COMPARISON OF TWO HUMAN THERMOREGULATORY MODELS

by

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1. INTRODUCTION

Man's physiological functions and his capacity to survive in a wide range of environmental conditions have been of interest to scientists for a long time. It is no wonder that the human thermoregulatory system, being a part of the whole mystery, has been the subject of many studies and, inevitably, many controversies as well. The controversies result, in part, because of the complexity of the human body and its functions, and the simplifications necessary to quantify them for formulating a successful mathematical model. The need or reason for developing such quantitative models comes from the necessity to simulate certain regulatory behaviors and their results to better understand the actual body actions, or responses.

The primary reasons for the complexity of human thermoregulatory system are due to the number of variables involved and the feedback in the many control loops. The large number of quantitative models reflect the various approaches taken by the researchers to study and understand this complex system. The most successful of such models have been the so called "closed-loop" models. In the fore-front among these, in terms of their simplicity and generality of application, are the ones by Stolwijk (20) and Gagge (8).

2. LITERATURE REVIEW

An excellent review of the development of quantitative models on human thermoregulation is given by Dhiman (4). Concepts of current human thermoregulatory models have been thoroughly discussed by Fan, Hsu, and Hwang (6). One of the earliest mathematical models for a complete human body was given by Wissler (23); however, this model did not consider the physiological thermal regulation system and as such it was an "open-loop" type. A pioneer of the "closed-loop" models, where physiological thermal regulation is considered, was the one proposed by Stolwijk and Hardy (21). Since then other closed-loop models have also been proposed. However, most of these are for specific needs or requirements; the notables among them are the ones by Harrah (13) and Gagge (8). A more refined and generalized model has since been put forwarded by Stolwijk (20). In all of these models the main problem has been in finding the appropriate parameter values for the different theoretically reasoned emperical formulae. This problem becomes all the more important when the model is used for different subjects, and different physiological and environmental conditions.

In all of these models, the set-point or reference temperatures are assumed as constant. Moreover, the same set-point is associated with activating appropriate signals for both cold and warm conditions or responses from the feedback elements. However, it seems improbable that body regulatory actions are put into effect when just a single point in temperature is crossed in either direction. It is more probable that there is a neutral zone or band, however thin it may be, within which the body regulatory functions are not actually activated. This belief gives rise

to the concept of two set-points, one for cold and the other for warm signals. Interlinked with this is the concept of adjustable set-points. Hammel (11) shows on dogs that the set-points are in fact adjustable. Another offshoot from Hammel's study, though not pointed out by Hammel, is that his results substantiate, if not give credence, to the idea of two set-points.

Another drawback in the current models, which at first glance may seem trivial but in actuality has a great influence on the simulated results, is that they do not incorporate any sort of limit on the physiological regulatory actions. The fact is human body regulatory actions have physiological limits. Limits become more important when the body is subjected to severe stress, either or both of physiological and environmental stresses. The literature on medical physiology has dealt with this matter extensively. The generally accepted physiological limits which affect the model output should be on: cardiac output, blood flows to different segments of the body, total sweating rate, and rise in core or mean body temperature.

Guyton (10) indicates that the normal heart, under resting conditions, although capable of pumping 13-15 liters/minute, pumps approximately 5 liters/minute. However, for a person doing exercise, the output of the heart increases and the cardiac output can increase to 22 liters/minute, or 4.5 times the normal rate. Blood flow to fat areas remain essentially constant at the basal rate. But, for skeletal muscle, the blood flow during extreme exercise can increase by as much as 15-20 times the normal rate. With maximal vasodilation (when the skin is heated) the blood flow

to skin areas can increase by as much as 7 times the basal level of about 0.5 liters/minute (for an average person) to about 3.5 liters/minute. Under extreme exercise and environmental conditions, when blood flows to muscle and skin reach their maximal levels, the core blood flow can drop from the basal level (but not evenly from all core parts). In general, core blood flow remains fairly constant at the basal level.

Another important physiological limitation is the maximum rate of sweating in a human body. De-hydration of the body can be overcome by drinking water at frequent intervals but the sweating rate can not exceed a physiological limit. For an unacclimatized person the maximal sweating rate is about 1.5 liters/hour, Guyton (10), Slonim (19). However, this maximum sweating rate can be increased with acclimatization to about 3.0 liters/hour within 10 days and 3.7 liters/hour within six weeks, Guyton (10).

Temperature changes for different body segments are calculated in the models by considering the net heat gain in the segment and the thermal capacity (or specific heat) of the segment. In almost all the models, 0.97 W*h/^{o}C is generally taken as the specific heat of the body. However, this specific heat is not a constant since each tissue type, bone and fat has a different specific heat; the specific heat of a person's body depends on his body composition. A review of the specific heats for the different body parts is given by Minard (17). Minard also mentions that Hardy and DuBois (12) have found, from direct and indirect calorimetric measures, that the specific heat of a human body lies between 0.837 and 0.97 W*h/^{o}C, with a most probable value of 0.907 W*h/^{o}C for an average person.

Another associated source of error, which in turn affects the calculated temperatures, is the heat transfer coefficients used in different equations of a model. These coefficient values are affected by environmental conditions, body postures, and physiological conditions. A review of these effects on the heat transfer coefficients is given by Colin, Timbal, Guieu, Boutelier and Hondas (3). Kerslake (15) points out that though the heat of vaporization of sweat from skin is taken as a constant with values varying from 0.68 to 0.698 W*h/gm, this is, in fact, also a variable dependant upon the skin wettedness and skin temperature.

Thus, it is seen from this brief review that in spite of the availability of some models which predict fairly well the behaviors and actions of human temperature regulation, there is an ample scope to refine these models to simulate better. Refinements will also make the models, hopefully, more 'individualized' instead of being 'generalized' as they currently are.

3. OBJECTIVES

A human thermoregulatory system contains essentially two parts, regulator and regulated system, with a feedback loop connecting them. When a human body is placed in an environmental condition different from that of thermoneutrality, regulatory mechanisms are activated to bring back the thermoneutral condition of the body. These built-in mechanisms, acting automatically, are necessary. In most cases they are vital to the survival of the body itself. Many of the body functions are initiated and regulated through a complex maze of bio-chemical reactions. The single most important reason for the presence of the regulatory mechanisms is that these bio-chemical reactions take place within a very narrow temperature range inside the body.

