.2[1,2]
			Tty	0.1[1,2]	0.1[1,2]	0.1[1,2]	0.1[1,2]
			Tsk	2.4[1,2]	2.4[1,2]	2.4[1,2]	2.4[1,2]
	Stolwijk and Hardy (1966)	f6	Tre	0.4[1,2]	0.4[1,2]	0.4[1,2]	0.4[1,2]
			Tty	0.4[1,2]	0.4[1,2]	0.4[1,2]	0.4[1,2]
			Tsk	2.4[1,2]	2.4[1,2]	2.4[1,2]	2.4[1,2]
	Stolwijk and Hardy (1966)	f7	Tre	0.6[1]	0.9[1,2]	0.9[1,2]	0.9[1,2]
			Tty	0.8[1]	1.0[1,2]	1.0[1,2]	1.0[1,2]
			Tsk	3.3[1]	3.4[1,2]	3.4[1,2]	3.4[1,2]

(continued)

Table E-1 (continued)

		experiment code		warning unacclimatized subjects	danger unacclimatized subjects	warning acclimatized subjects	danger acclimatized subjects
15<Ta<=25 °C	Chappuis et al. (1976)	A	Tty	0.3[1,2]	0.3[1,2]	0.3[1,2]	0.3[1,2]
			Tsk	-1.3[1,2]	-1.3[1,2]	-1.3[1,2]	-1.3[1,2]
	Chappuis et al. (1976)	B	Tty	0.6[1,2]	0.6[1,2]	0.6[1,2]	0.5[1,2]
			Tsk	0.5[1,2]	0.5[1,2]	0.5[1,2]	0.5[1,2]
	Hirata et al. (1983)	20	Toe	0.2[2]	0.2[2]	0.2[2]	0.2[2]
			Tsk	-2.6[2]	-2.6[2]	-2.6[2]	-2.6[2]
	Hirata et al. (1983)	35	Toe	0.7[2]	0.7[2]	0.7[2]	0.7[2]
			Tsk	-1.2[2]	-1.2[2]	-1.2[2]	-1.2[2]
	Hirata et al. (1983)	45	Toe	1.2[2]	1.2[2]	1.2[2]	1.2[2]
			Tsk	-0.4[2]	-0.4[2]	-0.4[2]	-0.4[2]
	Shvartz (1976)	cool	Tre	1.0[2]	1.0[2]	1.0[2]	1.0[2]
			Tsk	0.2[2]	0.2[2]	0.2[2]	0.2[2]
25<Ta<=35 °C	Chappuis et al. (1976)	C	Tty	0.9[1,2]	0.9[1,2]	0.9[1,2]	0.9[1,2]
			Tsk	1.9[1,2]	1.9[1,2]	1.9[1,2]	1.9[1,2]

(continued)

Table E-1 (continued)

		experiment code		warning unacclimatized subjects	danger unacclimatized subjects	warning acclimatized subjects	danger acclimatized subjects
35<Ta °C	Kobayashi et al. (1980)	moderate work	Tre Tac Tsk	−0.1[1] 0.9[1] 3.8[1]	0[1] 1.0[1] 3.9[1]	0.1[1] 1.0[1] 3.9[1]	0.5[1] 1.3[1] 4.2[1]
	Kobayashi et al. (1980)	heavy work	Tre Tac Tsk	−0.3[1] 0.7[1] 3.7[1]	−0.2[1] 0.9[1] 3.8[1]	−0.2[1] 0.9[1] 3.8[1]	0[1] 0.9[1] 3.8[1]
	Mairiaux et al. (1986)	WD-1	Tre Toe	0.9[1,2] 0.6[1,2]	0.9[1,2] 0.6[1,2]	0.9[1,2] 0.6[1,2]	0.9[1,2] 0.6[1,2]
	Mairiaux et al. (1986)	WD-2	Tre Toe	0.9[1,2] 0.5[1,2]	0.9[1,2] 0.5[1,2]	0.9[1,2] 0.5[1,2]	0.9[1,2] 0.5[1,2]
	Mairiaux et al. (1986)	WD-3	Tre Toe	0.7[2] 0.3[2]	0.7[2] 0.3[2]	0.7[2] 0.3[2]	0.7[2] 0.3[2]
	Mairiaux et al. (1986)	WH-1	Tre Toe	1.0[1,2] 0.6[1,2]	1.0[1,2] 0.6[1,2]	1.0[1,2] 0.6[1,2]	1.0[1,2] 0.6[1,2]
	Mairiaux et al. (1986)	WH-2	Tre Toe	1.1[1,2] 0.7[1,2]	1.1[1,2] 0.7[1,2]	1.1[1,2] 0.7[1,2]	1.1[1,2] 0.7[1,2]
	Mairiaux et al. (1986)	WH-3	Tre Toe	1.0[2] 0.6[2]	1.0[2] 0.6[2]	1.0[2] 0.6[2]	1.0[2] 0.6[2]
	Shvartz (1976)	hot	Tre Tsk	1.5 2.4	2.0[2] 2.6[2]	2.0[2] 2.6[2]	2.0[2] 2.6[2]

(continued)

Table E-1 (continued)

		experiment code		warning unacclimatized subjects	danger unacclimatized subjects	warning acclimatized subjects	danger acclimatized subjects
				nude/work/wind			
25<Ta<=35 °C	Henane et al. (1979)	nude	Tre	0.6[2]	0.6[2]	0.6[2]	0.6[2]
35<Ta °C	Mitchell et al. (1976)	day 1	Tre Tsk	0.4 2.3	0.9 2.6	1.1 2.6	1.7 3.4
				clothed/work/no-wind			
25<Ta<=35 °C	Randle and Legg (1985)	wk	Tac Tsk	0.6 2.7	0.8 2.8	0.9 2.8	1.0 2.9
	Randle and Legg (1985)	cy	Tac Tsk	0.5 2.6	0.7 2.8	0.6 2.7	1.0 2.8
	Smith (1986)	wc	Tac Tsk	0.3[1,2] 2.0[1,2]	0.3[1,2] 2.0[1,2]	0.3[1,2] 2.0[1,2]	0.3[1,2] 2.0[1,2]
	Smith (1986)	wa	Tac Tsk	0.4[1] 2.5[1]	0.1[1] 2.2[1]	0.5[1,2] 3.0[1,2]	0.5[1,2] 3.0[1,2]
35<Ta °C	Smith (1986)	hc	Tac Tsk	0.3[1] 2.4[1]	0.5[1] 3.0[1]	0.4[1] 2.8[1]	0.2[1] 2.5[1]
	Smith (1986)	ha	Tac Tsk	0.7[1] 3.5[1]	0.6[1] 3.3[1]	0.6[1] 3.3[1]	0.8[1] 3.4[1]

(continued)

Table E-1 (continued)

		experiment code		warning unacclimatized subjects	danger unacclimatized subjects	warning acclimatized subjects	danger acclimatized subjects
clothed/work/wind							
35<Ta °C	Henane et al. (1979)	A1	Tre	0.6	0.7	0.7	0.8
	Henane et al. (1979)	A2	Tre	0.4	0.5	0.4	0.5
nude/work/wind (acclimatized subjects)							
35<Ta °C	Mitchell et al. (1976)	day 10	Tre Tsk	0.3 2.1	0.6 2.4	0.8 2.4	1.2 2.6

(continued)

Table E-1 (continued)

		experiment code		warning unacclimatized subjects	danger unacclimatized subjects	warning acclimatized subjects	danger acclimatized subjects
clothed/work/wind (acclimatized subjects)							
25<Ta<=35 °C	Haisman and Goldman (1974)	wn	Tre Tsk	0.6 1.8	0.8 2.0	0.8 2.0	1.0 2.2
	Haisman and Goldman (1974)	wl	Tre Tsk	0.4 1.8	0.6 2.1	0.4 2.0	0.7 2.2
	Haisman and Goldman (1974)	ws	Tre Tsk	0.4 1.7	0.6 2.0	0.4 1.8	0.6 2.1
35<Ta °C	Haisman and Goldman (1974)	dn	Tre Tsk	0.3 1.9	0.6 2.0	0.6 2.0	0.9 2.2
	Haisman and Goldman (1974)	dl	Tre Tsk	0.3 2.0	0.2 2.2	0.2 2.1	0.5 2.5
	Haisman and Goldman (1974)	ds	Tre Tsk	0.3 2.0	0.3 2.3	0.3 2.2	0.5 2.5
	Pimental et al. (1987)	lw	Tre	0	0	0	0
	Pimental et al. (1987)	hw	Tre	0.1	0.2	0.1	0.2

[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

Contemporary Ergonomics 1986 (Edited by: D. J. Oborne)
(Taylor & Francis: London).

MODELS OF HUMAN RESPONSE TO HOT AND COLD ENVIRONMENTS

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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.

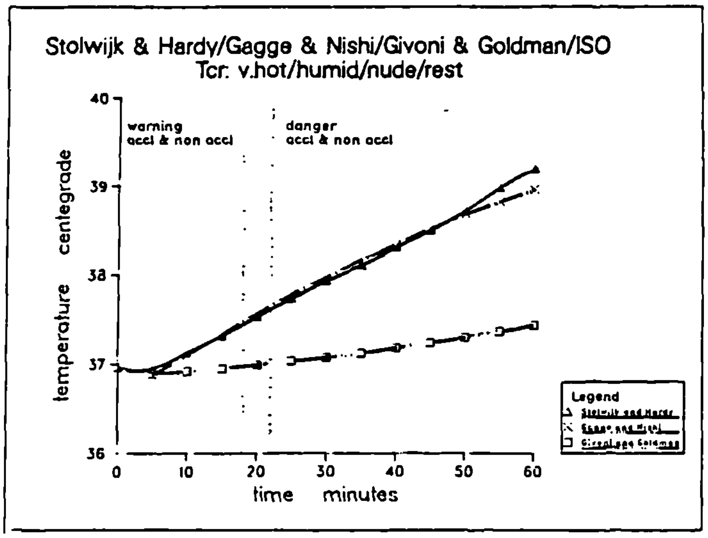

Figure 1

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.

