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

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by

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ABSTRACT

Influential models, capable of predicting human responses to hot and cold environments and potentially suitable for use in practical applications, have been identified and implemented in usable forms onto computers. Six models have been evaluated: the Gagge and Nishi 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, the ISO/DIS 7933 analytical determination and interpretation of thermal stress using calculation of required sweat rate model, the Ringuest 25-node model of human thermoregulation, and the Wissler 225-node model of human thermoregulation. A preliminary evaluation enabled the Ringuest and Wissler models to be eliminated from further investigation. In the case of the Ringuest model this was because of its poor predictions, and for the Wissler model because of practical difficulties with its implementation and use. The remaining models were modified to quantify the insulative effects of clothing by the method considered to be most appropriate, given the current state of knowledge. The modified versions of the models were evaluated by comparing their predictions with human data published previously in the literature. Experimental data were available for a wide range of environmental conditions, with air temperatures ranging from -10 to 50 °C, and with different levels of air movement, humidity, work and clothing. Data for a total of 590 subject exposures were used. The experimental data were grouped into environment categories to enable effects such as the influence of wind or clothing, on the accuracy of the models' predictions to be examined. This categorization also enables advice to be given as to which model is likely to provide the most accurate predictions for a particular combination of environmental conditions. For the majority of environment categories, for which evaluation data were available, at least one of the models was able to predict to an accuracy comparable with the degree of variation that occurred within the data from the human subjects. It may be concluded from the evaluation that it is possible to accurately predict deep body and mean skin temperature responses to cool, neutral, warm and hot environmental conditions. The models' predictions of deep body temperature in the cold are poor. Overall, the 25-node model probably provided the most accurate predictions. The 2-node model was often accurate, but could be poor for exercise conditions. The rectal temperature model usually overestimated deep body temperature, except for very hot or heavy exercise conditions, where its predictions were reasonable. The ISO model's allowable exposure times were often acceptable, but would not have protected subjects for some exercise conditions.

STATEMENT

Sections of the research presented in this thesis were conducted for the Army Personnel Research Establishment (agreement 2170/106) and have been published by Loughborough University of Technology as a series of reports. These sections are incorporated here with the permission of the Ministry of Defence. The author was responsible for the planning and execution of all of the research presented in this thesis.

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LIST OF SYMBOLS AND ABBREVIATIONS[1]

Ab	body surface area	(m^2)
Ah&h	surface area of head and hands	(m^2)
Am	manikin surface area	(m^2)
Ar/Ab	fraction of radiative skin surface	(ND)
C	convective heat transfer	(W/m^2)
CET	corrected effective temperature	(°C)
Cres	respiratory convective heat transfer	(W/m^2)
C+R	total dry heat transfer	(W/m^2)
cb	specific heat of blood	(J/kg.°C)
Cb	blood convective heat transfer	(W/m^2)
Dry	dry heat transfer through clothing	(W/m^2)
d	thickness or distance	(m)
E	evaporative heat transfer	(W/m^2)
Emax	maximum evaporative capacity of environment	(W or W/m^2)
Ereq	required evaporative cooling	(W or W/m^2)
Eres	respiratory evaporative heat transfer	(W/m^2)
Esk	skin evaporative heat transfer	(W/m^2)
ET	effective temperature	(°C)
ET*	revised effective temperature	(°C)
Fpcl	permeation efficiency factor	(ND)
fcl	clothing area factor	(ND)
Hr+c	sensible environmental heat load	(W)
HSI	heat stress index	(ND)
hc	convective heat transfer coefficient	(W/m^2.°C)
hcl	dry heat transfer coefficient for clothing	(W/m^2.°C)
he	evaporative heat transfer coefficient	(W/m^2.kPa)

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[1]The symbols and abbreviations used have been chosen to comply with those suggested by the International Union of Physiological Sciences (1987).

hecl	evaporative heat transfer coefficient for clothing	($W/m^2.kPa$)
heT	total evaporative heat transfer coefficient for clothing and environment	($W/m^2.kPa$)
hr	linear radiation heat transfer coefficient	($W/m^2.°C$)
hT	total dry heat transfer coefficient for clothing and environment	($W/m^2.°C$)
Ia	resistance of environment to dry heat transfer	(clo)
Icl	resistance of clothing to dry heat transfer (intrinsic clothing insulation)	(clo)
Icle	effective clothing insulation	(clo)
Icl'	resistance of clothing to dry heat transfer applying to the clothed area of the body	(clo)
Ie	resistance of environment to evaporative heat transfer	($m^2.kPa/W$)
Iecl	resistance of clothing to evaporative heat transfer	($m^2.kPa/W$)
IeT	total resistance of clothing and environment to evaporative heat transfer	($m^2.kPa/W$)
IREQ	required clothing insulation index	(clo)
IT	total resistance of clothing and environment to dry heat transfer (total clothing insulation)	(clo)
ITS	index of thermal stress	(W/m^2)
IT'	total resistance of clothing and environment to dry heat transfer applying to the clothed area of the body	(clo)
iL	permeation ratio	(ND)
im	moisture permeability index	(ND)
imL	permeation ratio	(ND)
K	heat transfer by conduction	(W/m^2)
k	thermal conductivity	($W/m^2.°C$)
l	length	(m)
M	metabolic rate	(W or W/m^2)
Mnet	metabolic heat load	(W)

m	weight change due to sweat evaporation	$(g/hr.m^2)$
Pa	partial pressure of water vapour in air	(kPa)
Pcl	partial pressure of water vapour at clothing surface	(kPa)
Psat	saturated water vapour pressure	(kPa)
Psk	partial pressure of water vapour at skin	(kPa)
P4SR	predicted four hour sweat rate	(l)
R	heat transfer by radiation	(W/m^2)
rh	relative humidity	(ND)
rmsd	root mean square deviation	$(°C$ or $W/m^2)$
r1	radius	(m)
r2	radius	(m)
S	heat storage	(W/m^2)
SET	standard effective temperature	(°C)
Ta	air temperature	(°C)
Tac	auditory canal temperature	(°C)
Tart	arterial blood temperature	(°C)
Tav	(Tsurf + Tr)/2 + 273.2	(K)
Tax	axillary temperature	(°C)
Tb	blood temperature	(°C)
Tcl	mean clothing surface temperature	(°C)
Tcr	deep body temperature	(°C)
Td	temperature at material surface	(°C)
Tft	foot skin temperature	(°C)
Tga	gastrointestinal temperature	(°C)
Thd	hand skin temperature	(°C)
To	operative temperature	(°C)
Toe	oesophageal temperature	(°C)
Tr	mean radiant temperature	(°C)
Tre	rectal temperature	(°C)

Tref	final equilibrium rectal temperature	(°C)
Tsb	sublingual temperature	(°C)
Tsk	mean skin temperature	(°C)
Tsurf	mean surface temperature	(°C)
Tt	tissue temperature	(°C)
Tty	tympanic temperature	(°C)
T1	temperature	(°C)
T2	temperature	(°C)
v	air speed	(m/s)
v	volumetric flow rate	(m^3/s)
W	external work	(W or W/m^2)
WBGT	wet bulb globe temperature	(°C)
WCI	wind chill index	(ND)
WGT	wet globe thermometer temperature	(°C)
w	skin wettedness	(ND)
wreq	required skin wettedness	(ND)
ε	emissivity	(ND)
λ	latent heat of vaporization	(J/g)
ρ	density	(kg/m^3)
σ	Stefan Boltzman constant	(W/m^2.K4)

CHAPTER 1

1. INTRODUCTION

The exposure of personnel to extreme heat or cold is unavoidable in certain industrial and military situations. For example, industrial engineers work within the confines of decommissioned nuclear reactors that have not fully cooled down, in order to perform routine maintenance operations (Featherstone, 1988). Engine room personnel on ships may be subject to high levels of heat stress when performing emergency repair work (Collins et al., 1971). Firemen perform duties that often involve strenuous exercise, while wearing heavy impermeable clothing, and exposure to high levels of heat (Mawby and Street, 1985). At the other extreme, food preparation and storage workers may have to spend periods of time handling cold materials or working inside refrigeration units (Nielsen, 1986; and Williamson et al., 1984).

Military personnel may be required to work in hot dry desert conditions (Kerstein et al., 1984) or the hot humid tropics (Macpherson, 1960). Crew in military aircraft may be subject to high heat loads from equipment and solar radiation (Richardson, 1988). Servicemen engaged in the 1982 Falkland Islands campaign had to contend with cold wet climatic conditions (McCaig and Gooderson, 1986).

The effects of heat and cold on human responses may be examined in several ways, with laboratory trials and field studies being the usual methods of investigation. However, these procedures are expensive and it is difficult to investigate the extremes of human tolerance because of ethical considerations. Recently a number of sophisticated computer based models have been developed that are capable of predicting human responses to the thermal environment. If accurate, these models provide a useful alternative to laboratory trials and field studies and this potential is already being exploited by computer based advice systems (Symington and Warren, 1989; and Wadsworth and Parsons, 1988 and 1989).

This thesis is concerned with the identification, implementation and evaluation of models capable of predicting human responses to hot and cold environments.

1.1. Effects of Heat and Cold

Extreme thermal conditions can affect a person's health and performance and may cause great discomfort. It has long been realized that hyperthermia or hypothermia may result in serious illness and death (e.g. Burton and Edholm, 1955; Collins, 1983; Edholm, 1978; Kerslake, 1972; and Leithead and Lind, 1964). Tactile sensitivity and manual dexterity are known to be reduced in the cold (Enander, 1984; and Fox, 1967). Although controversial, there is some evidence to suggest that performance at certain cognitive and psychomotor tasks is reduced in both the heat (Hancock, 1980a; Wilkinson et al., 1964; and Wing, 1965) and the cold (Enander, 1984 and 1987; and Fox, 1967). 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; and Gagge et al., 1967).

1.2. Thermal Indices

Attention has been focused for many years on predicting how long extreme environments may be tolerated without risk to health or performance. The origins of the sophisticated computer based models of human response to the thermal environment may be traced back to the early indices developed at the beginning of this century.

Several environmental and subject parameters affect human response to the thermal environment: air temperature, the radiant temperature of the surroundings, air movement, air humidity, the resistance of the subject's clothing to dry and evaporative heat transfer, and the subject's activity level. Thus, an index of the thermal conditions should take account of the parameters that significantly affect the human response to the type of environment of interest.

1.2.1. Thermometric and Physical Indices

One of the simplest indicators of potential environmental stress is air temperature and it has been used for many years to indicate how hot or cold a climate is likely to feel. An advance was made when the use of the wet bulb thermometer was suggested by Haldane (1905) as an indicator of the physiological effects of hot environments. Other thermometric indices developed since include Kata thermometer cooling time (Hill et al., 1916), Wind Chill Index (WCI, Siple and Passel, 1945), Wet Bulb Globe Temperature (WBGT, Yaglou and Minard, 1957), and the Wet Globe Thermometer temperature (WGT, Botsford, 1971) also known as the Botsball.

The advantage of the thermometric indices lies in their simplicity, as they are very convenient for use in practical applications. Conversely, their simplicity is also a disadvantage. The most widely used of the thermometric heat stress indices is the WBGT, which has now been adopted as an International Standard (ISO, 1982). While the simplicity, and ease of use of the WBGT are recognized as being major advantages, its widespread use has been criticized as it is not affected by combinations of environmental variables in the same way as humans (Azer and Hsu, 1977, Gagge and Nishi, 1976; Kerslake, 1972 and 1982; and Lotens, 1985).

The Wind Chill Index is probably the best known cold stress index, as it is often reported by television and radio weather forecasters during the winter months. The index relates to the rate of cooling of water in a suspended cylinder. However, the WCI has been criticized on theoretical grounds as being inappropriate for clothed subjects (Burton and Edholm, 1955; and Kaufman and Bothe, 1986). Nevertheless, the index is appropriate to exposed areas of the skin and has proved useful in preventing frostbite (Kerslake, 1982).

1.2.2. Subjective and Physiological Indices

Other indices that relate more directly to the human experience of environmental conditions have also been developed. The Effective Temperature (ET) scale put forward by Houghten and Yagloglou (1923) was based on judges' subjective feelings of equivalent warmth between a test and a reference environment. A modification to the Effective

Temperature scale was suggested by Vernon and Warner (1932), in order to correct for radiative heat loads, and the revised scale became known as Corrected Effective Temperature (CET). However, the ET and CET scales do not necessarily predict the physiological effects of environmental conditions, and the prediction of sensation is based on the instantaneous impressions of subjects passing backwards and forwards between test and reference environments, and not on their sensations after a period of exposure (Leithead and Lind, 1964; and Kerslake, 1972).

McArdle et al. (1947) suggested the use of the Predicted Four Hour Sweat Rate (P4SR) as a heat stress index, to counter some of the limitations of ET. The P4SR uses the notion that the amount of sweating correlates well with the severity of the environmental conditions in the heat, and was developed using a large body of empirical data. While Leithead and Lind (1964) concluded from a review of the literature that the P4SR is one of the more accurate heat stress indices, Kerslake (1972) points out that because of its empirical nature, its strict application is limited.

1.2.3. Rational Indices

Another approach to the assessment of human response to the thermal environment has been the development of rational indices that are based on the heat exchanges between the human body and the environment. Probably the first rational index was the operative temperature of Winslow et al. (1937). Operative temperature is an average of air and mean radiant temperatures, weighted by the convective and linear radiation heat transfer coefficients. Subsequently the Heat Stress Index (HSI) of Belding and Hatch (1955) and the Index of Thermal Stress (ITS) of Givoni (1962, 1963) were proposed. Both indices construct and solve an equilibrium heat balance equation. The HSI is the ratio of the required evaporative cooling (Ereq) to the maximum evaporative capacity of the environment (Emax). The ITS goes a stage further and uses the ratio of Ereq to Emax to predict the sweat rate required for thermal equilibrium. A modified version of this approach, based on the work of Vogt et al. (1981, 1982) predicts allowable exposure times to given combinations of environmental conditions, and has recently been published as a Draft International Standard (ISO, 1987).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers have adopted an index known as the Revised Effective Temperature (ET*), which is based on a two compartment model of human thermoregulatory control and response (Gagge et al., 1971). ET* is the dry bulb temperature of a uniform thermal environment, with still air, a relative humidity of 50%, a standard clothing insulation of 0.6 clo and with a sedentary activity level, that would result in the same heat exchanges, mean skin temperature and skin wettedness as in the actual environment. A modified version of this index has also been developed, known as the Standard Effective Temperature (SET), which allows for different levels of clothing and activity (Gagge et al., 1972; and Nishi and Gagge, 1977). The thermoregulatory model is used to predict the heat exchanges and body temperatures necessary to calculate ET* or SET, and therefore the accuracy of the index depends on the accuracy of the model's predictions. There is little published evidence validating the model.

Using a rational approach for cold environmental conditions, Holmér (1984 and 1988) has proposed the Required Clothing Insulation (IREQ) index. IREQ uses the minimal clothing insulation required to maintain an adequate thermal balance as its index value.

1.3. Computer Based Models of Human Response to the Thermal Environment

While most of the indices described above have proved useful they each have their limitations. The simplest indices are only applicable to narrow categories of environmental exposure, and many of the more complex indices are not appropriate to all conditions. For example, in severe environments it may not be possible for the human body to achieve a state of thermal equilibrium; all of the rational indices described above base their heat transfer calculations on the assumption that equilibrium has been reached. In addition, although it may be possible to experimentally relate an index value to human health, comfort or performance, the degree of precision is low and it may be difficult to extrapolate to previously unencountered situations.

The physiological responses to thermal environments that affect health, comfort and performance are either related to or are the temperatures of the body tissues. With the advance of computing technology over the past thirty years it has been possible to set up computer programs to make the complex calculations necessary to predict body temperature and other physiological responses, such as sweating or shivering, on exposure to a set of environmental conditions. Consequently a large number of computer based models have been proposed in the literature (see the recent review by Richardson, 1985a, for example). It is clear that if these models are capable of predicting temperature changes and other thermoregulatory responses accurately, they would have many potential applications. Unfortunately, published validation of these models is scarce.

1.4. Aims

The aim of the research presented in this thesis was to identify and implement models capable of predicting human responses, such as deep body and skin temperature changes, to hot and cold conditions and to evaluate the accuracy of their predictions by comparing them with the responses of human subjects.

The study has been confined to human responses to sea-level air environments; exposure to hypobaric, hyperbaric or water immersion conditions have not been considered.

CHAPTER 2

2. HUMAN THERMOREGULATION

Human thermoregulation depends on four processes: the physical transfer of heat between the body and the environment, the physical transfer of heat within the body, the physiological effector mechanisms used by the body to influence the physical heat exchanges, and the regulating system that controls these effector mechanisms. These four processes are discussed below.

2.1. Heat Transfer Between the Nude Human Body and an Air Environment

The discussion here is confined to the nude case. The insulative effects of clothing on the physical heat exchanges are discussed in chapter 5.

The mechanisms of heat transfer between the human body and the environment are well understood (e.g. Burton and Edholm, 1955; Gagge and Nishi, 1977; Hardy, 1949; Kerslake, 1972; McIntyre, 1980; Monteith, 1973; and Winslow and Herrington, 1949). Heat is exchanged by convection (C), conduction (K), radiation (R), and evaporation (E). The human body produces metabolic heat, which is equal to the metabolic rate (M), less a subtraction for any external mechanical work that is accomplished (W). 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 a net heat storage (S). Thus, a heat balance equation may be constructed:

$$S = M - W - C - K - R - E \quad (W/m^2) \qquad (2.1)$$

With the exception of M, the terms in equation 2.1 may be positive or negative, that is representing either losses or gains.

The convective and evaporative heat exchanges are made up of transfers at the skin and exchanges due to respiration. Whereas it has been customary to partition the evaporative heat exchanges into those of the skin (Esk) and respiratory tract (Eres), the convective heat transfer due to respiration (Cres) is usually ignored as it is negligible in comparison to the skin convective heat exchange.

As heat production and transfer vary with an individual's size, it is convenient to express these in relation to unit surface area (i.e. W/m^2 rather than W). Body surface area (Ab) may be estimated using formulae such as those of DuBois and DuBois (1916) or Jones et al. (1985).

2.1.1. Heat Transfer by Convection

Heat transfer by convection between the skin surface and air may be described by the equation:

$$C = hc\ (Tsk - Ta) \quad (W/m^2) \qquad (2.2)$$

where:

hc = convective heat transfer coefficient ($W/m^2.°C$)

Tsk = mean skin temperature (°C)

Ta = air temperature (°C)

The theoretical determination of the convective heat transfer coefficient (hc) 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 hc for forced convection conditions in air, for a range of air speeds and body postures (e.g. Colin and Houdas, 1967; Mitchell et al., 1969; and Nishi and Gagge, 1970a). The findings of these experiments have often been expressed as equations that are the product of the air speed raised to a fractional power and a constant, in view of the theoretical expectation (Kerslake, 1972). The formula of Nishi and Gagge (1970a) is representative:

$$hc = 8.6 \cdot v^{0.53} \quad (W/m^2.^\circ C) \qquad (2.3)$$

where:

v = air speed (m/s)

Thus, hc may be estimated if the air speed is known. There are also experimental equations that determine hc as a function of the subject's activity, for example Gagge et al. (1976):

$$hc = 5.66\ (M/58.2 - 0.85)^{0.39} \quad (W/m^2.^\circ C) \qquad (2.4)$$

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.

Values of hc for natural convection conditions are available in the literature (e.g. Nishi and Gagge, 1970a) and are typically around 3.0 $W/m^2.^\circ C$.

2.1.2. Heat Transfer by Conduction

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. Where heat transfer by conduction is significant and the steady state has been reached (adapted from Cornwell, 1977):

$$K = \frac{k}{d}(Tsk - Td) \quad (W/m^2) \qquad (2.5)$$

where:

k = thermal conductivity of material in contact with the skin (W/m.°C)

d = thickness of material (m)

Td = temperature at material surface (°C)

2.1.3. Heat Transfer by Radiation

Heat transfer by radiation between the skin and environment is related to the difference between the fourth powers of the absolute temperatures of the radiating surfaces:

$$R = \sigma \cdot \varepsilon \, (Ar/Ab)[(Tsk + 273)^4 - (Tr + 273)^4] \quad (W/m^2) \qquad (2.6)$$

where:

σ = Stefan Boltzman Constant

= 5.67×10^{-8} (W/m².K4)

ε = emissivity of skin (0.97) (ND)

Ar/Ab = fraction of skin surface involved in radiative heat exchange (ND)

Tr = mean radiant temperature (°C)

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:

$$R = hr\ (Tsk - Tr) \quad (W/m^2) \qquad (2.7)$$

where:

hr = linear radiation heat transfer coefficient ($W/m^2.°C$)

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

$$hr = 4 \cdot \sigma \cdot (Ar/Ab)\ (Tav)^3 \quad (W/m^2.°C) \qquad (2.8)$$

where:

Tav = (Tsurf + Tr)/2 + 273.2 (K)

Tsurf = mean surface temperature (°C)

(Tsurf = Tsk when nude)

Thus, hr 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 Ar/Ab, from experiments using optical methods.

2.1.4. 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:

$$Esk = w \cdot he\,(Psk - Pa) \quad (W/m^2) \qquad (2.9)$$

where:

w = skin wettedness (ND)

he = evaporative heat transfer coefficient ($W/m^2.kPa$)

Psk = mean partial pressure of water vapour at the skin (kPa)

Pa = partial pressure of water vapour in the air (kPa)

Skin wettedness (w) is the ratio of the skin surface area covered with sweat to the total skin surface area. For the theoretical case where w=1 (i.e. the skin surface area completely covered with sweat), Esk is the maximum evaporative capacity of the environment (Emax). It is not possible to measure w directly and it is therefore not possible to obtain Esk using equation 2.9. However, Esk can be determined from the rate of weight change due to the evaporation of sweat:

$$Esk = \frac{m}{3600} \cdot \lambda \quad (W/m^2) \qquad (2.10)$$

where:

m = rate of weight change due to the evaporation of sweat ($g/hr.m^2$)

λ = latent heat of vaporization of sweat (J/g)

Changes in weight loss due to the evaporation of sweat may be obtained by measuring body weight and making appropriate adjustments for sweat that has dripped or been absorbed by clothing and for weight changes due to respiratory gas exchanges. The latent heat of vaporization of sweat may be taken as being that of water, which is 2450 J/g (McIntyre, 1980).

Psk is the saturated vapour pressure of air at skin temperature and may be obtained from steam tables or calculated using a formula such as that of Antoine (cited by Gagge et al., 1976), substituting Tsk for Ta:

$$Psat = 0.1333 \cdot e^{(18.6686 - 4030.183/(Ta + 235))} \quad (kPa) \quad (2.11)$$

where:

Psat = saturated vapour pressure of air at Ta (kPa)

Using equation 2.11 and the relative humidity (rh) as a fraction, Pa may be calculated:

$$Pa = rh \cdot Psat \quad (kPa) \quad (2.12)$$

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 he to hc is nearly constant and is equal to 16.5 °C/kPa at 25 °C. This ratio is known as the Lewis relation. Therefore, if hc is known, he may be calculated.

2.1.5. Heat Exchanges due to Respiration

The heat exchanges due to respiration have been considered by Fanger (1967 and 1970). A review of the work of Asmussen and Nielsen (1946), Datta and Ramanathan (1969), Liddel (1963) and McCutchan and Taylor (1951) lead Fanger to propose the following equations to predict the respiratory heat exchanges due to convection and evaporation:

$$Cres = 0.0014 \cdot M\ (34 - Ta) \qquad (W/m^2) \qquad (2.13)$$

$$Eres = 0.0173 \cdot M\ (5.87 - Pa) \qquad (W/m^2) \qquad (2.14)$$

2.2. Heat Transfer Within the Human Body

Heat flows in the body occur by conduction within and between the body tissues, and by convection between the blood and the body tissues.

2.2.1. Tissue Conduction

The flow of heat by conduction through a body tissue is proportional to the temperature gradient across it (adapted from Cornwell, 1977):

$$K = \frac{k}{d}\ (T2 - T1) \qquad (W/m^2) \qquad (2.15)$$

where:

k = thermal conductivity of the tissue ($W/m.^{\circ}C$)

d = distance between T1 and T2 (m)

T1 = temperature at point 1 (°C)

T2 = temperature at point 2 (°C)

Equation 2.15 assumes that there is no heat transfer at the tissue edges.

In practice, the interest is usually in radial conduction. With the exception of the head, the trunk and limbs of the body are approximately cylindrical in shape. The heat flow from the inner surface to the outer surface of a layer of cylindrical tissue is as follows (adapted from Cornwell, 1977):

$$K = \frac{2 \cdot \pi \cdot k \cdot l}{\ln(r2/r1)} (T2 - T1) \qquad (W) \qquad (2.16)$$

where:

l = length of cylinder (m)

r1 = inner radius (m)

r2 = outer radius (m)

T1 = temperature at inner radius (°C)

T2 = temperature at outer radius (°C)

The conductive heat transfer in this case is expressed without reference to surface area as the surface area varies with the radii considered. This equation assumes that there is no axial heat flow, that is, the end surfaces of the cylinders are perfectly insulated. Other more complex methods exist that allow two-dimensional heat flows to be described (e.g. Kuznetz, 1979).

2.2.2. Blood Convection

Heat transfer between the blood and the tissues through which the blood vessels pass depends on the temperatures of the blood and tissues, and the rate of blood flow:

$$Cb = v \cdot \rho \cdot cb\,(Tb - Tt) \qquad (W) \qquad (2.17)$$

where:

Cb = convective heat transfer between the blood and body tissues (W/m^2)

v = volumetric blood flow rate (m^3/s)

ρ = blood density (kg/m^3)

cb = specific heat of blood ($J/kg.°C$)

Tb = temperature of blood (°C)

Tt = temperature of tissues (°C)

Equation 2.17 assumes that the blood flows out of the tissues at tissue temperature. In practice this may not be true for the larger blood vessels. However, the major sites for convective heat exchange between the blood and tissues are in the precapillary and capillary beds, where this assumption is probably valid (Shitzer and Eberhart, 1985).

2.3. Human Thermoregulatory Effector Mechanisms

The human body maintains its deep body tissues at a temperature around 37 °C over a wide range of environmental conditions. In order to achieve this regulation the body has to balance its internal metabolic heat generation with heat exchanges to and from the environment. This is accomplished in two ways: by using effector mechanisms that influence the body's heat generation and heat exchanges, and by behavioural means such as reducing clothing, or seeking shelter. The effector mechanisms used to maintain deep body temperature at a steady level have been widely described (e.g. Burton and Edholm, 1955; Clark and Edholm, 1985; Edholm, 1978; Houdas and Ring, 1982; Kerslake, 1972;

Leithead and Lind, 1964; and Winslow and Herrington, 1949). Behavioural temperature regulation is not considered here.

2.3.1. Vasomotor Regulation

The human body is in a state of thermal neutrality when it is able to achieve thermal equilibrium without the use of its effector mechanisms. This occurs for the nude and resting human in a still air environment at around 30 °C. For environmental conditions slightly either side of thermal neutrality, the body uses vasomotor control to adjust the peripheral blood circulation. Arteries and veins have a layer of smooth muscle in their walls that enables their diameter to be adjusted under central nervous system control. In the heat the peripheral blood vessels vasodilate to increase blood flow and in the cold they vasoconstrict to reduce it. Vasomotor control can reduce the skin blood flow to below 1 ml/min per 100 g of skin and increase it up to 100 ml/min (Edholm, 1978).

Besides the heat transfer within the body tissues by conduction, heat flows between them by convection to and from the blood. Thus, in the heat the circulatory system allows more blood to flow from the deep body tissues to the periphery, warming the skin and subcutaneous fat tissues, thereby increasing heat transfer to or decreasing heat transfer from the environment. In the cold, vasoconstriction reduces the peripheral blood flow, conserving heat in the deeper tissues of the body, and reducing the heat exchanges with the environment.

2.3.2. Sweating

When subject to larger deviations from thermal neutrality, in addition to vasomotor control, the body employs sweating in the heat and shivering in the cold to keep its deep body temperature constant. In the heat, sweat is produced by the sweat glands in the dermis of the skin and reaches the skin via ducts. The sweat is then free to evaporate, thus cooling the skin surface. Although not sustainable for long periods of time it is possible that sweat rates of over 2 l/hr can be achieved (Leithead and Lind, 1964). The maintenance of sweating depends on the replenishment of depleted body fluids and salts.

2.3.3. Shivering

In the cold the body uses shivering to generate additional heat. Shivering consists of uncoordinated activity in which groups of muscle fibres contract and relax out of phase with each other, and as with any muscular activity, heat is generated. Shivering does not usually occur continuously, but in bursts. Averaged over a period of time, shivering may increase the metabolic rate to over three times the basal level (Edholm, 1978).

2.3.4. Variation in Effector Responses due to Acclimatization

As with most physiological parameters, the responses of the thermoregulatory effector mechanisms can vary greatly between individuals. One factor that can affect the responses of the effector mechanisms is the subject's state of acclimatization. Acclimatization to the heat results in the ability to produce greater quantities of sweat and reduced heart rate (Edholm, 1978; and Leithead and Lind, 1964). In addition, Collins and Weiner (1968) suggested that heat acclimatization might also result in a slight, but biologically significant, lowering of basal metabolic rate.

The question of whether or not any acclimatization to the cold occurs is controversial. Recently, Young et al. (1986) reviewed evidence which suggested that repeated exposure to cold air may possibly cause two different patterns of adaption. In one, metabolic heat production increases by a greater amount in the adapted state. In the other, shivering is reduced and body temperature allowed to fall.

2.4. Human Thermoregulatory Control

That the human body attempts to exert control over its temperature is self evident given the existence of the various effector mechanisms, and it follows that human thermoregulation is not due merely to a fortuitous balance between heat production and loss.

The fundamental question is what does the human body control, and how does it achieve this? It is widely held that body temperature is the attribute that is controlled (e.g. Benzinger, 1961 and 1969; Bligh, 1966, 1973 and 1978; Hammel, 1968; Hardy, 1961; Heller et al., 1978; Hensel 1973 and 1981; and Pickering, 1958). Alternatively, Houdas and Ring (1978) and Snellen (1972) have suggested that it is body heat storage rather than temperature that is sensed and regulated.

2.4.1. Temperature Detection

In order for the body to be able to maintain its temperature at a steady level, it must have the means of detecting its thermal state. It is accepted that temperature sensitive cells concerned with thermoregulation exist at deep body sites and at the periphery (Benzinger, 1969; Bligh, 1966, 1973, 1978 and 1985; Cabanac, 1975; Hardy, 1961 and 1973; Heller et al., 1978; Hensel, 1973 and 1981; Necker, 1981; Pickering, 1958; Simon et al., 1986; and Wyndham, 1969). The primary deep body or central temperature sensors are thought to be located in the preoptic anterior hypothalamus, although central receptors have also been found in other regions of the brain, spinal cord and elsewhere in the body (Bligh, 1966 and 1973; Cabanac, 1975; Hardy, 1961 and 1973; Hensel, 1973 and 1981; and Simon et al., 1986). It has been suggested that some of the extrahypothalmic temperature sensitive cells are not involved in autonomic temperature regulation, but may play a part in behavioural regulation.

The action of the temperature sensitive neurons has been investigated (Bligh, 1966 and 1973; Hammel, 1972; Hardy, 1961; Hensel, 1973 and 1981; Necker, 1981; and Simon et al., 1986). It has been found that cutaneous temperature sensors tend to have firing rates with bell shaped distributions. According to the temperature at which they have their peak discharge rate, they may be classified as being either hot or cold sensors. The hot sensors have peak discharge rates at temperatures higher than normal local body temperature and the cold sensors have peak discharge rates at temperatures lower than normal local body temperature.

Less is known about the functioning of the central thermoreceptors. It has been postulated that they might be the temperature sensitive endings of primary peripheral receptors, or that they might be primary receptors in their own right, in which case they may operate in a similar manner to those at the skin (Bligh, 1973).

2.4.2. The Thermoregulatory Controller

The operation of the thermoregulatory controller has been studied extensively but as yet is still not fully understood. It is generally acknowledged that the thermoregulatory controller behaves as though effector mechanisms are activated by the deviation of sensed temperatures from reference or set point temperatures, although whether this is the actual process is not known. It is also recognized that the anterior and posterior hypothalamus centres play crucial roles in this process (Benzinger, 1961 and 1969; Bligh, 1966, 1973, 1978 and 1985; Cabanac, 1975; Hammel, 1968 and 1972; Hammel et al., 1963; Hardy, 1961 and 1973; Heller et al., 1978; Hensel, 1973 and 1981; and Pickering, 1958).

Engineering concepts have often been used to help describe thermoregulatory control. This has lead to the mammalian thermoregulatory controller being described as having components of proportional and rate control (Bligh, 1966 and 1973; and Hardy, 1961). Proportional control is where an error signal is generated of strength proportional to the deviation of the controlled variable from the reference variable. In rate control, an error signal is generated that is in proportion to the rate of change of the controlled variable. Thus, the thermoregulatory controller would be sensitive to both changes in temperature and continuous displacement.

2.4.2.1. Integration of Central and Peripheral Signals

In the past, the relative importance that the controller places on the signals generated by the central and peripheral temperature receptors has been the cause of some disagreement (e.g. Benzinger, 1961 and Wyndham, 1965). However, it now contended that peripheral and central receptors influence the effector responses in both the heat and the cold. Blood flow, sweating and shivering are all thought to be affected by changes in peripheral and deep body temperatures (Bligh, 1973; and Hensel, 1973 and 1981).

There have been several suggestions as to how the thermoregulatory controller might integrate the central and peripheral signals from the temperature sensors. Pickering (1958) suggested that in certain circumstances the effector mechanisms could be activated as reflex responses, without central intervention taking place. Bligh (1973 and 1978) argued that there was strong evidence to show that the peripheral temperature sensors provide an input to the central nervous system. This would mean that the controller must be able to integrate the peripheral and central signals. Hardy (1961 and 1973) suggested that the central and peripheral signals both provide inputs to the central controller and that integration occurs there.

2.4.2.2. Variation of the Thermoregulatory Set Point

If body temperature is maintained at a steady level using regulation against a set point, there has been some discussion over whether the setting of the set point may vary.

It had long been held that the set point became elevated during exercise, to account for evidence which suggested that body temperature increased to a level independent of ambient temperature, air movement and humidity. However, this is now widely disputed (Bligh, 1966 and 1973; Cabanac, 1975; Hammel, 1968; Hensel, 1973 and 1981; and Snellen, 1972). This is because any increase in the set point temperature during exercise would not be compatible with the increase in the activity of the effector defence mechanisms that is observed. The increase in body temperature may be explained as being due to equilibrium having been reached between the controller induced increased heat loss and the heat generation of the exercise.

When the body is in a state of fever, it would appear that the position of the thermoregulatory set point is altered. This is because thermoregulation carries on as normal, although directed at maintaining body temperature at a higher level (Bligh, 1973; and Hensel, 1981).

An interesting proposition has been that the controller regulates the central temperature against a set point that is modulated according to the temperatures sensed at the periphery (Bligh, 1978; Hammel, 1968; Hammel et al., 1963; and Heller et al., 1978). This account would also explain the integration of the central and peripheral signals.

2.4.3. Thermoregulatory Models and Thermoregulatory Control

Most thermoregulatory models assume a fixed set point theory of temperature regulation. Although this may not describe the precise mechanism of the central controller, it does provide an account compatible with the apparent operation of the normal thermoregulatory processes. For the purposes of providing a useful computer based model of human temperature response, is does not matter whether a controller method used is a precise description of the actual real life system, providing the observable results are similar.

CHAPTER 3

3. COMPUTER BASED MODELS OF HUMAN RESPONSE TO THE THERMAL ENVIRONMENT

Models of human response to the thermal environment, and the different approaches that have been taken, have been widely reviewed. Bligh (1973), Dinnar (1979), Fan et al. (1971 and 1972), Hardy (1972), Houdas (1981), Houdas and Guieu (1975), Hwang and Konz (1977), Iberall (1972), Kitney (1974), Lotens (1981 and 1988), Mitchell et al. (1972), Richardson (1985a), Shitzer (1973), and Wissler (1984 and 1988) have reviewed models that are capable of predicting human temperature and other thermoregulatory responses. These models range from the empirical, where equations are derived to provide a best fit to existing human response data (Givoni and Goldman, 1972 and 1973b), to complex three-dimensional representations of the human body and its associated control systems (Werner and Buse, 1988).

Details of influential computer based models, with regard to historical development and current use, are summarized in table 3.1.

3.1. Selection of Models for Evaluation

Given the large number of different models that have been described in the literature, it was decided to limit the evaluation to the most influential models. The models that were selected were the Gagge and Nishi, Stolwijk and Hardy, Givoni and Goldman, ISO/DP 7933, Ringuest, and Wissler models. With the exception of the Ringuest model, these models have been particularly influential. The Gagge and Nishi model is an integral component of the American Society

Table 3.1. Computer based models of human response to hot and cold environments.

Authors	Description
Atkins and Mitchell (1971) and Atkins and Wyndham (1969)	Nude model of human thermoregulation. Analogue simulation, represents body as 4 layer cylinder. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
Behling et al. (1971)	Nude model of human thermoregulation. Analogue simulation, represents body as 2 layer cylinder. Model incorporates shivering and sweating responses, represents vasomotor effects by varying core–periphery conductance. Predicts steady state temperatures and heat exchanges of each layers.
Cornew et al. (1967)	Nude model of human thermoregulation. Analogue simulation, represents body as 3 layer cylinder. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
Crosbie et al. (1961)	Nude model of human thermoregulation. Early analogue simulation, using layered slab representation of body. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
Gagge et al. (1971 and 1986), and Nishi and Gagge (1977)	Clothed model of human thermoregulation. Represents body with 2 layer cylinder, incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
Givoni and Goldman (1972 and 1973b)	Rectal temperature response of nude and clothed, resting and working subjects in the heat. Based on equations derived as best fit to large body of empirical data.

(continued)

Table 3.1. (continued)

Authors	Description
Gordon (1974), Gordon and Roemer (1975a and 1975b), and Gordon et al. (1976)	Nude model of human thermoregulation. Represents body with multiple layer cylinders and spherical segments. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges at 154 nodal points.
Hsu et al. (1972 and 1973)	Model of human thermoregulation, with an external thermal regulation device. Based on Wissler model with slightly modified torso-blood heat exchange representation.
Hsu (1977) and Azer and Hsu (1977)	Clothed model of human thermoregulation. Based on Gagge et al. model with modified effector controller functions.
Huckaba et al. (1973)	Nude model of human thermoregulation. Based on Stolwijk and Hardy model, with modified data for passive (or controlled) system.
Huckaba and Tam (1980)	Nude model of human thermoregulation. Represents body with 11 cylinders each with 4 layers. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
ISO/DIS 7933 (1987) (ISO/DP 7933, 1983)	Constructs and solves heat balance equation to determine sweat rate required to maintain equilibrium for nude and clothed subjects. On the basis of sweat rates, dehydration and heat storage that may be achieved in practice, predicts allowable exposure times.
Kuznetz (1975 and 1979)	Model of human thermoregulation, with external liquid cooling garment. Represents body with multiple layer cylinders. Each segment is also divided into angular quadrants enabling effects of asymmetrical heat generation or exposure to be modelled. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of 361 nodal points.

(continued)

Table 3.1. (continued)

Authors	Description
Ringuest (1981)	Nude model of human thermoregulation. Modified form of Stolwijk and Hardy model, with Stolwijk and Hardy effector controlling mechanisms replaced by statistically derived functions.
Smith and Twizell (1980a, 1980b, 1982 and 1984) and Twizell and Smith (1982)	Clothed model of human thermoregulation. Uses 6 segment, multiple layer representation of body. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges at 612 nodal points.
Smith and James (1964)	Nude model of human thermoregulation. Analogue simulation, represents body as 6 cylinders, each having three layers. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
Stolwijk (1971), and Stolwijk and Hardy (1966 and 1977)	Nude model of human thermoregulation. Represents body with 5 cylinders and a sphere, each having 4 layers. Model incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges of each layer.
Timbal et al. (1976)	Nude model of human thermoregulation in the cold. Represents the body with 2 layer cylinder. Model incorporates shivering response, represents vasomotor effects by varying core-periphery conductance. Predicts temperature changes and heat exchanges of each layer.
Volpe and Jain (1982)	Nude model of human thermoregulation (has facility for external water heated suit). Based on Huckaba and Tam model model with addition of axial conduction between body segments and modification of controller functions for blood flow and metabolic rate.

(continued)

Table 3.1. (continued)

Authors	Description
Werner (1975 and 1977), Werner and Buse (1988), and Buse and Werner (1985)	Nude model of human thermoregulation. Represents body with grid of 400,000 points. Model allows for both radial and axial heat flows, incorporates vasomotor, shivering and sweating responses. Predicts temperature changes and heat exchanges at each point.
Wissler (1961, 1964, 1970, 1984 and 1985a)	Clothed model of human thermoregulation. Represents body with multiple layer cylinders. Model incorporates vasomotor, shivering and sweating responses, and in addition, model computes oxygen, carbon dioxide and lactate concentrations. Predicts temperature changes and heat exchanges at 225 nodal points.

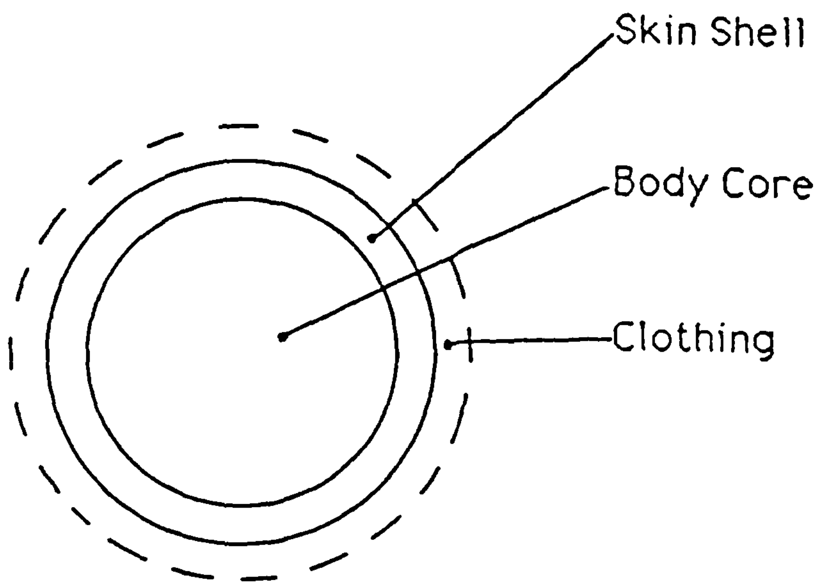
of Heating, Refrigerating and Air-conditioning Engineers' (ASHRAE) Standard 55-81 (1981a). The Stolwijk and Hardy model has formed the basis of many other more specialized models and was used during the Apollo and Skylab space programs (Waligora, date unknown). The Givoni and Goldman model was developed during the 1970's at the US Army Research Institute of Environmental Medicine (USARIEM) and the model has been used by the US Army (Pandolf et al., 1986). ISO/DP 7933 is being adopted by the International Standards Organization (ISO) as part of a series of standards concerning the assessment of the thermal environment. The Wissler model has been developed under the sponsorship of the US army, US air force and US Navy (Wissler, 1964, 1980 and 1988), it has also formed the basis of several other models. The Ringuest model has been included for this study as it provides an interesting alternative to the hypothesized theoretical controller suggested by Stolwijk and Hardy.

3.2. Gagge and Nishi 2-Node Model of Human Thermoregulation

3.2.1. Description of Model

The Gagge and Nishi 2-node model of human thermoregulation (Gagge et al., 1971; and 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 a two layer cylinder: a body core surrounded by a skin shell, figure 3.1. The relative masses of the two compartments are adjusted according to the blood flow. For example, if the

Figure 3.1. Gagge and Nishi 2-node model representation of the human thermoregulatory controlled (passive) system.



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 with 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.

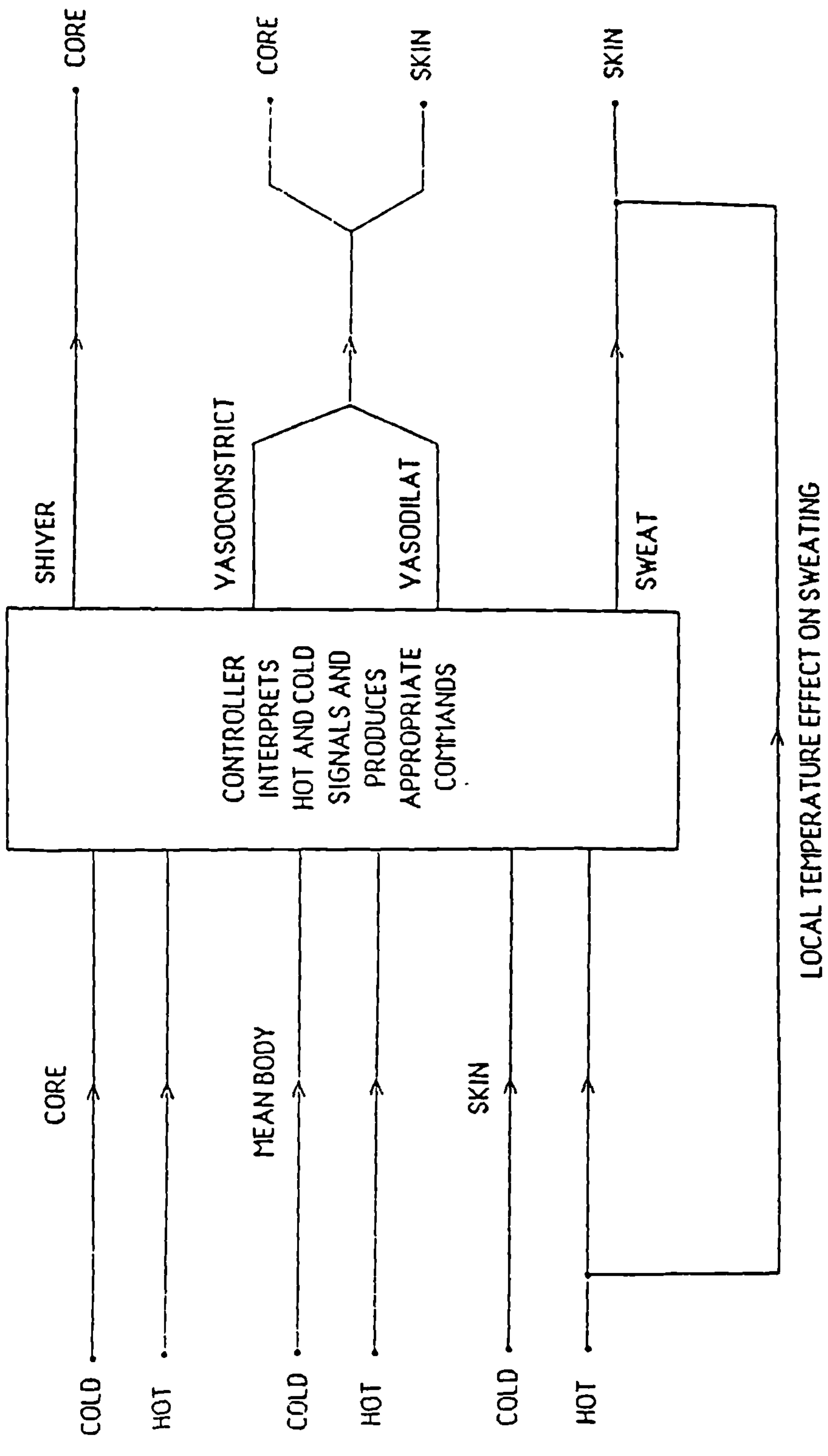
The controlling system assumes a fixed set point, proportional control, theory of human thermoregulation, figure 3.2. Controlling signals result from deviations of the body's actual temperatures from reference temperatures. These signals are integrated by the controller, which then produces appropriate effector commands. Effector action takes the form of shivering, vasoconstriction, vasodilation and sweating.

The model predicts the heat exchanges and temperature changes of the two body compartments at one minute intervals.

3.2.2. Computer Program

The computer program for the version of the model that was used for this evaluation was based on the FORTRAN program listing given by Nishi and Gagge (1977) and modified according to information provided by Gagge (1985). A program listing for the model and an example of its predictions are given in appendix A. The program was tested for correct operation against data provided by ASHRAE

Figure 3.2. Gagge and Nishi 2-node model representation of the human thermoregulatory controlling system.



(1981b).

3.3. Stolwijk and Hardy 25-Node Model of Human Thermoregulation

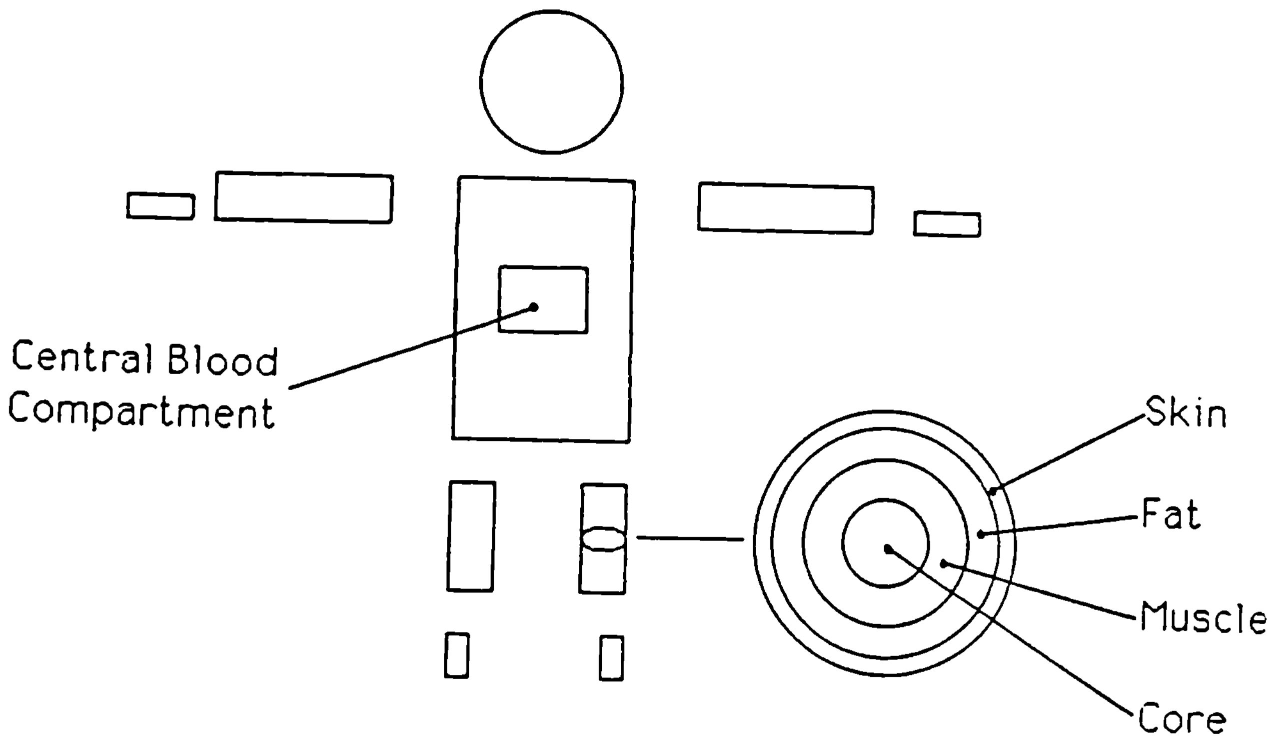
3.3.1. Description of Model

The Stolwijk and Hardy 25-node model of human thermoregulation (Stolwijk, 1971; and Stolwijk and Hardy, 1966 and 1977) represents the human body as 25 compartments, as shown in figure 3.3.

The model represents the head as a sphere, and the trunk, arms, hands, legs and feet as cylinders. The model assumes that the body is symmetrical in order to reduce the number of calculations required. Each of the segments is divided into four layers: core, muscle, fat and skin compartments (6x4=24 compartments). The major veins and arteries are 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 radially by conduction from a compartment to the adjacent compartment; and from segment to segment, by convective transfer to and from the blood. Metabolic heat production is divided proportionately between the various segments and their layers. External body compartments exchange heat with the environment by means of convection, radiation and the evaporation of sweat.

Figure 3.3. Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlled (passive) system (6 body segments x 4 layers + 1 blood = 25 compartments).



A schematic representation of the Stolwijk and Hardy controlling system is given in figure 3.4. The controlling system is based on a fixed set point, proportional control, theory of human thermoregulation. The model also has a mechanism incorporated to allow for rate control, but this is not used in the current version of the model because of insufficient data.

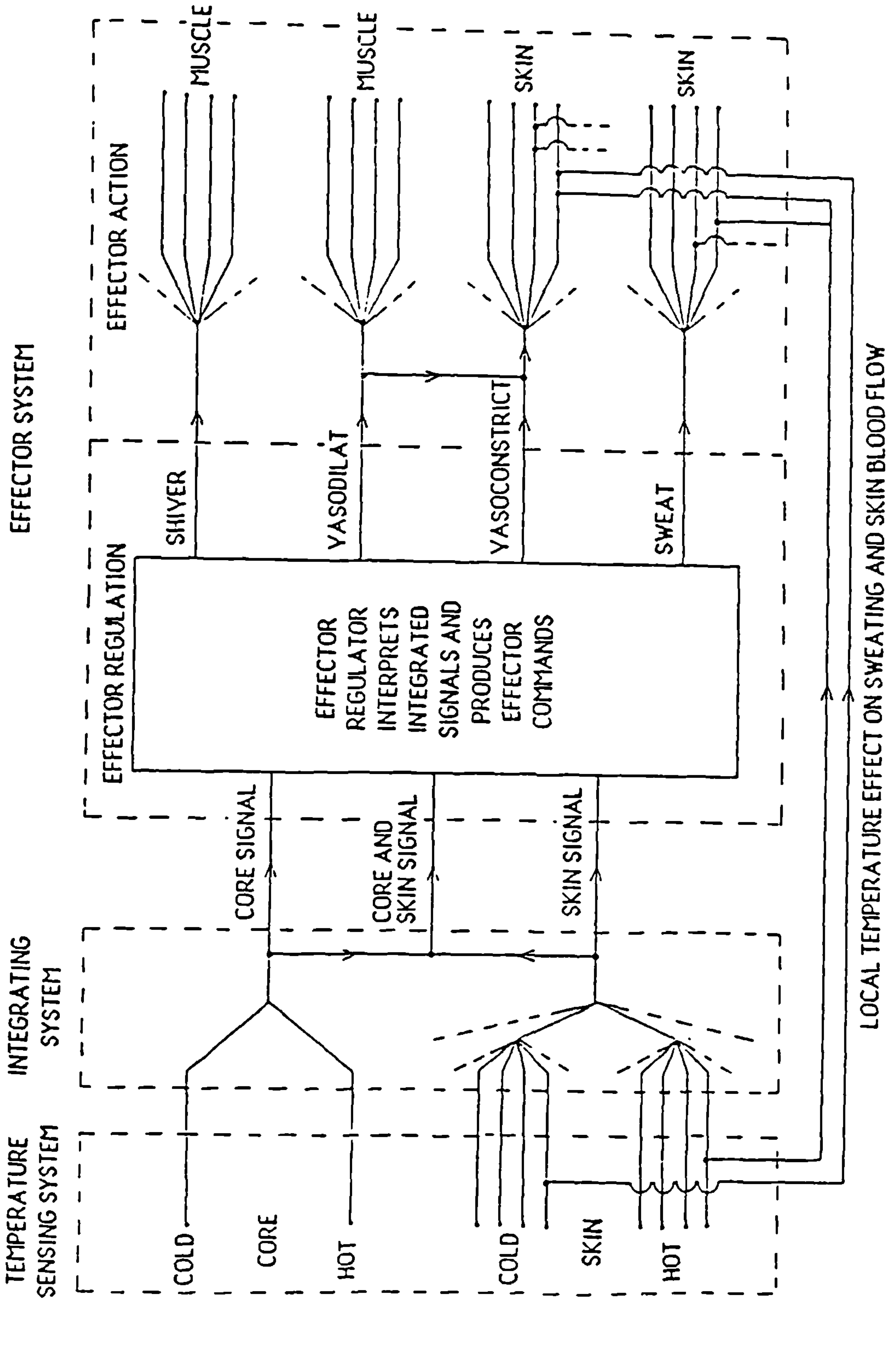
Signals controlling vasodilation, vasoconstriction, sweating and shivering are calculated as a function of the difference of the actual temperatures of the compartments, from reference temperatures for those compartments. The local signals are modified according to the density of thermoreceptors for a compartment. These signals are then integrated to produce core, core and skin and skin signals. The effector regulator interprets the integrated signals and produces effector commands. The effector commands are implemented as effector action: shivering, vasodilation, vasoconstriction and sweating, after being modified according to local compartmental conditions.

The model predicts the heat exchanges and temperature changes of the 25 compartments every minute, unless compartmental temperatures are changing rapidly, when the model decreases the time interval between each step so that none of the temperatures change by more than 0.1 °C per time step.

3.3.2. Computer Program

The computer program for the version of the 25-node model used for this study was adapted from the FORTRAN program

Figure 3.4. Stolwijk and Hardy 25-node model representation of the human thermoregulatory controlling (active) system.



listing given by Stolwijk and Hardy (1977). Modifications to the published program listing were required to correct errors in the program logic that prevented it from executing. It was also necessary to change the program to prevent the model from shivering in the heat. Comparison of the tabulated constants given by Stolwijk and Hardy with those used by the computer program revealed a number of discrepancies. Several of the values used by the computer program were unrealistic, therefore, the coefficient values used by the computer program were corrected using the values tabulated by Stolwijk and Hardy.

A program listing for the Stolwijk and Hardy model is given in appendix A, along with an example of its predictions. The operation of the program was tested by comparing its predictions with published predictions from an earlier version of the model (Stolwijk, 1971). While the predictions were not exactly the same, they were very similar; slight differences would be expected in view of the changes made to the model by Stolwijk and Hardy up to 1977. Moreover, previous evaluation had shown the predictions of this version of the model to be reasonable (Haslam, 1983; Parsons and Haslam, 1984; and Watkins, 1984).

3.4. Givoni and Goldman Prediction Equations

3.4.1. Description of Model

Givoni and Goldman (1972, 1973b) presented 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 is simple enough to 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:

$$Tref = F1(Mnet) + F2(Hr{+}c) + F3(Ereq-Emax)$$

Where[1]: Tref = final equilibrium rectal temperature (°C)

Mnet = metabolic heat load (W)

Hr+c = sensible environmental heat load (W)

Ereq = required evaporative cooling

= Mnet + Hr+c (W)

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

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[1]The symbols and units here were those used by Givoni and Goldman (1972).

temperature, as a function of time, for 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 profiles of each type of activity.

3.4.2. Computer Program

The computer program for the version of the model used for this study was written using the information given by Givoni and Goldman (1971, 1972, 1973a and 1973b) and Berlin et al. (1975). Although this program also predicts metabolic and heart rates, in addition to rectal temperature response, these prediction have not been considered by this evaluation.

A computer program listing for the model is given in appendix A, together with an example of the model's predictions. The operation of the model was tested against sample program runs given by Berlin et al. (1975), and data used by Haisman and Goldman (1974). It should be made clear that the version of the Givoni and Goldman model evaluated here was based on the most recent published information available, as far as the author was aware. Since this information was published (1972, 1973 and 1975) work has continued with the model and changes have been made to it (Goldman, 1985 and 1987). However, as these changes were not available in the open literature they have not been included in this version of the model.

3.5. ISO/DP 7933 (1983)

3.5.1. Description of Model

ISO/DP 7933 (1983) 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 the person and the environment, and determines the sweat rate and skin wettedness that would be required for the body to achieve thermal equilibrium. The required sweat rate is related to required evaporative cooling by taking account of the efficiency of sweating. The required evaporative cooling is calculated according to the heat balance equation:

$$E_{req} = M - W - C - R$$

where: 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 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 ISO model can also predict allowable exposure times for successive combinations of environmental conditions. The model calculates allowable exposure times for each individual environment and then calculates time weighted average values of M, Ereq, Emax and required skin wettedness (wreq). It uses these time weighted average values to predict allowable exposure times to the successive environments.

3.5.2. Computer Program

The FORTRAN computer program for the ISO/DP 7933 model, used for this evaluation, was translated from the BASIC program listing given in the draft standard. This computer program does not predict allowable exposure times for more than two successive environmental exposures.

A program listing for the model and an example of its predictions are given in appendix A. The operation of the model was checked against sample program runs given in the draft standard.

3.6. Ringuest 25-Node Model of Human Thermoregulation

3.6.1. Description of Model

The Ringuest (1981) model of human thermoregulation is adapted from the Stolwijk and Hardy 25-node model. The model uses the same 25 compartment representation of the human body as the Stolwijk and Hardy model (figure 3.3), but includes a modification to the controlling system. The Ringuest model replaces the Stolwijk and Hardy controller, with a mechanism developed from a statistical analysis of human response data. This therefore provides an alternative to the theoretical controller hypothesized by Stolwijk and Hardy.

The statistical control equations were developed by analyzing published data using multiple regression techniques. This involved fitting equations to the controller responses over limited temperature ranges. These equations were estimated over all temperatures for which data were available, for the vasomotor, shivering and sweating responses. The inputs for each of these statistical controller equations are based on the difference between mean skin temperature from a reference temperature. No account is taken of deep body temperature. While this is contrary to the current view of human thermoregulatory control described in chapter 2, given the statistical nature of the Ringuest controller, this does not matter providing it produces accurate responses. The model predicts the heat exchanges and temperature changes of the 25 body compartments.

3.6.2. Computer Program

The computer program for this model is adapted from the FORTRAN computer program for the Stolwijk and Hardy model, with the controller sections modified according to instructions given by Ringuest (1981). No published predictions were available against which to test the correct operation of the model. The program listing of the model used for this evaluation and an example of its predictions are provided in Appendix A.

3.7. Wissler Model of Human Thermoregulation

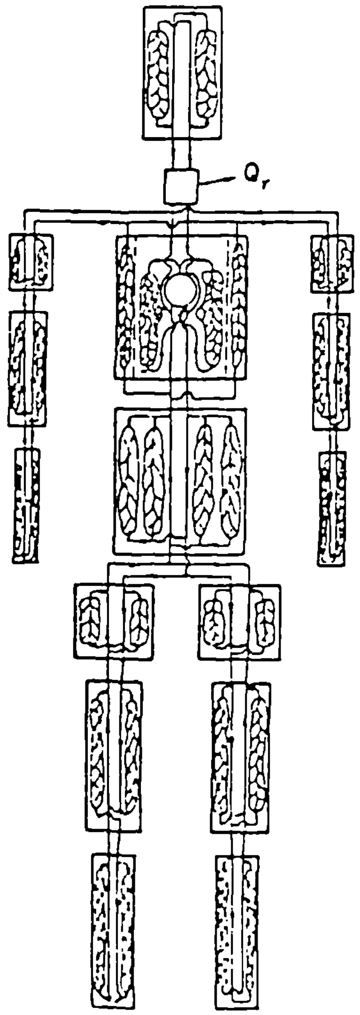
3.7.1. Description of Model

The Wissler (1961, 1964, 1970, 1984, and 1985a) model of human thermoregulation represents the human body with 15 cylindrical segments, figure 3.5. Each of these segments is divided into a variable number of layers of skin, subcutaneous fat, muscle, bone and viscera. The model uses finite difference techniques to calculate temperatures at enough nodal points to obtain an accurate temperature profile through each layer, with appropriate property values assigned to each layer.

The Wissler model has a vascular system that can be divided into three subsystems representing the arteries, veins and capillary beds. These are present in each body segment, and in addition there is a central blood pool at the heart. Counter-current heat exchange may occur between adjacent arteries and veins.

The Wissler model's controlling system is similar to that used by the Stolwijk and Hardy model, with the addition of rate of change of temperature being used as an input to the controller equations, as well as absolute temperature level. The Wissler model also accounts for material balances for oxygen, carbon dioxide and lactic acid to provide the information required for control equations for perfusion and ventilation. The Wissler model predicts the heat exchanges and temperature changes at 225 nodal points.

Figure 3.5. Wissler model representation of the human thermoregulatory controlled (passive) system (reproduced from Wissler, 1985a).



3.7.2. Computer Program

A program listing for the Wissler model has not been published and because the model is particularly complex, insufficient detail is available in the literature to enable one to be written. Wissler (1985b) agreed to allow a copy of his program to be taken, and suggested it should be obtained from researchers at the RAF Institute of Aviation Medicine (IAM). The view of these researchers was that because of the complexity of setting the program up to run, rather than supplying a copy of the program, it would be most practical for them to run the model if they were provided with the appropriate input conditions (Richardson, 1985b).

3.8. The Models' Inputs and Predictions

Although each of the models included for this evaluation accounts for the important parameters that affect human thermal responses to the environments to which they are applicable, the manner in which they do this varies. The inputs required by the models and predictions that they make are detailed in table 3.2.

3.9. Published Evaluation of the Models Considered by this Study

Most authors have published details of validation of their model alongside the description of the model itself. In some cases the only information given is for a comparison of the model's predictions with the data used to construct the model, in which case the model's predictions could be

Table 3.2. Model inputs and predictions.

Inputs:	Gagge & Nishi	Stolwijk & Hardy	Givoni & Goldman	ISO/DP 7933	Ringuest	Wissler
Air temperature (Ta)	Yes	Yes	Yes	Yes	Yes	Yes
Mean radiant temperature (Tr)	Yes	Tr=Ta	Tr=Ta	Yes	Tr=Ta	Yes
Solar Radiation	No	No	No	No	No	No
Air speed (v)	Yes	Yes	Yes	Yes	Yes	Yes
Relative humidity (rh)	Yes	Yes	Yes	From vapour pressure	Yes	Yes
Clothing insulation[1]	Icl	Nude only	IT	Icle	Nude only	IT
Clothing moisture permeation resistance[1]	From Icle (Icle from Icl)	Nude only	im	From Icle	Nude only	im
Metabolic rate (M)	Yes	Yes	Yes	Yes	Yes	Yes
External work (W)	Yes	Fixed assuming bicycle exercise	Yes	Yes	Fixed assuming bicycle exercise	Yes

[1]IT = total, Icl = intrinsic and Icle = effective clothing insulation (Haslam and Parsons, 1988); im is after Woodcock (1962)

(continued)

Table 3.2. (continued)

Predictions:	Gagge & Nishi	Stolwijk & Hardy	Givoni & Goldman	ISO/DP 7933	Ringuest	Wissler
Core (Tcr)	Tcr	T head-core	Tre	No	T head-core	Tre, T arterial
Mean skin (Tsk)	Temperature of skin shell	Weighted average of each skin compartment	Fixed at 36 °C	Fixed at 36 °C	Weighted average of each skin compartment	Weighted average of skin temperatures
Other	Dynamic heat exchanges; shivering and sweat rates	Dynamic heat exchanges; shivering and sweat rates	Equilibrium heat exchanges	Allowable exposure times; equilibrium heat exchanges and sweat rates	Dynamic heat exchanges; shivering and sweat rates	Dynamic heat exchanges; shivering and sweat rates

expected to be reasonably accurate. Usually, however, the model's predictions have been compared with at least one unrelated set of experimental data. In addition, there have been a number of independent assessments of the models. In some instances the models' predictions have been compared with each other, elsewhere the models' predictions have been compared with experimental data. Details of evaluations that have been published are presented in table 3.3.

It may be seen from table 3.3 that the Stolwijk and Hardy model has received most attention, the Ringuest and Wissler models least. In the case of the Wissler model this is probably due to the model's complexity having precluded other researchers from implementing it. Unfortunately, even the most extensive of the evaluations that have been published have been confined to limited numbers of environments and subjects. It is not possible to deduce from these studies which model would provide the most accurate predictions for different environments, and how accurate those predictions are likely to be. In view of the level of influence and usage of some of these models, further evaluation is clearly desirable.

Table 3.3. Published evaluation of the models considered by this study.

Model(s)	Authors of Evaluation	Findings
Gagge and Nishi	Doherty and Arens (1988)	Accurate for resting subjects, less accurate for exercise simulations, with predictions of skin wettedness and deep body temperature tending to be low and mean skin temperature high.
Givoni and Goldman	Givoni and Goldman (1972 and 1973b)	Predicted rectal temperature in good agreement with experimental results from several different studies other than those used to develop the model.
	Haisman and Goldman (1974)	Accuracy of prediction acceptable and within the variability expected for military and industrial populations.
	Pandolf and Goldman (1978)	Responses of acclimatized working subjects predicted with reasonable accuracy.
	Wissler (1984)	Agreement between computed and measured rectal temperatures generally quite good, although with a tendency to overestimate increase during heavy exercise in hot environmental conditions.
ISO/DP 7933	Wadsworth (1985) and Wadsworth and Parsons (1986)	Would not have protected subjects for the conditions examined.
Ringuest	Ringuest (1981)	Reasonably accurate for an independent experimental data set.

(continued)

Table 3.3. (continued)

Model(s)	Authors of Evaluation	Findings
Stolwijk and Hardy	Cooper et al. (1987)	Examined the effects of specifying body composition data on the model's ability to predict the responses of a range of different sized subjects; found that generally the predictions were more accurate with the original published body composition data for a "standard sized" man.
	Duncan (1977)	Predictions reasonable in a heat stress environment.
	Hancock (1978, 1980b, 1981a and 1981b)	Predictions reasonable in the heat, less accurate in cooler environments; predicted a dip at the onset of exercise not found in the observed data.
	Haslam (1983) and Parsons and Haslam (1984)	Predictions reasonable in hot and neutral conditions, poorer in the cold.
	Konz et al. (1977)	Accurate for a sedentary man in a heat stress environment.
	Stolwijk (1971) and Stolwijk and Hardy (1977)	Accurately predicted dynamic responses to heat and exercise; predictions of deep body temperature in the cold low; model predicted a dip at the onset of exercise not found in the observed data.
	Wissler (1984)	Yields good results when used to simulate exercise in a warm environment, results less satisfactory as environmental temperatures decrease, with predictions of deep body temperature lower and mean skin temperature appearing to be higher than measured values.
Wissler	Wissler (1984 and 1985a)	Predicts well in the heat, although mean skin temperature out of phase for work-rest cycles; reasonable in the cold.

(continued)

Table 3.3. (continued)

Model(s)	Authors of Evaluation	Findings
Gagge and Nishi, Givoni and Goldman, ISO/DP 7933 and Stolwijk and Hardy	Haslam and Parsons (1986 and 1987)	Comparison of the models' predictions; Gagge and Nishi, ISO/DP 7933 and Stolwijk and Hardy models' predictions were in reasonable agreement for hot conditions, Givoni and Goldman predictions differed considerably; discrepancies between Gagge and Nishi and Stolwijk and Hardy models in the cold for deep body temperature, with the Stolwijk and Hardy model predicting greater cooling than the Gagge and Nishi model.
Gagge and Nishi, Givoni and Goldman, and Stolwijk and Hardy	Lotens (1988)	Comparison of final rectal temperatures; Gagge and Nishi model predicted the lowest final values, considerably lower than those of the Givoni and Goldman model; Stolwijk and Hardy final temperatures systematically 0.5 °C greater than those of Gagge and Nishi model.
Gagge and Nishi and ISO/DP 7933	Parsons (1987)	Comparison of the models' predictions; concluded that similar practical decisions for allowable exposure times etc. would be made based on the two models.
Stolwijk and Hardy and Wissler	Wissler (1971)	Comparison of early versions of the Stolwijk and Hardy and Wissler models; predictions similar in the heat; deep body temperature predictions were similar in the cold, although Stolwijk and Hardy skin temperatures cooled considerably more than those of the Wissler model.

CHAPTER 4

4. PRELIMINARY EVALUATION OF MODELS

A preliminary evaluation was conducted to gain experience using the models and to determine whether any could be eliminated from further investigation.

4.1. Method

The models' predictions were compared with experimental data already available at Loughborough University of Technology (LUT) (Haslam, 1983; and Watkins, 1984), and a set of data reported in the literature by Wagner and Horvath (1985).

4.1.1. Experimental Data

The LUT data were observations of auditory canal (Tac) and Tsk collected from the exposure of male subjects to 5 environments, with air temperatures ranging from 5 to 40 °C. The environmental conditions used for the LUT experiments are given in table 4.1. A total of 30 subjects were used, with 6 subjects exposed to each of the 5 environments. The subjects were aged between 18 and 35, and were drawn from the student and teaching populations of Loughborough University. Each exposure lasted 75 minutes, and for all conditions the subjects wore minimal clothing (i.e. swimming trunks or shorts and briefs only).

The Wagner and Horvath study investigated the effects of age and gender on human thermoregulatory responses to cold exposures. Data were reported for the rectal (Tre) and Tsk responses of ten young male subjects exposed nude to environments ranging from 10 to 28 °C. The environmental conditions used by Wagner and Horvath are given in table

Table 4.1. LUT environmental conditions.

environment	air temperature (Ta, °C)	air speed (v, m/s)	relative humidity (rh, %)	metabolic rate (M, W)	external work (W, W)
A	40	0.1	60	95	0
B	35	1.0	25	635	150
C	30	0.1	40	95	0
D	10	0.1	55	635	150
E	5	1.0	55	100	0

Table 4.2. Wagner and Horvath (1985) environmental conditions.

environment	air temperature (Ta, °C)	air speed (v, m/s)	relative humidity (rh, %)	metabolic rate (M, W)	external work (W, W)
28	28	0.1	40	100	0
20	20	0.1	40	100	0
15	15	0.1	40	100	0
10	10	0.1	40	100	0

4.2. Each exposure lasted for two hours.

4.1.2. Running the Models

The environmental conditions for the LUT experiments were measured for each subject exposure. The environmental parameters used as inputs to the models' were the mean measured values for each experimental condition. Two of the environments contained forced air movement. This air movement was provided by an electric fan placed 1 m in front of the subjects. The air speed entered into the model programs was the mean air speed measured at the subjects' chests.

Two of the LUT environments included continuous exercise on a bicycle ergometer set at an external loading of 150 W. Metabolic rate was measured by taking Douglas bag samples from 6 of the 12 subjects exposed to these conditions. Metabolic rate during the resting conditions was measured by the same method for 9 of the 18 subjects exposed. With the exception of environment E, the values of metabolic rate used for the model programs were the means of all the individual metabolic rates measured for the particular type of activity (excluding those obtained for environment E, 95 W for rest and 635 W for cycling). For the cold condition E, metabolic rates were only available for 2 of the 6 subjects. However, these values were slightly higher than those measured for the other resting conditions, and the value of metabolic rate used for the model programs was therefore increased to 100 W.

The models were run for the Wagner and Horvath data using the mean experimental conditions reported.

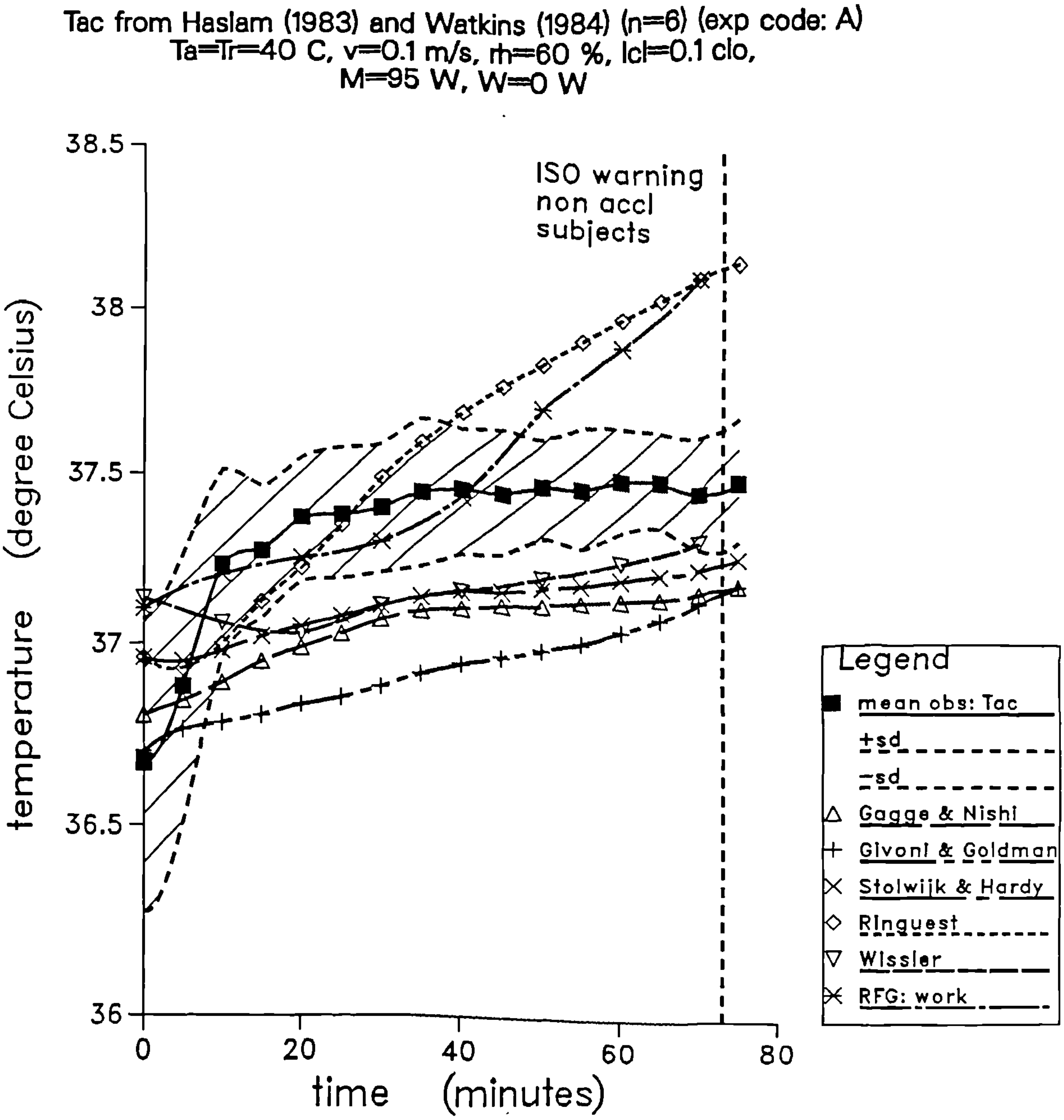
The Gagge and Nishi, Stolwijk and Hardy, Givoni and Goldman, ISO/DP 7933 and Ringuest models were run at LUT on a Honeywell Multics main frame computer system. The Wissler model was run by researchers at the RAF Institute of Aviation Medicine (Hayes, 1986). In addition, Goldman (1987) ran a recent version of his model for the LUT experimental data, thus making it possible to examine the consequences of using an earlier version of the model for this study.

4.2. Results

The results of the preliminary evaluation are presented in figures 4.1 to 4.24. Each graph shows the observed mean temperature response against time and the corresponding model predictions. Curves have also been plotted for the mean observed response plus and minus one standard deviation, to provide information regarding the variation of the observed responses.

Graphs have been plotted for the deep body temperature (Tcr) and Tsk responses for each of the experimental conditions. Graphs have also been plotted for the observed and the Stolwijk and Hardy and Ringuest predicted hand (Thd) and foot (Tft) skin temperature responses, for the LUT cool and cold environments, as these are of interest in relation to human performance and health. There are no predictions of hand and foot temperature responses from the Gagge and Nishi and Givoni and Goldman models because they are unable to

Figure 4.1. Observed auditory canal temperature response (Tac) and the models' predictions for LUT exposure A.



ISO/DP 7933 (1983) Allowable Exposure Times:

warning non-accl: 1 hr 23 min; excessive skin wettedness
danger non-accl : 1 hr 40 min; excessive skin wettedness
warning accl : 2 hr 44 min; excessive skin wettedness
danger accl : 3 hr 17 min; excessive skin wettedness

Figure 4.2. Observed mean skin temperature response (Tsk) and the models' predictions for LUT exposure A.

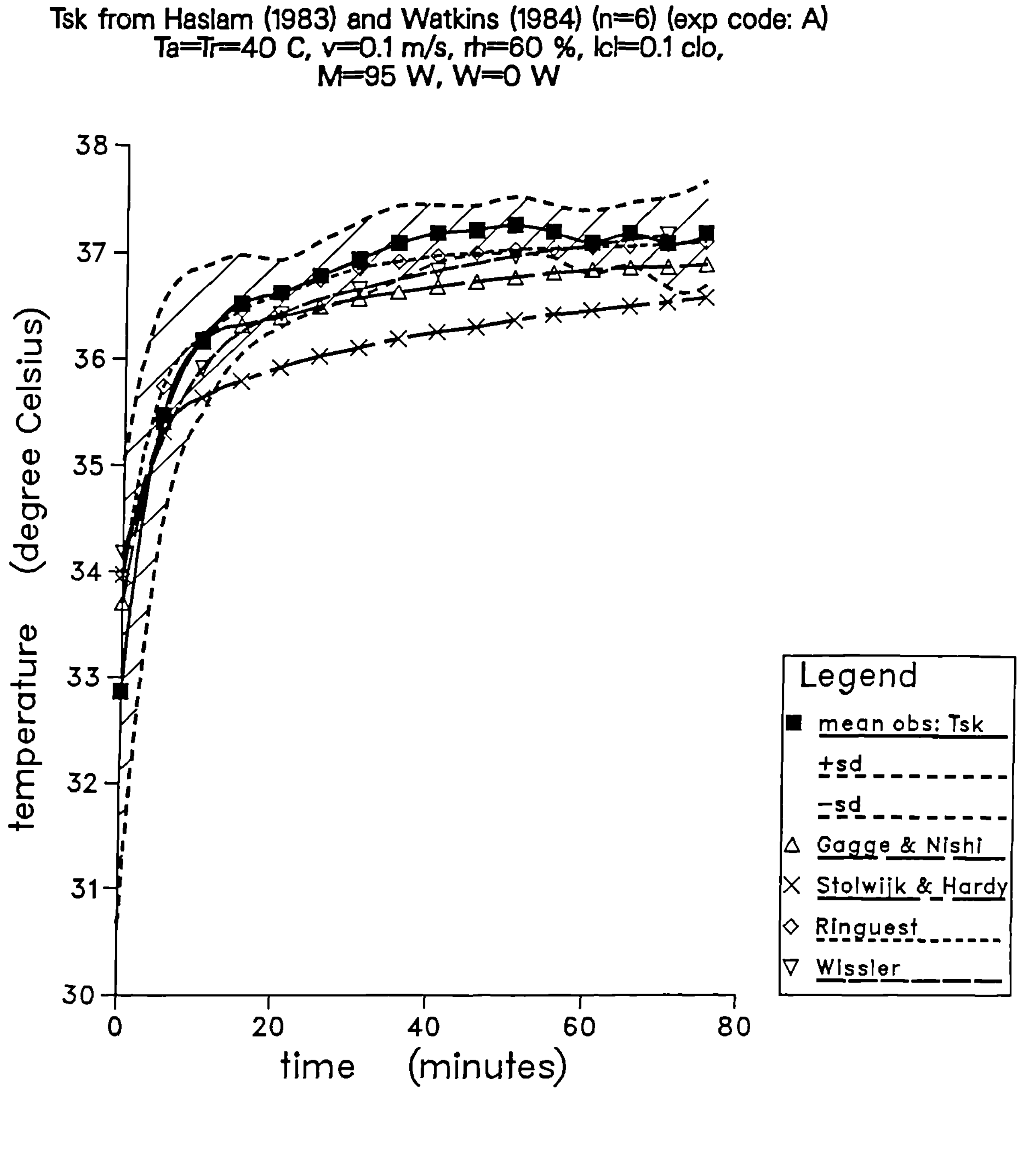
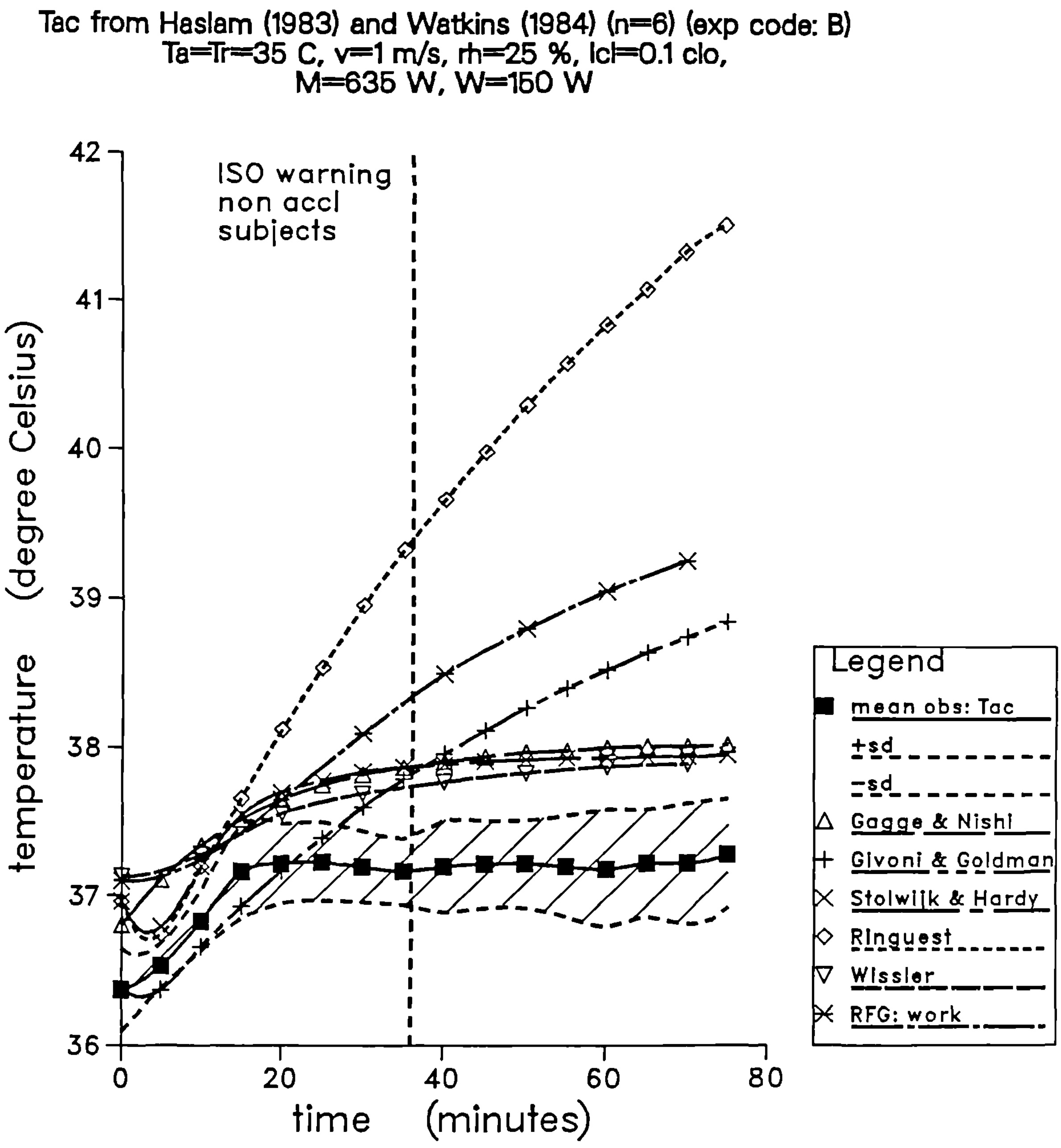


Figure 4.3. Observed auditory canal temperature response (Tac) and the models' predictions for LUT exposure B.