Both the Stolwijk (20) and Gagge (8) models aim to duplicate the thermoregulatory mechanisms in a mathematical form with, of course, simplification and degrees of uncertainties. Both the models have been written by their original authors in Fortran language for use in digital computers. As usual, these models are being constantly scrutinized and updated at various research centers.

The main purpose of this study was to adapt Gagge's model for the specific requirements of Kansas State University; Stolwijk's model has already been adapted in this respect. However, a prime thrust of this study was to make both models more flexible in terms of their input conditions, regulatory functions, and output results. Both models use a host of equations involving a large number of parameters; these equations and parameter values were modified, where necessary, in light

of other recent studies at various places. Changes have also been made to make both models compatable to each other to make comparisons meaningful. And, last but not the least important, the simulated results from these two modified models were compared with experimental results gathered at Kansas State University in 1972 and 1974. These comparisons were made to get some quantitative as well as qualitative measure of the accuracy of the simulations and thereby the models themselves.

4. HUMAN THERMOREGULATION

Introduction: Before going into the model description itself, it is appropriate at this point to describe, in brief, some of the salient features of human thermoregulation itself. Then, we would be in a better position to appreciate the complexity of the system as well as the difference in model sophistication.

From a physiological point of view, the human body is a homeotherm. That is, the body temperature is kept relatively constant over a wide range of environmental and physiological conditions. Since the body interacts constantly with the environment, it always acts to minimize thermal equilibrium upsets. Body thermal equilibrium can also be upset by increased metabolic activity (both positive and negative work) even without changing the thermoneutral environmental conditions. Contingent upon the environmental conditions or the stress on the body, specific regulatory functions are activated. It has been generally accepted by physiological scientists that the monitoring part of the body thermoregulation comes from the thermoreceptors located all across the skin plus the hypothalamus. It is interesting to note that, within limits of exercise level and ambient temperatures studied, internal temperature (essentially the core temperature) is solely proportional to exercise level and the mean skin temperature is solely proportional to ambient temperature, Stolwijk and Nadel (22).

Probably the most important temperature receptors for control of body temperature are the many special heat sensitive neurons located in the anterior or preoptic hypothalamus, Guyton (10). With the rise in temperature these neurons increase their impulse output and do the reverse when the

temperature decreases. The output might increase by as much as 10 fold with an increase in body temperature of $10^{o}C$. In addition to these thermoreceptors (or neurons) in the anterior hypothalamus, there are other temperature sensitive receptors in the body. They are: a) a few cold sensitive neurons found in other parts of hypothalamus (there is doubt, however, about their role, if any, in body thermoregulation); b) skin temperature receptors, including both warmth and cold receptors, that send their signals to the hypothalamic region through the spinal cord (the number of these receptors vary to a large extent depending on the skin region); c) perhaps temperature receptors in some internal organs of the body that probably also transmit signals to help thermoregulation, Guyton (10).

In neurophysiological terms, the general properties of the cutaneous (or skin) thermoreceptors can be described as follows, Hensel (14):

1. They have a static sensitivity to constant temperature (T).
2. They show a dynamic sensitivity to temperature changes (dT/dt), with a positive temperature coefficient for warm receptors and a negative coefficient for cold receptors.
3. They are not excited, within reasonable limits of intensity, by mechanical stimuli.

The body thermal receptors pick up the signals and these are integrated in the hypothalamus (or integrating unit), considered as the temperature regulating center. When the body thermal equilibrium is upset, by whatever means, the body immediately puts into action certain of its control mechanisms. The mechanisms depend on the nature of the imbalance. There are

three prime regulatory actions that the body can take: vasomotor function, sweating, and increased body heat production.

Vasomotor function: Vasomotor function, or vascular control of blood to and from the skin surface, is manifested in vasoconstriction (to lessen the blood flow) and vasodilation (to increase the blood flow). This vascular control is performed to change heat flow from the central core to the skin surface area when the body is exposed to a cool environmental condition, but when the body is exposed to a hot environment this is done so that heat can not flow into the core. Vasomotor control has limits in the sense that a minimum amount of blood always must flow to the skin area (basal blood flow to skin) for physiological sustenance. There is also an upper limit that the blood supply can reach (maximum blood flow to skin). With maximal vasodilation, the blood circulation to skin can reach up to 7 times the basal level, Guyton (10). Vasoconstriction is usually associated with the sense of cold, so that the heat out-flow is reduced. Vasodilation always occurs during regulatory sweating and is associated with the sense of warmth. Without sweating, vasodilation may cause a sense of comfort or well-being although skin temperature may be well below the temperature threshhold expected for a neutral sensation, Gagge, Stolwijk and Nishi (9).

Sweating: Man's best protection against heat is his ability to use the evaporative cooling caused by sweating. Sweating is actuated by thermal stimuli from both core and skin; there are both local controls and central controls, Gagge, Stolwijk and Nishi (9). The center for overall control of regulatory sweating is in the anterior (or preoptic) region of the hypothalamus. This center is excited by: a) afferent impulses from cutaneous

thermal receptors, b) the direct effect of temperature changes within the center itself either by local metabolism and/or the temperature of its arterial blood supply, and c) impulses originating from neuromuscular activity that also contribute to the activity of the center and the sweating regulation during exercise, Slonim (19). The skin temperature exerts an influence on sweating through two mechanisms: 1) affecting directly sweat gland functions locally, 2) through thermal receptors and integration in the central nervous system in a neutral way, Bullard, Banerjee, Chen, Elizando and MacIntyre (1).

There are two main forms of sweating: insensible and sensible. Evaporation of water from the skin without secretory activity of the sweat glands is called insensible perspiration. It is generally caused by diffusion through the epidermis (or outer skin layer) from the deeper skin layers; this occurs continuously, even in cool or cold environments, Slonim (19). Normal sweating, or sensible perspiration, takes place from two types of sweat glands: apocrin glands located chiefly in the axillae and pubic regions, and eccrine glands distributed over the entire skin. It is the eccrine glands that primarily function in temperature regulation, Slonim (19). Eccrine glands are normally activated to secrete thermal sweating by impulses along sympathetic motor fibers.