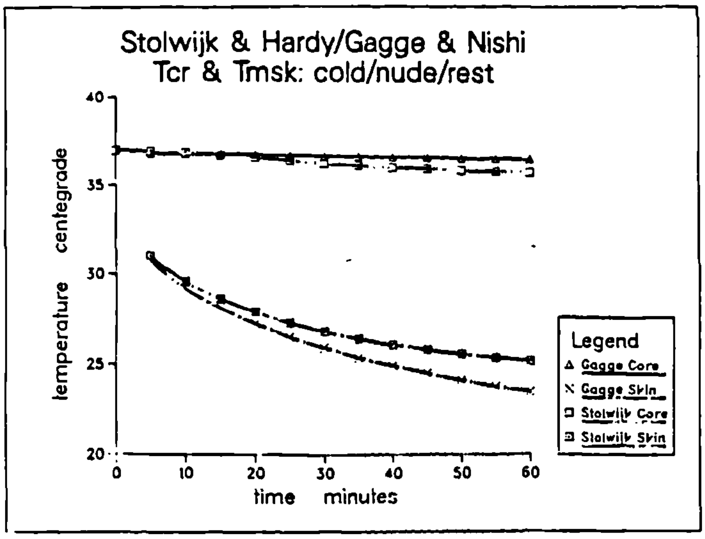

Figure 2.

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.

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

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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

Note: Symbols used in this paper comply with those suggested by the International Union of Physiological Sciences (Bligh and Johnson 1973).

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:

$$E_{req} = M - W - C - R \quad ---- \quad (1)$$

where: E_{req} = required evaporative cooling (W)

M = metabolic heat production (W)

W = external work (W)

C = heat loss by convection (W)

R = heat loss by radiation (W)

The final equilibrium rectal temperature is then calculated as:

$$T_{ref} = F1(M - W) + F2(C + R) + F3(E_{req} - E_{max})$$

Where: T_{ref} = final equilibrium rectal temperature (C)

$M - W$ = metabolic heat load (W)

$C + R$ = dry environmental heat load (W)

E_{req} = required evaporative cooling

$= (M - W) + (C + R)$ (W)

E_{max} = maximum evaporative capacity of environment (W)

E_{max} depends on the humidity of the air and the resistance of the clothing, if any is worn, to evaporative heat transfer. $F1$, $F2$ and F3 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).

2.2. *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_{req}) is then calculated as:

$$W_{req} = E_{req}/E_{max} \qquad \text{(ND)}$$

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

$$SW_{req} = E_{req}/r \qquad \text{(W)}$$

where: SW_{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/m^2.hr); the control coefficient for vasodilation (CDIL) has been changed from 150 to 200 (l/m^2.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.

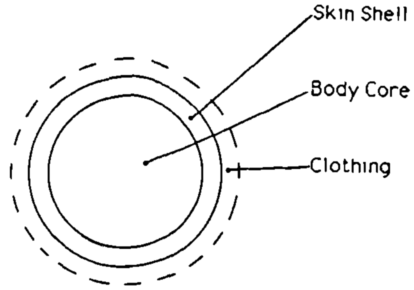


Figure 1. J. B. Pierce Lab. 2-node model representation of the human thermoregulatory controlled (passive) system.

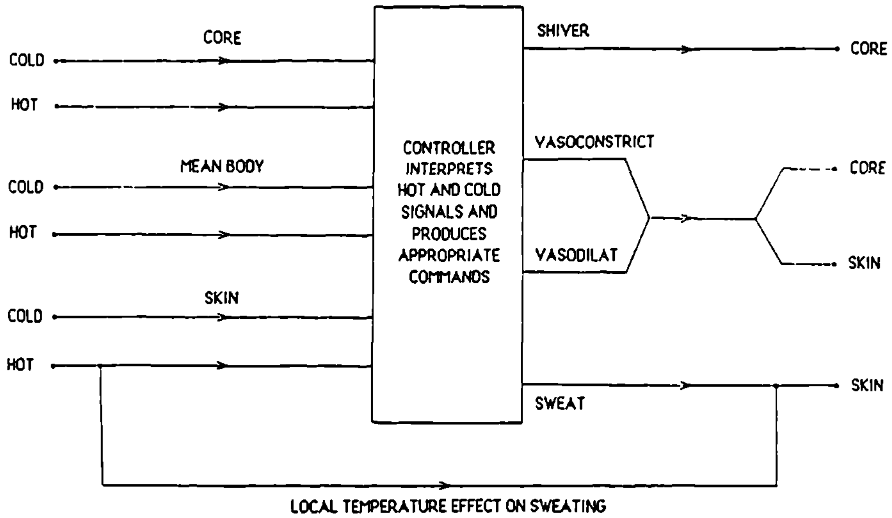


Figure 2. J. B. Pierce Lab. 2-node model representation of the human thermoregulatory controlling (active) system.

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 $1{\cdot}89\ m^2$.

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

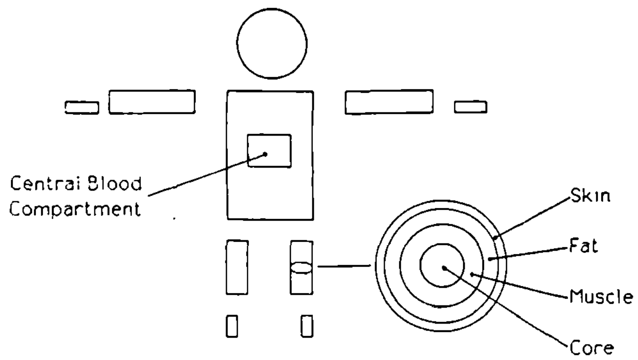


Figure 3. Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlled (passive) system (6 body segments × 4 layers + 1 blood = 25 compartments).

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 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 1 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.

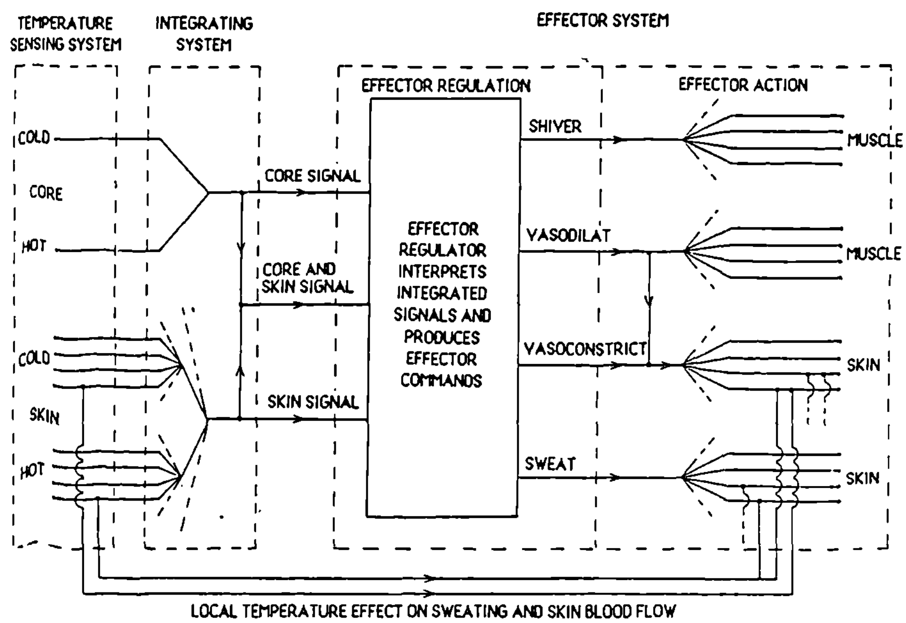


Figure 4. Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlling (active) system.

Table 1. Model inputs and predictions.

	Givoni & Goldman	Model ISO DIS 7933	2-node	25-node
Inputs:				
Air temperature T_a	Yes	Yes	Yes	Yes
Mean radiant temperature ($\bar{T}_r$)	$\bar{T}r = Ta$	Yes	Yes	$\bar{T}r = Ta$
Air speed (v)	Yes	Yes	Yes	Yes
Relative humidity (rh)	Yes	From vapour pressure	Yes	Yes
Clothing insulation	I_T	I_{cl}	I_{cl}	Nude only
Clothing moisture permeation resistance	i_m	From I_{cl}	From I_{cl}	Nude only
Metabolic rate (M)	Yes	Yes	Yes	Yes
External work (W)	Yes	Yes	Yes	Fixed assuming bicycle exercise
Predictions:				
Core (T_{cr})	T_{re}	No	T_{cr}	T head-core
Mean skin ($\bar{T}_{sk}$)	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_{cl} = 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° 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° and 0·9°C by the 2-node and 25-node models. This

Table 2. Environmental conditions for comparison of models' predictions.

Environment	Exposure Time (mins)	Ta (°C)	v (m/s)	rh (ND)	I_{cl} (clo)	M (W/m^2)	W (W/m^2)
A	60	5	0·10	0·70	0·0	58	0
B	60	5	0·10	0·70	0·0	167	0
C	60	45	0·25	0·65	0·0	58	0
D	120	40	0·25	0·50	0·6	150	0
rest	30					58	0
E work	60	35	0·50	0·55	0·0	222	22
recovery	30					58	0

Note:
For all environments $Tr = Ta$.
For Environment D, $i_m = 0{\cdot}5$ (ND).

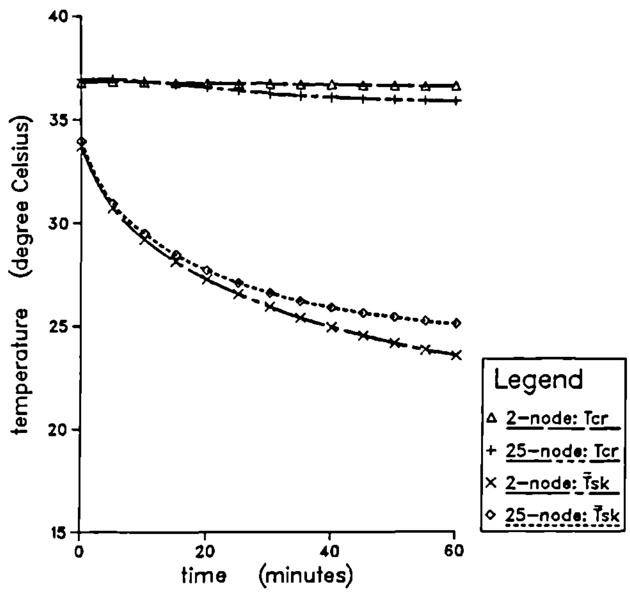


Figure 5. Comparison of the models' predictions for nude, resting subjects in the cold (environment A).