ISO/DP 7933 (1983) Allowable Exposure Times:
warning non-accl: 0 hr 36 min; Ereq not achievable
danger non-accl : 1 hr 50 min; Ereq not achievable
warning accl : 5 hr 17 min; dehydration
danger accl : 7 hr 03 min; dehydration

Figure 4.4. Observed mean skin temperature response (Tsk) and the models' predictions for LUT exposure B.

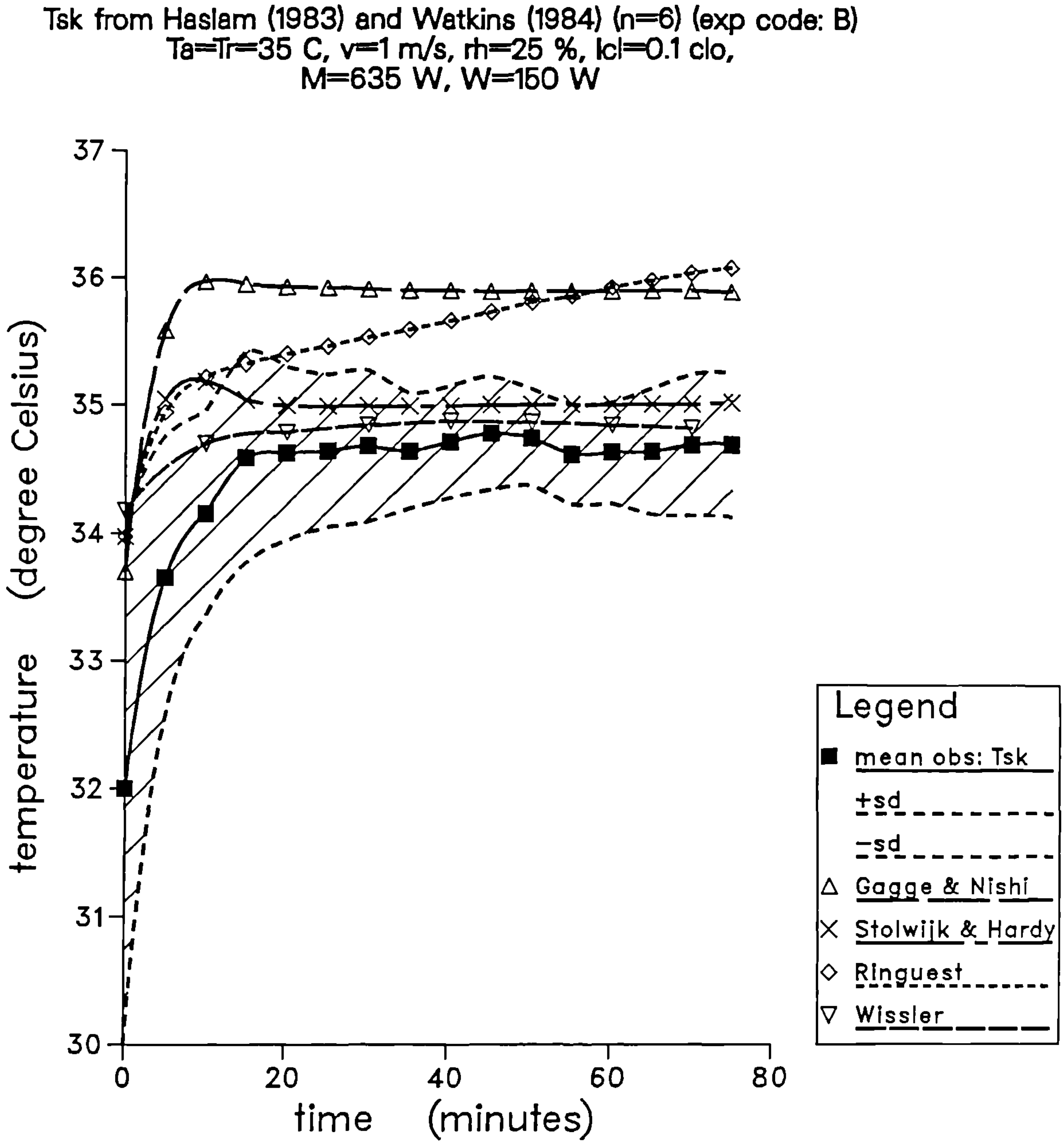


Figure 4.5. Observed auditory canal temperature response (Tac) and the models' predictions for LUT exposure C.

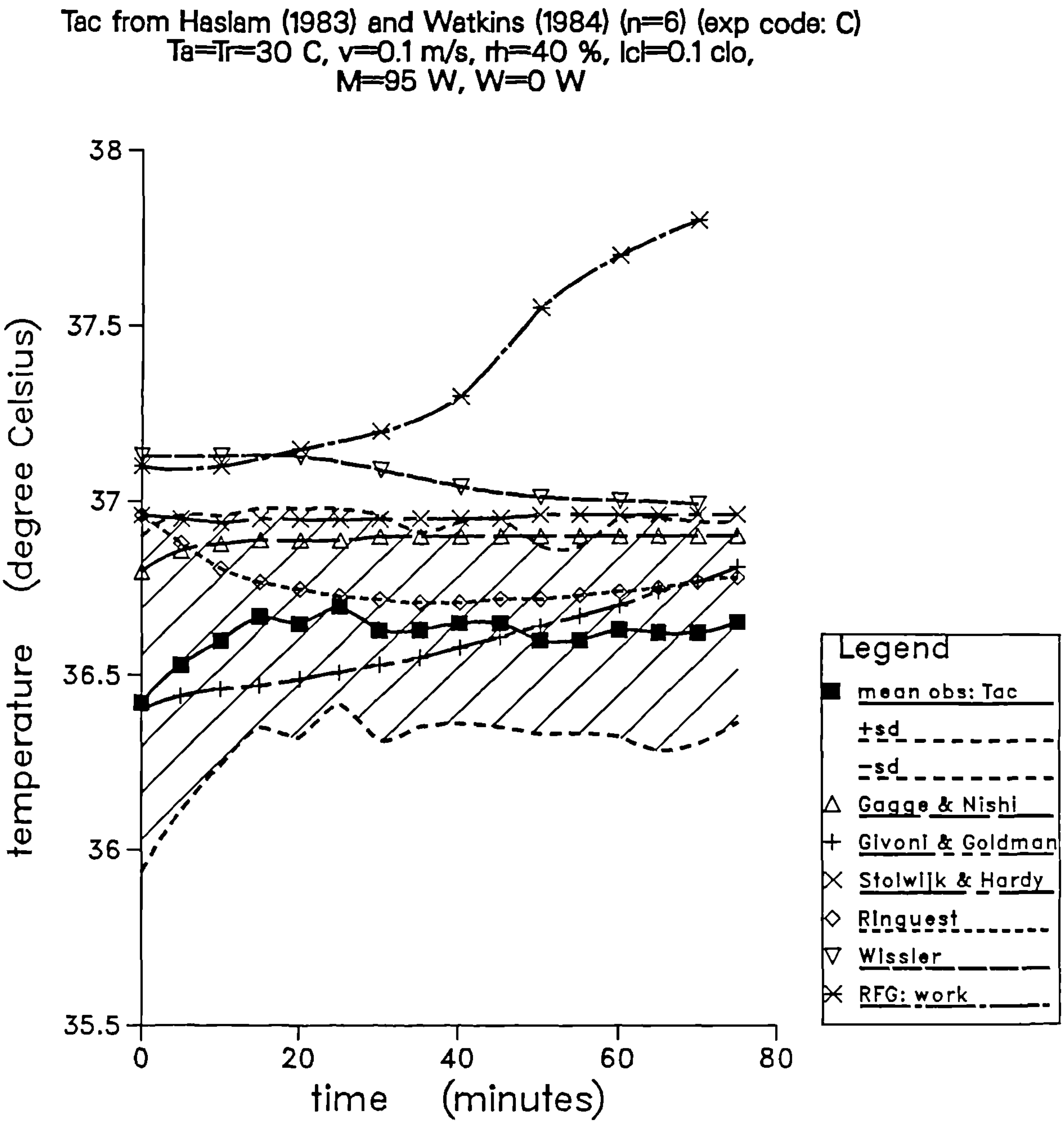


Figure 4.6. Observed mean skin temperature response (Tsk) and the models' predictions for LUT exposure C.

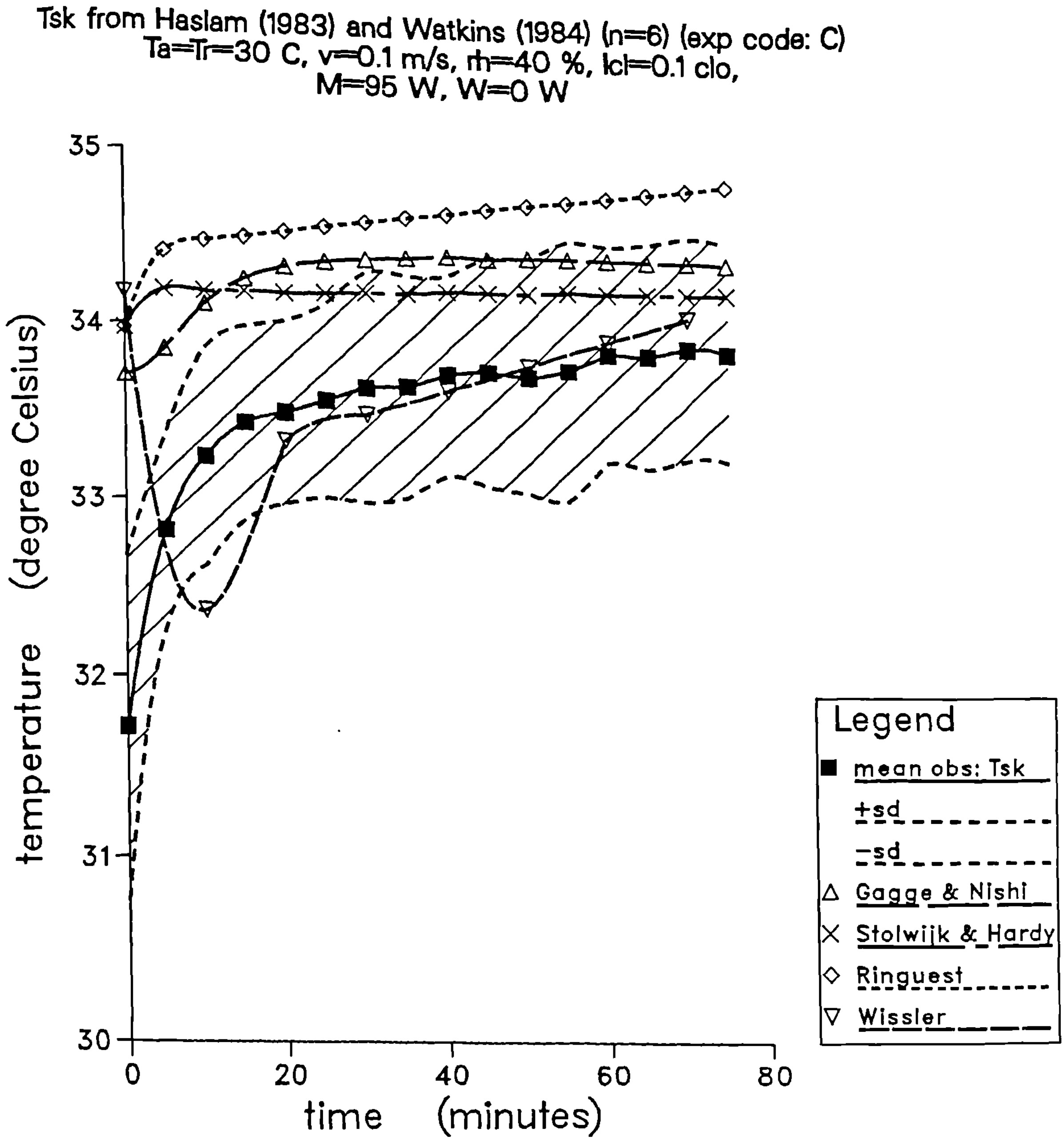


Figure 4.7. Observed hand skin temperature response (Thd) and the models' predictions for LUT exposure C.

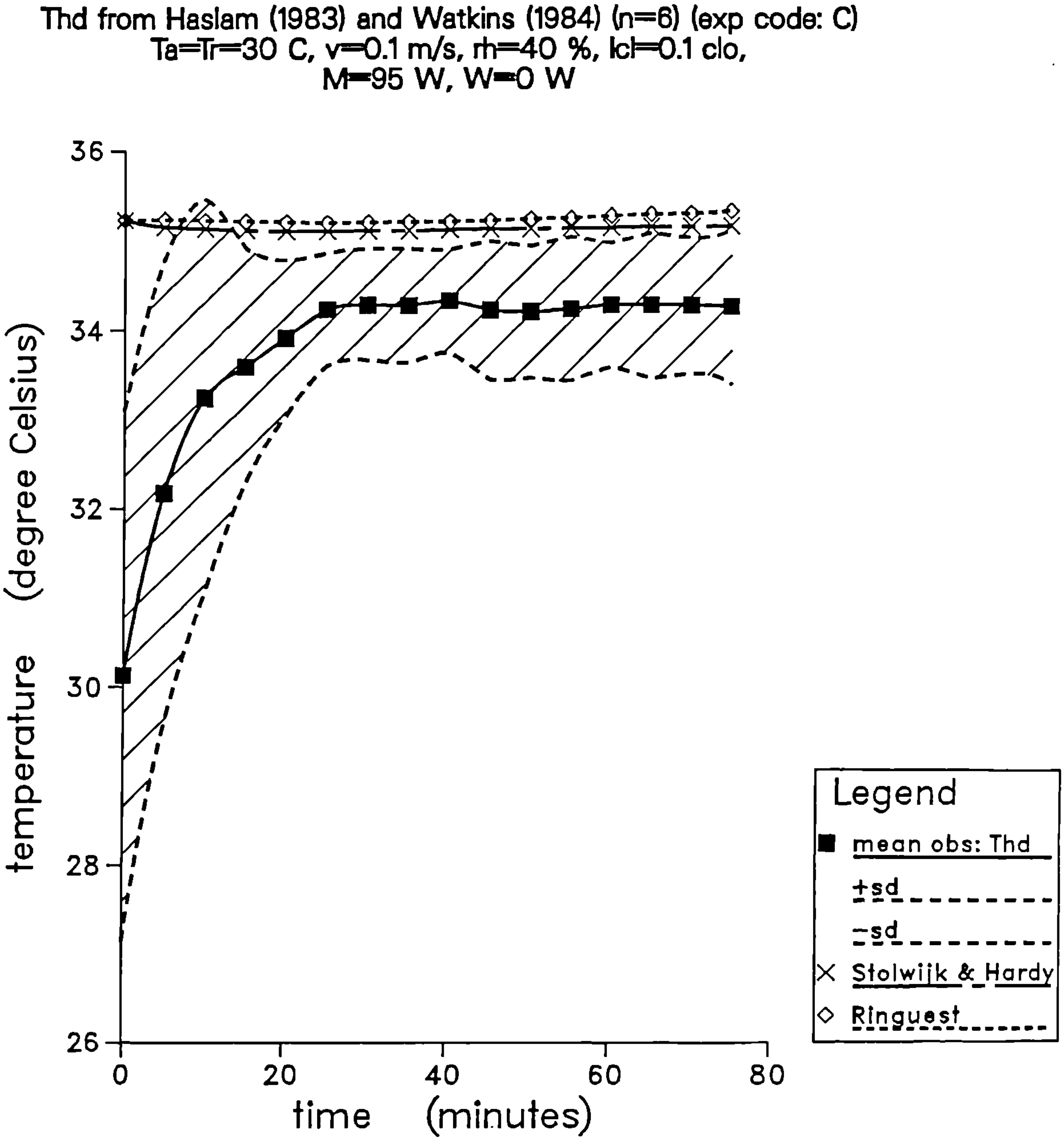


Figure 4.8. Observed foot skin temperature response (Tft) and the models' predictions for LUT exposure C.

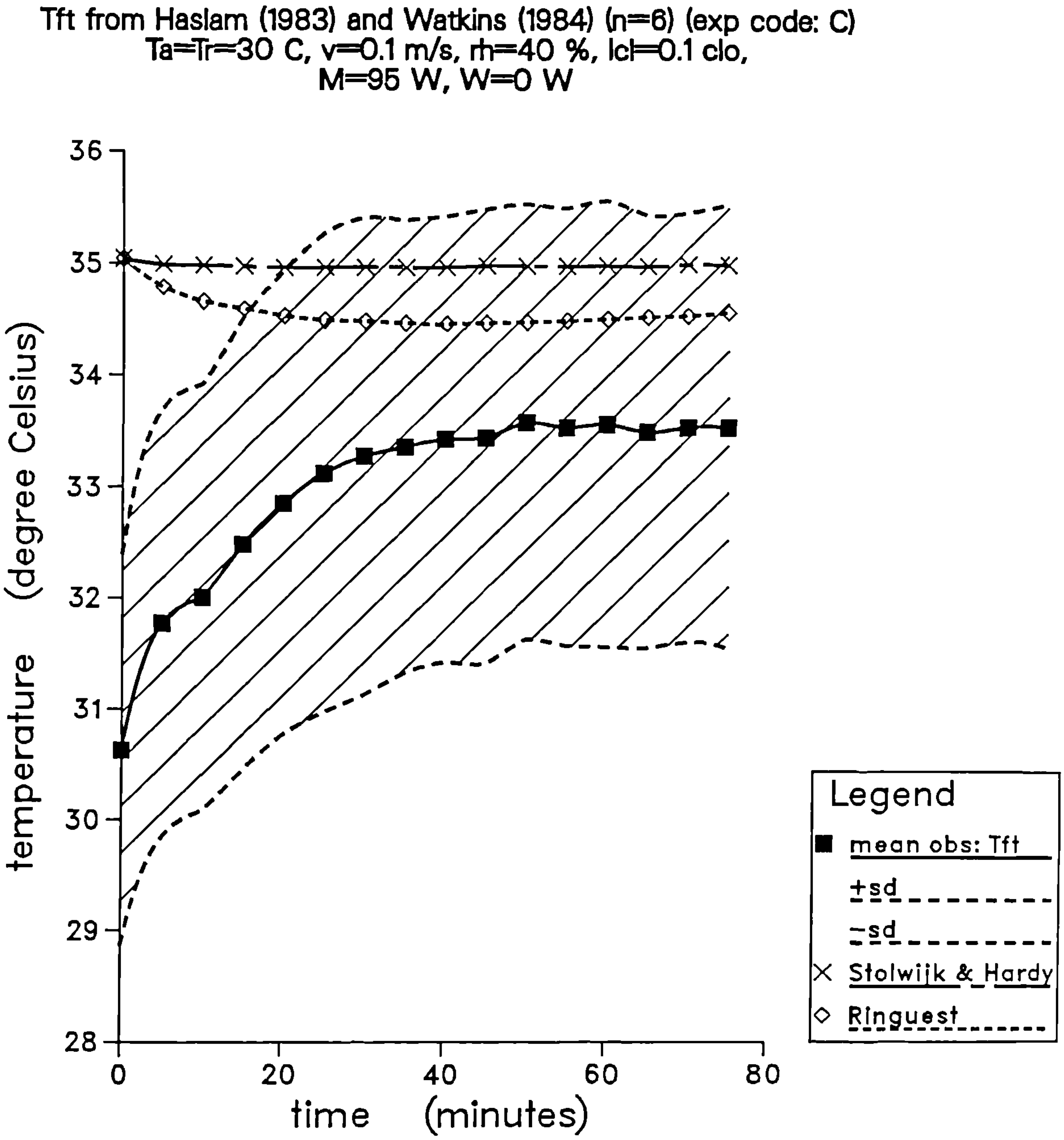


Figure 4.9. Observed auditory canal temperature response (Tac) and the models' predictions for LUT exposure D.

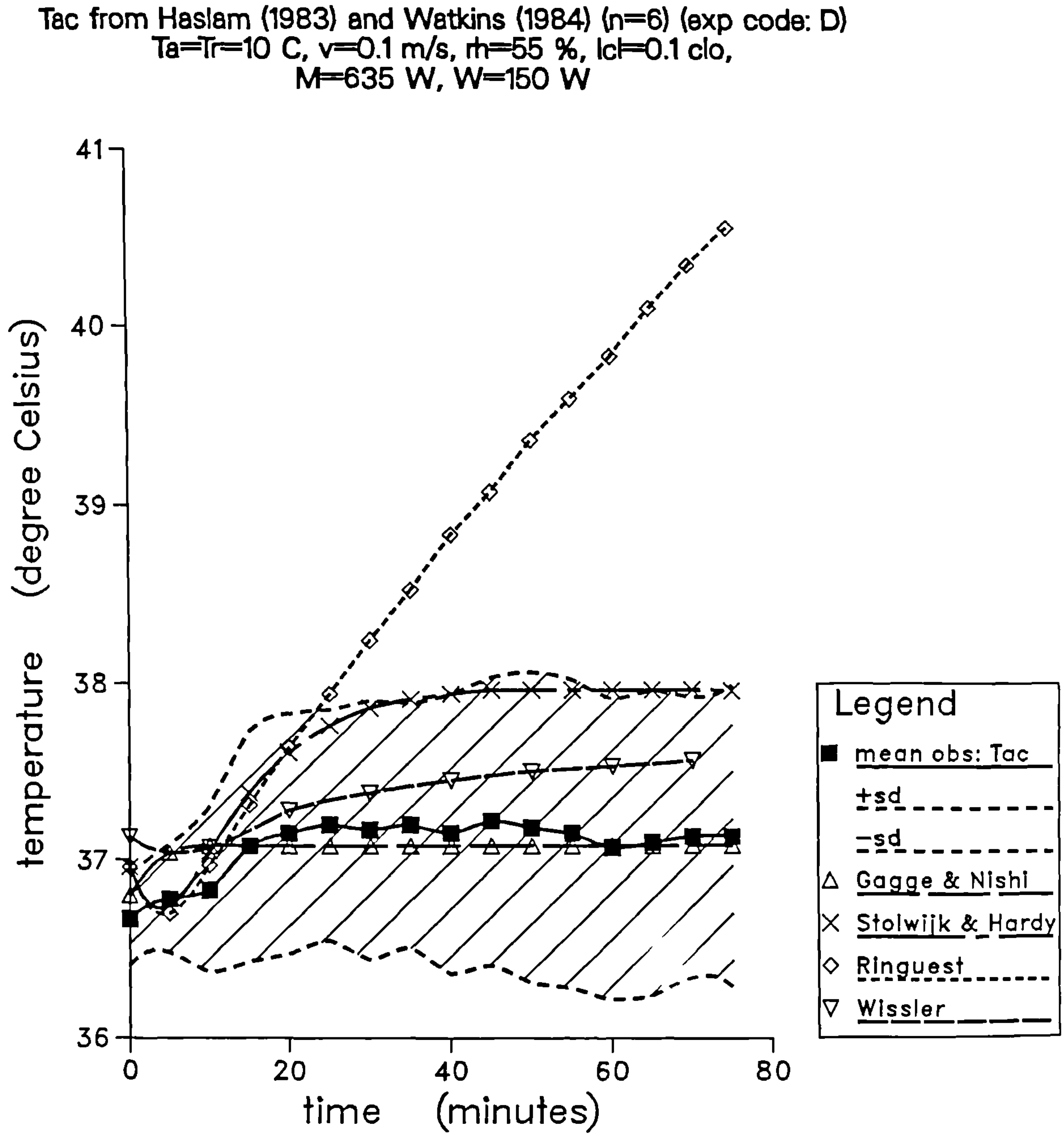


Figure 4.10. Observed mean skin temperature response (Tsk) and the models' predictions for LUT exposure D.

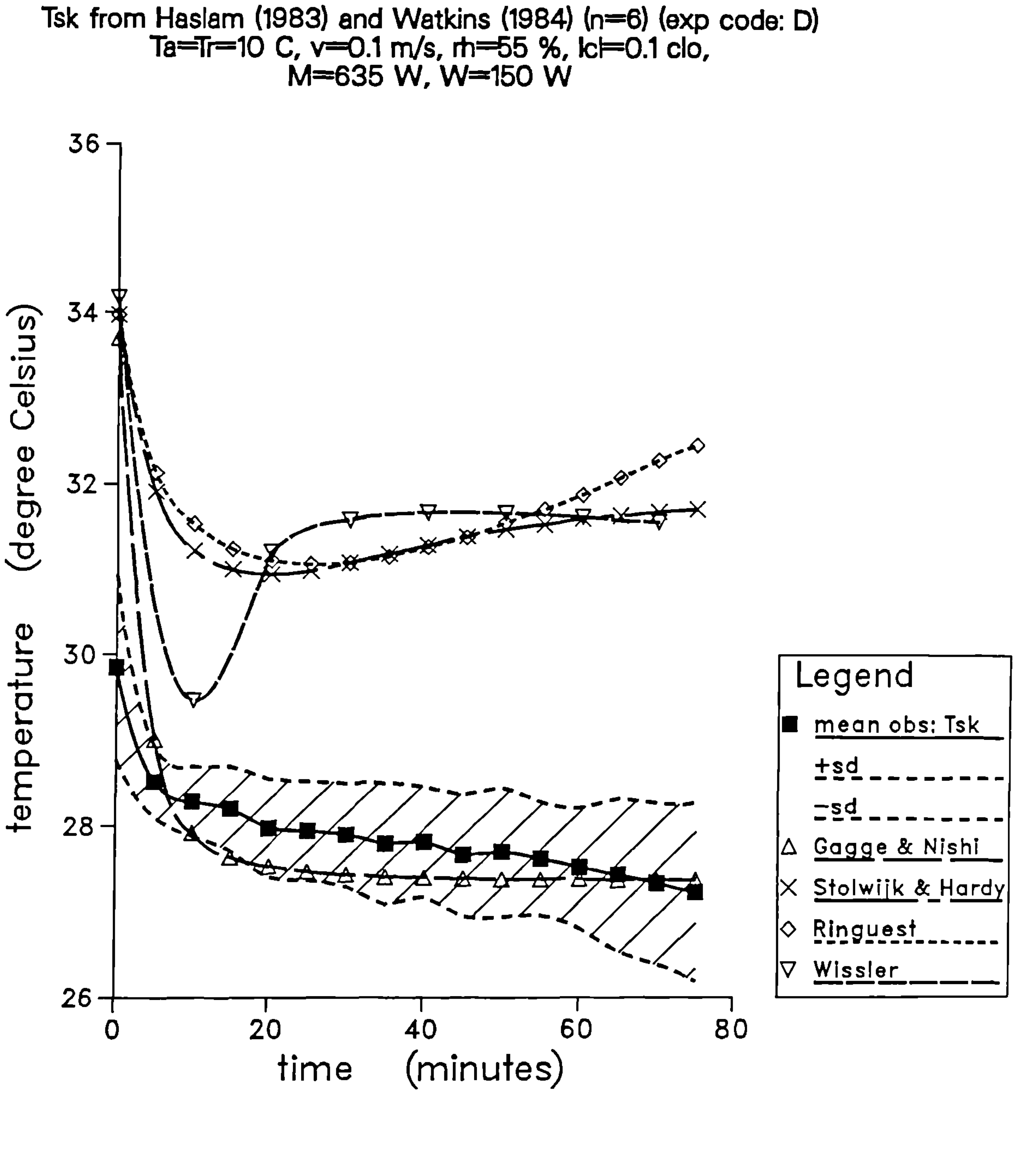


Figure 4.11. Observed hand skin temperature response (Thd) and the models' predictions for LUT exposure D.

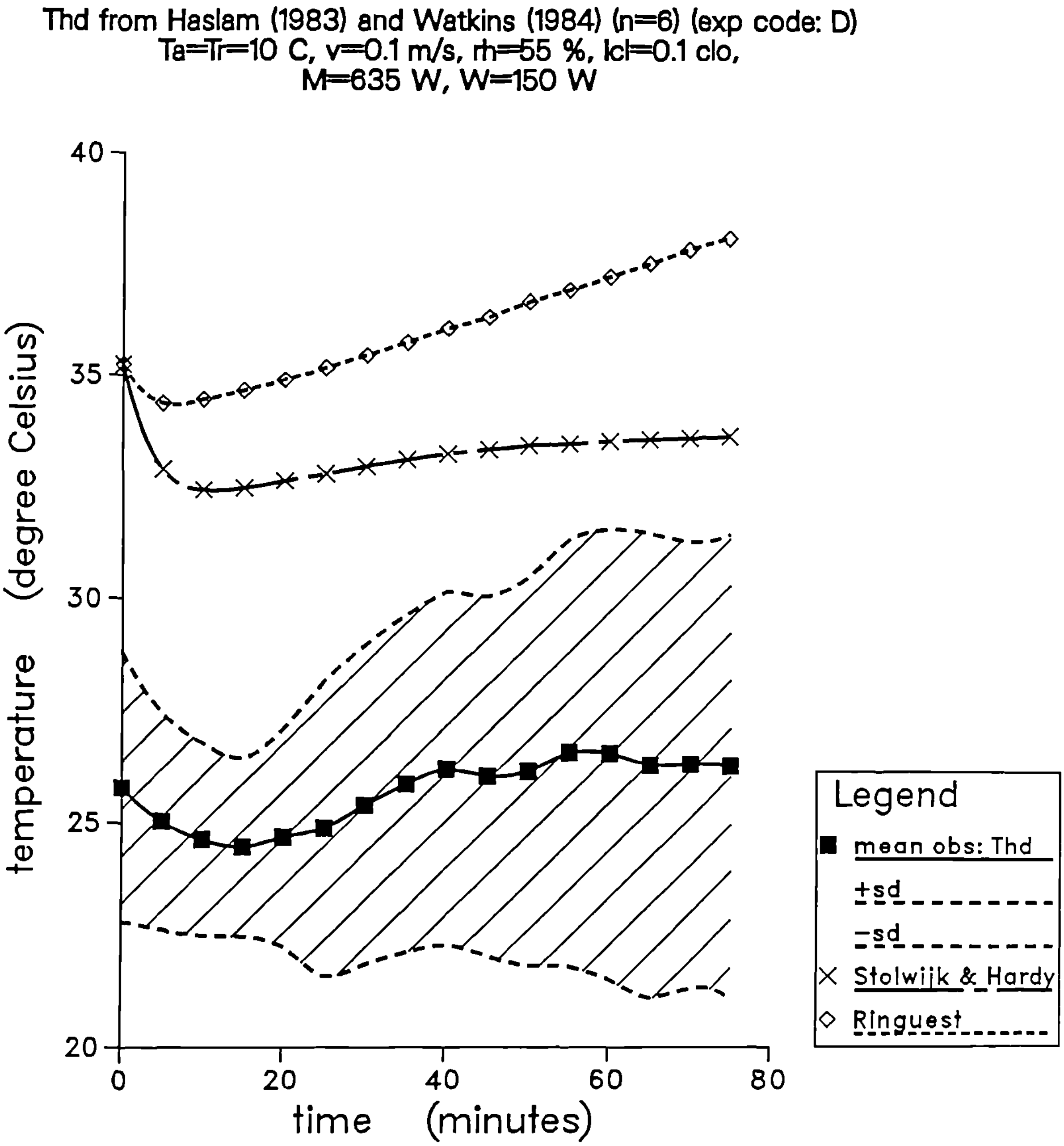


Figure 4.12. Observed foot skin temperature response (Tft) and the models' predictions for LUT exposure D.

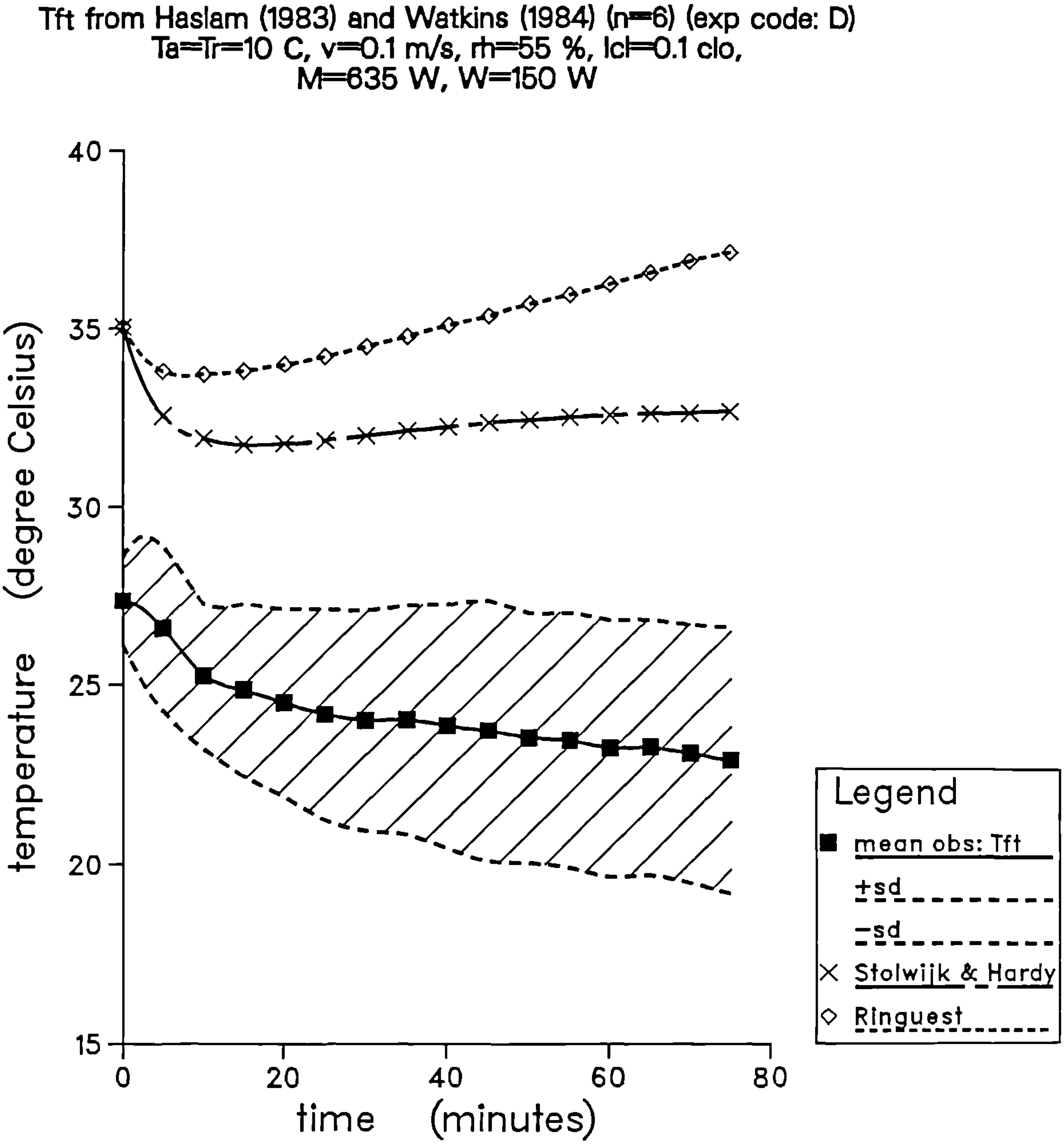


Figure 4.13. Observed auditory canal temperature response (Tac) and the models' predictions for LUT exposure E.

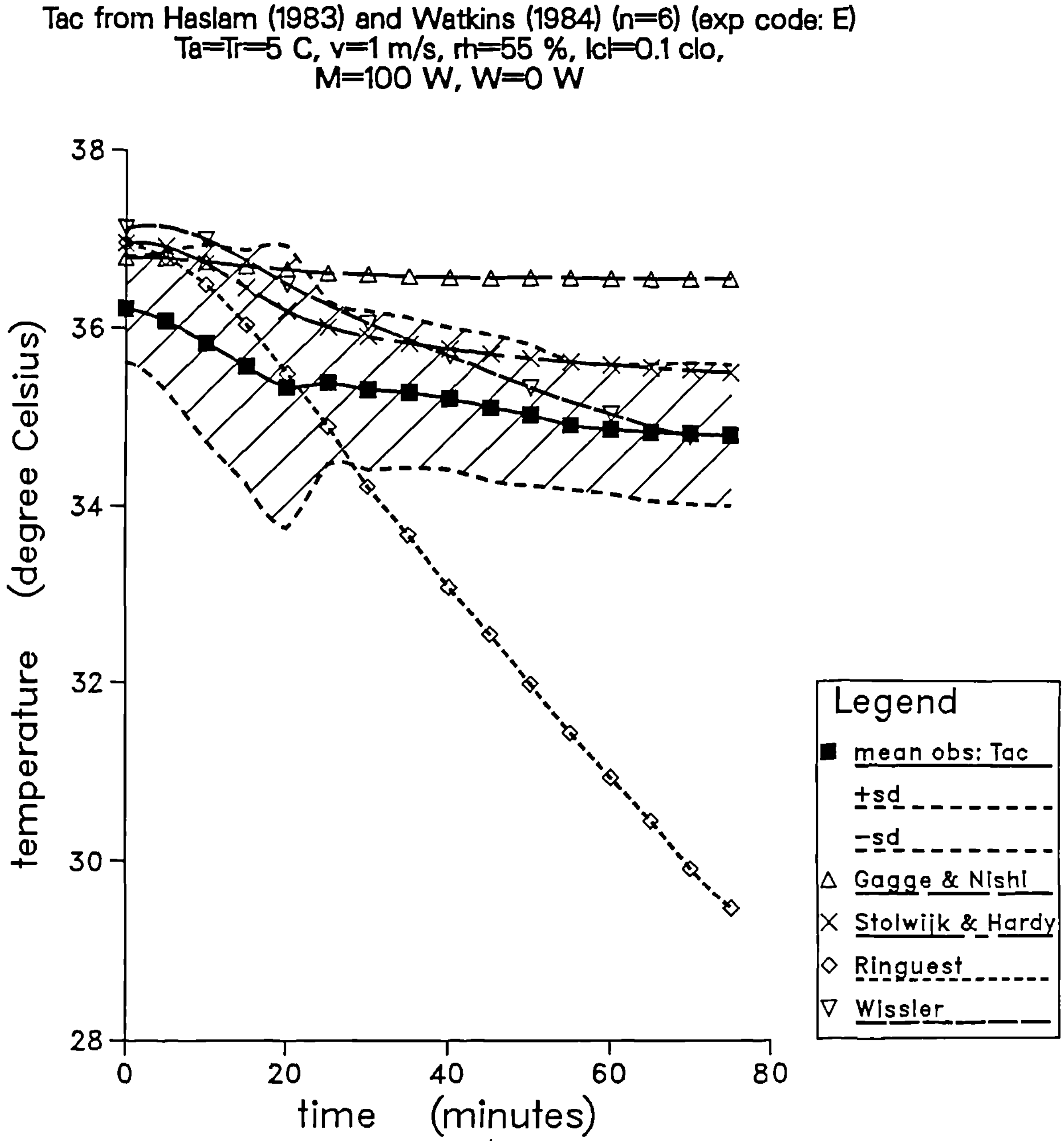


Figure 4.14. Observed mean skin temperature response (Tsk) and the models' predictions for LUT exposure E.

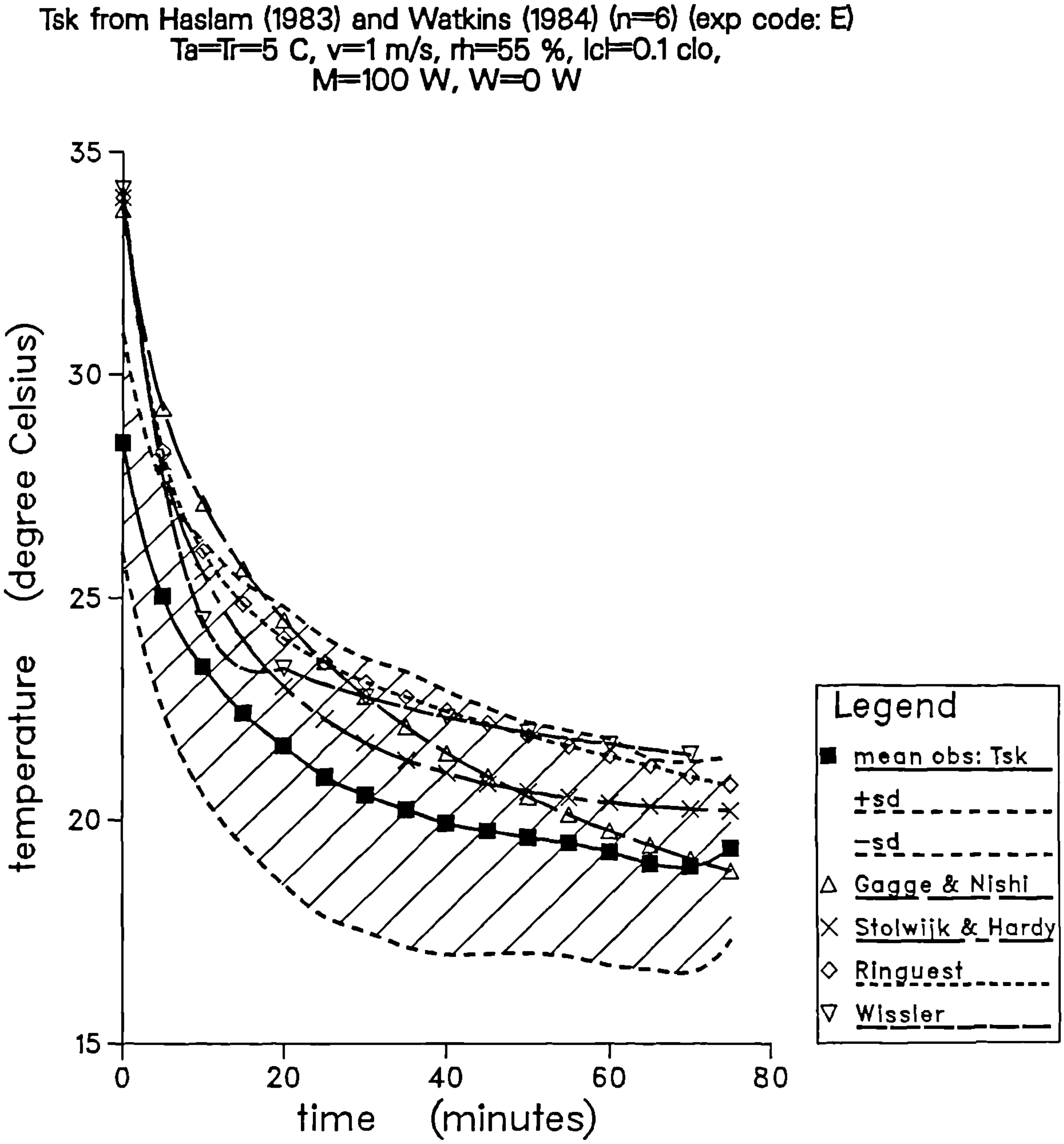


Figure 4.15. Observed hand skin temperature response (Thd) and the models' predictions for LUT exposure E.

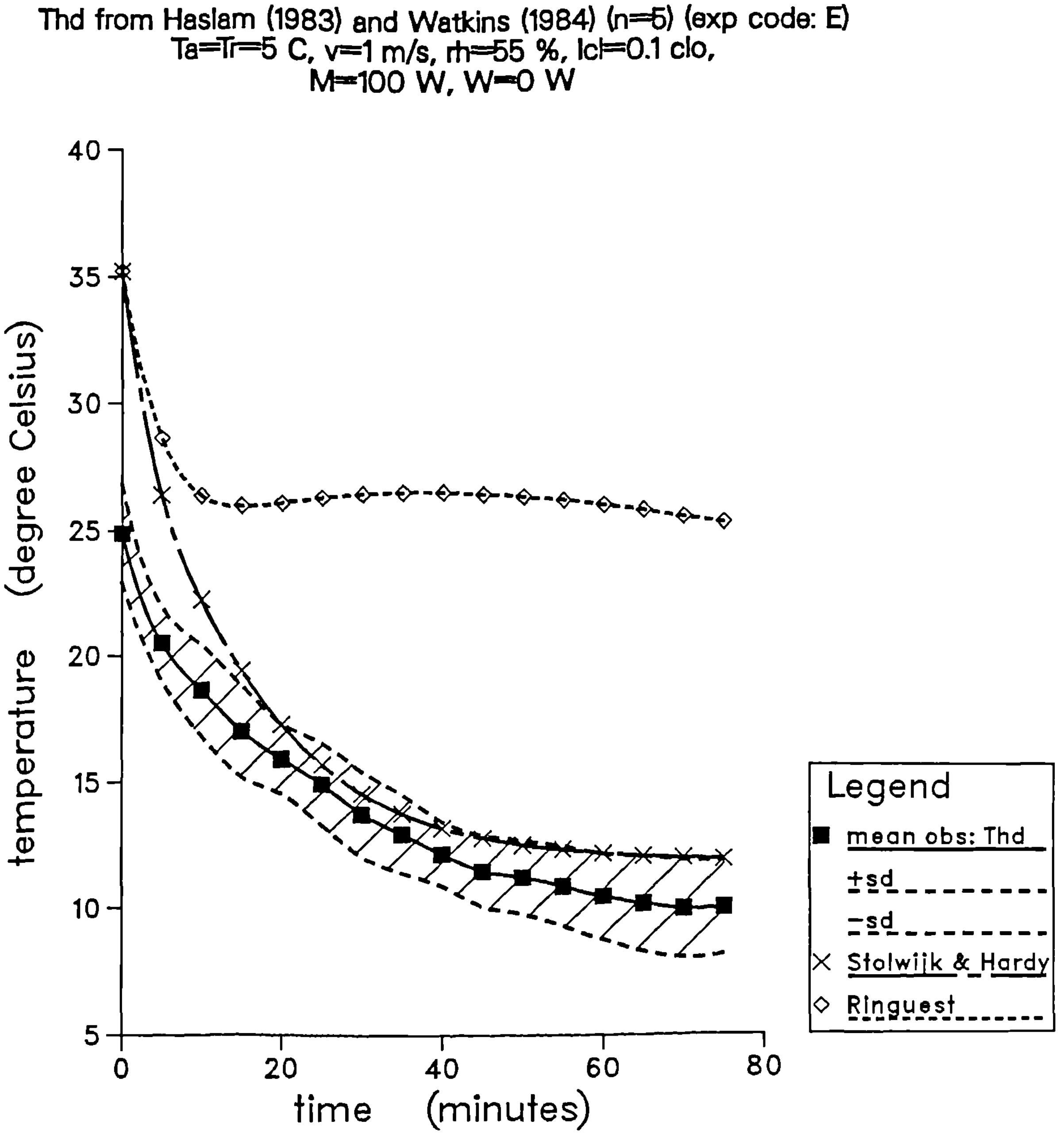


Figure 4.16. Observed foot skin temperature response (Tft) and the models' predictions for LUT exposure E.

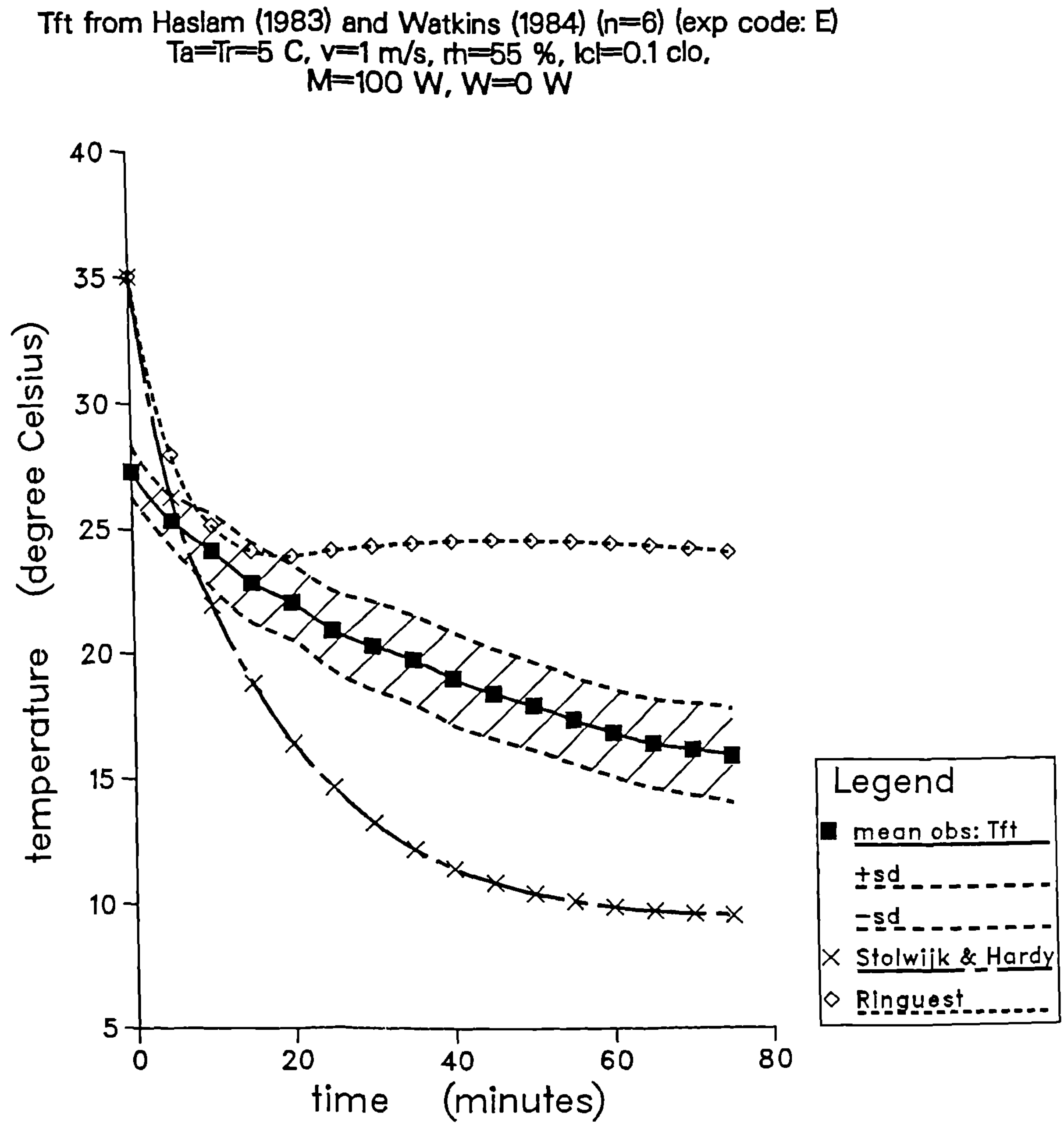


Figure 4.17. Observed rectal temperature response (Tre) and the models' predictions for Wagner and Horvath exposure 28.

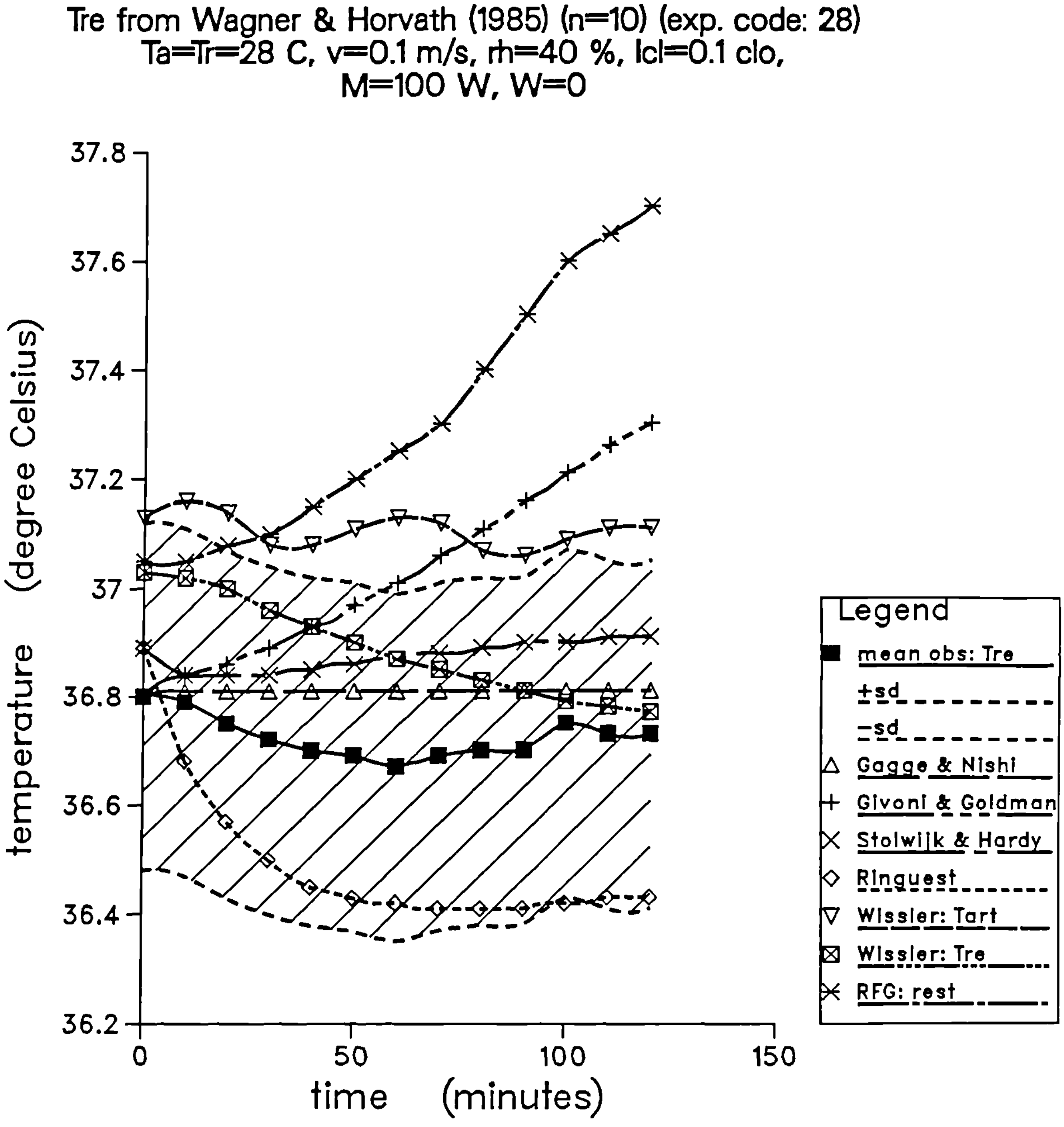


Figure 4.18. Observed mean skin temperature response (Tsk) and the models' predictions for Wagner and Horvath exposure 28.

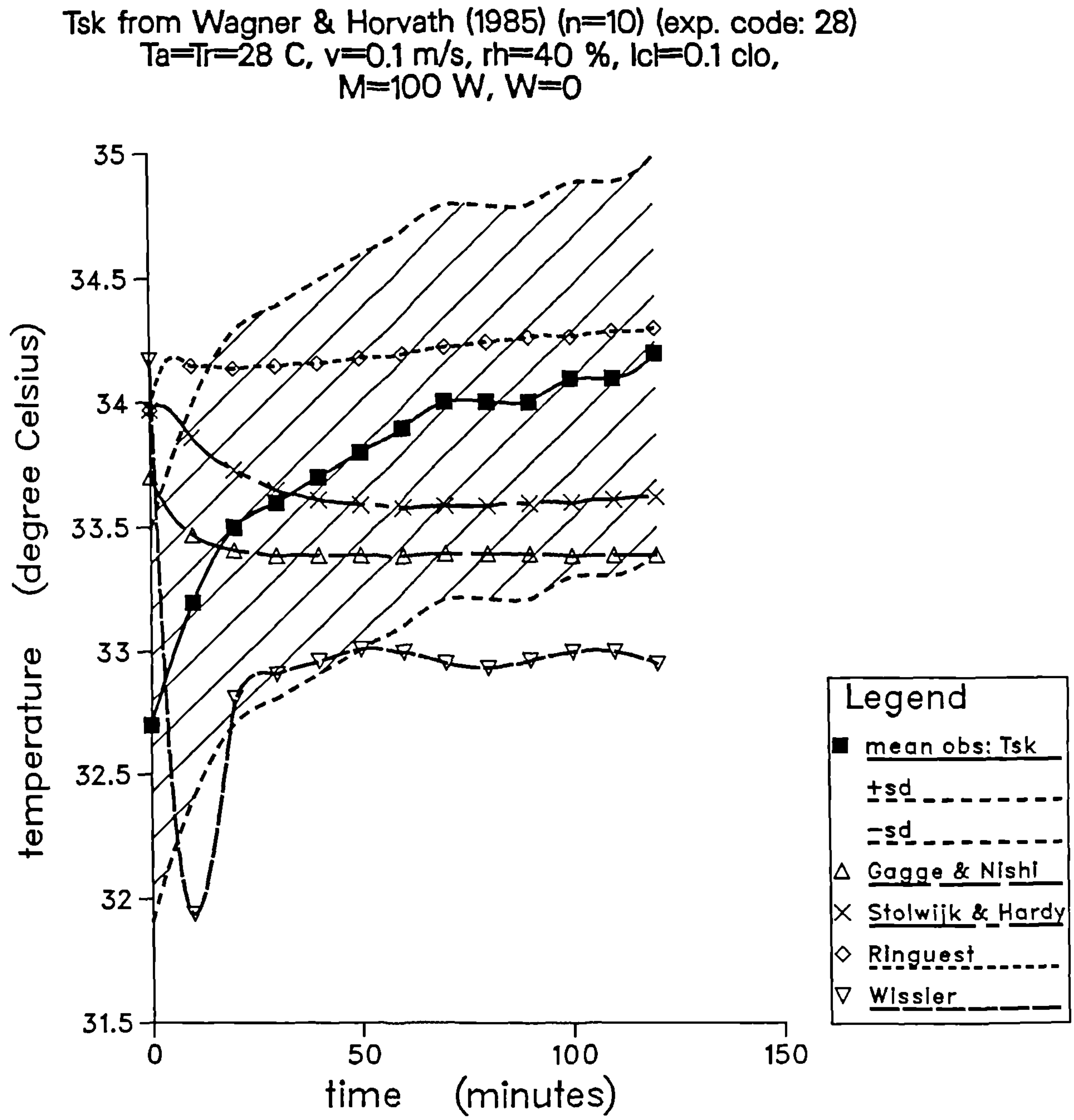


Figure 4.19. Observed rectal temperature response (Tre) and the models' predictions for Wagner and Horvath exposure 20.

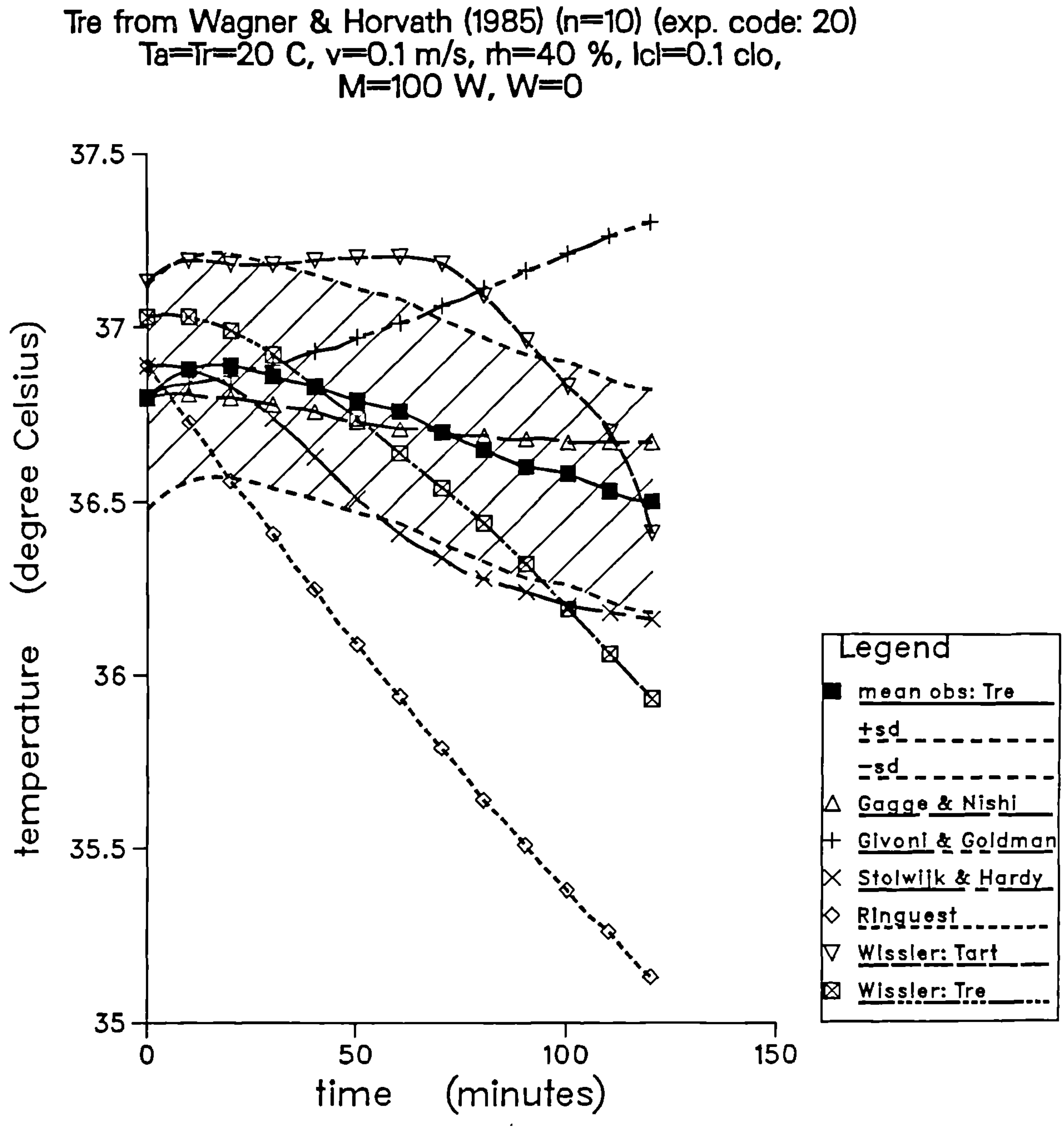


Figure 4.20. Observed mean skin temperature response (Tsk) and the models' predictions for Wagner and Horvath exposure 20.

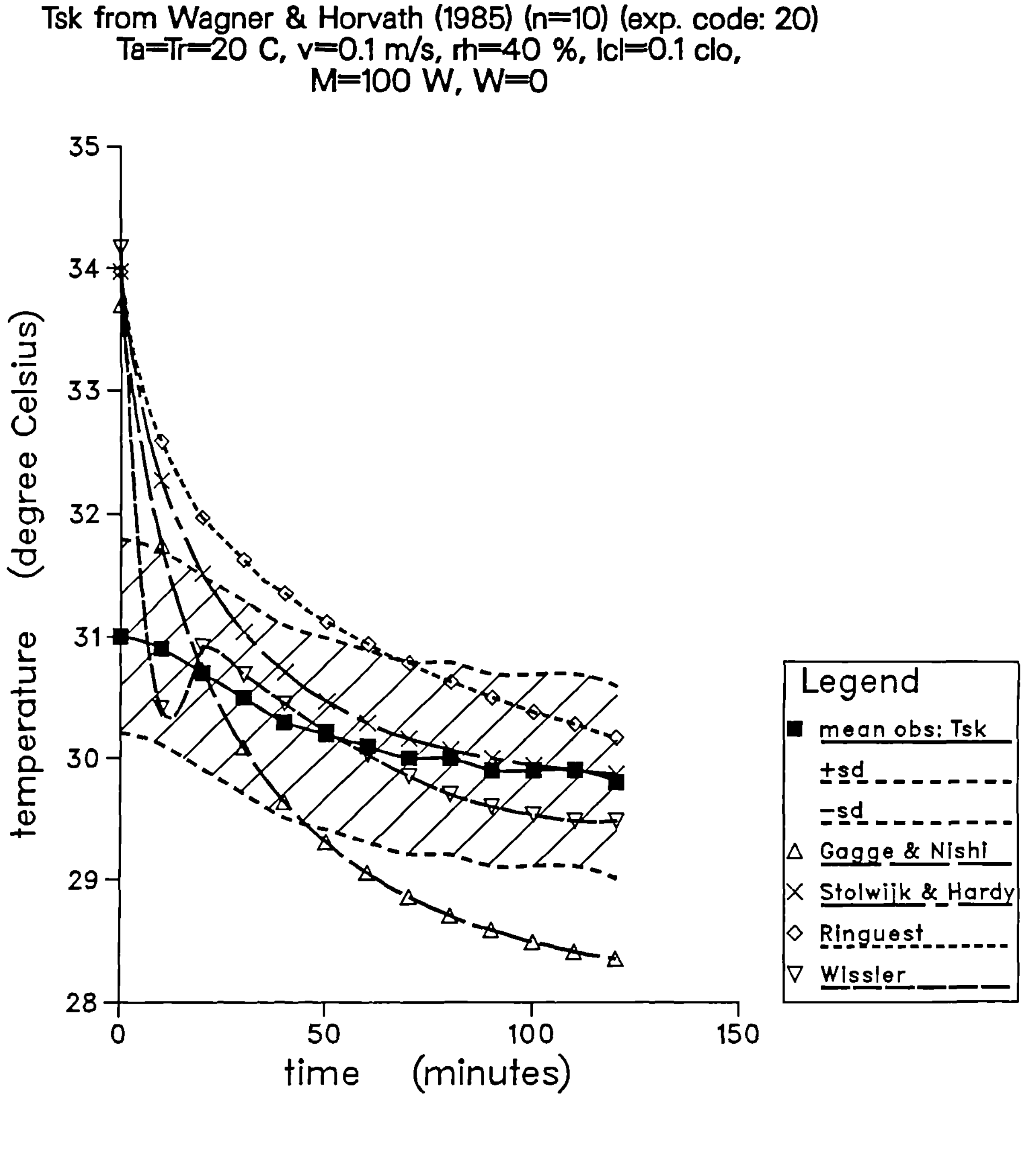


Figure 4.21. Observed rectal temperature response (Tre) and the models' predictions for Wagner and Horvath exposure 15.

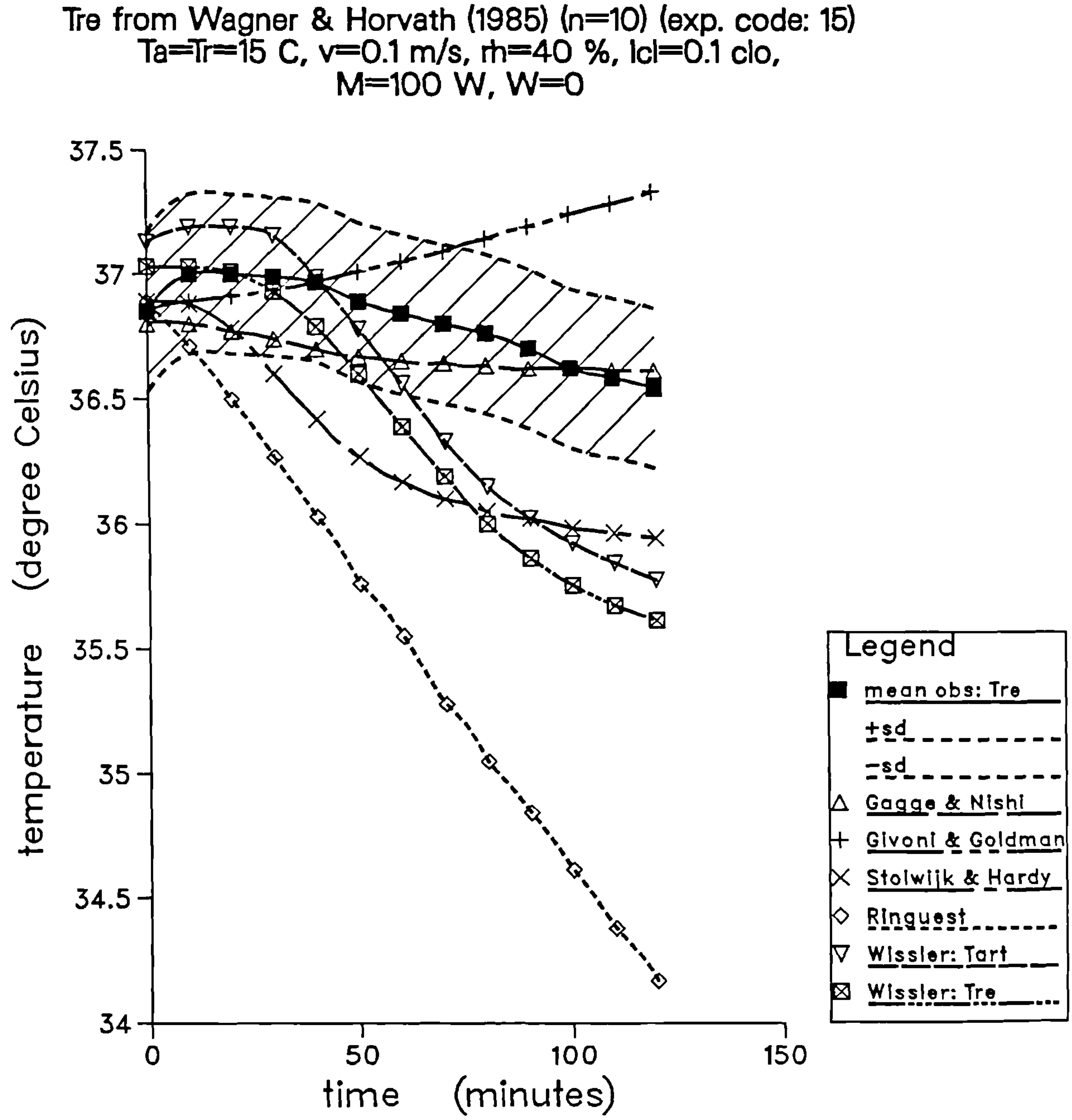


Figure 4.22. Observed mean skin temperature response (Tsk) and the models' predictions for Wagner and Horvath exposure 15.

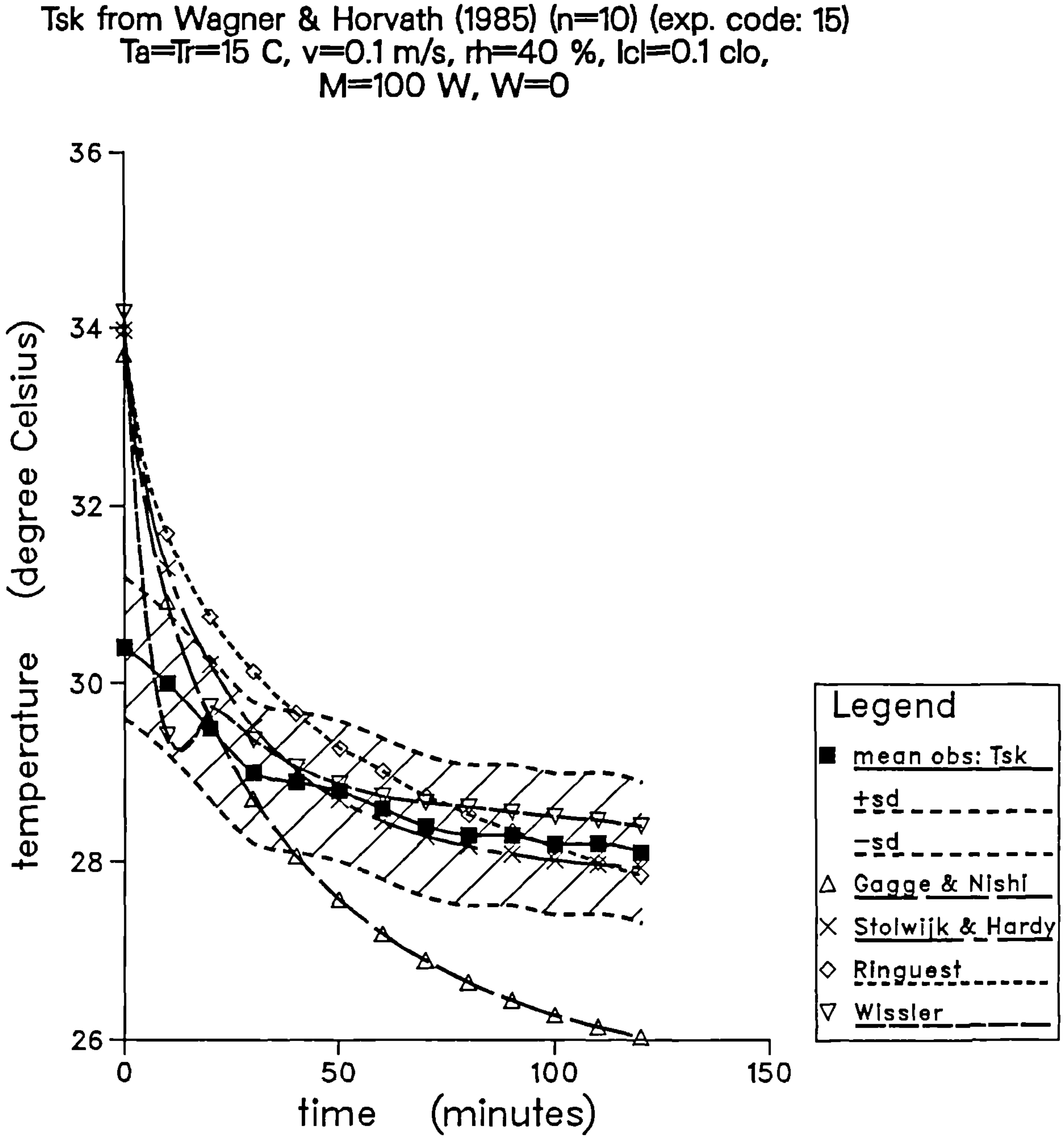


Figure 4.23. Observed rectal temperature response (Tre) and the models' predictions for Wagner and Horvath exposure 10.

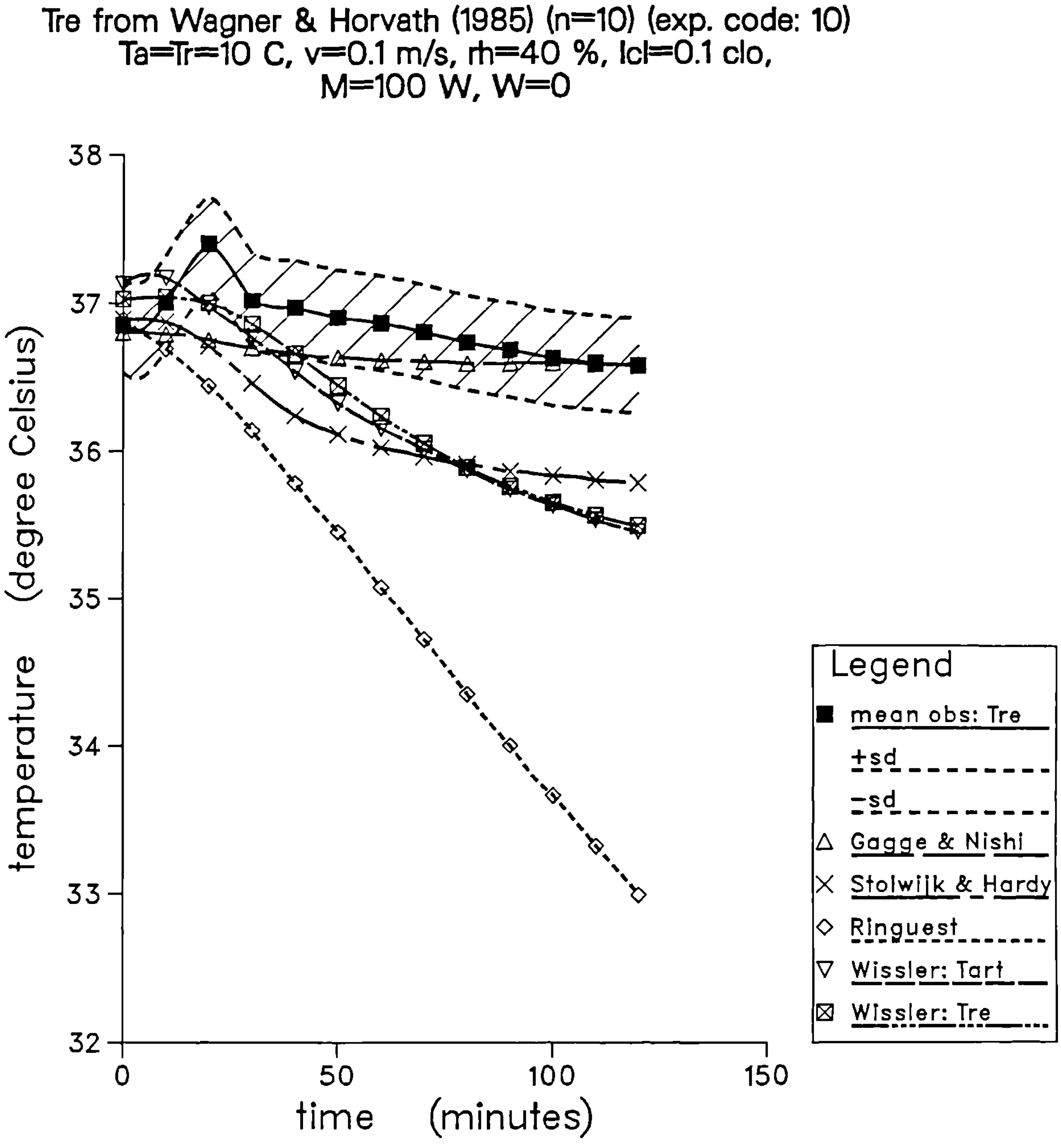
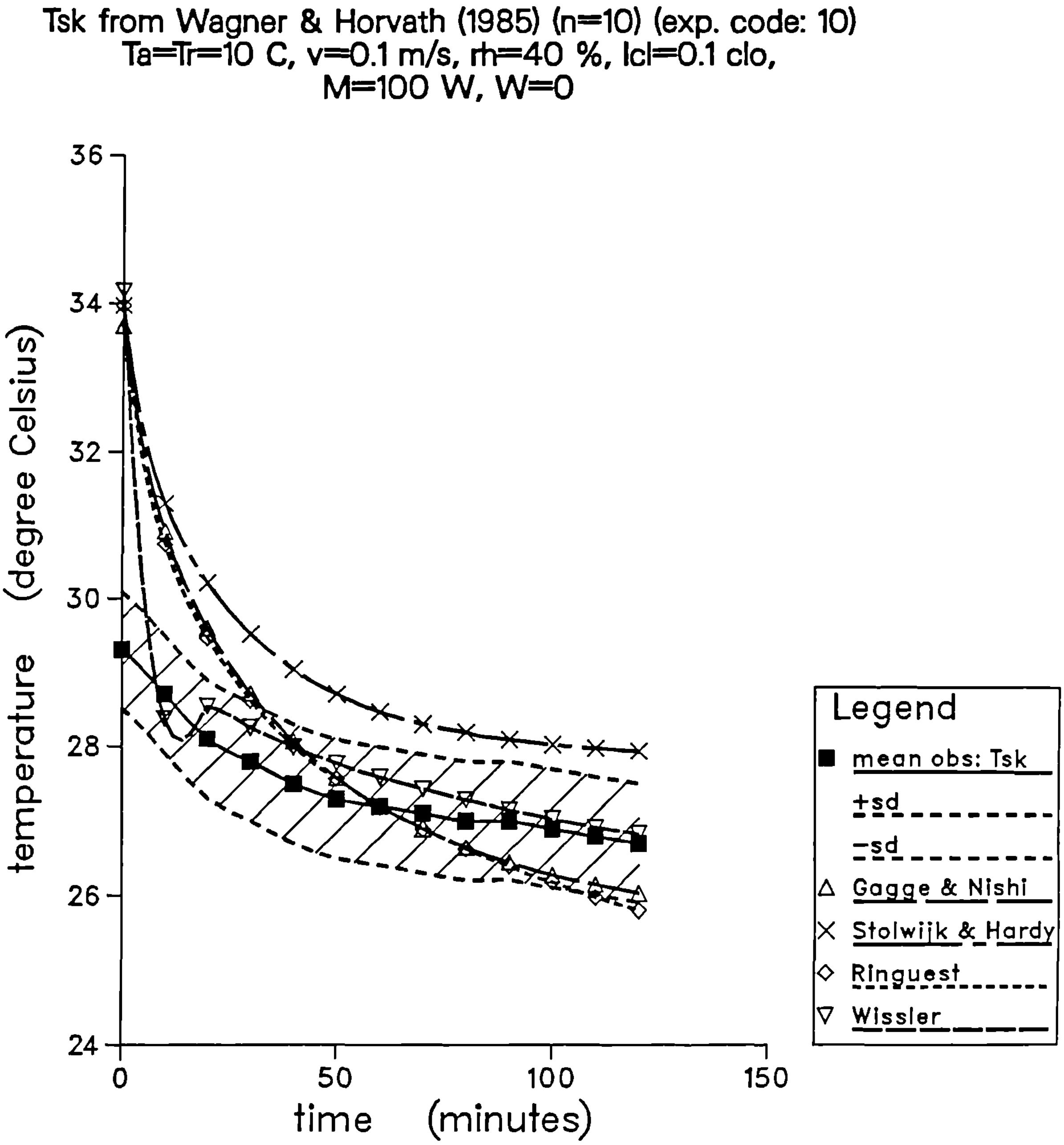


Figure 4.24. Observed mean skin temperature response (Tsk) and the models' predictions for Wagner and Horvath exposure 10.



predict these temperatures. Thd and Tft responses were not available from the predictions supplied for the Wissler model.

As the Givoni and Goldman and ISO/DP 7933 models are intended for hot environments their predictions are absent from the graphs for the cool and cold conditions. Goldman provided predictions from his model for all of the environmental conditions, but noted that he would not expect them to be accurate for the cooler environments. Goldman's predictions have only been included for those environments for which he thought they might be reasonable and are labelled as RFG on the graphs. Surprisingly, Goldman ran his model using the work equations (see chapter 3) for all but one of the environments, although several had the subjects at rest.

The temperature of the Stolwijk and Hardy head core compartment has been taken as the model's deep body temperature, as this compartment is used to produce the central signal for the thermoregulatory controller. The temperature of the model's trunk core compartment has not been used for comparison with the observed Tre data of Wagner and Horvath, as this temperature varies only slightly from that of the head core. This is because the Stolwijk and Hardy model does not provide the anatomical resolution necessary to distinguish the pelvic region from the rest of the body trunk.

The Wissler model makes arterial temperature (Tart) and Tre estimations of Tcr. It was the view of the IAM researchers that the model's Tart response was likely to most accurately represent Tcr. Moreover, Wissler (1984) used Tart to compare his model's deep body temperature predictions with observed oesophageal (Toe) and tympanic (Tty) temperatures. Therefore, the Wissler model's predictions for Tart have been used as its predictions of Tcr and appear on each of the Tcr graphs. For the Tre data of Wagner and Horvath, (figures 4.17 to 4.24) the Wissler model's Tre predictions are also given.

The ISO/DP 7933 model's predicted allowable exposure times are tabulated at the bottom of the figures for which they are appropriate. For the environments where an allowable exposure time fell within the period of the experimental exposure, the time has been indicated on the deep body temperature response graph. The model's allowable exposure times may be related to increases in Tcr of 0.8 and 1.0 °C and Tsk of 2.4 and 3.0 °C, for warning and danger respectively.

4.3. Discussion of Results

The observed data and each models' predictions are discussed in turn.

4.3.1. Observed Data

The observed experimental data were obtained from the exposure of minimally clothed subjects to unchanging environments. To be of use for most practical applications it would be necessary for the models to be able to predict the responses of clothed subjects to changing environmental conditions. However, as the exposure of minimally clothed subjects to unchanging conditions is the simplest case, it is unlikely that a model incapable of making reasonable predictions for simple conditions would be able to provide accurate predictions for more complex environmental exposures.

The LUT Tcr experimental data were measurements of Tac, while Wagner and Horvath recorded Tre. Each of these estimations of Tcr have their own characteristic response. For example, Tac can be affected by the environmental conditions and Tre is known to respond slowly to thermal transients. A consequence of the different characteristic responses is that temperatures measured simultaneously at different sites used for estimating deep body temperature may differ by over 1 °C. These issues and their implications for assessing the models' predictions are discussed fully in chapter 7.

4.3.2. Gagge and Nishi Model's Predictions

The Gagge and Nishi model's predictions were usually reasonable for both Tcr and Tsk, in terms of both response pattern and absolute temperature level. The model's predictions were the most accurate for several of the experimental environments, see for example figures 4.9, 4.10 and 4.17. It was therefore decided that this model should be included for further investigation.

4.3.3. Stolwijk and Hardy Model's Predictions

The Stolwijk and Hardy model's predictions of Tcr and Tsk compared reasonably with the observed data for many of the environmental conditions, for example figures 4.13 and 4.14, although there were exceptions, figure 4.10. The model's predictions for Thd were poor for LUT condition D, figure 4.11, but very good for condition E, figure 4.15. The model's predicted Tft responses did not compare well with the observed data.

These results suggested that it would be worthwhile to evaluate the Stolwijk and Hardy model against a broader range of experimental data.