The principal purpose of regulatory sweating is to cool the body, or, in other words, to take away from the body the excess heat generated. The main cooling, or heat transfer, effect comes from the evaporation of the sweat on the body surface. Evaporation, however, depends to a great extent on the environmental conditions: ambient air temperature (dry bulb), water vapor pressure, and radiant temperature. Not all the evaporative effect

takes place on the skin surface itself. Some evaporative heat loss also takes place through the respiratory system; if the ambient air temperature is high compared to the esophageal temperature then the body may gain heat, instead of lose, by this process. Respiratory heat transfer depends to a large extent on the rate of respiration which is directly dependent on the exercise, or activity, level. Moreover, a greater cooling effect is obtained if the sweat is evaporated directly from the skin. As such, a clothed person, whose sweat is evaporated from his clothes, gets less cooling benefit. When the environment does not allow complete evaporation of all the regulatory sweat secreted, a portion of sweat stays on the skin or drips off.

Increased body heat production: When the central control senses cold, it increases body heat production, in addition to vasoconstriction, to neutralize the heat flowing out due to the thermal upset. Increased heat production may be achieved in two ways, Guyton (10):

1. Hypothalamic stimulation of shivering -- When the preoptic receptors sense cold, they, in turn, activate the primary motor center for shivering located in the posterior hypothalamus. Its impulses are non-rythmic and do not cause actual muscle shaking. Instead they increase the tone of the skeletal muscle which result in an increase in muscle metabolism manifested in the form of shivering. However, this increased metabolic heat production may increase up to 50 percent even before appreciable shivering occurs.
2. Chemical excitation of heat production -- Sympathetic stimulation or circulation of certain chemical compounds in blood can cause

an immediate increase in the rate of cellular metabolism.

The result is that far more oxidation of food-stuffs occurs.

A further complication to the above thermoregulatory functions occurs because many of the regulatory actions are greatly affected by acclimatization to a climate.

Cold acclimatization: Acclimatization to cold results in, Slonim (19):

1. Metabolic changes --Field studies have indicated that, at any given skin temperature, acclimatized subjects have a smaller increment in body heat production than non-acclimatized subjects.
2. Changes in the peripheral circulation -- Another observation in the above studies was that hand temperatures were higher and finger pulse height diminished less during the test cold exposure for acclimatized subjects compared to the non-acclimatized ones. The inference from these and results from experiments with animals suggest that peripheral blood circulation is also changed due to both long- and short-term acclimatization.

Heat acclimatization: A more dramatic effect is seen in the case of acclimatization to heat. With repeated daily exposure to the same combination of hot environment and work stress, physically fit men can acclimatize rapidly. Within ten days almost all the acclimatization benefits are obtainable. With heat acclimatization, Slonim (19):

1. There is a gradual improvement in evaporative cooling, and in the sensitivity and activity of sweat mechanism; in fact, within ten days the sweat rate doubles. Thus, with acclimatization, the sweat glands become conditioned and increase their capacity to sweat.

2. A gradual improvement in temperature regulation itself, enabling a person to work in heat without increased rectal to skin temperature gradients.
3. A markedly improved circulatory stability with reduced heart rate.
4. A decreased concentration of sodium chloride (or common salt) in the sweat secreted, which allows progressively better conservation of salt.

One more aspect of thermoregulation in the human body has to be considered at this point. All that has been explained till now are the actions taken by the built-in body mechanisms themselves. However, it is also possible, and has successfully been applied in many cases, to use an external regulatory system. These external thermoregulatory systems may take the simple form of clothing or highly sophisticated body-cooling mechanisms.

5. MODEL DESCRIPTIONS

5.1 Model Philosophy:

From the description of the human thermoregulatory system in the previous section we can very well understand why, from a philosophical point of view, all the quantitative models of a human thermoregulatory system are similar. Their differences are only due to individual approaches for simplifications in modelling. Basically, a thermoregulatory model has two principal sections: a regulated or controlled section, and a regulator or controller. Both these sections are connected via a feed-back loop. Figure 1 shows a simplified block diagram of such a concept of human thermoregulatory system.

The regulator (or controller) part of the system gets its inputs from feed-back elements in the form of thermoreceptors located in skin and hypothalamus. The feed-back signals are primarily temperatures and the rate of change of temperatures. These signals are then compared with set references (or set-points). Depending on the signal received, the integrator (or controller) determines which of the control elements would be put into action. The activated control elements then execute the necessary control action to bring back the thermoneutral condition inside the body (or controlled system). The regulatory (or control) action taken might be one or more depending on the severity of departure from reference of the feed-back signal. Environmental conditions directly affect the feed-back signals whereas activity (or exercise) affects a control element, the result of which is reflected in the feed-back

signal. The control element muscle is associated with the control action heat production; the action is performed by shivering the body muscles. An exercise or activity (which can be considered as an impressed action on the system) also produces the same result. The control element sweat glands is associated with the control action evaporative heat loss; the action is performed by secreting sweat. The control element blood vessels is associated with the control action dry heat loss; the action is performed by vasomotor function.

Most of the closed-loop models use this concept of regulation and the body itself is believed to follow the same general logic. However, from the modelling point of view, simplifications are necessary to simulate the body actions. A specific example is the discretization of feed-back signals in the models whereas in the body it is a continuous process.

Though all models follow the same basic concept, their differences arise mainly due to the representation of the body to one or more particular geometric shapes and the mathematical equation formulations for the control actions. In both the models under study, the human body is represented as one or more cylinders with more than one concentric layers in each. However, in Stolwijk's model, the head is considered as a sphere. In both models, each cylinder and each layer thereof represent a particular part or segment of the human body. The models also assume that the heat flow is radial only (except the heat flow through blood) and that the layers are uniform in thickness and homogeneous.

Heat exchange between the human thermal system and the environment continuously takes place at the skin surface. Heat production continuously occurs inside the body by various biochemical actions or by exercise, simply because of increased cellular activity. Heat generated inside the body is transferred to the skin surface area by convection through blood flow, and conduction and convection through the various layers in-between. From the skin, heat is transferred to the environment by: convection, conduction, radiation, evaporation of sweat, and conduction to an external cooling system, if any. Heat in excess of that which can be dissipated is stored in the tissues, resulting in a rise of body temperature. The mathematical relation of the body heat balance can be shown to be as:

$$\pm S = M \pm E \pm R \pm C \pm K - W, W \tag{5.1}$$

where,

S = net heat storage, or rate of heating (+) or cooling (-) of the body, W

M = net rate of total metabolic activity, W

E = rate of total evaporative heat gained (+) or lost (-), W

R = rate of heat gained (+) or lost (-) by radiation, W

C = rate of heat gained (+) or lost (-) by convection, W

K = rate of heat gained (+) or lost (-) by conduction, W

W = net rate of mechanical work accomplished, W

In a thermal equilibrium condition, S (or net rate of heat storage) should equal to zero.