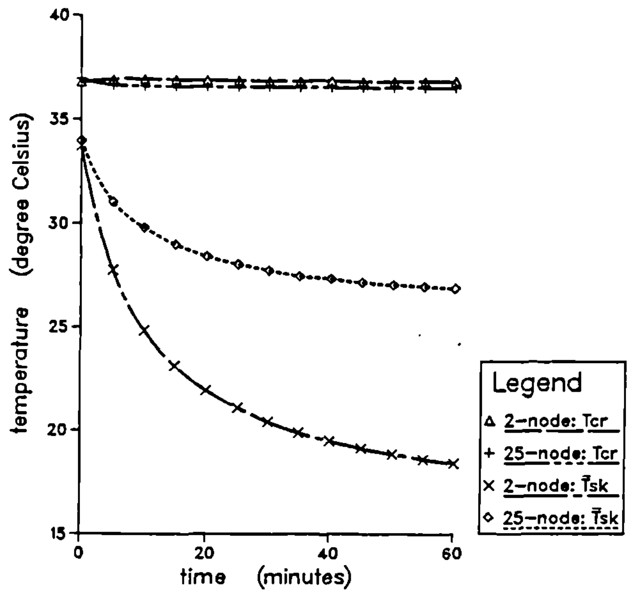


Figure 6. Comparison of the models' predictions for nude, working subjects in the cold (environment B).

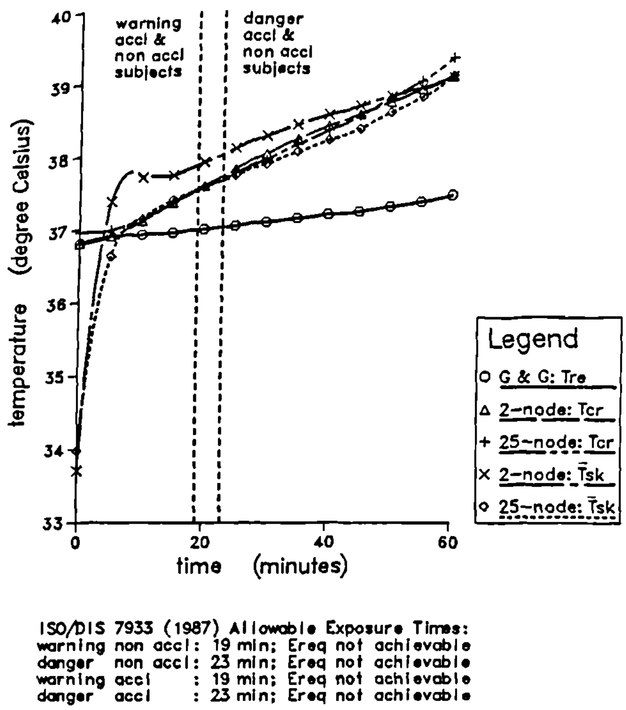


Figure 7. Comparison of the models' predictions for nude, resting subjects in the heat (environment C).

agrees with the limiting criteria of body heat storage set by the ISO/DIS 7933 model (rises in deep body temperature of 0·8° 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.

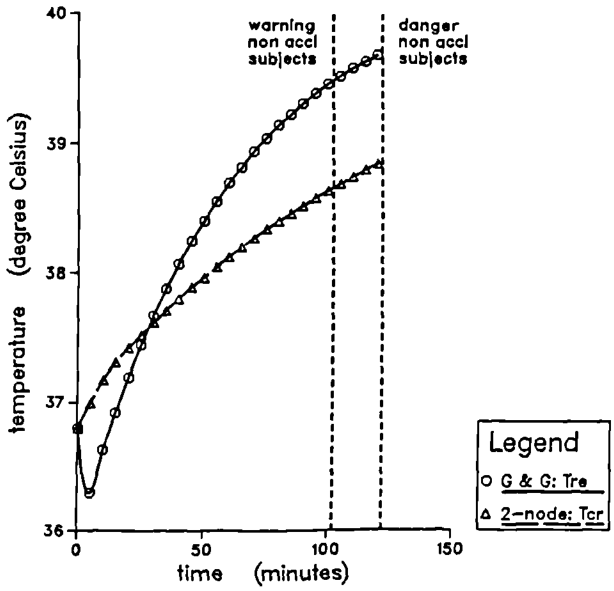
The 2-node and 25-node models' predictions of mean skin temperature differ by 0·6°C after 10 minutes of the exposure, with this difference decreasing to less than 0·1°C after 60 minutes.

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*

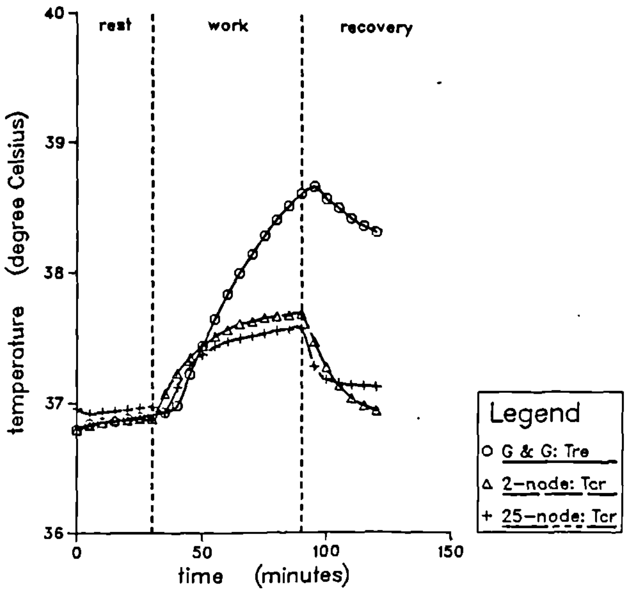
The four models' predictions for a rest, work and recovery exposure, in the heat and for unclothed subjects (environment E) are given in figure 9.

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



ISO/DIS 7933 (1987) Allowable Exposure Times:
warning non accl: 1 hr 42 min; Ereq not achievable
danger non accl: 2 hr 2 min; Ereq not achievable
warning accl : 5 hr 0 min; dehydration
danger accl : 5 hr 0 min; dehydration

Figure 8. Comparison of the model's predictions for clothed, working subjects in the heat (environment D).



ISO/DIS 7933 (1987) Allowable Exposure Times (for work period):
warning non accl: 5 hr 21 min; dehydration
danger non accl: 6 hr 41 min; dehydration
warning accl : 8 hr 0 min; unlimited duration of work
danger accl : 8 hr 0 min; unlimited duration of work

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 were 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, 1981 a, 1981 b), 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 Ginovi 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_{pcl}) 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 tendancy 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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On décrit et on évalue les capacités prédictives de quatre modèles importants relatifs à la résponse 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 ait pu évaluer leur précision sur un large éventail de sujets et d'ambiances thermiques et déterminer pour quelles ambiances ils conviennent le mieux.

Vier bedeutende Modelle, die Reaktionen des Menschen auf Hitze oder Kälte abschätzbar machen, sind beschrieben und ihre Ergebnisse miteinander verglichen worden. Die behandelten Modelle waren die Givoni- und Goldman Berechnungs-gleichungen, die ISO/DIS 7933, das J. B. Pierce Lab. 2-Knoten-Modell und das 25-Knoten-Modell von Stolwijk und Hardy für die menschliche Thermoregulation.

Die Modelle vereinigen die wichtigen Klimaeinzelfaktoren (Lufttemperatur, Strahlungstemperatur, Windgeschwindigkeit und relative Luftfeuchte) mit individualspezifischen Variablen (Isolation der getragenen Kleidung und metabolische Wärmeproduktion), um beispeilsweise Körperkern- und Haut-temperatur sowie zulässige Expositionsdauern vorherzusagen. Die Ergebnisse der Modelle sind für eine Reihe heißer und kalter Klimaten verglichen worden. Dieser Vergleich hat gezeigt, daß die Ergebnisse zwar für einige Klimabedingungen ähnlich sind, für andere jedoch sehr unterschiedlich. Diese Unterschiede würden auf abweichende, in der Praxis zu treffende Entscheidungen hinauslaufen.

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.

熱いまたは寒い環境に対する人間の反応を予測する4つの有力なモデルを記述し，その予測を比較した。考察したモデルはGivoni と Goldmanの予測式，ISO/DIS 7933，J. B. Pierce Lab.の2ノード体温調節モデル，Stolwijk と Hardyの25ノード体温調節モデルであった。これらモデルは重要な環境変数（気温，平均輻射温，風速，相対湿度）を被験者変数（着用衣服の断熱性，代謝性熱産生）と統合し，核心温度と皮膚温度の反応，許容暴露時間等の予測を行う。モデル予測値は一定範囲の熱い環境と寒い環境に対して比較した。この比較はモデル予測値が類似している環境もあり，非常に相違している環境もあることを示した。これらの相違点のために実際の決定も異なることもある。広範囲の被験者と環境条件に対する詳しい評価によってモデルの精度が確認されるまでは注意して使用し，また最も適する環境のみに使用すべきである。

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AN EVALUATION OF COMPUTER-BASED MODELS THAT PREDICT HUMAN RESPONSES TO THE THERMAL ENVIRONMENT

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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.

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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 Haslam 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 m^2.