4.3.4. Givoni and Goldman Model's Predictions

The Givoni and Goldman model's predicted Tre responses were satisfactory for the resting experimental conditions, for example figure 4.5, although for the Tre data of Wagner and Horvath, experiment code: 28, figure 4.17, the predictions followed a different response pattern. Figure 4.3 shows that the Givoni and Goldman model's predictions for the LUT conditions where the subjects were exercising in the heat differed markedly from the observed response. However, it should be noted that as the predicted Tre is compared with an observed Tac response, some of the discrepancy could have been due to the different characteristics of the temperatures at those sites.

The data used for this preliminary evaluation were for the exposure of minimally clothed subjects. Because of the empirical nature of the Givoni and Goldman model it is not possible to extrapolate findings of an evaluation of the model against nude data to the clothed case.

With regard to these factors, it was decided that the Givoni and Goldman model should undergo further evaluation.

4.3.5. ISO/DP 7933 Model's Predictions

The ISO/DP 7933 model's predictions were appropriate for the LUT environments A and B, figures 4.1 and 4.3. The model's warning allowable exposure times were broadly compatible with the increases in body temperatures observed. For both environments the skin temperatures had increased by over 2.5 °C at the model's warning allowable exposure times, figures 4.2 and 4.4. As the subjects were able to tolerate the environmental conditions for the full duration of the experiments with only slight increases of Tcr, for the ISO/DP model to have issued danger allowable exposure times within these periods would have been inappropriate.

As the ISO/DP 7933 model's predicted allowable exposure times had proved reasonable for the limited number of environmental exposures available for comparison, and in view of the direct applicability of the model's predictions, it was decided to include it for further evaluation.

4.3.6. Ringuest Model's Predictions

The Ringuest model's predictions of Tcr were poor, for example figures 4.3 and 4.19. This was surprising as the model's predicted Tsk responses were generally reasonable and in some instances very accurate, for example figure 4.2. The Ringuest model's predicted Thd and Tft responses were poor, for example figures 4.15 and 4.16.

It had not been possible to compare the predictions of this implementation of the Ringuest model with any published predictions from Ringuest's (1981) original version of the model. Because of the poor predictions, a check was made to ensure that the implementation instructions given by Ringuest had been followed correctly. No mistakes were found.

Given the poor Tcr predictions obtained, it is doubtful whether the model as implemented for this study is working as Ringuest had intended it to. It was therefore decided not to examine the model further.

4.3.7. Wissler Model's Predictions

As the Wissler model is the most sophisticated of those examined, it might have been expected to provide the most accurate predictions. This was not the case for the Tcr responses, where its predictions were neither clearly more or less accurate than those of the other reasonable models, for example figures 4.1 and 4.19. There appeared to be little difference in accuracy between the model's Tart and Tre responses, when compared with observed Tre data, figures 4.21 and 4.23. The model's predictions for Tsk were often very close to the observed responses, for example figures 4.4, 4.6, 4.22 and 4.24. An exception was for the data from LUT experiment D, where the subjects were exercising, figure 4.10.

The results of this preliminary evaluation suggested that the Wissler model is capable of making useful predictions. However, when making a large number of comparisons of a model's predictions against experimental data, it is essential, for the task to be manageable, that the model is able to produce its predictions in the form required for the graphics software used. As the Wissler model was not available at LUT and it was not possible to arrange this, it was decided that it would not be practical to include it in any further evaluation. In addition, the difficulties associated with implementing the Wissler model and the high level of computing power and time that are required to run it would prove major disadvantages to using the model in many potential applications.

4.3.8. Predictions Provided by Goldman (1987)

The predictions supplied by Goldman were less accurate than those of the version of the Givoni and Goldman model implemented for this study, for three of the four experimental exposures for which they were appropriate, figures 4.1, 4.3, 4.5, and 4.17.

Because of the empirical nature of the Goldman model, it is not possible to extrapolate the findings of this comparison to conditions where the subjects are wearing clothes. It would appear that for the nude case at least, there is no disadvantage in using the early version of the Givoni and Goldman model for this study.

4.4. Conclusions

It was concluded from this preliminary evaluation that the Gagge and Nishi, Stolwijk and Hardy, Givoni and Goldman and ISO/DP 7933 models can make sensible predictions and should be evaluated further against a wider range of experimental data.

It was decided not to include the Ringuest and Wissler models for any additional evaluation. In the case of the Ringuest model this was because of the model's poor Tcr predictions, and for the Wissler model because of practical difficulties with implementing and using the model.

CHAPTER 5

5. QUANTIFYING THE INSULATIVE EFFECTS OF CLOTHING

Clothing is worn under most circumstances to keep human body heat in or environmental heat and noxious substances out. Therefore, a model suitable for practical use should be able to adequately account for the insulative effects of clothing on heat transfer.

It may be seen from table 3.2 that not all of the published versions of the models considered by this evaluation allow for clothing, and those that do use a variety of different parameters to quantify its effects. This chapter reviews methods for quantifying the heat transfer properties of clothing and discusses their limitations and suitability for use with prediction models. Modifications that have been made to the models as a result of this review are then described.

5.1. The Effects of Clothing on Heat Transfer Between the Human Body and the Environment

Heat transfer between the nude human body and the environment has been discussed in chapter 2. Clothing usually reduces the heat flow between the human body and environment. Figure 5.1 shows how heat may pass through clothing.

5.1.1. 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.

Figure 5.1. Heat transfer through clothing.

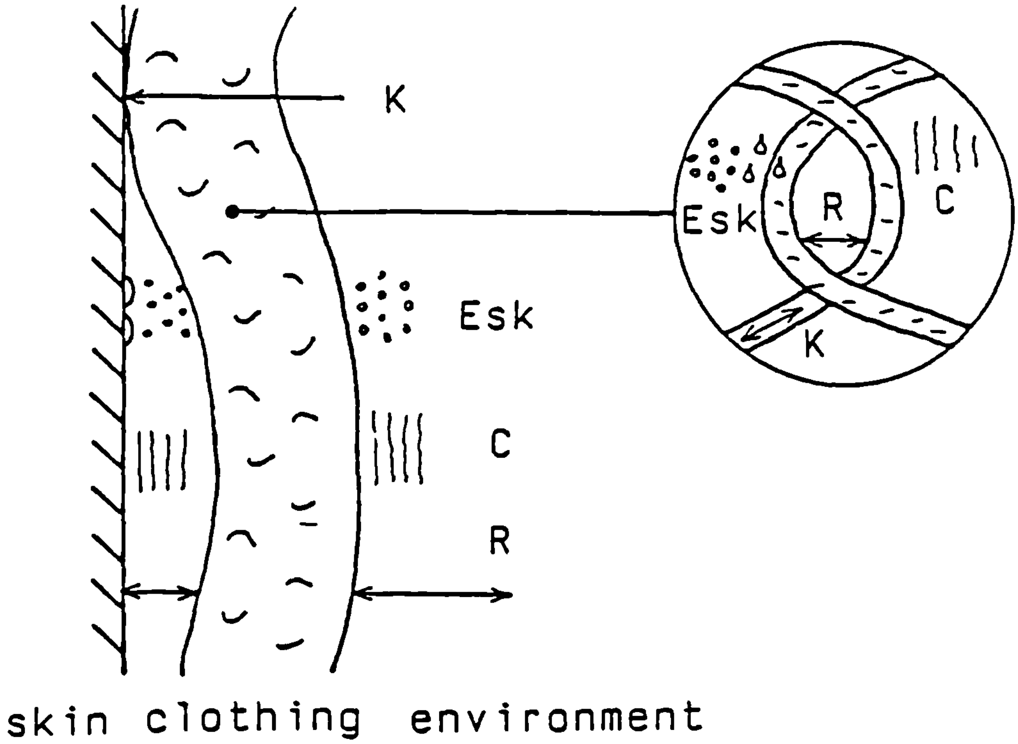
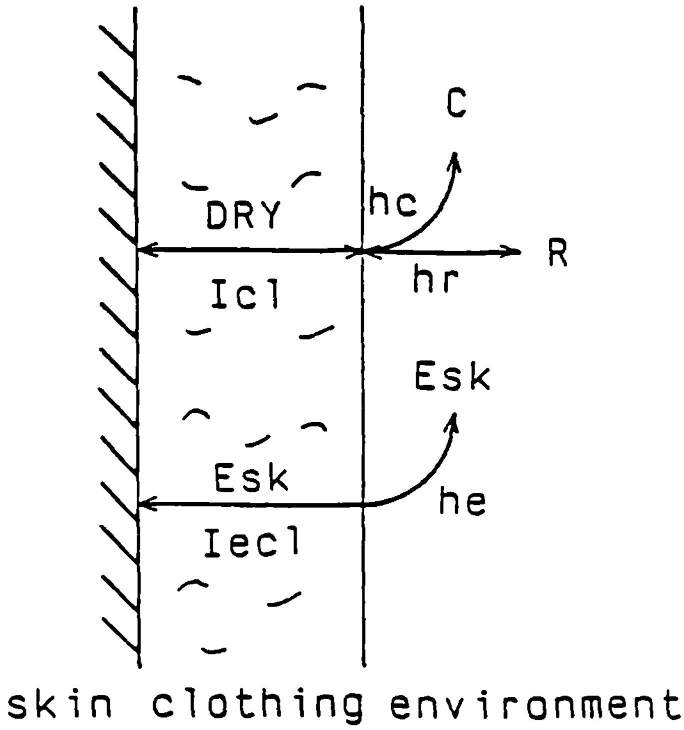


Figure 5.2. Simplified two parameter quantification of heat transfer through clothing.



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.

5.1.2. 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 can 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, 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.

5.2. 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. This simplified view of the effects of clothing on the heat transfer between the human and environment is depicted in Figure 5.2.

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

2.2, 2.7, and 2.9 in chapter 2 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:

$$Ia = \frac{1}{hc + hr} \quad (m^2.°C/W) \qquad (5.1)$$

where:

Ia = resistance of environment to dry heat transfer ($m^2.°C/W$)

Also:

$$Ie = \frac{1}{he} \quad (m^2.kPa/W) \qquad (5.2)$$

where:

Ie = resistance of environment to evaporative heat transfer ($m^2.kPa/W$)

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:

$$Dry = \frac{(Tsk - Tcl)}{Icl} \quad (W/m^2) \qquad (5.3)$$

where:

Dry = dry heat transfer through clothing (W/m^2)

Icl = resistance of clothing to dry heat transfer ($m^2.°C/W$)

Tcl = mean surface temperature of clothed body (°C) and for the evaporative heat transfer:

$$Esk = w \cdot \frac{(Psk - Pcl)}{Iecl} \quad (W/m^2) \qquad (5.4)$$

where:

Iecl = resistance of clothing to evaporative heat transfer ($m^2.kPa/W$)

Pcl = 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:

$$C = hc \cdot fcl\ (Tcl - Ta) \quad (W/m^2) \qquad (5.5)$$

$$R = hr \cdot fcl\ (Tcl - Tr) \quad (W/m^2) \qquad (5.6)$$

$$Esk = w \cdot he \cdot fcl\ (Pcl - Pa) \quad (W/m^2) \qquad (5.7)$$

where:

fcl = clothing area factor

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

The clothing area factor accounts for the increased surface area of the clothed compared to the nude body.

5.3. Measuring the Insulative Effects of Clothing

To quantify 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 Icl and Iecl and the coefficient fcl for the clothing-environment system of interest.

5.3.1. 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; McCullough, 1986; 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 (To) is an average of the air and mean radiant temperatures weighted by their respective heat transfer coefficients:

$$To = \frac{(hc \,.\, Ta + hr \,.\, Tr)}{(hc + hr)} \qquad (^\circ C) \qquad (5.8)$$

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:

$$Dry = \frac{(Tsk - To)}{Ia} \qquad (W/m^2) \qquad (5.9)$$

When clothing is worn:

$$Dry = \frac{(Tsk - To)}{IT} \qquad (W/m^2) \qquad (5.10)$$

where:

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

$$= Icl + \frac{Ia}{fcl} \qquad (m^2.°C/W) \qquad (5.11)$$

For the special case when the air and mean radiant temperatures are equal it can be shown that To is equal to Ta. Ta may therefore be substituted for To in equation 5.10.

Thus, for a clothed, dry manikin that has reached equilibrium in an environment where Ta and Tr are equal:

$$IT = \frac{(Tsk - Ta)\ Am}{H} \qquad (m^2.°C/W) \qquad (5.12)$$

where:

H = power input to manikin (W)

Am = manikin surface area (m^2)

Equation 5.11 shows that in order to calculate Icl, it is also necessary to know Ia and fcl. Ia can be obtained by operating the manikin nude and fcl may 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 and from reports (e.g. ASHRAE, 1985; McCullough, 1986; McCullough et al., 1982; McCullough et al., 1985; McCullough and Jones, 1984; 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 transfer.

In order to estimate fcl, Fanger (1970) suggested the relationship:

$$fcl = 1.0 + 0.15 \cdot Icl \quad (ND) \qquad (5.13)$$

McCullough and Jones (1984), McCullough et al. (1985), McCullough et al. (1983), and Olesen (1985) examined this relationship and found that it tends to underestimate the fcl associated with a clothing ensemble. From a study on a large number of clothing ensembles McCullough et al. (1985) suggested a relationship of:

$$fcl = 1.0 + 0.31 \cdot Icl \quad (ND) \qquad (5.14)$$

However, they emphasized that the relationship between fcl and Icl is poor. Wherever possible measured values of fcl 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 (IT), intrinsic insulation (Icl) and effective insulation (Icle). IT and Icl are as defined above; the effective clothing insulation is defined as:

$$\text{Icle} = \text{IT} - \text{Ia} \qquad (m^2.°C/W) \qquad (5.15)$$

The effective clothing insulation is obtained by subtracting the resistance of the environment, as obtained by operating a manikin nude, from the total resistance of the clothing and environment to dry heat transfer without correcting for the increased surface area due to the clothing. Icl is more convenient than Icle for use in heat transfer analysis but requires that fcl is known or can be estimated. IT varies with the environmental conditions. If Icle or IT and the conditions under which they were measured are known for a clothing ensemble, then it is possible to estimate Icl from them.

The clothing insulation values reported in the literature for the resistance of clothing to dry heat transfer are usually reported in clo units, with 1 clo = 0.155 $m^2.°C/W$ (Gagge et al., 1941).

5.3.2. Resistance of Clothing to Evaporative Heat Transfer

The resistance of clothing to evaporative heat transfer (Iecl) 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; McCullough, 1986; and McCullough et al., 1982).

The equation for evaporative heat transfer through clothing, in terms of the vapour pressure gradient between the skin and the environment is given by:

$$Esk = w \cdot \frac{(Psk - Pa)}{IeT} \quad (W/m^2) \qquad (5.16)$$

where:

IeT = total resistance of clothing and environment to evaporative heat transfer

$$= Iecl + \frac{Ie}{fcl} \quad (W/m^2) \qquad (5.17)$$

Iecl is the parameter that quantifies 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 reported the effects of the clothing in terms of several permeability indices, although measurements of IeT have been reported from studies on human subjects (Holmér 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 Iecl.

5.3.2.1. Woodcock Moisture Permeability Index

A moisture permeability index (im), first introduced by Woodcock (1962) has been used extensively to quantify the effects of clothing on the transmission of water vapour between the skin and the environment (e.g. Givoni and Goldman, 1972; McCullough, 1986; 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 im index expands the equation for evaporative heat transfer so that:

$$Esk = w \cdot \frac{16.5 \cdot im}{IT} (Psk - Pa) \quad (W/m^2) \qquad (5.18)$$

where:

im = the moisture permeability index

$$= \frac{heT/hT}{he/hc} \quad (ND) \qquad (5.19)$$

where:

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

$$= \frac{1}{IT} \quad (W/m^2.°C)$$

heT = the total evaporative heat transfer coefficient for the clothing and air system ($W/m^2.kPa$)

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

The Woodcock permeability index has been measured on a wetted manikin for a range of clothing garments and ensembles (Breckenridge and Goldman, 1977; McCullough, 1986; and McCullough et al, 1982). IT is measured with the manikin dry. As IT varies with the environmental conditions, the same conditions should be used when the manikin is wet. With the manikin wet, Esk is equal to the power input to the manikin less the power input when the manikin was dry. Psk and Pa can be calculated from Tsk, Ta and the air humidity. The index can then be derived from equation 5.18, assuming w=1.

In theory im varies from 0 to 1, with a value of 1 indicating that the maximum evaporative heat transfer can occur. In practice im 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 im given in the literature, it is also necessary to know the thermal conditions such as Ta, Tr, Tsk, v etc. prevailing when they were measured.

5.3.2.2. Nishi Permeation Efficiency Factor

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

$$Esk = w \cdot Fpcl \cdot he\ (Psk - Pa) \qquad (W/m^2) \qquad (5.20)$$

where:

Fpcl = permeation efficiency factor

$$= \frac{Ie}{Iecl + Ie} \qquad (ND) \qquad (5.21)$$

Fpcl varies between 0 and 1 for minimum and maximum vapour permeation respectively. Nishi and Gagge (1970b) reported a series of experiments which used napthalene sublimation to determine the permeation efficiency factor of light cotton clothing. From these experiments they obtained the empirical equation:

$$Fpcl = \frac{1}{1 + 0.92 \cdot hc \cdot Icle} \qquad (ND) \qquad (5.22)$$

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 Fpcl available in the literature and equation 5.22 is valid only for light cotton clothing.

5.3.2.3. Lotens Permeation Ratio

Oohori et al., (1984) introduced a factor (iL) that they called the Lotens permeation ratio. This ratio is similar to the Woodcock im, and is the ratio of the Lewis number for the clothing layer alone, to the Lewis number for the air layer:

$$iL = \frac{hecl/hcl}{he/hc} \quad \text{(ND)} \qquad (5.23)$$

where:

$$hcl = \frac{1}{Icl} \quad (W/m^2.{}^\circ C) \qquad \text{and } hecl = \frac{1}{Iecl} \quad (W/m^2.kPa)$$

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

$$E = w \; . \; \frac{(Psk - Pa)}{\dfrac{Icl}{16.5 \; . \; iL} + \dfrac{1}{fcl}} \quad (W/m^2) \qquad (5.24)$$

Unlike im, iL is not affected by air speed, or radiative heat exchange. Oohori et al., (1984) give values of iL, for a range of fabrics, measured by weighing the evaporation of water from a vessel covered with clothing samples.

Lotens and Linde (1983) and Lotens (1988) define a slightly different ratio (imL), where:

$$imL = \frac{heT/hcT}{he/hc} \quad \text{(ND)} \qquad (5.25)$$

where:

hcT = the total dry non-radiative heat transfer coefficient for the clothing and air system ($W/m^2.{}^\circ C$)

Thus, imL 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.

5.3.2.4. Determining Iecl from im, Fpcl or iL

If im or Fpcl and the conditions under which they were measured or iL are known for a clothing ensemble, then it is possible to calculate Iecl from these factors.

At present the literature contains few reported values of Fpcl or iL and only the method for calculating Iecl from im will be derived here.

Substituting IeT in equation 5.16 with equation 5.17, equating with equation 5.18 and rearranging gives:

$$Iecl = \frac{IT}{16.5 \cdot im} - \frac{Ie}{fcl} \qquad (m^2.kPa/W) \qquad (5.26)$$

Ie in this equation is that prevailing when im was measured, and may be determined from the value of Ia obtained from operating the manikin dry and nude. However, it is necessary to remove the hr component from Ia; hr is in turn dependent on Tcl and Tr. Tcl is not usually measured, but both hr and Tcl may be determined using numerical iteration (e.g. see Gagge et al., 1986, Appendix B).

5.4. 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 are 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 (Holmér and Elnas, 1981) calorimetry, thus enabling the insulation of their clothing to be determined.

5.4.1. 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 and 1984). Nielsen et al. (1985) and Olesen and Nielsen (1984) have observed decreases in Icl 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 and 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.

A number of researchers have attempted to quantify the effects of clothing ventilation. Birnbaum and Crockford (1978), Lotens and Havenith (1988) and Sullivan et al. (1987a and 1987b) described methods for measuring the air exchange between clothing and environment on human subjects. Breckenridge (1977) and Givoni and Goldman (1972) provided 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. IT and im 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.

5.4.2. Movable Thermal Manikins

It is 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 Icl 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 suggested 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 attributed 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 resistance to dry heat transfer 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. Developments in manikin technology may enable further advances in these areas to be made. Recently a life-sized robot based manikin has been developed, capable of performing complex activities such as walking or crawling, and breathing and sweating in a realistic manner (New Scientist, 1988).

5.4.3. 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 hc and he. 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 apparent 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.

5.4.4. Estimating Clothing Insulation from Garment Insulations

McCullough and Jones (1984) and 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.

5.4.5. Clothing Area Factor

Care is required when using measured values of the clothing area factor (fcl) for clothing that may be worn in a variety of different ways as this may affect the fcl. For example, a shirt may be worn tucked into trousers or left hanging loose. For some types of clothing, the measured fcl may have been considerably affected by the way in which the manikin was dressed when the fcl was measured (McCullough et al., 1982).

5.5. Theoretical Limitations of the Two-Parameter Quantification of the Insulative Effects of Clothing

The two-parameter quantification of clothing insulation described above has been criticized as being theoretically inadequate (Lotens and Linde, 1983). The two-parameter quantification assumes that the dry and evaporative heat transfer processes are independent, but it is clear that this is not the case. As described earlier, the evaporative heat transfer through clothing may affect the dry heat transfer when water vapour either condenses or evaporates within the clothing, giving or taking up heat. 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.

Another shortcoming of the two-parameter quantification 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.

The two-parameter approach as described above 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 methods 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 quantification 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 methods to be of use in practice. Although the two-parameter quantification 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 quantification of clothing insulation are Icl and Iecl. While suitable data exist for Icl for a varied range of clothing ensembles, little data are available for Iecl. However, as described above, Iecl may be calculated from im for which some data have been published.

5.6. Clothing and the Models of Human Response to Thermal Environments

The methods used by each model, in their latest published versions, to account for the insulative effects of clothing are outlined and any modifications required as a result of this review described below.

5.6.1. Gagge and Nishi Model

5.6.1.1. Published Model's Quantification of Clothing Insulation

A more recent version of the Gagge and Nishi model than used for the preliminary evaluation detailed in chapter 4, has been published (Gagge et al., 1986). The Gagge et al. (1986) model uses Icl and IeT to quantify the insulative effects of clothing. IeT is calculated from iL.

5.6.1.2. Modifications to the Published Model

Gagge et al. (1986) did not provide a complete program listing for the revised version of their model. It was, therefore, decided to update the working version of the model used for the preliminary evaluation with the modifications that had been made by Gagge et al. to their model. These changes mainly improved the structure of the computer program and did not significantly affect its predictions.

The model has also been modified so that it takes im as an input, rather than iL, and calculates Iecl from this using equation 5.26 above. IeT is then calculated from Iecl using equation 5.17.

5.6.2. Stolwijk and Hardy Model

5.6.2.1. Published Model's Quantification of Clothing Insulation

The published version of the Stolwijk and Hardy model (Stolwijk and Hardy, 1977) does not account for clothing. Montgomery (1974) modified an earlier version of the Stolwijk and Hardy model to account for wet-suit clothing but this extension is only valid for water immersion exposures.

5.6.2.2. Modifications to the Published Model

To enable the Stolwijk and Hardy model to be of practical use it was necessary to extend it to account for the insulative effects of clothing in air environments. Although the multi-segment nature of the Stolwijk and Hardy model would enable clothing to be applied realistically over the body, there is insufficient information available regarding clothing distribution to make this approach worthwhile. It was therefore decided to use the two-parameter approach described above. Further research regarding the distribution of clothing over the body would enable the Stolwijk and Hardy model to account for the distribution of resistance and this might prove useful for practical applications where the range of clothing is restricted.

The two-parameter quantification of the insulative effects of clothing provides mean values of resistance in terms of unit surface area. The most straightforward method of adding clothing onto the Stolwijk and Hardy model was to apply the same measured resistance to each segment. Thus, clothing resistance is applied to the head and the hands. While this situation may arise, in practice the head and the hands are often left uncovered.

An alternative implementation was possible where the head and the hands are left uninsulated. The resistances that are measured on a thermal manikin are determined in terms of the surface area of the whole manikin. Thus, if the head and hands were nude, the insulation over the rest of the manikin would have been greater than that measured in terms of the whole manikin, for this measured mean value to have been determined. In order to apply the clothing insulation to the Stolwijk and Hardy model, while leaving the head and hands uncovered, it is necessary to correct the clothing insulation, as measured on the manikin, for the reduced surface area to which it applies. Stolwijk and Hardy provided surface areas for each of the body segments so this correction can be made.

The total clothing insulation that applies to the clothed surface area of the body may be estimated using the laws for addition of parallel resistances, and adjusting for the surface areas to which they apply so that:

$$IT' = \frac{Ab - Ah\&h}{\frac{Ab}{IT} - \frac{Ah\&h}{Ia}} \quad (clo) \qquad (5.27)$$

where:

IT' = total insulation applicable to the clothed area of the body when the head and hands are nude (clo)

$Ah\&h$ = surface area of the head and hands (m^2)

This calculation assumes that all parts of the manikin were operated at the same temperature when measuring the clothing insulation. Having determined IT', the corresponding Icl' may be calculated by adjusting for Ia and fcl as in equation 5.11. The correction for Iecl may be calculated in the same way.

Two versions of the Stolwijk and Hardy model were developed to implement the methods of applying clothing insulation described above. While modifying the Stolwijk and Hardy model to account for the insulative effects of clothing, it was also convenient to modify it to account for environments where the air and mean radiant temperatures of the surroundings are different. This modification is described in appendix B.

5.6.3. Givoni and Goldman Model

5.6.3.1. Published Model's Quantification of Clothing Insulation

The Givoni and Goldman model (Givoni and Goldman, 1972) uses

IT, im and a "velocity modifier" to quantify the insulative effects of clothing (Berlin et al., 1975). An effective air speed is calculated as a function of the environmental air speed and the metabolic rate of the subject. An effective clothing insulation (IT) and effective permeability index ratio (im/IT) are then determined as functions of IT, im, the effective air velocity and the velocity modifier. The model requires values of IT and im appropriate to an environment with an air movement of 1 m/s.

These modifications to the insulation values of the clothing measured on a manikin were derived as those that maximized the accuracy of the model's predictions when compared with the responses of exercising subjects (Breckenridge, 1977; and Givoni and Goldman, 1972). There is no theoretical basis for these equations.

5.6.3.2. Modifications to the Published Model

The Givoni and Goldman model has been modified so that it uses values of Icl and im measured in an environment with an air movement of 0.1 m/s to calculate the IT and im that would have been obtained had manikin measurements been made in an environment with a 1 m/s air movement. Full details of these calculations are provided in the program listing for the revised version of the model, given in appendix A. The adjustments made by the model to IT and im/IT, to account for the increased convection associated with exercise have been retained.

5.6.4. ISO/DIS 7933 (1987) Model

5.6.4.1. Published Model's Quantification of Clothing Insulation

The version of the ISO 7933 model used for the preliminary evaluation was that provided by ISO/DP 7933 (1983). An updated version of the model has been published as ISO/DIS 7933 (1987). ISO/DIS 7933 accounts for the resistive effects of clothing in terms of Icle and IeT. IeT is determined from Fpcl, which in turn is calculated as a function of Icle according to equation 5.22 above. However, the 0.92 constant in this equation has been shown by Lotens and Linde (1983) to be incorrect.

In a similar manner to the Givoni and Goldman model, the ISO model makes an adjustment to the air speed as a function of a subject's metabolic rate, thereby taking some account of the increased body movement during exercise.

5.6.4.2. Modifications to the Published Model

The ISO model has been modified to use Icl and so that IeT is calculated from Iecl, fcl and Ie using equation 5.17. Iecl is determined from im, using equation 5.26.

5.7. Terminology and Program Listings

So that the versions of the models that have been modified for this research may be distinguished from the original published versions of the models, they will be referred to as lut2, lut25, luttre and lutiso for the Gagge and Nishi, Stolwijk and Hardy, Givoni and Goldman and ISO/DIS 7933 models respectively. The two implementations of the the Stolwijk and Hardy model will be referred to as "lut25 hhc" (head and hands clothed) and "lut25 hhn" (head and hands nude). Full program listings and example runs are given in appendix A.

Table 5.1 shows the inputs used by the four modified versions of the models. These may be compared with the inputs of the original published versions of the models, given in table 3.2.

Table 5.1. Inputs for revised models.

Inputs:	lut2	lut25	luttre	ISO/DIS 7933
Air temperature (Ta)	Yes	Yes	Yes	Yes
Mean radiant temperature (Tr)	Yes	Yes	Tr=Ta	Yes
Solar Radiation	No	No	No	No
Air speed (v)	Yes	Yes	Yes	Yes
Relative humidity (rh)	Yes	Yes	Yes	Yes
Clothing insulation[1]	Icl	Icl	Icl	Icl
Clothing moisture permeation resistance[1]	im	im	im	im
Metabolic rate (M)	Yes	Yes	Yes	Yes
External work (W)	Yes	Yes	Yes	Yes

[1]Icl = intrinsic clothing insulation (Haslam and Parsons, 1988); im is after Woodcock (1962)

CHAPTER 6

6. COMPREHENSIVE EVALUATION OF MODELS

To determine which models would provide the most accurate predictions for an environment and whether these predictions would be of sufficient accuracy for practical use, a comprehensive evaluation was conducted for a wide range of environmental conditions.

6.1. Method

The models' predictions were compared with the responses of human subjects reported in the literature. The lut2, lut25 and luttre models' Tcr predictions and the lut2 and lut25 models' Tsk, M, dry heat transfer (C+R), E and Esk predictions were evaluated. The lutiso model's allowable exposure times were compared with the increases of the observed Tcr and Tsk responses at its allowable exposure times (these should compare with increases of 0.8 and 1.0 °C for Tcr and 2.4 and 3.0 °C for Tsk, for warning and danger respectively). The lut25 model's Thd and Tft predictions were not examined.

6.1.1. Experimental Data

The data used to evaluate the models was obtained from the literature. Most of the data was taken from papers published in reputable journals such as Aviation, Space and Environmental Medicine; Ergonomics; the European Journal of Applied Physiology; and the Journal of Applied Physiology. Papers were identified that provided sufficient information to run the models.

Most of the data used were published in the form of graphs displaying the mean responses of groups of subjects. Numerical data were obtained from the graphs by reading the temperature or heat transfer values at each time interval where data were recorded on the graphs. No attempt was made to interpolate or extrapolate from the data. Where data were given for the standard deviation, these values were also recorded. It was usually possible to read the data from the graphs to an accuracy greater than reported by the experimenters for their measuring instrumentation, for example within $\pm$ 0.05 °C for Tcr and $\pm$ 0.1 °C for Tsk. Where reports presented the time course responses of individual subjects, this information was extracted and the mean and standard deviation values calculated.

Most of the data considered were collected from the exposure of fit, unacclimatized male subjects, although some data for acclimatized and for female subjects were included. Data for a wide range of environmental conditions were identified, involving a total of 590 subject exposures.

6.1.2. Running the Models

6.1.2.1. Model Inputs

The models were run using the environmental conditions detailed in the literature reports. Where necessary the data were converted to the units expected by the models (e.g. °F to °C). Relative humidity was determined from any other measurements of humidity given (e.g. dew-point temperature). The conversion factors and formulae used were those given by ASHRAE (1985).

For exposures where the subjects were minimally clothed, values of Icl=0.1 clo, fcl=1.00 (nd), and im=0.5 (nd) were used. Where the subjects were clothed, insulation values given by the experimenters were used as inputs to the models, when these were provided. When insulation values were not available, the tables of McCullough (1986), McCullough et al. (1982) and McCullough and Jones (1984) were used to estimate the values based on the clothing descriptions provided.

It was recognized that estimating the clothing insulation parameters from tables could introduce errors. However, when using the models for practical application, data might often not be available for the insulation characteristics of the clothing and would have to be estimated.

The models require M and W to be input in units of W/m^2. Where this information was given in a report in units of W, it was converted to W/m^2 either using the body surface areas reported; calculating the mean body surface area from height and weight using the formula of Du Bois and Du Bois (1916); or using an estimated value of 1.8 m^2.

The luttre model requires for input the number of days acclimatization to the heat. A value of zero was used for experimental data where the subjects were unacclimatized. Where the subjects were acclimatized, the number of days acclimatization given by the experimenters was used. Although not explicitly stated by the original authors of the lut2 and lut25 models, it is probable that the coefficient values published with the models are appropriate to unacclimatized subjects. The lutiso model predicts for both unacclimatized and acclimatized subjects.

Givoni and Goldman (1972) suggested that their model should be able to predict rectal temperature response for environments where 15<=Ta<30 °C, assuming Ta=30 °C. This is because for the study used to develop their prediction equations, Givoni and Goldman found that within the temperature range 15<=Ta<30 °C, Tre at rest or work was independent of Ta. The luttre model was therefore evaluated against observed data where 15<=Ta<30 °C, using an input value of Ta=30 °C.

The lutiso model was intended to assess environments that could result in heat stress. The lutiso model was therefore evaluated for all environments where Ta>30 °C, and for environments where 20<=Ta<=30 °C when the subjects were exercising.

6.1.2.2. Model Outputs

Graphs were plotted of the observed data and the lut2, lut25 and luttre models' predictions. Where data were available, curves of the mean plus and minus one standard deviation were also plotted to provide information regarding variation around the mean response.

The lutiso predicted allowable exposure times are given at the bottom of the Tcr graphs for the environments where they were applicable. The lutiso single allowable exposure times are given for experimental data where the subjects were exposed to a single set of environmental conditions. For environments where the subjects were exposed to two successive combinations of environmental conditions, the time weighted average allowable exposure times are reported, providing the allowable exposure time for the first combination of environmental conditions exceeded the actual period of exposure to them. Where the allowable exposure time for the initial environment was less than the actual period of exposure, this time is reported.

The temperature changes observed up to the lutiso predicted allowable exposure times have been calculated assuming starting temperatures of 37.0 and 33.5 °C for Tcr and Tsk respectively.

6.1.3. Root Mean Square Deviation (rmsd)

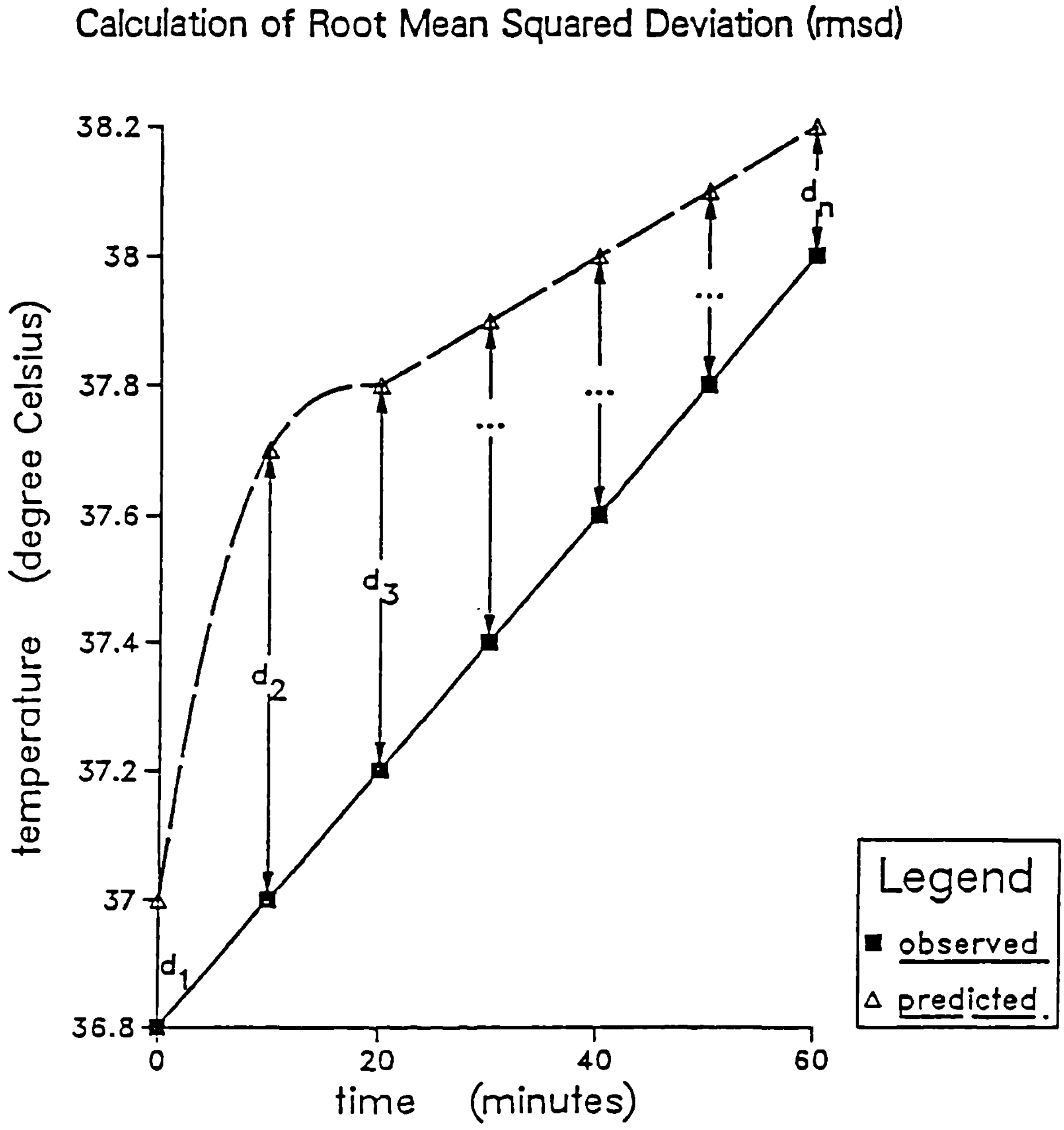
Due to the large amount of data produced by this evaluation (82 environments resulting in 221 graphs) a statistic has been developed to summarize the data.

6.1.3.1. Definition of Rmsd

Where the evaluation of the models' predictions requires comparison of an observed with a predicted temperature time course (e.g. where an observed Tre response is compared with a model's predicted Tcr response), the root mean square deviation (rmsd) has been used, figure 6.1. This statistic is defined as:

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

Figure 6.1. Root mean squared deviation statistic used to quantify the accuracy of a model's predictions.



$$\text{r m s d} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_i^2}$$

$$= \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + \ldots\ldots + d_n^2}{n}} = 0.45\ ^{\circ}\mathrm{C}$$

where:

d_i = difference between observed and predicted temperature at each time point

n = number of time points of interest

This statistic gives a figure for the average difference between the observed and predicted time courses in units of °C and enables direct comparison to be made with the mean standard deviation of the observed data, if available (see section 6.1.3.3).

6.1.3.2. Potential Sources of Bias of Rmsd

The rmsd statistic is an estimate of the deviation between an observed and predicted time course. While the accuracy of its estimate should improve with the number of time points on which the calculation is based, it should not be biased by this factor. The rmsd statistic could however be biased by the length of the exposure. For example, where an observed response and a model's predictions diverge with time, the rmsd will be greater with the period over which it is calculated.

To examine this potential source of bias, Pearson product moment correlation coefficients were calculated between the periods of exposure and the corresponding rmsds, for each model. Coefficients were calculated for the Tcr data, combining all of the estimates of Tcr (such as Tre and Tty), and for the Tsk data. Coefficients were calculated for the complete data set, and with it broken down into exposures with only one combination of environmental conditions and for exposures with more than one (e.g. rest followed by work).

Excluding the results for the lut25 (hhn) model, whose predictions were suitable for only a small number of experimental exposures, the only significant correlations were for the lut25 (hhc) model. These correlations were -0.29 ($p=0.003$, $n=103$) for Tcr for the complete data set; -0.37 ($p=0.002$, $n=69$) for Tsk for the complete data set; and -0.37 ($p=0.03$, $n=34$) for Tsk for single environment exposures. As these correlations were all negative this indicates that the rmsds obtained tended to be smaller for the longer experimental exposures. This could be due to convergence between the model's predictions and the observed responses over time, or it may be due to characteristics of the data not examined, for example, the longer experimental exposures might be associated with experimental conditions for which the model is able to predict more accurately than those associated with shorter exposures.

In view of the absence of correlation between the length of exposure and the rmsds for the lut2 and luttre models, and the small negative correlations for the lut25 (hhc) model, it was considered that as the rmsd provides a convenient means of summarizing the evaluation data, its use could be justified in conjunction with the time course information provided by the temperature response graphs. Therefore, a rmsd value was calculated between each prediction shown on the graphs and the mean observed time courses.

6.1.3.3. Mean Standard Deviation of Observed Responses

It is possible to calculate a mean for the standard deviation of the observed response over the duration of an experimental exposure. This has been calculated where standard deviation data were available.

There were no clear differences between the mean standard deviations obtained for Tcr from different measuring sites (such as Tre or Tty) over the range of environmental conditions examined. The mean standard deviations observed for Tcr ranged 0.1 - 0.5 °C, the largest value being obtained for an exposure in the heat. The mean standard deviations for Tsk ranged 0.3 to 1.6 °C, the largest values being obtained in the cold. The mean standard deviations of the observed M responses ranged 4 - 20 W/m^2.

6.1.4. Data Analysis

Due to the large number of graphs obtained and rmsds calculated it was necessary to employ some further form of data reduction.

6.1.4.1. Multiple Regression Analysis

The use of multiple regression analysis was considered as a means of relating the environmental parameters to the accuracy of the models' predictions. Multiple regression analysis would have enabled equations to be derived relating the independent variables such as Ta, v, rh, Icl etc. to the rmsd for each model (the dependent variable). Given a particular environment, it would have then been possible to predict the rmsd for each model and on the basis of these select which model to use. However, preliminary analysis showed that there was clear evidence of deviation from normality and inequality of variance and some evidence of multicollinearity within the data. These findings showed that important assumptions necessary to perform regression analysis would have been violated (Norusis, 1988).

6.1.4.2. Analysis by Environmental Categorization

It was decided to assign the environmental conditions to broad categories and to examine the models' accuracy for each of these categories. It was decided to use categories for air temperature of $T_a \le 5$, $5 < T_a \le 15$, $15 < T_a \le 25$, $25 < T_a \le 35$, $T_a > 35$ (°C); air speed: $v \le 0.4$, $v > 0.4$ (m/s) (no-wind and wind), clothing insulation: $I_{cl} \le 0.2$, $I_{cl} > 0.2$ (clo) (nude and clothed); and metabolic rate: $M \le 70$, $M > 70$ (W/m^2) (rest and work). Table 6.1 presents the sources of the experimental data by environment category.

The distribution of the environmental conditions available to this evaluation did not justify any finer resolution than these categories. Even with this coarse resolution it can be seen from table 6.1 that data were not available for a number of categories. The data for acclimatized to heat or female subjects were considered as separate categories, because of their limited extent. Where the subjects were exposed to several successive environments that fell into more than one category, the data were either categorized according to the time weighted averages of the environmental conditions, or where the data were collected from the exposure of subjects to a thermally neutral environment,

Table 6 1. Experimental data used for the model evaluation presented by environment category ([] indicates experiment code).

nude/rest/no-wind	
Ta< 5 °C	Raven and Horvath (1970) [] Young et al. (1986) []
5<T =15 °C	Hardy and Stolwijk (1966) [f7] Iampietro et al. (1958) [1] Iampietro et al. (1958) [4] Iampietro et al. (1958) [6] O'Hanlon and Horvath (1970) [] Wagner and Horvath (1985) [10] Wagner and Horvath (1985) [15]
15<Ta<=25 °C	Hardy and Stolwijk (1966) [f1] Hardy and Stolwijk (1966) [f6] Iampietro et al. (1958) [2] Wagner and Horvath (1985) [20]
25<Ta<=35 °C	Stolwijk and Hardy (1966) [f3] Stolwijk and Hardy (1966) [f4] Wagner and Horvath (1985) [28]
35<Ta °C	Hardy and Stolwijk (1966) [f3] Stolwijk and Hardy (1966) [f5] Stolwijk and Hardy (1966) [f6] Stolwijk and Hardy (1966) [f7]
nude/rest/wind	
Ta<=5 °C	
5<Ta<=15 °C	Iampietro et al. (1958) [3] Iampietro et al. (1958) [5] Iampietro et al. (1958) [7]
15<Ta<=25 °C	Iampietro et al. (1958) [8]
25<Ta<=35 °C	
35<Ta °C	

(continued)

Table 6.1. (continued)

nude/work/no-wind	
T <=5 °C	
5<Ta<-15 °C	
15<Ta -25 °C	Chappuis et al. (1976) [A] Chappuis et al. (1976) [B] Hirata et al. (1983) [20] Hirata et al. (1983) [35] Hirata et al. (1983) [45] Shvartz (1976) [cool]
25<Ta<=35 °C	Chappuis et al. (1976) [C]
35<Ta °C	Kobayashi et al. (1980) [moderate work] Kobayashi et al. (1980) [heavy work] Mairiaux et al. (1986) [WD-1] Mairiaux et al. (1986) [WD-2] Mairiaux et al. (1986) [WD-3] Mairiaux et al. (1986) [WH-1] Mairiaux et al. (1986) [WH-2] Mairiaux et al. (1986) [WH-3] Shvartz (1976) [hot]
nude/work/wind	
Ta<=5 °C	
5<Ta<=15 °C	
15<Ta<=25 °C	
25<Ta<=35 °C	Henane et al. (1979) [nude]
35<Ta °C	Mitchell et al. (1976) [day 1]
clothed/rest/no-wind	
Ta<=5 °C	Budd (1965) [ ] Iampietro and Buskirk (1960) [e3] Iampietro and Buskirk (1960) [e5]
5<Ta<=15 °C	Iampietro and Buskirk (1960) [e6] Iampietro and Buskirk (1960) [e7]
15<Ta<=25 °C	
25<Ta<=35 °C	
35<Ta °C	

(continued)

Table 6.1. (continued)

	clothed/rest/wind
Ta< 5 °C	Iampietro and Buskirk (1960) [e2] Iampietro and Buskirk (1960) [e8]
5<Ta< 15 °C	Iampietro and Buskirk (1960) [e1] Iampietro and Buskirk (1960) [e4]
15<Ta<-25 °C	
25<Ta<=35 °C	
35<Ta °C	
	clothed/work/no-wind
Ta<=5 °C	Walsh and Graham (1986) [e2] Walsh and Graham (1986) [e3] Walsh and Graham (1986) [e4]
5<Ta<=15 °C	Nielsen and Nielsen (1984) [ct] Nielsen and Nielsen (1984) [cl] Walsh and Graham (1986) [e1]
15<Ta<=25 °C	
25<Ta<=35 °C	Randle and Legg (1985) [wk] Randle and Legg (1985) [cy] Smith (1986) [wc] Smith (1986) [wa]
35<Ta °C	Smith (1986) [hc] Smith (1986) [ha]
	clothed/work/wind
Ta<=5 °C	Hampton and Knibbs (1986) [dry] Hampton and Knibbs (1986) [wet]
5<Ta<=15 °C	
15<Ta<=25 °C	
25<Ta<=35 °C	Henane et al. (1979) [A1] Henane et al. (1979) [A2]
35<Ta °C	

(continued)

Table 6.1. (continued)

nude/work/wind (Acclimatized)	
Ta<=5 °C	
5<Ta<=15 °C	
15<Ta<=25 °C	
25<Ta<=35 °C	
35<Ta °C	Mitchell et al. (1976) [day 10]

clothed/work/wind (Acclimatized)	
Ta<=5 °C	
5<Ta<=15 °C	
15<Ta<=25 °C	
25<Ta<=35 °C	Haisman and Goldman (1974) [wn] Haisman and Goldman (1974) [wl] Haisman and Goldman (1974) [ws]
35<Ta °C	Avellini et al. (1980) [] Haisman and Goldman (1974) [dn] Haisman and Goldman (1974) [dl] Haisman and Goldman (1974) [ds] Pimental et al. (1987) [lw] Pimental et al. (1987) [hw]

clothed/work/no-wind (female)	
Ta<=5 °C	Walsh and Graham (1986) [e2] Walsh and Graham (1986) [e3] Walsh and Graham (1986) [e4]
5<Ta<=15 °C	Walsh and Graham (1986) [e1]
15<Ta<=25 °C	
25<Ta<=35 °C	
35<Ta °C	

(continued)

Table 6.1. (continued)

clothed/work/wind (Acclimatized - female)	
Ta<-5 °C	
5<Ta<-15 °C	
15<Ta<=25 °C	
25<Ta -35 °C	
35<Ta °C	Avellini et al. (1980)

followed by exposure to a more extreme environment, the data were categorized according to the more extreme environmental conditions.

Categorization of the evaluation data in this manner enabled different aspects of the models' performance to be examined. Of particular interest were the models' abilities to account for the insulative effects of clothing, the effects of increased metabolic heat production due to exercise and shivering, and the manner by which the models account for wind and its effects on convective and evaporative heat transfer. The influence of these factors on human heat exchanges varies according to the environmental temperature. Thus, the breakdown into temperature ranges enabled these influences to be examined across the temperature spectrum.

Furthermore, categorization of the experimental data in the way described enables practical advice to be given as to which model is likely to provide the most accurate predictions for a particular combination of environmental conditions.

The rmsds between each models' predictions and the observed time course data were categorized as described above. The mean and standard deviation of the rmsds falling into each category were then calculated. It was not possible to check for differences between the means using statistical significance tests because of the small number of observations in many of the categories.

Bar charts have been used to display the mean rmsds for the Tcr, Tsk and M responses for each environment category.

Charts have not been produced for the C+R, E and Esk heat flows because of the small extent of data available.

6.2. Results

6.2.1. Time Course Graphs

The full set of comparison graphs is provided in appendix C. The graph titles contain the references of the reports from which the experimental data were taken and full details of the environmental conditions used to run the models. Experiment codes have been used to identify different environmental exposures where several were taken from a single paper or report. These were usually related to the identification used by the original authors.

The graphs for each environment category are analysed in tables 6.2 and 6.3. Figures 6.2 - 6.65 provide examples of the observed and predicted responses.

6.2.2. Rmsd Bar Charts

The rmsds have been tabulated for each literature report and are presented in appendix D.

Figures 6.66 - 6.100 display the mean rmsds, obtained for each environment category, in the form of bar charts. The mean rmsds are represented by the height of the thick bars on the charts, the thin bars at the top of the thick bars represent the standard deviation of the rmsds in that category, and the numbers enclosed at the top of the thick bars are the number of individual rmsds that fell into that category and that were used to calculate the mean and

Table 6.2. Analysis of time course graphs for each environment category (male, unacclimatized subjects).

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
nude/ rest/ no-wind	Ta<=5	Tcr	6.2	Observed Tre responses followed slight initial increase followed by steady decline pattern. Single observed Tty response had similar pattern but approximately 0.4 °C lower. The lut2 and lut25 models predicted steady decreases, markedly lower than those observed.
		Tsk	6.3	Observed and predicted responses steadily decreased. Relation of models' predictions to observed responses varied.
		M	6.4	Observed responses increased sharply at first, followed by steady, slower increases. Models did not predict sharp initial increase. After approximately 50 minutes, models' predictions remained close to observed responses.
	5<Ta<=15	Tcr		As for Ta<=5 °C temperature range.
		Tsk		As for Ta<=5 °C temperature range.
		M	6.5	As for Ta<=5 °C temperature range. For higher temperatures, extent of initial increase in observed data became less and equilibrium was reached at lower level. Models overestimated increase in warmer environments, lut2 model more so than lut25 model.
	15<Ta<=25	Tcr	6.6	Similar to results found where Ta<=5 °C, although extent of observed initial increase and models' overestimation of decrease were reduced. Where data were available for both Tre and Tty, models' predictions were closer to Tty response. The luttre model predicted steady continuous increase for each environment.
		Tsk	6.7	Observed and predicted responses showed slight decreases or steady equilibrium responses. Orientation of models' predictions to observed responses varied.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
nude/ rest/ no-wind	15<Ta<=25	M	6.8	Observed responses remained steady at resting levels. The lut2 and lut25 models predicted increases.
		Esk		Observed and predicted responses remained steady at basal levels
	25<Ta<=35	Tcr	6.9	Observed responses, lut2 and lut25 predictions generally followed steady unchanging courses. The luttre model predicted steady increases. Where applicable, lutiso allowable exposure times were compatible with observed data.
		Tsk	6.10	Observed responses either increased or decreased slightly at beginning of exposure to reach equilibrium at around 33-34 °C. Models' predictions followed similar patterns to observed data.
		M		Observed and predicted responses followed steady unchanging patterns.
		Esk		Observed and predicted responses followed steady unchanging patterns.
	35<Ta	Tcr	6.11 6.12	All experimental data for this category were reported by Stolwijk and Hardy, from experiments where subjects were exposed to initial cool or neutral environment, followed by exposure to heat, finishing with exposure to conditions used during initial period. Observed Tre and Tty data, and lut2 and lut25 models' predictions mostly followed similar patterns, decreasing initially, increasing during heat, and decreasing during final component of exposures. The luttre model predicted steady increases for each experimental exposure and, with exception of hottest environment, its predictions were noticeably greater than observed responses. The lutiso model's allowable exposure times were compatible with observed data.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
nude/ rest/ no-wind	35<Ta	Tsk	6.13	Observed responses, lut2 and lut25 models' predictions followed similar patterns. The lutiso model's predictions were compatible with observed data.
		M		Observed and predicted responses followed steady unchanging patterns.
		Esk	6.14	Observed and predicted responses were similar.
nude/ rest/ wind	Ta<=5			No experimental data available.
	5<Ta<=15	Tcr	6.15	Observed data displayed initial increase followed by steady decrease. Models predicted steady decreases much greater than those observed. The more severe the cooling effect of environment, the greater the initial increase shown by observed data, and the greater the decrease predicted by models.
		Tsk	6.16	Observed data and models' predictions followed similar patterns. The lut25 predictions tended to be closest to observed data, with lut2 falling slightly below.
		M	6.17	Observed responses increased rapidly at first, and then remained steady. Models did not predict sharp initial increase and generally reached equilibrium at higher level.
	15<Ta<=25			As for 5<Ta<=15 °C temperature range. For single environment for which data were available, luttre model predicted steady Tre increase.
	25<Ta<=35			No experimental data available.
	35<Ta			No experimental data available.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
nude/ work/ no-wind	Ta<=5			No experimental data available.
	5<Ta<=15			No experimental data available.
	15<Ta<=25	Tcr	6.18 6.19	Observed data increased over exposures, the rate of increase being greater the higher the temperature or rate of work. The lut2 model underestimated observed increase in Tcr for all environments. The lut25 model's predictions were generally closest to observed responses, although tended to be slightly lower. The lut25 model's predictions showed a marked dip during first 20 minutes of onset of exercise. The luttre model usually considerably overestimated increases of Tcr observed. An exception was for data shown in figure 6.19, where luttre model's predictions were most accurate. The lutiso model's allowable exposure times would not have protected subjects against its own criteria for several exposures.
		Tsk	6.20 6.21	Observed and predicted responses generally remained steady or, during periods of heavier exercise, increased to slightly higher equilibrium levels. For some exposures there were large discrepancies between observed data and models' predictions at beginning of experiment.
		C+R	6.22	Observed and lut25 model's predicted responses followed similar patterns. The lut2 model considerably overestimated extent of cooling.
		E	6.23	Observed and lut25 model's predicted responses followed similar patterns. The lut2 model underestimated cooling during work periods.
	25<Ta<=35			As for 15<Ta<=25 °C temperature range.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
nude/ work/ no-wind	35<Ta	Tcr	6.24 6.25	Observed responses increased steadily throughout experimental exposures. Where comparable, Tre responses increased by around 0.3–0.5 °C more than corresponding Toe data. Some observed Tac responses increased by around 1.0 °C more than simultaneously recorded Tre data. Models generally predicted steady increases with lut2 model predicting least, lut25 greater than lut2, and luttre model greatest. For environments where conditions fluctuated, lut2 and lut25 models' predictions changed with environmental conditions, unlike observed data. Relationship of lut2 and lut25 models' predictions to observed data depended on site used to measure Tcr. The luttre model generally predicted greater increases than observed. The lutiso model would not have protected subjects against its own criteria, in one case Tre increased by 2.0 °C without model having *issued danger allowable exposure time*.
		Tsk	6.26	Observed Tsk responses increased rapidly to reach equilibrium during rest components of exposures and increased steadily during work. Models' predictions were similar to observed data during rest, lut2 model underestimated and lut25 model overestimated increase during work.
		Esk	6.27	Observed responses and lut25 models' predictions were similar during rest components of exposures, lut2 were high. During work, lut2 model considerably overestimated and lut25 model underestimated evaporative cooling.
nude/ work/ wind	Ta<=5			No experimental data available.
	5<Ta<=15			No experimental data available.
	15<Ta<=25			No experimental data available.
	25<Ta<=35	Tcr		As for nude/work/wind 35<Ta °C temperature range.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
nude/ work/ wind	35<Ta	Tcr	6.28	Observed and predicted responses displayed steady increases. The lut2 and lut25 models' predictions were similar to observed data. The luttre model overestimated increase observed. The lutiso model's predicted allowable exposure times would have protected subjects against its criteria of safety.
		Tsk	6.29	Observed and predicted responses were similar.
		C+R	6.30	Models underestimated heat gain by approximately 50 W/m^2.
		E	6.31	Models underestimated heat loss by approximately 50 W/m^2.
clothed/ rest/ no-wind	Ta<=5	Tcr	6.32	Observed data displayed initial increase followed by steady decrease. Models predicted steady decreases much greater than observed. The more severe the cooling effect of the environment, the greater the initial increase shown by observed data, and the greater the decrease predicted by models. The lut25 hhc predictions were similar to those of lut25 hhn version of model.
		Tsk	6.33	Observed data and models' predictions followed similar patterns. The lut25 hhc predictions were similar to those of lut25 hhn version of model.
		M	6.34	Observed responses steadily increased during exposures. Models tended to slightly overestimate increases observed. There were slight differences between hhc and hhn versions of lut25 model.
	5<Ta<=15			As for Ta<=5 °C category.
	15<Ta<=25			No experimental data available.
	25<Ta<=35			No experimental data available.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
	35<Ta			No experimental data available.
clothed/ rest/ wind	Ta<=5	Tcr	6.35	Observed responses displayed slight initial increases followed by slight decreases. Models predicted marked decreases. Differences between hhc and hhn versions of lut25 model were small compared with differences with observed responses.
		Tsk	6.36	Observed and predicted data followed similar patterns. The hhc and hhn versions of lut25 model predicted similar responses.
		M	6.37	Observed and predicted data followed similar patterns. Differences between hhc and hhn versions of lut25 model were generally small compared with differences from observed responses.
	5<Ta<=15			As for Ta<=5 °C temperature range.
	15<Ta<=25			No experimental data available.
	25<Ta<=35			No experimental data available.
	35<Ta			No experimental data available.
clothed/ work/ no-wind	Ta<=5	Tcr	6.38	Observed data displayed initial increase followed by a decline. Models' predictions remained at lower level. Predictions fluctuated to a greater extent than observed data during work/rest cycles. Differences between hhc and hhn versions of lut25 model were small compared with differences with observed responses.
		Tsk	6.39	Observed responses and lut25 model's predictions followed similar patterns. The lut2 model overestimated decrease for several exposures. The hhc and hhn versions of the lut25 model predicted similar responses.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
clothed/ work/ no-wind	5<Ta<=15	Tcr	6.40 6.41 6.42	Observed data of Nielsen and Nielsen (1984) showed initial slight decrease, followed by increase during exercise. Data for Toe followed similar pattern to Tre data, but remained consistently 0.2–0.3 °C lower. Observed data from Walsh and Graham (1986) increased initially, followed by decrease. The lut2 model predicted Nielsen and Nielsens' data closely while underestimating increase shown by Walsh and Grahams' data. The lut25 model overestimated increase displayed by Nielsen and Nielsens' data, but its predictions followed similar pattern to Walsh and Grahams' responses.
		Tsk	6.43 6.44	Models' predictions followed different patterns to Nielsen and Nielsens' (1984) observed data. Walsh and Grahams' (1986) experimental data and models' predictions followed similar patterns, although with predictions at higher level. The hhc and hhn versions of lut25 model predicted similar responses.
	15<Ta<=25			No experimental data available.
	25<Ta<=35	Tcr	6.45	Only Tac data available. Observed data increased during work periods and decreased during rest. Models' predictions followed similar pattern, with lut2 always closest. The lut25 and luttre models overestimated increases observed. The lutiso model's allowable exposure times were generally compatible with observed data, although how times based on time weighted averages should be interpreted is not clear. The hhc and hhn versions of lut25 model predicted similar responses.
		Tsk	6.46	Observed data increased during work periods and decreased during rest. The lut2 model predicted observed responses closely. The lut25 model overestimated observed increases. The hhc and hhn versions of lut25 model predicted similar responses. The lutiso model's allowable exposure times were compatible with observed data.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
clothed/ work/ no-wind	35<Ta	Tcr	6.47	As for 25<Ta<=35 °C category, although lut2, lut25 and luttre models overestimated increases shown by observed data. The lutiso model's allowable exposure times were conservative against Tac data.
		Tsk	6.48	As for 25<Ta<=35 °C category, although lut2 and lut25 models overestimated increases observed. The lutiso model's allowable exposure times were compatible with observed data.
clothed/ work/ wind	Ta<=5	Tcr	6.49 6.50	Subjects were exposed to clothing dry and clothing wet conditions. Observed responses increased during work periods and decreased during rest. The lut2 model underestimated observed responses. The lut25 model accurately predicted observed response in clothing dry condition, but overestimated it when clothing was wet. The hhc and hhn versions of lut25 model predicted similar responses. Large differences of over 1 °C occurred between lut2 and lut25 models' predictions and observed data for clothing wet condition.
		Tsk	6.51	Observed data decreased over exposures. Models overestimated decrease by around 5 °C in clothing dry condition. For clothing wet condition lut2 model's predictions were close to observed response, lut25 model's were slightly above. The hhc and hhn versions of lut25 model predicted similar responses. Models' predictions fluctuated more than observed data.
	5<Ta<=15			No experimental data available.
	15<Ta<=25			No experimental data available.

(continued)

Table 6.2. (continued)

Environment Category	Temperature Range (°C)	Response	Example Figures	Comments
clothed/ work/ wind	25<Ta<=35	Tcr	6.52	Observed and predicted data increased steadily over duration of exposures. The lut2 model overestimated rate of increase. The lut25 model accurately predicted observed response for one data set available, but overestimated increase of observed responses in other (figure 6.52). The luttre model overestimated increase of observed responses. The lutiso model's predicted allowable exposure times were slightly conservative against the observed Tre data.
	35<Ta			No experimental data available.

Table 6.3. Analysis of time course graphs for each environment category (acclimatized male, and female subjects).

Environment Category	Subject Status	Response	Example Figures	Comments
nude/ work/ wind	heat acclimatized	Tcr	6.53	Observed response, lut2 and lut25 models' predictions followed similar patterns. The luttre model overestimated increase observed. The lutiso model's allowable exposure times were compatible with observed data.
		Tsk	6.54	Models predicted similar steady response to that observed, although at slightly higher level. The lutiso model's allowable exposure times were compatible with observed data.
		C+R	6.55	Models underestimated heat gain.
		E	6.56	Models underestimated heat loss.
clothed/ work/ wind	heat acclimatized	Tcr	6.57 6.58	Observed responses increased during experimental exposures. Models predicted similar patterns of response, although tended to overestimate increase in some cases. The luttre model predicted large drop mid way through one exposure. This occurred at transition between luttre model's rest and work equations. It was not clear how lutiso model's allowable exposure times based on time weighted averages should be interpreted.
		Tsk	6.59	Models predicted similar patterns of response to observed but at higher level.
clothed/ work/ no-wind	female	Tcr	6.60	Responses of female subjects were very similar to those of male subjects exposed to same conditions. The lut2 model underestimated increase observed for each experimental exposure. The lut25 model's predictions were closer to observed responses, although differed considerably in coldest environments. Models' predictions were slightly closer to female responses than male.

(continued)

Table 6.3. (continued)

Environment Category	Subject Status	Response	Example Figures	Comments
clothed/ work/ no-wind	female	Tsk	6.61	Responses of female subjects were similar in pattern to those of male subjects exposed to same conditions, although at slightly higher level. The lut2 model's predictions differed markedly from observed responses in coldest conditions. The lut25 model's predictions were more accurate. Models' predictions were closer to female responses in warmer environments for which data were available, and closer to males in colder.
clothed/ work/ wind	female, heat acclimatized	Tcr	6.62 6.63	Responses of female subjects were similar to those of male subjects exposed to same conditions. The lut2 and lut25 models' predictions were similar to female responses, but overestimated increase of male. The luttre model overestimated increase for both female and male subjects. It was not possible to compare lutiso predicted allowable exposure times with available data because they had been reported at too low frequency.
		Tsk	6.64 6.65	Responses of female subjects were similar in pattern to those of male subjects exposed to same conditions, although at slightly higher level. The lut2 and lut25 models' predictions were closer to female responses than male.

Figure 6.2. Example of deep body temperature responses (Tcr) for the nude, rest and no-wind environment category, where Ta<=5 °C.

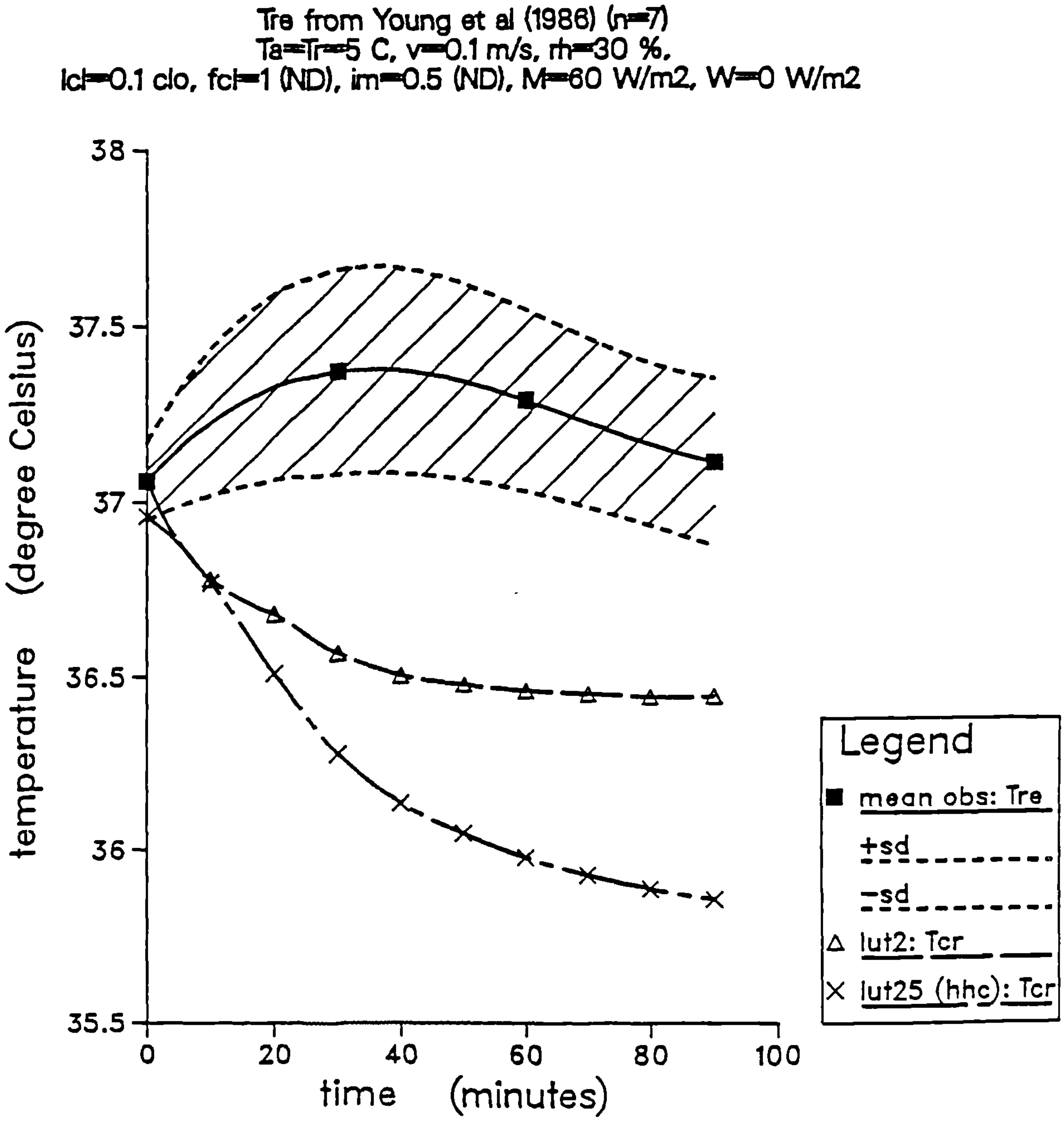


Figure 6.3. Example of mean skin temperature responses (Tsk) for the nude, rest and no-wind environment category, where Ta<=5 °C.

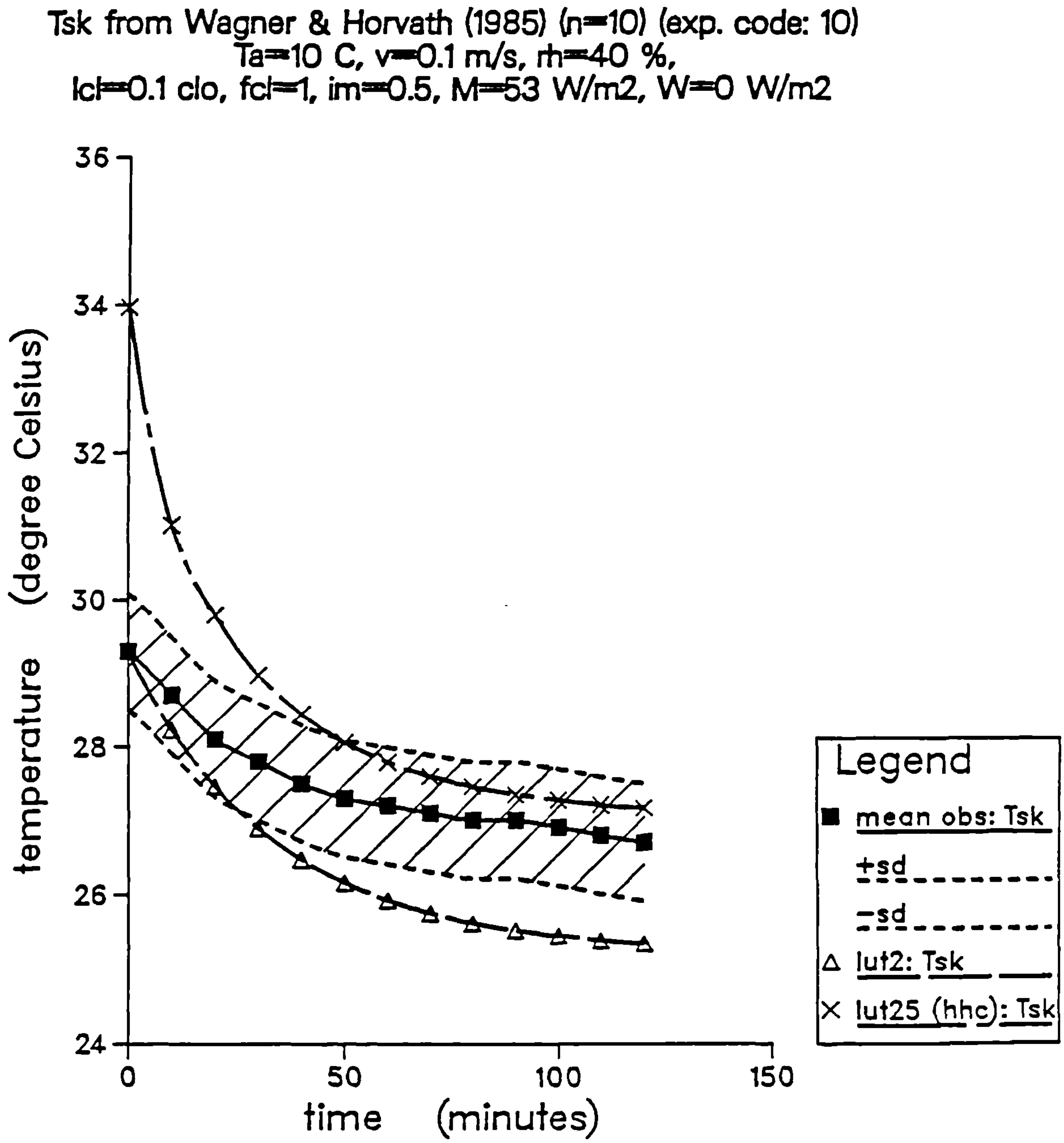


Figure 6.4. Example of metabolic rate responses (M) for the nude, rest and no-wind environment category, where Ta<=5 °C.

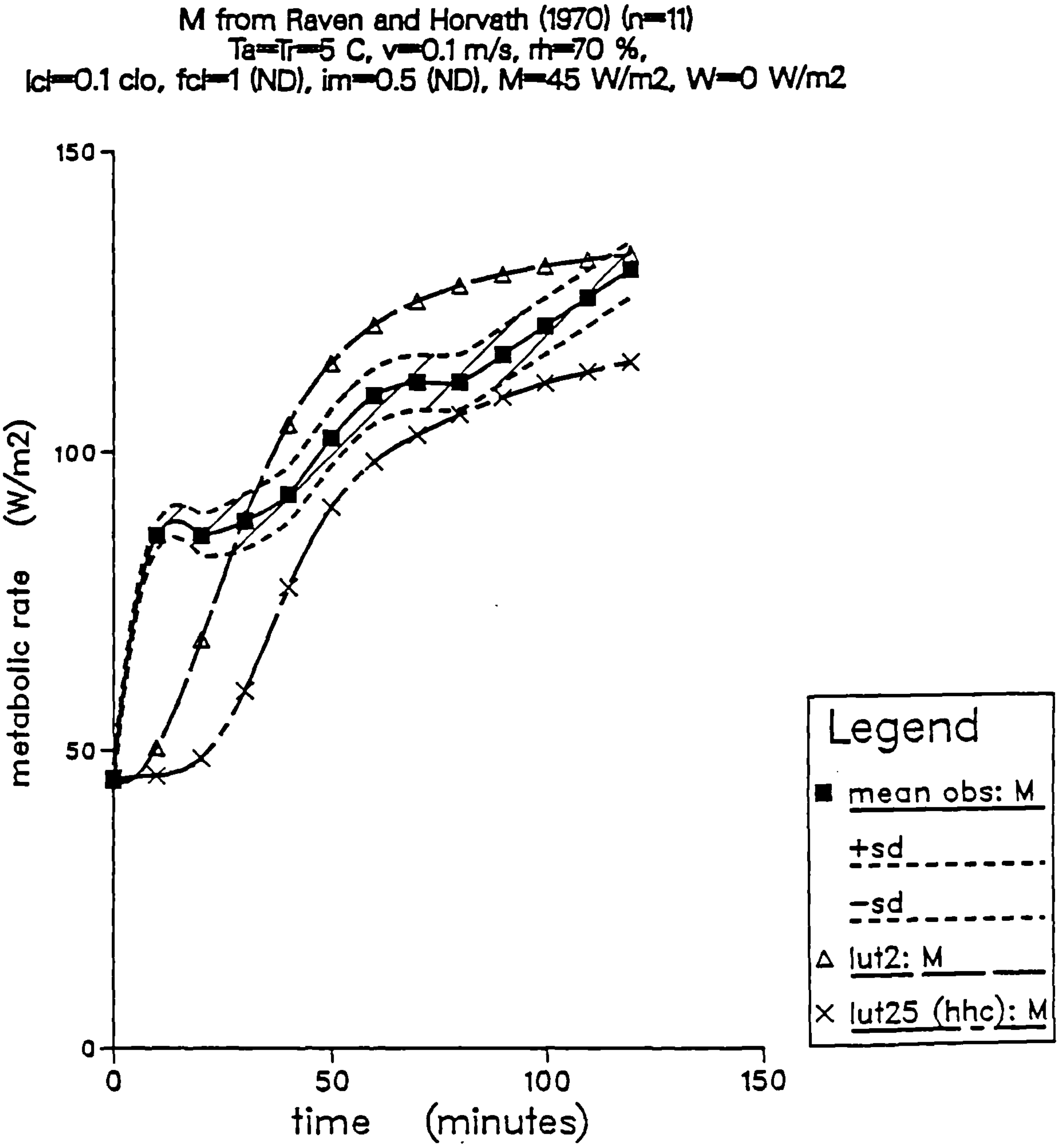


Figure 6.5. Example of metabolic rate responses (M) for the nude, rest and no-wind environment category, where 5<Ta<=15 °C.

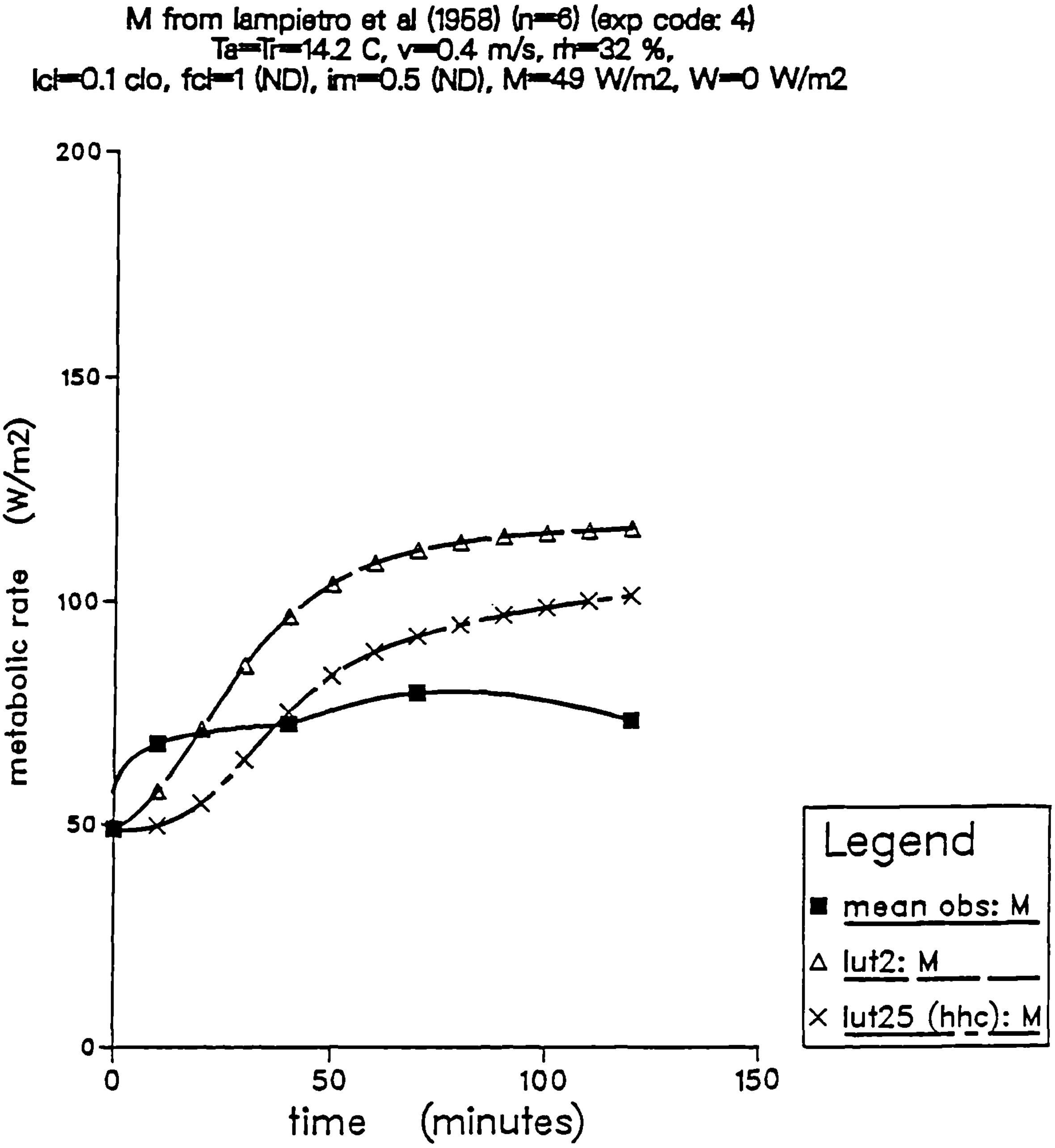


Figure 6.6. Example of deep body temperature responses (Tcr) for the nude, rest and no-wind environment category, where 15<Ta<=25 °C.

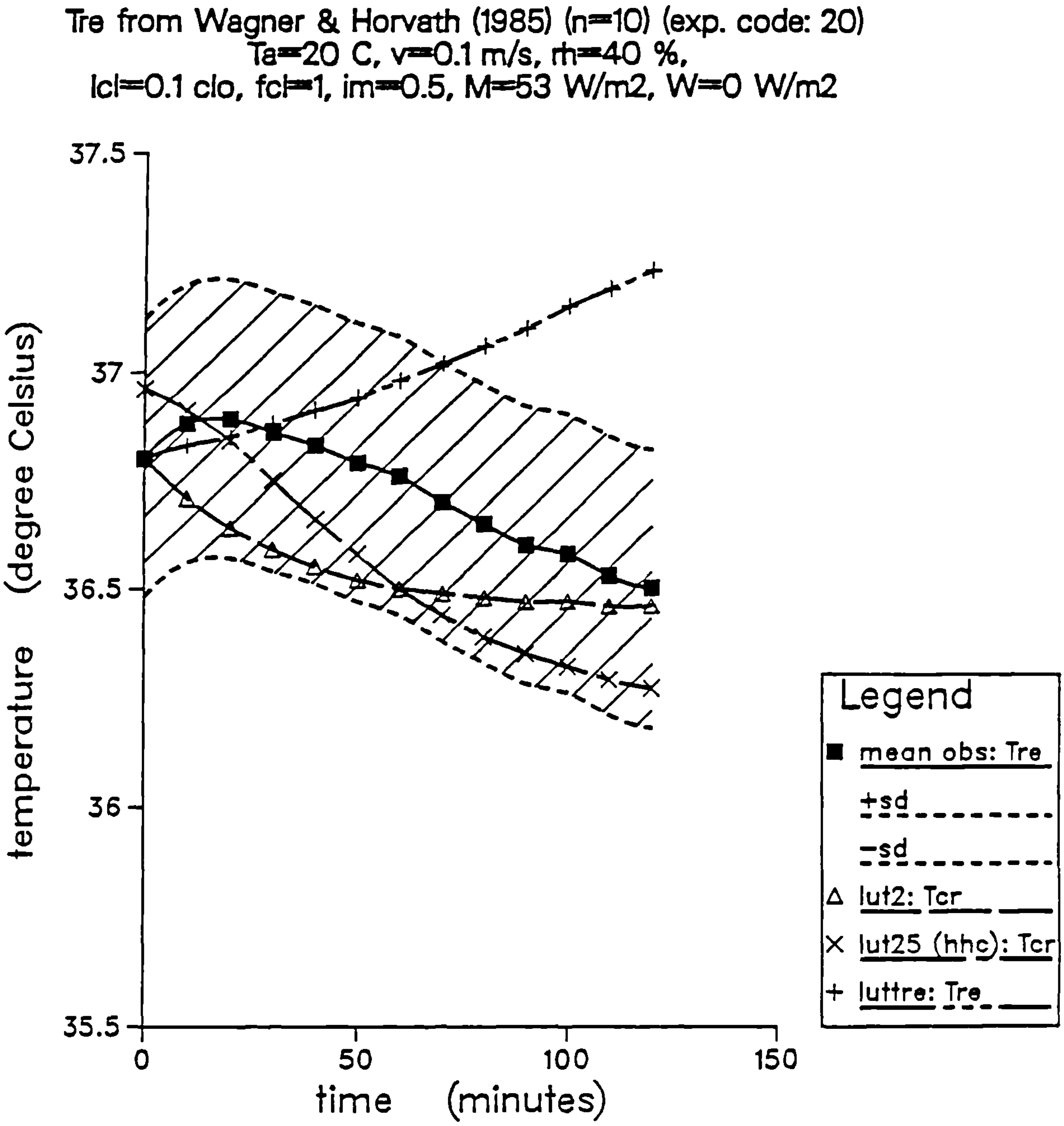


Figure 6.7. Example of mean skin temperature responses (Tsk) for the nude, rest and no-wind environment category, where 15<Ta<=25 °C.

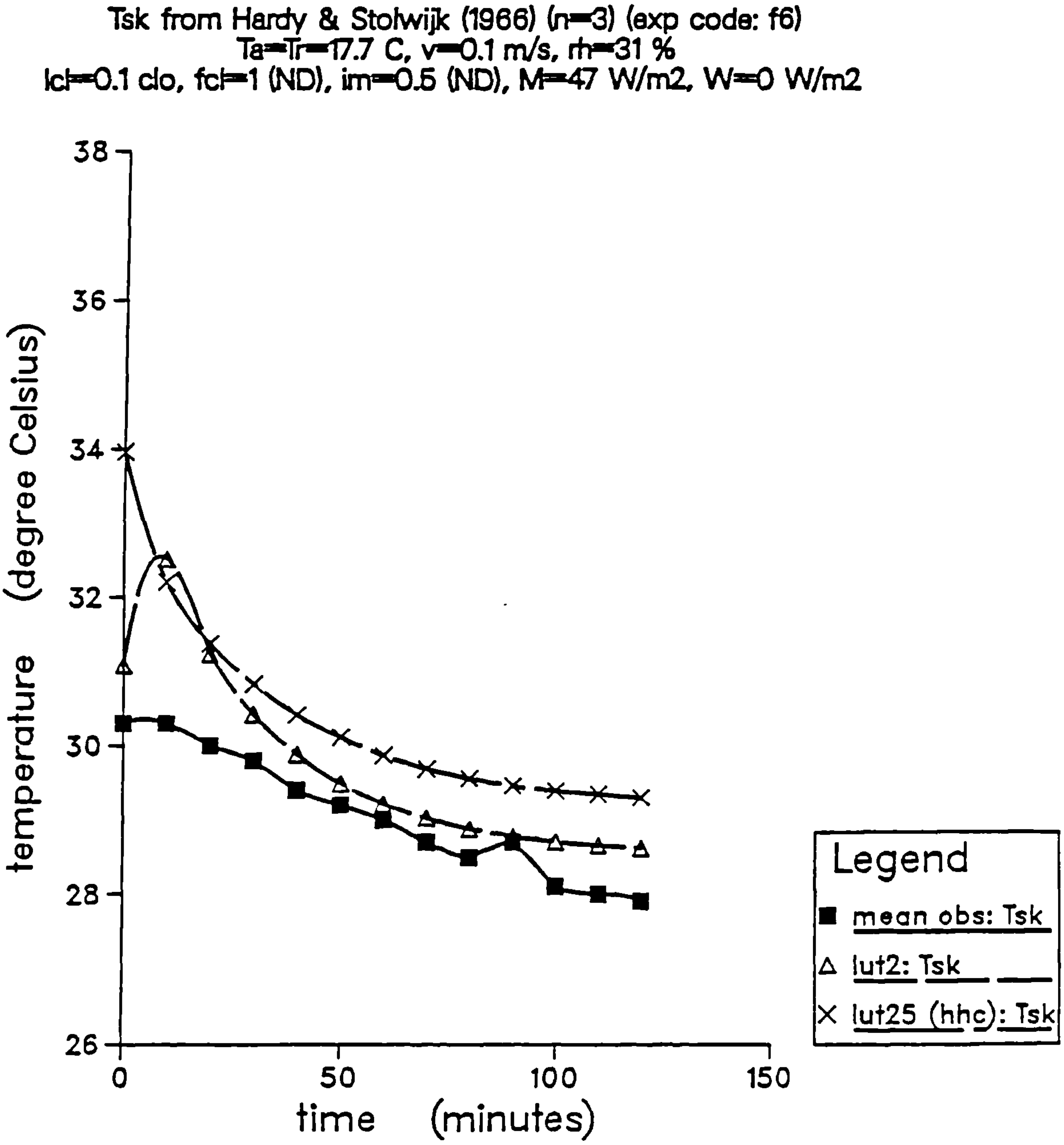


Figure 6.8. Example of metabolic rate responses (M) for the nude, rest and no-wind environment category, where 15<Ta<=25 °C.