5.2 Stolwijk's Model:

In this section we shall give a brief description of Stolwijk's model. A detailed description and discussion on this model has been given by Stolwijk (20) and Dhiman (4). In Stolwijk's model, the controlled or regulated system is divided into six segments: head, trunk, arms, hands, legs, and feet. Each of these segments, in turn, consists of four layers: core, muscle, fat, and skin. In addition, a central blood compartment links each of the segments together through appropriate blood flows. Thus, this model divides the human body into twenty-five compartments. A complete list of all the symbols used in the model, their definitions, and units are given in Table 1.

The controlling system receives from each of these twenty-five compartments the instantaneous temperature and the rate of change of temperature. These signals are then integrated and translated into effector command signals. The resulting effector actions, after being subjected to local modulation, if necessary, are applied to the controlled system.

Thermo-receptor output: The first step in the controller is to determine the thermo-receptor output. The equation for this calculation is:

$$ERROR(N) = T(N) - TSET(N) + RATE(N) * F(N)$$

Thus, the thermo-receptor output is equal to the difference between instanteneous temperature (T(N)) and the set-point or reference temperature for that compartment (TSET(N)), plus the product of the dynamic

sensitivity factor of the receptors (RATE(N)) and the rate of change of temperature (F(N)). At present, sensitivity has been set equal to zero. Next, for each compartment, the thermo-receptor output is tested for its sign. If it is positive, then it represents warm-receptor output and is re-defined as WARM(N); if it is negative, it indicates an output from cold-receptors and the absolute value is re-defined as COLD(N). Then, the total of all warm-receptor outputs from the six segments is added (WARMS) and similarly those of cold-receptors are also added (COLDS).

Effector command signals: The next step is to determine the type and magnitude of effector command signals which will go out to the periphery. The four effector commands considered in this model are: SWEAT, DILAT, STRIC, and CHILL, for sweating, vasodilation, vasoconstriction, and shivering respectively. The expressions for calculating the efferent commands are:

SWEAT = CSW*ERROR(1) + SSW*(WARMS-COLDS) + PSW*ERROR(1)*(WARMS-COLDS)

DILAT = CDIL*ERROR(1) + SDIL*(WARMS-COLDS) + PDIL*WARM(1)*WARMS

STRIC = -CCON*ERROR(1) - SCON*(WARMS-COLDS) + PCON*COLD(1)*COLDS

CHILL = (CCHIL*ERROR(1) + SCHIL*(WARMS-COLDS))*PCHIL*(WARMS-COLDS)

In these equations, two possible types of integration of afferent signals have been considered; they are:

1. Integration by linear addition of central and peripheral outputs.
2. Integration by multiplication of central and peripheral outputs.

Stolwijk puts the PSW, PDIL, and PCON equal to zero and supplies specific values for CSW, SSW, CDIL, SDIL, CCON, SCON, CCHIL, SCHIL, and PCHIL; that is, he considers the additive effect only.

Effector actions: The next step is to estimate the effector actions in the various compartments. The effector actions are: BF(N), Q(N), and E(N) for blood flow, metabolic heat production, and evaporative heat loss respectively. In the following relations for any segment I, N refers to the core, N+1 to the muscle, N+2 to the fat, and N+3 to the skin layers.

Core:

```
Q(N) = QB(N)
BF(N) = BFB(N)
E(N) = EB(N)
```

Thus, the effector actions in core remain at their basal level; the basal level being the actions at a thermoneutral condition.

Muscle:

```
Q(N+1) = QB(N+1) + WORKM(I)*WORK + CHILM(I)*CHILL
BF(N+1) = BFB(N+1) + Q(N+1) - QB(N+1)
E(N+1) = 0.0
```

For a particular segment, the heat produced in the muscle layer consists of the basal heat production plus the heat produced due to activity metabolism in that muscle layer and the heat produced due to shivering in the muscle. Blood flow to the muscle consists of basal blood flow plus one liter of blood for each watt of increased metabolic rate over the basal level. The evaporative heat loss is equal to zero.

Fat:

```
Q(N+2) = QB(N+2)
BF(N+2) = BFB(N+2)
E(N+2) = 0.0
```

For the fat layer, the effector actions remain at their basal level with the evaporative loss being equal to zero.

Skin:

```
Q(N+3) = QB(N+3)
BF(N+3) = (BFB(N+3) + SKINV(I)*DILAT)/(1. + SKINC(I)*STRIC)
E(N+3) = EB(N+3) + SKINS(I)*SWEAT*2.**((T(N+3)-TSET(N+3))/4.)
```

In the skin layer, metabolic heat production remains at its basal level. The blood flow is determined by the vasoconstriction and vasodilation commands. Since skin in some segments is more responsive than others, weighing coefficients for dilation (SKINV) and for constriction (SKINC) are different for each of the six segments. Evaporative heat loss consists of basal level plus regulatory sweating. In the calculation of regulatory sweating, the sweating command (SWEAT) is multiplied by: 1) SKINS(I), which accounts for the difference in responsiveness of different skin areas to sweating stimulation; and, 2) the term 2.**((T(N+3)-TSET(N+3))/4.), which is the modification effect of the central command by the local skin temperature.

Finally, since the sweat evaporation from skin is limited by the ambient vapor pressure, the maximum possible rate of evaporation, EMAX(I), is calculated:

```
EMAX(I) = (PSKIN-PAIR)*2.14*(H(I)-HR(I)*S(I))
```

where, PSKIN and PAIR are the water vapor pressures at the skin surface and in the environment respectively, 2.14 is the Lewis relationship, H(I) is the total heat transfer coefficient, HR(I) is the radiant heat transfer coefficient and S(I) is the skin surface area. Whenever E(N+3) exceeds EMAX(I), it is set equal to EMAX(I).