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 th 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 compartmenta 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:

$$Tref = F1(M-W) + F2(C+R) + F3(Ereq-Emax)$$

where:

Tref = final equilibrium rectal temperature (^{o}C)
M-W = metabolic heat load (W)
C+R = sensible environmental heat load (W)
Ereq = required evaporative cooling (W)
= (M-W) + (C+R)
Emax = maximum evaporative capacity of environment (W)

F1, F2, and F3 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:

$$Ereq = M - W - C - R$$

where:

Ereq = required evaporative cooling (W/m^2)
M = metabolic heat production (W/m^2)
W = external work (W/m^2)
C = heat loss by convection (W/m^2)
R = heat loss by radiation (W/m^2)

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 (Icl) and Woodcock's (1962) moisture permeability index (i_m). The Givoni and Goldman model uses the total clothing insulation (I_T) and i_m. ISO/DIS 7933 (1987) uses the effective clothing insulation (Icle) and the permeation efficiency coefficient (Fpcl) (Nishi and Gagge 1970). The definitions of Icl, Icle, and I_T 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 Icl, the clothing area factor (fcl), and i_m. Icl 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 i_m 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 Icl, fcl, as i_m and their clothing inputs. For the Givoni and Goldman model, I_T is determined from these inputs so that the Givoni and Goldman empirical pumping coefficient can be used to estimate the effects of exercise motion on the clothing insulation. In addition, two versions of the Stolwijk and Hardy model have been developed; one applies any clothing insulation equally over the whole body, including the head and hands, while the other leaves the head and hands nude and adjusts the insulation over the rest of the body to account for this.

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, luttre 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 luttre 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).

ROOT MEAN SQUARED DEVIATION

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:

$$rmsd = \left(\frac{1}{n} \sum_{i=1}^{n} d_i^2 \right)^{\frac{1}{2}}$$

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 Icl=0.1 clo, fcl=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 response. 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) =

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 ergonometer with metabolic rate (M) = 150 W/m^2, 50 minutes with M=257 W/m^2, and 30 minutes rest (M=57 W/m^2). Ta was equal to mean radiant temperature (Tr), relative humidity (rh) = 30 %, room air movement (v) = 0.2 m/s, and the subjects wore shorts (Icl=0.1 clo, fcl=1, (ND), and i_m=0.5 (ND)).

Figures 3 and 4 show the observed and predicted tympanic (Tty) 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 suppoorted 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 Ta=Tr=49.5 °C, v=0.1 m/s, rh=32 %, Icl=0.1 clo, fcl=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/m^2 for the moderate work and M=306 W/m^2 for the heavy work conditions.

Figures 5, 6, 7 show the responses of the auditory canal (Tac), rectal (Tre), 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 Tac 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 Tac increase but not with the observed Tre response.

The predicted skin temperature response (Figure 7)shows that the models' predictions are fairly 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 Tac temperatures, while the luttre model predicts the observed Tre response more accurately.

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 Ta=Tr=5 °C, v=0.1 m/s, rh=30 %, Icl=0.1 clo, fcl=1 (ND), i_m=0.5 (ND), and M=60 W/m^2 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 of 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: Icl=0.1 clo, fcl=1 (ND), and i_m=0.5 (ND); A1: Icl=1.0 clo, fcl=1.3 0 (ND), and i_m=0.35 (ND); A2: Icl=2.6 clo, fcl=1.40 (ND), and i_m=0.30 (ND)) to the environmental conditions of Ta=Tr=35 °C, v=1 m/s, and rh=54 %. 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/m^2 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 luttre models' predictions are less accurate than those of the lut2 and lut25 models.

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 ct: Icl=1.22 clo, fcl=1.38 (ND), and i_m=0.35 (ND); experiment code cl: Icl=1.67 clo, fcl=1.52 (ND), and i_m=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/m^2.

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 Tac 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 Tsk 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 (hc) 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 hc 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, Tac, 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 Tac 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.

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TABLE 1

Rmsd's (°C) between observed and predicted responses for Chappuis et. al. (1976) core (Tcr, tympanic), and mean skin temperature ($\bar{T}sk$) data

	environment					
	A		B		C	
model	Tcr	$\bar{T}sk$	Tcr	$\bar{T}sk$	Tcr	$\bar{T}sk$
sd (obs)	0.16	0.37	0.22	0.71	0.30	0.61
lut2	0.23	0.78	0.37	0.30	0.43	0.48
lut25	0.29	0.84	0.13	0.41	0.23	0.46
luttre	0.96	/	0.74	/	0.54	/

TABLE 2

Rmsd's Between Observed and Predicted Responses for Kobayashi Et Al. (1980) Auditory Canal (Tac), Rectal (Tre) and Mean Skin Temperature ($\bar{T}sk$) Data

	moderate work			heavy work		
model	Tac (°C)	Tre (°C)	$\bar{T}sk$ (°C)	Tac (°C)	Tre (°C)	$\bar{T}sk$ (°C)
lut2	0.52	0.50	0.73	0.40	0.66	0.79
lut25	0.30	0.73	0.36	0.48	1.05	0.69
luttre	0.71	0.30	/	0.66	0.43	/

TABLE 3

Rmsd's Between Observed and Predicted Responses for Young Et Al. (1980) Core (Tcr, Rectal), and Mean Skin Temperature ($\bar{T}sk$) Data

model	Tcr (°C)	$\bar{T}sk$ (°C)
sd (obs)	0.24	1.60
lut2	0.67	1.88
lut25	1.06	3.31

TABLE 4

Rmsd's (°C) Between Observed and Predicted Responses for Henane Et Al. (1979) Core (Tcr, Rectal) Temperature Data

model	clothing nude	A1	A2
sd (obs)	0.33	0.33	0.27
lut2	0.20	0.37	1.27
lut25 (hhc)	0.22	0.20	0.60
lut25 (hhn)	/	0.21	/
luttre	0.46	0.59	0.69

TABLE 5

Rmsd's (C°) Between Observed and Predicted Responses for Nielson and and Nielson (1984) Rectal (Tre), Oesophageal (Toe) and Mean Skin Temperature ($\bar{T}sk$) Data

model	clothing on trunk (ct) Tre	Toe	$\bar{T}sk$	clothing on limbs (cl) Tre	Toe	$\bar{T}sk$
lut2	0.08	0.16	1.39	0.19	0.09	1.45
lut25 (hhc)	0.39	0.22	1.27	0.49	0.38	1.20
lut25 (hhn)	0.36	0.21	1.18	0.48	0.38	1.17

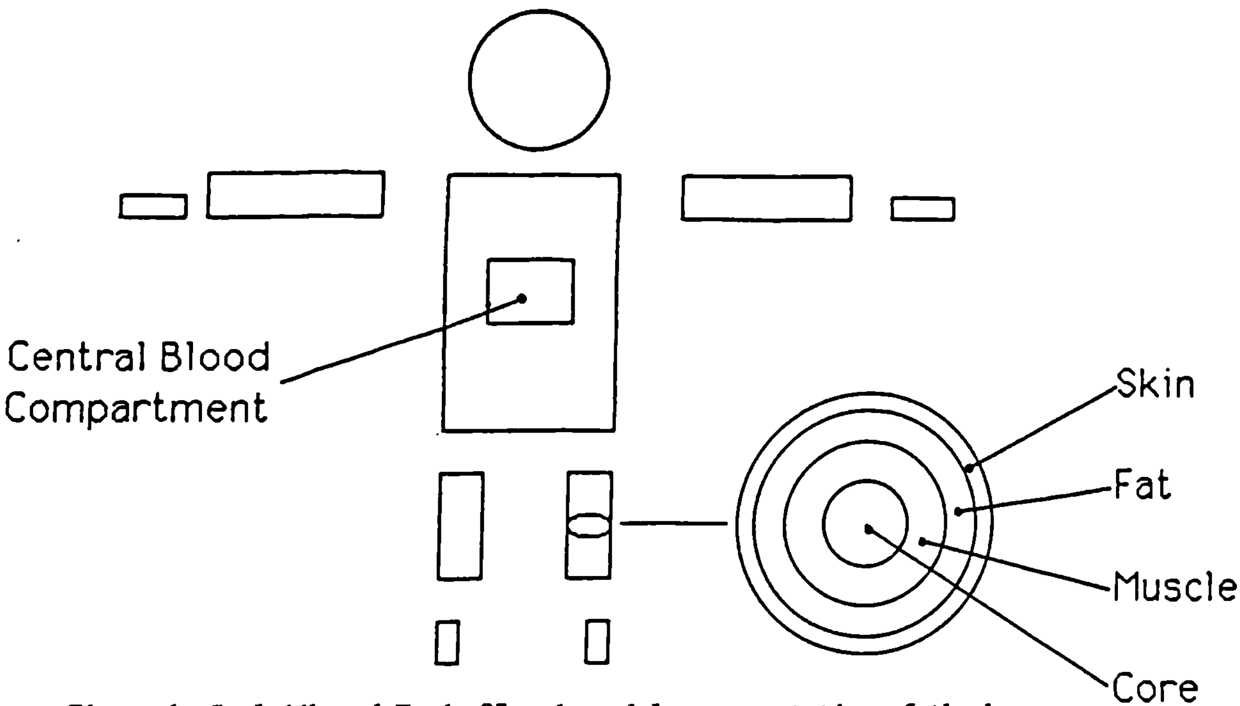


Figure 1 Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlled (passive) system (6 body x 4 layers + 1 blood = 25 compartments)