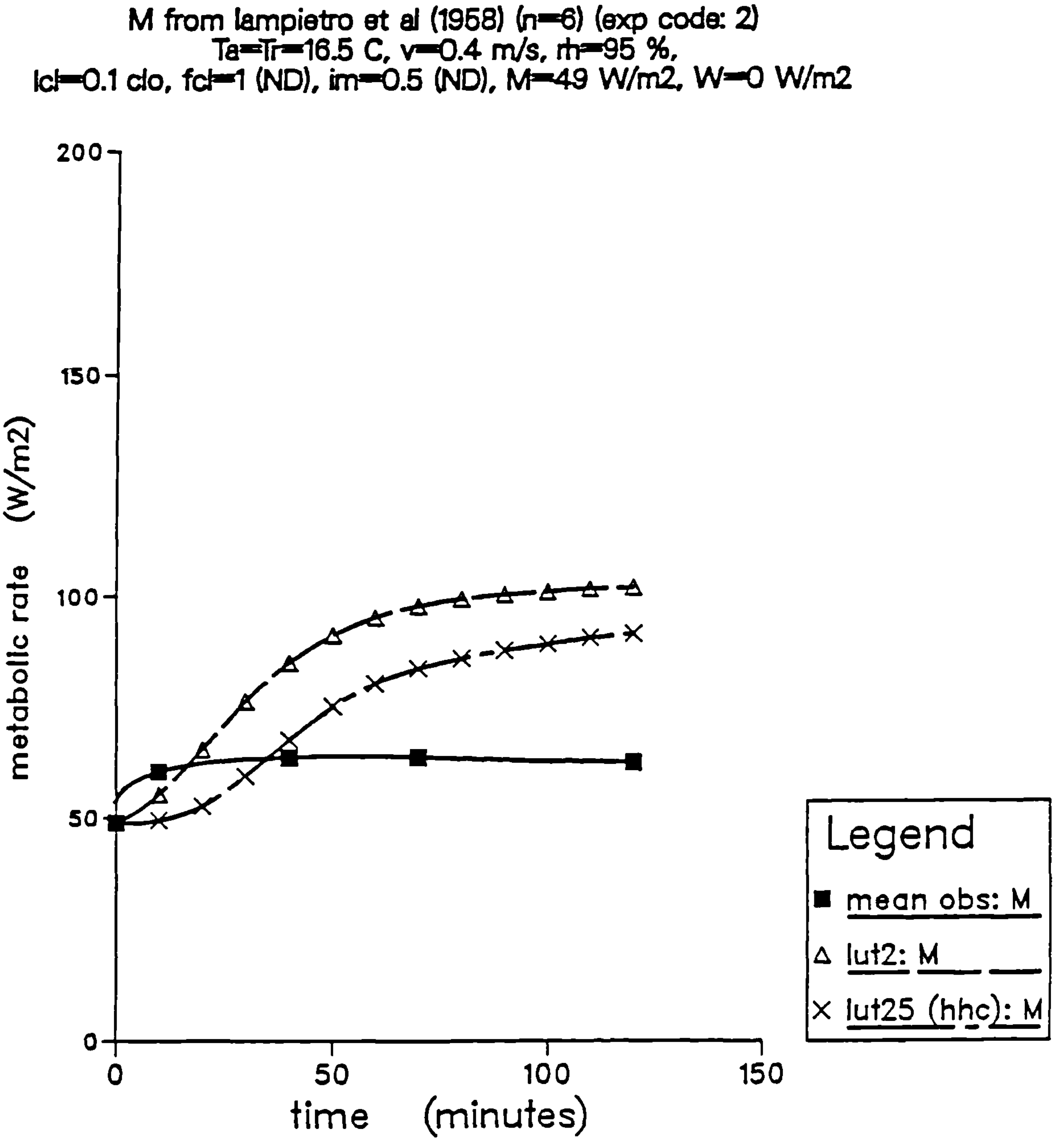


Figure 6.9. Example of deep body temperature responses (Tcr) for the nude, rest and no-wind environment category, where 25<Ta<=35 °C.

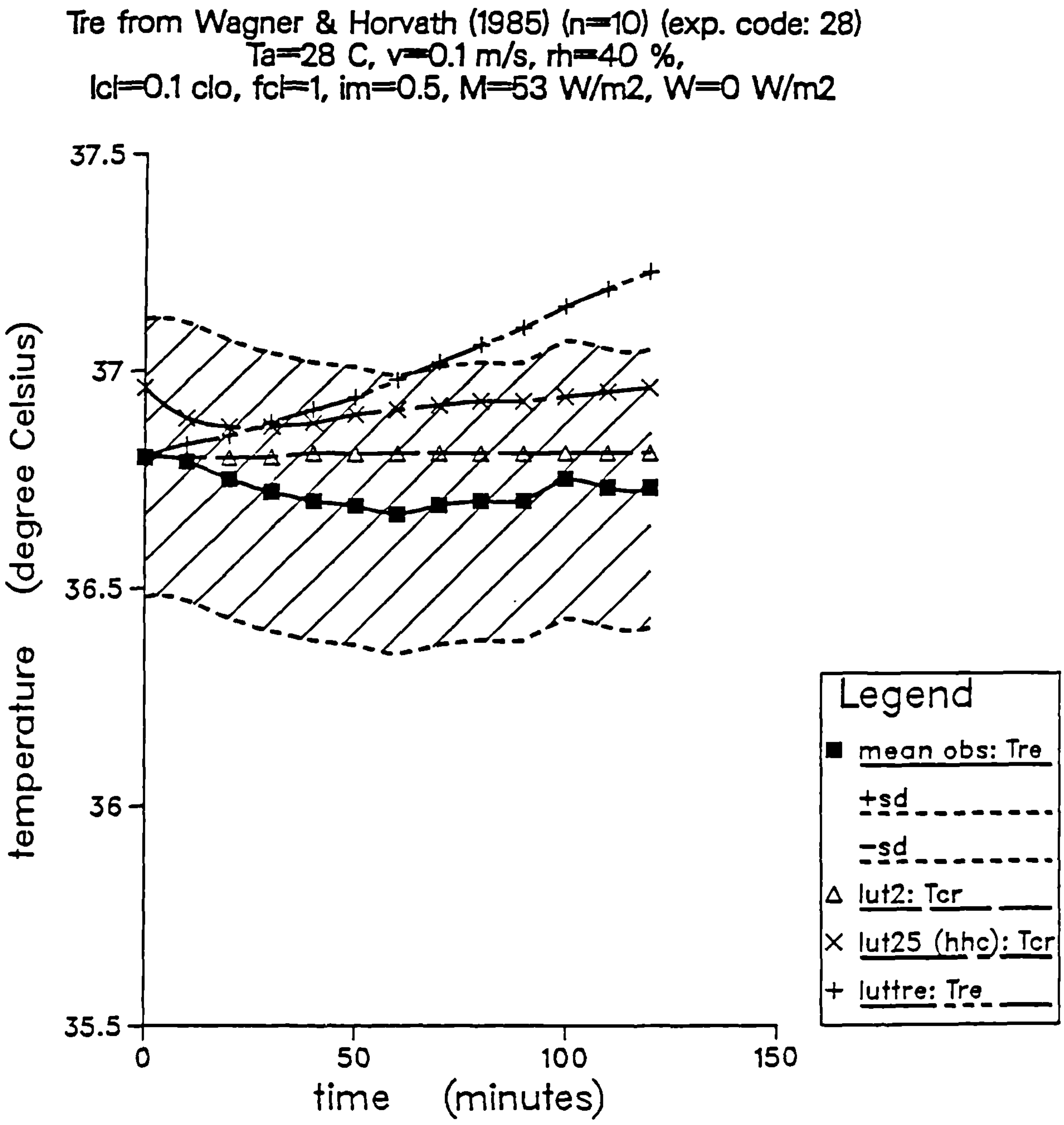


Figure 6.10. Example of mean skin temperature responses (Tsk) for the nude, rest and no-wind environment category, where 25<Ta<=35 °C.

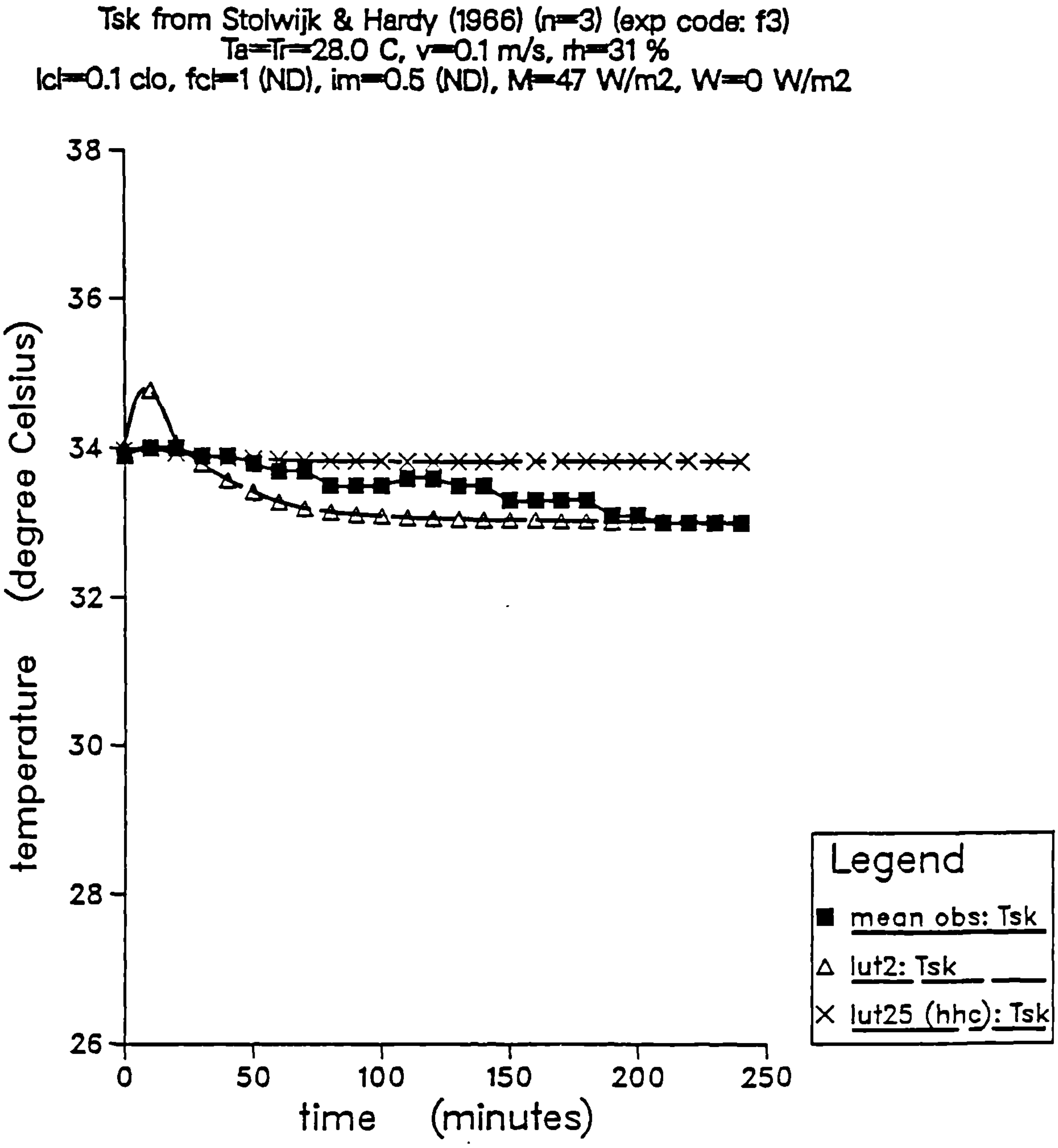
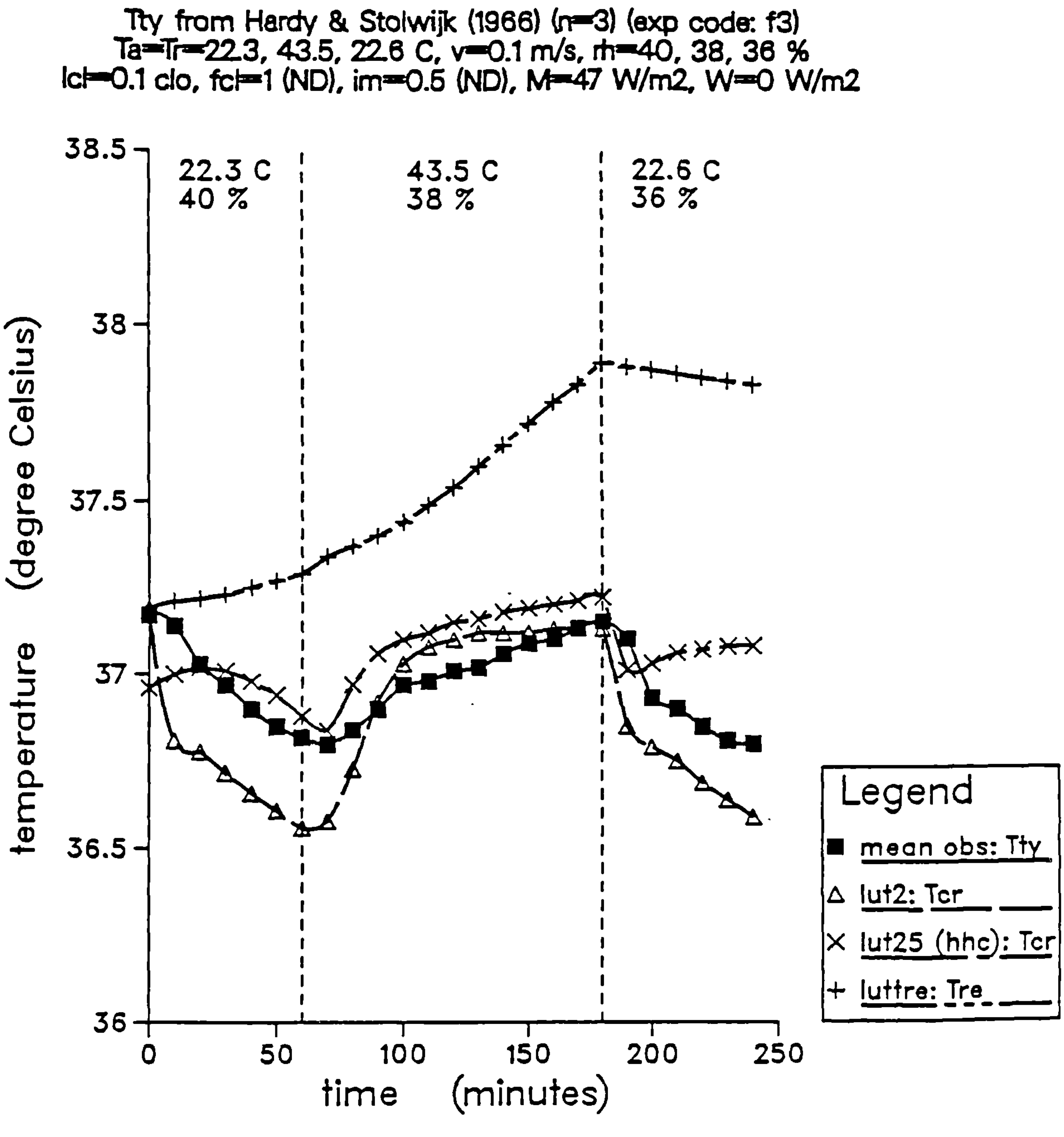
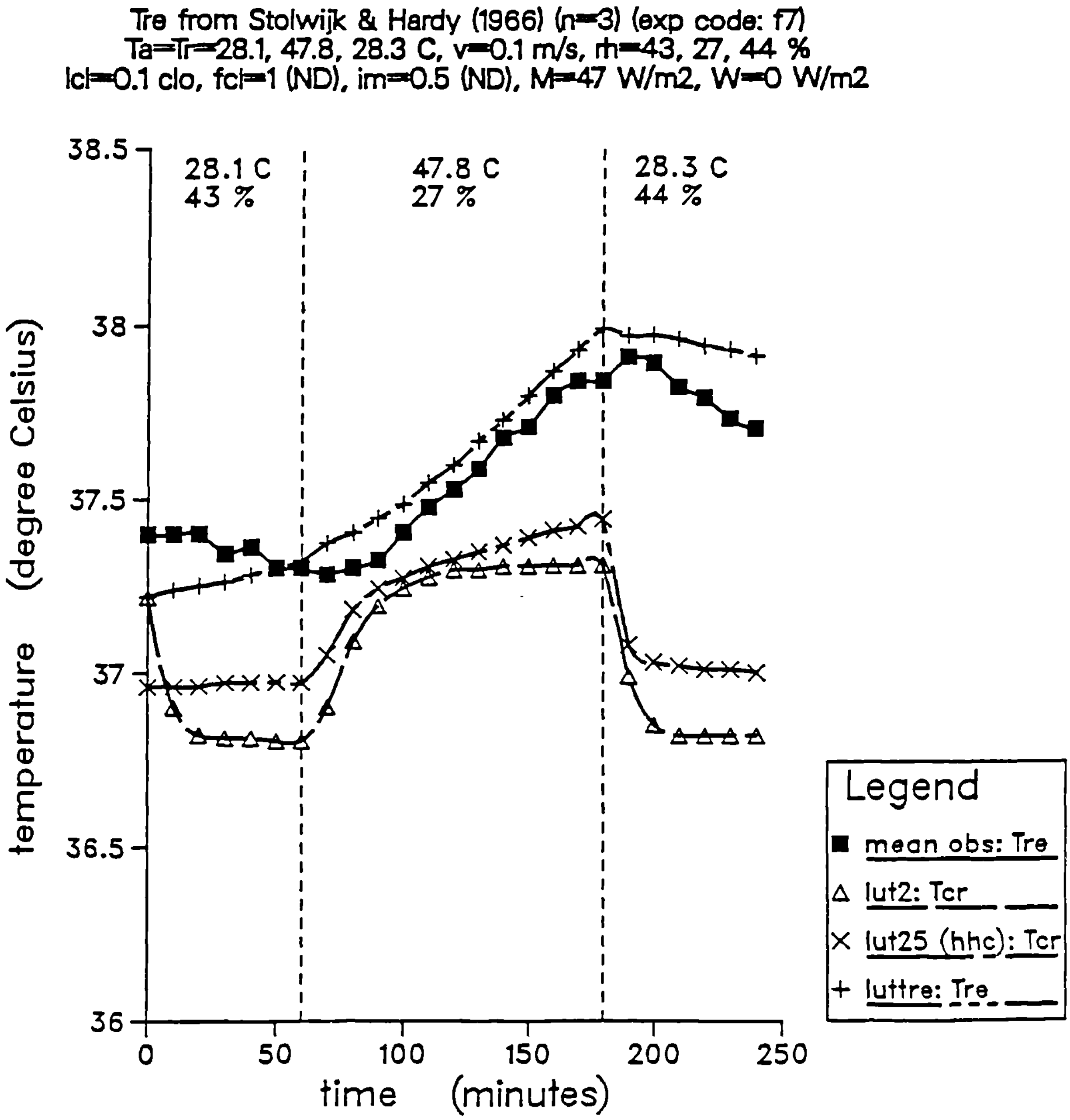


Figure 6.11. Example of deep body temperature responses (Tcr) for the nude, rest and no-wind environment category, where Ta>35 °C.



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 6.12. Example of deep body temperature responses (Tcr) for the nude, rest and no-wind environment category, where Ta>35 °C.



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

Figure 6.13. Example of mean skin temperature responses (Tsk) for the nude, rest and no-wind environment category, where Ta>35 °C.

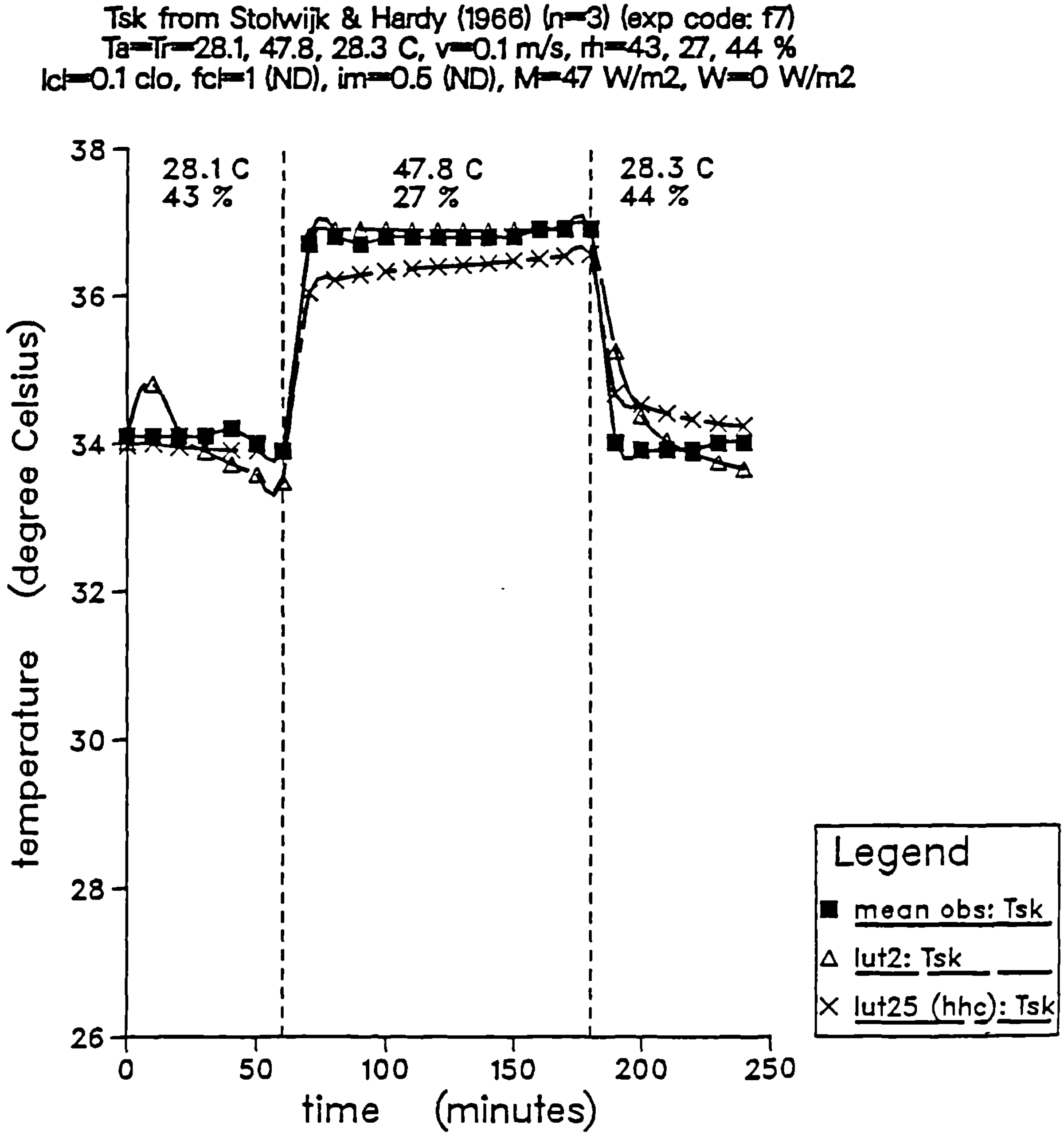


Figure 6.14. Example of evaporative heat transfer at the skin responses (Esk) for the nude, rest, no-wind environment category, where Ta>35 °C.

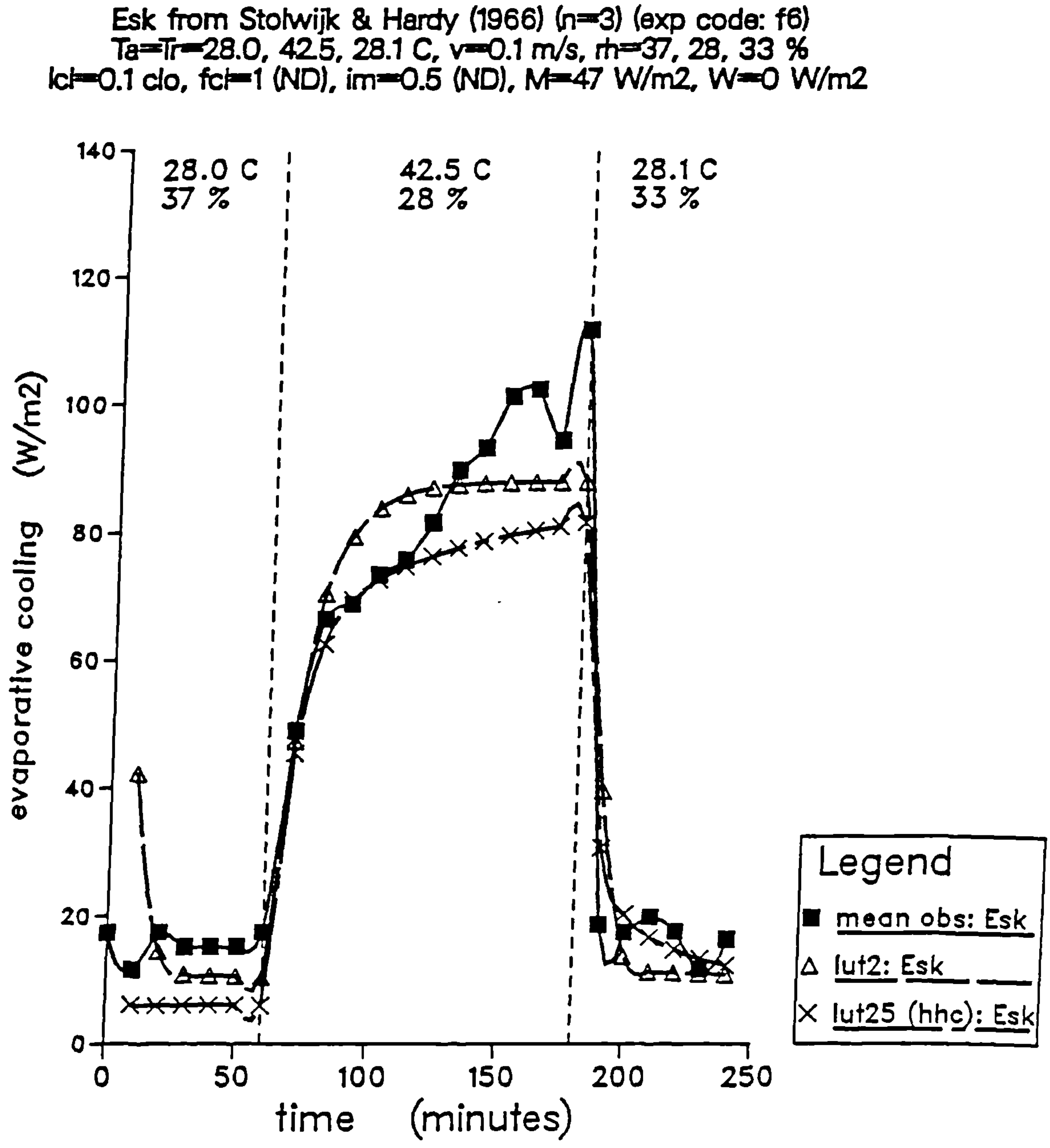


Figure 6.15. Example of deep body temperature responses (Tcr) for the nude, rest and wind environment category, where 5<Ta<=15 °C.

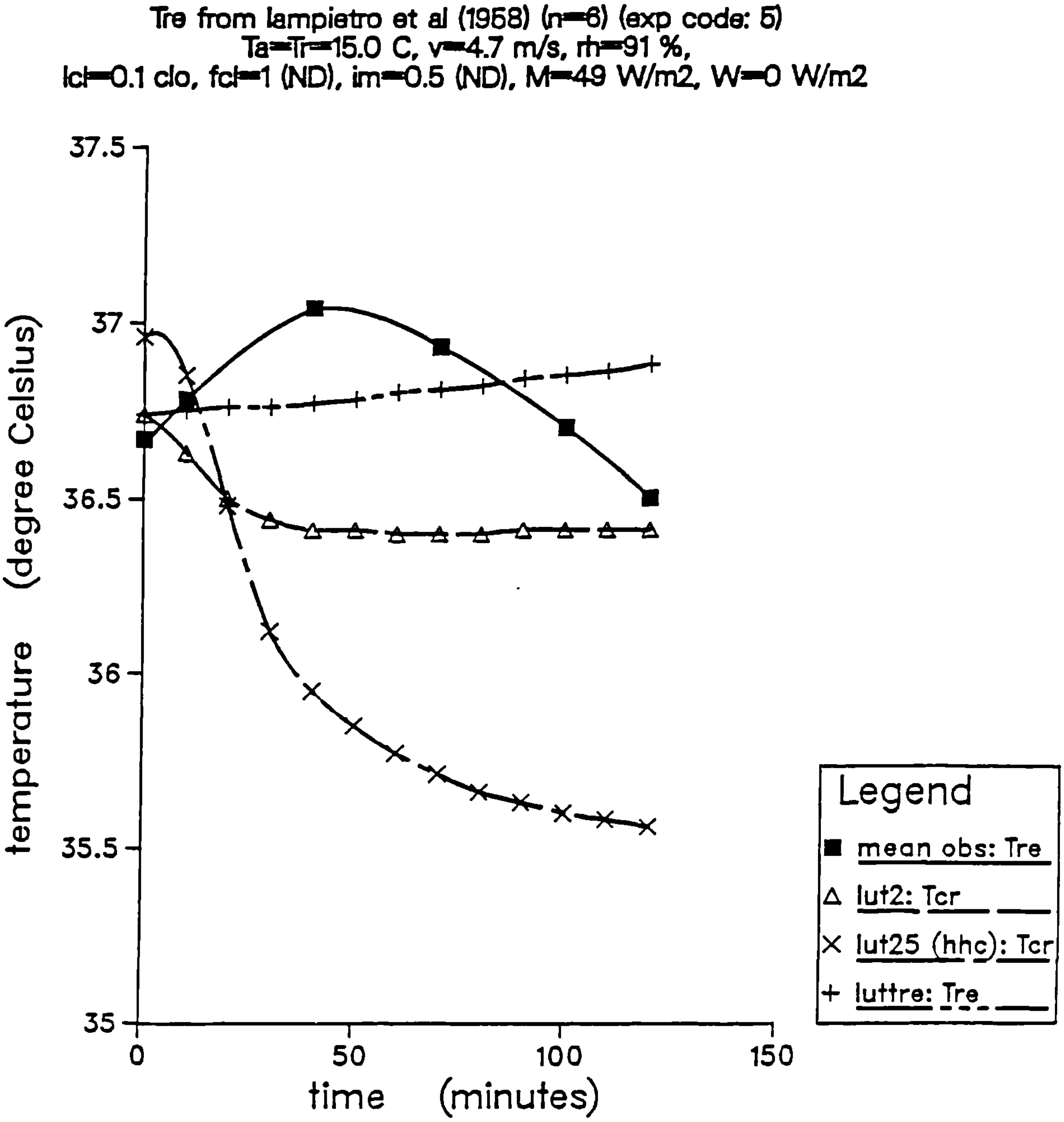


Figure 6.16. Example of mean skin temperature responses (Tsk) for the nude, rest and wind environment category, where 5<Ta<=15 °C.

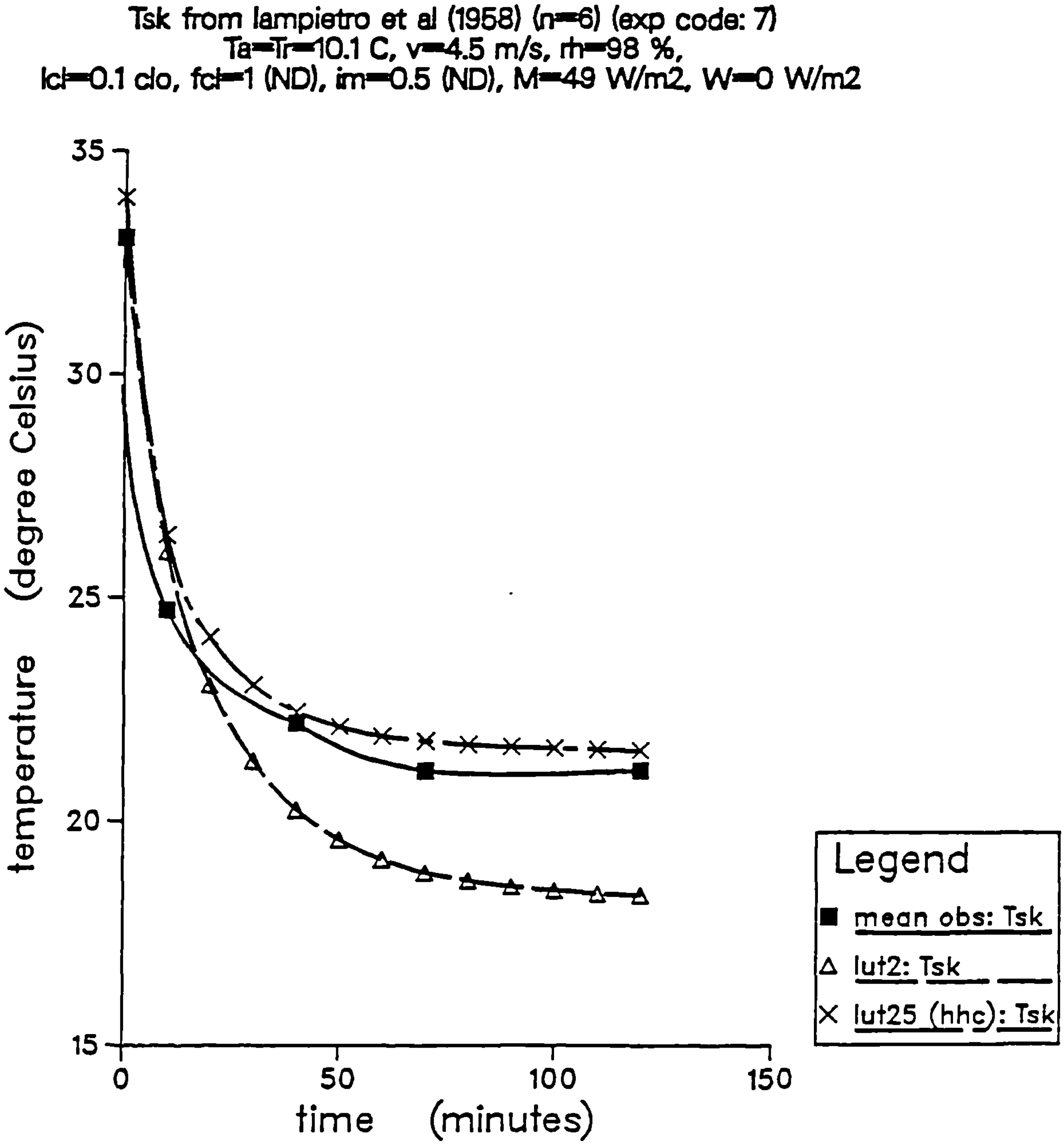


Figure 6.17. Example of metabolic rate responses (M) for the nude, rest and wind environment category, where 5<Ta<=15 °C.

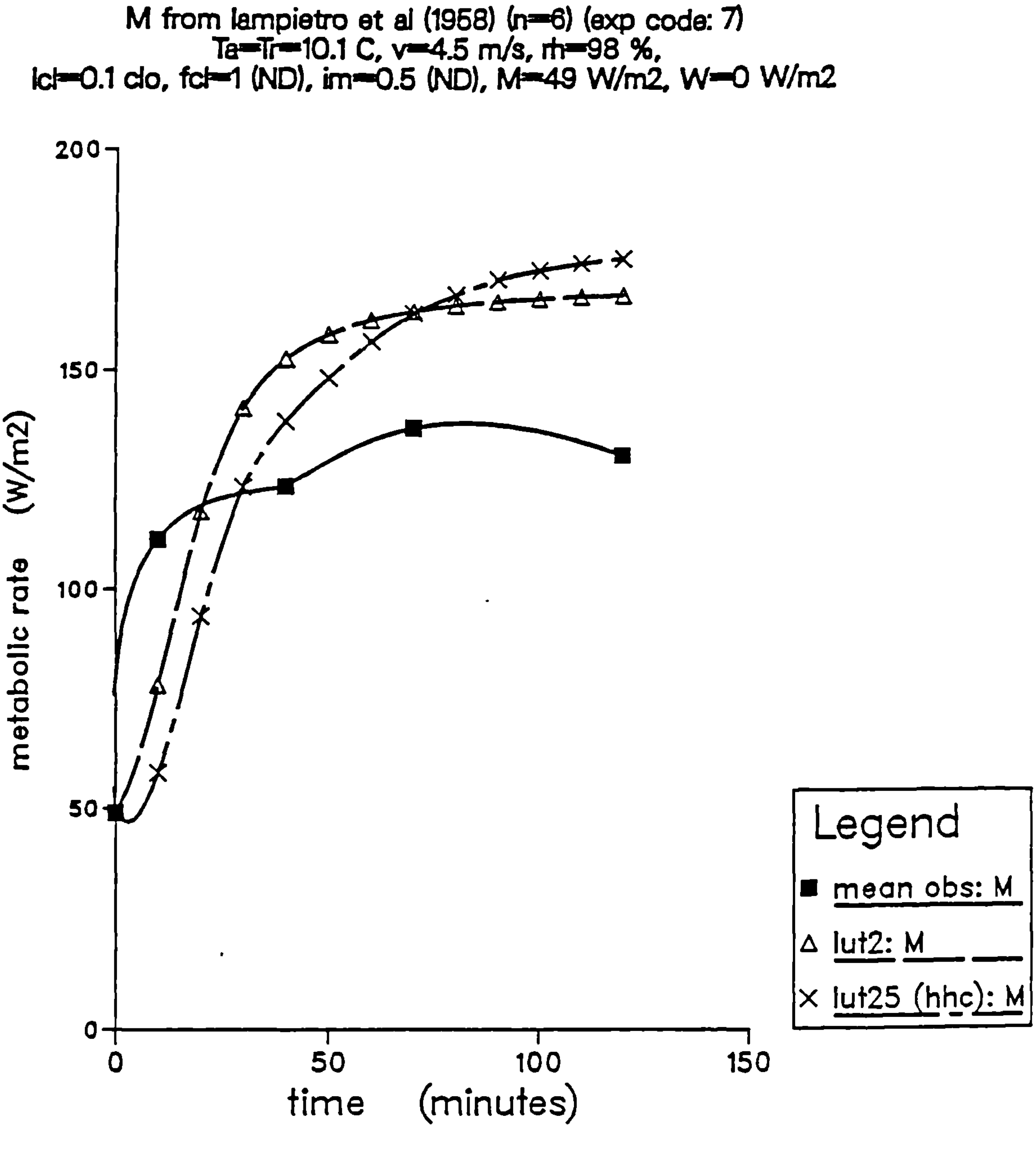
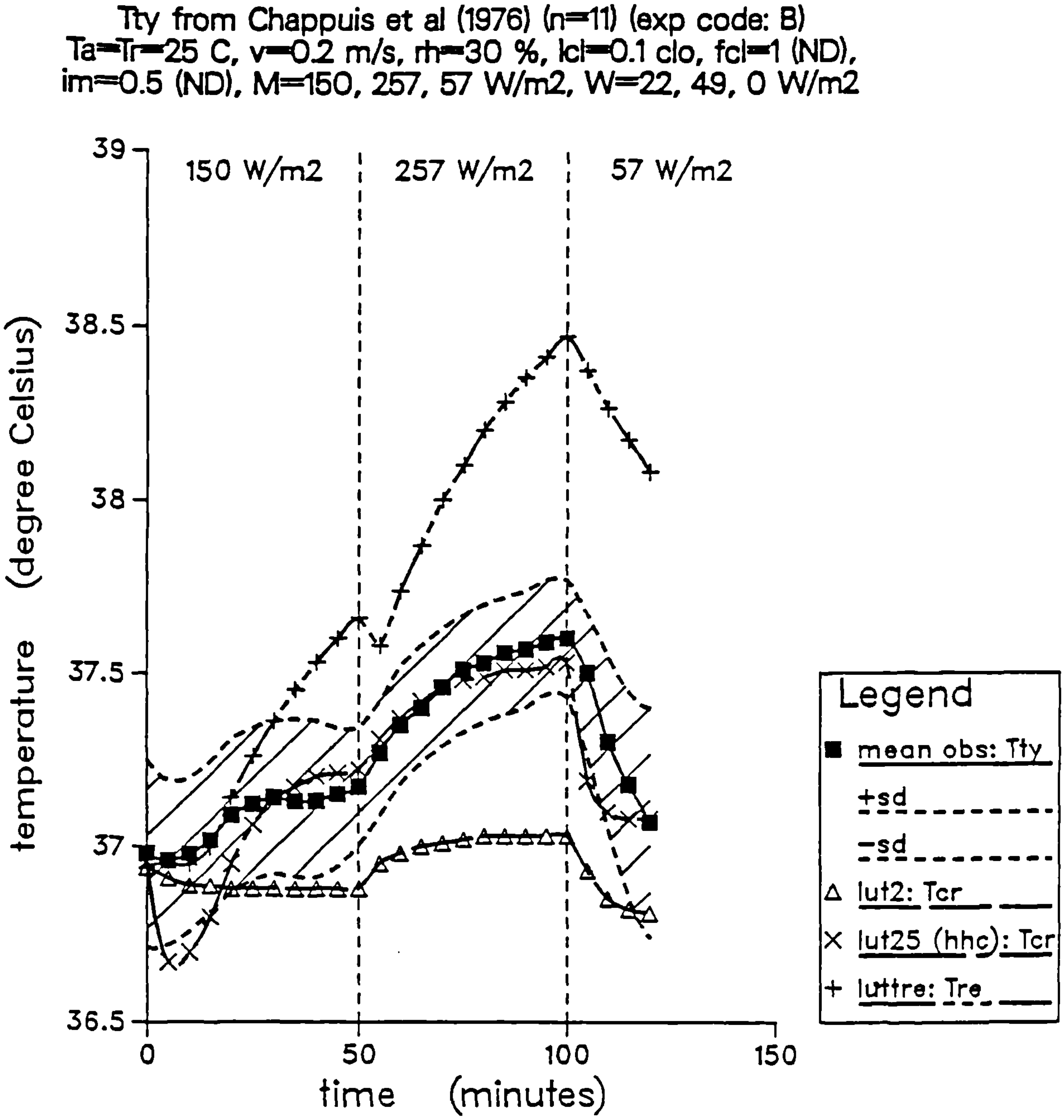
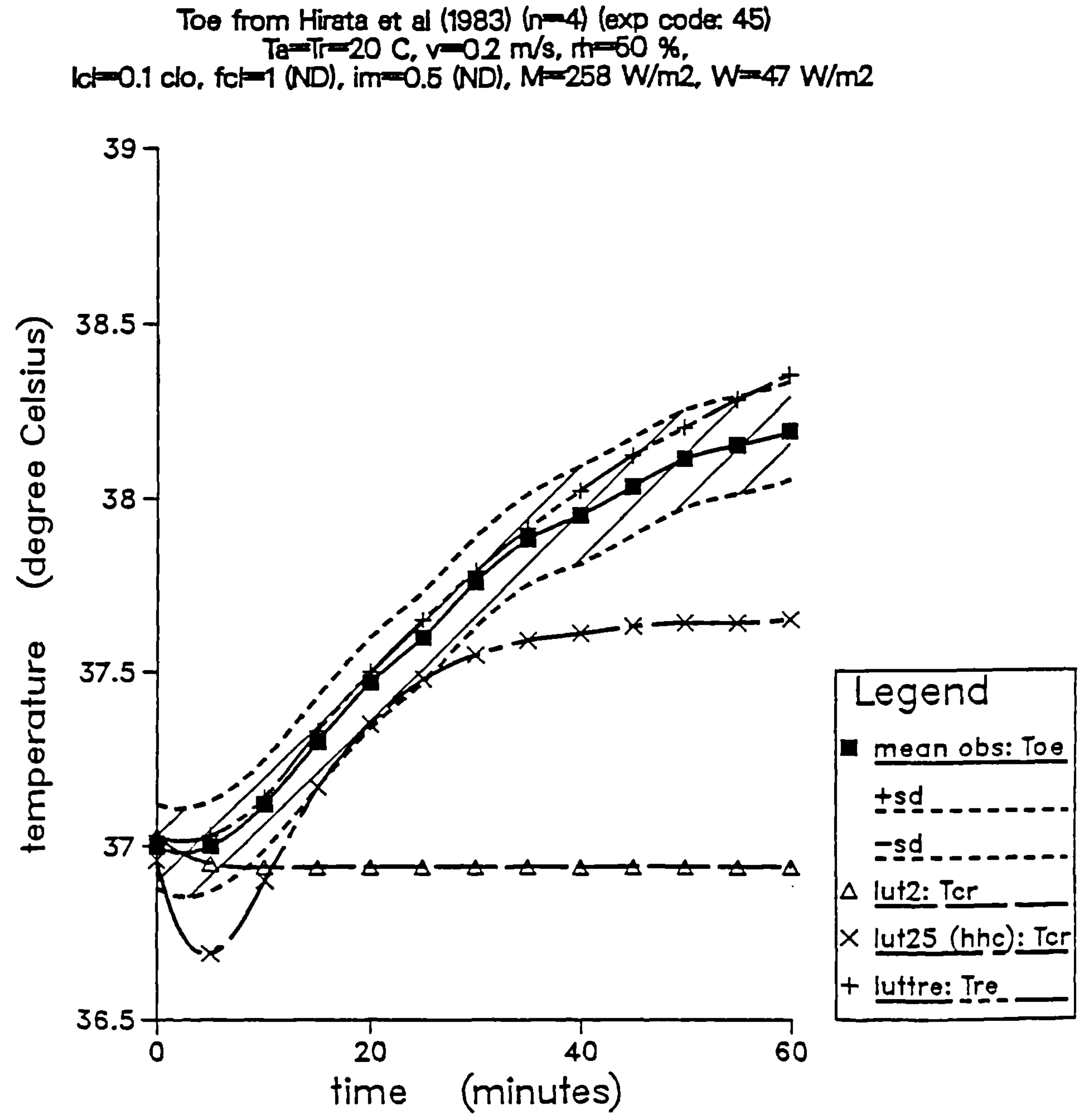


Figure 6.18. Example of deep body temperature responses (Tcr) for the nude, work and no-wind environment category, where 15<Ta<=25 °C.



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 6.19. Example of deep body temperature responses (Tcr) for the nude, work and no-wind environment category, where 15<Ta<=25 °C.



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

Figure 6.20. Example of mean skin temperature responses (Tsk) for the nude, work and no-wind environment category, where 15<Ta<=25 °C.

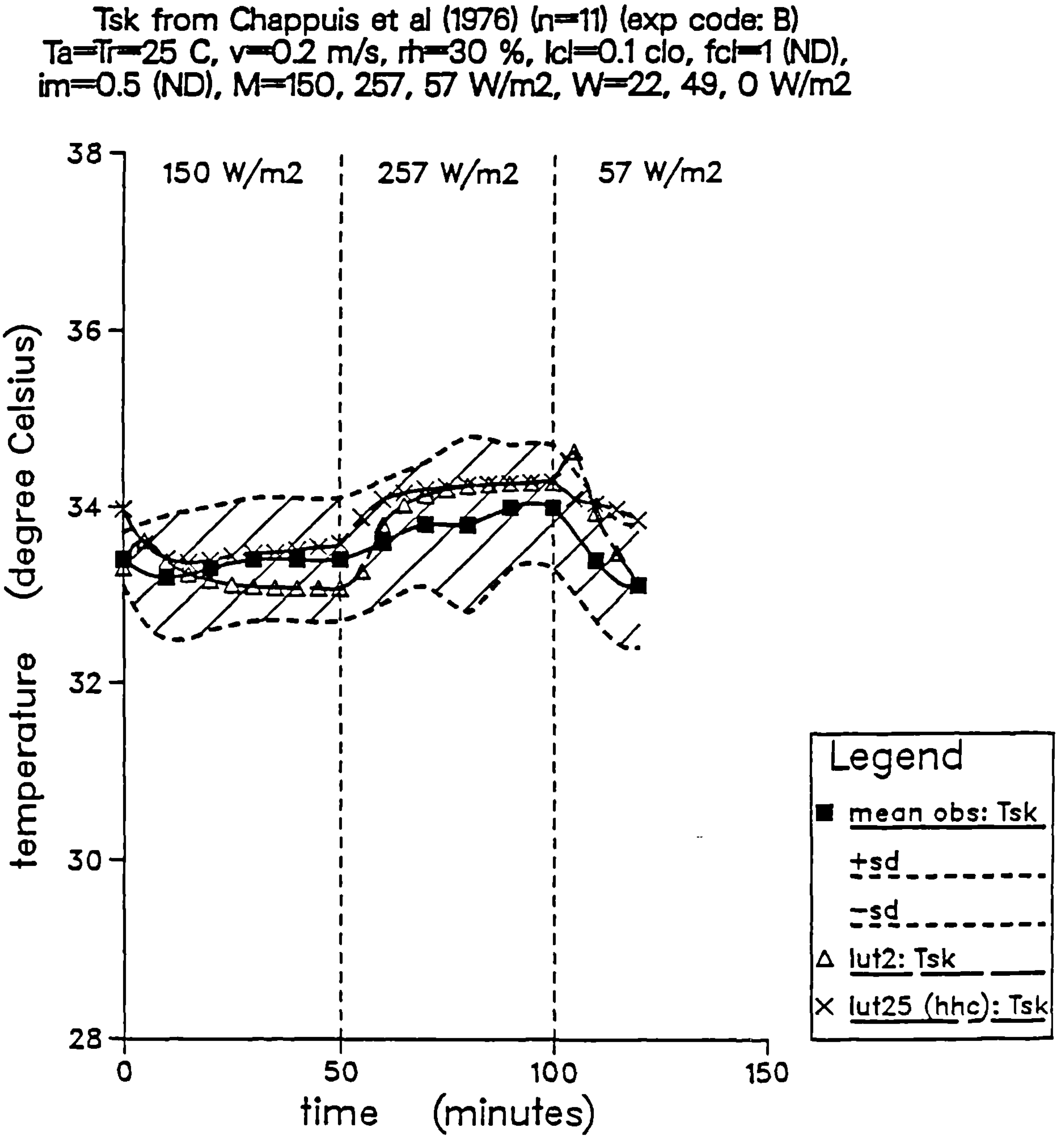


Figure 6.21. Example of mean skin temperature responses (Tsk) for the nude, work and no-wind environment category, where 15<Ta<=25 °C.

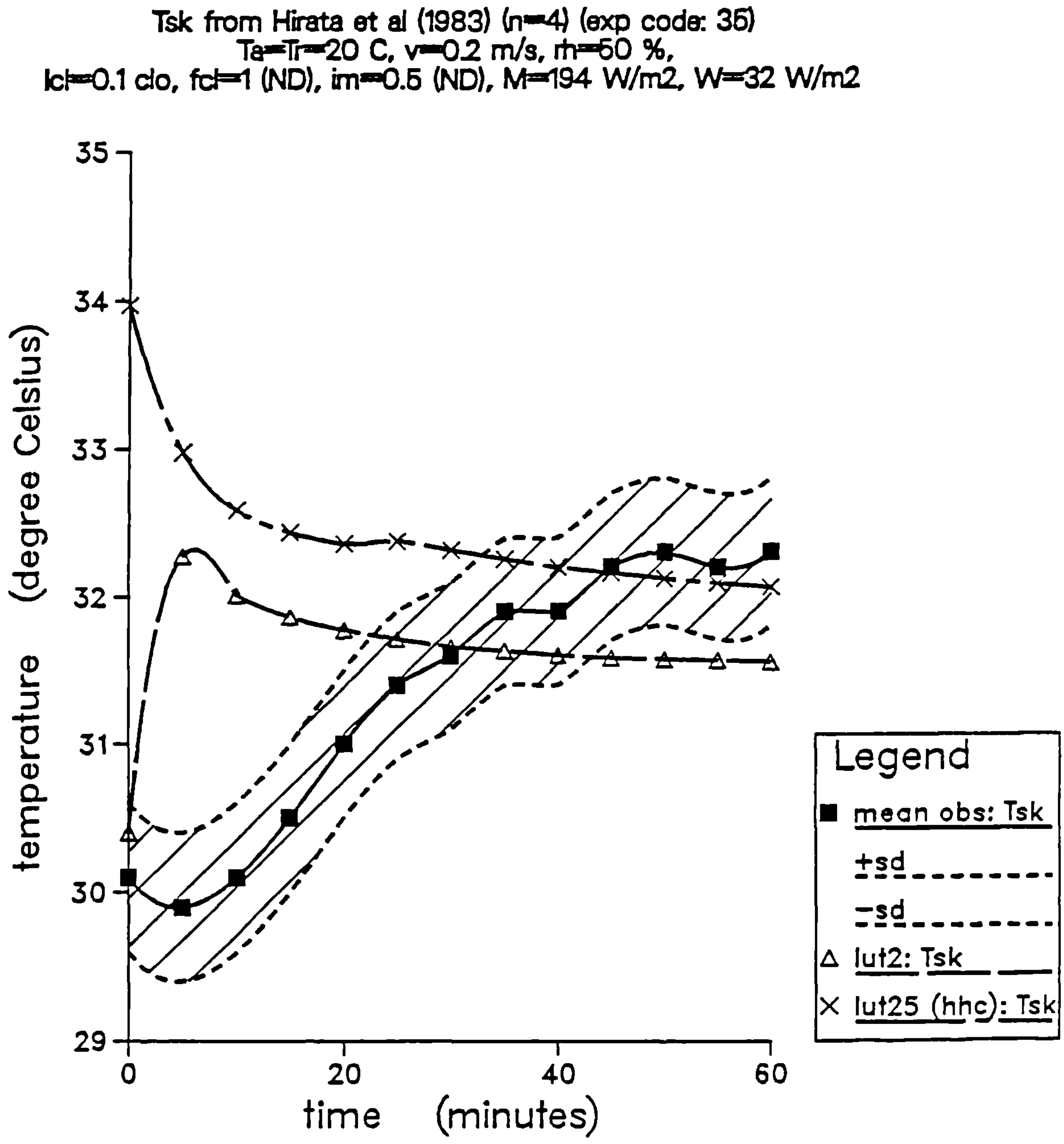


Figure 6.22. Example of dry heat transfer responses (C+R) for the nude, work and no-wind environment category, where 15<Ta<=25 °C.

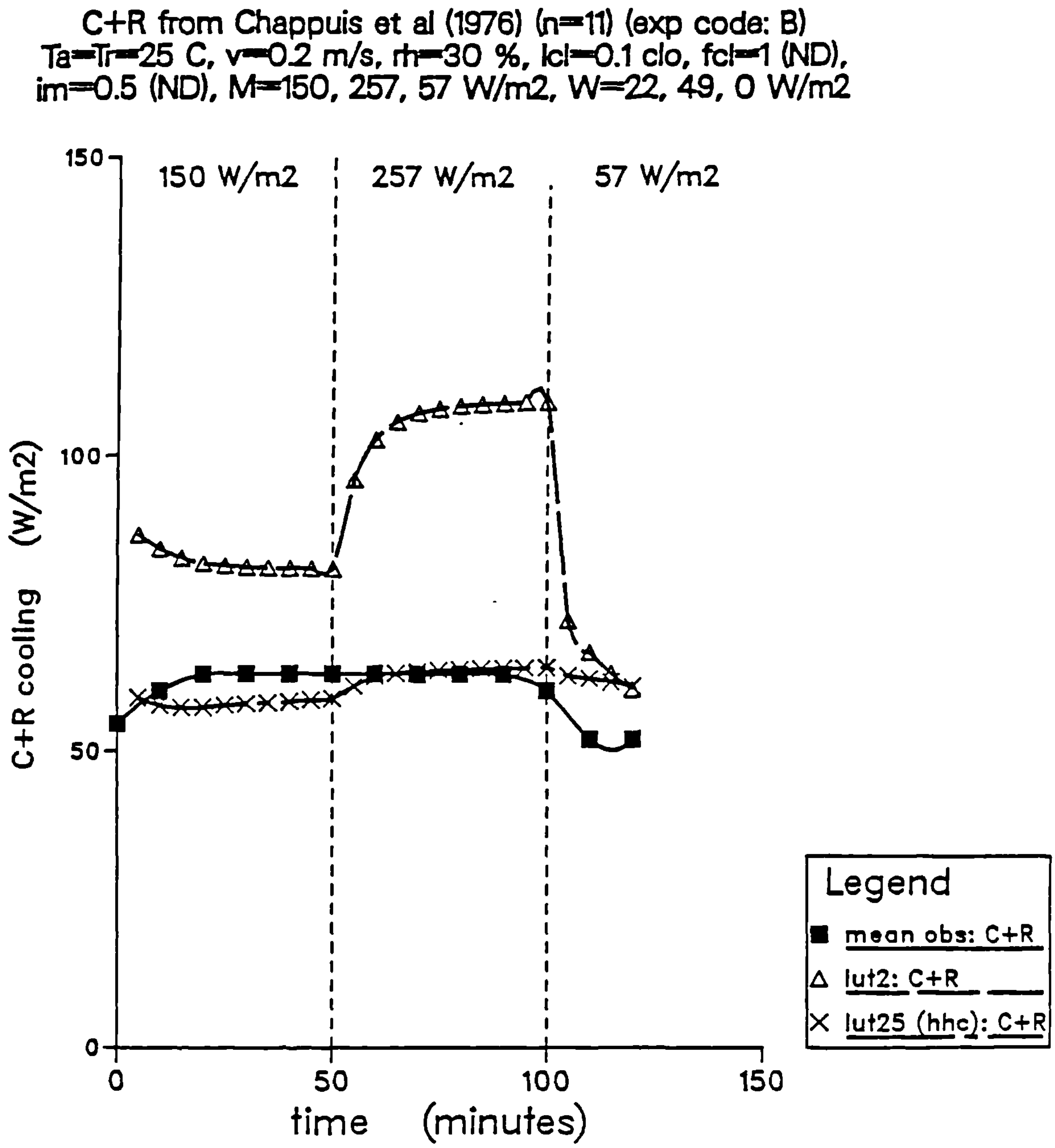


Figure 6.23. Example of total evaporative heat transfer responses (E) for the nude, work and no-wind environment category, where 15<Ta<=25 °C.

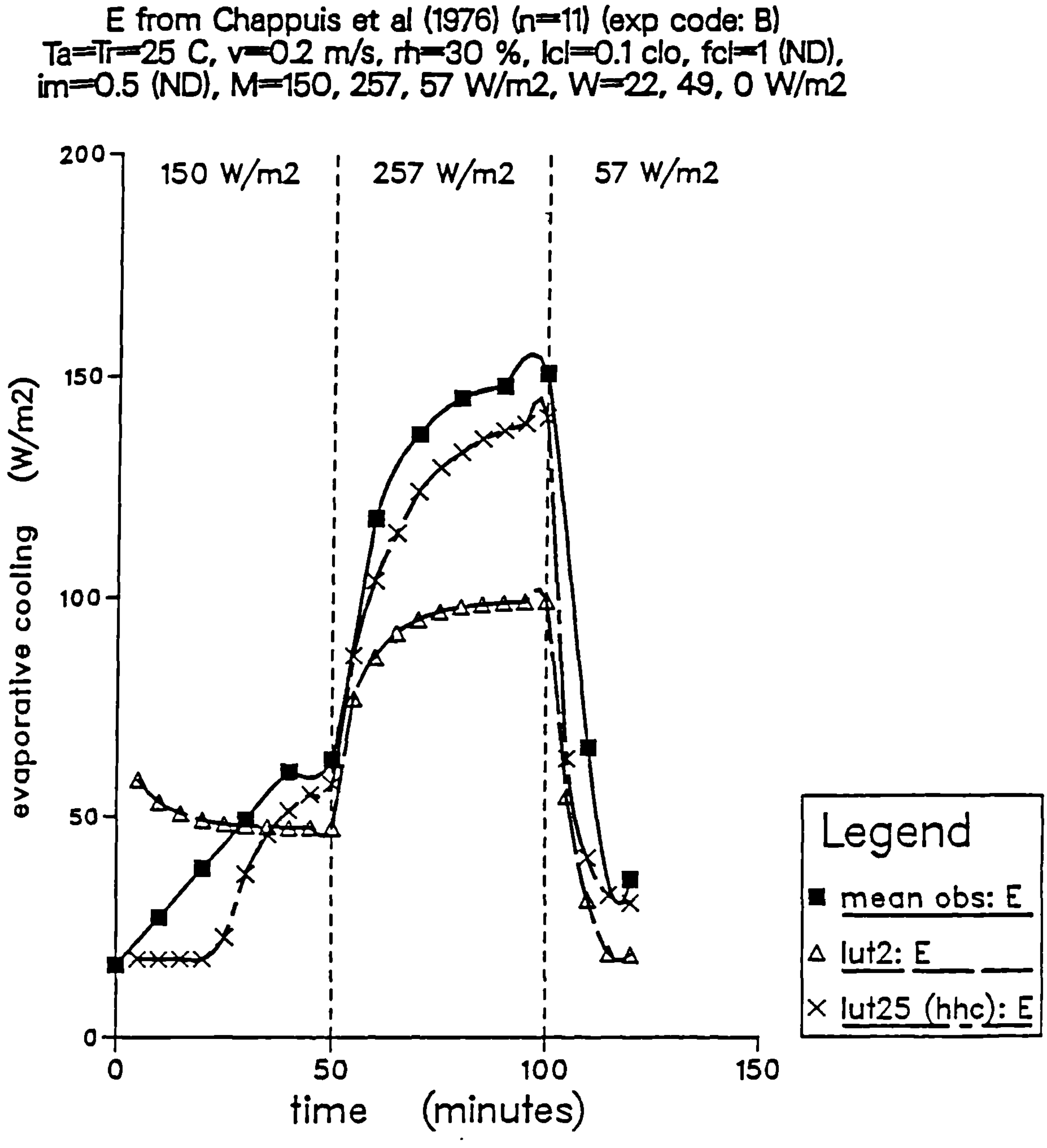
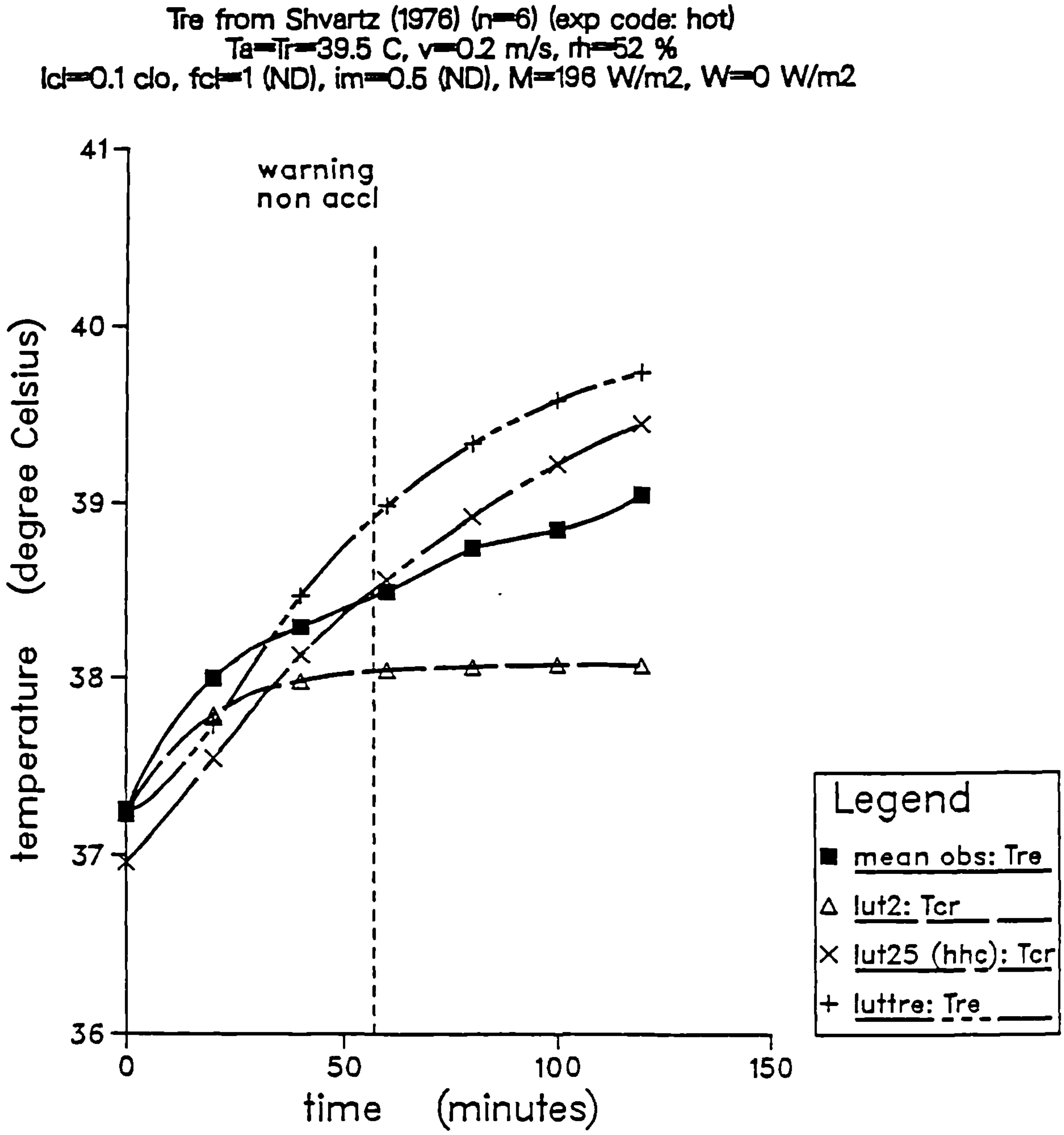
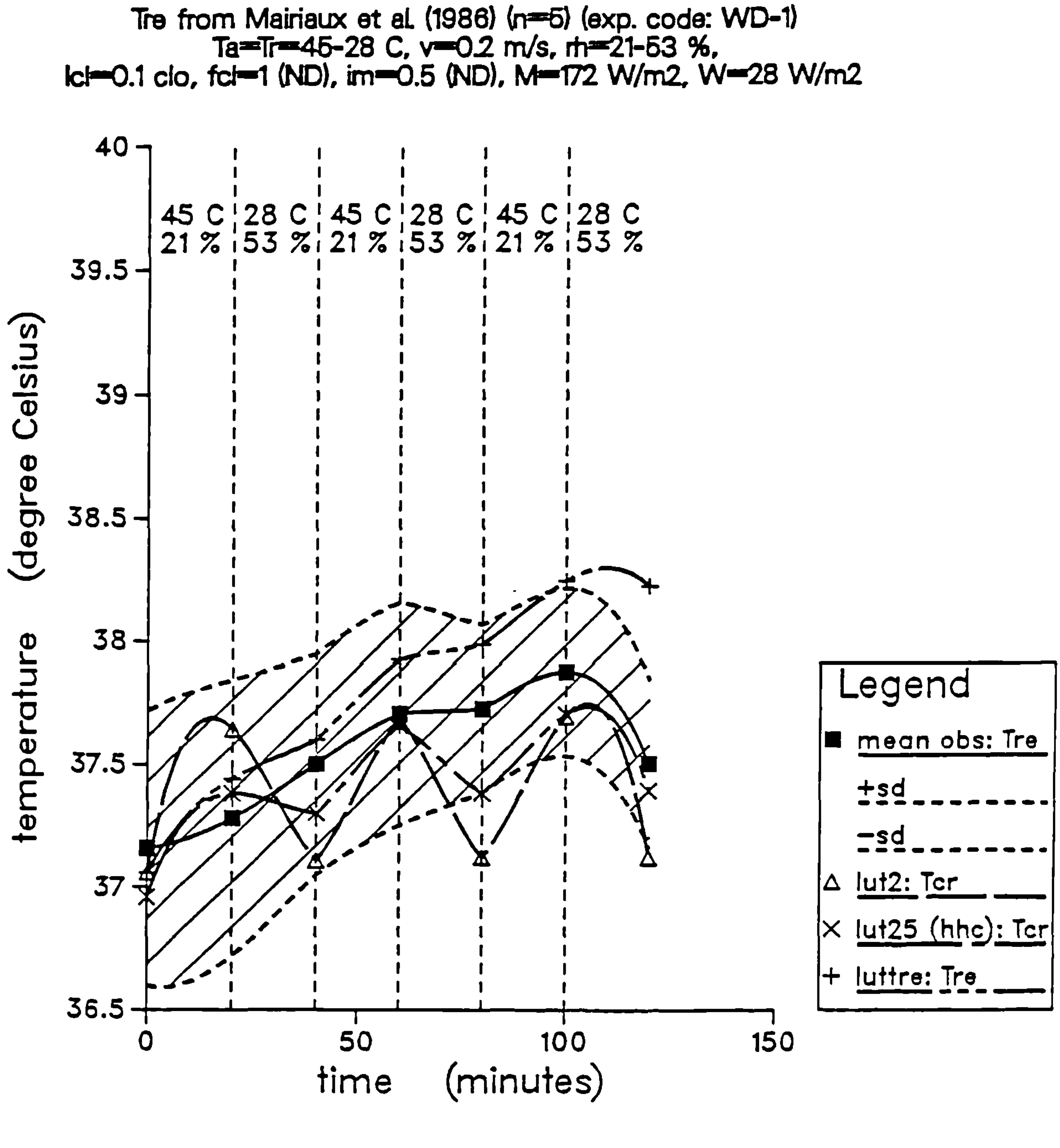


Figure 6.24. Example of deep body temperature responses (Tcr) for the nude, work and no-wind environment category, where Ta>35 °C.



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

Figure 6.25. Example of deep body temperature responses (Tcr) for the nude, work and no-wind environment category, where Ta>35 °C.



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

Figure 6.26. Example of mean skin temperature responses (Tsk) for the nude, work and no-wind environment category, where Ta>35 °C.

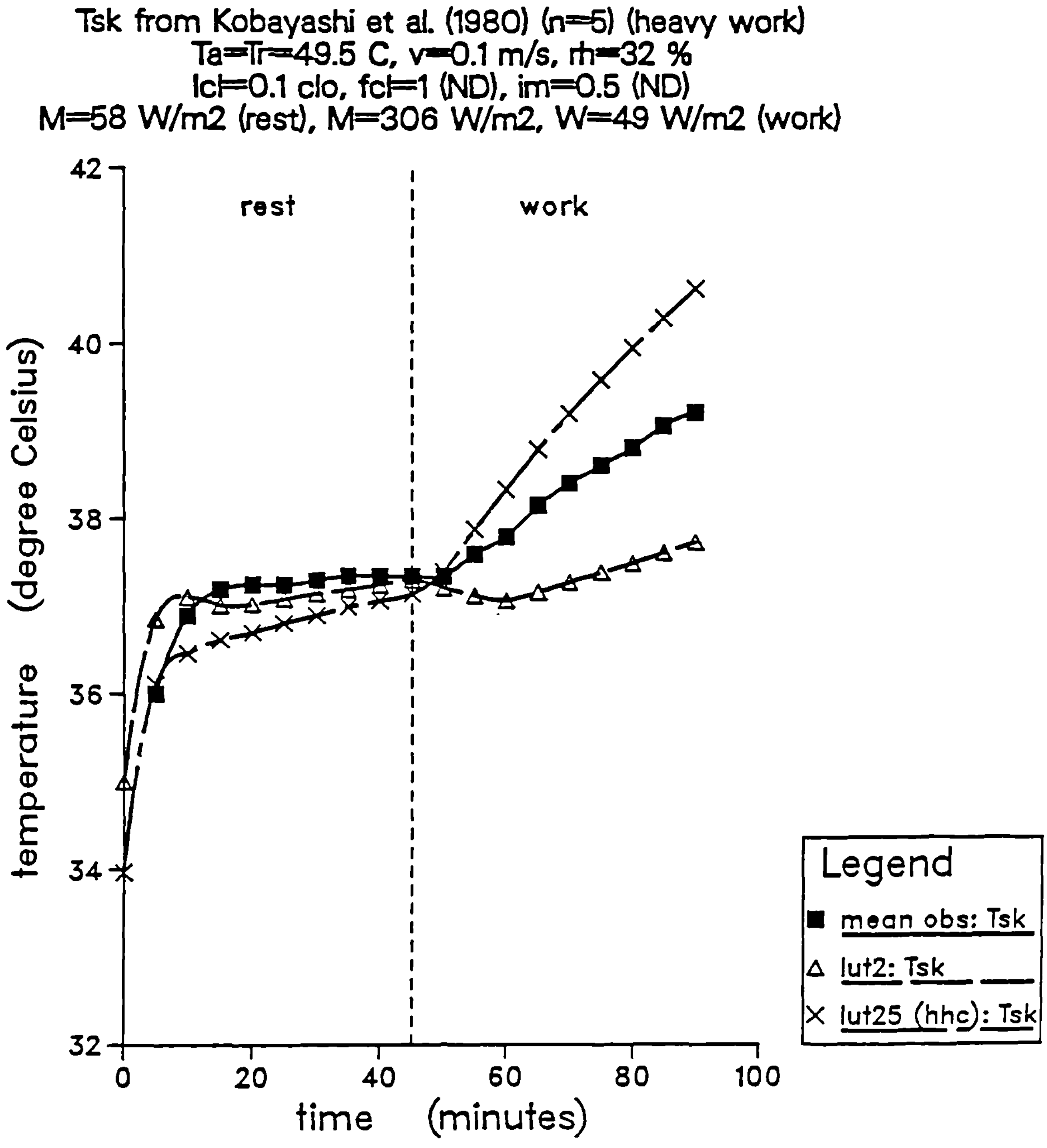


Figure 6.27. Example of evaporative heat transfer at the skin responses (Esk) for the nude, work and no-wind environment category, where Ta>35 °C.

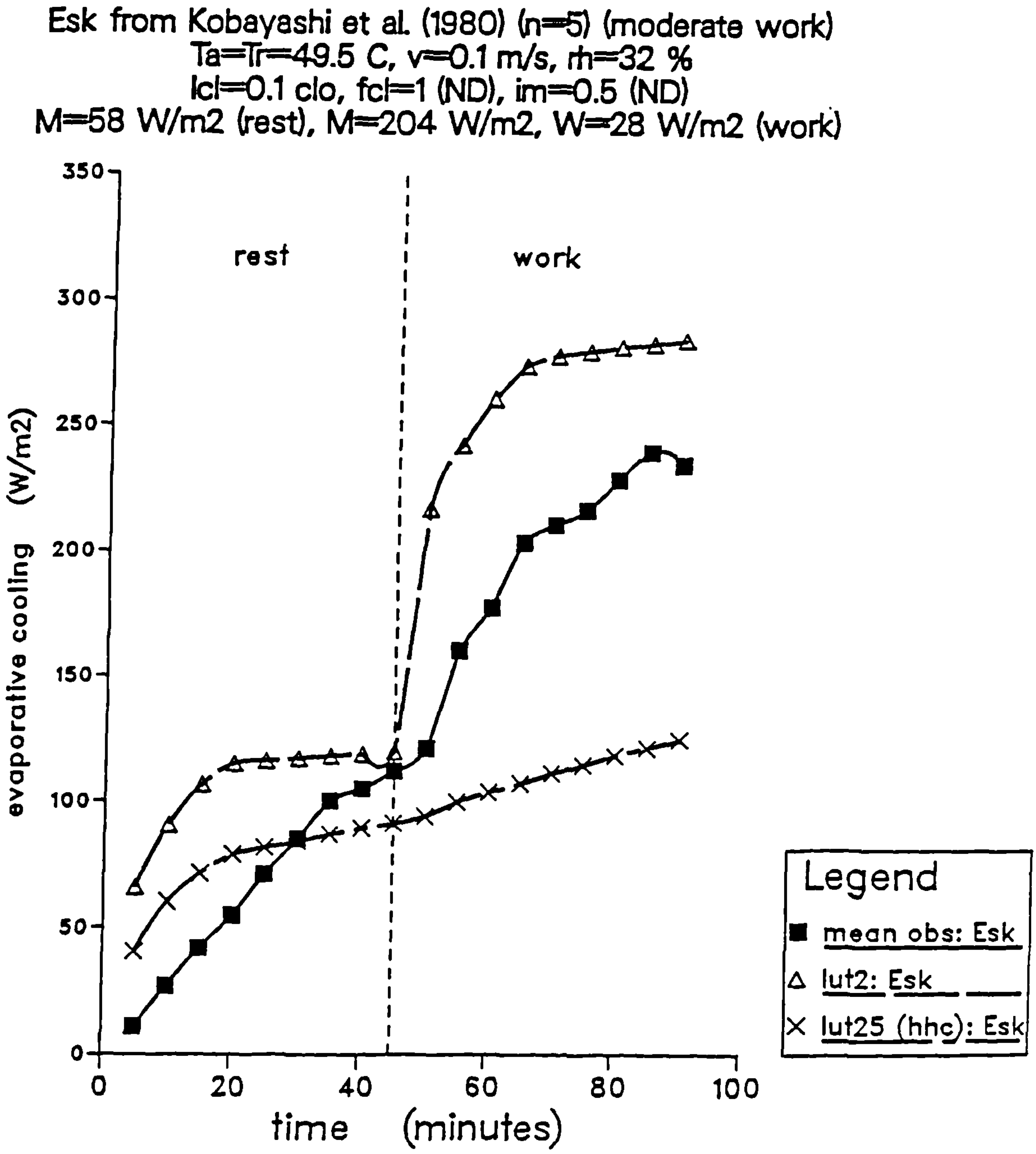
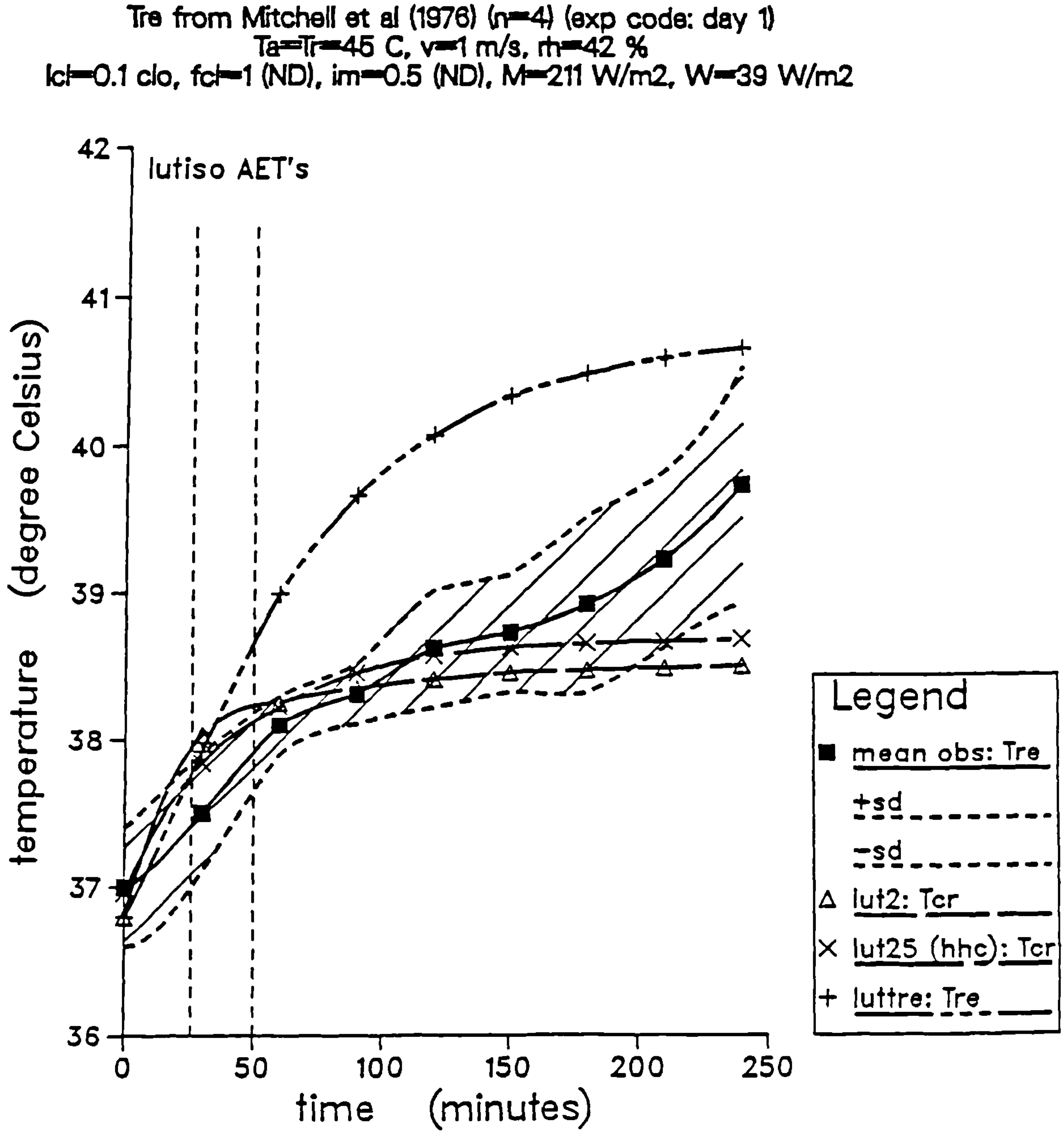


Figure 6.28. Example of deep body temperature responses (Tcr) for the nude, work and wind environment category, where Ta>35 °C.



Iutiso 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

Figure 6.29. Example of mean skin temperature responses (Tsk) for the nude, work and wind environment category, where Ta>35 °C.

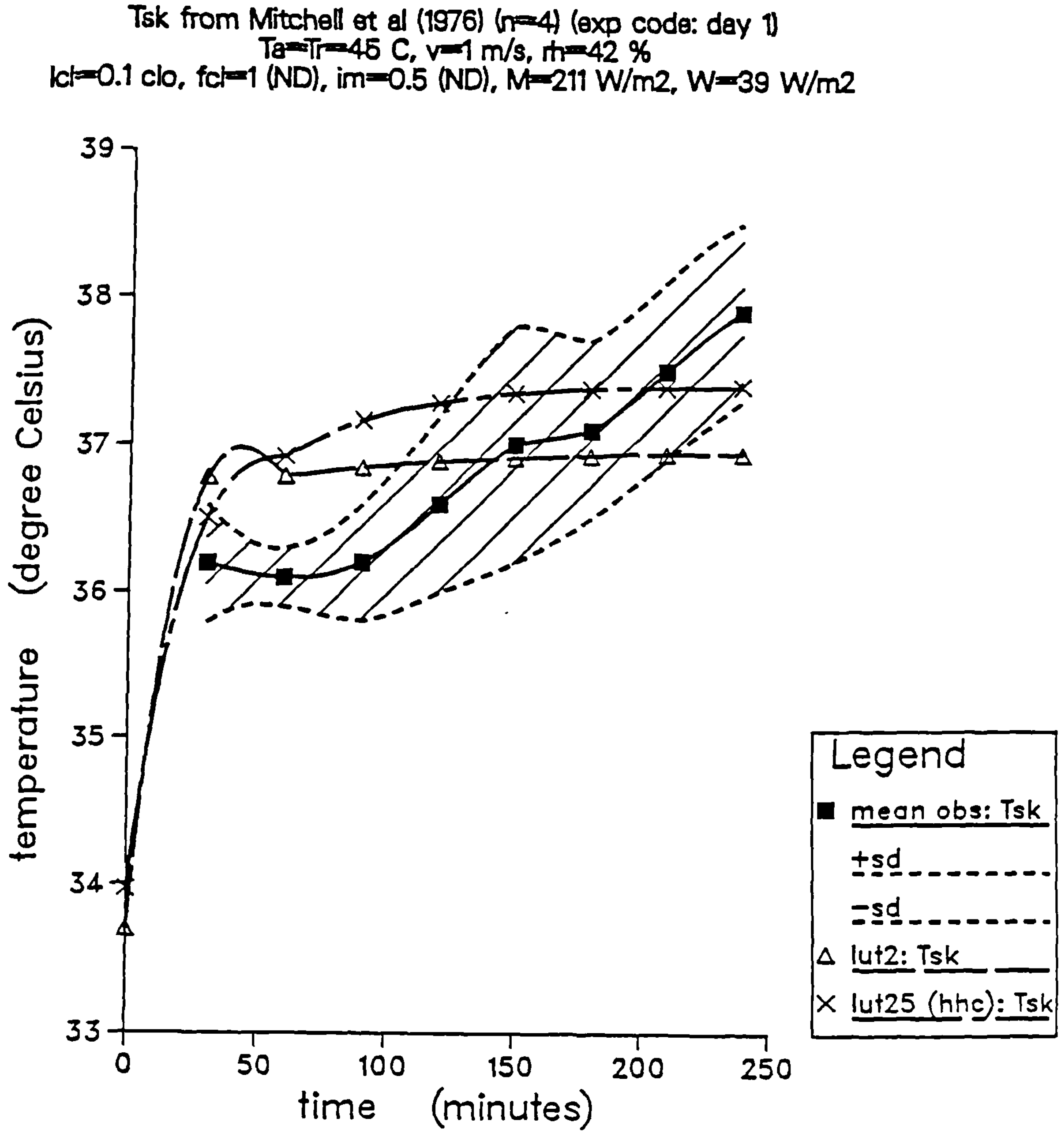


Figure 6.30. Example of dry heat transfer responses (C+R) for the nude, work and wind environment category, where Ta>35 °C.