Heat flows: Next, the net heat flows into or out of each of the twenty-five compartments are computed. First, the convective heat flow, BC(K), and the conductive heat flow, TD(K), are calculated:

$$BC(K) = BF(K)*(T(K) - T(25))$$

$$TD(K) = TC(K)*(T(K) - T(K+1)),\ K = 1,24$$

Then, all the net heat flow components are totaled for each compartment to get the heat flow, HF(K), for that compartment.

$$HF(K) = Q(K) - E(K) - BC(K) - TD(K)$$

$$HF(K+1) = Q(K+1) - BC(K+1) + TD(K) - TD(K+1)$$

$$HF(K+2) = Q(K+2) - BC(K+2) + TD(K+1) - TD(K+2)$$

$$HF(K+3) = Q(K+3) - BC(K+3) - E(K+3) + TD(K+2) - H(I)*(T(K+3) - TAIR)$$

where, I = 1,6 and K = 4*I-3. For the central blood compartment, the net heat flow consists of the sum of all the convective heat flows minus the respiratory heat loss:

$$HF(25) = HF(25) + BC(K),\ K = 1,24$$

then,

$$HF(25) = HF(25) - 0.08*WORK.$$

where, 0.08*WORK adjusts for respiratory dry heat loss.

Integration time: The optimum integration time is determined in the next step. Initially the time increment for numerical integration is set to one minute. Based on this increment, the temperature increment in each compartment is calculated; if any of these temperature increments exceeds $0.1^{o}C$, then the time increment, DT (in hours), is reduced

so that the maximum temperature change in any compartment in each iteration is kept to $0.1^{o}C$ or less.

```
DT = 0.016666667
F(K) = HF(K)/C(K)
U = ABS(F(K)), K = 1,25
```

If, U*DT is greater than 0.1, then: DT = 0.1/U.

Based on the time increment thus arrived at, the next section calculates the new temperatures and the new elapsed time.

```
T(K) = T(K) + F(K)*DT, K = 1,25
TIME = TIME + DT
```

If output is desired at this time, then the program proceeds on to the next step; otherwise it reverts back to the step where new thermo-receptor output is calculated.

Output: If output is desired then the value of variables which refer to compartments or segments are combined to yield values for reporting thermo-physiological variables. These variables are: cardiac output (CO), heat produced (HP), evaporative heat loss (EV), mean skin temperature (TS), and skin blood flow (SBF).

The flow-diagram of the model in Figure 2 shows the major steps in the computations.

5.3 Modification of Stolwijk's Model:

A number of modifications to Stolwijk's model have been made as part of this study. These modifications have been made to make the model more flexible and up-to date. The modifications can be catagorized as:

1. Read in variables. These include new variables which were constants in different equations of the original model and the modified values of originally read in constants.
2. Parameter values. These include modified parameter values in different equations.
3. Equations. These include new and modified equations.

Body surface area: Instead of supplying the model with the surface areas of different body segments, we now read in the percentage distribution of the total skin area for all the segments (PS(I)). We also read in the weight (WT) and height (HT) of the subject. The model then calculates the total skin area (SA) by the modified DuBois formula (18) and the skin area for different segments.

```
SA = 0.208 + 0.945*(0.007184*(HT**0.725)*(WT**0.425))
S(I) = PS(I)*SA, I = 1,6
```

Heat capacitance: The heat capacitance, C(I), of all the compartments is also computed instead of being supplied as constants for the controlled system. For the calculation of C(I), the following information is supplied to the program: the percentage distribution (by weight) of different tissue types in each segment (PCT(K)), the specific heat of fat (SHF), the specific heat of bone (SHB), and the specific heat of tissue (SHT). For the core layer of each segment, C(I)'s are calculated as follows:

```
C(J) = (WT*SHF*PCT(K) + WT*SHB*PCT(K+1) + WT*SHT+PCT(K+2))/100.
```

where, I = 1,6, J = 4*I-3, and K = 12*(I-1) + 1. Calculations for muscle, fat, and skin layers of each segment are done in a similar way.

Instead of being used as constants in different equations, basal metabolism (WORKB) and mechanical efficiency (WEFF) have now been made variables whose values are supplied to the model as initial conditions.

Basal blood flows and initial temperatures: The basal blood flow levels in the modified model are different than those used by Stolwijk. Similarly, all the input constants have been checked and changes have been made, where appropriate, to make them up-to-date. Also, the initial input temperatures for all the compartments have been recalculated from experimental results to reflect the differences in experimental conditions.

Set-point temperatures: To make the model adaptable to the concept of two set-point or reference temperatures, one for cold and the other for warmth, two set-points are read in (TSETC for cold and TSETW for warmth) for each of the compartments. Thus, the ERROR calculations are modified as:

```
IF(T(N).GT.TSETW(N))ERROR(N) = T(N) - TSETW(N) + RATE(N)*F(N)
IF(T(N).LT.TSETC(N)) ERROR(N) = T(N) - TSETC(N) + RATE(N)*F(N)
```

In the present study however, we have used the same values of temperatures for TSETW and TSETC.

Lewis relationship: Stolwijk used a constant Lewis relation (LR) of 2.14; however, LR is actually a variable dependent on the barometric pressure (BARO). So, we supply the value of BARO as an experimental condition to the model and LR is calculated in the model as follows:

```
LR = 2.2*(760./BARO)
```

CHILL calculation: The calculation of CHILL as done in Stolwijk's model may lead to a false shivering signal even when the thermo-receptors sense warmth. The reason for this possibility is that in the present equation the additive and multiplicative integrations are multiplied. So, to avoid that situation, we have separated the two integration effects and only one of them is used in the calculation. Thus, the modified relation is:

```
CHILL = -CCHIL*ERROR(1) - SCHIL*(WARMS-COLDS) + PCHIL*
                                        ERROR(1)*(WARMS-COLDS)
```

In our calculations, we have used only the additive effect and as such the value of PCHIL has been set equal to zero.