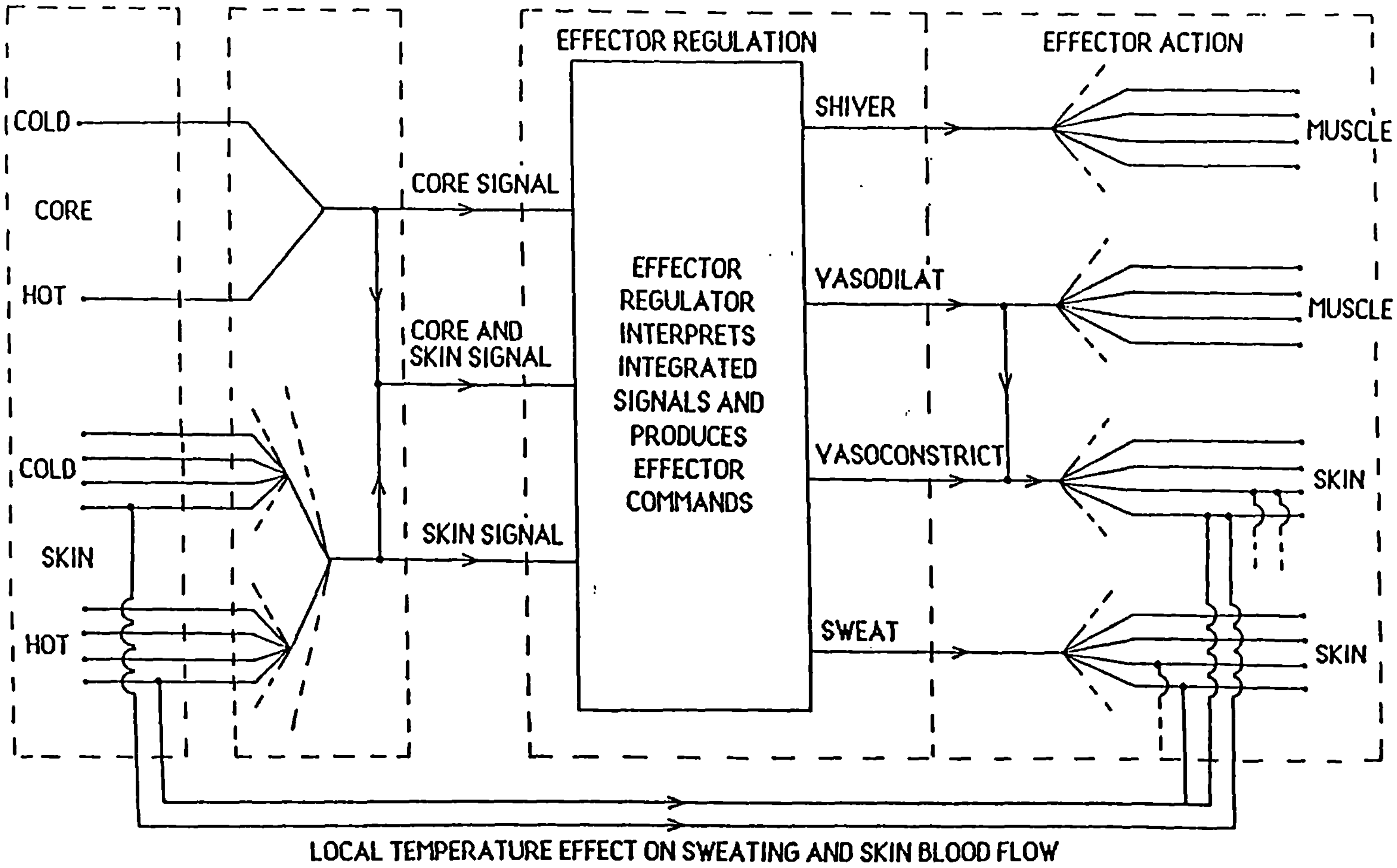
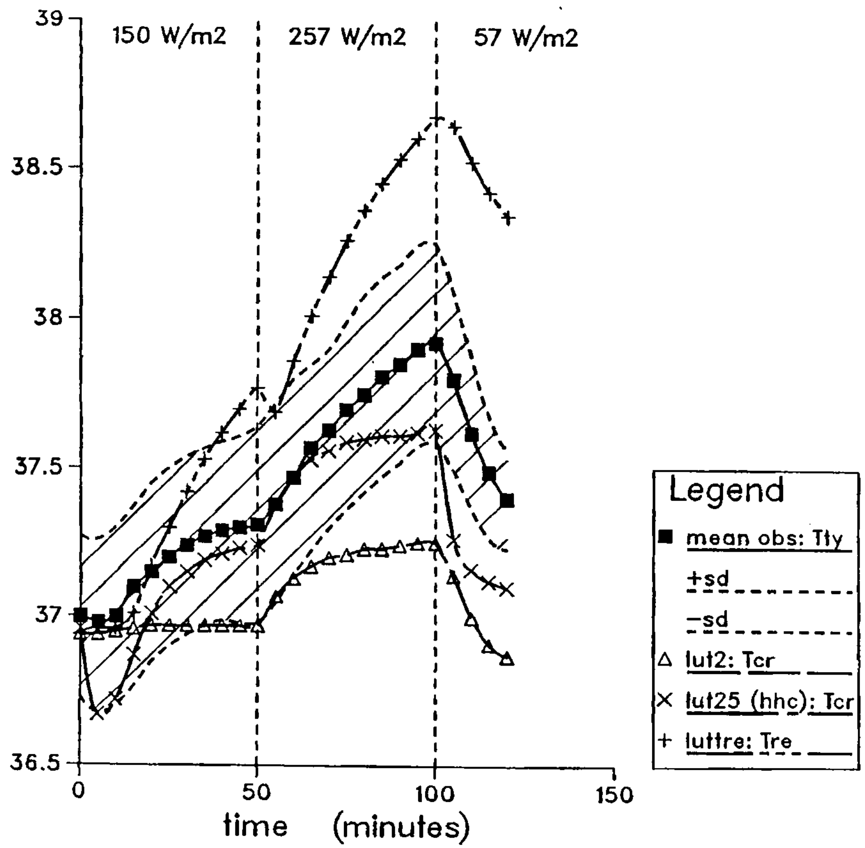


Figure 2 Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlling (active) system



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

Figure 3 Tty from Chappuis et al (1976) (n=11) (exp code: C), Ta=Tr=30 C, v=0.2 m/s, rh=30%, Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0, 0 W/m2

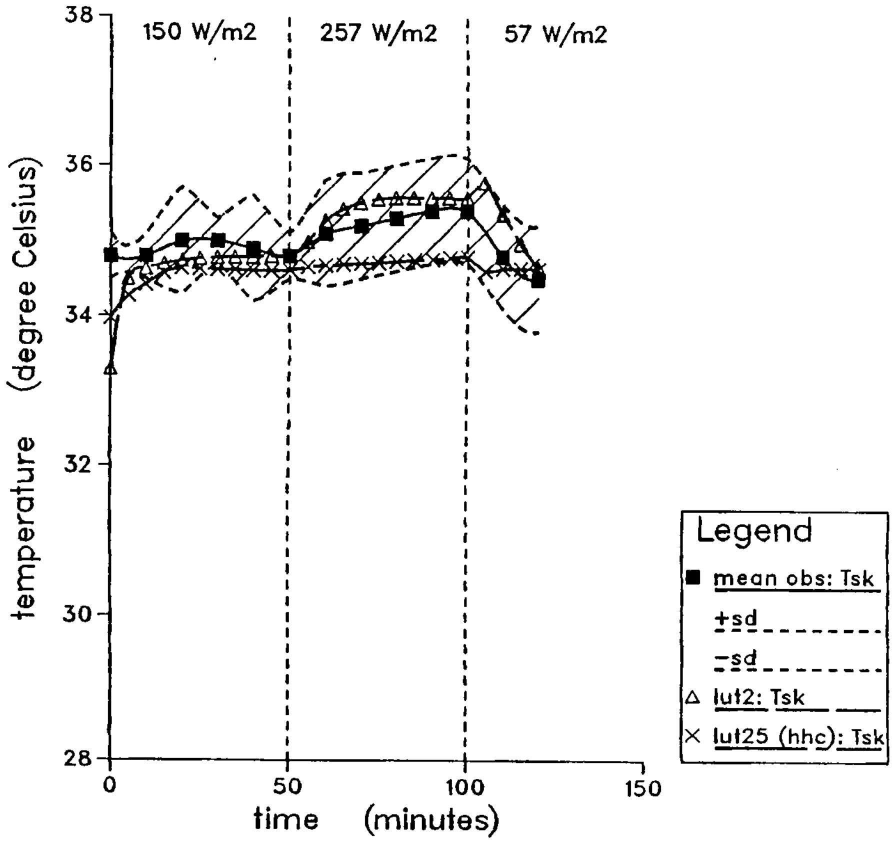
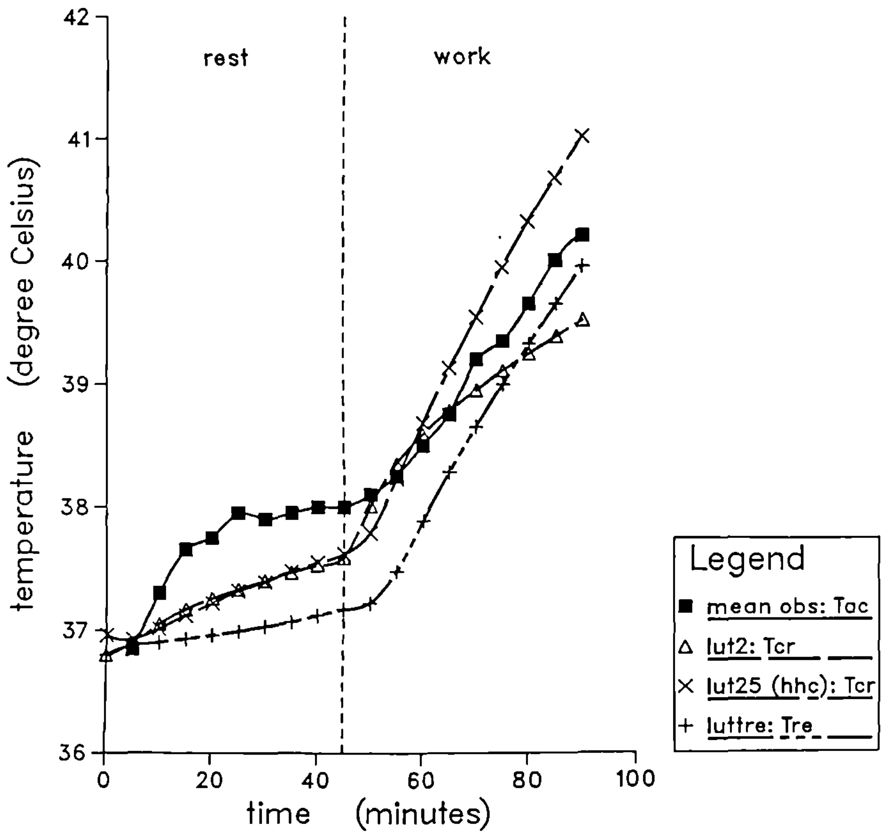
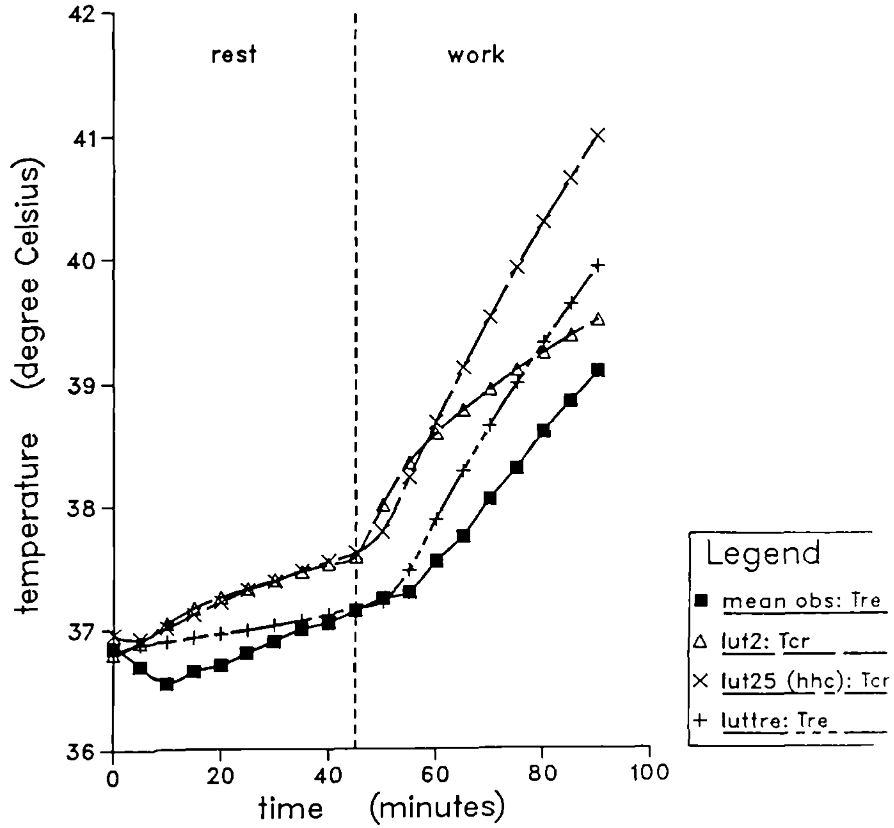