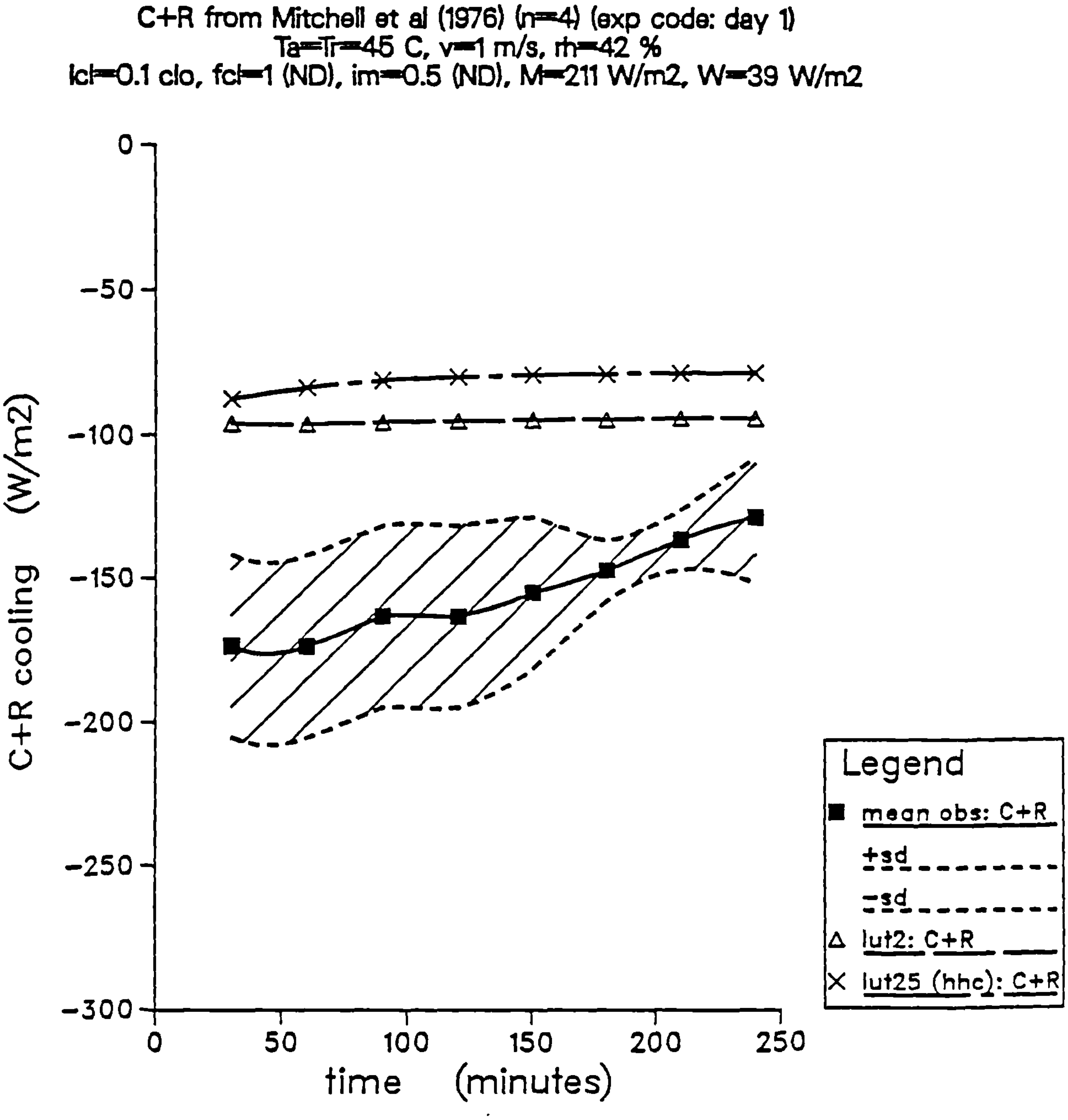


Figure 6.31. Example of total evaporative heat transfer responses (E) for the nude, work and wind environment category, where Ta>35 °C.

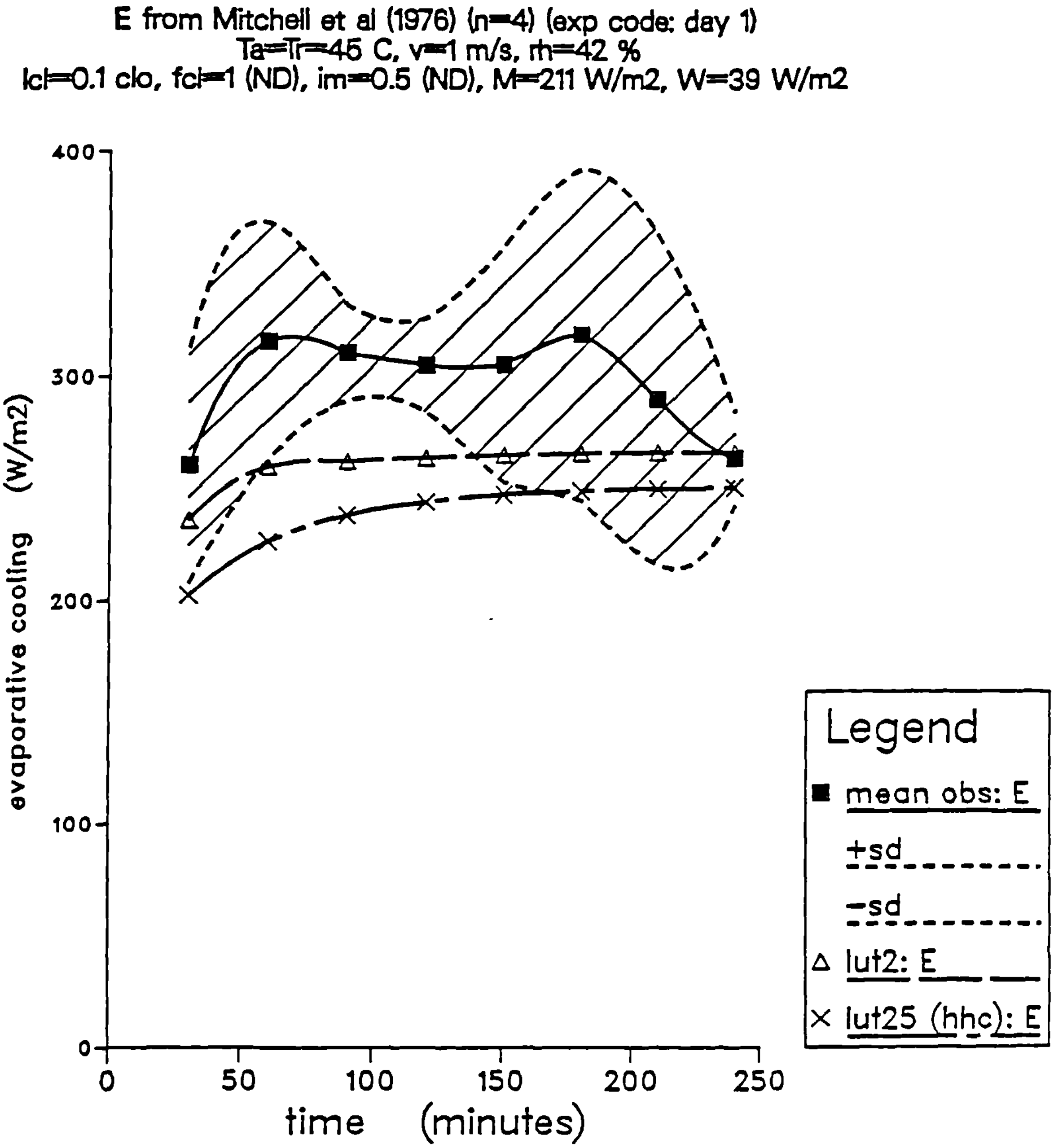


Figure 6.32. Example of deep body temperature responses (Tcr) for the clothed, rest and no-wind environment category, where Ta<=5 °C.

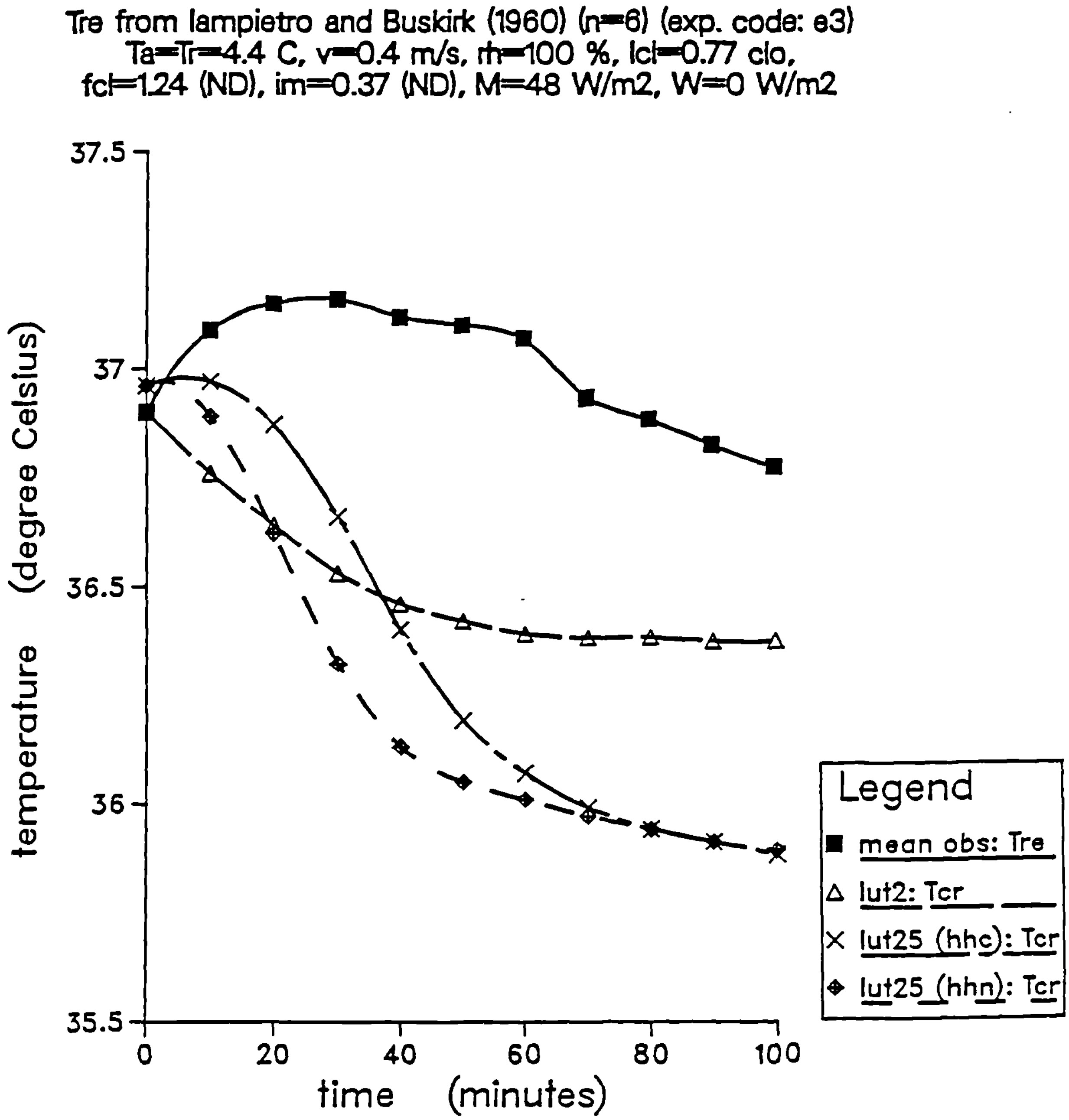


Figure 6.33. Example of mean skin temperature responses (Tsk) for the clothed, rest and no-wind environment category, where Ta<=5 °C.

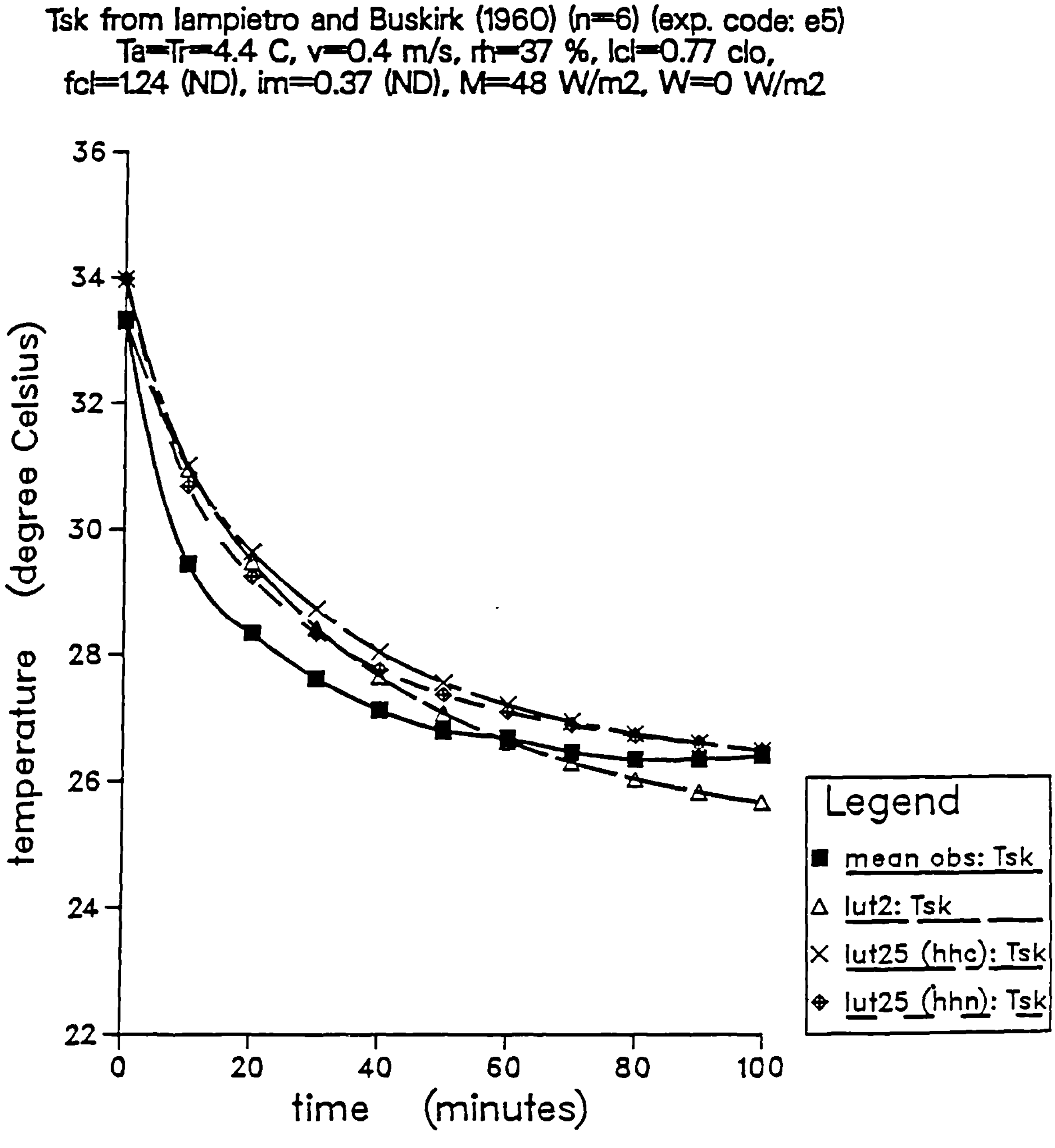


Figure 6.34. Example of metabolic rate responses (M) for the clothed, rest and no-wind environment category, where Ta<=5 °C.

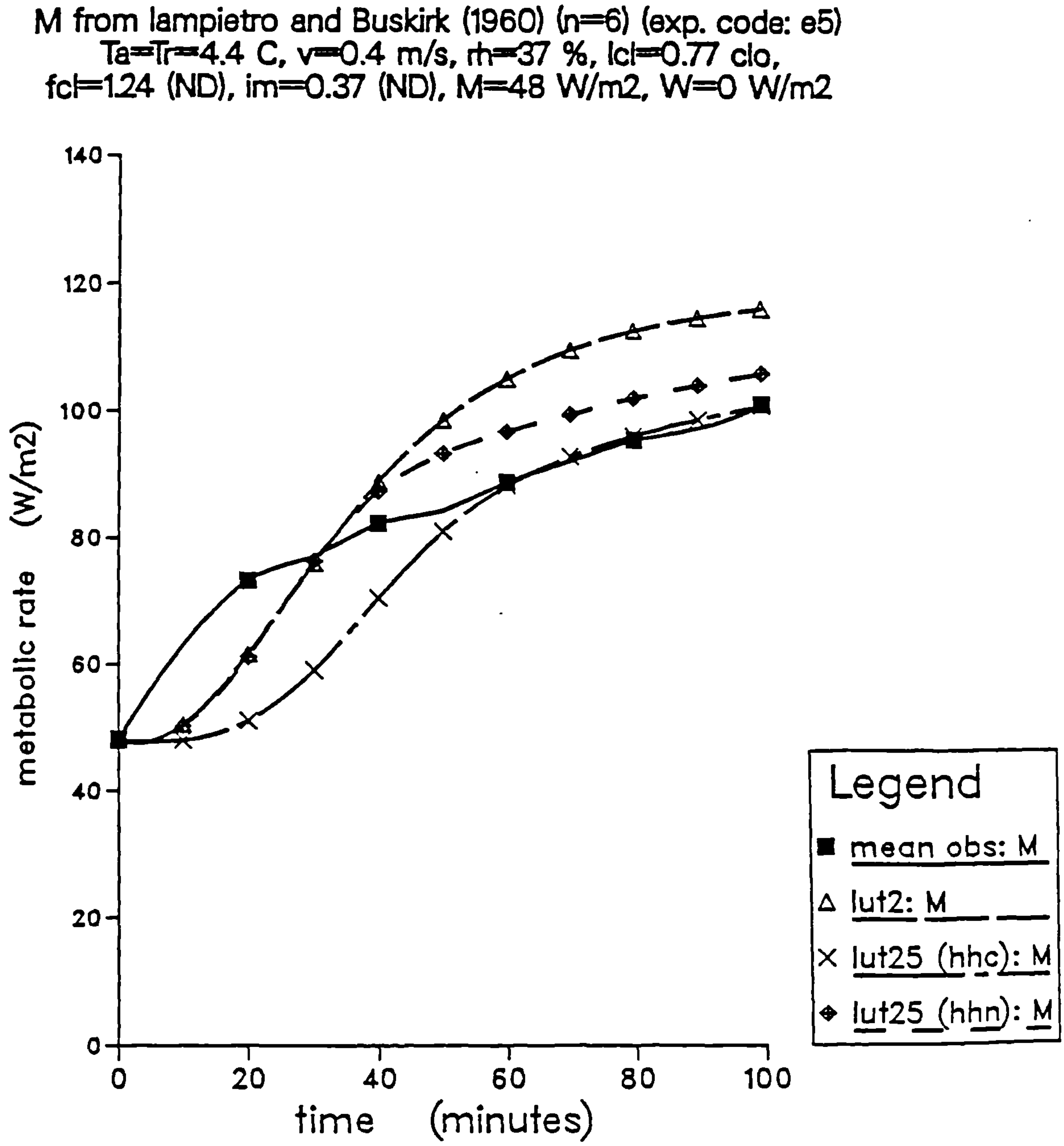


Figure 6.35. Example of deep body temperature responses (Tcr) for the clothed, rest and wind environment category, where Ta<=5 °C.

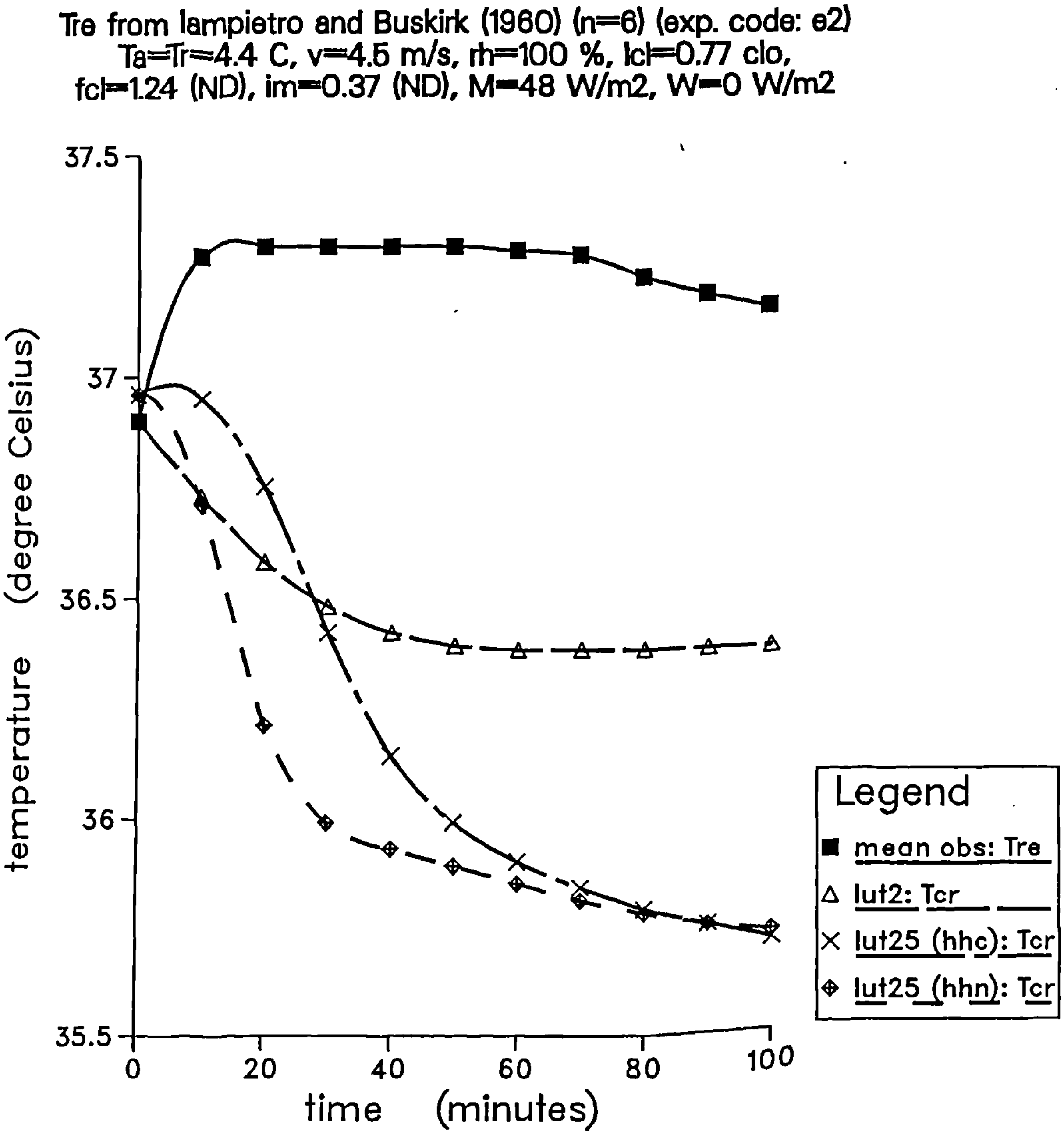


Figure 6.36. Example of mean skin temperature responses (Tsk) for the clothed, rest and wind environment category, where Ta<=5 °C.

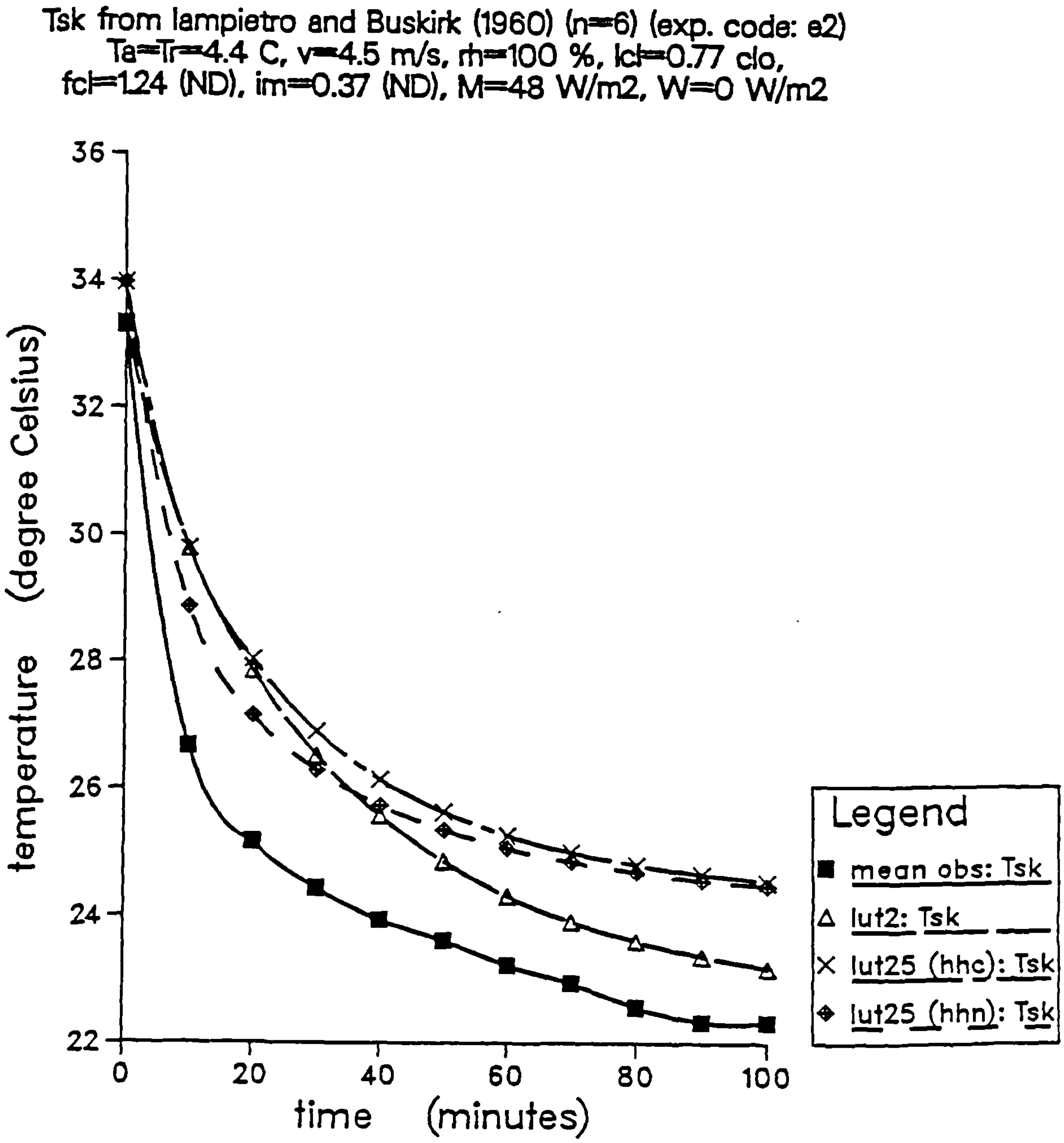


Figure 6.37. Example of metabolic rate responses (M) for the clothed, rest and wind environment category, where Ta<=5 °C.

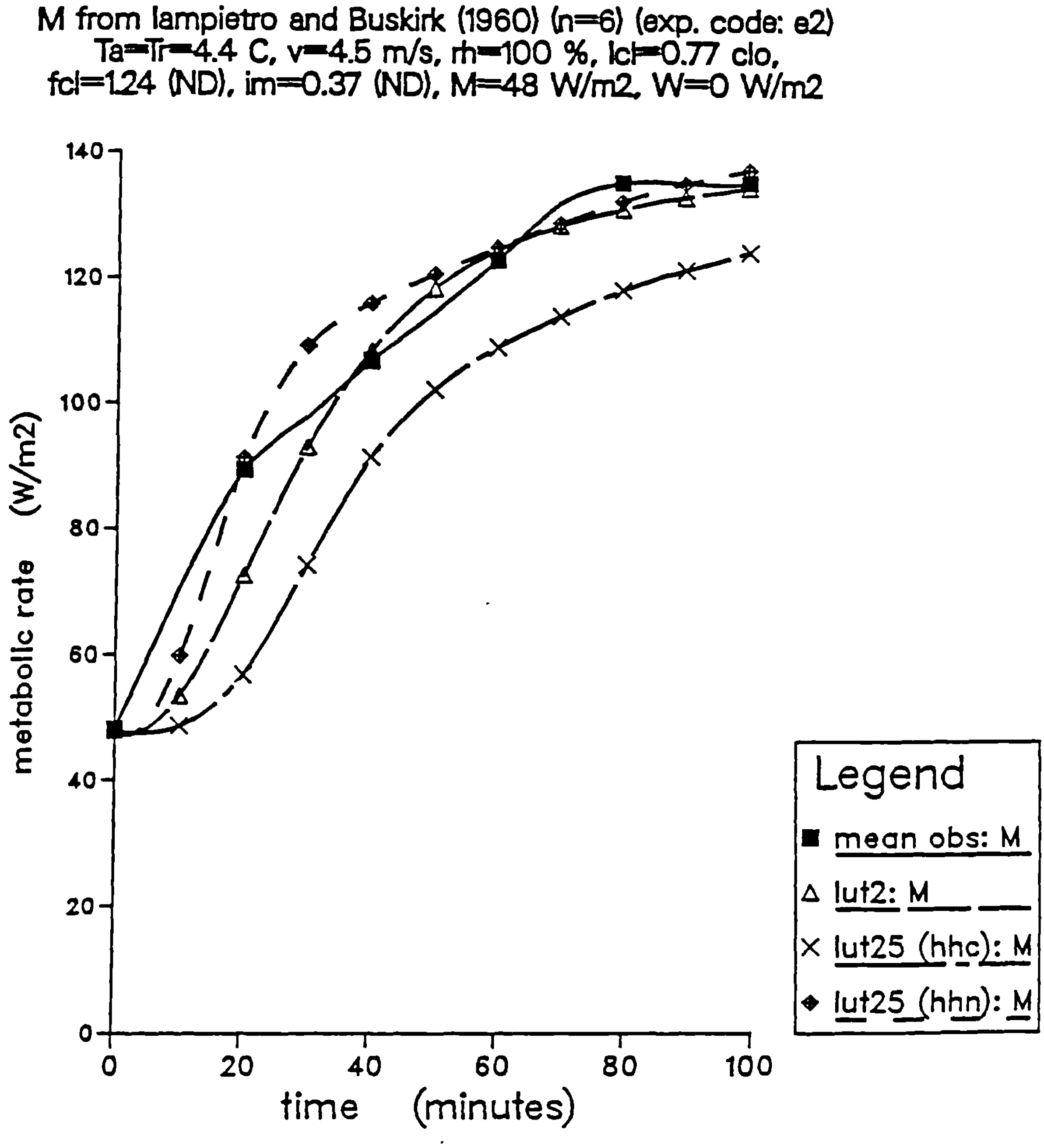


Figure 6.38. Example of deep body temperature responses (Tcr) for the clothed, work and no-wind environment category, where Ta<=5 °C.

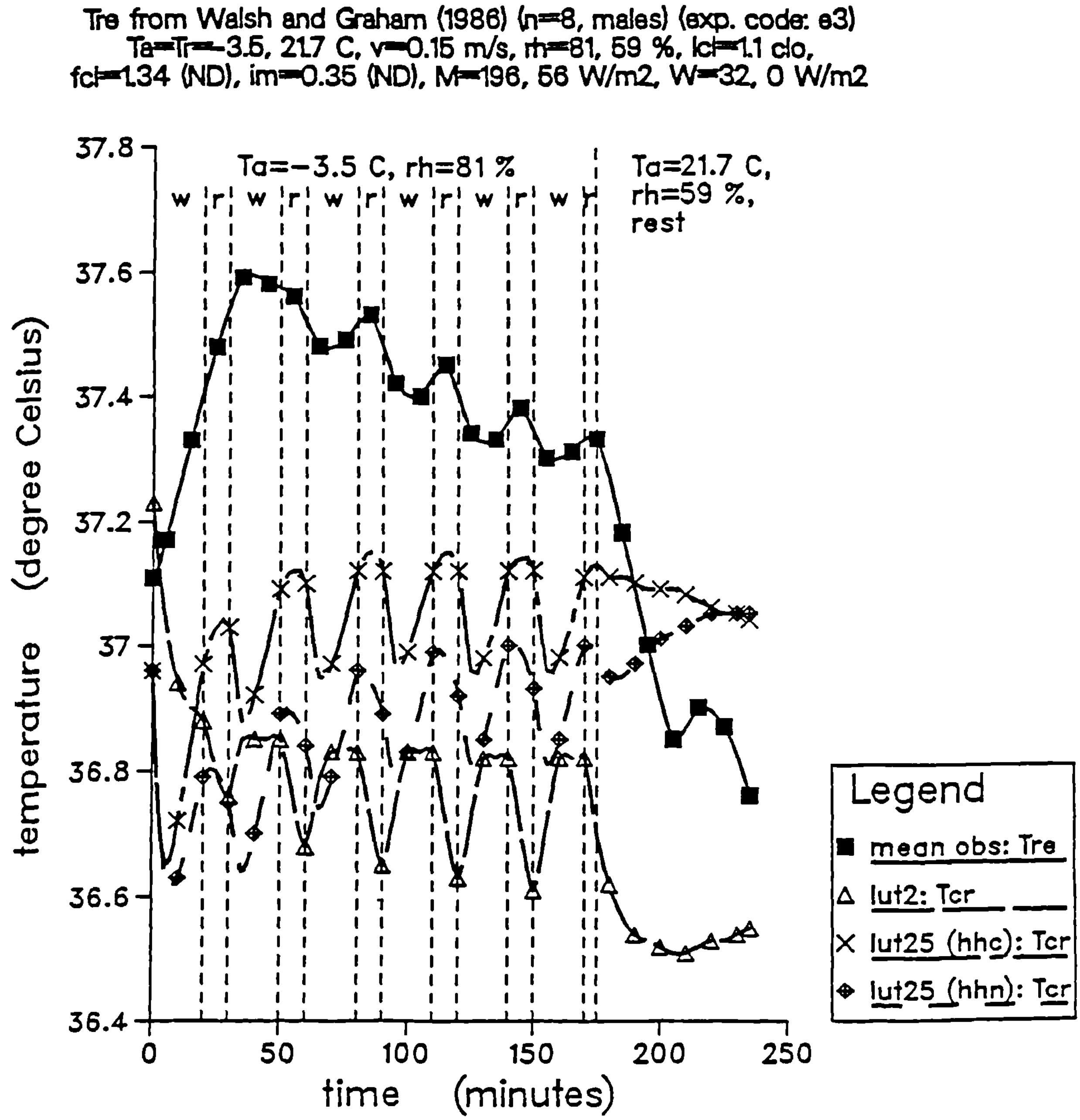


Figure 6.39. Example of mean skin temperature responses (Tsk) for the clothed, work and no-wind environment category, where Ta<=5 °C.

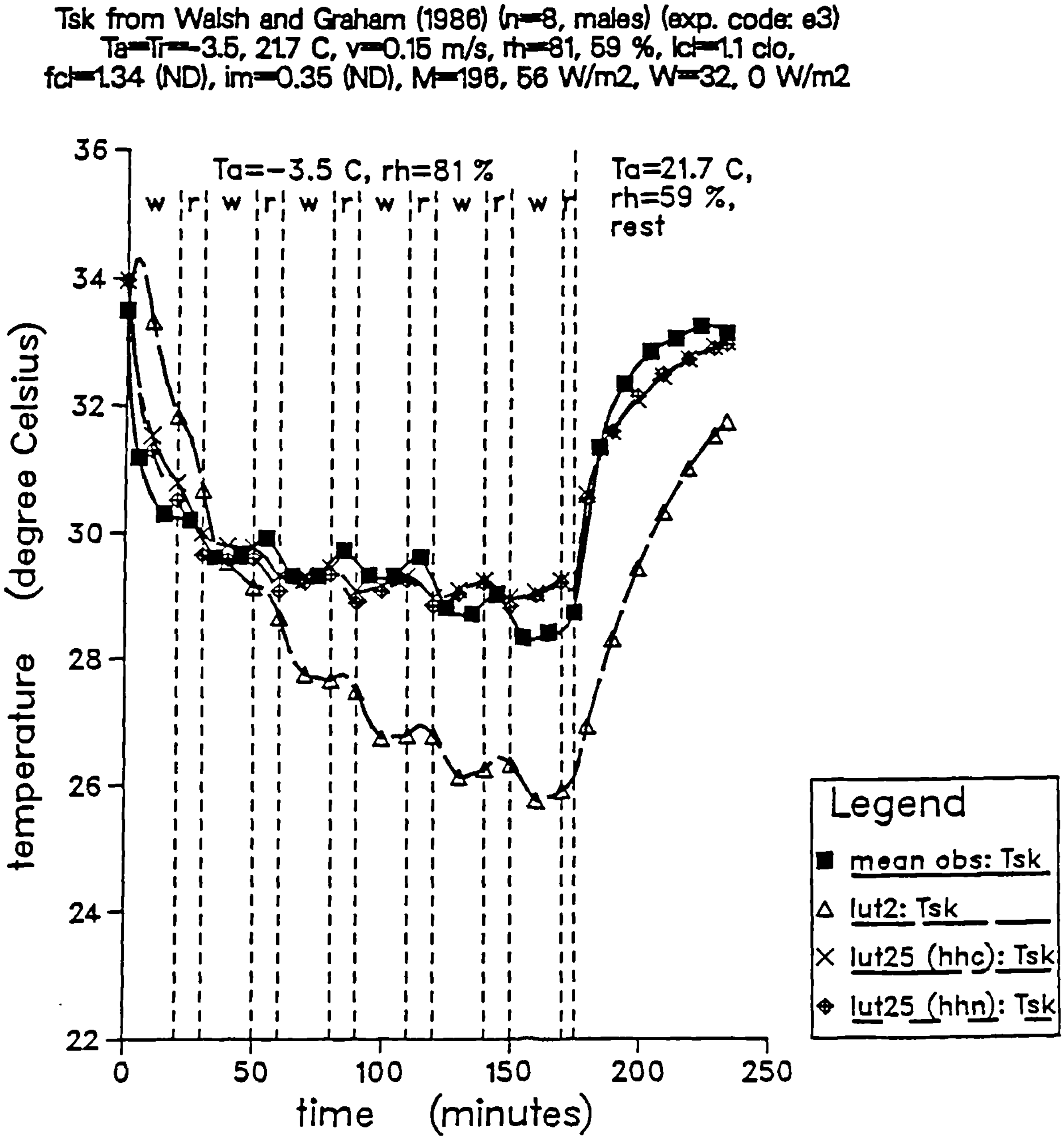


Figure 6.40. Example of deep body temperature responses (Tcr) for the clothed, work and no-wind environment category, where 5<Ta<=15 °C.

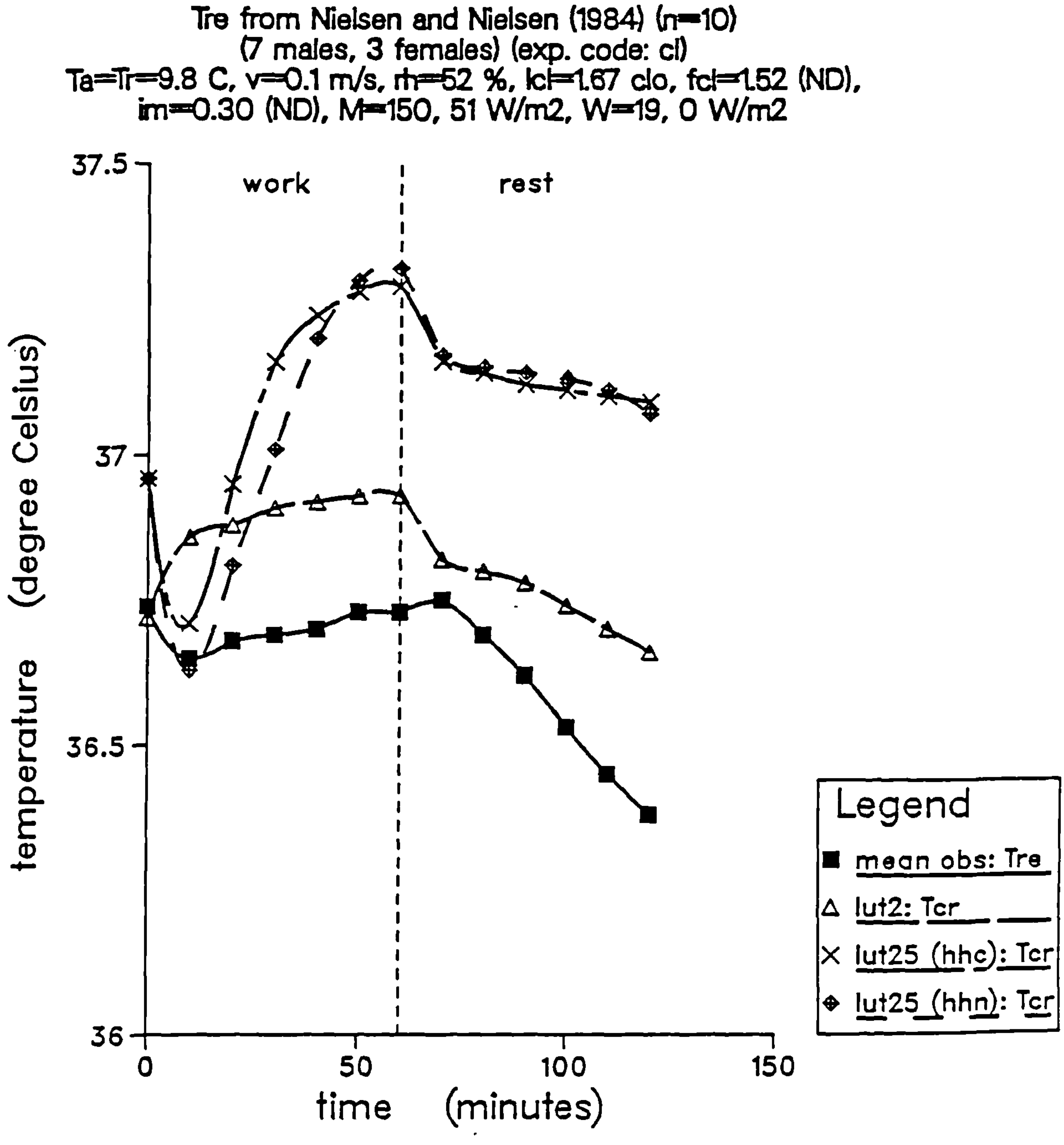


Figure 6.41. Example of deep body temperature responses (Tcr) for the clothed, work and no-wind environment category, where 5<Ta<=15 °C.

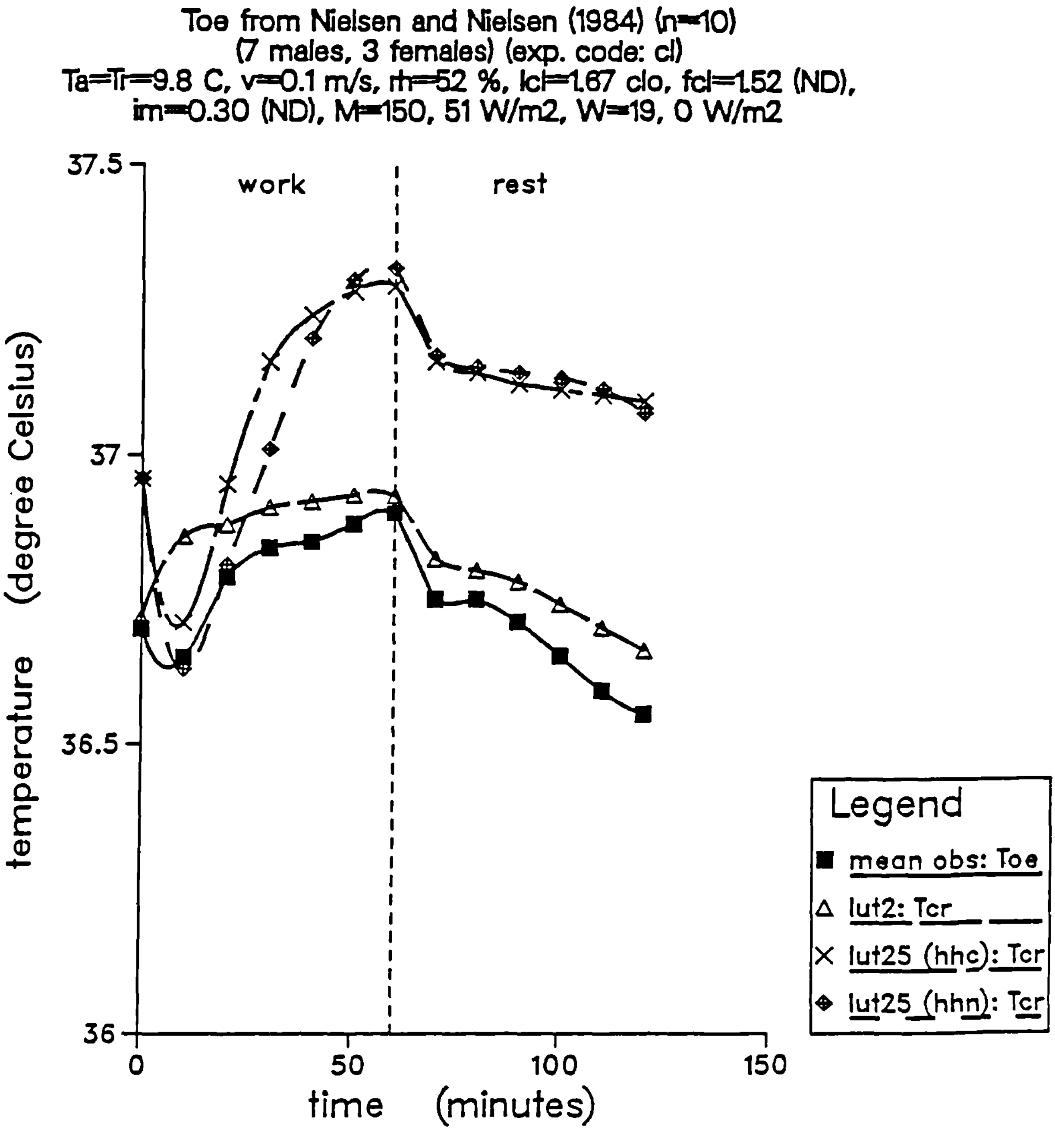


Figure 6.42. Example of deep body temperature responses (Tcr) for the clothed, work and no-wind environment category, where 5<Ta<=15 °C.

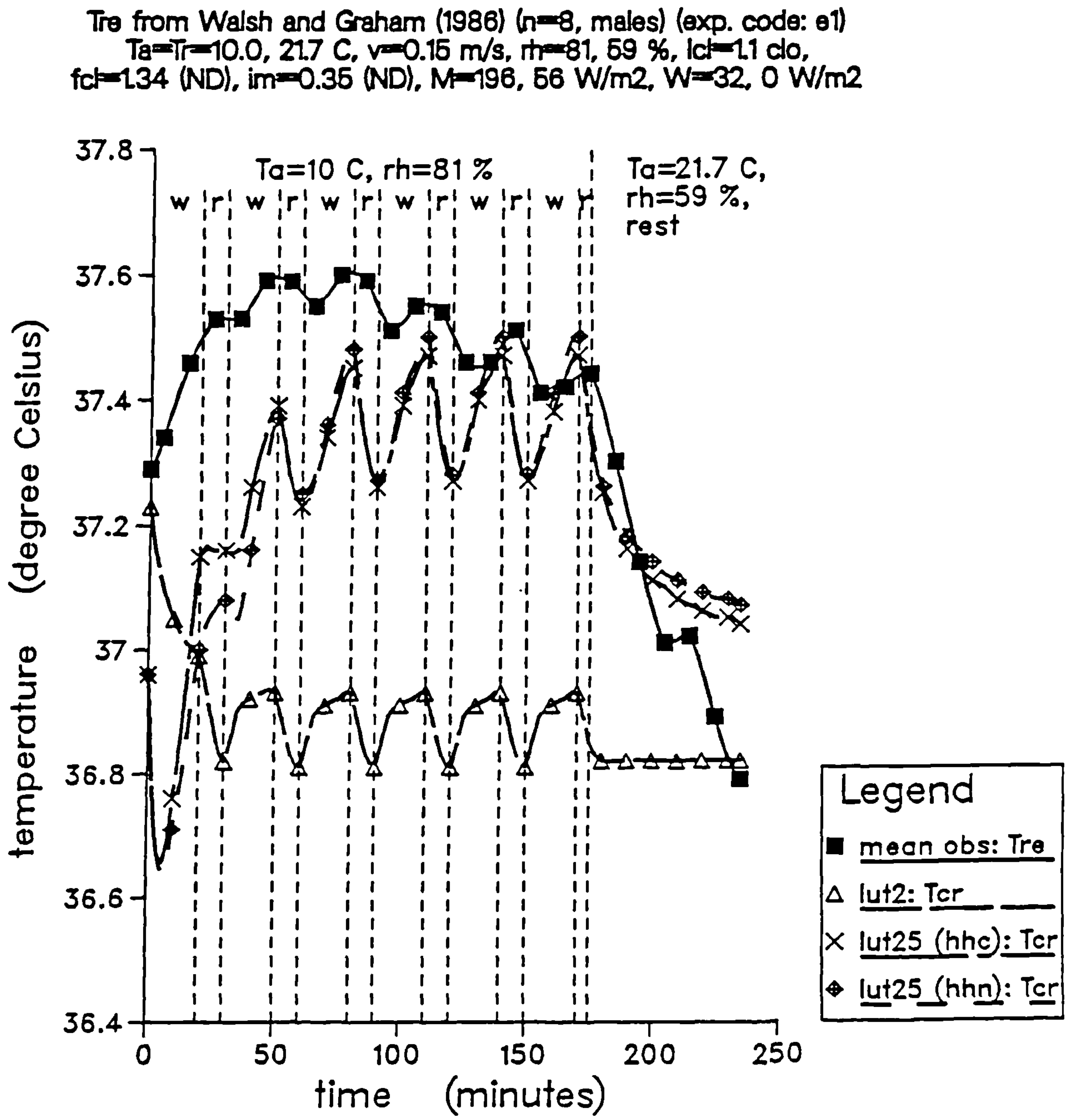


Figure 6.43. Example of mean skin temperature responses (Tsk) for the clothed, work and no-wind environment category, where 5<Ta<=15 °C.

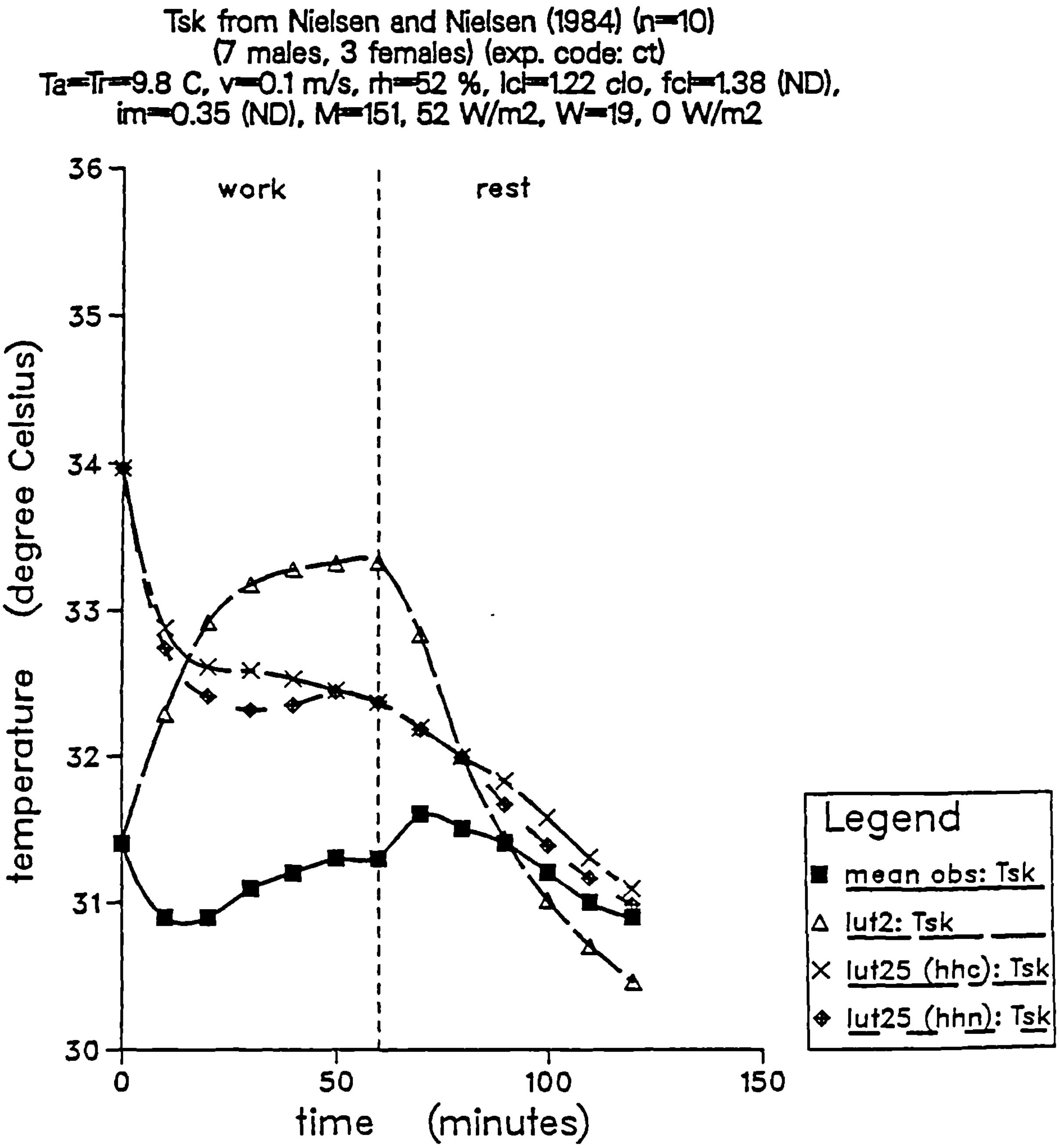


Figure 6.44. Example of mean skin temperature responses (Tsk) for the clothed, work and no-wind environment category, where 5<Ta<=15 °C.

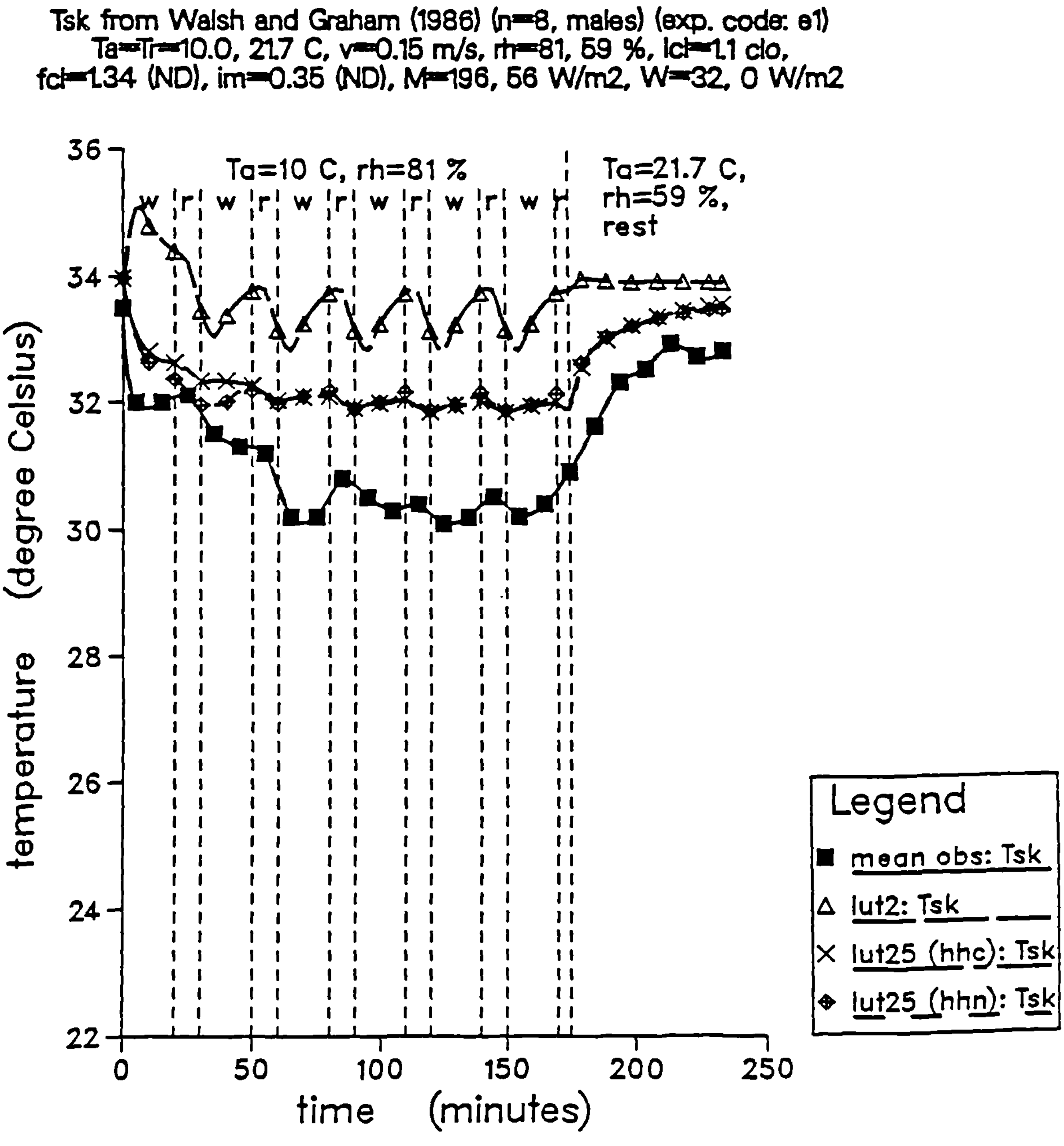
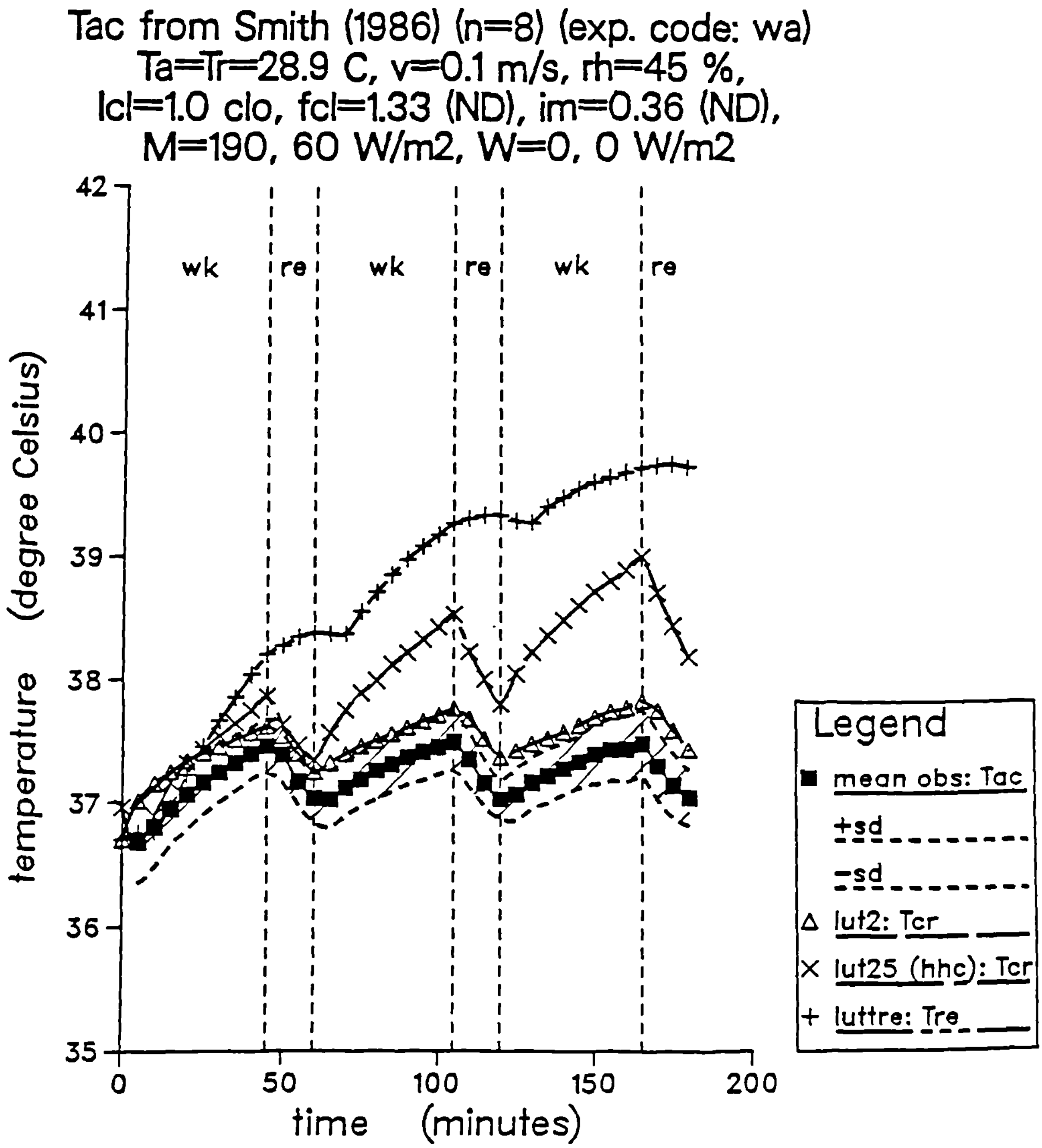


Figure 6.45. Example of deep body temperature responses (Tcr) for the clothed, work and no-wind environment category, where 25<Ta<=35 °C.



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

Figure 6.46. Example of mean skin temperature responses (Tsk) for the clothed, work and no-wind environment category, where 25<Ta<=35 °C.

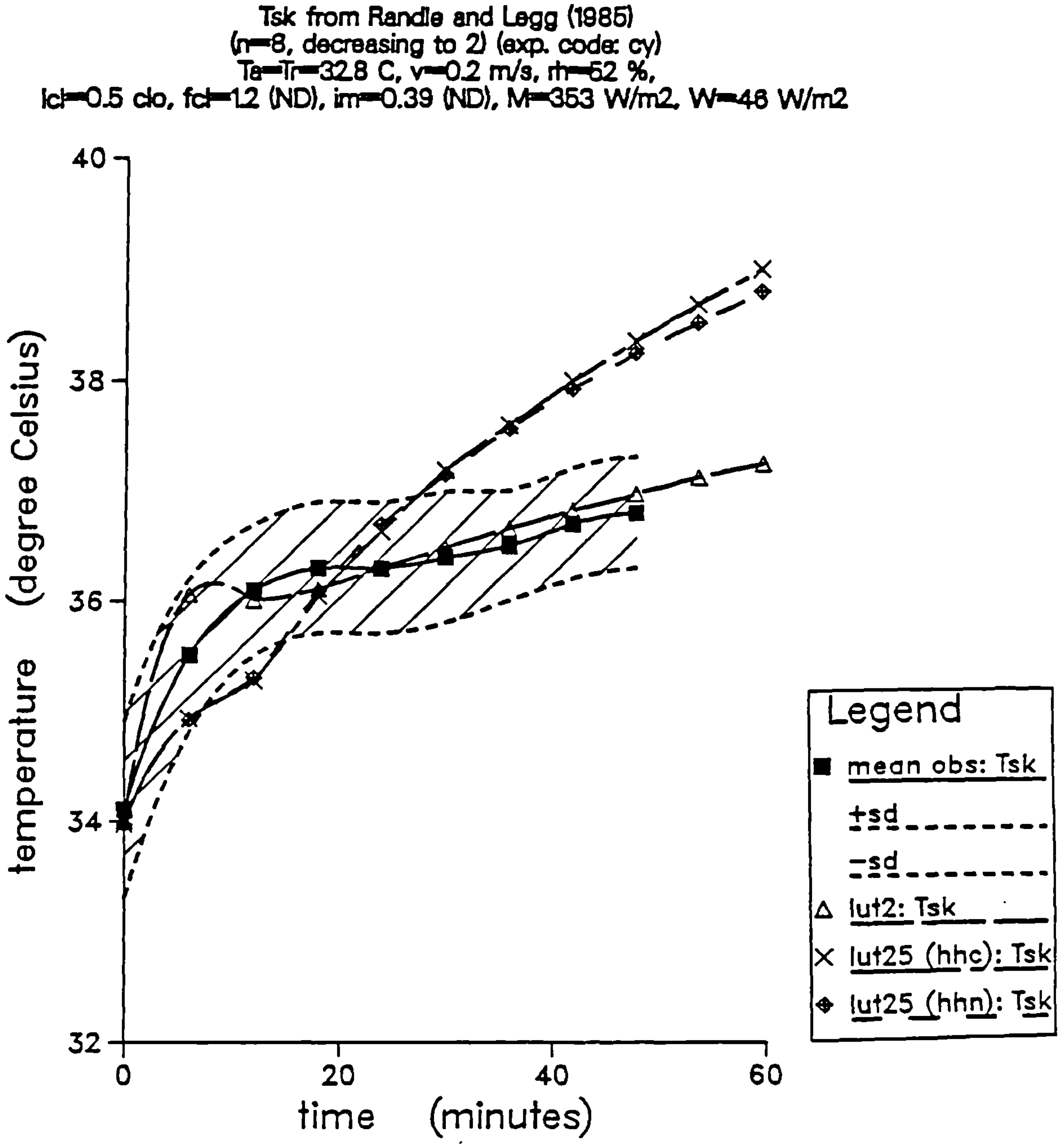
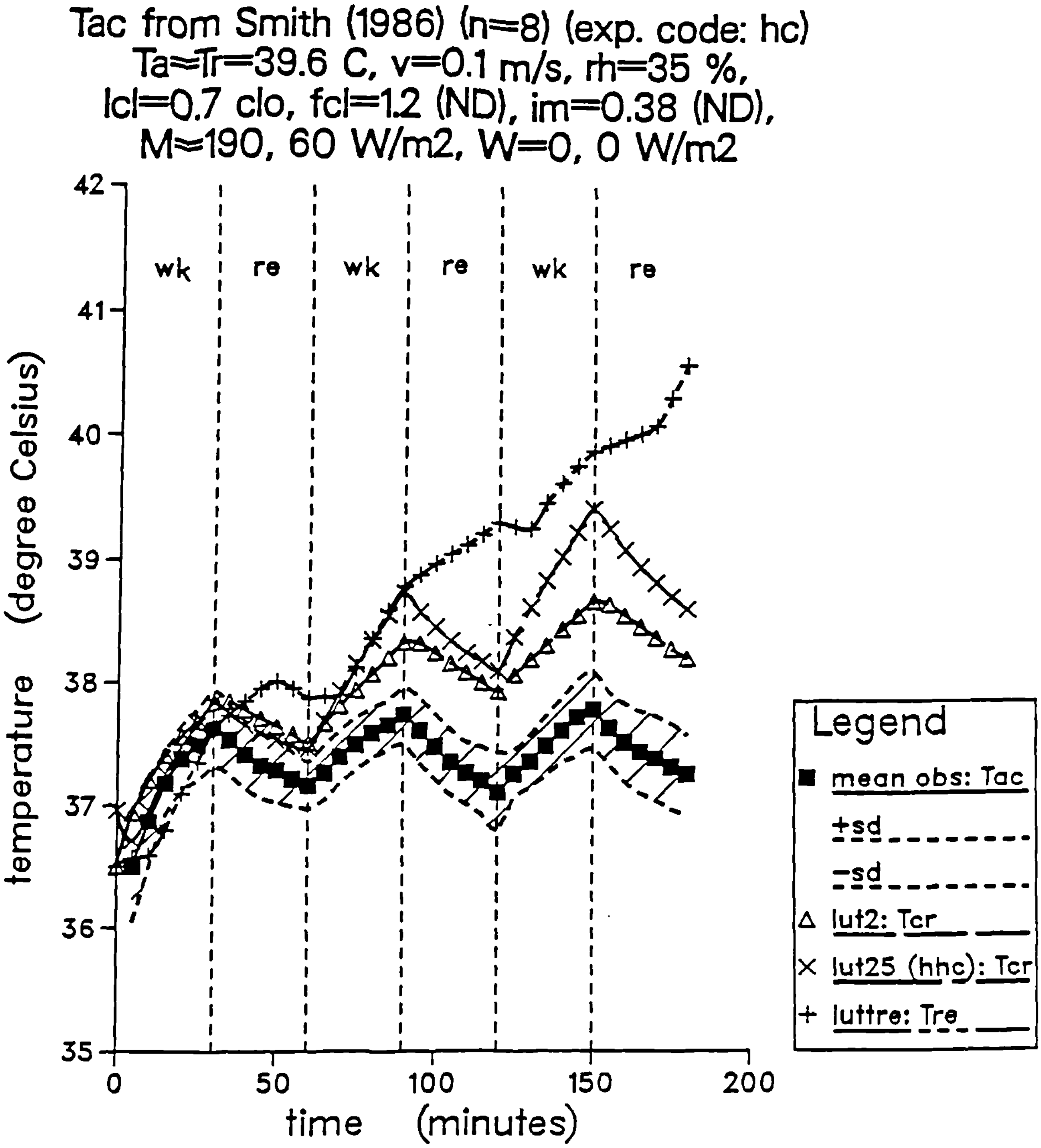


Figure 6.47. Example of deep body temperature responses (Tcr) for the clothed, work and no-wind environment category, where Ta>35 °C.



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

Figure 6.48. Example of mean skin temperature responses (Tsk) for the clothed, work and no-wind environment category, where Ta>35 °C.

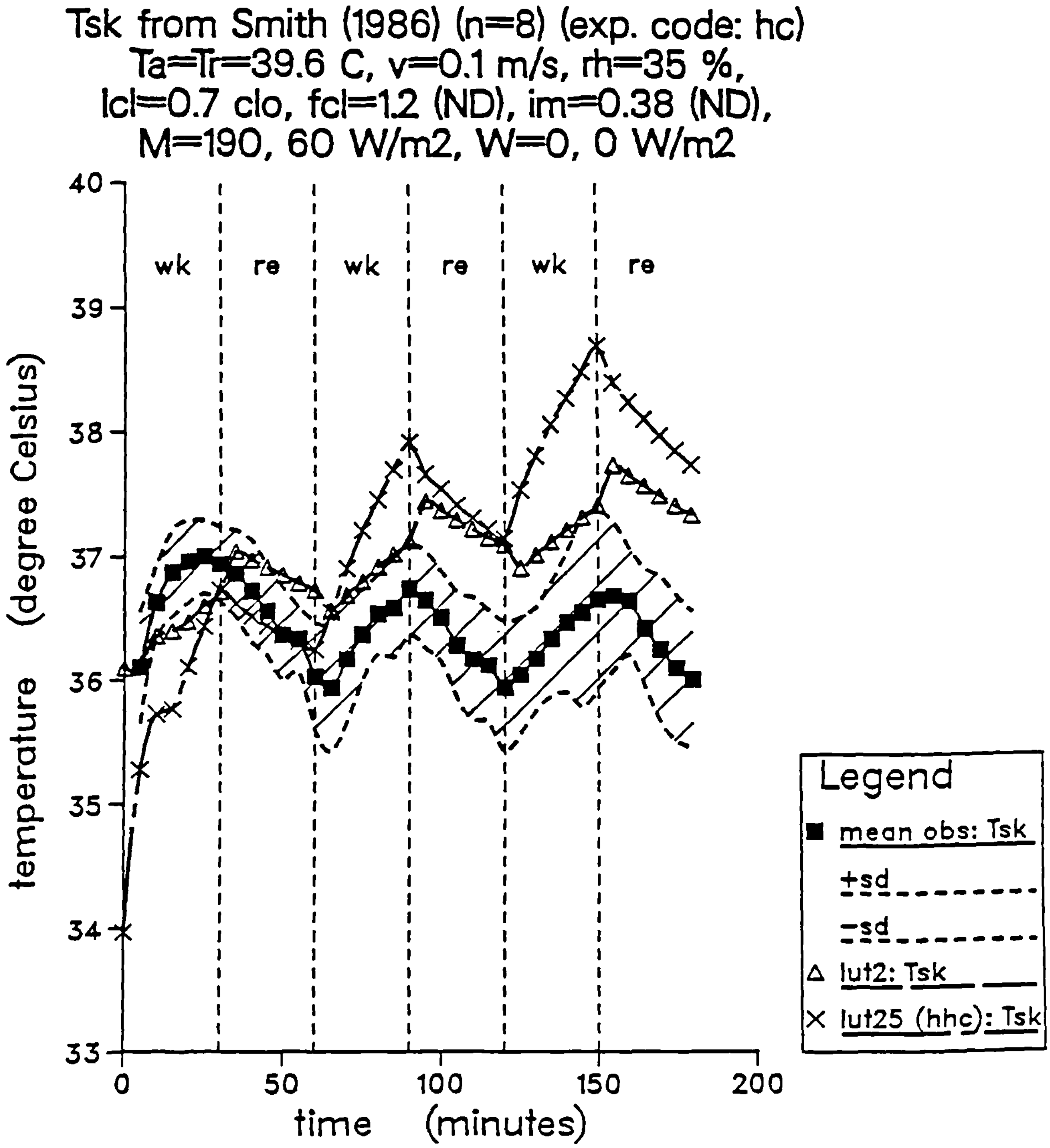


Figure 6.49. Example of deep body temperature responses (Tcr) for the clothed, work and wind environment category, where Ta<=5 °C.

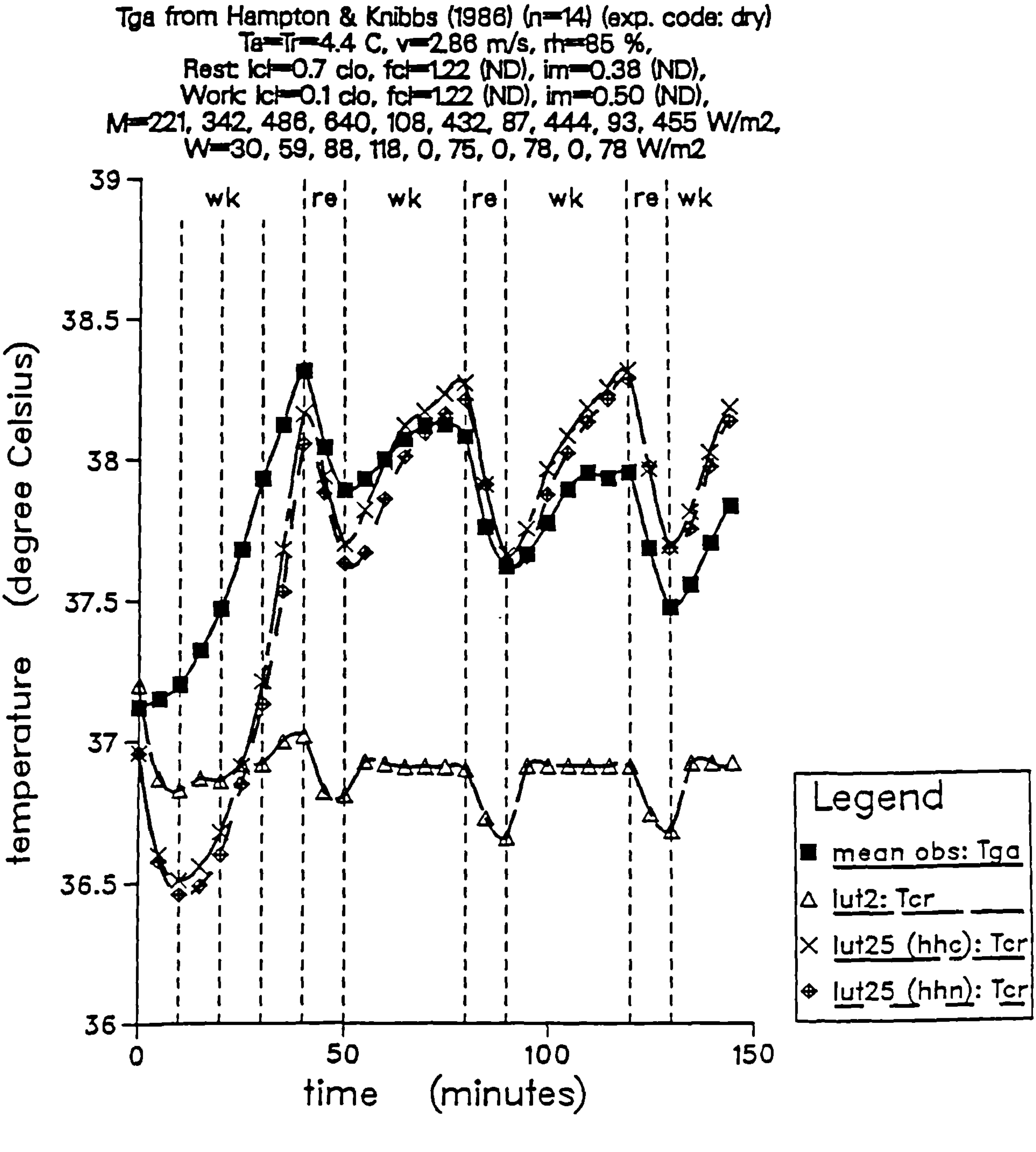


Figure 6.50. Example of deep body temperature responses (Tcr) for the clothed, work and wind environment category, where Ta<=5 °C.

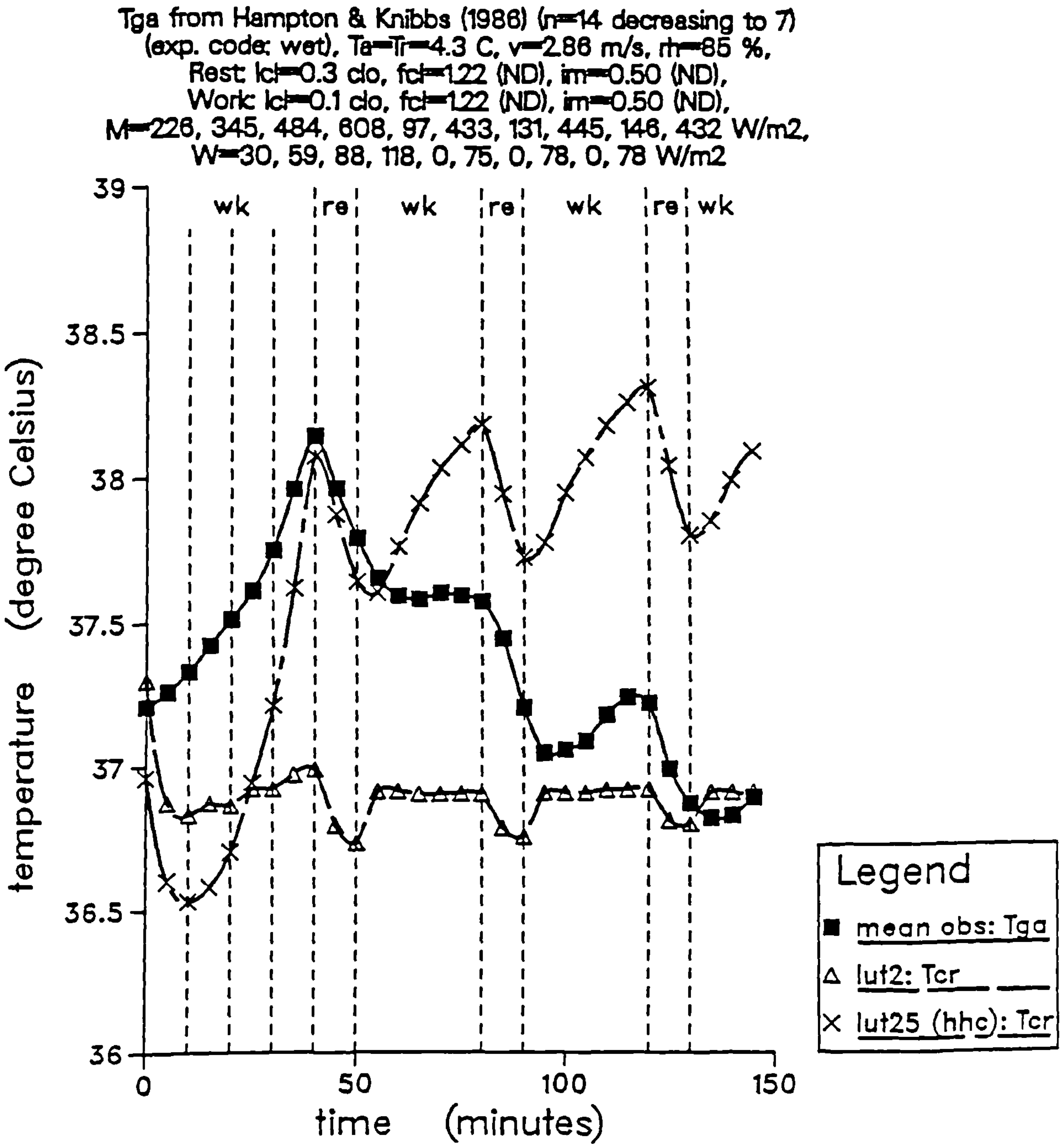


Figure 6.51. Example of mean skin temperature responses (Tsk) for the clothed, work and wind environment category, where Ta<=5 °C.