Heat of sweat: The regulatory sweat rates are calculated by the present model in heat units (watt); however, in experiments the sweat rates are measured in weight units (gm/hr). So, to get the sweat rate in weight units, we divide the present output by the heat of vaporization of sweat. However, the heat of vaporization of sweat is not a constant, Kerslake (15), but a variable dependent on skin wettedness and skin temperature. Consequently, this factor has also been taken into account to get the weight of sweat secreted. The sequence of calculations is as follows:

```
EWET(I) = E(N+3)/EMAX(I), I = 1,6 and N = 4*I-3
  AEWET = AEWET + EWET(I)*(S(I)/SA)
   PPHG = PSKIN(I)
    SVP = EMAX(I)
   PWET = EWET(I)
   TEMP = T(N+3)
   CALL SWVP(PWET,PPHG,SVP,TEMP,HVAPS)
```

```
EVCP(I) = HVAPS
EG(N+3) = E(N+3)/EVCP(I)
SWCG(I) = SWPCP(I)/EVCP(I)
SWEAG   = SWEAG + SWCG(I)
```

The calculations inside the SUBROUTINE SWVP are:

```
PHIS  = PWET + ((1. - PWET)*PPHG)/SVP
K1    = 2806.55 - 762.8*PHIS + 390.2*(PHIS**2.)
K2    = 1.1435 + 1.75*PHIS - 0.6386*(PHIS**2.)
HVAPS = (K1 - K2*(TSK - 30.))*0.0002778
```

Respiratory heat loss: In addition to the skin surfaces, heat transfer with the environment also takes place in the respiratory tract. In Stolwijk's model this heat transfer is calculated by 0.08*WORK and it is assumed that the heat transfer takes place between the central blood pool and the environment. However, we have changed this relation, because we believe that since the heat transfer take place in the respiratory tract, its effect should be in the trunk-core layer not in central blood pool. Heat transfer in the respiratory tract take place in two forms, Fanger (7): evaporative heat loss (RWET) and convective heat loss (RDRY).

```
RWET = 0.0023*WORK*(44. - PAIR(I))
RDRY = 0.0014*WORK*(34. - TAIR(I))
```

To calculate the heat of vaporization in the respiratory tract, we assume that it is 100% wet and use the following relations:

```
HVP  = (2433.95 - 2.2549*(T(5) - 30.))*0.0002778
E(5) = RWET
EG(5) = E(5)/HVP
```

We also modify the heat flow from the trunk-core to account for these heat losses. First, HF(5) is calculated according to the relation given by Stolwijk and in this calculation RWET is accounted for. Next, RDRY is subtracted from this HF(5) value:

```
HF(5) = HF(5) - RDRY
```

Maximum blood flow: Next, to take into account the maximum physiological limit on blood flows to different layers, we calculate the maximum blood flows (MAXBF(K)) by the following relations:

```
Core------ MAXBF(4*I-3) = BFB(4*I-3)
Muscle---- MAXBF(4*I-2) = BFB(4*I-2)*18.
Fat------- MAXBF(4*I-1) = BFB(4*I-1)
Skin------ MAXBF(4*I)   = BFB(4*I)*7.
```

where, I = 1,6. Then, we check if any of the calculated blood flows exceed these limits; if it does then it is set equal to the maximum limit:

```
IF(BF(I).GT.MAXBF(I)) BF(I) = MAXBF(I), I = 1,24
```

External cooling: Since we want use the model for conditions when the body is cooled by the use of a dry-ice cooling jacket, some program changes were necessary. Dhiman (4) suggested the following modification to the heat transfer equation for trunk-core:

```
HF(8) = HF(8) - (0.517*137.*0.75)
```

where, HF(8) is first calculated as outlined by Stolwijk but with changed values for convective heat transfer coefficient (HC(8)) and radiant heat transfer coefficient (HR(8)). In the above equation, 0.517 refers to a constant dry-ice sublimation rate in Kg/hr; 137.0 refers to the heat of sublimation of dry-ice; and, 0.75 refers to the fact that 75% of heat of sublimation comes from the body, i.e., 75% of the cooling effect of the

jacket goes directly to the body (CEFF). In this study, however, we have modified this approach. Instead of changing the values of HC(8) and HR(8), we have retained the same values used by Stolwijk but have used the temperature of the air inside the jacket as TAIR for the trunk-skin portion instead of the ambient air temperature. This has resulted in making TAIR a variable rather than a constant for all the segments of body. We have also made the sublimation rate (SUBRAT) a variable over the time of exposure; this change has been made because as of this time we are not sure whether the sublimation rate remains constant throughout the exposure time. However, in the simulations for this study we have used a constant sublimation rate. Thus, in the modified model, HF(8) is first calculated using Stolwijk's approach and then modified as (where, 0.159 = latent heat of vaporization, W/gm):

```
HF(8) = Q(8) - BC(8) - E(8) + TD(7) - H(I)*(T(8) - TAIR(I))

HF(8) = HF(8) - (SUBRAT(K)*0.159*CEFF)
```

Cumulative sweat loss: We are also interested to know the cumulative sweat loss in gm and to calculate this the following relations have been used:

```
EVG(K) = EG(K)*DT

CEVG   = CEVG + EVG(K)
```

Heart rate: In our experiments, we have always measured the heart rate of the subject and as such we are interested to know the heart rate (HEARTR) in beats/min from the model. To compute HEARTR, we divide cardiac output (CO) by the stroke volume (STROV). The stroke volume is not a constant but a variable dependent on many factors; however, with some loss in accuracy, this can be taken as constant and in our model it has been assumed as constant:

```
STROV = 0.09
HEARTR = CO/STROV
```

Evaporative heat loss: Total evaporative heat loss consists of not only the evaporative losses from different skin segments but also the loss in the respiratory tract. Thus, evaporative heat loss (EV) is calculated by adding the losses from 6 skin compartments plus respiration.

Mean body and skin temperatures: In Stolwijk's model, the mean skin temperature (TS) and mean body temperature (TB) are calculated by using constant values of 3.9 and 68.79 W*h/C as skin heat capacitance (CT) and body heat capacitance (CN), respectively. However, we have already made modifications whereby the heat capacitance of different layers are calculated depending on the subject weight. Thus, CT and CN are no longer constants. So, in the calculation of TS and TB, the following changes have been made:

```
CT = CT + C(4*I), I = 1,6
TS = TS + T(4*I)*C(4*I)/CT
CN = CN + C(N), N = 1,25
TB = TB + T(N)*C(N)/CN
```

Maximum body temperature: Finally, we have made a change in the stopping criteria also. Since many physiologists consider that when the body temperature rises above 41^{o}C the body thermo-regulatory mechanisms fail, we have added a stopping criteria whereby if TB rise above 41^{o}C, the simulation will come to a stop.