Figure 4 $\overline{\text{T}}$sk from Chappuis et al (1976) (n=11) (exp code: C), Ta=Tr=30 C, v=0.2 m/s, rh=30%, Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=150, 257, 57 W/m2, W=22, 49, 0, 0 W/m2



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

Figure 5 Tac from Kobayashi et al (1980) (n=5) (heavy work), Ta=Tr=49.5 C, v=0.1 m/s, rh=32%, Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)



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

Figure 6 Tre from Kobayashi et al (1980) (n=5) (heavy work), Ta=Tr=49.5 C, v=0.1 m/s, rh=32%, Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)

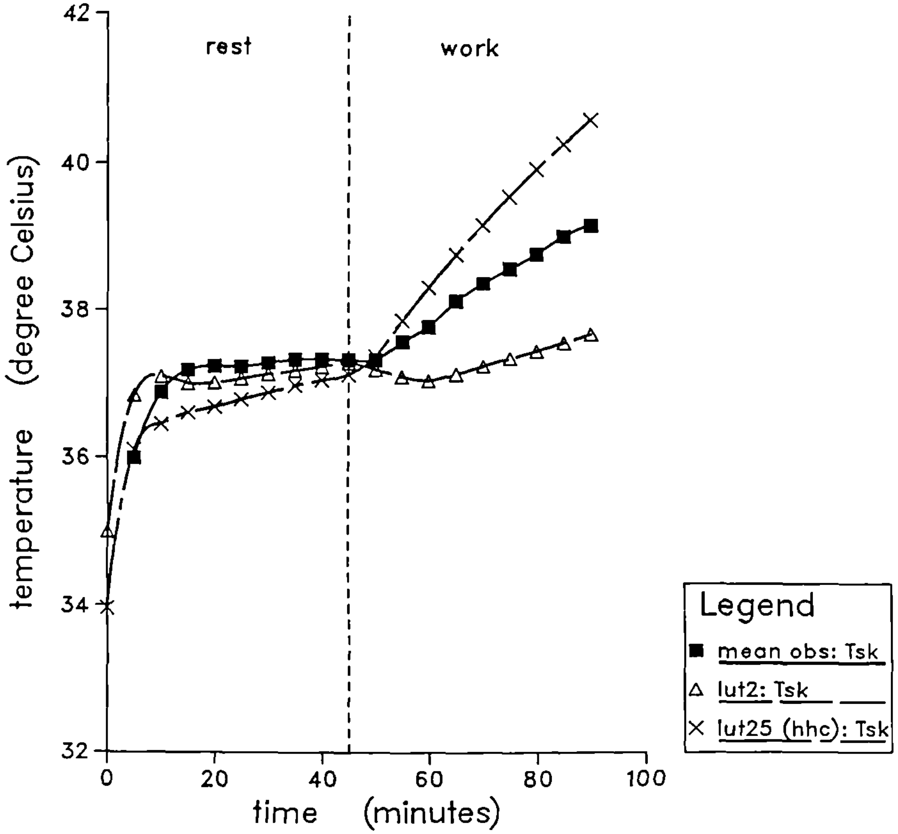


Figure 7 $\overline{T}sk$ from Kobayashi et al (1980) (n=5) (heavy work), Ta=Tr=49.5 C, v=0.1 m/s, rh=32%, lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=58 W/m2 (rest), M=306 W/m2, W=49 W/m2 (work)

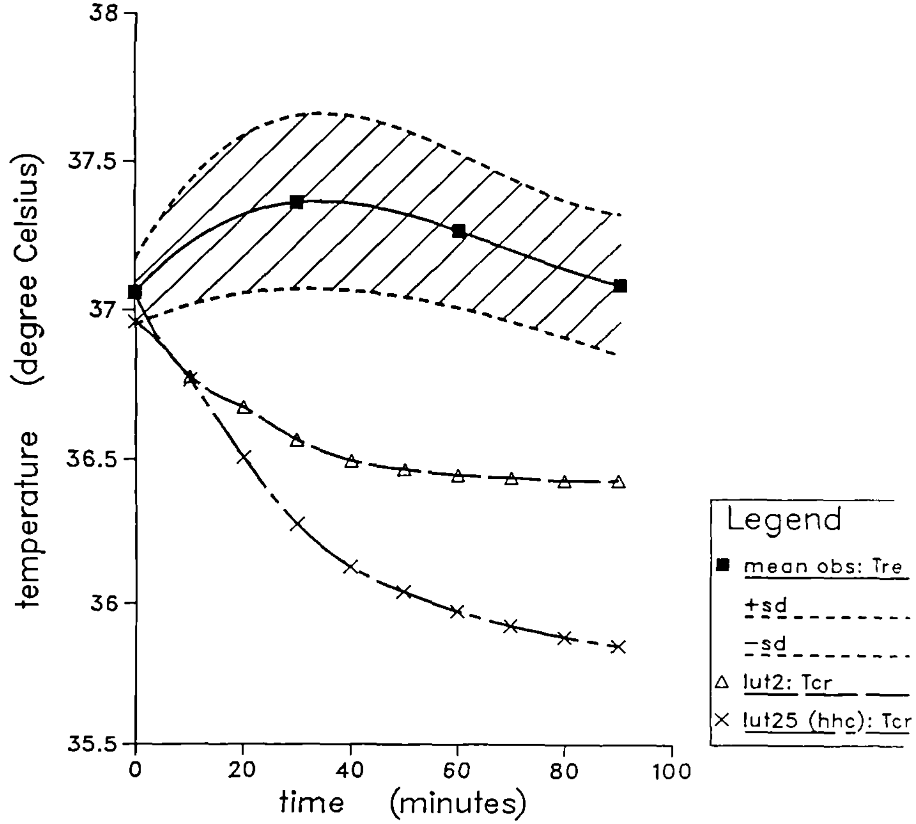


Figure 8 Tre from Young et al (1986) (n=7), Ta=Tr=5 C, v=0.1 m/s, rh=30%, lcl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m2, W=0 W/m2

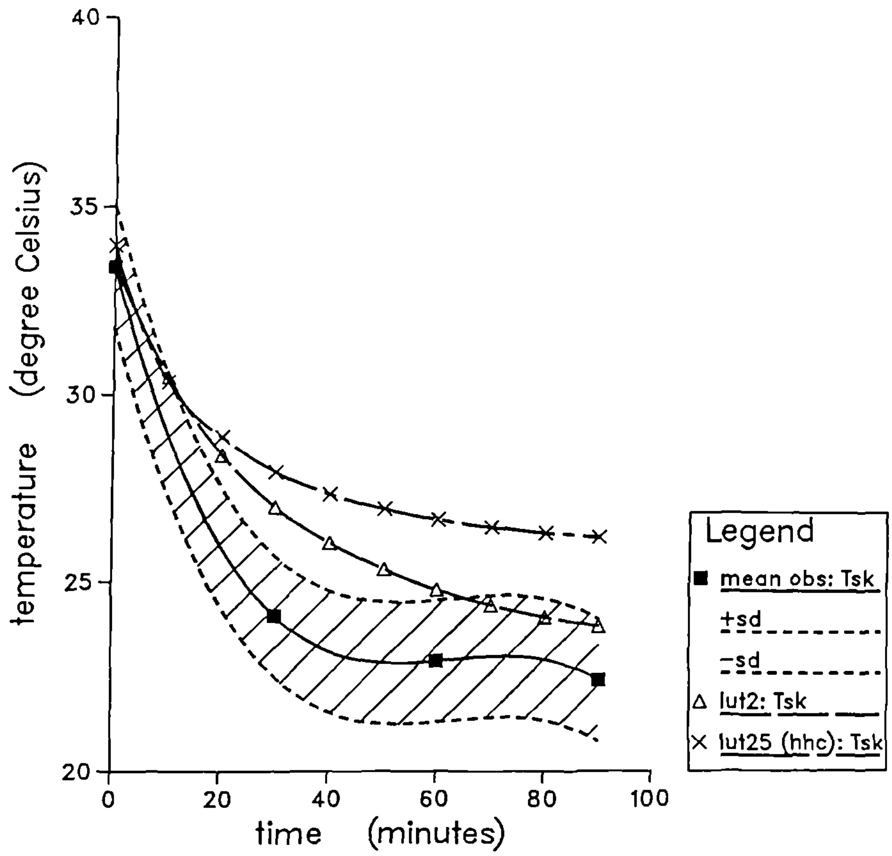


Figure 9 $\overline{T}sk$ from Young et al (1986) (n=7), Ta=Tr=5 C, v=0.1 m/s, rh=30%, Icl=0.1 clo, fcl=1 (ND), im=0.5 (ND), M=60 W/m2, W=0 W/m2

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 envirommental conditions.