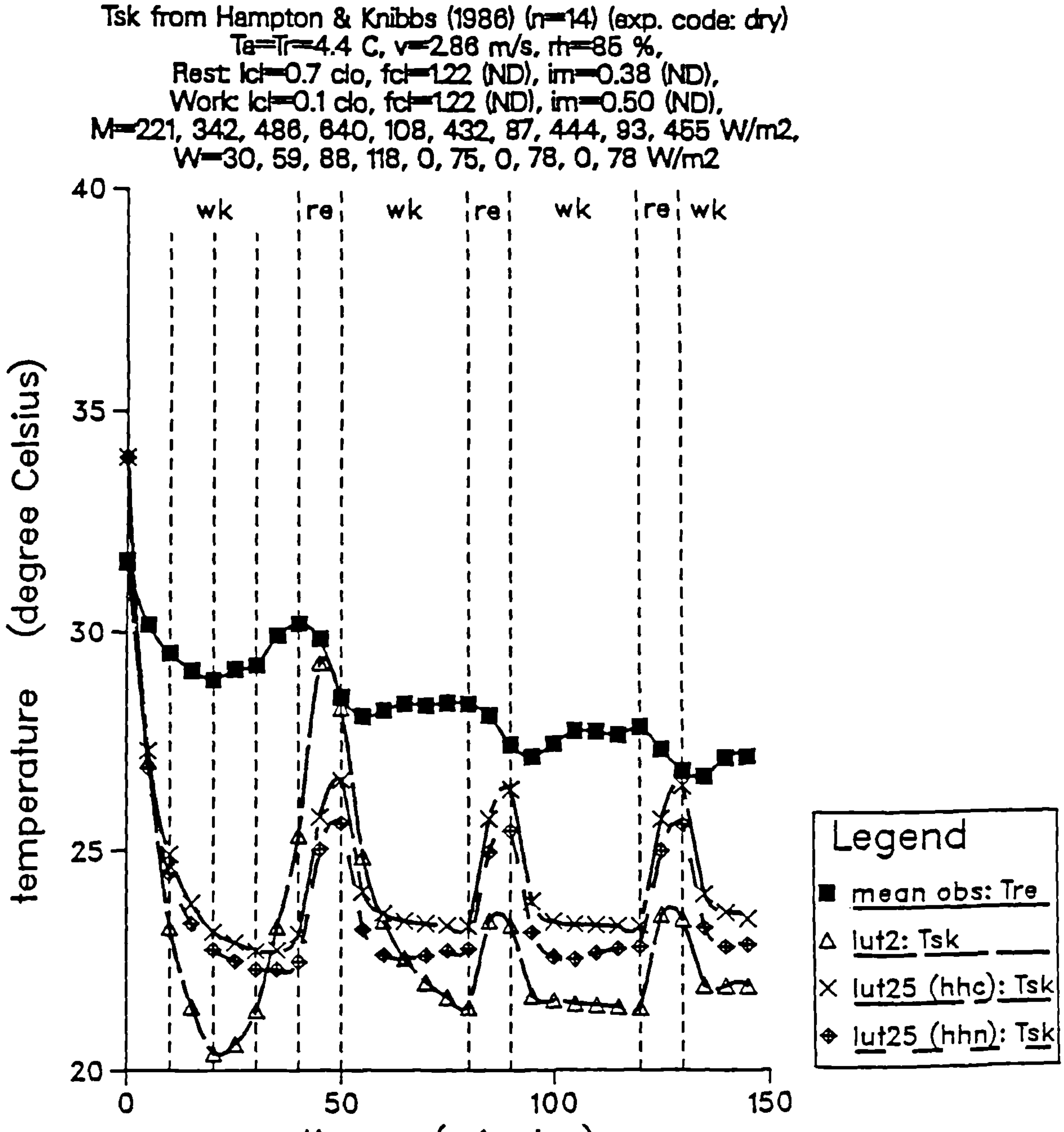
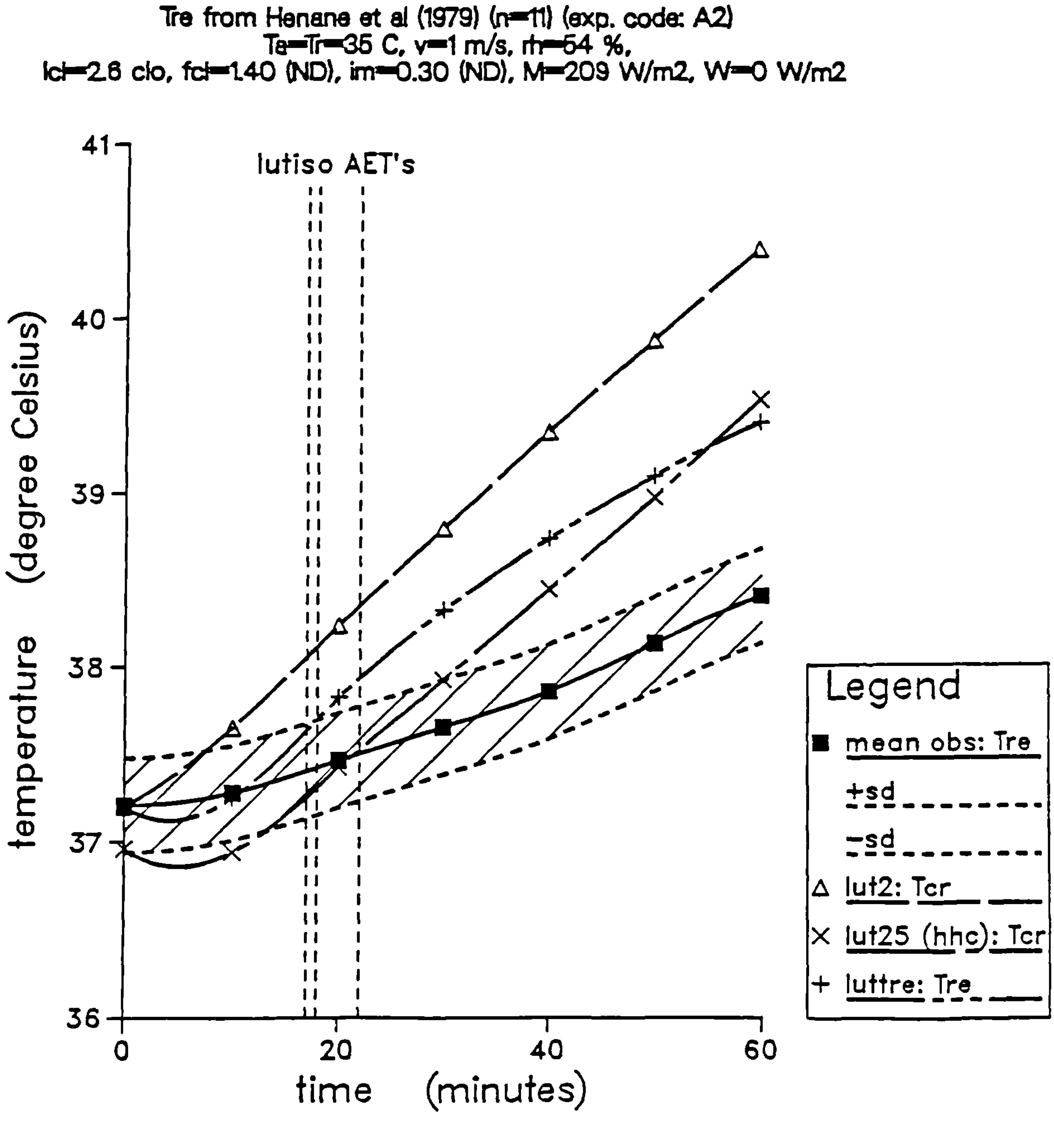
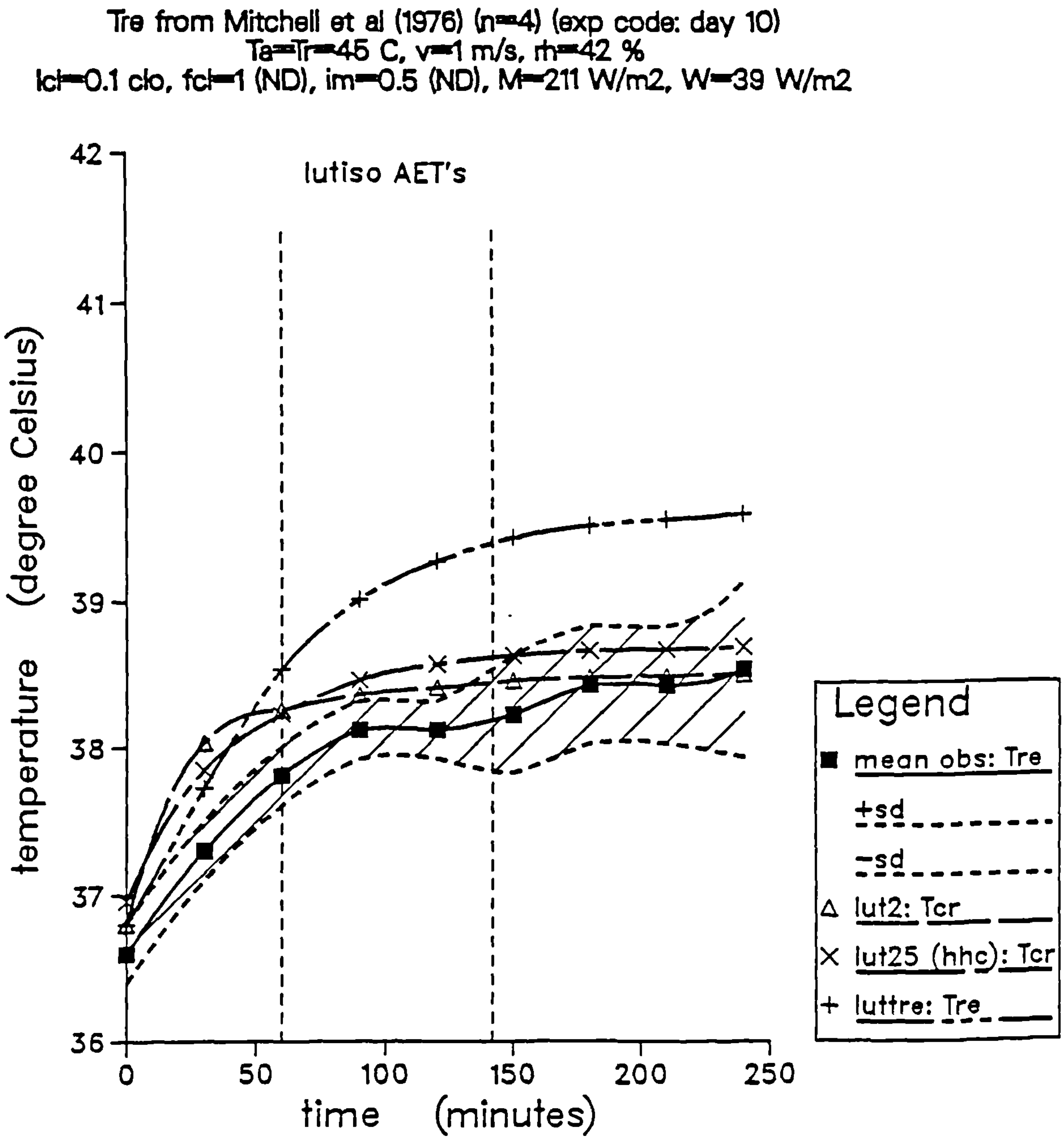


Figure 6.52. Example of deep body temperature responses (Tcr) for the clothed, work and wind environment category, where 25<Ta<=35 °C.



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

Figure 6.53. Deep body temperature responses (Tcr) for acclimatized subjects in the nude, work and wind environment category.



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

Figure 6.54. Mean skin temperature responses (Tsk) for acclimatized subjects in the nude, work and wind environment category.

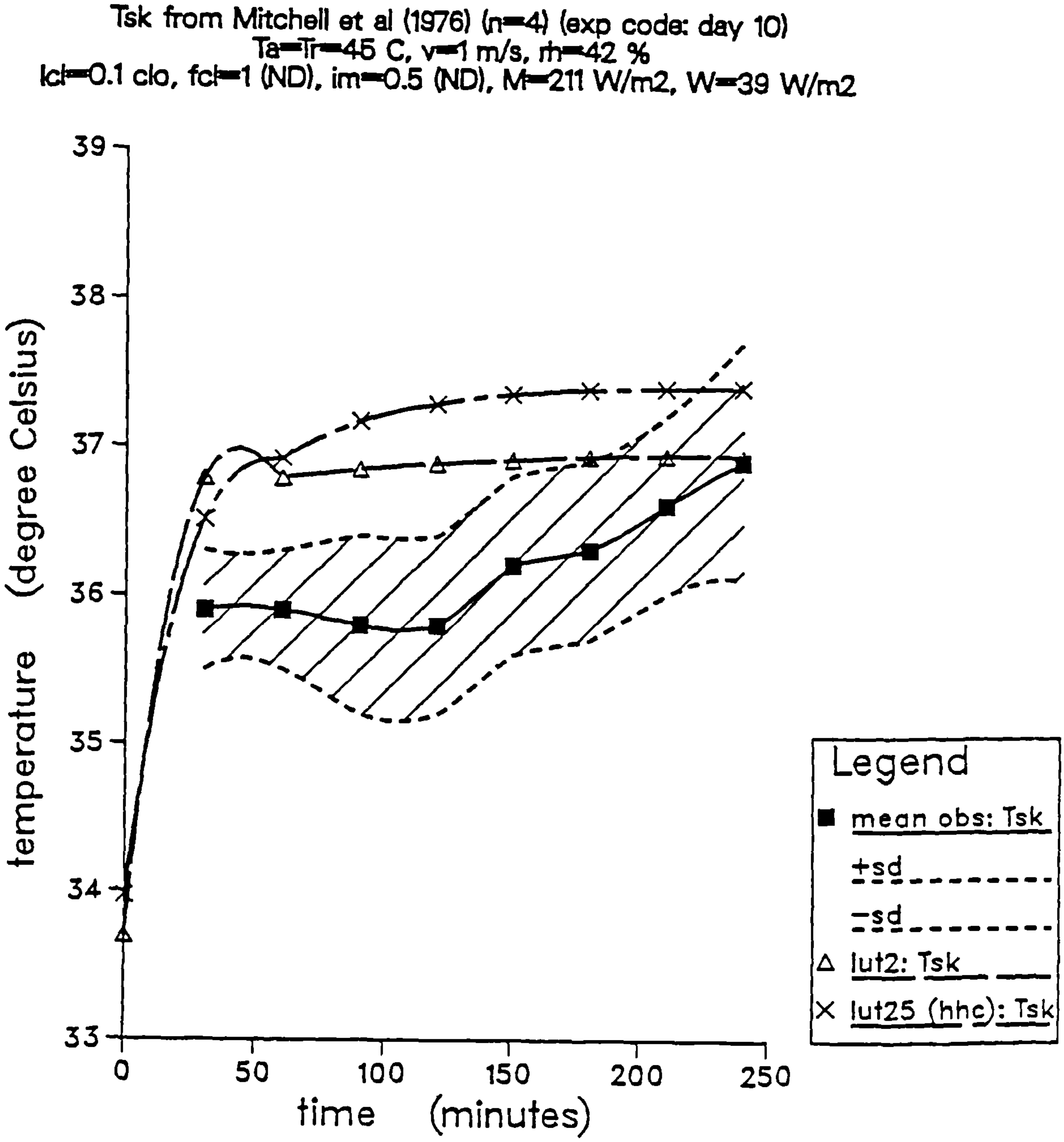


Figure 6.55. Dry heat transfer responses (C+R) for acclimatized subjects in the nude, work and wind environment category.

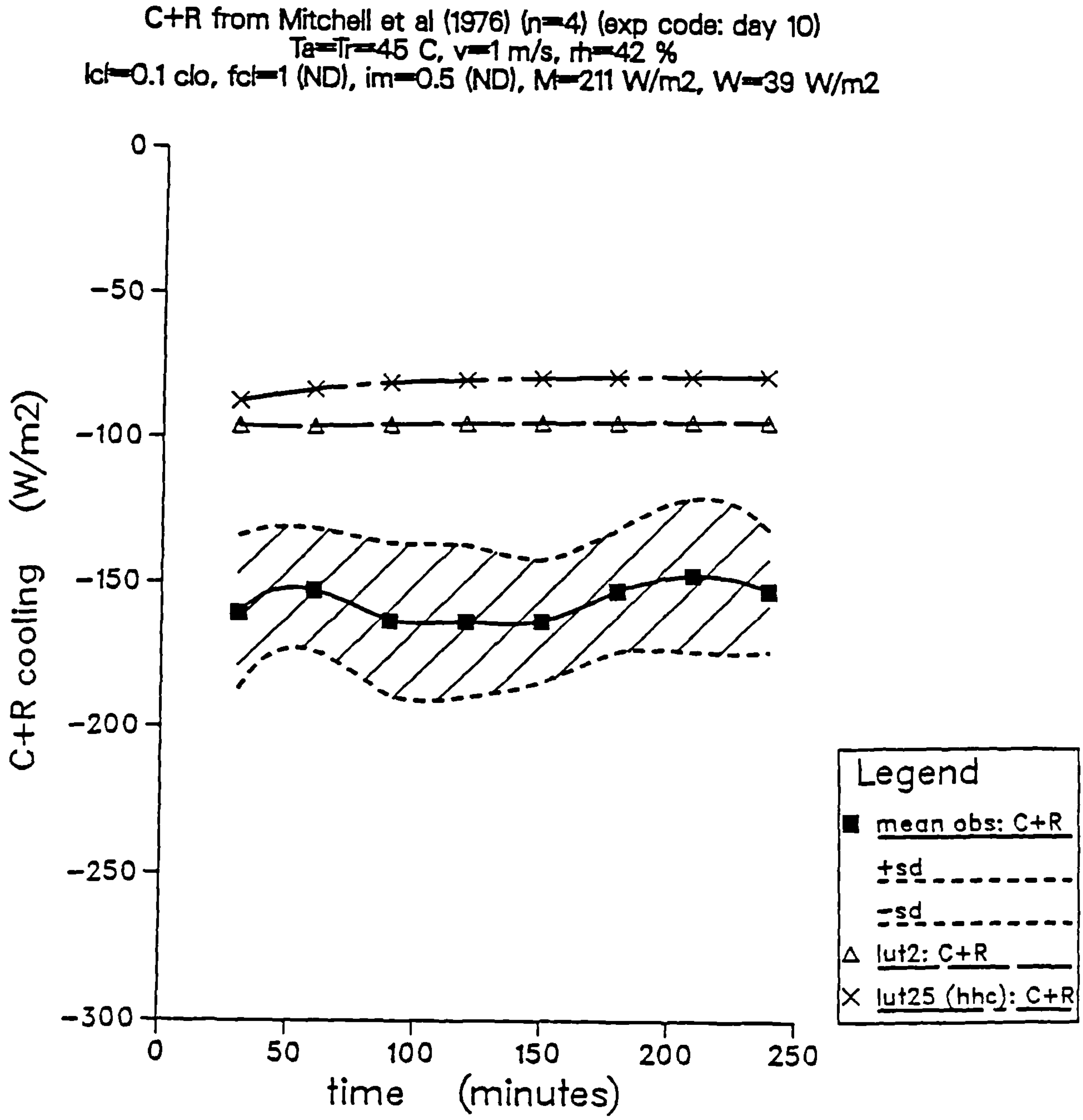


Figure 6.56. Total Evaporative heat transfer responses (E) for acclimatized subjects in the nude, work and wind environment category.

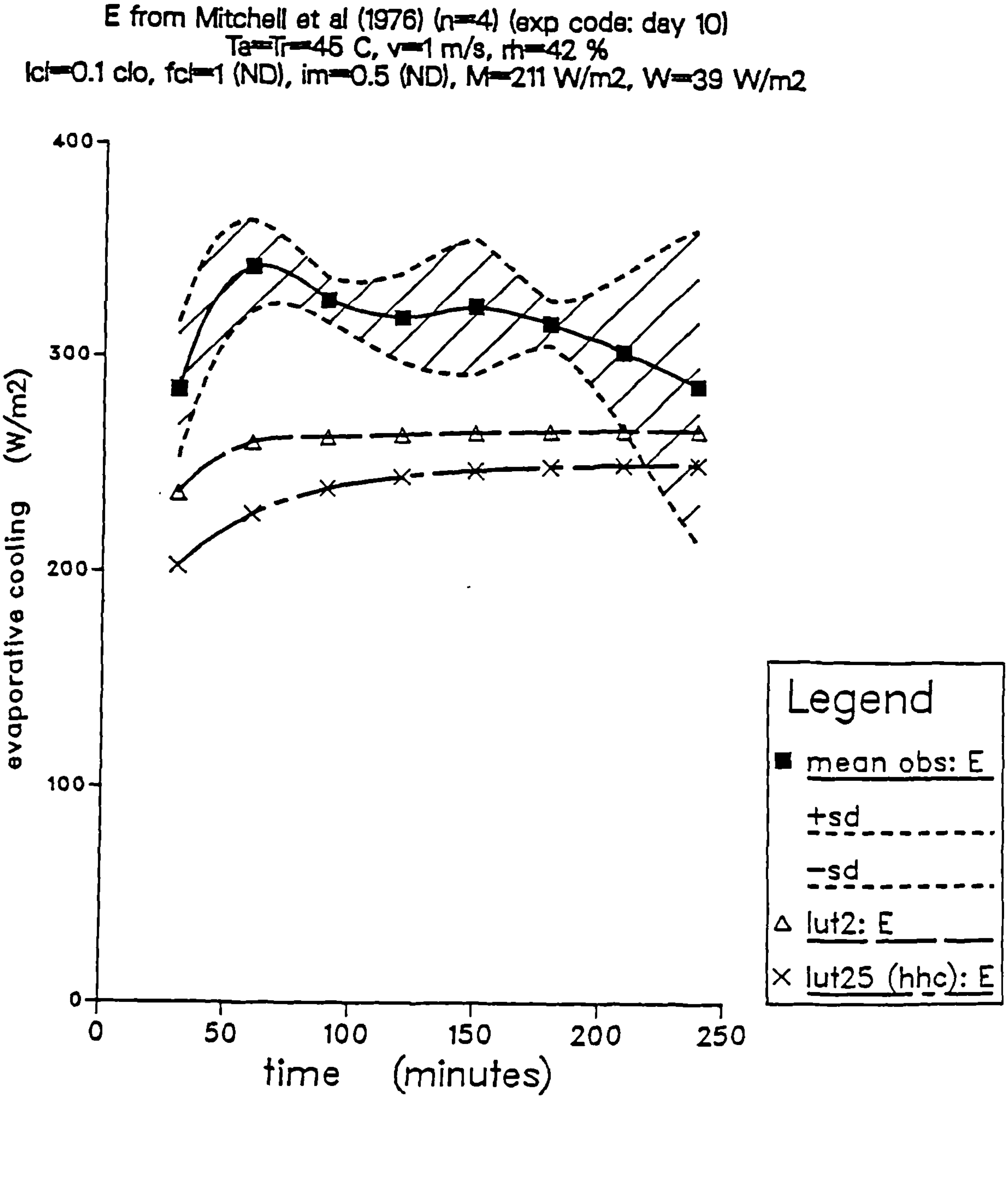
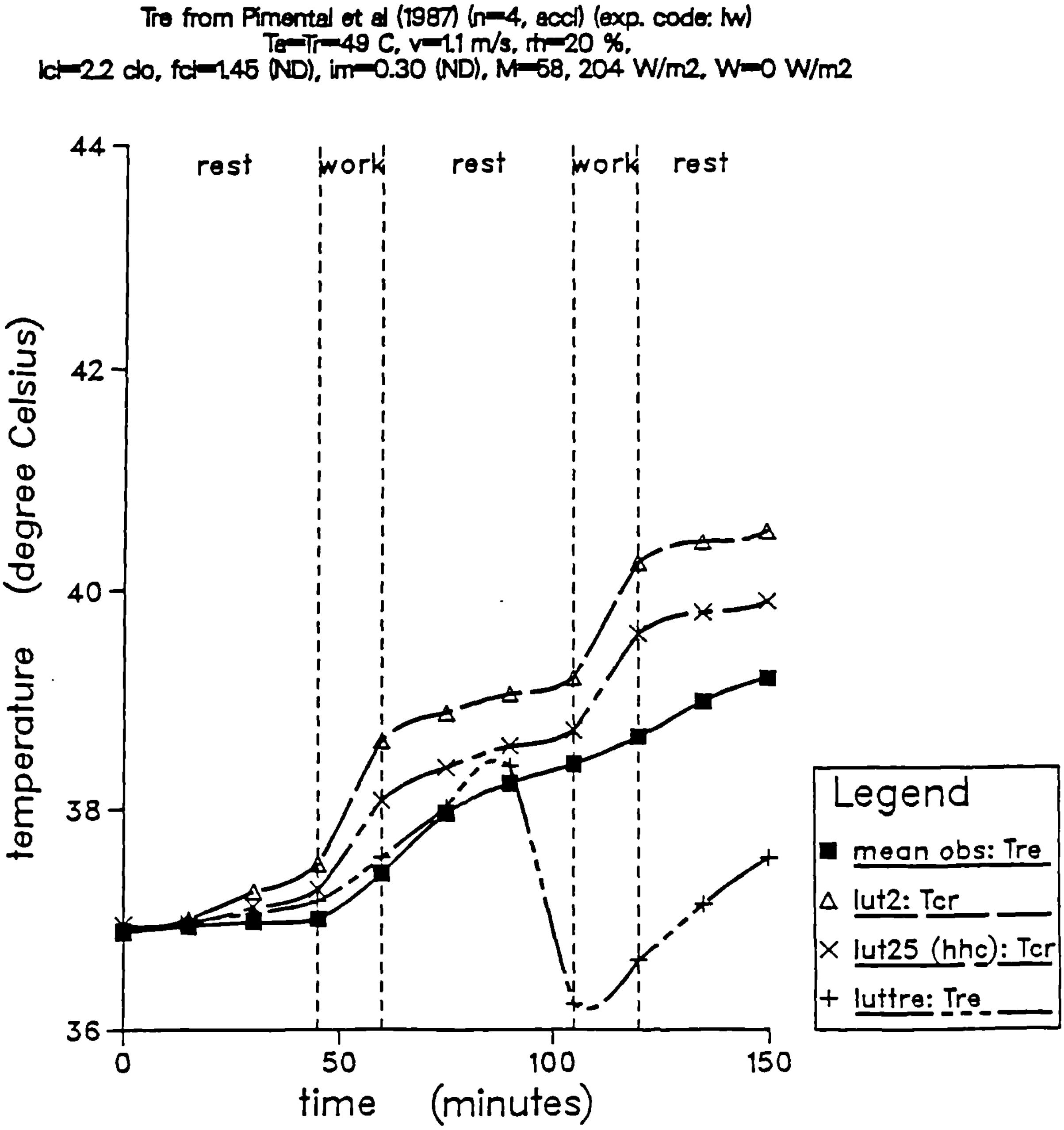
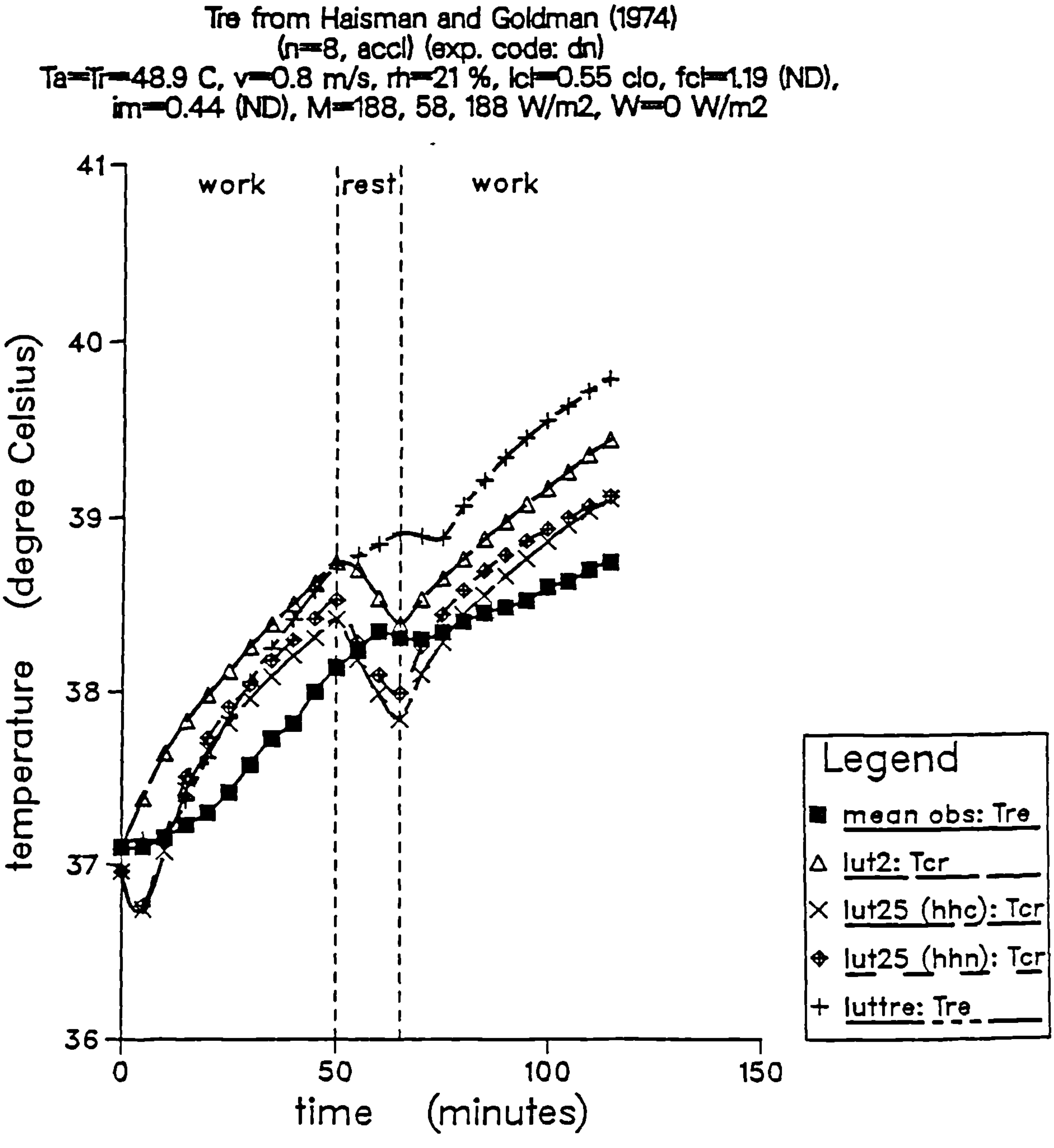


Figure 6.57. Example of deep body temperature responses (Tcr) for acclimatized subjects in the clothed, work and wind environment category.



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

Figure 6.58. Example of deep body temperature responses (Tcr) for acclimatized subjects in the clothed, work and wind environment category.



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

Figure 6.59. Example of mean skin temperature responses (Tsk) for acclimatized subjects in the clothed, work and wind environment category.

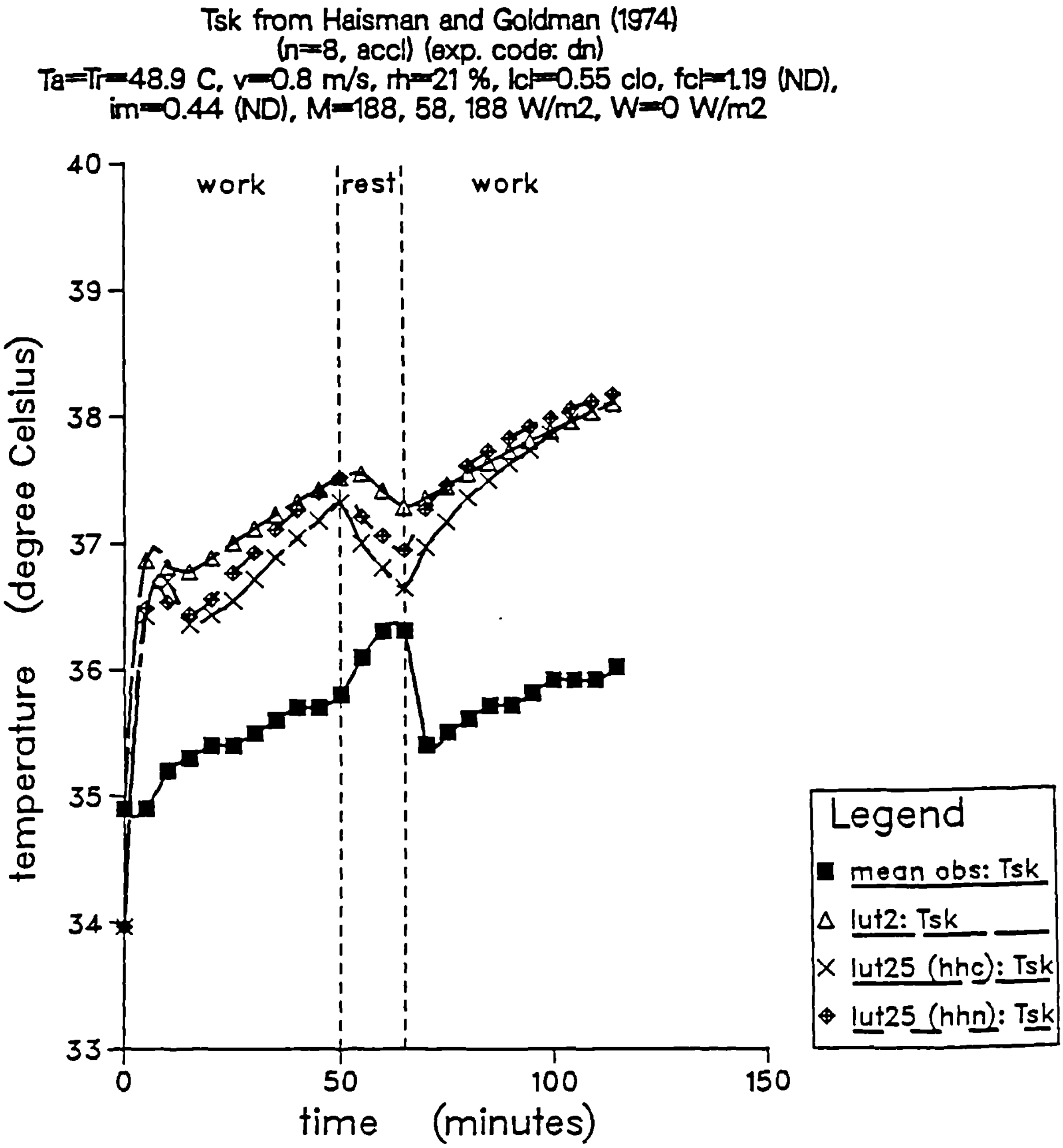


Figure 6.60. Example of deep body temperature responses (Tcr) for female subjects in the clothed, work and no-wind environment category.

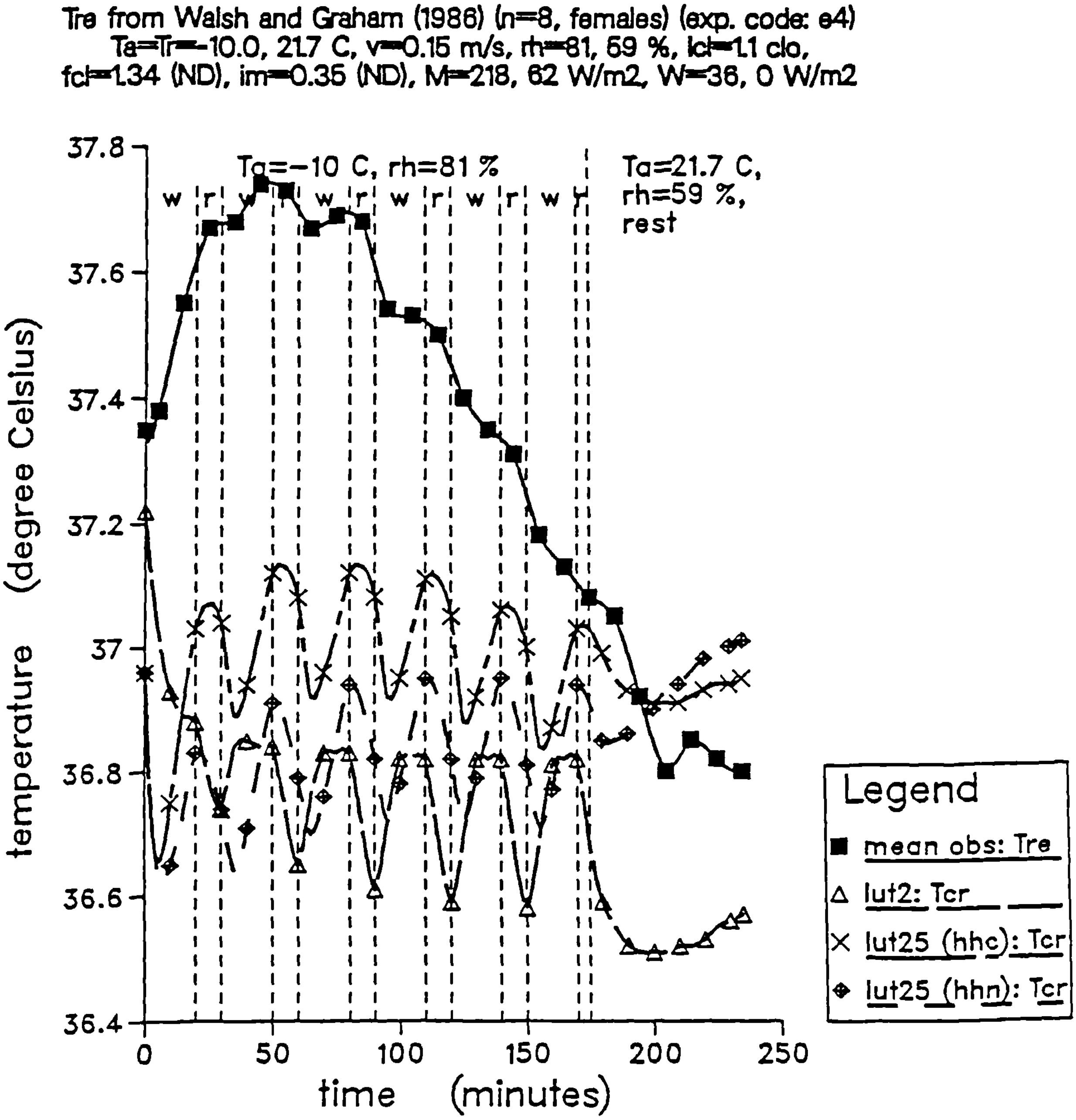


Figure 6.61. Example of mean skin temperature responses (Tsk) for female subjects in the clothed, work and no-wind environment category.

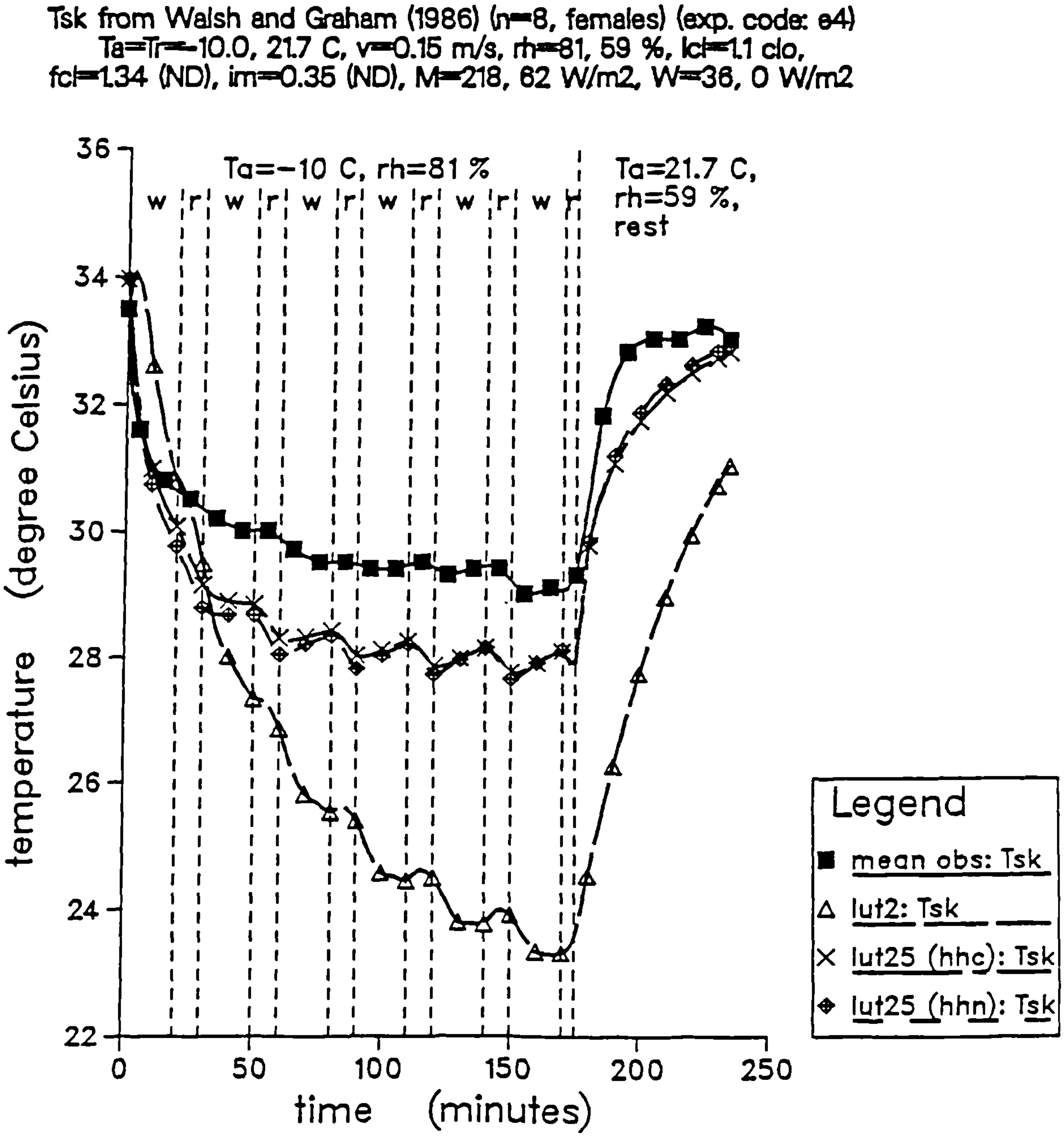
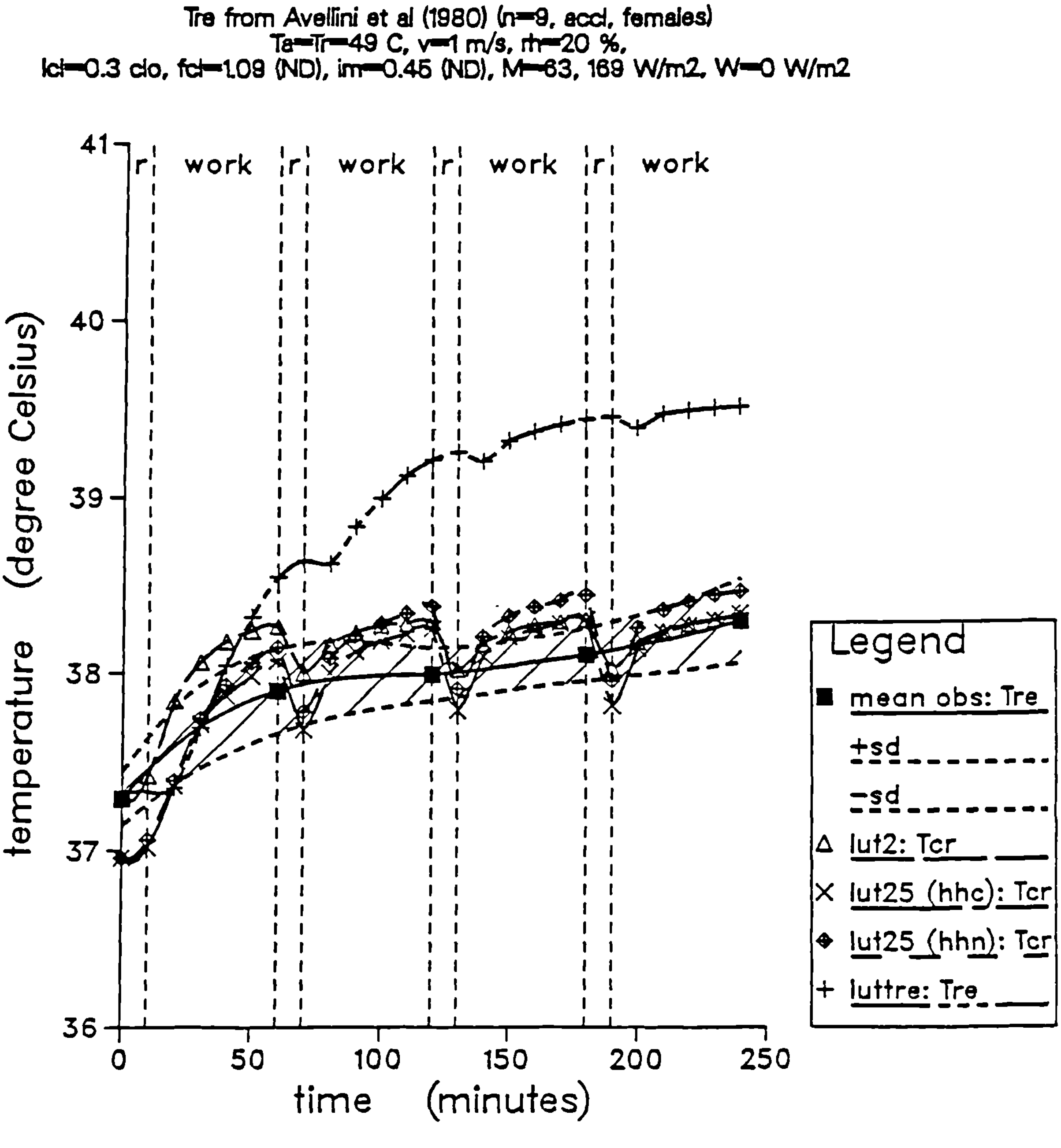


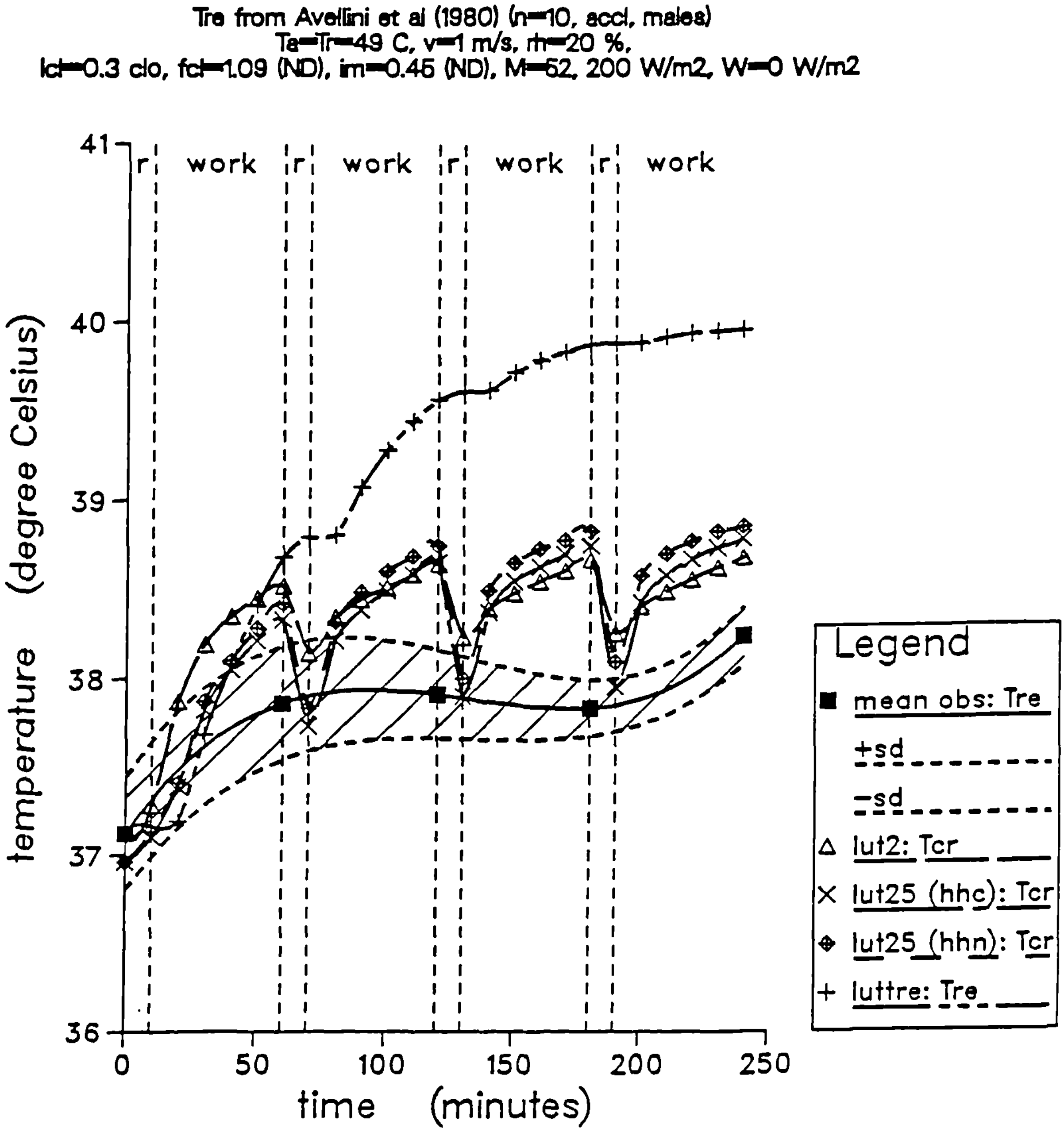
Figure 6.62. Deep body temperature responses (Tcr) for acclimatized female subjects in the clothed, work and wind environment category.