To make a distinction between the original Stolwijk model and the model that we have after all these modifications have been made, we shall henceforth refer to the modified model as the KSU-Stolwijk model. A simple flow diagram of the KSU-Stolwijk model is shown in Figure 3. The complete FORTRAN program of the model with the data used is given in Appendix C.

5.4 Gagge's Model:

A forerunner of Gagge's model was the one proposed by Gagge, Stolwijk, and Nishi (9). This model was developed to determine an environmental temperature scale based on the knowledge of the physiological heat regulation as it applies to comfort, temperature sensation, and health. Gagge's model is a revised version of the above model. This model considers the control of body temperature to be accomplished primarily by the mean skin temperature (TSK) and a central core temperature (TCR); the latter may be the rectal or the esophageal temperature. There are seven independent environmental variables in the model. They are: a) the metabolic rate (MR), b) the work accomplished (WK), c) the combined heat transfer coefficient (CTC), d) the conductive heat transfer coefficient (CHC), e) the insulation of normal clothing used (CLO), f) the dry bulb temperature of ambient air (TA), g) the humidity of ambient air as measured by relative humidity, wet bulb temperature, or dew-point temperature. The principal physiological factors predicted by the model are: 1) mean skin temperature (TSK), 2) core temperature (TCR), 3) total evaporative heat loss (EV), 4) skin blood flow (SKBF), and 5) ratio of mass of the skin shell to mass of the central core (ALPHA).

In Gagge's model, a human body is considered as a single cylinder with two concentric layers. The inner layer is the central core and the outer layer is the skin shell, Figure 4. Heat flow is considered to be by conduction in the radial direction and by convection through the blood flows. The units used throughout are Watts per unit area of body surface. Different considerations in this model formulation have been discussed in detail by Gagge, Stolwijk, and Nishi (9). We shall confine our discussion to the FORTRAN program itself. A complete list of symbols, their definitions and units are given in Table 2.

The model is based on an average man with the following characteristics:

Body weight = 70.0 Kg

Body surface area = 1.8 m^2 (by DuBois formula)

Ratio of body's radiating area to total area = 0.72

Minimum skin conductance = 5.28 $W/(m^2.{}^oC)$

Normal skin blood flow = 6.3 $liters/(m^2.h)$

The values of different coefficients used in the model are:

Specific heat of blood = 1.163 $W.h/(1.{}^oC)$

Latent heat of water = 0.68 W.h/gm

Specific heat of body = 0.97 $W.h/(Kg.{}^oC)$

Lewis relation at sea level = 2.2 $^oC/mmHg$

Sea level barometric pressure = 760.0 mmHg

Stefan-Boltzmann constant = 5.67E-8 $W/(m^2.K^4)$

As an input to the model, the values of different independent variables are supplied. The independent variables are: metabolic rate (MR), work rate accomplished (WK), intrinsic clothing insulation in clo units (CLO), linear radiation exchange coefficient (CHR), convective heat transfer coefficient (CHC), barometric pressure (BARO), ambient air temperature (TA), mean radiant temperature (TR), and ambient vapor pressure (PPHG).

Initially the body is considered to be in a thermo-neutral condition. As an initial condition, the following values are assigned to the different dependent and independent variables:

TSK = 34.0

TCR = 37.0 (rectal) or 36.6 (esophageal)

SKBF = 6.3

ALPHA = 0.1

EV = 5.0

For the sedentary case:

MR = 58.2

RM = MR

WK = 0.0

CHR = 5.0

CHC = 2.9

For the exercising case:

CHC = 5.4 (bicycle ergometer at 50 RPM)

CHC = 6.0 (bicycle ergometer at 60 RPM)

Initial value: The initial step is to calculate the initial definitions: respired evaporative heat loss (ERES), respired convective heat loss (CRES), Burton clothing efficiency factor (FCL), and operative temperature (TO).

```
ERES = 0.0023*RM*(44. - PPHG)
CRES = 0.0012*RM*(34. - TA)
FCL  = 1./(1. + 0.155*CTC*CLO)
TO   = (CHR*TR + CHC*TA)/CTC
```

Dry heat loss: The first step in the simulation is to calculate the dry heat loss (DRY) which consists of conductive and convective heat transfer from skin to the environment. To compute this, the following factors need to be calculated first: clothing surface temperature (TCL), factor to increase body surface due to clothing (FACL). Since convective heat transfer coefficient (CHC) varies with TSK and TCL during regulation, it needs to be recalculated also. This leads to recalculation of CTC and FCL.

```
TCL = TO + FCL*(TSK - TO)

FACL = 1. + 0.15*CLO

CHR = 4.*5.67E - 08*((TCL + TO)/2. + 273.)**3.*FACL*0.72

CTC = CHC + CHR

FCL = 1./(1. + 0.155*CTC*CLO)

DRY = CTC*FCL*(TSK - TO)
```

Heat storages: Next, the following are calculated: the rate of heat storage in body core (HFCR), the rate of heat storage in skin shell (HFSK), thermal capacity of core (TCCR), thermal capacity of skin shell (TCSK), change in core temperature (DTCR), change in skin shell temperature (DTSK).

```
HFCR = RM - ERES - CRES - WK - (5.28 + 1.163*SKBF)*(TCR - TSK)

HFSK = (5.28 + 1.163*SKBF)*(TCR - TSK) - DRY - (EV - ERES)

TCCR = 0.97*(1. - ALPHA)*70.0

TCSK = 0.97*ALPHA*70.0

DTCR = (HFCR*1.8)/TCCR

DTSK = (HFSK*1.8)/TCSK
```

Integration step: The third step consists of determining the optimum integration step. Initially the time increment is set to one minute. However, if the absolute values of DTCR or DTSK is greater than 0.1, then the time increment is reduced so that DTCR or DTSK do not change by more than 0.1.

Based on the time increment thus arrived at, elapsed time (TIM) and new temperatures are calculated:

```
TIM = TIM + DTIM

TSK = TSK + DTSK*DTIM

TCR = TCR + DTCR*DTIM
```

Control signals: The next step is to calculate the control signals: SKSIG from skin-shell and CRSIG from body core. These control signals are deviations from set-point or reference temperatures.