However, we recognize that, depending on the nature of the model, the predictions may depend on the accuracy of the underlying simulation, inlcuding 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 wth 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.

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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.

Symbols used in this paper comply with those suggested by the International Union of Physiological Sciences (BLIGH, J., and JOHNSON, K. G. 1973, Glossary of terms for thermal physiology. *Journal of Applied Physiology*, **35**, 941–961).

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:

$$M = C + K + R + E + S + \text{Res}\ (\text{W/m}^2) \tag{1}$$

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:

$$C = h_c(\bar{T}_{sk} - T_a) \quad (\text{W/m}^2) \tag{2}$$

where:

h_c = convective heat transfer coefficient (W/m^2.°C)
$\bar{T}_{sk}$ = 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 1970 a). 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 (1970 a) is typical:

$$h_c = 8{\cdot}6\, v^{0{\cdot}53} \quad (\text{W/m}^2.°\text{C}) \tag{3}$$

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 1970 a). 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:

$$R = h_r(\bar{T}_{sk} - \bar{T}_r) \quad (\mathrm{W/m^2}) \tag{4}$$

where:

h_r = linear radiation heat transfer coefficient (W/m².°C)
$\bar{T}_r$ = mean radiant temperature (°C)

The linear radiation heat transfer coefficient (h_r) is defined (Gagge and Nishi, 1977) as:

$$h_r = 4\,.\,\sigma\,.\,(A_r/A_d)\,(T_{av})^3 \quad (\mathrm{W/m^2.{}^\circ C}) \tag{5}$$

where:

σ = Stefan Boltzman Constant
= $5{\cdot}67 \times 10^{-8}$ (W/m².k⁴)
A_r/A_d = fraction of skin surface involved in radiative heat exchange (ND)
$T_{av} = (\bar{T}_{surf} + \bar{T}_r)/2 + 273{\cdot}2$ (K)
$\bar{T}_{surf}$ = mean surface temperature (°C)

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:

$$E = h_e(\bar{P}_{sk} - P_a) \quad (\mathrm{W/m^2}) \tag{6}$$

where:

h_e = evaporative heat transfer coefficient (W/m².kPa)
$\bar{P}_{sk}$ = 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_c 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_c is known, h_e 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.

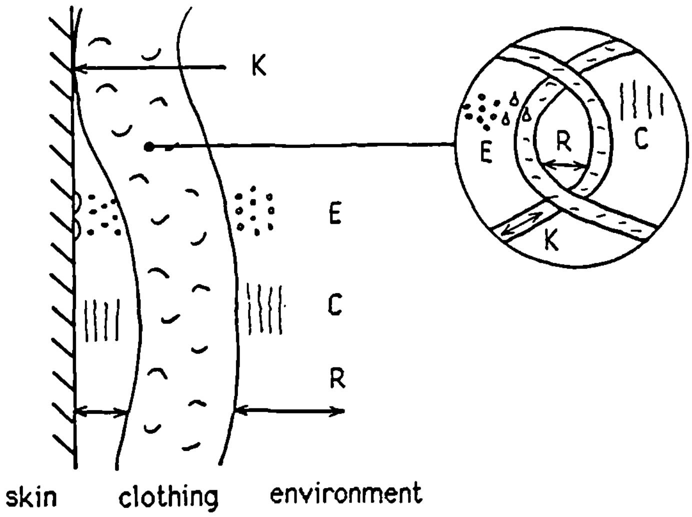

Figure 1. Heat transfer through clothing.

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

(Lotens and Linde 1983, and Renbourn and Rees 1972). 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_a = resistance of environment to dry heat transfer (m^2.°C/W) (7)

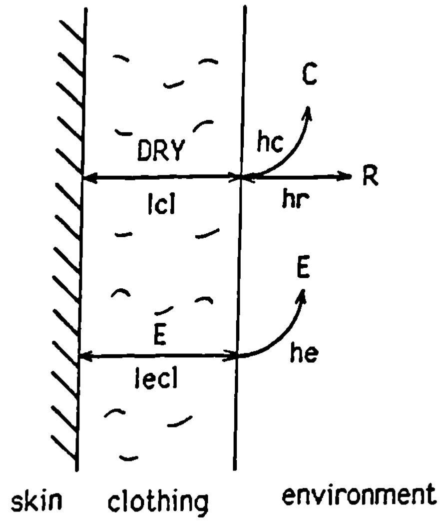

Figure 2. Simplified two-parameter description of heat transfer through clothing.

Also:

$$I_e = \frac{1}{h_e} \quad (\mathrm{m^2.kPa/W}) \tag{8}$$

where:

I_e = resistance of environment to evaporative heat transfer ($\mathrm{m^2.kPa/W}$)

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:

$$\mathrm{Dry} = \frac{(\bar{T}_{sk} - \bar{T}_{cl})}{I_{cl}} \quad (\mathrm{W/m^2}) \tag{9}$$

where:

Dry = dry heat transfer through clothing ($\mathrm{W/m^2}$)
I_{cl} = resistance of clothing to dry heat transfer ($\mathrm{m^2.°C/W}$)
$\bar{T}_{cl}$ = mean surface temperature of clothed body (°C)

and for the evaporative heat transfer:

$$E = \frac{(\bar{P}_{sk} - \bar{P}_{cl}}{I_{ecl}} \quad (\mathrm{W/m^2}) \tag{10}$$

where:

E = evaporative heat transfer through clothing ($\mathrm{W/m^2}$)
I_{ecl} = resistance of clothing to evaporative heat transfer ($\mathrm{m^2.kPa/W}$)
$\bar{P}_{cl}$ = 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:

$$C = h_c \cdot f_{cl}(\bar{T}_{cl} - T_a) \quad (\mathrm{W/m^2}) \tag{11}$$

$$R = h_r \cdot f_{cl}(\bar{T}_{cl} - \bar{T}_r)(\mathrm{W/m^2}) \tag{12}$$

$$E = h_e \cdot f_{cl}(\bar{P}_{cl} - P_a) \quad (\mathrm{W/m^2}) \tag{13}$$

where:

f_{cl} = clothing area factor

$$= \frac{\text{surface area clothed}}{\text{surface area nude}} \quad (\mathrm{ND})$$

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 I_{cl} and I_{ecl} 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_o) is an average of the air and mean radiant temperatures weighted by their respective heat transfer coefficients:

$$T_o = \frac{(h_c \cdot T_a + h_r \cdot \bar{T}_r)}{(h_c + h_r)} \quad (^\circ\mathrm{C}) \tag{14}$$

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:

$$\mathrm{Dry} = \frac{(\bar{T}_{sk} - T_o)}{I_a} \quad (\mathrm{W/m^2}) \tag{15}$$

where I_a is defined as above (equation 7).
When clothing is worn:

$$\mathrm{Dry} = \frac{(\bar{T}_{sk} - T_o)}{I_T} \quad (\mathrm{W/m^2}) \tag{16}$$

where:

I_T = total resistance of clothing and environment to dry heat transfer

$$= I_{cl} + \frac{I_a}{f_{cl}} \quad (\mathrm{m^2 \cdot ^\circ C/W}) \tag{17}$$

For the special case when the air and mean radiant temperatures are equal it can be shown that T_o is equal to T_a. T_a may therefore be substituted for T_o in equation 16.

Thus, for a clothed, dry manikin that has reached equilibrium in an environment where T_a and $\bar{T}_r$ are equal:

$$I_T = \frac{(\bar{T}_{sk} - T_a)A_d}{H} \quad (\mathrm{m^2.°C/W}) \tag{18}$$

where:

H = power input to manikin (W)
A_d = manikin surface area (m^2)

Equation 17 shows that in order to calculate I_{cl}, it is also necessary to know I_a and f_{cl}. I_a can be obtained by operating the manikin nude and f_{cl} can be estimated using photographic techniques (e.g., Fanger 1970, and Olesen *et al.* 1982).

Tabulated 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_{cl}, Fanger (1970) suggests the relationship:

$$f_{cl} = 1{\cdot}0 + 0{\cdot}15 \,.\, I_{cl} \quad (\mathrm{ND})$$

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_{cl} associated with a clothing ensemble. From a study on a large number of clothing ensembles McCullough *et al.* (1985) suggest a relationship of:

$$f_{cl} = 1{\cdot}0 + 0{\cdot}31 \,.\, I_{cl} \quad (\mathrm{ND})$$

However, they emphasize that the relationship between f_{cl} and I_{cl} is poor. Wherever possible measured values of f_{cl} 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_{cl}) and effective insulation (I_{cle}). I_T and I_{cl} are as defined above; the effective clothing insulation is defined as:

$$I_{cle} = I_T - I_a \quad (\mathrm{m^2.°C/W}) \tag{19}$$

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_{cl} is more convenient than I_{cle} for use in heat transfer analysis but requires that f_{cl} is known or can be estimated. I_T varies with the environmental conditions. If I_{cle} or I_T and the conditions under which they were measured are known for a clothing ensemble, then it is possible to estimate I_{cl} 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 $= 0{\cdot}155\ m^2.°C/W$ (Gagge *et al.* 1941).