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
```

Figure 6.63. Deep body temperature responses (Tcr) for acclimatized male subjects in the clothed, work and wind environment category.



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

Figure 6.64. Example of mean skin temperature responses (Tsk) for acclimatized female subjects in the clothed, work and wind environment category.

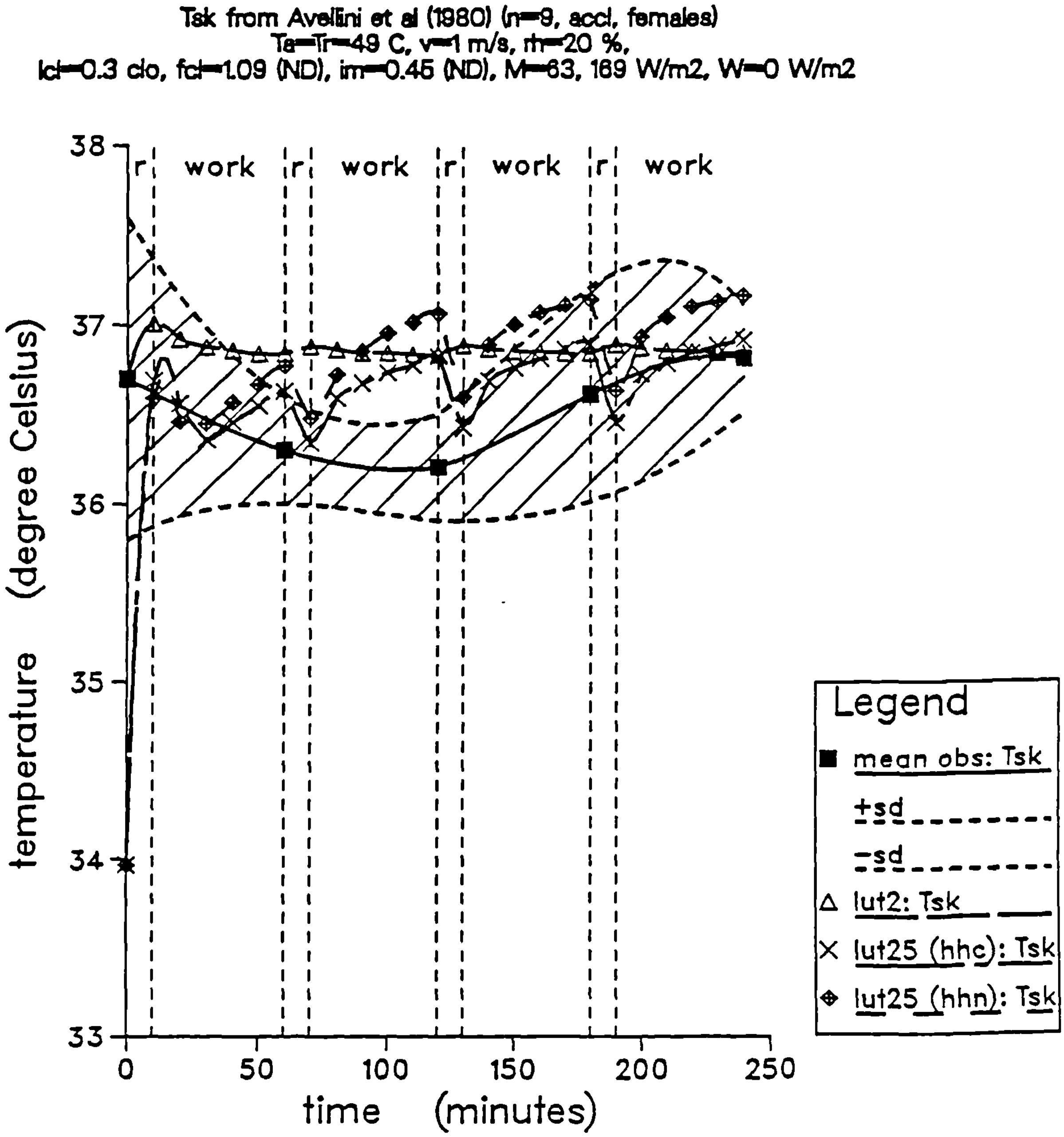
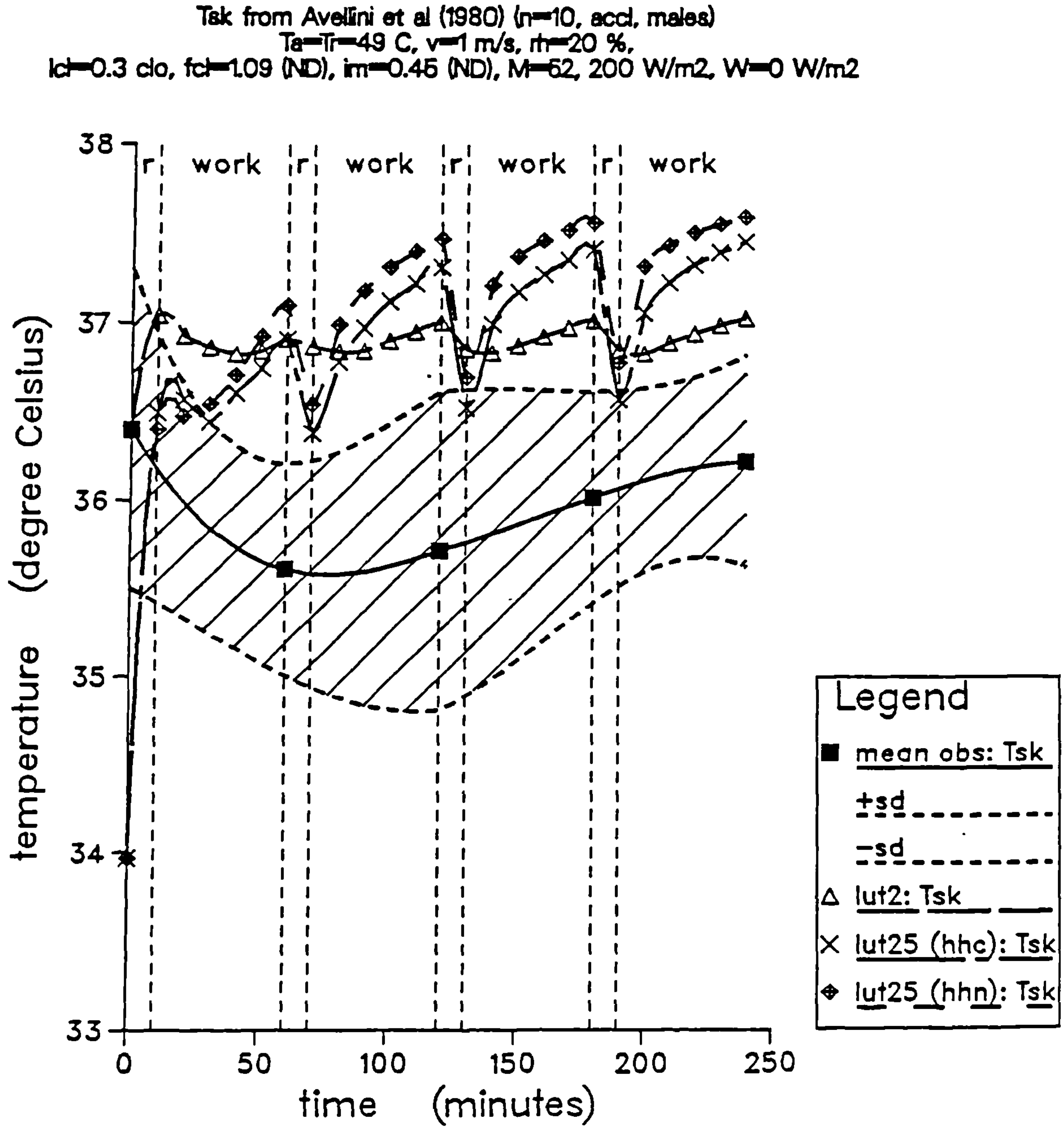


Figure 6.65. Example of mean skin temperature responses (Tsk) for acclimatized male subjects in the clothed, work and wind environment category.



standard deviation.

The mean rmsds for each environment category are analysed in Table 6.4. When comparing mean rmsd values, the standard deviations were also taken into account.

6.2.3. Comparison of lutiso Model's Predictions with Observed Temperature Changes

The temperature changes of the observed data corresponding to the lutiso model's allowable exposure times are tabulated in appendix E.

6.2.4. Summary Results Tables

Table 6.5 summarizes the results of the evaluation of the temperature prediction models, showing which models had average rmsds within the maximum average standard deviations of the observed data (0.5 °C for Tcr and 1.6 °C for Tsk), for each environment category. Mean rmsd values for Tcr were calculated combining observations from the different measuring sites.

The dashes on table 6.5 indicate environments for which no experimental data were available. Where categories have an entry of "NONE", this indicates that none of the models had an average rmsd within the maximum average standard deviation of the observed data. The models are entered in the table in descending order of accuracy, thus, the top entry in a category was the model with the lowest average rmsd for that category.

Table 6.6 is structured in the same way as table 6.5 and

Table 6.4. Analysis of rmsds for each environment category.

Environment Category	Response	Figure	Comments
nude/rest/no-wind	Tre	6.66	Mean rmsds decreased as air temperature increased to $25<Ta<=35$ °C. Mean rmsds for lut2 and lut25 models increased slightly where $Ta>35$ °C from $25<Ta<=35$ °C levels, while mean rmsds for luttre model were similar. The lut2 model had lowest mean rmsd where $Ta<=5$ °C, luttre in range $5<Ta<=25$, and lut25 where $Ta>25$.
	Tty	6.67	Similar pattern of accuracy as found for Tre response. The luttre model may have had slightly higher rmsds for Tty than Tre.
	Tsk	6.68	Mean rmsds tended to decrease as air temperature increased. Where $Ta<=5$ °C, lut2 model had lowest mean rmsd, for other temperature ranges lut2 and lut25 models were similar.
	M	6.69	Mean rmsds tended to decrease as air temperature increased. The lut25 model tended to have slightly lower mean rmsds than lut2. Values were lowest when $Ta>25$, where resting responses were observed and predicted.
nude/rest/wind	Tre	6.70	The luttre model had lowest rmsds, followed by lut2, with lut25 model having highest. Mean rmsds for lut2 model were of similar magnitude to those found for nude/rest/no-wind (figure 6.66), lut25 model's were greater for nude/rest/wind; values for luttre were lower for nude/rest/wind.
	Tsk	6.71	The lut25 model had lowest mean rmsds. Values for lut2 and lut25 models were similar to those found for nude/rest/no-wind (figure 6.68), except lut2 value for $15<Ta<=25$ which was increased for nude/rest/wind.
	M	6.72	Mean rmsds for lut2 and lut25 models were similar size. These were noticeably greater than found for nude/rest/no-wind (figure 6.69).
nude/work/no-wind	Tre	6.73	Mean rmsds were of similar size, except single high value for lut2 model for $15<Ta<=25$ temperature range. Values for lut25 model were similar to those for nude/rest/no-wind category (figure 6.66), while values for lut2 and luttre models were similar or increased for nude/work/no-wind.

(continued)

Table 6.4. (continued)

Environment Category	Response	Figure	Comments
nude/work/no-wind	Tty	6.74	The lut25 model had lowest mean rmsds. Where comparable, lut2 and lut25 models appear to have predicted Tty more accurately than Tre. The luttre model appears to have predicted Tre more accurately than Tty. Compared with values for nude/rest/no-wind (figure 6.67), lut2 mean rmsds were similar, lut25 similar or less, and luttre similar or greater for nude/work/no-wind.
	Toe	6.75	The lut25 model had lowest mean rmsds for two temperature ranges for which experimental data were available. Comparison with Tre shows Toe mean rmsds were less except for luttre where Ta>35 °C.
	Tac	6.76	Data only available where Ta>35 °C. The lut2 and lut25 models' mean rmsds were similar and lowest. Compared with values for Tre, lut2 and lut25 were of similar magnitude, luttre had higher mean rmsd for Tac.
	Tsk	6.77	The lut2 and lut25 models' rmsds were similar for each temperature range and lowest where 25<Ta<=35 °C. Compared with nude/rest/no-wind (figure 6.68), rmsds were perhaps slightly increased for nude/work/no-wind.
nude/work/wind	Tre	6.78	Limited data suggest that lut2 and lut25 models were most accurate. Compared with nude/rest/no-wind (figure 6.66), values for lut2 and lut25 were similar, luttre value was increased for nude/work/wind.
	Tsk	6.79	The rmsds were similar for lut2 and lut25 models, and similar to those for nude/rest/no-wind (figure 6.68).
clothed/rest/no-wind	Tre	6.80	The lut2 model had lowest mean rmsd, values for two versions of lut25 model were similar. Compared with nude/rest/no-wind (figure 6.66), mean rmsds were noticeably lower for clothed/rest/no-wind where Ta<=5 °C, similar where 5<Ta<=15 °C.
	Tsk	6.81	Mean rmsds were similar for lut2 and lut25 models. Values were lower than found for nude/rest/no-wind (figure 6.68).

(continued)

Table 6.4. (continued)

Environment Category	Response	Figure	Comment
clothed/rest/no-wind	M	6.82	The hhc and hhn versions of lut25 model had lower mean rmsds than lut2 model. Compared with nude/rest/no-wind (figure 6.69), clothed/rest/no-wind values were lower.
clothed/rest/wind	Tre	6.83	The lut2 model had lower mean rmsds than the hhc and hhn versions of lut25 model. Values found were of similar size to those for nude/rest/no-wind where Ta<= 5 °C, increased where 5<Ta<=15 °C for clothed/rest/wind (figure 6.66).
	Tsk	6.84	Mean rmsds for lut2 and hhc and hhn versions of lut25 models were similar. These were of comparable magnitude found for nude/rest/no-wind (figure 6.68).
	M	6.85	Mean rmsds indicate that hhn version of lut25 model made most accurate predictions, followed by lut2 model; hhc version of lut25 model was less accurate. Compared with values obtained for nude/rest/no-wind (figure 6.69), lut25 hhc mean rmsds were similar, values obtained for lut2 and lut25 hhn were reduced for clothed/rest/wind.
clothed/work/no-wind	Tre	6.86	The lut25 hhc model had lowest mean rmsd where Ta<=5 °C, the lut2 where 5<Ta<=15 °C. These values were noticeably less than found for nude/rest/no-wind category (figure 6.66).
	Toe	6.87	The lut2 model had lowest mean rmsd for limited data available. The hhc and hhn versions of lut25 model had similar values. Values appear lower than found for Tre.
	Tac	6.88	The lut2 model had lowest mean rmsds, followed by lut25 and luttre. Compared with mean rmsds obtained for Tre and Tty for nude/rest/no-wind (figures 6.66 and 6.67), values for lut2 were similar where 25<Ta<=35 °C, greater where Ta>35 °C for clothed/work/no-wind. Values for lut25 and luttre models were much greater than found for either Tre or Tty for the nude/rest/no-wind category.

(continued)

Table 6.4. (continued)

Environment Category	Response	Figure	Comments
clothed/work/no-wind	Tsk	6.89	The lut25 model had lowest mean rmsds for Ta<=5 and 5<Ta<=15 °C ranges, while lut2 model was slightly more accurate where Ta>25 °C. Mean rmsds for hhc and hhn versions of lut25 model were similar. Compared with nude/rest/no-wind (figure 6.68), lut25 model was more accurate in cold and less accurate in heat for clothed subjects. The lut2 model was less accurate in cold for clothed subjects and similar for warmer conditions.
clothed/work/wind	Tre	6.90	The lut25 model had lowest mean rmsds. Compared with the nude/rest/no-wind category (figure 6.66), where Ta<=5 °C, lut2 and lut25 models had lower mean rmsds for clothed/work/wind. Each models' mean rmsd was increased where 25<Ta<=35 for clothed/work/wind, except single value for lut25 hhn which was similar to lut25 value found for nude/rest/no-wind.
	Tga	6.91	Available values were similar to Tre.
	Tsk	6.92	The mean rmsds for lut2 and lut25 hhc models were similar. The hhn version of lut25 model had large value for experiment where its predictions were appropriate. Values were considerably greater than found for nude/rest/no-wind category (figure 6.68).
heat acclimatized subjects: nude/work/wind	Tre	6.93	The lut2 and lut25 models had lowest rmsds. Values were slightly less than found for same subjects unacclimatized (figure 6.78).
	Tsk	6.94	The lut2 and lut25 models had similar rmsds. Values were slightly greater than found for same subjects unacclimatized (figure 6.79).
heat acclimatized subjects: clothed/work/wind	Tre	6.95	The lut25 model had lowest mean rmsds, followed by lut2 and luttre. Values for hhn version of lut25 model were slightly lower than hhc. Compared with data for unacclimatized subjects (figure 6.90), for 25<Ta<=35 range for which data were available, mean rmsds were similar.
	Tsk	6.96	Values for lut2 and lut25 models were similar, no data were available for unacclimatized subjects for comparison.

(continued)

Table 6.4. (continued)

Environment Category	Response	Figure	Comments
female subjects: clothed/work/no-wind	Tre	6.97	The lut25 model had lowest mean rmsds, hhc and hhn versions of model were similar. Values for lut2 model were slightly increased, while lut25 decreased compared with comparable males (figure 6.86).
	Tsk	6.98	The lut25 model had lowest mean rmsds, hhc and hhn versions were similar. The lut2 model's mean rmsds were similar to those found for men (figure 6.89), lut25 values were increased where Ta<=5°C and decreased where 5<Ta<=15 for females.
heat acclimatized female subjects: clothed/work/wind	Tre	6.99	The lut2 and lut25 models had similar rmsds, while value for luttre model was much greater. Compared with mean values obtained for men (figure 6.95), lut2 lut25 models appear to have predicted acclimatized female responses more accurately than male. Value for luttre model was similar for female and male subjects.
	Tsk	6.100	The lut2 model had lowest value, lower than mean rmsd found for comparable male exposures (figure 6.96). Values obtained for lut25 model were similar for females and males.

Figure 6.66. Mean rmsds for rectal temperature (Tre) (thick bars) for the nude, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

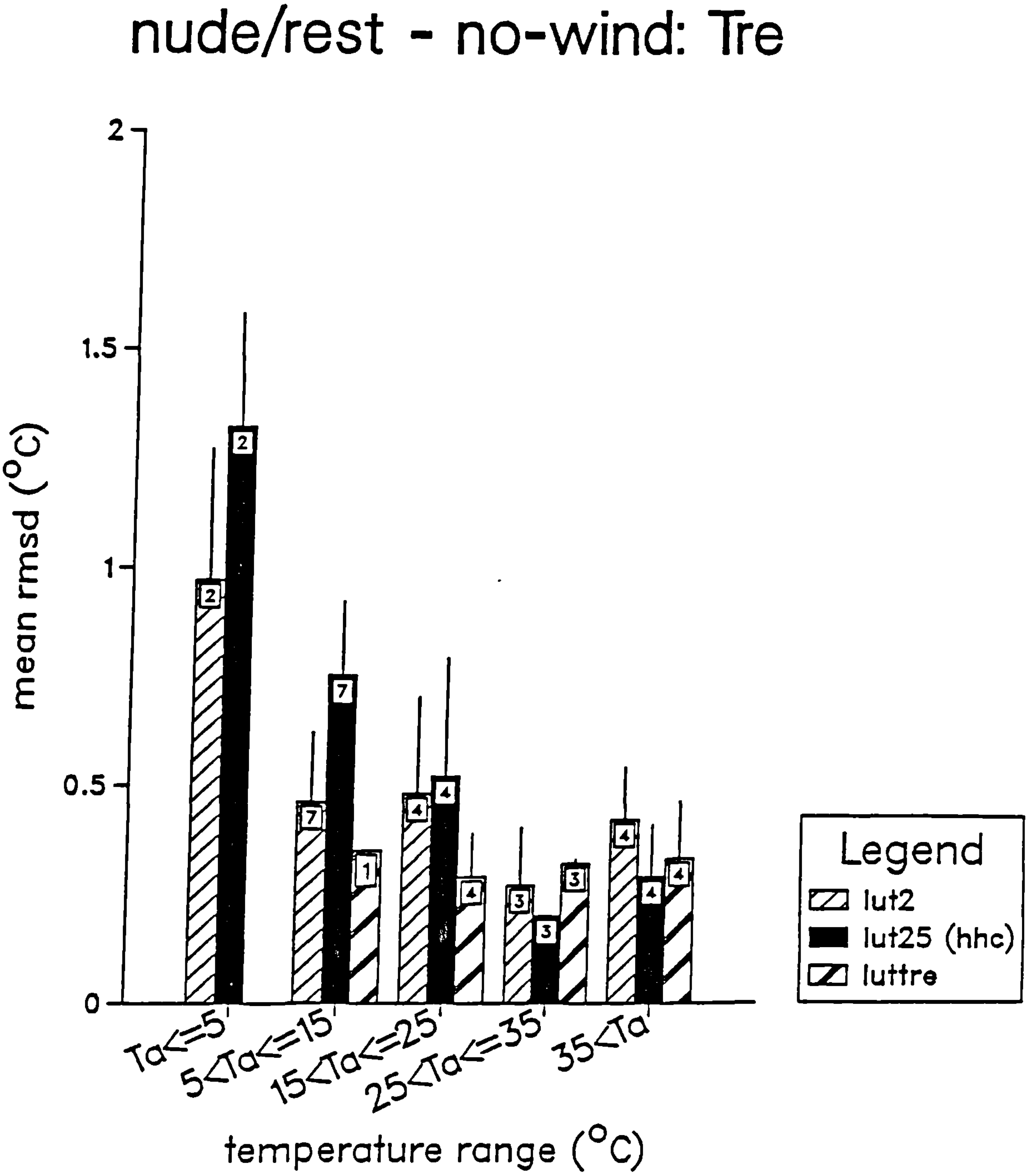


Figure 6.67. Mean rmsds for tympanic temperature (Tty) (thick bars) for the nude, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

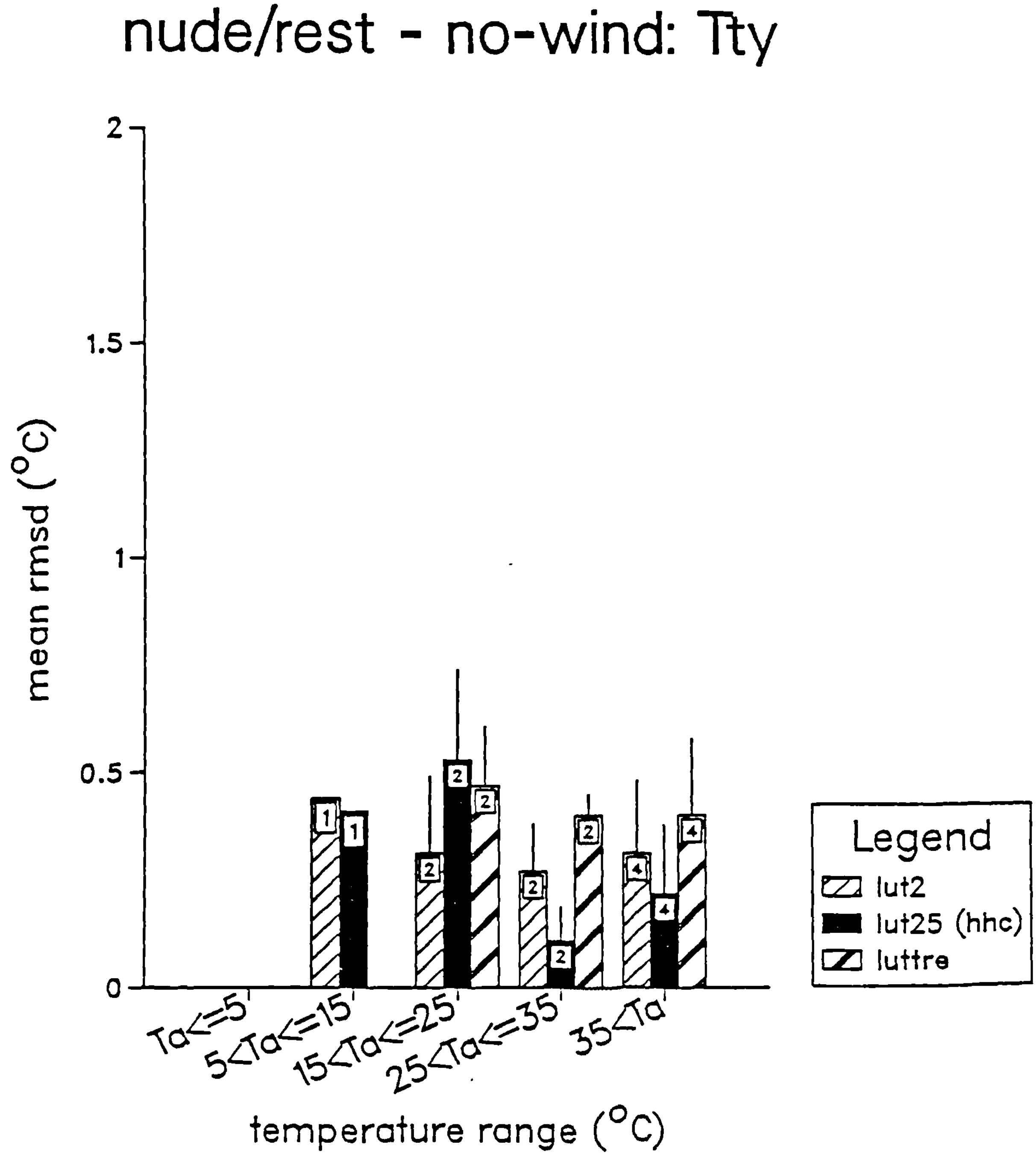


Figure 6.68. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the nude, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

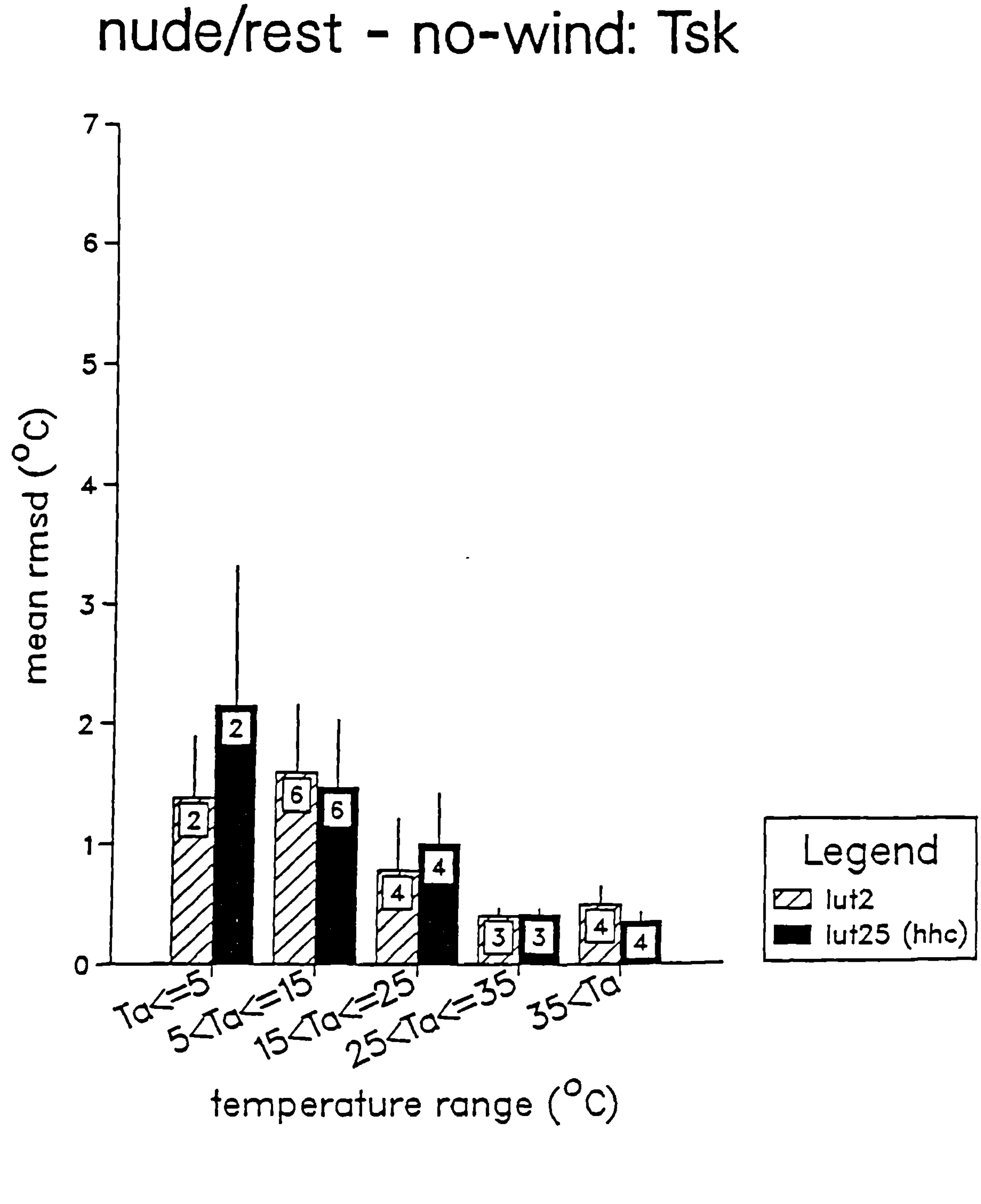


Figure 6.69. Mean rmsds for metabolic rate (M) (thick bars) for the nude, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

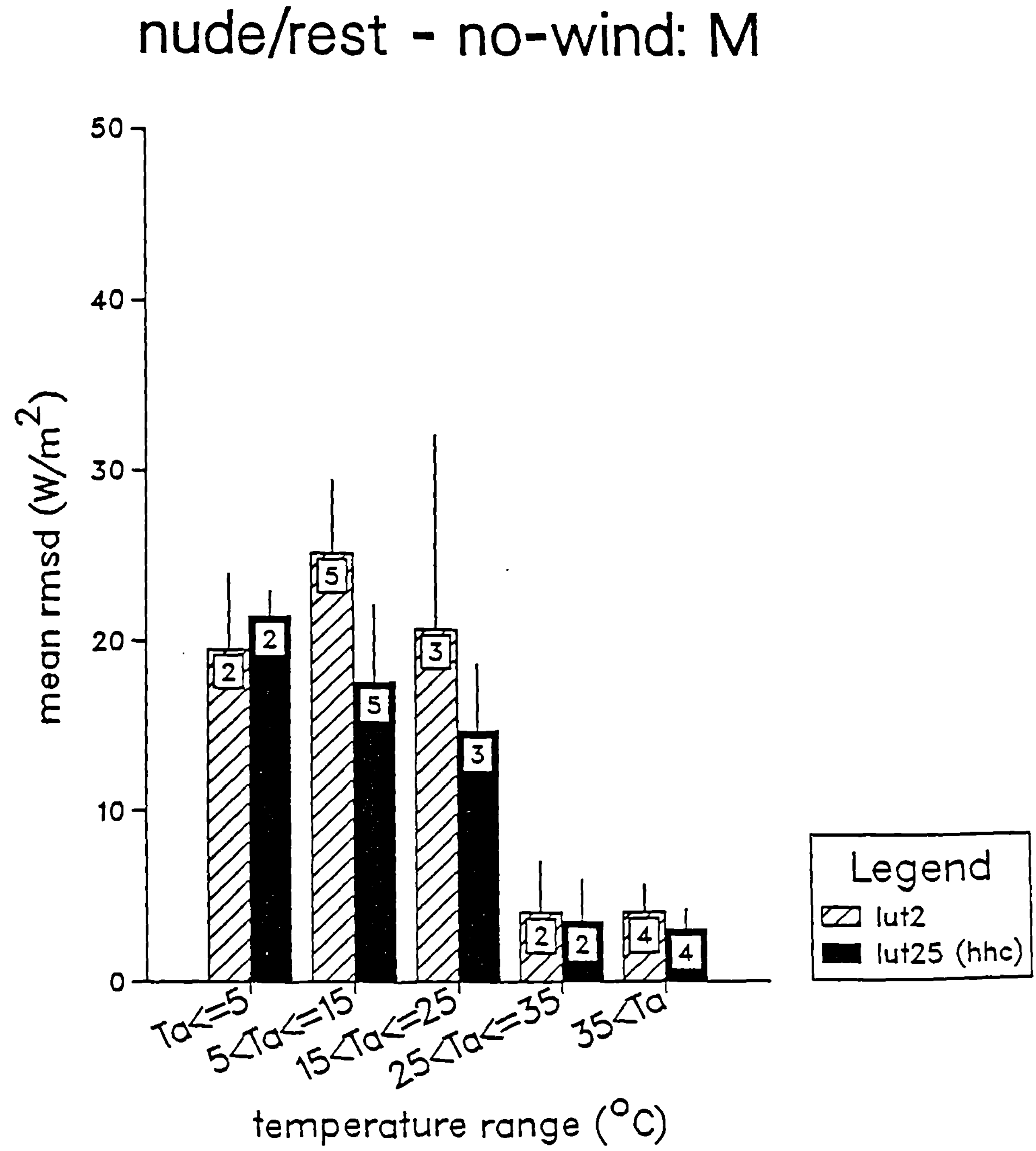


Figure 6.70. Mean rmsds for rectal temperature (Tre) (thick bars) for the nude, rest and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

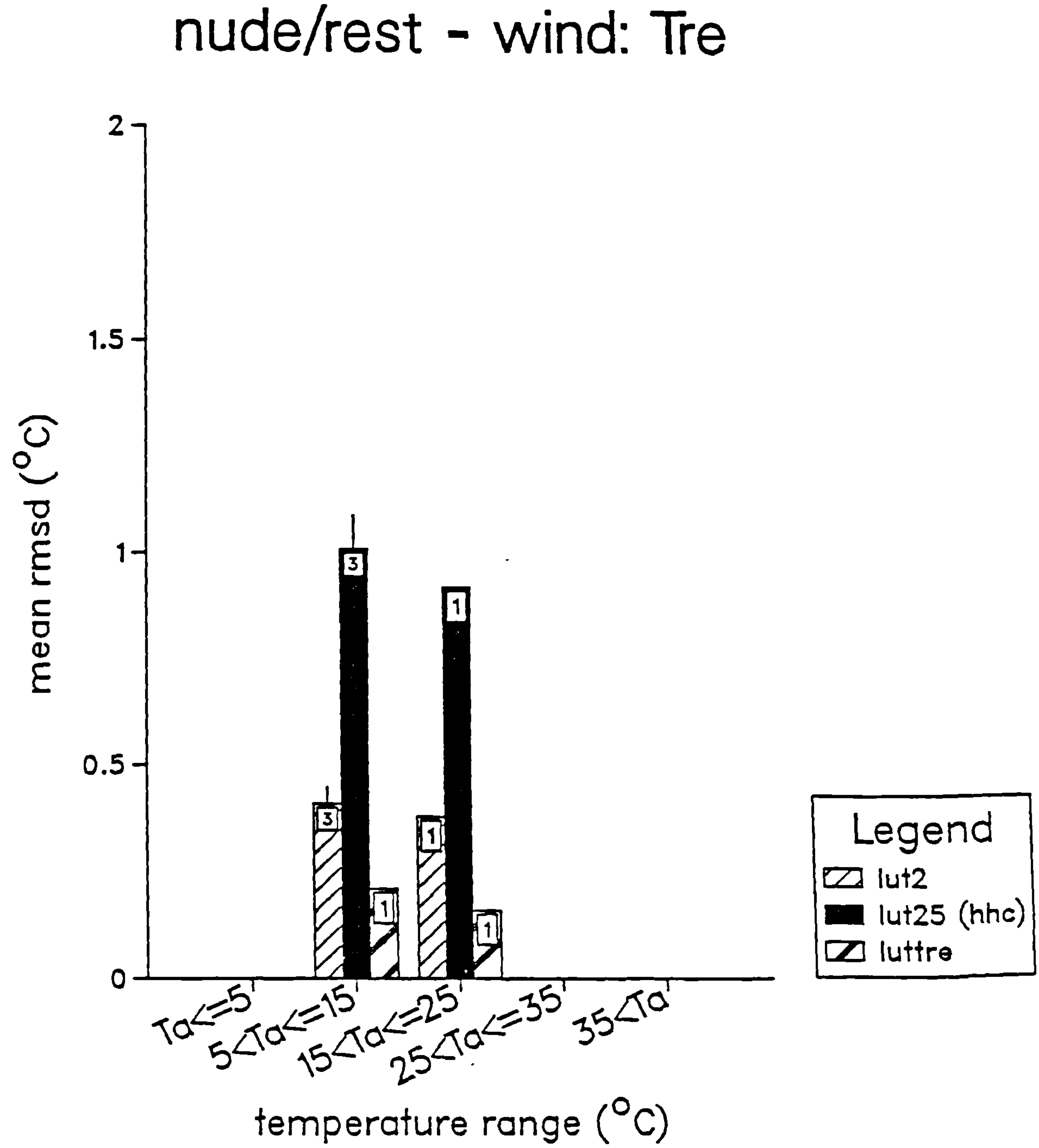


Figure 6.71. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the nude, rest and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

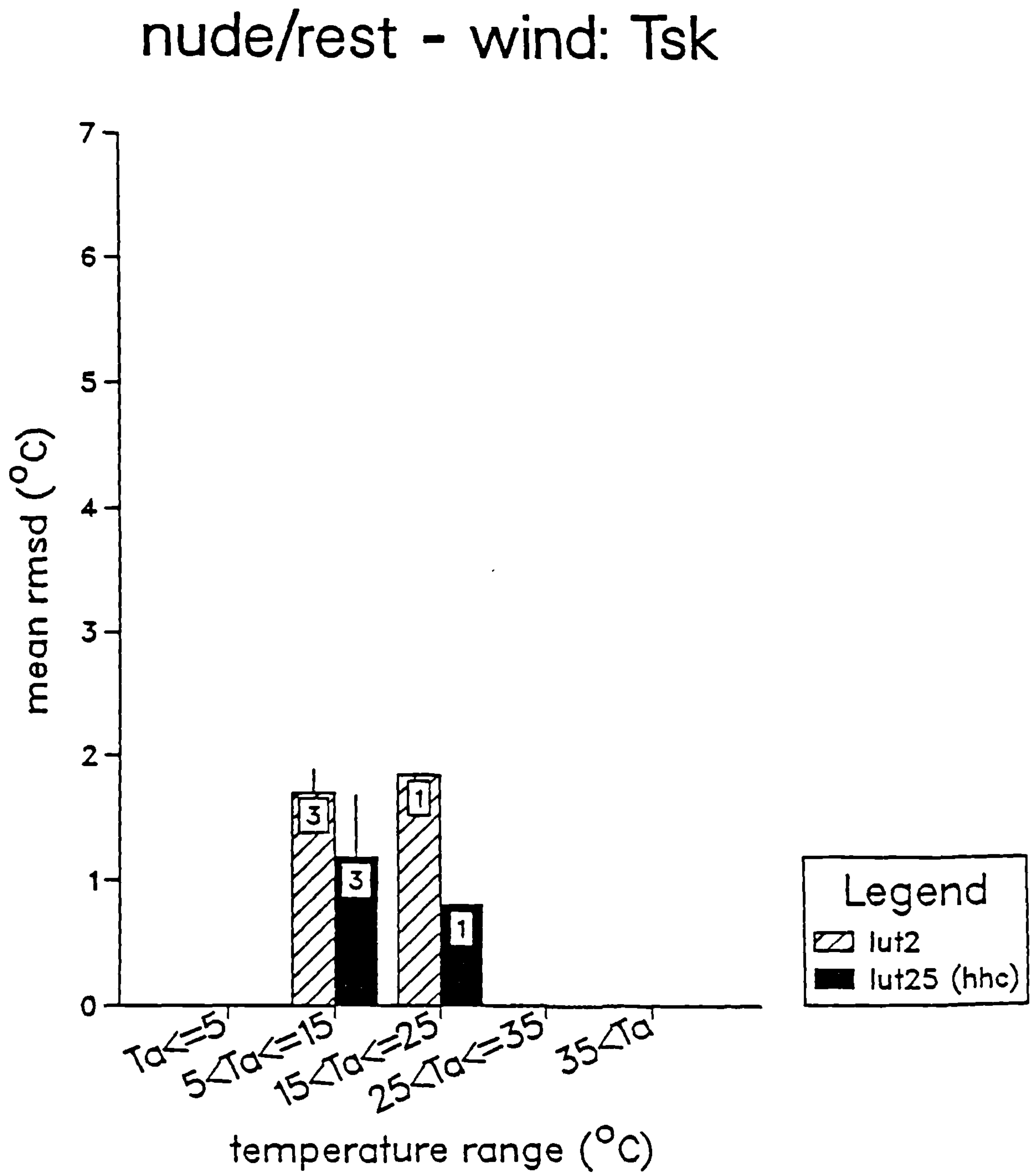


Figure 6.72. Mean rmsds for metabolic rate (M) (thick bars) for the nude, rest and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

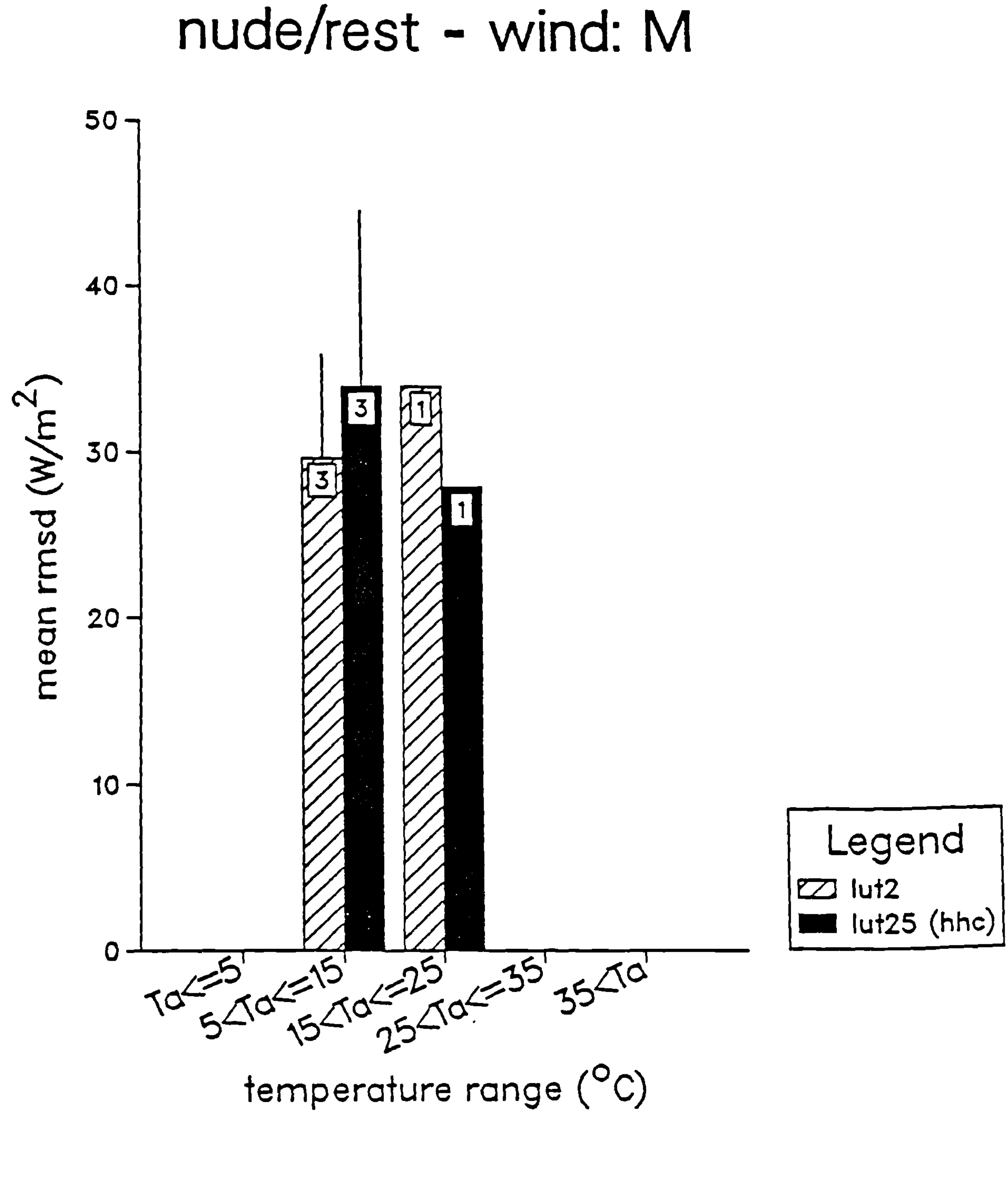


Figure 6.73. Mean rmsds for rectal temperature (Tre) (thick bars) for the nude, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

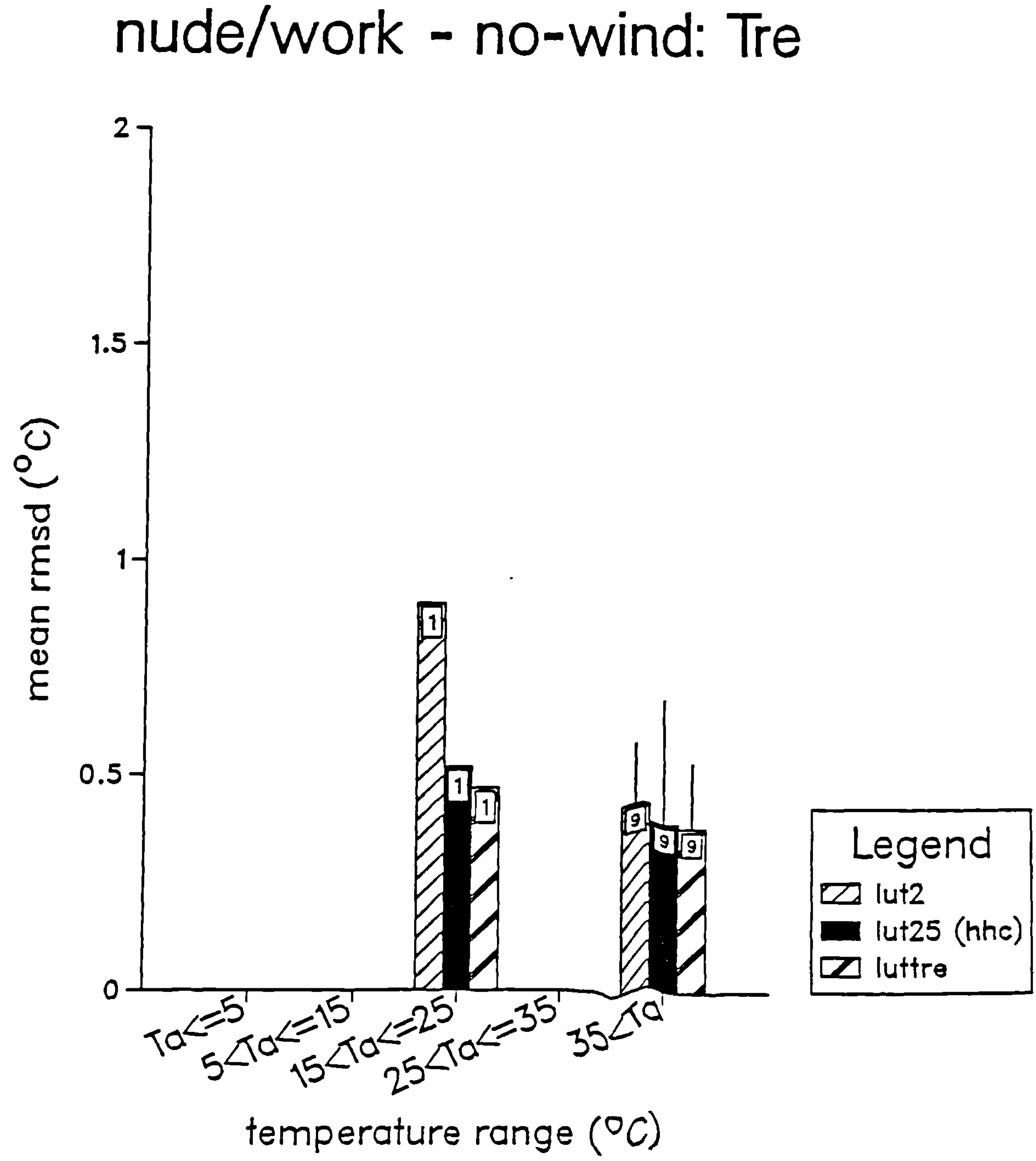


Figure 6.74. Mean rmsds for tympanic temperature (Tty) (thick bars) for the nude, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

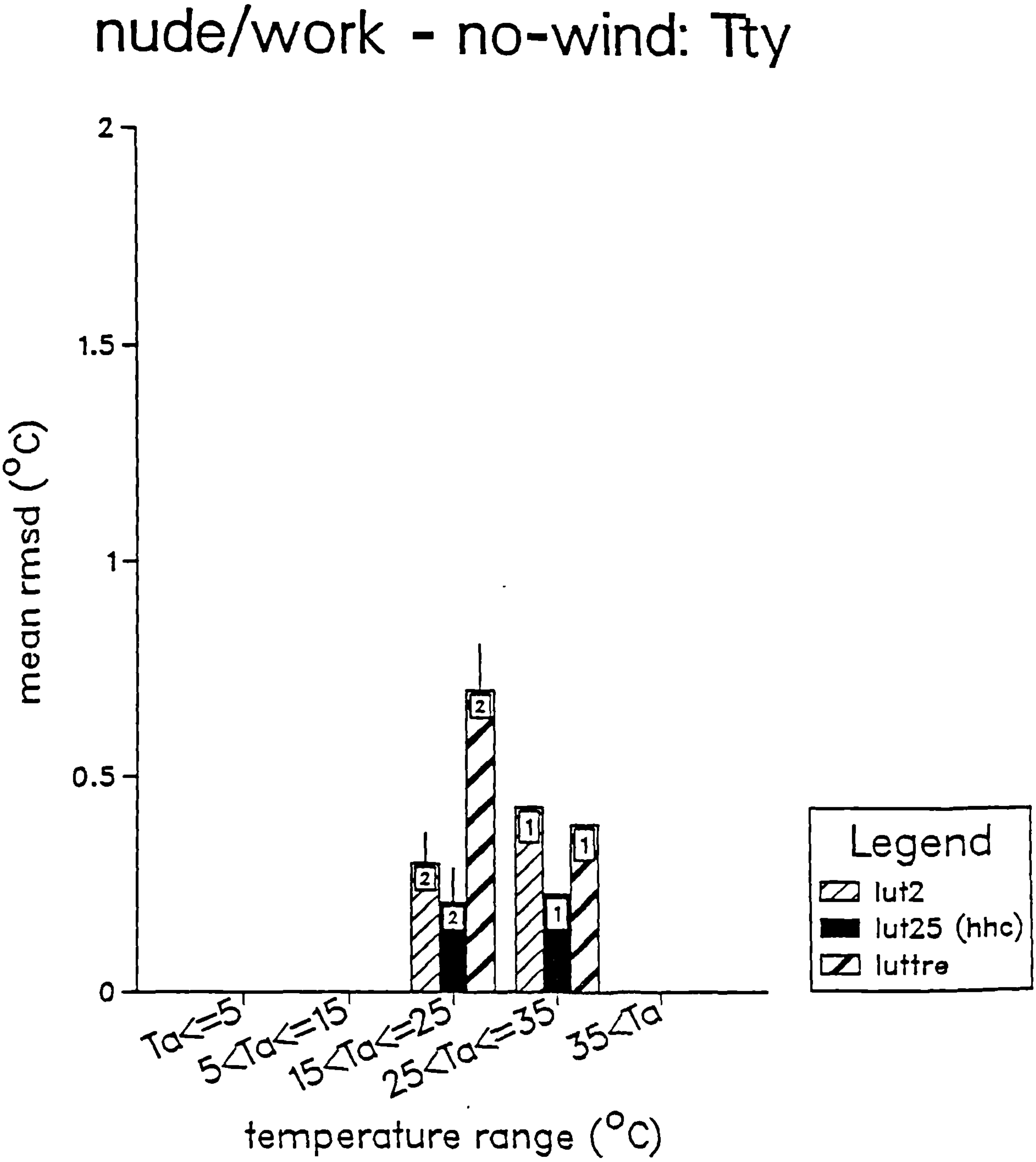


Figure 6.75. Mean rmsds for oesophageal temperature (Toe) (thick bars) for the nude, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

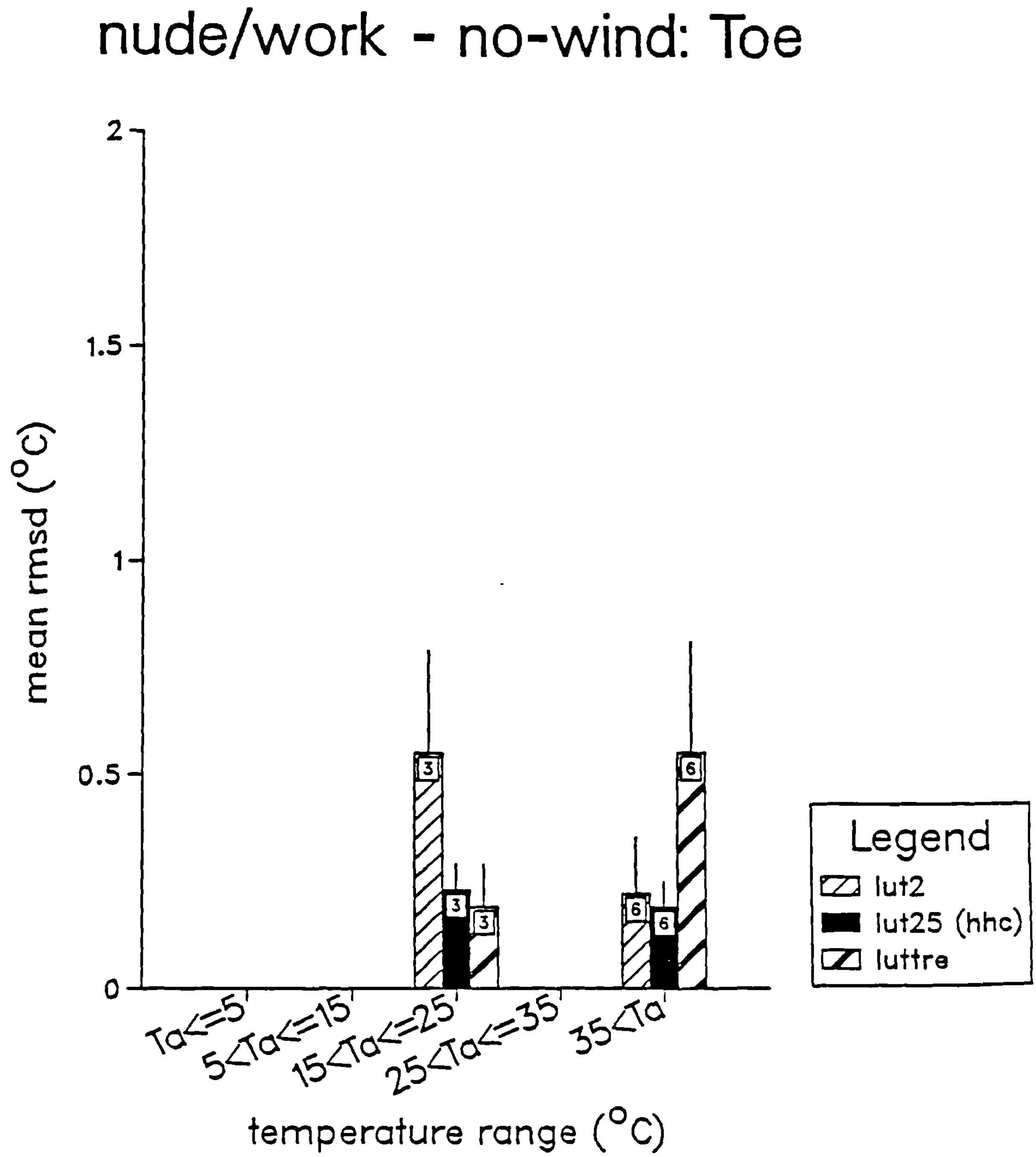


Figure 6.76. Mean rmsds for auditory canal temperature (Tac) (thick bars) for the nude, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

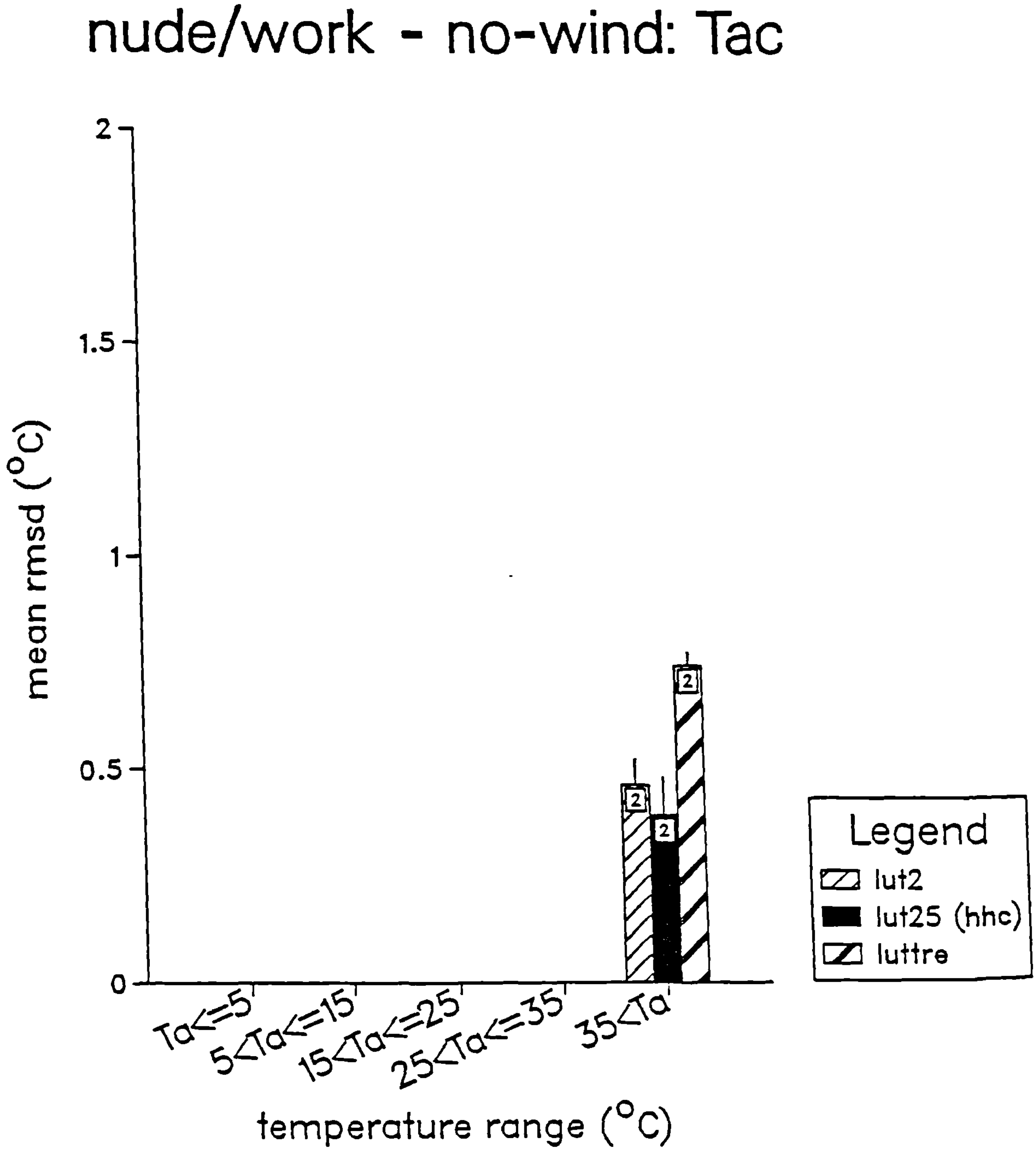


Figure 6.77. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the nude, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

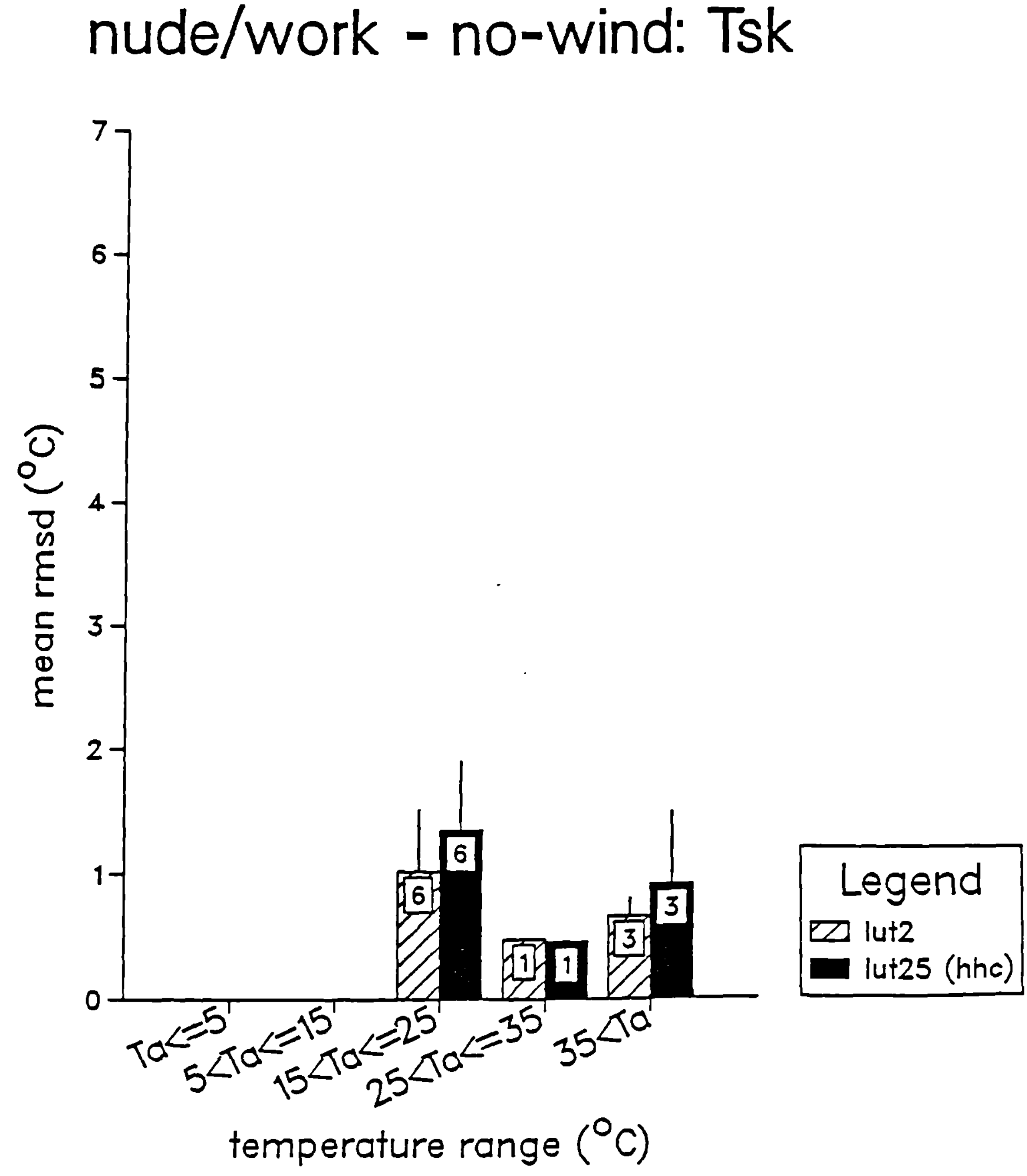


Figure 6.78. Rmsds for rectal temperature (Tre) for the nude, work and wind environment category (numbers at the top of thick bars are the number of rmsds available in environment category).

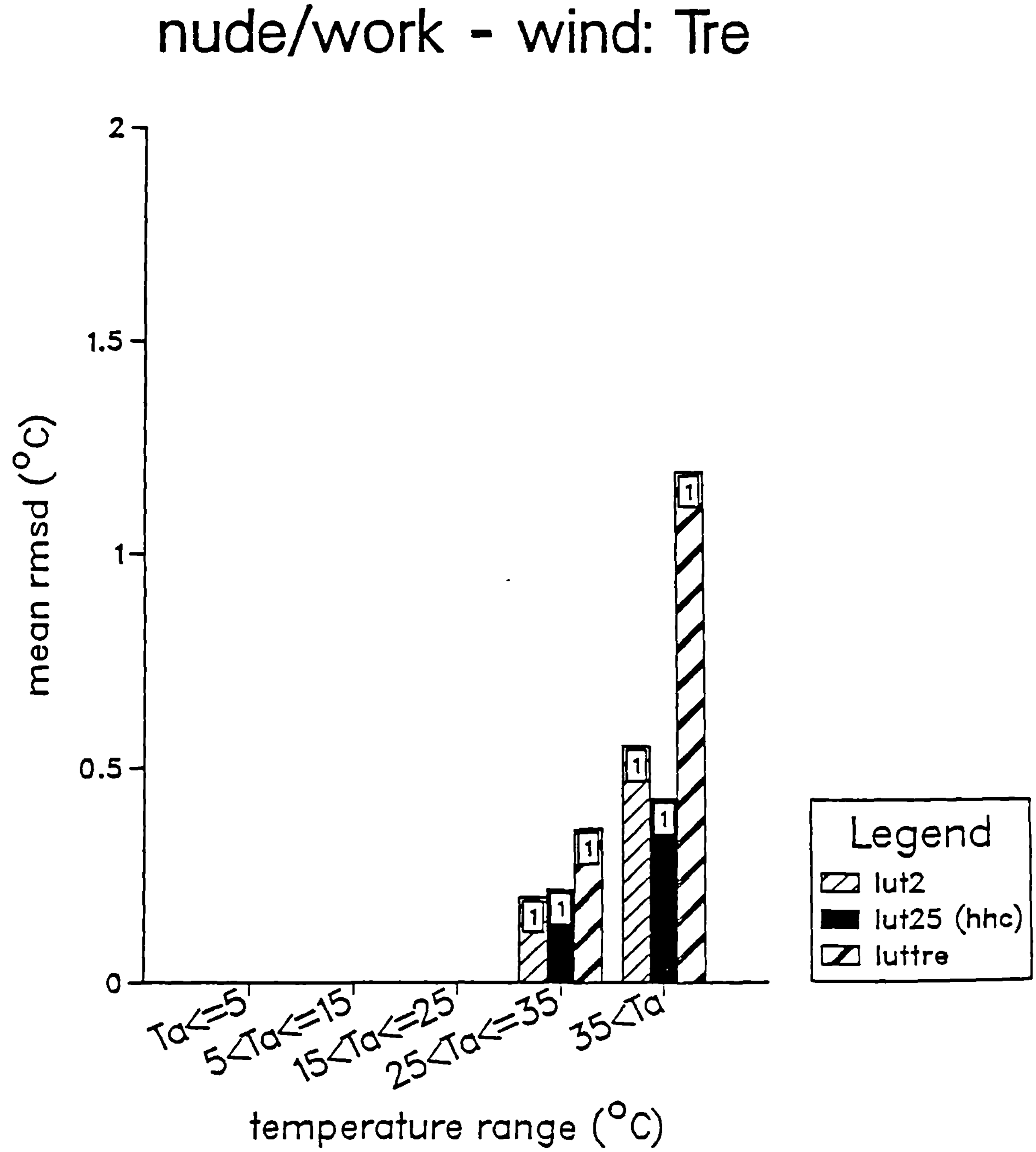


Figure 6.79. Rmsds for mean skin temperature (Tsk) for the nude, work and wind environment category (numbers at the top of thick bars are the number of rmsds available in environment category).

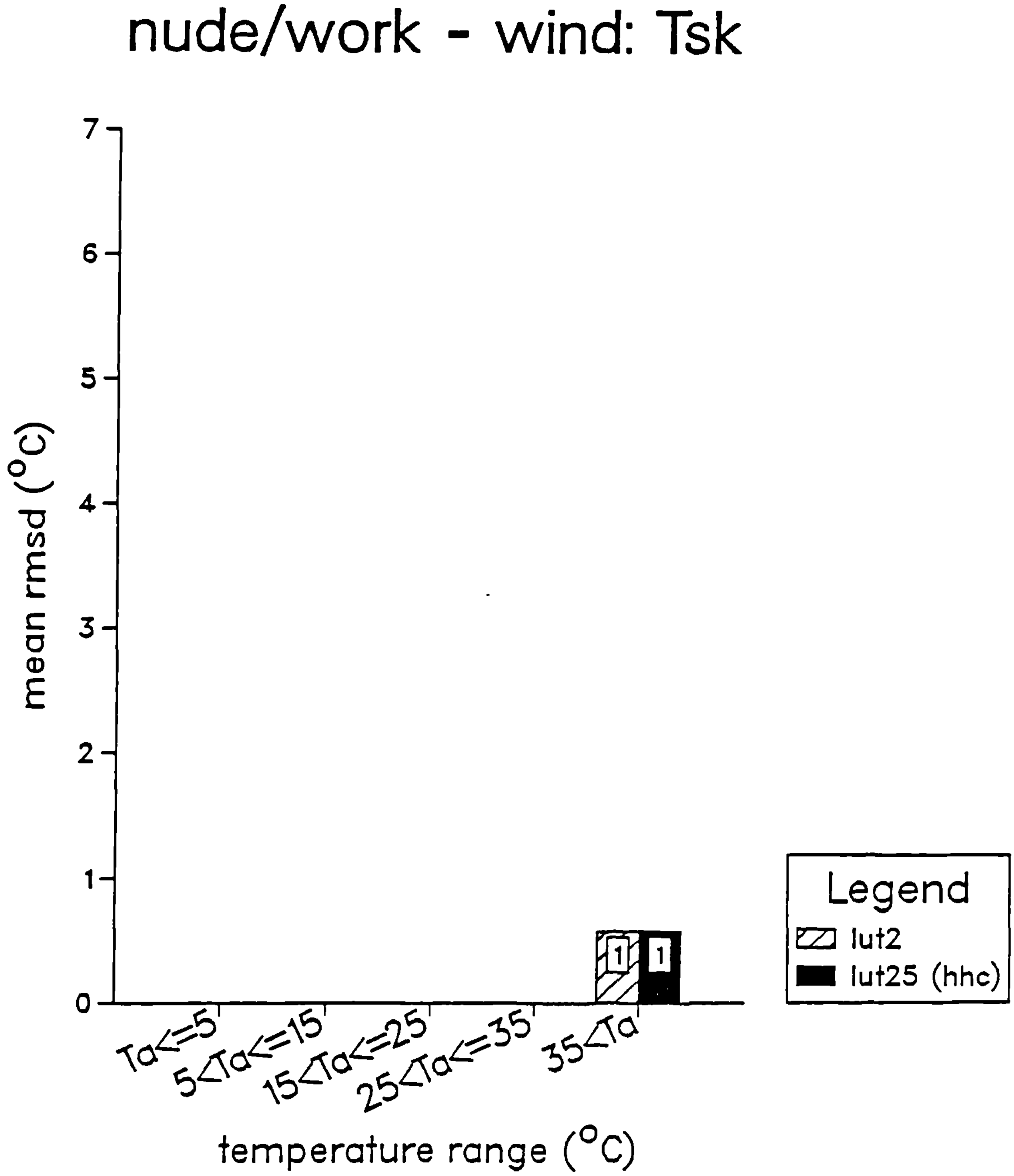


Figure 6.80. Mean rmsds for rectal temperature (Tre) (thick bars) for the clothed, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

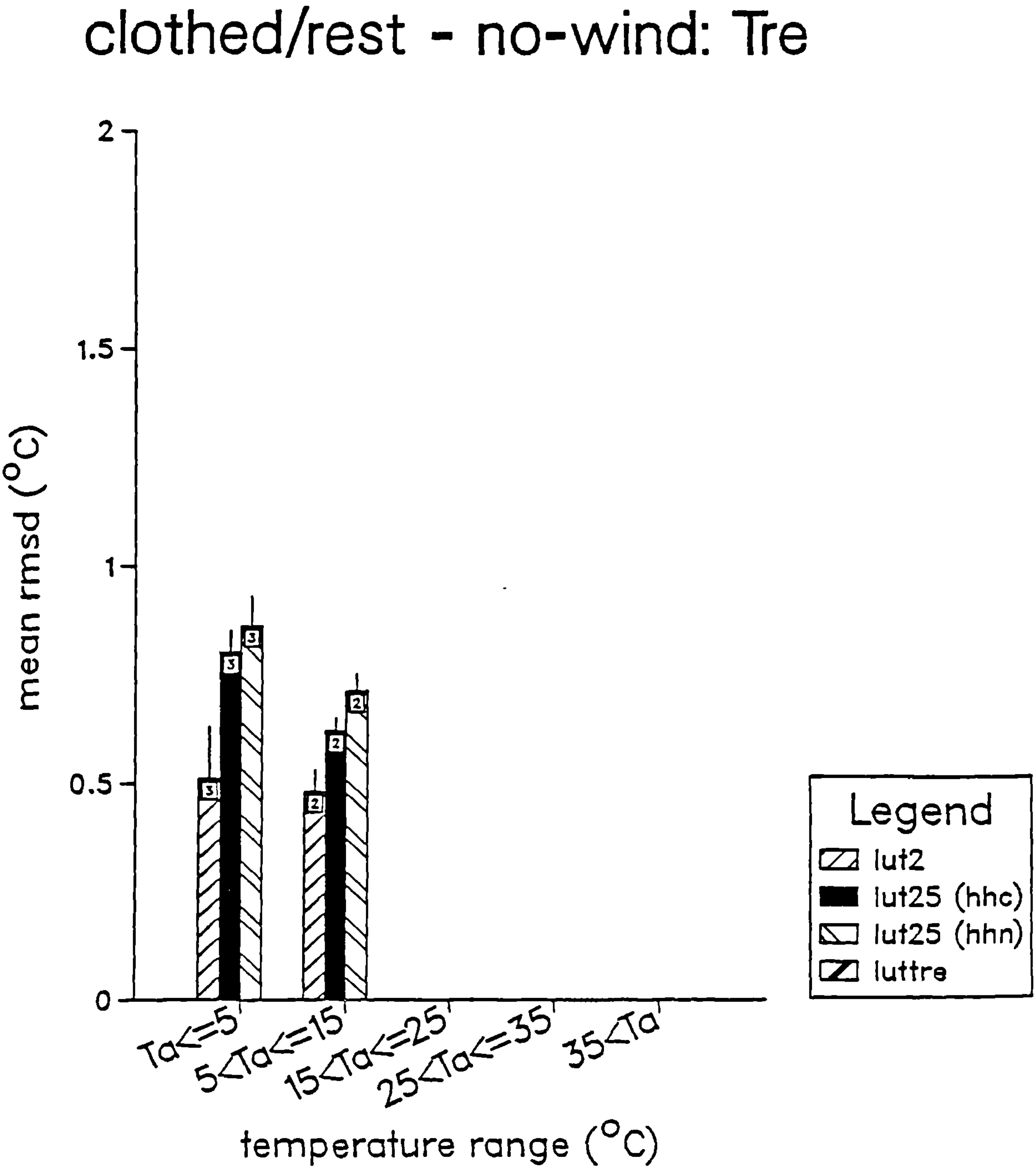


Figure 6.81. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the clothed, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

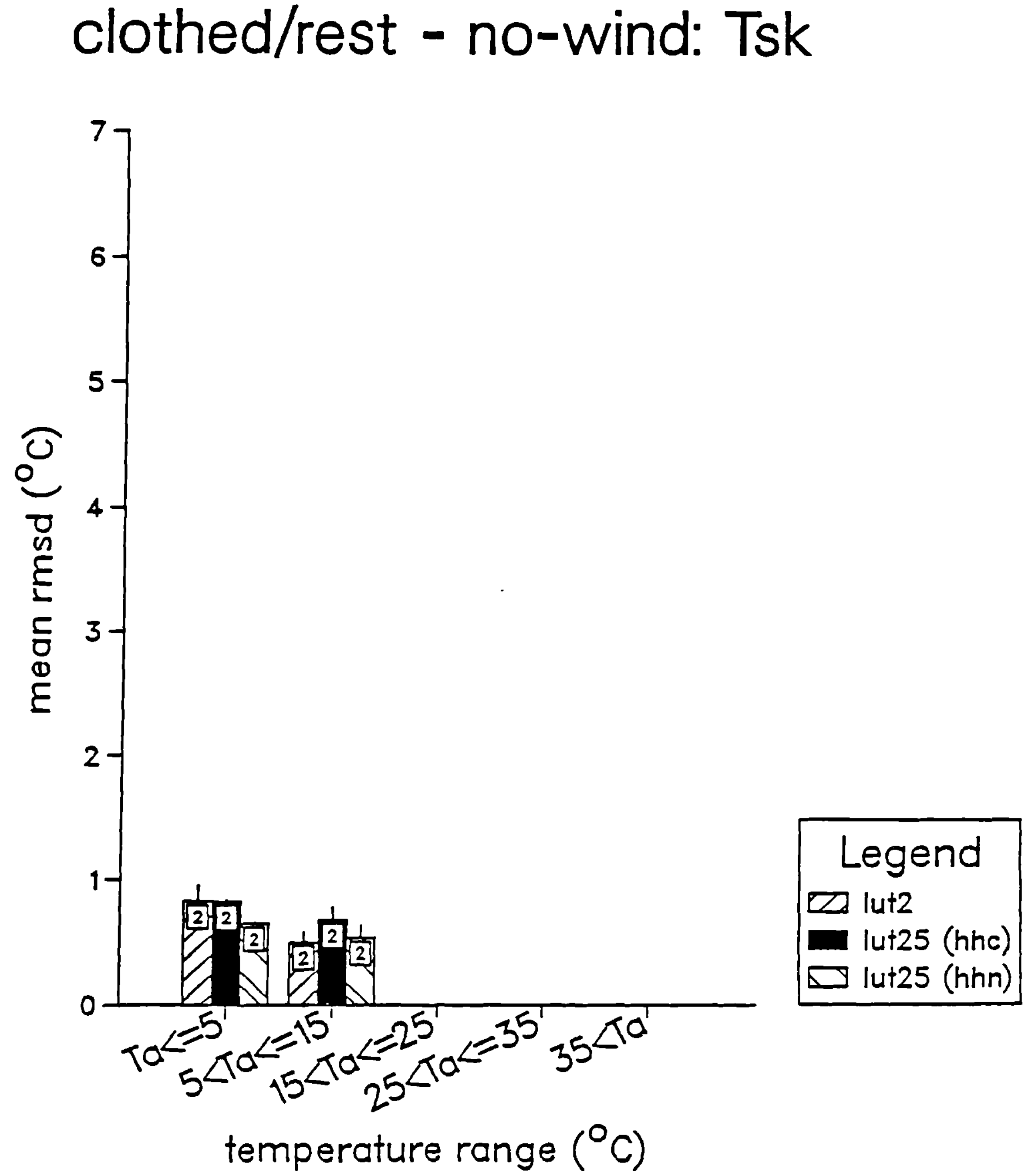


Figure 6.82. Mean rmsds for metabolic rate (M) (thick bars) for the clothed, rest and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

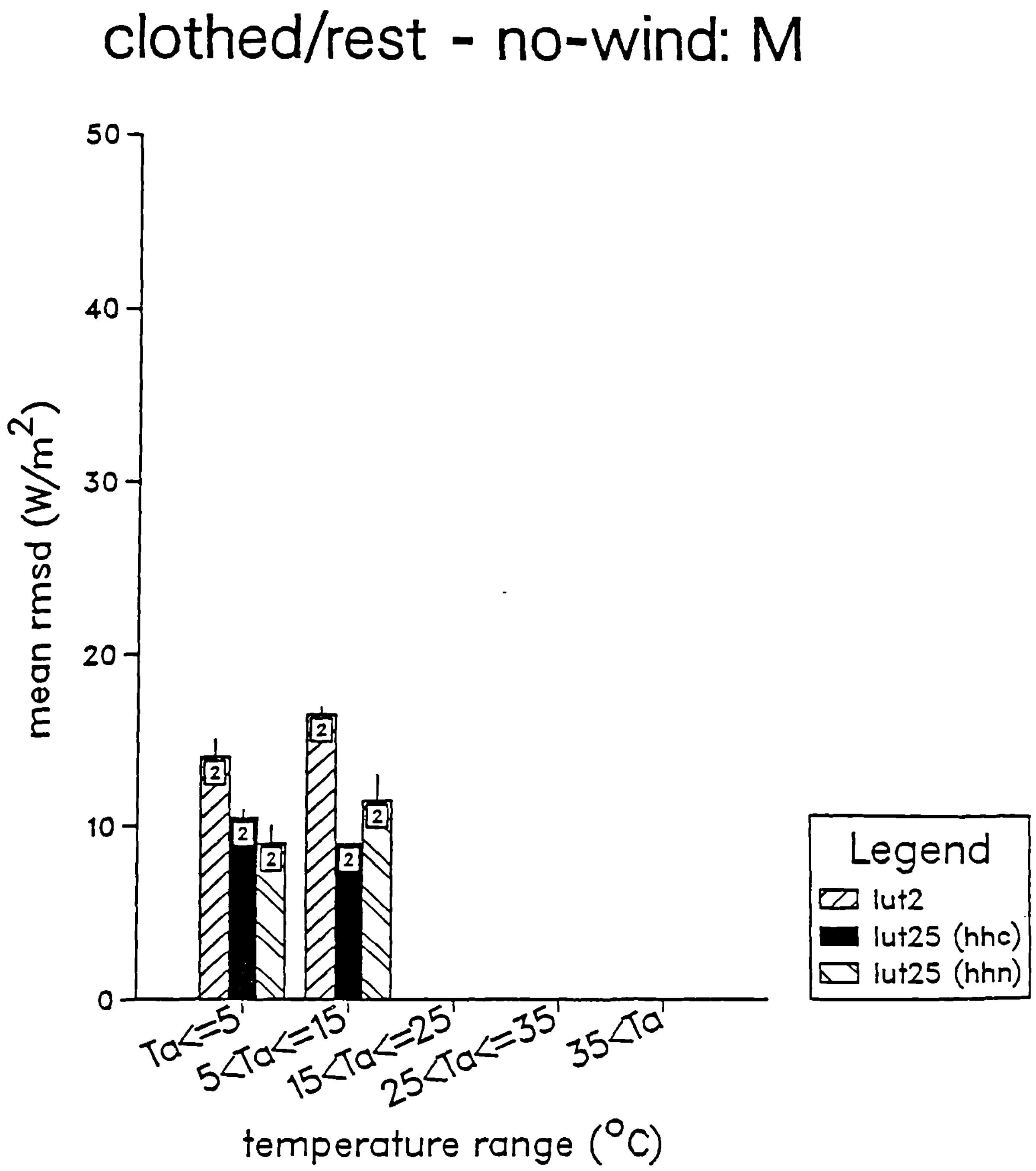


Figure 6.83. Mean rmsds for rectal temperature (Tre) (thick bars) for the clothed, rest and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

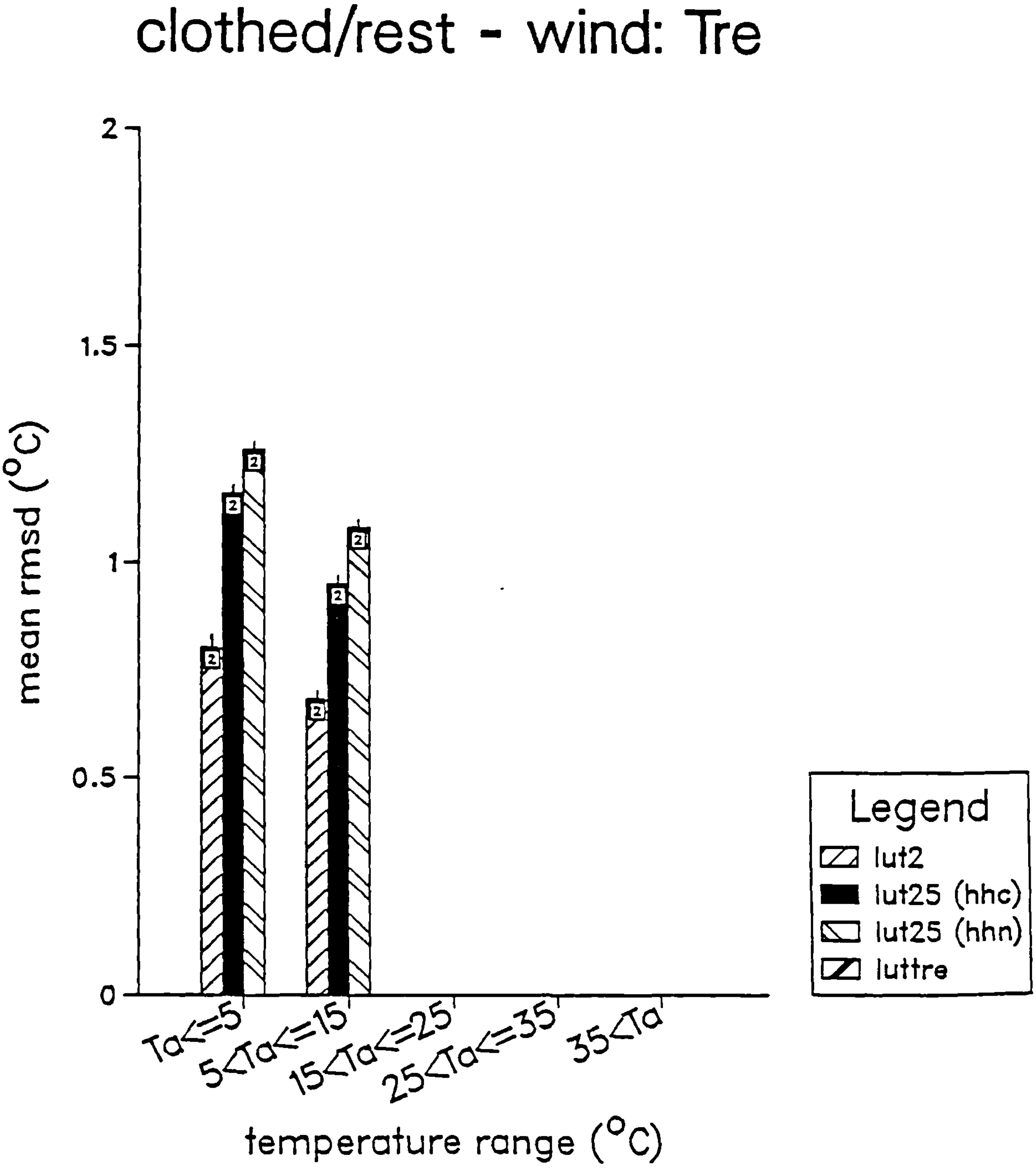


Figure 6.84. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the clothed, rest and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

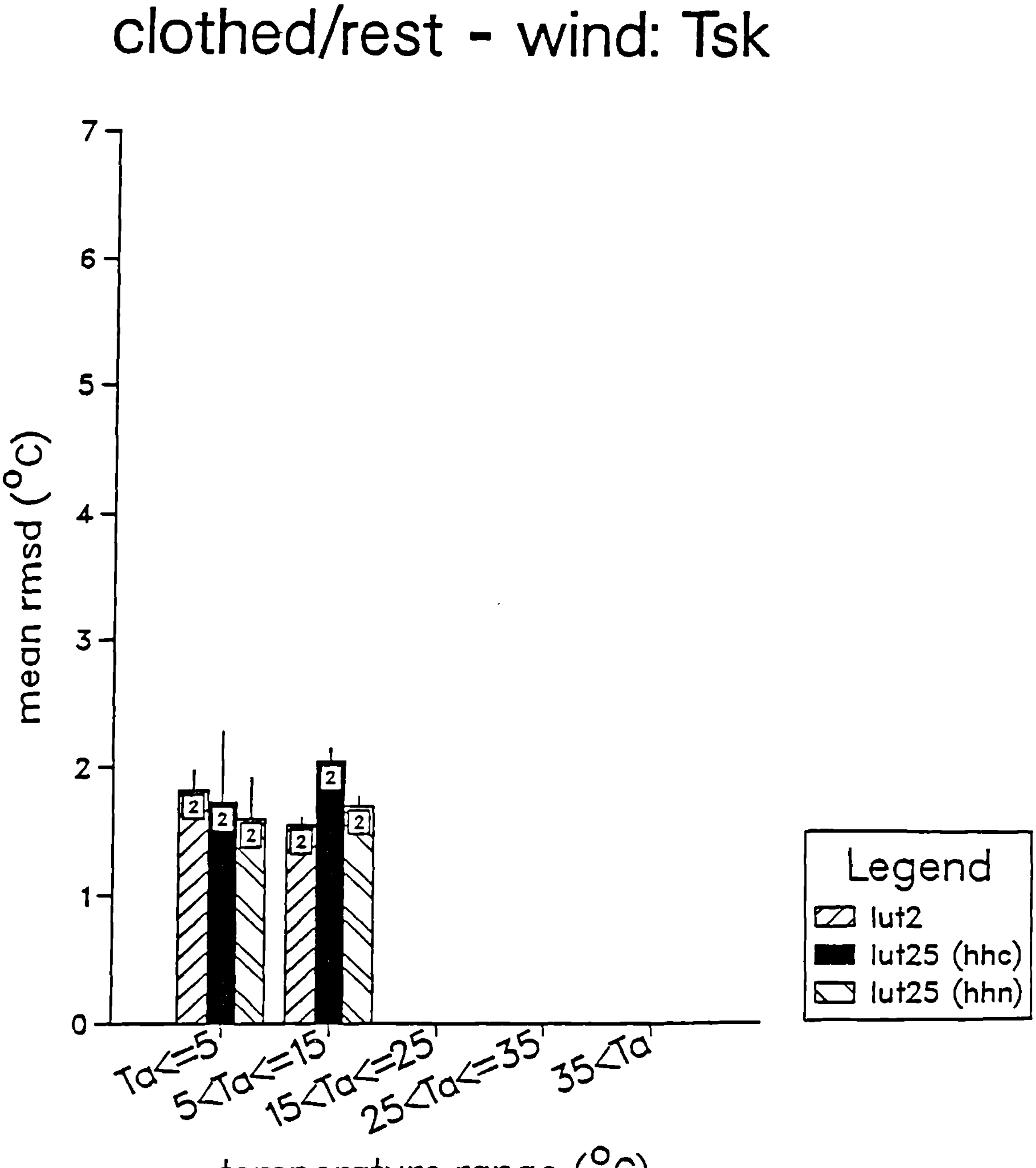


Figure 6.85. Mean rmsds for metabolic rate (M) (thick bars) for the clothed, rest and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

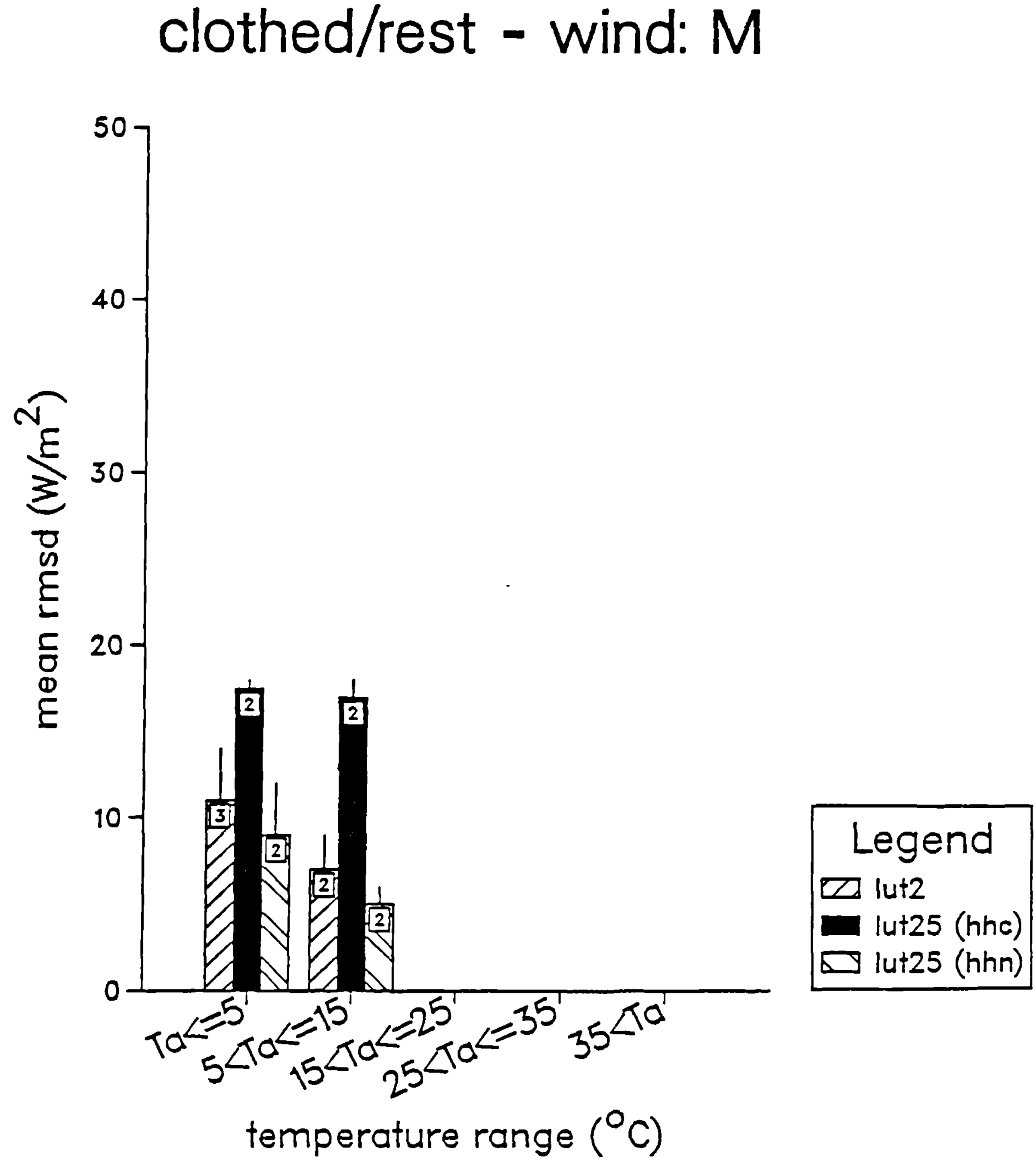


Figure 6.86. Mean rmsds for rectal temperature (Tre) (thick bars) for the clothed, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

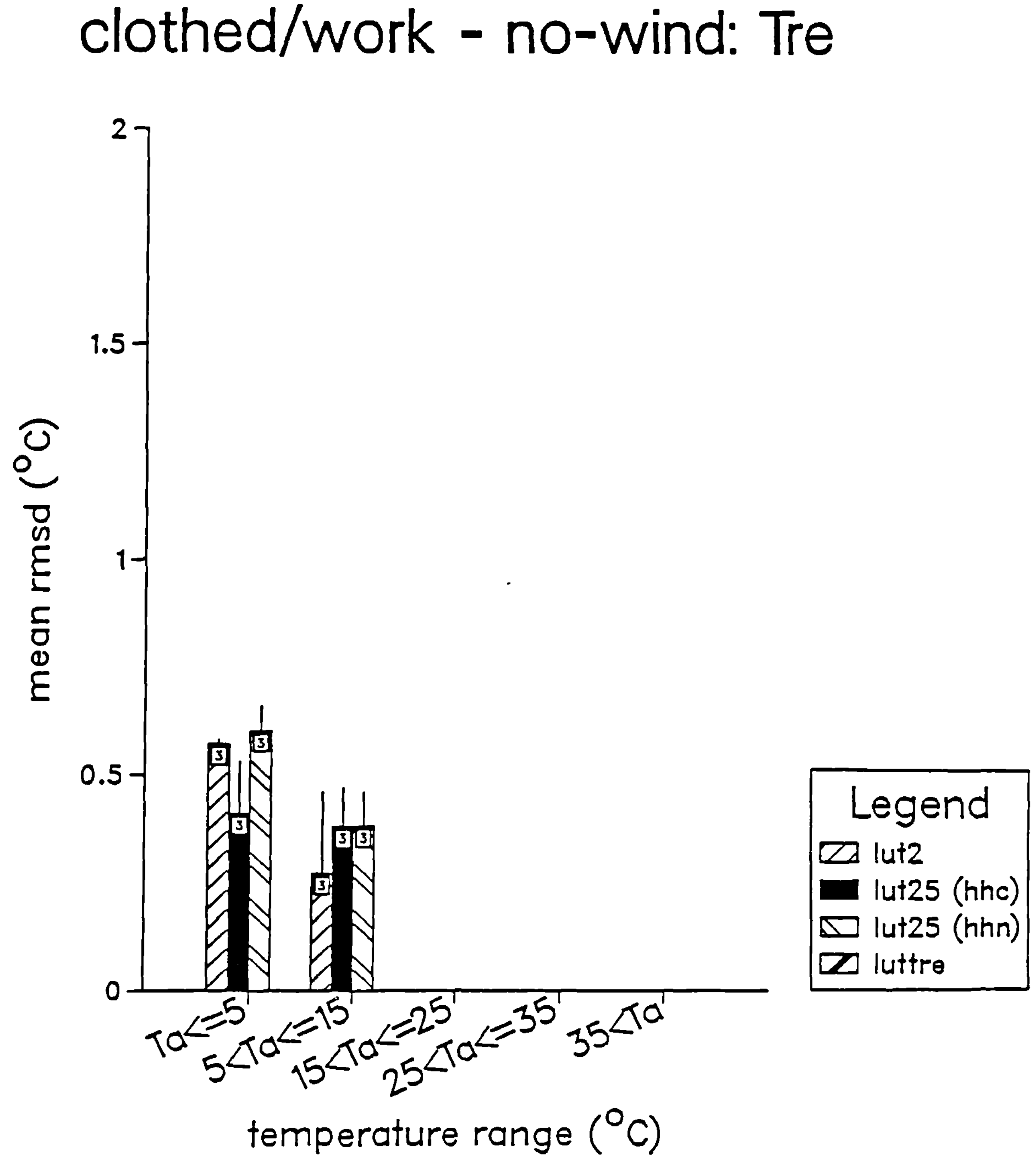


Figure 6.87. Mean rmsds for oesophageal temperature (Toe) (thick bars) for the clothed, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

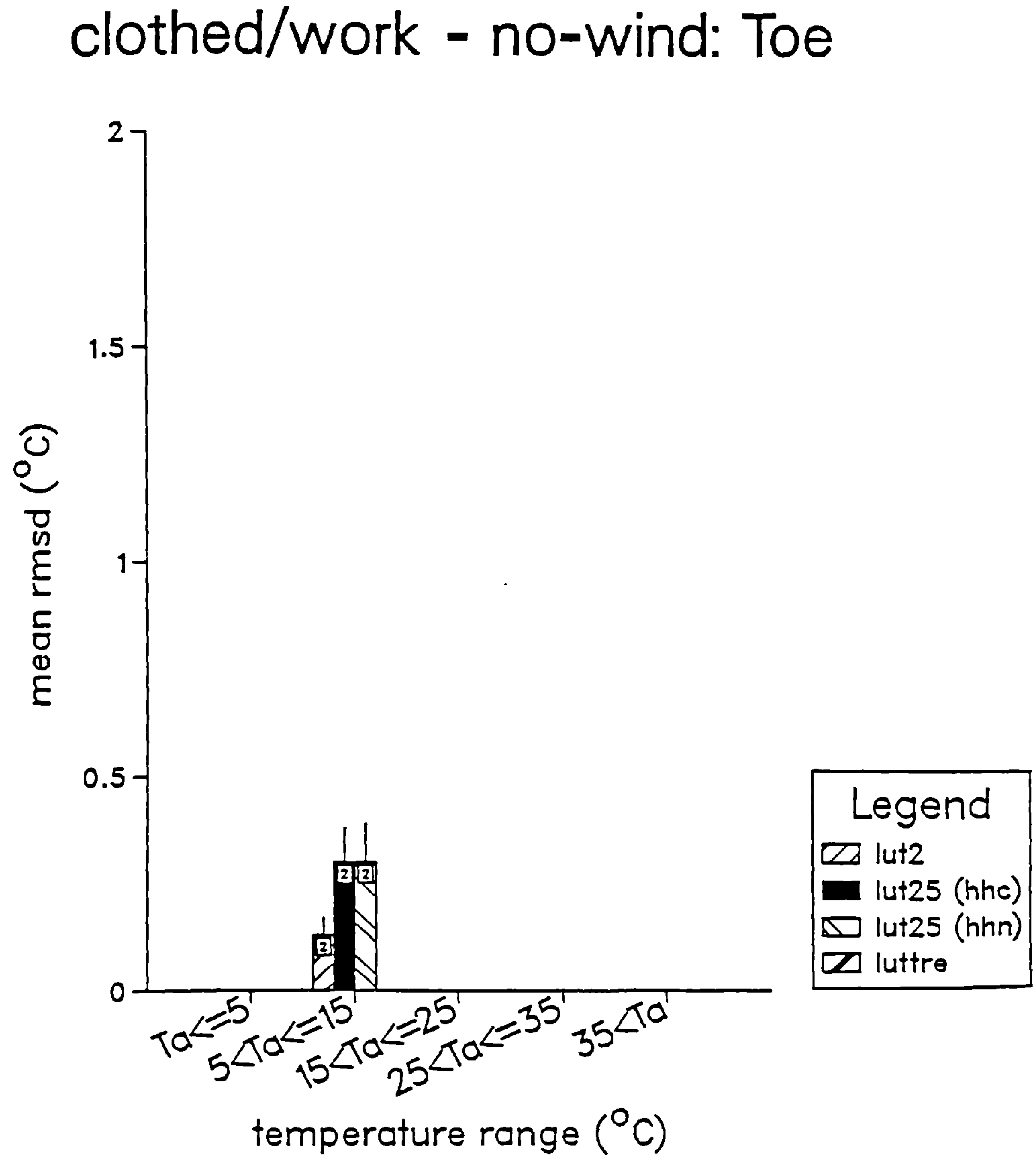


Figure 6.88. Mean rmsds for auditory canal temperature (Tac) (thick bars) for the clothed, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

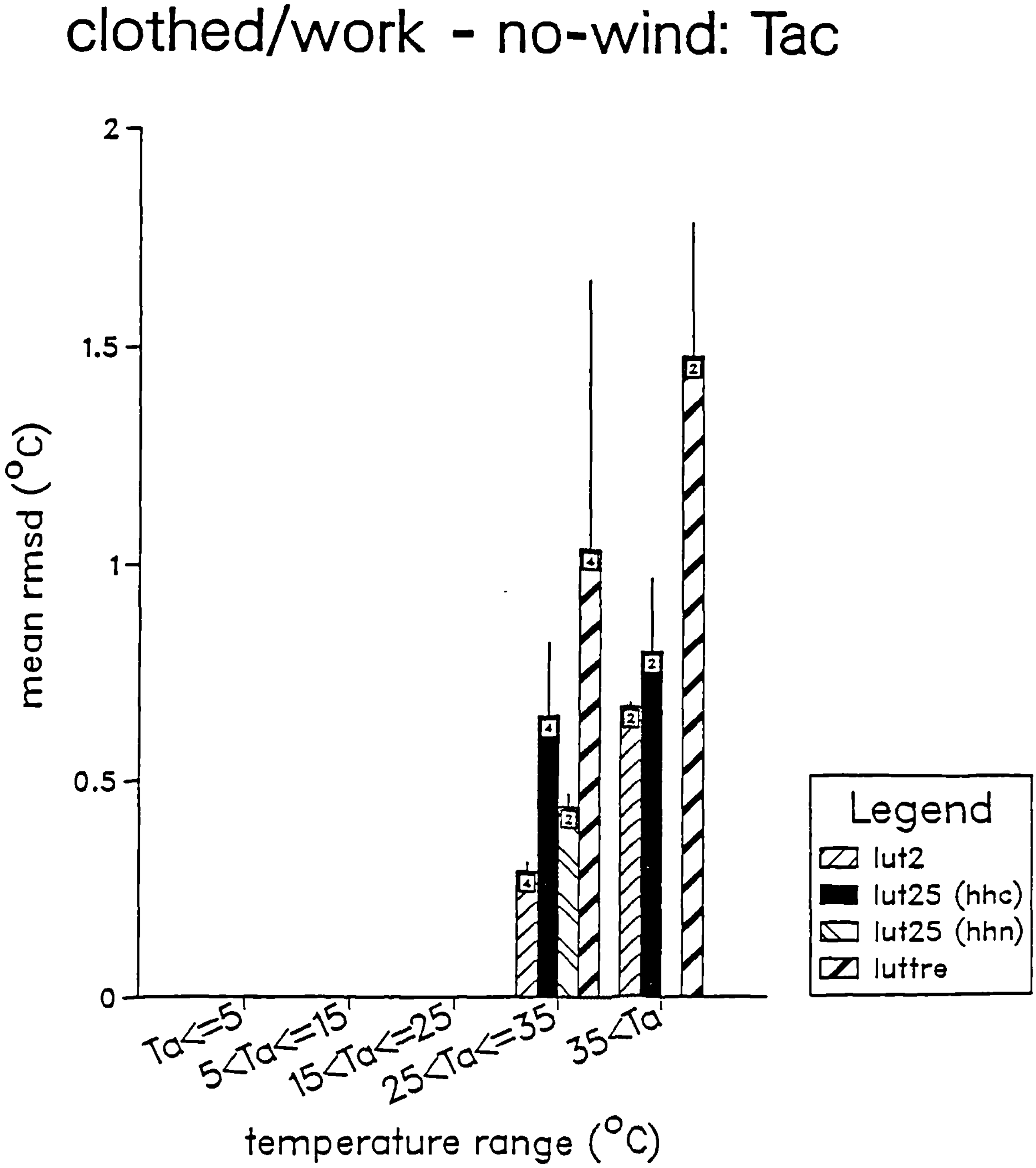


Figure 6.89. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the clothed, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

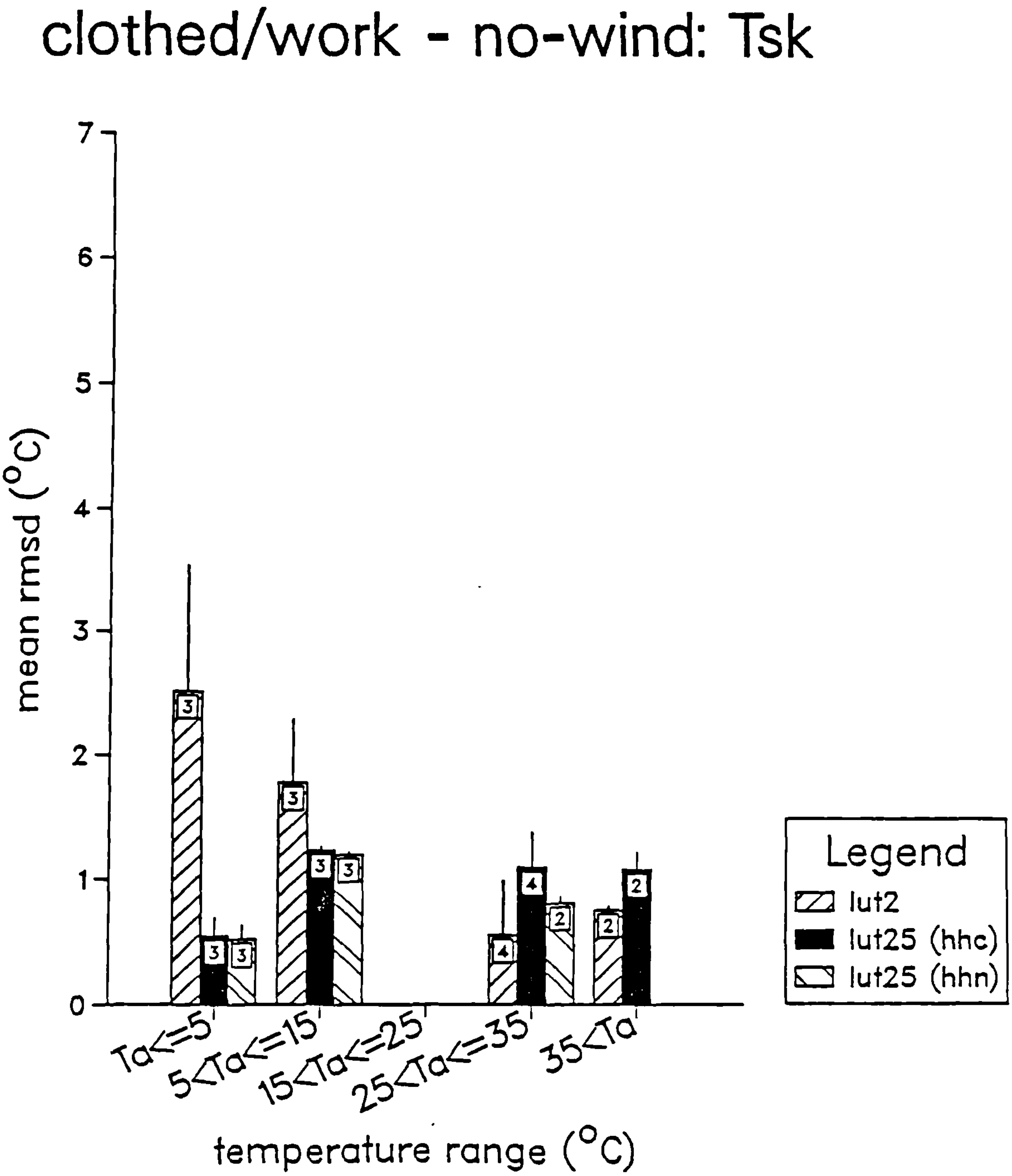


Figure 6.90. Mean rmsds for rectal temperature (Tre) (thick bars) for the clothed, work and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

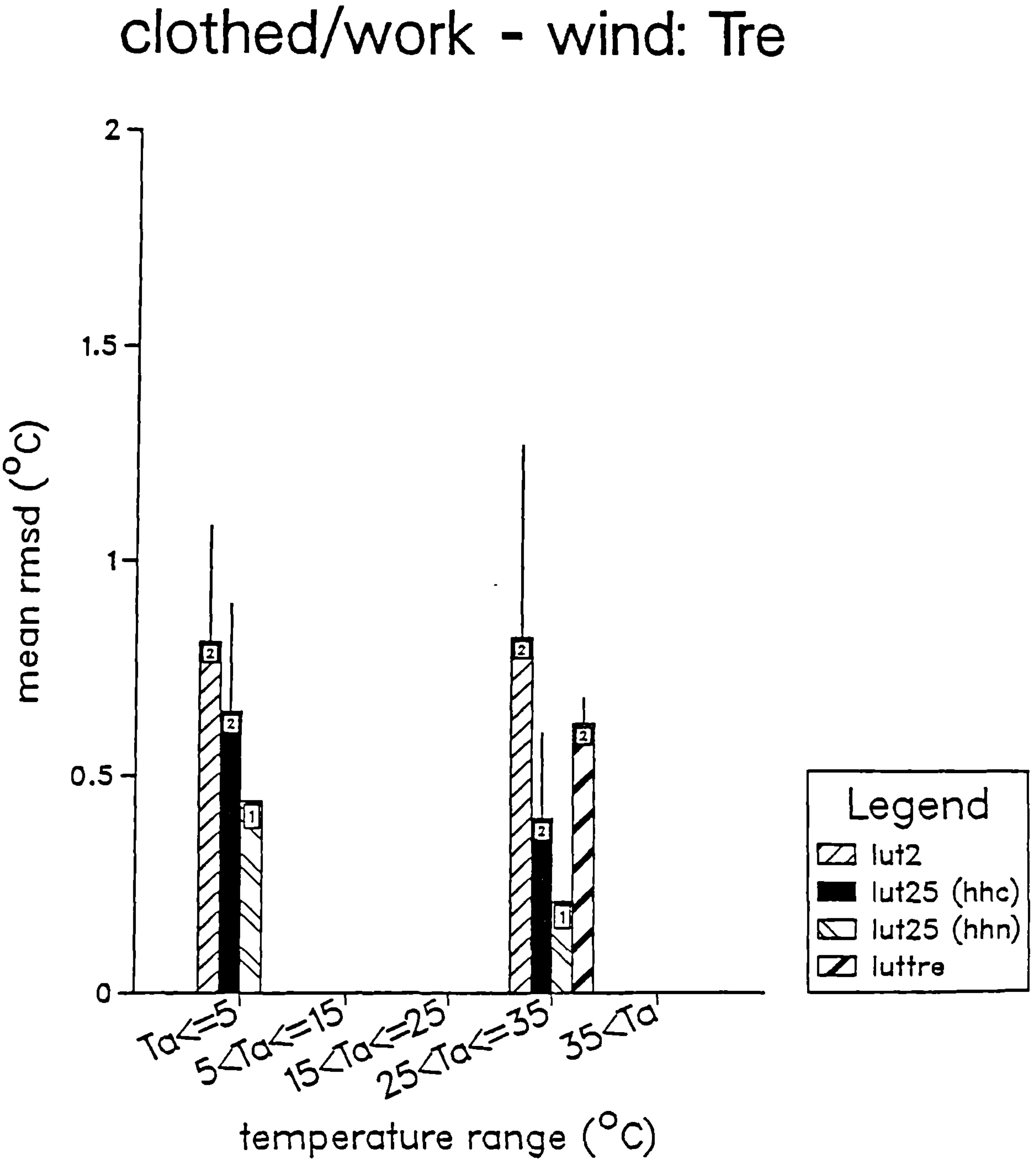


Figure 6.91. Mean rmsds for gastrointestinal temperature (Tga) (thick bars) for the clothed, work and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

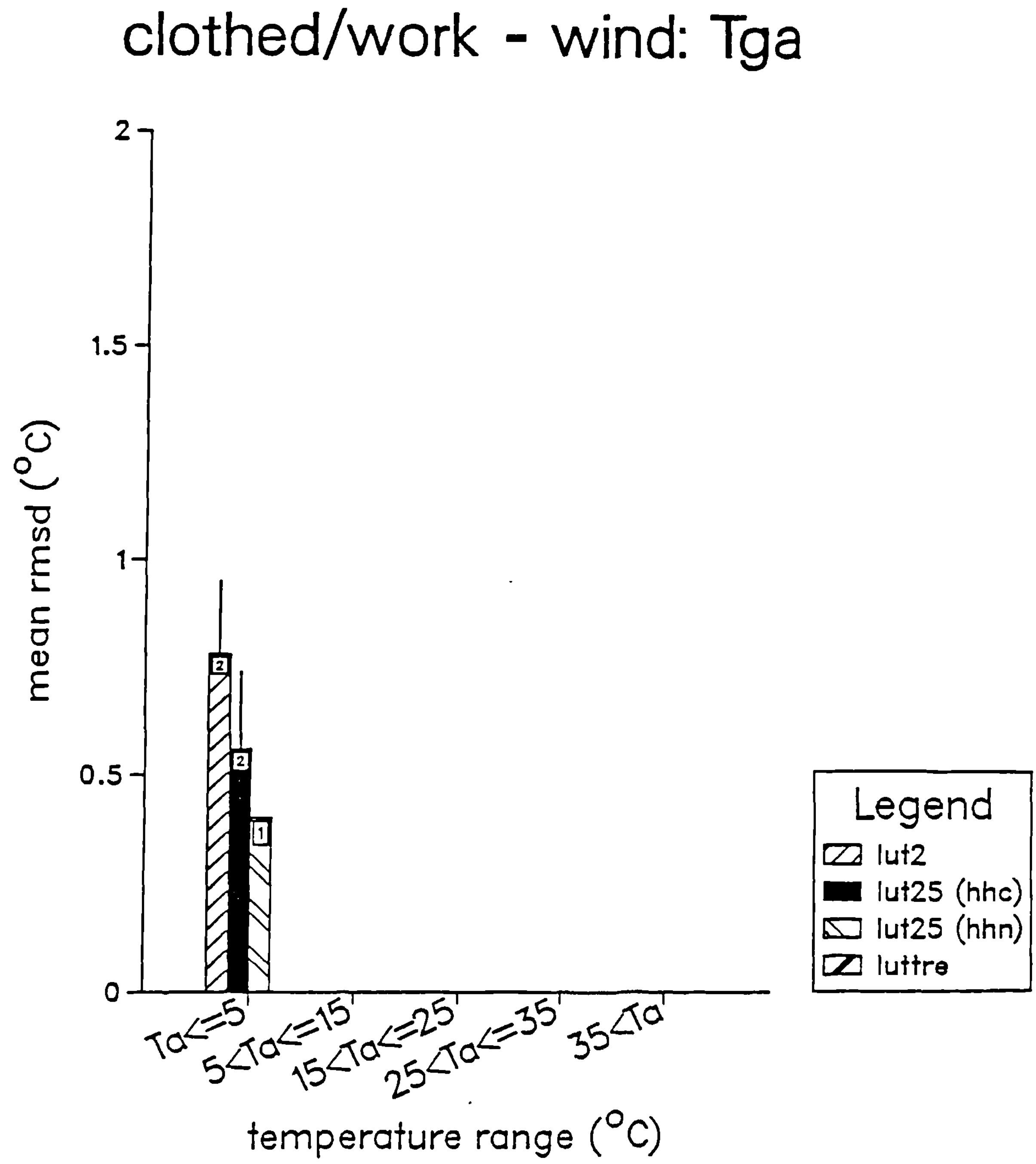


Figure 6.92. Mean rmsds for mean skin temperature (Tsk) (thick bars) for the clothed, work and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

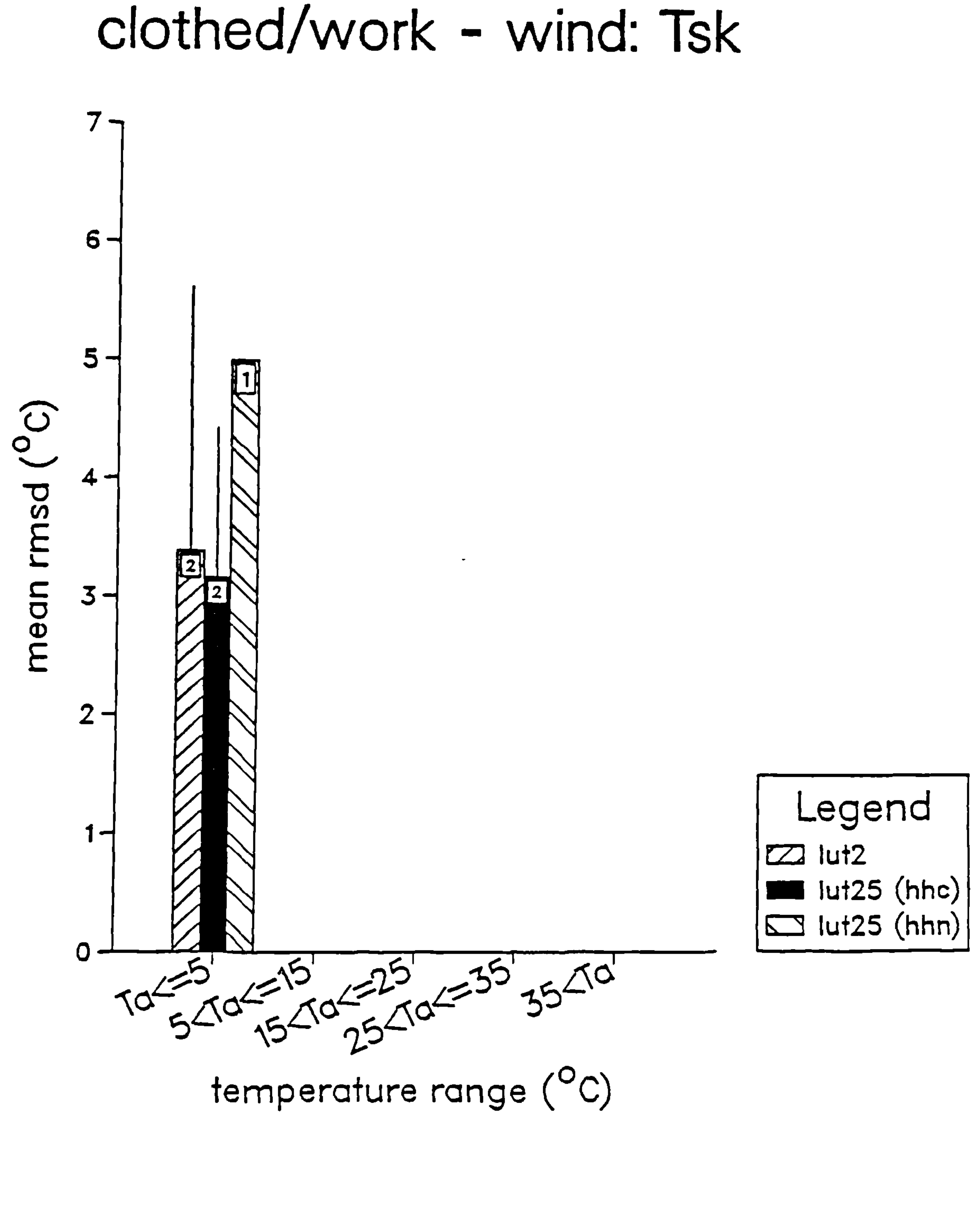


Figure 6.93. Rmsds for rectal temperature (Tre) for acclimatized subjects in the nude, work and wind environment category (numbers at the top of thick bars are the number of rmsds available in environment category).

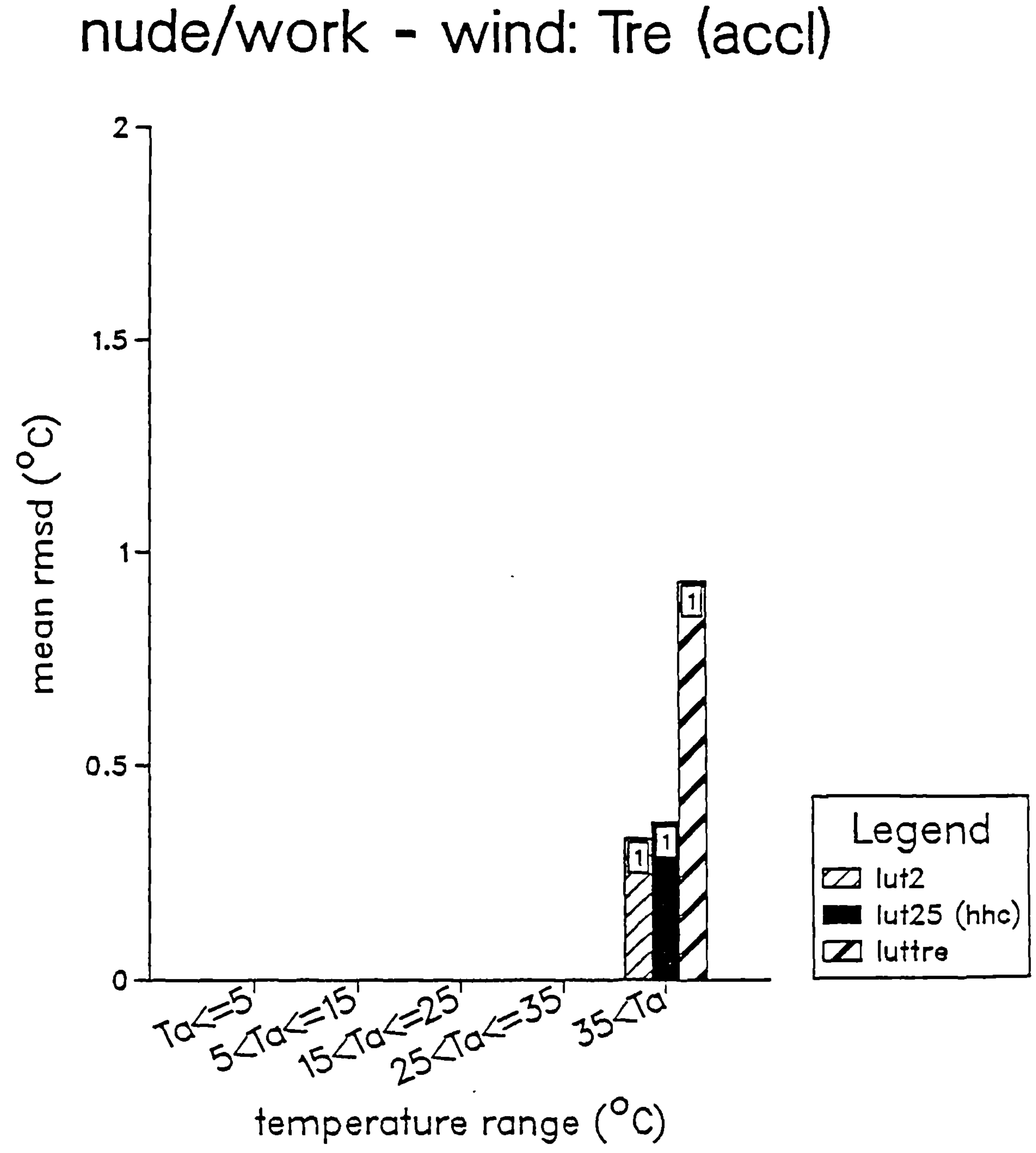


Figure 6.94. Rmsds for mean skin temperature (Tsk) for acclimatized subjects in the nude, work and wind environment category (numbers at the top of thick bars are the number of rmsds available in environment category).

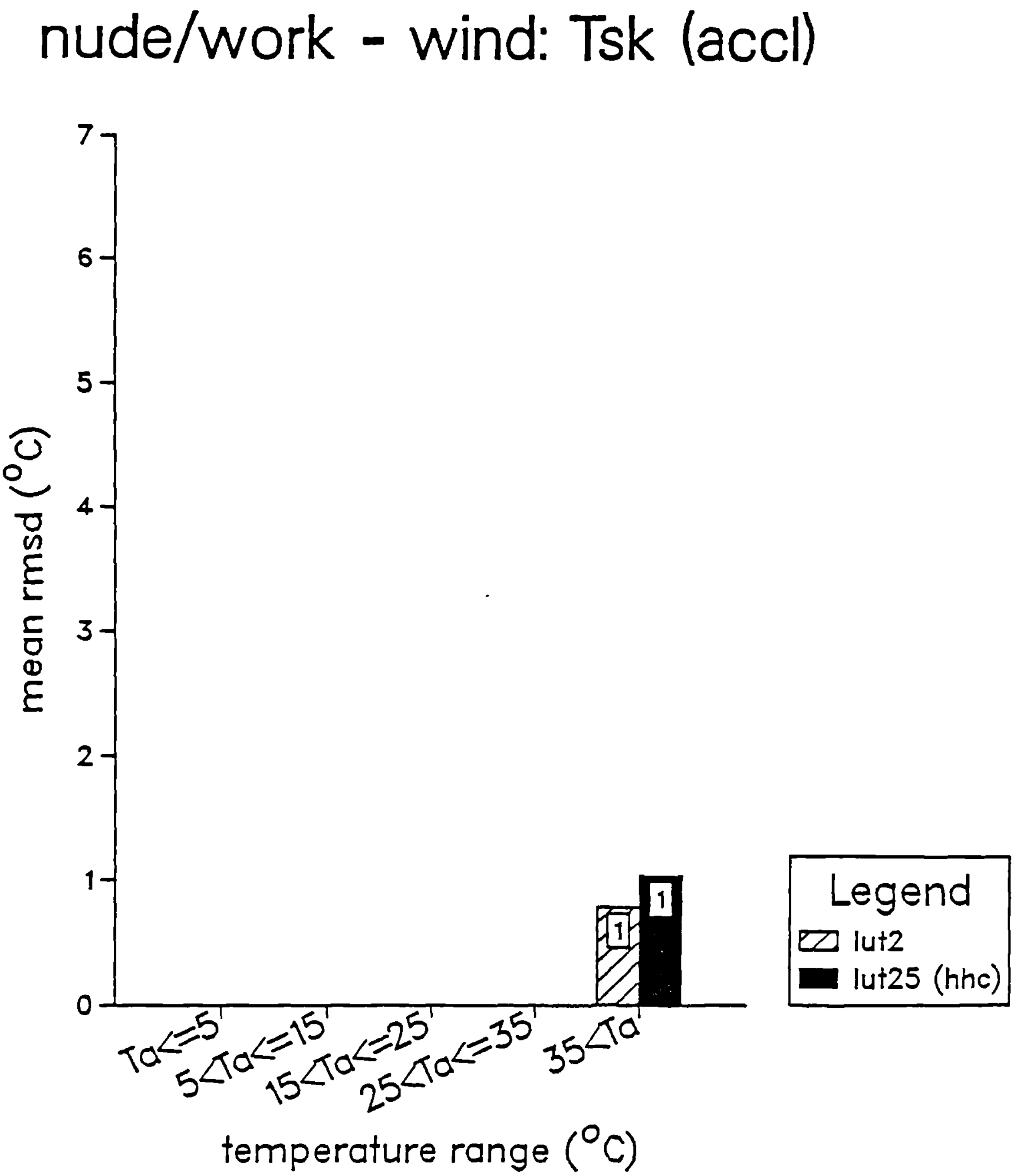


Figure 6.95. Mean rmsds for rectal temperature (Tre) (thick bars) for acclimatized subjects in the clothed, work and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

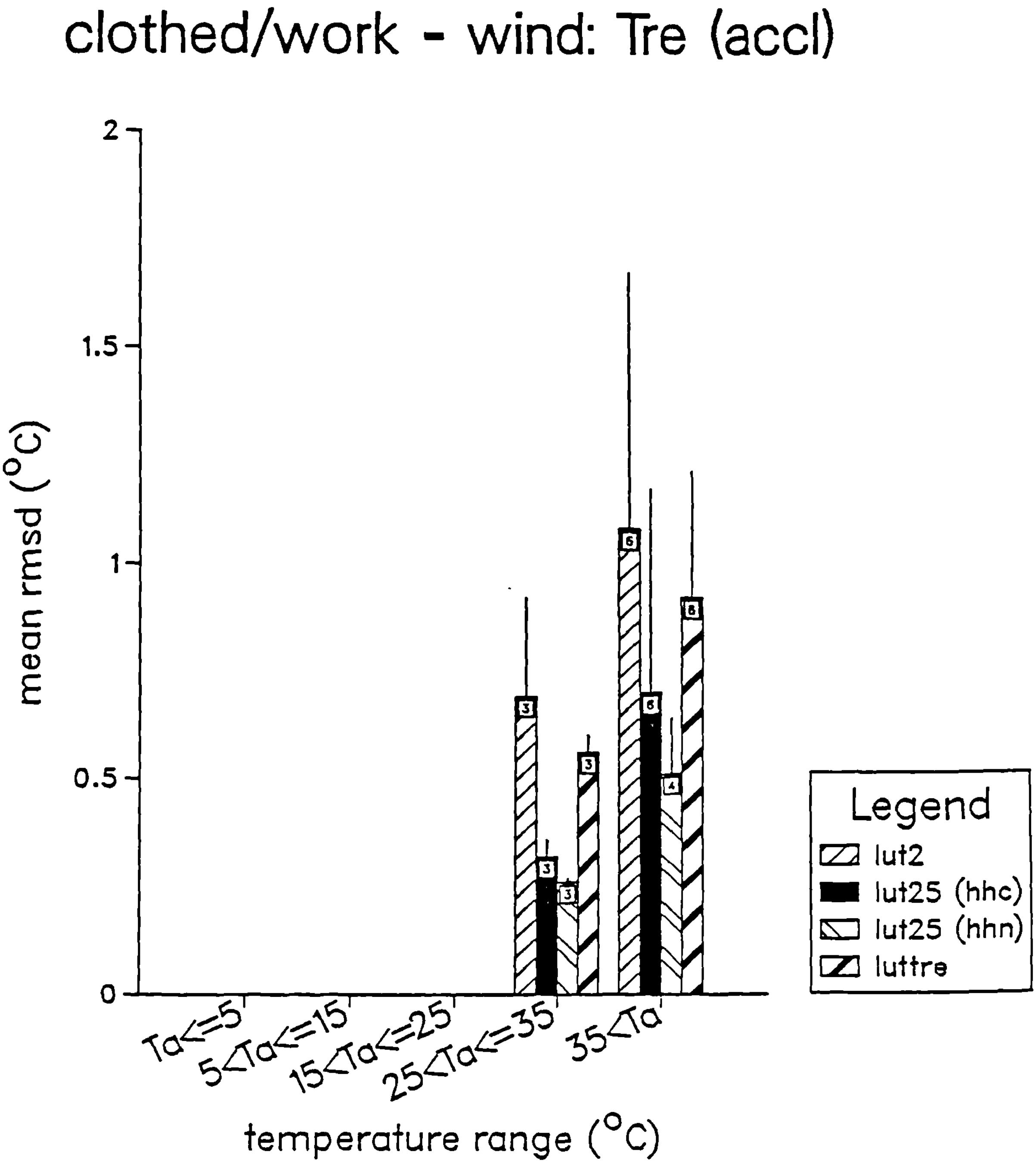


Figure 6.96. Mean rmsds for mean skin temperature (Tsk) (thick bars) for acclimatized subjects in the clothed, work and wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

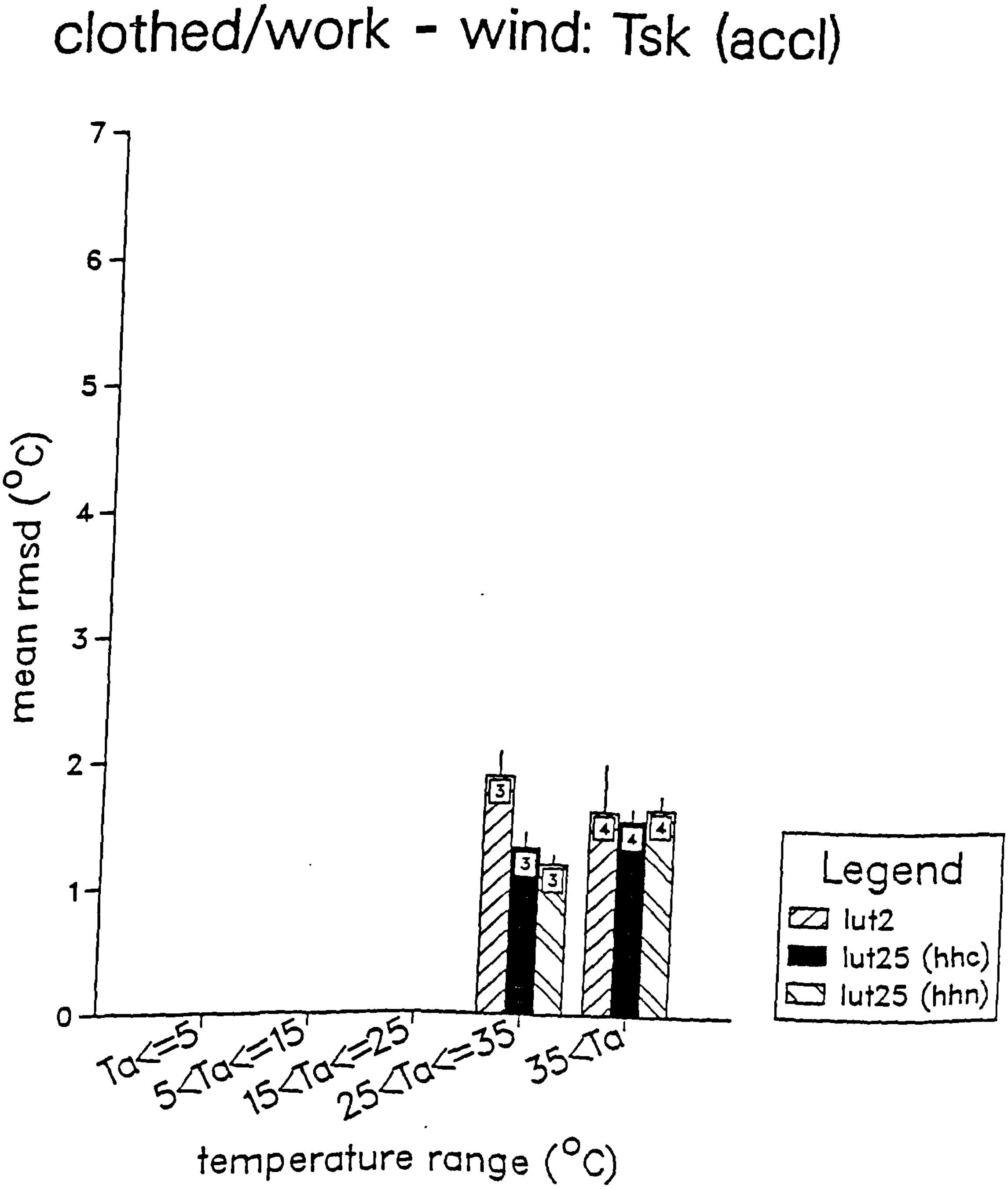


Figure 6.97. Mean rmsds for rectal temperature (Tre) (thick bars) for female subjects in the clothed, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

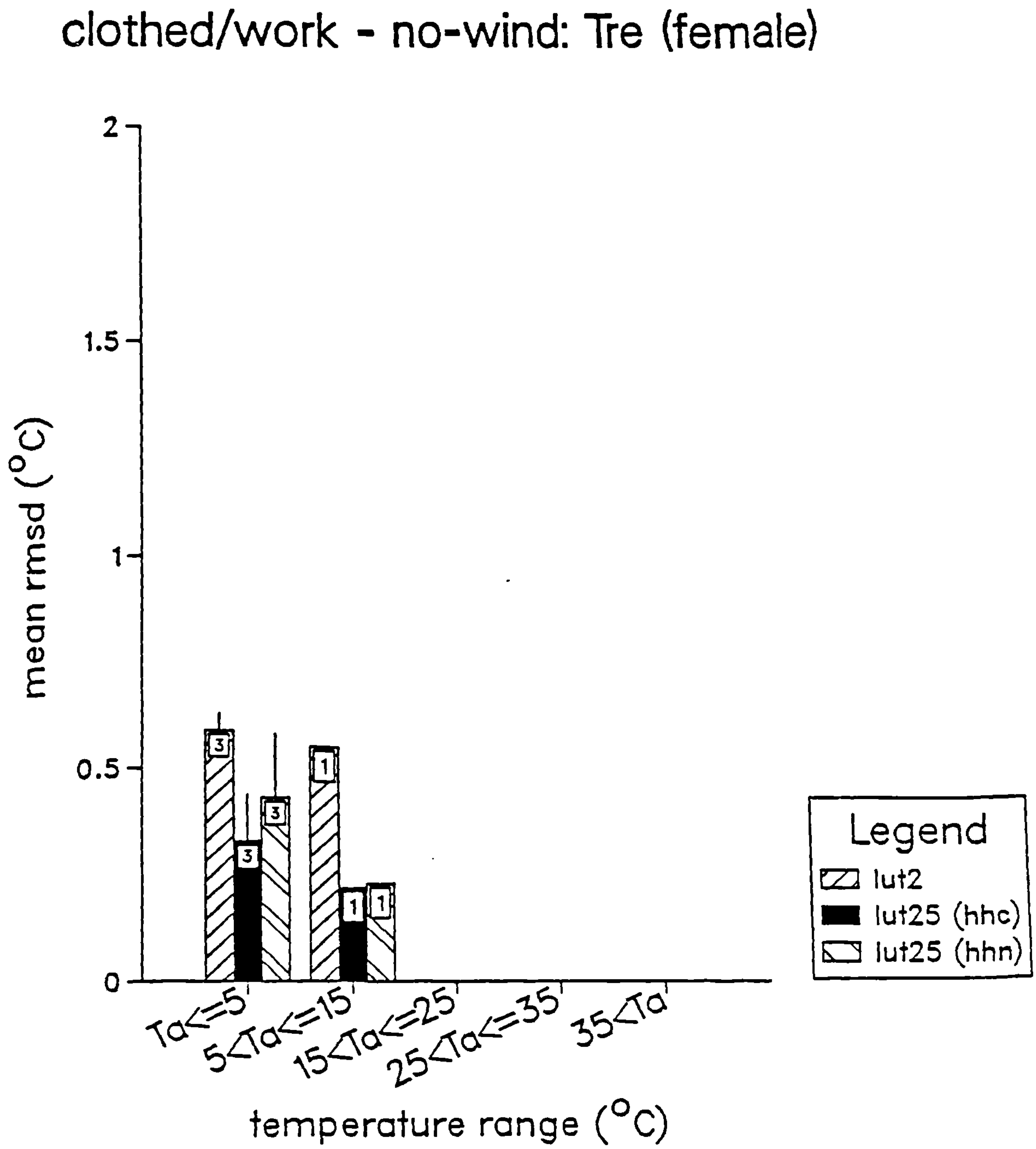


Figure 6.98. Mean rmsds for mean skin temperature (Tsk) (thick bars) for female subjects in the clothed, work and no-wind environment category (thin bars represent standard deviation, numbers at the top of thick bars are the number of rmsd values used to calculate the mean and standard deviation).

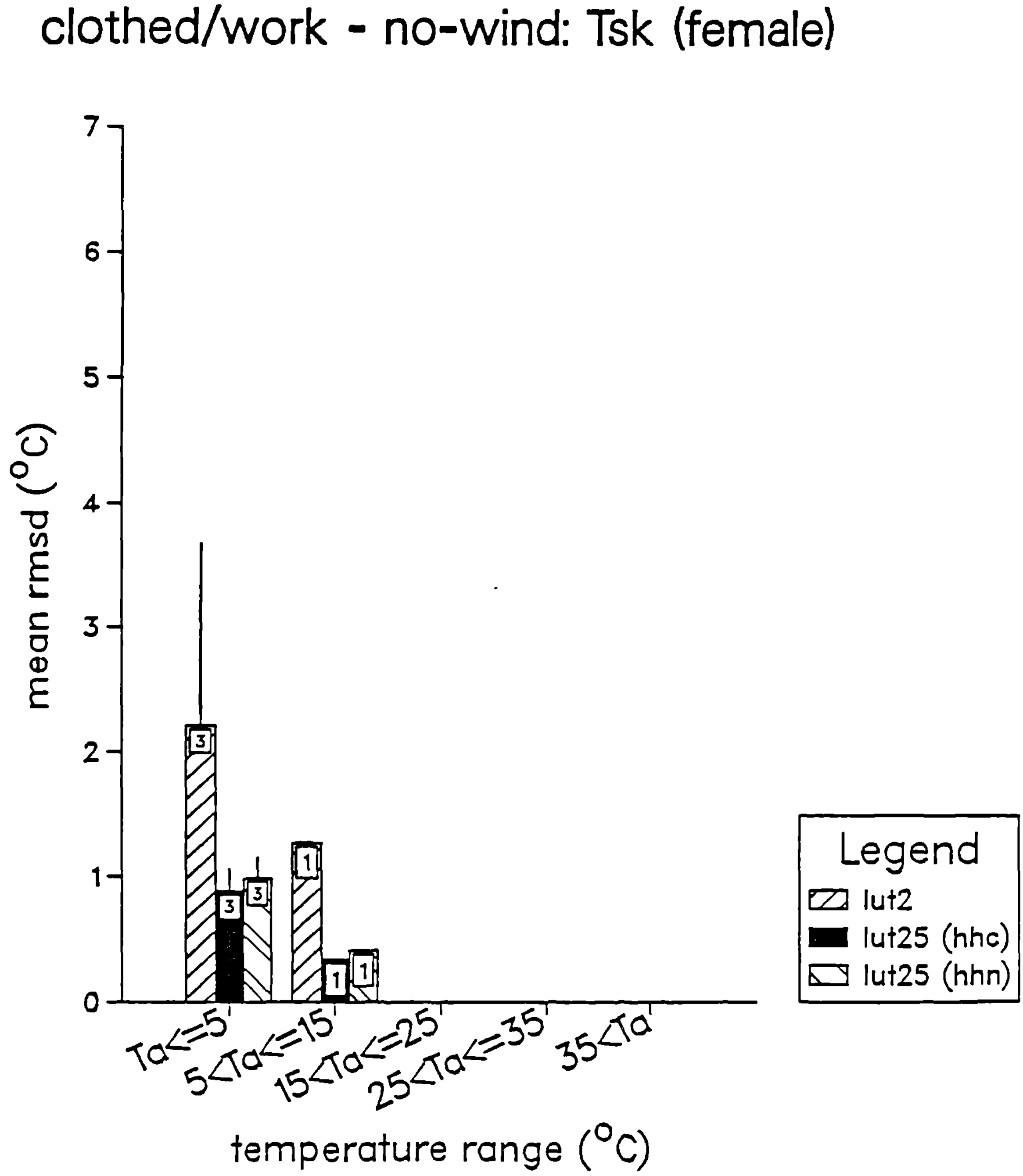


Figure 6.99. Rmsds for rectal temperature (Tre) for acclimatized female subjects in the clothed, work and wind environment category (numbers at the top of thick bars are the number of rmsds available in environment category).

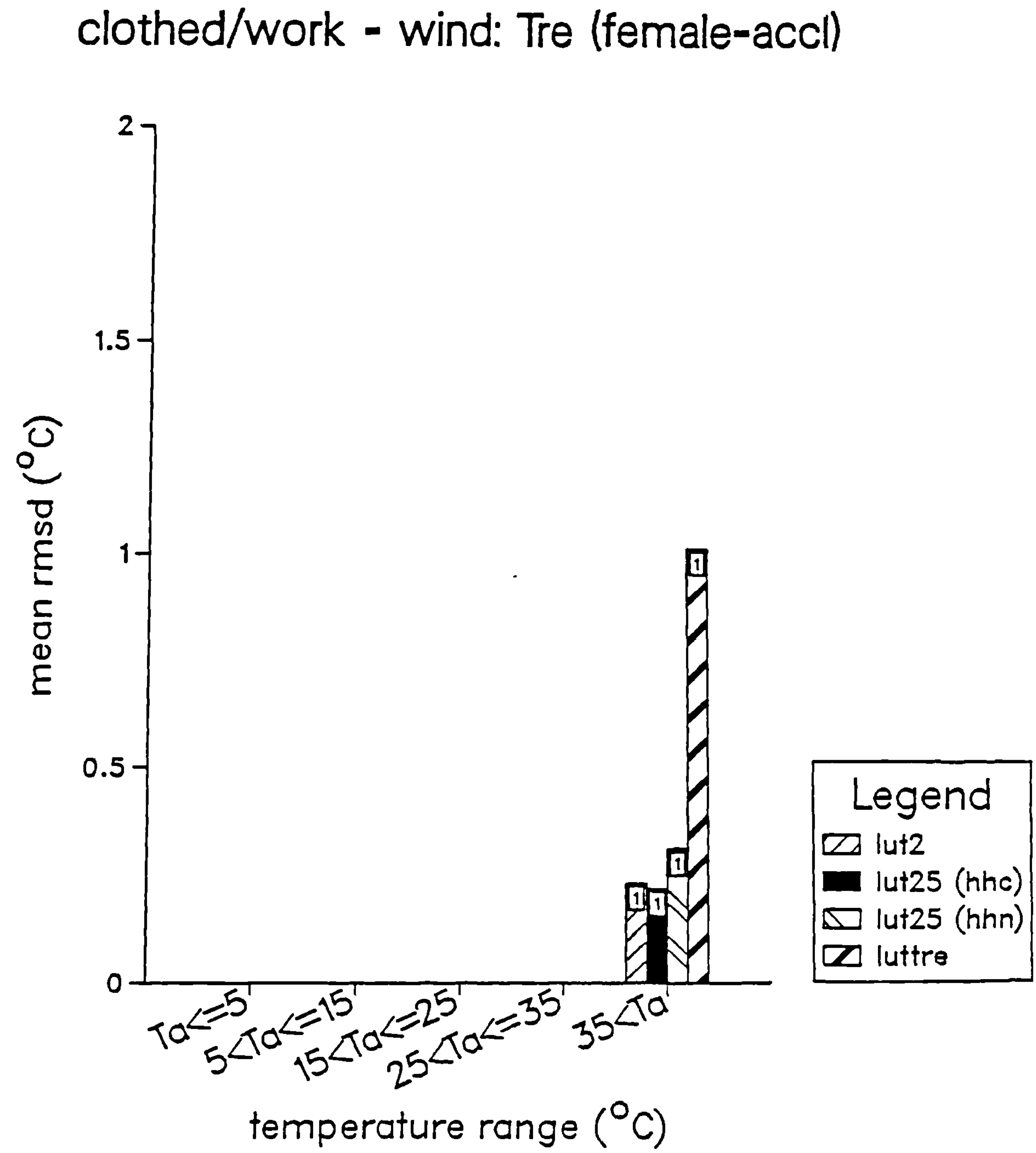
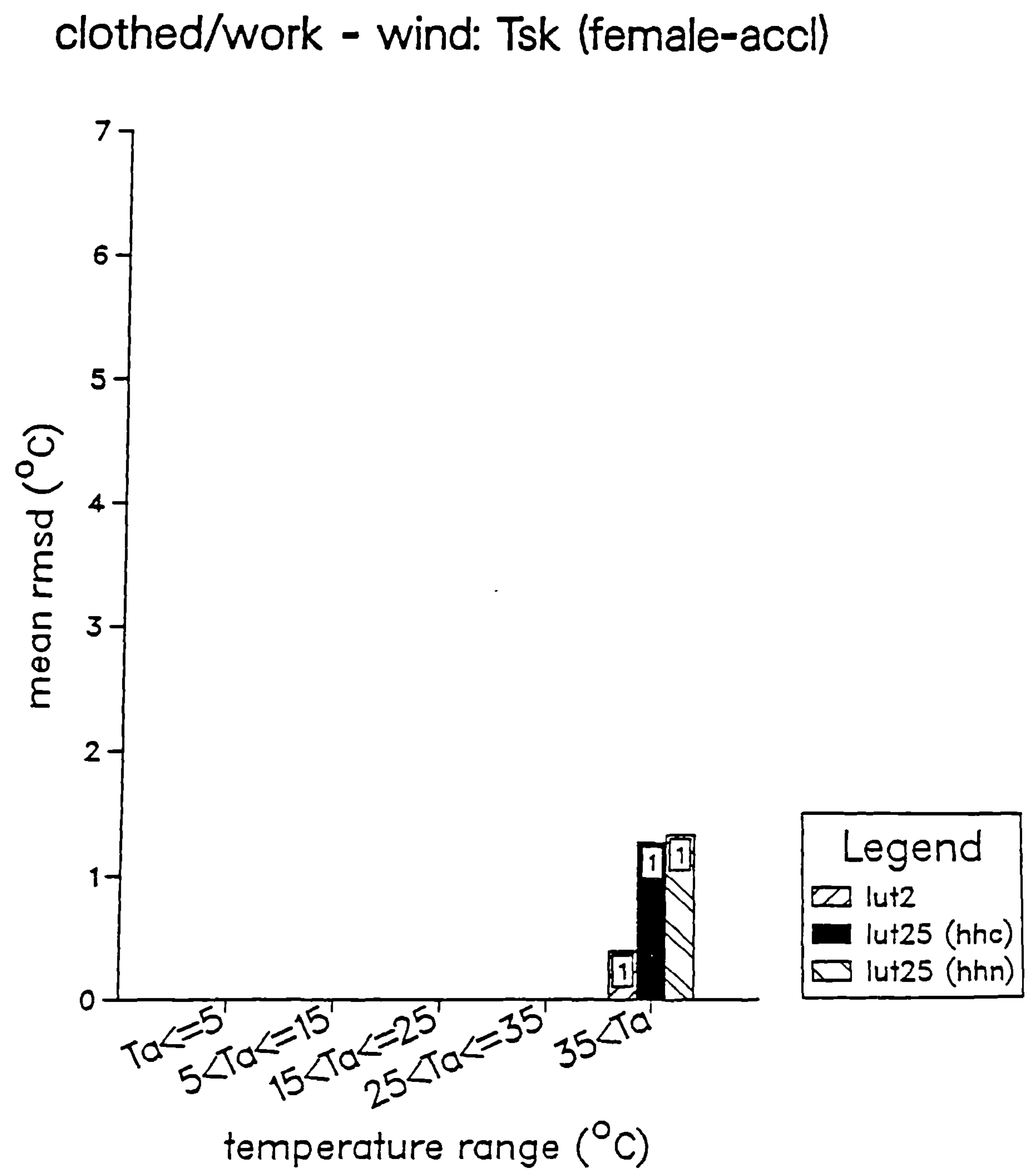


Figure 6.100. Rmsds for mean skin temperature (Tsk) for acclimatized female subjects in the clothed, work and wind environment category (numbers at the top of thick bars are the number of rmsds available in environment category).



	Ta<=5 °C		5<Ta<=15 °C		15<Ta<=25 °C		25<Ta<=35 °C		35<Ta °C	
	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
nude/rest/ no-wind	NONE	lut2	lut2	lut25 lut2	luttre lut2 lut25	lut2 lut25	lut25 lut2 luttre	lut2[1] lut25[1]	lut25 lut2[1] luttre[1]	lut25 lut2
nude/rest/ wind	—	—	lut2	lut25	luttre lut2	lut25	—	—	—	—
nude/work/ no-wind	—	—	—	—	lut25 luttre	lut2 lut25	lut25 luttre lut2	lut25[1] lut2[1]	lut25 lut2	lut2 lut25
nude/work/ wind	—	—	—	—	—	—	lut2 lut25 luttre	—	lut25	lut2[1] lut25[1]
clothed/rest/ no-wind	NONE	lut2[1] lut25[1]	lut2	lut2 lut25	—	—	—	—	—	—
clothed/rest/ wind	NONE	NONE	NONE	lut2	—	—	—	—	—	—
clothed/work/ no-wind	lut25	lut25	lut2 lut25	lut25	—	—	lut2[2]	lut2 lut25	NONE[2]	lut2 lut25
clothed/work/ wind	NONE	NONE	—	—	—	—	lut25	—	—	—

Table 6.5. The most accurate models for each environment category in descending order, where the mean rmsds for the models' predictions were within the maximum average standard deviations found for the observed data (ie. 0.5 °C for Tcr and 1.6 °C for Tsk). Dashes indicate that no experimental data were available for that environment category, "NONE" indicates that none of the models' predictions were within the maximum average standard deviations observed.
[1]Mean rmsds were equal in this environment category. [2]Data were available for Tac only.

	Ta<=5 °C		5<Ta<=15 °C		15<Ta<=25 °C		25<Ta<=35 °C		35<Ta °C	
	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk	Tcr	Tsk
nude/rest/ no-wind	NONE	NONE	NONE	NONE	NONE	lut2	lut25 lut2	lut2[1] lut25[1]	lut25	lut25 lut2
nude/rest/ wind	—	—	NONE	NONE	luttre	lut25	—	—	—	—
nude/work/ no-wind	—	—	—	—	lut25	NONE	lut25	lut25[1] lut2[1]	lut25	lut2
nude/work/ wind	—	—	—	—	—	—	lut2 lut25	—	NONE	lut2[1] lut25[1]
clothed/rest/ no-wind	NONE	NONE	NONE	lut2 lut25	—	—	—	—	—	—
clothed/rest/ wind	NONE	NONE	NONE	NONE	—	—	—	—	—	—
clothed/work/ no-wind	NONE	lut25	lut2	NONE	—	—	lut2[2]	lut2	NONE[2]	lut2
clothed/work/ wind	NONE	NONE	—	—	—	—	NONE	—	—	—

Table 6.6. The most accurate models for each environment category in descending order, where the mean rmsds for the models' predictions were within 0.3 °C for Tcr and 0.8 °C for Tsk. Dashes indicate that no experimental data were available for that environment category, "NONE" indicates that none of the models' predictions were within 0.3 °C for Tcr and 0.8 °C for Tsk.
[1]Mean rmsds were equal in this environment category. [2]Data were available for Tac only.

shows the models that had average rmsds within approximately half of the maximum average standard deviation of the observed data (0.3 °C for Tcr and 0.8 °C for Tsk).

6.3. Discussion of Results

It can be seen from table 6.5 that for most of the environment categories for which experimental data were available, at least one of the models had an average rmsd within the maximum standard deviation obtained for the observed data. The categories for which none of the models had average rmsds within the maximum average standard deviation of the observed data were almost exclusively confined to cold conditions. The models that feature most prominently in table 6.5 are the lut2 and lut25 models. The luttre model is present for several categories within the 15<Ta<=35 temperature range, although it was primarily intended as a heat stress model.

Table 6.6 demonstrates that the models' prediction were most accurate in the neutral and hotter conditions, and less accurate in the cold. For the neutral and hotter conditions it can be seen that usually at least one of the models was able to predict the observed mean Tcr and Tsk responses very accurately.

6.3.1. Nude, Rest and No-Wind Conditions

Evaluation for nude, rest and no-wind conditions enables the basic operation of a model to be tested. The lut2 and lut25 models' Tcr predictions in the cold were poor, with the models considerably overestimating the decreases that occurred in the observed data, see figure 6.2 for example. Despite this, the models' predictions of Tsk in the cold were often very close to the observed data, figure 6.3. The models' predicted M responses were also reasonable, figure 6.4.

The accuracy of the lut2 and lut25 models' predictions improved as the air temperature increased towards neutrality, figure 6.6. The luttre model often provided the most accurate predictions of Tcr in the cool environments in terms of absolute temperature level. However, the luttre model exhibited a different response pattern, showing a slow but steady increase over the durations of the exposures. The lut2 and lut25 models' predictions for air temperatures in the range 25<Ta<=35 were very accurate. The luttre model predicted an inaccurate steadily increasing temperature pattern.

The lut2 and lut25 models' predictions for warm and hot conditions were reasonable, figures 6.11 and 6.13. The luttre model overestimated the increases in Tcr observed. However, for very hot conditions, with Ta>45 °C, the luttre model provided the most accurate Tcr predictions, figure 6.12. The lutiso model's predicted allowable exposure times were in line with the increases in Tcr observed.

6.3.2. The Effects of Wind

External air movement increases convective heat transfer. Although any differences were small, the models' predictions were perhaps slightly less accurate for wind conditions. This suggests that for the most part, the models' calculations of the convective heat exchanges for resting subjects in the wind are reasonable.

6.3.3. The Effects of Exercise

Exercise requires the dissipation of internally generated heat. The lut25 model's predictions were generally most accurate for exercising subjects, apart from overexaggeration of an initial dip in Tcr at the onset of exercise, figure 6.18.

The lut2 model underestimated the rise in Tcr that accompanied exercise, for no-wind conditions. Comparison of the lut2 model's predicted convective and evaporative heat exchanges with observed data, for exercise and no-wind conditions, show that the model was not predicting these accurately, figures 6.22 and 6.23. This would affect the models Tcr predictions.

The luttre model usually overestimated the increase in Tcr observed, figure 6.18. Exceptions were for environments with a very high work load, resulting in a large increase in Tcr, figure 6.19.

The lutiso model would not have protected subjects against its own criterion of safety, for several of the exercise exposures, figure 6.24.

6.3.4. The Effects of Clothing

Clothing reduces heat transfer between the body and the environment. At a given temperature in the cold, the models predicted the responses of clothed subjects more accurately than those of nude. At a given temperature in the heat, the models' predictions were less accurate for clothed subjects.

6.3.5. Complex Environmental Conditions

The results suggest that as an environment becomes more complex, environments with increasing levels of wind, clothing and exercise for example, the accuracy of the models' predictions decreases. When the environmental conditions fluctuate within an experimental exposure, with short work and rest cycles for example, the models' predictions fluctuate considerably more than the observed data.

6.3.6. The Effects of Acclimatization

Acclimatized subjects have improved sweating efficiency, increasing their capacity for evaporative cooling. The accuracy of the models' predictions for acclimatized subjects was similar to that for unacclimatized subjects, even though the lut2 and lut25 models have no facility at present to account for the effects of acclimatization on their thermoregulatory responses.

6.3.7. The Effects of Gender

The differences in stature between men and women affect their thermal responses. However, there was no noticeable difference in accuracy for the models' predictions for male and female subjects.

6.4. Conclusions

From this extensive evaluation it may be concluded that:

1) Usually at least one of the models was able to accurately predict the human experimental responses. An exception was for Tcr in cold environmental conditions.

2) The lut25 model was probably the most consistently accurate of the models.

3) The lut2 model was often accurate, but on occasions it markedly underestimated the rise in Tcr of exercising subjects.

4) The luttre model usually overestimated the increase of Tcr, although for some hot or heavy exercise conditions its predictions were accurate.

5) The lutiso model's allowable exposure times were often reasonable, but the model would not have protected some exercising subjects against its own criteria of safety.

These findings and points relating to the interpretation of the models' predictions are discussed in chapter 7.

CHAPTER 7

7. DISCUSSION

The extensive evaluation reported in chapter 6 has shown that usually at least one of the models is capable of accurately predicting important human responses to hot and cold environments. Issues relating to the interpretation of the models' predictions and their practical use are discussed in this chapter.

7.1. Individual Differences

The four models examined by this evaluation predict the responses of a "standard" sized person. For the lut2 and luttre model this is a person who weighs 70 kg and is 1.7 m tall. The lut25 model's standard man weighs 74.4 kg and is 1.72 m tall. The limiting values for maximum sweat rate, maximum sweat loss and maximum heat storage used by the lutiso model were given by ISO (1987) and are those applicable to subjects ".....physically suited to the activity under consideration".

Exposing a group of subjects to an environment can result in a wide range of individual responses, particularly for exposures to cold environments. This evaluation has examined the mean responses of groups of subjects, but where available, information for plus and minus one standard deviation has also been examined. It can be seen from the Tre response given in figure 6.28 that at times during the exposure the standard deviation of the subjects' responses was greater than 0.5 °C. Most of the experimental data available to this study were collected from fit, male subjects, and therefore a comparatively homogeneous group.

The variation in the general population would be expected to be much greater.

Research has shown that men and women exhibit significantly different responses for exposures to both heat and cold (Avellini et al., 1980; Cunningham et al., 1978; Grucza et al., 1985; Mannino and Kaufman, 1986; Shapiro et al., 1981; Wagner and Horvath, 1985; and Walsh and Graham, 1986). Wyndham and Loots (1969) found differences in the responses of fat and thin men to cold conditions. Davies (1981) compared the responses of children and adults to a moderate environment and found quantitative differences between them. It has also been demonstrated that aging affects thermoregulatory responses (Collins et al., 1985; and Wagner and Horvath, 1985). It is well known that acclimatization can significantly affect thermal responses in the heat (Lind, 1964). Henane et al. (1977) has also suggested that endurance conditioning may have effects similar to heat acclimatization.

To be able to judge whether or not a model's predictions are accurate it is necessary to consider the variation of the observed responses. For the data available to this evaluation, the mean standard deviations for the Tcr responses ranged 0.1 - 0.5 °C, 0.3 - 1.6 °C for Tsk, and 4 - 20 W/m^2 for M. It should be remembered that because of the nature of the standard deviation, some of the observed values will have still fallen outside the range of the mean response plus or minus one standard deviation. However the mean response plus or minus one standard deviation is a useful gauge against which to judge the accuracy of the models' predictions. The maximum mean standard deviations observed for this evaluation may be compared with the ranges of ±0.5 °C for Tcr, ±2°C for Tsk, and ±10% for metabolic and sweat rates, within which Wissler (1988) proposed that a model can be said to yield "useful results".

If the variability of the observed responses is taken into account when assessing the accuracy of the models, then it can be seen from the results of this evaluation that their predictions are often reasonable. Table 6.5 shows that in most cases at least one of the models' mean rmsds were within the maximum mean standard deviations observed. The few exceptions were generally for environments where Ta<=5 °C.

The use of the models to predict an individual's temperature responses requires further research. The causes of the wide variations in response that occur between different people need to be identified, and consideration given to how these might be accounted for by the models.

7.2. Interpretation of Deep Body Temperature

The thermal geography of the human body does not have distinct regions at different temperatures, rather the temperature profile found is continuous, usually with the deeper body tissues, the brain, heart, liver etc., at higher temperatures and becoming cooler nearer to the skin and extremities. Moreover, the deep body tissues themselves may vary in temperature. Thus, although it is convenient to consider the body to have "core" and "shell" temperatures, the distinction is arbitrary.

It has long been known that the temperature of the deep body tissues may be taken as an index of disease or physiological stress. To estimate the temperature of the deep body tissues, usually a temperature is taken in a body orifice, such as the rectum, mouth, ear canal, or oesophagus. However, temperatures taken simultaneously at different sites may vary by over 1 °C.

An understanding of the variations in temperature between the sites commonly used for estimating deep body temperature may be gained by considering the characteristics of the different sites.

7.2.1. Axillary and Sublingual Temperatures

Axillary (Tax) and sublingual (Tsb) temperatures are often used as estimates of deep body temperature for medical observation.

The Tax and Tsb sites are close to the surface of the body and have been shown to take a relatively long time to reach equilibrium. The temperature measured may vary considerably within the location itself (Abrams et al., 1980; Cranston et al., 1954). Tsb temperature may be affected by mouth breathing, and recently consumed food and drink (Leithead and Lind, 1964; and Mairiaux et al., 1983). For more extreme environments these temperatures may be influenced by the ambient conditions (Abrams et al., 1980; and McCaffrey et al., 1975).

7.2.2. Rectal Temperature

Tre is often used by physiologists, as well as for medical observation, and reflects the temperature of the tissues contained within the pelvic girdle. These tissues have a relatively high thermal inertia, and the temperature measured in the rectum does not show the effects of thermal transients that may be detected by measurements made elsewhere (Benzinger, 1969; Edwards et al., 1978; and Gibson et al. 1981). Tre temperature is also particularly influenced by the heat generated from leg exercise (Mairiaux et al., 1983; and Strydom et al., 1965). It has been shown that Tre may vary by as much as 0.8 °C depending on the depth and location of the rectal catheter tip within the rectum (Mead and Bonmarito, 1949).

7.2.3. Tympanic and Auditory Canal Temperatures

It is now considered that the hypothalamus centres in the brain play a major role in regulating human body temperature, and the hypothalmic temperature itself is recognized as being the most important sensed deep body temperature (Benzinger, 1969; and Hammel, 1968). In view of this, physiologists investigating human thermoregulation began to use Tty as an estimate of hypothalmic temperature (Benzinger, 1959).

However, the validity of Tty as an estimate of Tcr has been questioned. Nadel and Horvath (1970) compared Tty and Tre temperatures and found that Tty was related to air temperature. In particular it was found that Tty was lower than Tre in the cold and was higher in the heat, with a maximum discrepancy of 0.4 °C for the environments considered. McCaffrey et al. (1975) suggested that the dependence of Tty on air temperature may be explained by the thermal exchanges between arteries and veins in the cervical and cephalic regions.

Tty is measured by positioning a thermistor against the tympanum, which often causes discomfort to the subject. Tac is measured at a lessor depth in the ear canal. However, Tac is dependent upon the external thermal conditions to a greater extent than Tty. Greenleaf and Castle (1972) found that for environmental conditions with $Ta<=35$ °C Tac was always less than Tre temperature, and found differences between the two of as great as 1.1 °C at the end of an exercise period. Moreover, Tac may be affected by the depth of insertion of the thermistor probe as a considerable temperature gradient can exist along the auditory canal (Cooper et al., 1964). Provision of external insulation around the ear may reduce the dependency of Tac on the external conditions (Morgans et al., 1981), as may the use of an external servo-controlled heating device (Keatinge and Sloan, 1973 and 1975).

7.2.4. Oesophageal Temperature

Toe is considered by physiologists to provide the best indirect measure of the temperature of arterial blood (Edwards et al., 1978; Gibson et al., 1981; and Mairiaux et al., 1983). Although, Cranston et al. (1954) and Gibson et al. warn that Toe may be influenced by hyperventilation and the swallowing of saliva. The data of Edwards et al. and

Mairiaux et al. suggest the Toe is usually slightly lower than Tre.

7.2.5. Gastrointestinal Tract Temperature

It is also possible to estimate deep body temperature using a swallowed radio pill (Gibson et al., 1981; and Higenbottam and Wellicome, 1979). However, Tga varies according to the location of the pill in the gastrointestinal tract.

7.2.6. The Models' Deep Body Temperatures

The lut25 model's core compartments have physiological counterparts. The lut25 model's head core compartment temperature is taken to be its deep body temperature because it is the compartmental temperature that is used to produce the core signal for the model's controlling system.

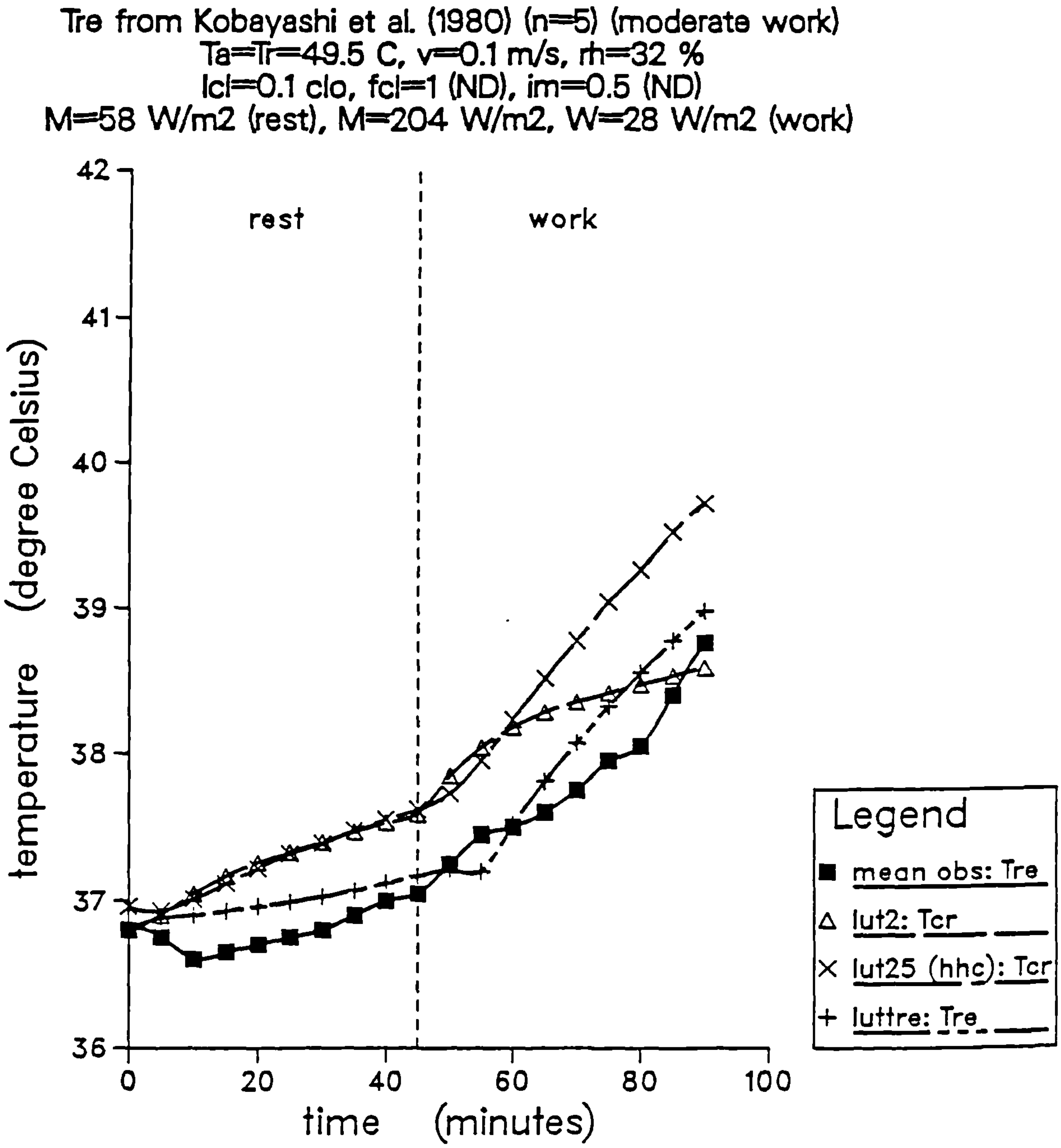
However, comparing the lut25 model's different core temperature predictions, for a hot condition (Ta=Tr=45 °C, v=0.1 m/s, rh=30 %, Icl=0 clo, im=0.5 (ND), M=60 W/m²) the head core compartment temperature was 0.11 °C greater than the trunk core compartment after 60 minutes; for a cold conditions (Ta=Tr=0 °C, v=0.1 m/s, rh=90 %, Icl=0 clo, im=0.5 (ND), M=60 W/m²) the head core compartment temperature was 0.05 °C less than the temperature of the trunk core compartment, after 60 minutes; and for a heavy work condition (Ta=Tr=30 °C, v=0.1 m/s, rh=50 %, Icl=0 clo, im=0.5 (ND), M=350 W/m² W=0 W/m²) the temperature of the head core compartment was 0.09 °C greater than the temperature of the trunk core compartment after 60 minutes. These differences are much smaller than those found in practice between observed Tty and Tre responses.

The core compartment of the lut2 model does not have a physiological counterpart as such, and its temperature can be interpreted as being an average temperature for all of the deep body tissues. The luttre model attempts to predict rectal temperature response. As described previously, the lutiso model does not predict deep body temperature response, but predicts heat storage and its predicted allowable exposure times should relate approximately to increases of 0.8 and 1.0 °C in deep body temperature.

It is clear from the above discussion that deep body temperature responses may vary considerably, depending on the site at which they are measured. Accordingly, it is also clear that the accuracy of the models' predictions will vary depending on the deep body temperature estimate with which they are compared. It would be expected that the lut25 model's predictions should be closest to observed tympanic temperatures and the luttre model's would be closest to observed rectal temperatures. Because Toe is taken to be the most representative estimate of arterial blood temperature as it leaves the heart, it is possible that the lut2 and lutiso models' predictions would compare best with the Toe estimate of deep body temperature.

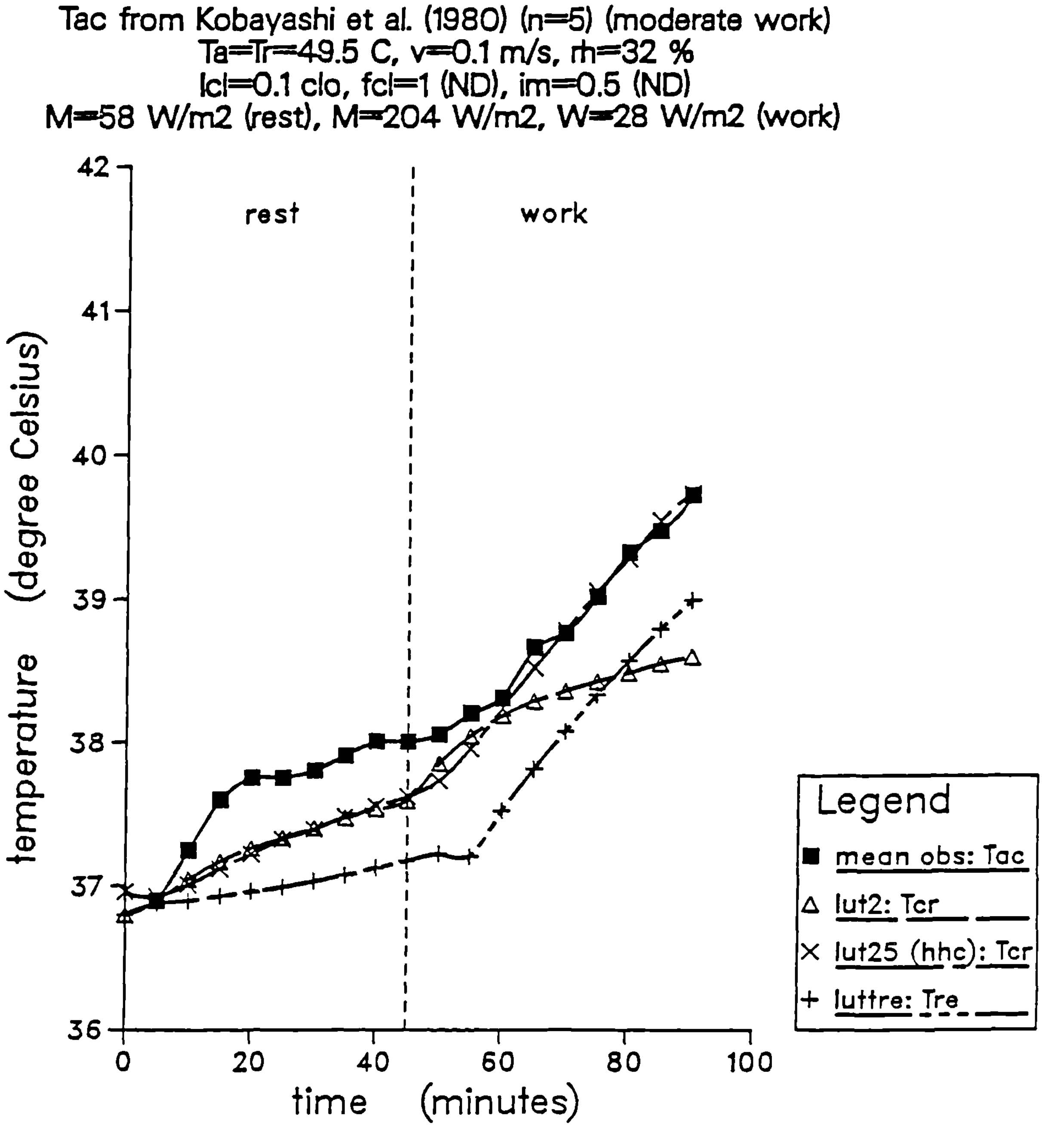
Comparison of figures 7.1 and 7.2 shows that there were differences in the observed Tcr responses measured at different sites, in this case Tre and Tac. Examination of the experimental data, where Tcr was measured at more than one location, suggests that the lut2 and lut25 models'

Figure 7.1. Example of rectal temperature response (Tre).



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

Figure 7.2. Example of auditory canal temperature response (Tac).



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

predictions may have been closer to Toe and Tty than Tre, whereas the luttre model's predictions appeared to be closer to Tre than other estimates of Tcr. However, the rmsds obtained for the Tcr predictions indicate that the differences in the accuracy of the models' predictions of Tcr measured at different sites were probably small when compared with differences between the models' predictions and the observed responses. For environmental conditions that would induce a rapid rise in body temperature, there is evidence to suggest that the lutiso model's allowable exposure times will correspond more closely to Tcr temperature estimates that respond quickly, such as Tty, than Tre which is subject to a greater degree of thermal inertia.

7.3. Interpretation of Mean Skin Temperature

The experimental Tsk data used for this evaluation were collected using temperature sensors attached to between 3 and 13 skin locations and then calculated using a weighting formula such as one of those described by Mitchell and Wyndham (1969).

7.3.1. Measurement of Mean Skin Temperature

Several investigations have been conducted to examine the effect of the number of skin points used on the accuracy of Tsk estimation (Livingstone et al., 1987; Lund and Gisolfi, 1974; Mitchell and Wyndham, 1969; Nielsen and Nielsen, 1984b; and Olesen, 1984). The consensus of these studies has been that the more points used to determine Tsk, the more accurate it will be. However, even with a large number of skin sites, the precise measuring positions used may be important. Livingstone et al. (1987) used thermography to measure skin temperature and found that within a particular area of the skin, the temperature that would be measured with a thermistor could vary considerably depending on its location. This effect was particularly noticeable in the cold.

7.3.2. The Models' Mean Skin Temperatures

The lut2 model's skin shell compartment is intended to represent the average thermal state of the human skin, and its temperature predictions should correspond to Tsk. The lut25 model predicts the temperature of the outer skin compartment for each of its 6 body segments. A mean skin temperature is determined from these temperatures by calculating an area weighted average. The lutiso model does not predict Tsk response (it assumes a fixed value of 36 °C), but its predicted allowable exposure times should relate approximately to increases of 2.4 and 3.0 °C in Tsk for warning and danger respectively.

The comparisons of the observed and predicted Tsk responses were examined to see whether the accuracy of the models' predictions could be affected by the number of points that were used to estimate the observed Tsk. It was not possible to identify any obvious relationship from the data available.

7.4. Initial Discrepancies Between the Models' Predictions and Observed Data

Unless changed, the lut2 and lut25 models' initial state is that which would occur after a long period of exposure to thermal neutrality. At the beginning of the experimental exposures, there were sometimes clear differences between the lut25 model's predicted temperatures and those observed, particularly for Tsk, for example figure 6.3. In most cases the experimental protocols used for the observed data collection included an initial period at thermal neutrality, to ensure that the subjects started from the same initial state. However, there were exceptions.

It is possible to set the starting Tcr and Tsk temperatures for the lut2 and luttre models, although the lut2 model does have other related variables that it is not possible to set, for example the state of vasodilation or vasoconstriction. In the case of the lut25 model, its complexity precludes the setting of all of the initial compartment temperatures. Previous experience with the 25-node model (Haslam, 1983) indicated that using a few selected body temperatures to estimate the remaining compartment temperatures made the model's predictions less accurate during the initial periods. It was thought that this occurred because the temperatures were changed without adjusting other thermoregulatory responses that were still set for neutrality. The lutiso model's predicted heat exchanges are those occurring for the state of equilibrium, and are not affected by the initial conditions, although the model's calculation of allowable exposure times assumes a start from near neutrality.

Fortunately, any initial differences in starting temperatures between the models' predictions and the observed data tend to become insignificant after approximately 20 minutes of the exposures, see for example figure 6.3, so the predictions are still of use.

7.5. The Models' Predictions for Cold, Nude, Rest, and No-Wind Conditions

The lut2 and lut25 models' Tcr predictions consistently followed different patterns to the observed Tre responses that were available for the colder environments, where the subjects were at rest. The observed responses displayed an increase, steady decrease pattern, whereas the models' predictions showed a rapid initial decrease followed by a steady response pattern. The limited observed data available for Tcr measured at other temperatures sites followed a similar pattern to that observed for Tre. This suggests that the discrepancy between the models' predictions and the observed Tcr data is not due to the models' predictions having been compared with Tre responses.

The finding here that the lut25 model overestimates Tcr decrease in the cold supports the results of Stolwijk and Hardy (1971 and 1977) and Wissler (1984). Stolwijk and Hardy suggested that the poor accuracy in the cold might be due to errors in the heat flow calculations caused by the large temperature gradients that occur between the body compartments, and that the introduction of additional compartments might improve the predictions. However, it is interesting to note that the lut2 model's predictions in the cold were consistently more accurate for the data considered by this evaluation than those of the lut25 model, even though it has fewer compartments.

Wissler (1984) found that the Stolwijk and Hardy model's computed Tsk responses appeared to be higher than those observed, and suggested that it is possible that the model does not properly account for the vasomotor responses resulting from cold stress, with the blood transporting too much heat from the core compartments to the skin, cooling the core and heating the skin. However, the results of this evaluation do not support this finding for Tsk as in some cases the lut25 model's predicted Tsk responses were slightly above the observed responses and for others slightly below. This evaluation showed that both the lut2 and lut25 models' predictions of Tsk and M were reasonable in the cold.

Because of the complex nature of the models there are numerous mechanisms that affect their simulated responses to the cold, in the case of the lut25 model for example: the accuracy of the model's predicted environmental heat exchanges; the control of vasoconstriction and the subsequent blood flow redistribution; the distribution of metabolic heat generation between the model's body compartments; the adequacy of the mathematical representation of the human body; and the values of mass and specific heat that are assigned to each compartment. Further research is required to identify the modifications required to the models in order to improve their Tcr simulations in the cold.

7.6. The Models' Predictions for Cool and Neutral, Nude, Rest, and No-Wind Conditions

The lut2 and lut25 models' predictions of Tcr and Tsk became more accurate as the environmental conditions neared thermal neutrality, with the models' predictions generally within the standard deviations of the observed responses. In the cooler conditions, the models' Tcr predictions underestimated the level of the observed responses as found for the cold conditions. The lut2 and lut25 models' appeared to have an over sensitive shivering response in the cooler, but not cold conditions. For several of the environments examined by this evaluation the models had predicted that shivering would have occurred, when no such response was found in the experimental subjects.

The more accurate performance of the models nearer to the region of thermal neutrality is not surprising. For neutral environmental conditions the human body generates and loses heat to the environment in equal quantities, without requiring any thermoregulatory responses such as vasodilation or shivering. Thus, any inaccuracies in the models' simulations of these responses would not affect the models' predictions.

The luttre model's predicted Tre responses were often closest to the observed responses in the cooler environments, although they followed different patterns. Whereas the observed responses decreased, the luttre model's predictions displayed small but steady increases. Nearer to neutrality, the luttre model also predicted that the Tre response would steadily increase, although the observed data remained at a constant level.

Although intended to predict Tre response in the heat, Givoni and Goldman (1972) suggested that their model should also be able to predict for cooler conditions, assuming an air temperature of 30 °C. While the luttre version of the Givoni and Goldman model's predictions of absolute temperature level were fair, its predicted response pattern was poor.

7.7. The Models' Predictions for Warm and Hot, Nude, Rest, and No-Wind Conditions

The lut2 and lut25 models' predicted Tcr and Tsk responses for warm conditions were accurate to the degree of variability that may be found between individual subjects. The mean rmsds between the models' predictions and the observed responses were easily within the maximum average standard deviations found, although they were slightly greater than obtained for neutral conditions. Also available for consideration were continuous observed responses of Esk. Again the lut2 and lut25 models' predicted responses were reasonable.

The experimental data available for these conditions came exclusively from the experiments of Hardy and Stolwijk (1966) and Stolwijk and Hardy (1966), and these data were used for the development of their model. The lut25 model is a slightly modified form of the Stolwijk and Hardy (1977) model. The lut2 model was also derived from the Stolwijk and Hardy model (Gagge et al., 1971). Thus, it is not surprising that these two models should be able to accurately predict the experimental responses used for their development.

However, for the hottest experimental condition, where Ta=47.8 °C, the lut2 and lut25 models underestimated the observed increases in Tre and Tty. Both of the models' predicted Tsk and Esk responses for this environment were reasonably accurate, making this finding difficult to explain.

The luttre model overestimated the increases of the observed Tcr responses for the experimental exposures where Ta<47 °C. However, for the hottest experimental exposure the luttre model's predictions were accurate. Givoni and Goldman (1972) evaluated their model for resting subjects wearing shorts on exposure to a range of air temperatures and humidities and found good agreement between observed and predicted responses. It is not possible to explain why the luttre model's predicted temperature response pattern was too high for all but the hottest conditions. The luttre model uses three sets of equations to predict rectal temperature response to rest, work and recovery from work exposures. Thus, the data for resting subjects only tests the resting equations of the model.

The lutiso model's predicted allowable exposure times were in good agreement with the observed Tcr and Tsk data. For all except the hottest environment the model predicted that the environments could be tolerated for unlimited durations.

The maximum temperature increases observed were 0.5 °C for Tcr and 2.6 °C for Tsk, which are acceptable. For the hottest environment, the lutiso model's predicted warning allowable exposure time coincided with increases in Tre and Tty of 0.6 and 0.8 °C, which is in line with the model's warning critera. The model did not issue a limiting danger time, although the observed data increased by 0.9 and 1.0 °C for Tre and Tty respectively. The Tsk data increased by 3.4 °C, slightly higher than the model's criterion of 3.0 °C for danger.

7.8. Effects of Wind on the Models' Predictions

Limited data were available for nude, resting subjects for both no-wind and wind conditions, for the 5<Ta<=25 °C temperature range. The comparison of the models' predictions with these data suggested that the lut2 models' predictions of Tcr and Tsk were of similar accuracy to those found for the no-wind conditions. The data suggest however, that the lut25 model's predicted Tcr responses were slightly less accurate in the wind. Both models' predicted M responses were less accurate in the wind.

Data were available for nude, exercising subjects for both no-wind and wind conditions where Ta>35 °C. The Tcr and Tsk data suggest that the lut2 and lut25 models' predictions in the wind were of similar accuracy to those found for the no-wind conditions. The luttre model's predictions in the wind were less accurate than found for the no-wind conditions. The lutiso model's predicted allowable exposure times in the wind were in good agreement with the observed increases in Tcr and Tsk, as was found for the no-wind conditions.

For clothed subjects, both resting and working, the mean rmsds indicate, for the cold environments for which experimental data were available, that the lut2 and lut25 models' predictions of Tre and Tsk were less accurate for the wind conditions, than for the corresponding no-wind conditions.

Environmental wind increases convective heat transfer. For most situations this will mean increased cooling, but for conditions where the ambient temperature is greater than body temperature the wind can result in increased heating. The effect on body cooling or heating is similar to that caused by a decrease or increase in air temperature, and the human physiological responses are directed accordingly.

The transfer of heat between an object, such as the human form, and a surrounding fluid is a complex process (Kerslake, 1972). Where forced convection is occurring large quantities of heat can be transported. Errors in calculating this heat transfer would have an important effect on the models' predictions. In order for the models to predict the convective heat transfer between the human body and the environment, they estimate hc, and from this he, which is directly related by the Lewis relation (see chapter 2, section 2.1.4).

The determination of hc used by the models is only approximate. This may result in errors in the convective heat transfer calculations, especially under those conditions where high heat exchanges are occurring. Some of the estimation formulae used were developed from data for a particular type of exercise, such as cycling. The applicability of these formulae to other types of exercise, such as walking, may be limited.

7.9. Effects of Exercise on the Models' Predictions

Exercise results in increased metabolic heat production, which may impose severe heat dissipation problems for the human body, particularly in the heat, or when heavy clothing is worn. The human thermoregulatory system counters the heat load using the response mechanisms of vasodilation and sweating.

Generally it appears that the models' predictions became less consistently accurate or inaccurate for the exercise data available to this evaluation. This may reflect the increased complexity of the thermal conditions and associated thermoregulatory responses.

7.9.1. Convective and Evaporative Heat Exchanges During Exercise

A characteristic found for the lut2 model's predictions for exercise conditions was that the model tended to underestimate Tcr for cooler conditions with still air. Although this also applied to some warmer conditions as well. The lut2 model's predicted Tsk responses for these environments were generally reasonable. These findings are in line with those of Doherty and Arens (1988).

It is possible that the lut2 model's underestimation of Tcr may have been due to errors in the model's calculations of the C+R and E heat flows. For the C+R and E data available from the experiments of Chappuis et al. (1976) there were large discrepancies between the observed data and the lut2 model's predictions. The lut2 model considerably overestimated C+R and underestimated the E heat losses (e.g. figures 6.22 and 6.23). Surprisingly, the lut2 model consistently overestimated the Esk heat loss data of Kobayashi et al. (1980) (e.g. figure 6.27). For the nude, wind and exercise conditions of Mitchell et al. (1976) the lut2 model underestimated the C+R heat gain and underestimated the E heat loss by similar amounts (figures 6.30 and 6.31).

The lut25 model predicted the C+R and E data of Chappuis et al. (1976) with reasonable accuracy (e.g. figures 6.22 and 6.23). For the resting periods of the Kobayashi et al. (1980) experiments, the lut25 model's predicted Esk heat losses were close to the observed responses, but considerably underestimated them during the work periods (e.g. figure 6.27). Similar results were found for the E data of Mitchell et al. (1976), where nude subjects were exercising in the wind (figure 6.31). In this case data were also available for C+R, where the environment imposed a sensible heat gain (figure 6.30). However, this heat gain was underestimated to a similar extent that the E heat loss was underestimated.

It is possible that the discrepancies between the predictions of dry and evaporative heat transfer and the observed data were due to the manner by which the lut2 and lut25 models calculate hc. Exercising subjects tend to increase the air flow over their surface because of the movements of their body. The lut2 model uses an empirical equation to estimate hc when the M input to the model is above a resting level. This equation was developed for treadmill walking. As the data of Chappuis et al. (1976), Kobayashi et al. (1980) and Mitchell et al. (1976) were all collected for cycling subjects, it is possible that this equation is overestimating hc. This could then result in the model overcooling and inhibiting the sweating response, resulting in a low Tcr response and an underestimation of E. However, this would not explain the model's overestimation of the Kobayashi et al. (1980) Esk responses.

The lut25 model calculates hc for each body segment, assuming that any exercise is cycling. Thus, for other types of exercise, these calculations may not be valid. However, for the cycling data of Chappuis et al. (1976), Kobayashi et al. (1980) and Mitchell et al. (1976) the lut25 model's estimation of hc should have been appropriate.

It is possible that the thermoregulatory models do not properly account for the distribution of heat generation and the redistribution of blood flow that accompanies exercise. This could be a particular problem for the lut2 model because it has only two body compartments. Whereas, the lut25 model assigns heat generation to its muscle compartments, the lut2 model assigns it to its core compartment.

7.9.2. Initial Temperature Fall at the Onset of Exercise

For many of the exercise environments the lut25 model predicted an initial decrease in Tcr of around 0.3 °C during the first 20 minutes after the onset of exercise. Although some of the experimental data did display slight decreases, these were smaller than those predicted by the lut25 model. Stolwijk and Hardy (1977), and Hancock (1980, 1981a and 1981b) reported similar findings and suggested that they 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 explanation put forward by Stolwijk and Hardy is that in human muscle "compartments", not all muscles are likely to be active, so that those groups that are, warm up faster and cause less initial blood cooling than predicted by the model.

7.9.3. The luttre Model's Predictions for Exercise

The luttre model generally overestimated the observed increases in Tcr, as was found for resting conditions. This suggests that the cause of the overestimation lies in the luttre model's initial calculations of the equilibrium heat transfer rather than in the rest, work or recovery from work equations.

However, for the Hirata et al. (1983) experiment code 45 (figure 6.19) and the Kobayashi et al. (1980) moderate work and heavy work conditions (e.g. figure 7.1), the luttre model provided the most accurate predictions. These three experimental exposures imposed a high heat load on the subjects. In the case of the Hirata et al. experiments this came from the subjects exercising at 45% VO2max. For the Kobayashi et al. experiments the subjects were exercising in an environment with Ta=49.5 °C. These results suggest that although the luttre model overestimates Tcr responses for most conditions, for those where a high heat load is imposed on the subjects its predictions may be of use.

The findings of other researchers make the results of the evaluation of the luttre model surprising. Givoni and Goldman (1972) found that their model's predicted Tre responses for exercising subjects were in good agreement with the observed data. Haisman and Goldman (1974) found the accuracy of the model's predictions acceptable, and within the variability expected for military and industrial populations. Wissler (1984) found that agreement between computed and measured Tre was generally quite good, although the model had a tendency to overestimate increase during heavy exercise in hot environmental conditions.

As detailed in chapter 3, section 3.4.2, the predictions of the implementation of the Tre model used for this study compared well with several published sample runs from the original Givoni and Goldman model. The results of the evaluation of the luttre model are, therefore, difficult to explain.

7.9.4. The lutiso Model's Predictions for Exercise

The lutiso model's predicted allowable exposure times would not have protected nude, exercising subjects against its own criteria for body temperature increases for several experimental exposures considered by this evaluation. An extreme example is the data of Shvartz (1976), experiment code hot, where the subjects' mean Tre rose 1.5 °C before the model issued a warning and had increased by 2.0 °C by the end of the exposure without the model having issued a danger time (figure 6.24). The model's predictions were also underprotective for cooler environments with heavy exercise, for example the data of Hirata et al. (1983), experiment code 45 (figure 6.19). For the environments that did not have extreme heat or exercise levels, the lutiso model's predicted allowable exposure times agreed reasonably well with the increases in body temperatures observed.

A previous evaluation of the ISO/DP 7933 model by Wadsworth and Parsons (1986) found that the model would not have protected their working subjects, although their results would have been affected by an error in the published version of the model that they used, which caused the model to overestimate the evaporative cooling of clothed subjects (see chapter 5, section 5.6.4).

7.10. Effects of Clothing on Models' Predictions

Clothing insulates the body from the environment and thus reduces dry and evaporative heat transfer between the two. For cold and cool environments it was possible to compare results for resting no-wind and wind conditions for clothed and nude subjects. In almost all cases the models' predictions for the clothed subjects were more accurate than for the nude. This finding applied to both the lut2 and lut25 models for their predictions of Tcr, Tsk and M. For warm and hot environments, the limited data available for comparison suggested that the models' Tcr predictions were less accurate for the clothed conditions. The accuracy of the Tsk predictions were similar.

These findings support suggestions that the models become less accurate as their simulated deep body temperatures deviate from neutrality.

The lutiso model's predictions for clothed subjects were generally reasonable, its warning and danger times corresponding either with its criteria of deep body or skin temperature increases.

7.10.1. Accuracy of Clothing Parameters

It is possible that the models' predictions for clothed subjects could have been affected by inaccurate figures for the clothing parameters having been used. For most of the sets of experimental data for clothed subjects it was necessary to estimate the clothing insulation values from tables using the authors' descriptions of the clothing. McCullough and Jones (1984) conducted an experiment to examine the accuracy with which clothing insulation values could be estimated from tables and found that even for trained subjects there were often large errors.

It is possible that the errors introduced would increase with the level of clothing insulation worn. With the data available to this evaluation, however, it was not possible to determine whether the accuracy of the models' predictions was related in any way to the level of clothing worn.

7.10.2. Head and Hands Clothed (hhc) and Head and Hands Nude (hhn) Versions of the lut25 Model

Two versions of the lut25 model were evaluated for clothed conditions. One applies clothing equally over the entire body surface, including the head and the hands (hhc), the other leaves the head and hands uncovered (hhn). As would be expected, there were differences between the versions' predicted peripheral head and hand temperatures. These differences were sometimes large, particularly in the cold. However, these predictions were not considered by this evaluation. While there were some differences between the two versions of the model for their predictions of Tcr, Tsk and M, these differences were inconsistent and usually small when compared with the differences between the predictions and the observed data.

7.11. Transient Exposures

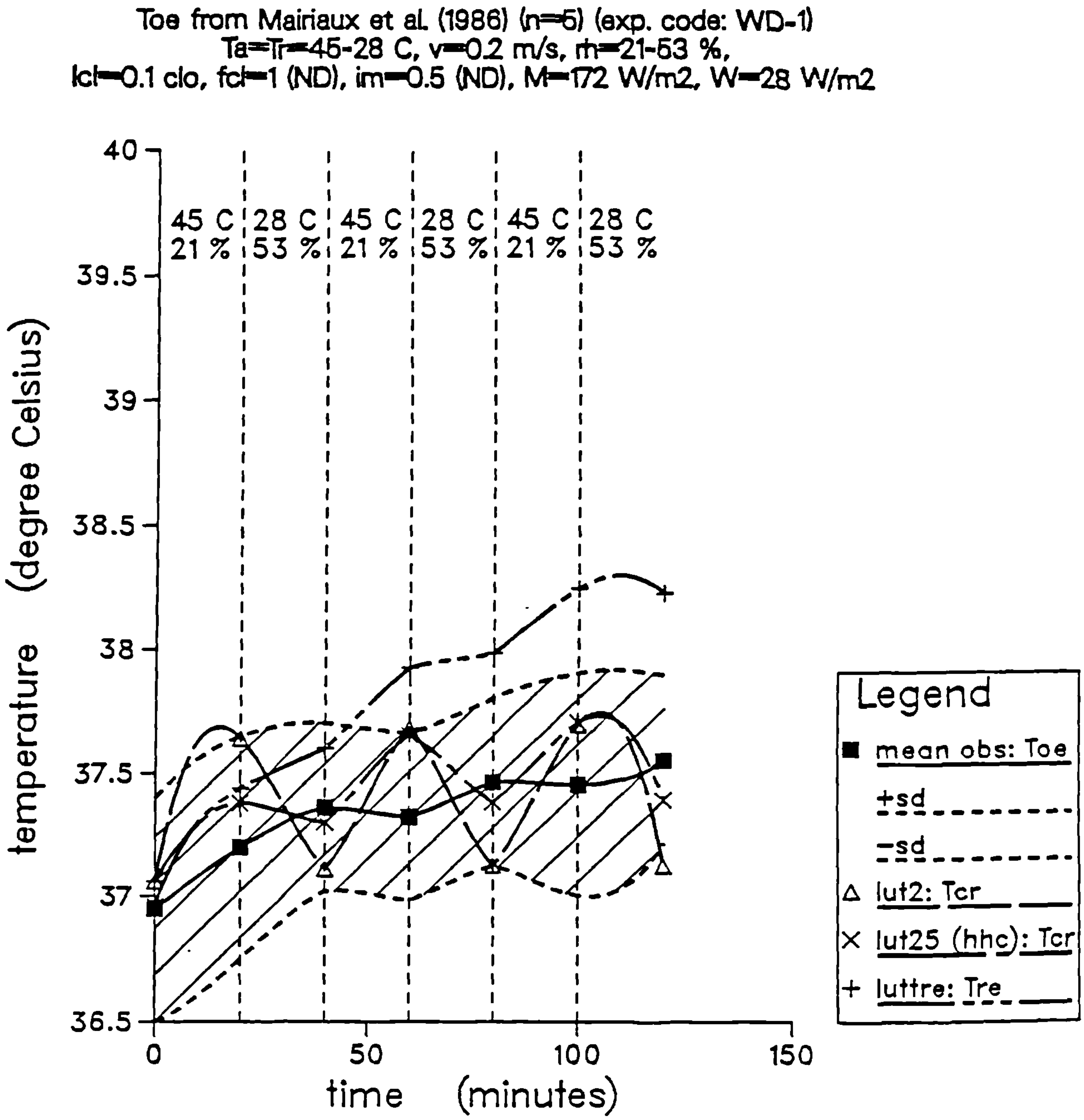
It is noticeable that for work-rest or environmentally transient exposures, particularly when the transients were of short duration, the thermoregulatory models' predicted responses fluctuated considerably more than the observed data. Clearly there are discrepancies between the models' descriptions of the thermal behaviour of the human body and that which occurs in practice on exposure to transient conditions. However, the models' predictions would have still been useful for some highly transient conditions as the fluctuations occurred about the mean observed responses, for example figure 7.3.

7.12. Effects of Heat Acclimatization on the Models' Predictions

The effects of acclimatization to the heat are well known (e.g. Leithead and Lind, 1964), and result in physiological changes directed at providing more efficient body cooling, mainly through increased sweating capacity. Thus, acclimatized subjects may demonstrate lower Tcr and Tsk responses to a hot environment than unacclimatized subjects. A small amount of data were available for experimental exposures of acclimatized subjects to warm and hot conditions, for the nude, work and wind, and clothed work and wind environment categories. Generally the rmsds obtained for the models' predictions for acclimatized subjects were slightly lower than obtained for the corresponding unacclimatized subjects. However, the differences in accuracy were small when compared with the differences between the models' predictions and the observed data.

The lutiso model's predictions for acclimatized subjects were generally reasonable. An exception was for the data of Pimental et al. (1987) where the model's warning and danger times corresponded to increases of 0 °C in Tre. These times were time weighted averages, and were shorter than the first component of the exposure. It is not clear from ISO (1987) how the times should be interpreted in these circumstances.

Figure 7.3. Example of deep body temperature responses (Tcr) to fluctuating environmental conditions.



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

The lut2 and lut25 models' predictions can not easily be adjusted for the state of heat acclimatization, whereas the luttre and lutiso models can predict for both unacclimatized and acclimatized subjects. It would appear, however, that the present models are not sensitive enough to be able to account for the different physiological responses that accompany acclimatization.

7.13. Effects of Gender on the Models' Predictions

Research has shown that men and women exhibit significantly different responses for exposures to both heat and cold (Avellini et al., 1980; Cunningham et al., 1978; Grucza et al., 1985; Mannino and Kaufman, 1986; Shapiro et al., 1981; Wagner and Horvath, 1985; and Walsh and Graham, 1986). These differences relate to differing physiological responses as well as to the effects of differences in body size and composition.

Comparing the results of this evaluation for female and male subjects showed that the accuracy of the models' predictions was similar for both, and in most cases the predictions were accurate enough to have been of some practical use. Any differences in accuracy between the models' predictions for female and male subjects were small in comparison to the differences between the models' predictions and the observed responses. It would appear that in their present forms the models are not sensitive enough to account for the different responses of men and women.

7.14. Accuracy of Experimental Parameters

Wherever possible for this evaluation the experimental values used to produce the models' predictions were taken directly from the appropriate reports. It is likely that reported values of Ta, Tr and rh would have been accurate.

7.14.1. External Air Movement

Environments with wind usually had an unidirectional air flow and reported values of v were usually measured at a stated distance from the subjects. However, the speed of flow of a moving fluid varies within the fluid, particularly if an object is placed in its course. Thus, the speed of air movement at a subject's head may differ significantly from the speed at the subject's feet. The models' base their predictions on the single value of air speed provided to them. As the models determine hc from experimental formulae, some account is taken of the variation in air speed over the body surface. However, the accuracy of these formulae could be affected by the position used by the experimenters to measure the air speed, and this in turn could affect the accuracy of the models' predictions. The margin for error would become greater with increasing air movement.

7.14.2. Clothing

The clothing values used to run the models were wherever possible those given by the experimenters. However, in most cases it was necessary to estimate the clothing insulation values from tables using the clothing descriptions provided by the authors. As discussed above, previous research has shown that estimating clothing insulation from tables may introduce errors (McCullough and Jones, 1984). Further research, using estimated clothing values as inputs to the models, where the actual clothing values are known from manikin measurements, is necessary to determine the extent of any inaccuracies that clothing estimation from tables may introduce into the models' predictions.

7.14.3. Energy Expenditure

The energy expenditure values used were wherever possible those given by the authors. However, it was often necessary to convert these values from W to W/m^2, requiring an average body surface area. For experimental data where body surface area was not reported an assumed value of 1.8 m^2 was used. This could have had an effect on the models' predictions. For example, a metabolic rate of 540 W is 300 W/m^2 using a body surface area of 1.8 m^2, whereas using 2.0 m^2 it is 270 W/m^2. This is a difference of 10 %. Using these values as inputs to the lut25 model for the following conditions: Ta=Tr=30 °C, v=0.1 m/s, rh=50 %, Icl=0 clo, im=0.5 (ND), W=0 W/m^2, results in Tcr predictions of 38.84 and 38.45 °C, and Tsk predictions of 37.29 and 36.72 °C after 60 minutes, for M=300 and 270 W/m^2 respectively. Thus, using the different body surface area estimates resulted in differences in Tcr of 0.4 °C and in Tsk of 0.6 °C. These differences could affect any practical decisions that were based on the model's predictions. In practice, it is unlikely that the estimated body surface areas would have been as inaccurate as for this example.

7.15. Practical Application of the Models

The lut implementations of the models evaluated for this research provide quick, repeatable predictions and can be accurate enough to contribute towards environment assessment and design.

Table 6.5 shows that for the environment categories for which experimental data were available, usually at least one of the models was able to supply predictions that would have been sufficiently accurate to be of use for practical applications. With the exception of environments with $Ta<=5$ °C, usually either the lut2 or lut25 models predictions had a mean rmsd within the maximum average standard deviations found for the observed data.

It is suggested that for practical applications it would be sensible to consider the predictions from both the lut2 and lut25 models, where the subjects are at rest. For exercising subjects the lut2 model's Tcr predictions should be interpreted with caution, as they have differed significantly from observed experimental data. For environments with heavy exercise ($M>250$ W/m^2) or high air temperatures ($Ta>45$ °C), it is also worth considering the luttre model's predictions. While the lutiso model's predicted allowable exposure times were often reasonable, the model cannot always be relied upon to protect against its own criteria of safety.

This evaluation has suggested that the accuracy of the models' predictions decreases with increasing complexity of exposure. The models appear best suited to predicting responses to steady conditions, with low levels of air movement, clothing and exercise; their predictions become less reliable as these increase, or as the environmental conditions fluctuate.

CHAPTER 8

8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

8.1. Conclusions

The aim of the research presented in this thesis was to identify and implement models capable of predicting human thermal responses to hot and cold environments, and to evaluate the accuracy of their predictions by comparing them with the responses of human subjects.

Six models have been evaluated, namely the Gagge and Nishi 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, the ISO/DIS 7933 analytical determination and interpretation of thermal stress using calculation of required sweat rate model, the Ringuest 25-node model of human thermoregulation, and the Wissler 225-node model of human thermoregulation.

A preliminary evaluation was conducted where the models predictions were compared with experimental data already available at Loughborough University. This evaluation found:

1) The Gagge and Nishi, Stolwijk and Hardy, Givoni and Goldman and ISO models were capable of making sensible predictions and were worthy of further investigation.

2) The Ringuest model's deep body temperature predictions were poor.

3) There were practical difficulties with the use and

implementation of the Wissler model.

A review of the methods used by the models to quantify the insulative effects of clothing enabled the models to be modified to account for clothing by an appropriate method given the current state of knowledge.

The modified versions of the Gagge and Nishi (lut2), Stolwijk and Hardy (lut25), Givoni and Goldman (luttre) and ISO (lutiso) models were evaluated against data previously published in the literature and reports. Suitable experimental data were identified for 82 combinations of environmental conditions, involving a total of 590 subject exposures, with a wide range of temperatures, air speeds, humidities, clothing and work rates. The data were divided into environment categories to enable examination of the effects of temperature, wind, clothing and work on the models' predictions, and to enable advice to be given as to which models to use for a particular application.

The results of this extensive evaluation have led to the following conclusions:

1) For the environment categories, for which data were available, usually at least one of the models was capable of providing accurate predictions. The categories where this was not the case were mostly confined to the coldest environments.

2) The models' predictions tended to be most accurate for the simplest thermal conditions, those where the

subjects were exposed minimally clothed and resting to still air conditions. Although, the models' Tcr predictions for environments where Ta<=5 °C were poor.

3) The models' predictions for environments where air movement occurred or where the subjects were exercising, tended to be less consistently accurate or inaccurate across different data sets.

4) The models' predictions for clothed subjects were more accurate in the cold and less accurate in the heat than for subjects wearing minimal clothing.

5) The models' predictions for acclimatized or female subjects were of a similar accuracy to those found for unacclimatized or male subjects. Any differences in accuracy were small when compared to the differences between the models' predictions and the observed data.

6) Despite its simple representation of the human body, the lut2 model of human thermoregulation often provided accurate predictions of temperature response. However, certain of the lut2 model's predictions for conditions where subjects were exercising were poor, with the model underestimating the rise in Tcr.

7) The lut25 model provided accurate predictions for many of the environment categories. However, the model's Tcr predictions in the cold were poor. This was despite the model's Tsk predictions often being very accurate in the

cold.

8) The luttre model's Tre predictions for resting subjects in cool and neutral environments were accurate in terms of predicting absolute temperature level, but the predicted response patterns were poor. The model always predicted steady continuous rises in temperature, whereas for many of the conditions the observed responses decreased. The model generally overestimated considerably the Tcr increases observed for exercising subjects or subjects exposed to the heat. Exceptions to this were for very hot environments (Ta>45 °C) or where the subjects were exercising heavily (M>250 W/m^2).

9) The lutiso model's predicted allowable exposure times were compared with the changes in Tcr and Tsk of the observed data at those times. For many of the experimental exposures, the lutiso model's predicted allowable exposure times were reasonable against its own body temperature increase criteria. However, it is of concern that for some exercise conditions the model was underprotective.

10) The results of this evaluation show that with the exception of Tcr in cold conditions (Ta<5 °C), the lut2 and lut25 models' predictions are accurate enough to be of practical use. It would be wise to examine both models' predictions for an environment, although caution should be used when considering the lut2 model's Tcr predictions for exercising subjects, as these have

differed markedly from observed experimental data. The luttre model's predictions should also be considered for conditions with high exercise levels (M>250 W/m²) or high air temperatures (Ta>45 °C). The lutiso model's allowable exposure times are often reasonable, but may not always be relied upon to protect against its criteria of safety.

8.2. Recommendations for Further Research

The following recommendations are made for further research:

1) Further work is required to identify why the models' deep body temperature predictions in the cold are poor, and how they might be improved.

2) The full evaluation did not examine the lut25 model's predictions of hand and foot temperatures, both potentially of practical use, especially in the cold. The preliminary evaluation suggested that the 25-node model might be able to predict hand and foot temperatures with reasonable accuracy. Further evaluation is required.

3) Research is required to identify the causes of variation in response that occur both within and between individuals, and how these might be accounted for by the models. This might enable the models' predictions for the mean response of a group of subjects to be improved and might enable predictions to be made for particular individuals.

4) In their present forms the models apply air movement or long wave radiation evenly over the body surface area. In practice air motion or radiation will usually be asymmetrical. Consideration should be given to modifying the models to account for this.

5) The current versions of the models do not account for short wave solar radiation. As many potential applications would be for outdoor conditions, the models should be extended to enable them to account for heating due to the sun.

6) Exercise results in increased convective cooling due to the motion of the body trunk and limbs. Further research is required to determine how the models could accurately account for the increased heat transfer for different types of exercise.

7) The present method used to describe the insulative effects of clothing makes assumptions that do not hold for many potential applications of the models. How to account for air movement within clothing as a result of exercise, reduction of insulation due to external wind penetration, thermal inertia due to clothing mass, uneven distribution of insulation over the body surface, and reduction of insulation due to the absorption of sweat are some of the areas that require further attention.

8) Physiological systems do not usually operate

independently. Consideration should be given to integrating models of human thermoregulation with models of the respiratory and cardiovascular systems.

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