5.2. *Resistance of clothing to evaporative heat transfer*

The resistance of clothing to evaporative heat transfer (I_{ecl}) 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:

$$E = \frac{(\bar{P}_{sk} - P_a)}{I_{eT}} \quad (W/m^2) \tag{20}$$

where:

I_{eT} = total resistance of clothing and environment to evaporative heat transfer

$$= I_{ecl} + \frac{I_e}{f_{cl}} \quad (W/m^2) \tag{21}$$

I_{ecl} 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_{eT} 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_{ecl}.

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:

$$E = \frac{16{\cdot}5 \, . \, i_m}{I_T}(\bar{P}_{sk} - P_a) \quad (W/m^2) \tag{22}$$

where:

i_m = the moisture permeability index

$$= \frac{h_{eT}/h_T}{h_e/h_c} \quad (ND) \tag{23}$$

where:

h_T = the total dry heat transfer coefficient for the clothing and environment

$$= \frac{1}{I_T} \quad (\mathrm{W/m^2.{}^\circ C})$$

h_{e_T} = the total evaporative heat transfer coefficient for the clothing and air system $(\mathrm{W/m^2.kPa})$

$$= \frac{1}{I_{e_T}} \quad (\mathrm{W/m^2.kPa})$$

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. $\bar{P}_{sk}$ and P_a can be calculated from $\bar{T}_{sk}$, 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, $\bar{T}_r$, $\bar{T}_{sk}$, v etc. prevailing when they were measured.

5.4. *Nishi permeation efficiency factor*

Nishi and Gagge (1970 b) introduced a factor (F_{pcl}) to describe the resistive effects of clothing on evaporative heat transfer, so that the equation for E becomes:

$$E = F_{pcl} \cdot h_e(\bar{P}_{sk} - P_a) \quad (\mathrm{W/m^2}) \tag{24}$$

where:

F_{pcl} = permeation efficiency factor

$$= \frac{I_e}{I_{ecl} + I_e} \quad (\mathrm{ND}) \tag{25}$$

Nishi and Gagge (1970 b) 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:

$$F_{pcl} = \frac{1}{1 + 0{\cdot}92 . h_c . I_{cle}} \quad (\mathrm{ND}) \tag{26}$$

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_{pcl} 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:

$$i_L = \frac{h_{ecl}/h_{cl}}{h_e/h_c} \quad \text{(ND)} \tag{27}$$

where:

$$h_{cl} = \frac{1}{I_{cl}} \quad (\text{W/m}^2.\,^\circ\text{C}) \quad \text{and} \quad h_{ecl} = \frac{1}{I_{ecl}} \quad (\text{W/m}^2.\text{kPa})$$

The equation for evaporative heat transfer can then be expanded to:

$$E = \frac{(\bar{P}_{sk} - P_a)}{\dfrac{I_{cl}}{16{\cdot}5\,.\,i_L} + \dfrac{1}{f_{cl}}} \quad (\text{W/m}^2) \tag{28}$$

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:

$$i_{mL} = \frac{h_{eT}/h_{cT}}{h_e/h_c} \quad \text{(ND)} \tag{29}$$

where:

h_{cT} = the total dry non-radiative heat transfer coefficient for the clothing and air system (W/m^2.°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_{ecl} from i_m, F_{pcl} or i_L

If i_m or F_{pcl} and the conditions under which they were measured or i_L are known for a clothing ensemble, then it is possible to calculate I_{ecl} from these factors.

At present the literature contains few reported values of F_{pcl} or i_L and only the method for calculating I_{ecl} from i_m will be derived here.

Substituting I_{eT} in equation 20 with equation 21, equating with equation 22 and rearranging gives:

$$I_{ecl} = \frac{I_T}{16{\cdot}5\,.\,i_m} - \frac{I_e}{f_{cl}} \quad (\text{m}^2.\text{kPa/W}) \tag{30}$$

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_a (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_r (the linear radiation heat transfer coefficient) component from I_a; h_r is in turn dependent on $\bar{T}_{cl}$ (the mean surface temperature) and $\bar{T}_r$ (the mean radiant temperature). $\bar{T}_{cl}$ is not usually measured, but both h_r and $\bar{T}_{cl}$ 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_{cl} 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

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_{cl} 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_c and h_e. 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_{ecl}. While suitable data exist for I_{cl} for a varied range of clothing ensembles, little data are available for I_{ecl}. However, as described above, I_{ecl} may be calculated from i_m for which some data are available.

8. An example application: ISO/DIS 7933 (1987)

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_{cle}) and the Nishi permeation efficiency factor (F_{pcl}) to describe the insulative effects of clothing. The factor F_{pcl} 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_{cl}), the clothing area factor (f_{cl}), and the Woodcock moisture permeability index (i_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_{pcl}.

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 $I_T = 1{\cdot}33$ clo, $I_{cl} = 0{\cdot}77$ clo, $f_{cl} = 1{\cdot}26$ (ND) and $i_m = 0{\cdot}40$ (ND). From these, the effective clothing insulation can be calculated as being $I_{cle} = 0{\cdot}61$ clo. The metabolic rate of 175 W/m^2 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_{pcl} respectively. The prediction of the published version of the model for unacclimatized subjects, with the calculation of F_{pcl} 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.

	Allowable exposure times (DLE) (mins)			
	Warning non-accl. subject	Danger non-accl. subject	Warning accl. subject	Danger accl. subject
ISO/DIS 7933 (1987) (using 0·92 coeff.)	300	355	426	480
ISO/DIS 7933 (1987) (using 2·22 coeff.)	94	155	300	364
Loughborough revised version	46	55	70	87

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

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          Loughborough University of Technology

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                      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                      : Veff =    0.86 (m/s)
Partial Vapour Pressure                     : Pa   =    1.69 (kPa)
Mean Skin Temperature                       : Tsk  =   36.00 (C)
Saturated Vapour Pressure on Skin           : Psk  =    5.94 (kPa)
Metabolic Heat Production                   : Mh   =  175.00 (W/m2)
Convective Heat Transfer Coefficient        : Hc   =    7.96 (W/m2.C)
Linear Radiation Heat Transfer Coefficient  : Hr   =    5.11 (W/m2.C)
Mean Clothing Surface Temperature           : Tcl  =   39.22 (C)
Intrinsic Evaporative Clothing Resistance   : Iecl =    0.02 (m2.kPa/W)
Total Evaporative Clothing Resistance       : IeT  =    0.03 (m2.kPa/W)
Convective Heat Transfer                    : C    =   42.38 (W/m2)
Radiation Heat Transfer                     : R    =  -69.39 (W/m2)
Required Evaporative Cooling                : Ereq =  202.01 (W/m2)
Maximum Evaporative Capacity of Environment: Emax =  161.01 (W/m2)
Required Skin Wettedness                    : Wreq =    1.25 (ND)
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Interpretation, Single Exposure:

Danger: Acclimatized Subject

Predicted Skin Wettedness   : Wp =   1.00 (ND)
Predicted Evaporation Rate : Ep =  161.01 (W/m2)
Predicted Sweat Rate        : Sp =  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   : Wp =   0.99 (ND)
Predicted Evaporation Rate : Ep =  159.42 (W/m2)
Predicted Sweat Rate        : Sp =  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   : Wp =   0.85 (ND)
Predicted Evaporation Rate : Ep =  136.86 (W/m2)
Predicted Sweat Rate        : Sp =  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   : Wp =   0.85 (ND)
Predicted Evaporation Rate : Ep =  136.86 (W/m2)
Predicted Sweat Rate        : Sp =  200.00 (W/m2) =  294.12 (g/h.m2)

Body Temperature Increase      DLE =  46 mins
                                   =   0 h  46 mins
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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.

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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 monter l'effet que peut avoir, sur les prédictions, les différentes méthodes de prise en compte de propriétés isolantes du vêtement.

Modelle, die die menschliche Reaktion auf die thermische Umgebung vorhersagen, müssen in der Lage sein, die Isolationswirkung der Kleidung adäquat zu erklären, um von praktischem Nutzen zu sein. Der Mechanismus des Wärmetransfers zwischen dem menschlichen Körper und der Umgebung sowie der Widerstands-Effekt der Kleidung auf diesen Wärmetransfers werden besprochen. Die weit verbreitete Zwei-Parameter Methode zum Quantifizieren des Widerstandes der Kleidung für den trockenen und den Verdunstungs-Wärmetransfer wird beschrieben und die Randbedingungen dieser Beschreibung werden angeführt. Es wird jedoch die Meinung vertreten, daß nicht genug Informationen existieren, um zu erlauben, daß andere, mehr komplexere Modelle in einer praktischen Anwendung benutzt werden. Bis weitere Informationen verfügbar sind, existieren genügend Daten für die Zwei-Parameter Beschreibung, um deren Benutzung durch die Modelle der menschlichen Reaktion zu ermöglichen.

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.

熱環境に対する人間の反応を予測するモデルは実用になるには，衣服の保温効果を適切に考慮する必要がある。人体と環境間の熱伝達機構とこの熱伝達に対する衣服の抵抗を考察する。乾燥，蒸発的熱伝達に対する衣服の抵抗を数量化するのに多用されている二母数法を述べ，本方法の限界に触れる。しかし，他のより複雑な方法を実用できるだけの情報が今のところないと言える。そのような情報が得られるまでは，二母数法を人間反応のモデルで使用するのに十分なデータが存在する。ＩＳＯ／ＤＩＳ 7933モデルの予測値の例をあげて，衣服の保温効果を記述する異なる方法がモデルの予測値に与える影響を実証する。