SKSIG = TSK - 34.0

CRSIG = TCR - 37.0

If any of these signals is negative, then its absolute value is redefined as "cold signal" (COLDS or COLDC):

COLDS = - SKSIG

WARMS = 0.0

and/or,

COLDC = - CRSIG

WARMC = 0.0

If the signals are positive, then they are redefined as "warm signals" (WARMS or WARMC):

WARMS = SKSIG

COLDS = 0.0

and/or,

WARMC = CRSIG

COLDC = 0.0

Effector commands: After getting the control signals, the next step is to calculate the type and magnitude of the effector command signals and the effector actions. Skin blood flow (SKBF) is controlled by vasoconstriction and vasodilation. The command for these vasomotor functions are calculated as follows:

STRIC = 0.5*COLDS (for vasoconstriction)

DILAT = 150.*WARMC (for vasodilation)

We should note here that the coefficient values of 0.5 and 150.0 may change due to acclimatization and thereby affect the time to equilibrium.

```
SKBF = (6.3 + DILAT)/(1. + STRIC)
```

Regulatory sweating (REGSW) is controlled both by body temperature and the peripheral skin temperature:

```
REGSW = 250.0*(ALPHA*SKSIG + (1. - ALPHA)*CRSIG)*EXP(SKSIG/10.7)
```

Computationally, REGSW could have a negative value which is, however, physiologically impossible. So, REGSW is set equal to zero if it is indeed calculated to be a negative number. REGSW is calculated in $gm/h/m^2$; multiplying this by the heat of vaporization (0.68 W.h/gm), it is converted to evaporative heat loss (ERSW):

```
ERSW = 0.68*REGSW
```

This equation assumes that all the sweat secreted is evaporated; however, this might not be the case if REGSW is more than that can be evaporated. The maximum possible evaporation (EMAX) depends on the Nishi permeation efficiency factor (FPCL) for clothing and saturated vapor pressure at TSK (SVP):

```
FPCL = 1./(1. + 0.143*CHC*CLO)
 SVP = EXP(18.66855 - (4030.1825/(TSK + 235)))
EMAX = 2.2*CHC*(SVP - PPHG)*FPCL/FACL
```

Even in the thermoneutral condition when there is no regulatory sweating, there is some diffusion of sweat from the inner layers of skin to the outer layers. This form of sweating (EDIF) is estimated to keep 6% of total skin area wet. So, the total skin wettedness (PWET) is calculated as follows:

PRSW = ERSW/EMAX

PWET = 0.06 + 0.94*PRSW

Evaporative heat loss due to diffusion is:

EDIF = PWET*EMAX - ERSW

Total evaporative heat loss (EV) consists of three parts: respired evaporative heat loss (ERES), evaporative heat loss from sweating (ERSW), and evaporative heat loss due to diffusion (EDIF).

EV = ERES + ERSW + EDIF

Now we check whether or not the PWET calculated as before exceeds 1.; if it exceeds, then the difference between ERSW and EMAX is defined as unevaporated sweat loss (DRIP) and ERSW is set equal to EMAX. For such a situation the calculations are:

EV = ERES + EMAX

DRIP = (ERSW - EMAX)/0.68

ERSW = EMAX

EDIF = 0.0

PRSW = 1.0

When the body senses cold then, in addition to vasoconstriction there could be shivering of the core muscles. This action will result in an increased total metabolic activity (RM). Moreover, due to the change in skin blood flow (SKBF), ALPHA will also change. Thus:

ALPHA = 0.0442 + 0.3509/(SKBF - 0.01386)

RM = MR + 19.4*COLDS*COLDC

Variable calculations: After the time of exposure specified, the model is now ready to give reevaluated values of the following dependent variables:

CHR, CTC, FCL, TSK, TCR, REGSW, EMAX, ERSW, EDIF, EV, DRIP, PRSW, PWET, ALPHA, and RM. If desired, then the rate of body heat storage (STORE) and the rate of change of mean body temperature (RTBM) can also be calculated by using the following relations:

STORE = RM - CRES - WK - EV - DRY

RTBM = STORE*1.8/(70.0*0.97)

The model next goes on to compute other variables relating to establishing an effective temperature scale for the measurement of human comfort zone. Since this part of the program is not directly related to the purpose of this study, the rest of the program has been deleted. A simple flow-diagram of the major steps of the model is given in Figure 5.

5.5 Modification of Gagge's Model:

In carrying out the modifications of Gagge's model to make it more flexible and up-to-date, we have also changed units from W/m^2 to W. As a result of this change in units, the model output will be in appropriate units for a specific subject. To make the model reflect the recent advances made, we checked every coefficient and constants used in different equations as well as those supplied as inputs to the model. Specific examples of the changes of this category are: specific heat of body (SPHTB) is now equal to 0.91 W*h/Kg/^{o}C instead of the original value of 0.97 W*h/Kg/^{o}C; likewise, basal skin blood flow (BSBF) is now 15.0 $1/m^2/h$ instead of 6.3 $1/m^2/h$.

Body surface area: In the original model, the body surface area was an imput to the model while in the modified Gagge's model (which we will, henceforth, refer to as KSU-Gagge model) it is calculated by the model

itself; only weight (WT) in kg and height (HT) in cm of the subject needs to be supplied. The body surface area (SA) in m^2 is calculated by using modified DuBois formula (18):

```
SA = 0.208 + 0.945*(0.007184*(HT**0.725)*(WT**0.425))
```

Sequence of calculations: Another major computational change is in the sequence of various steps of calculations. In the original model, the thermo-receptor output was calculated towards the end of the program; in KSU-Gagge model, this is calculated at the beginning of simulation. This distinction will be clear if we look at the flow diagrams of Gagge and KSU-Gagge models in Figures 5 and 6, respectively.

Lewis relationship: Lewis relation (LR) has a value of 2.2 at the sea level barometric pressure; however, this value changes as the barometric pressure changes. Similarly, convective heat transfer coefficient (CHC) also changes with the change of barometric pressure. Gagge has used the sea-level values for LR and CHC in his model; he has, however, given the relationship between barometric pressure (BARO), and LR and CHC. In the KSU-Gagge model we have incorporated these relations, so that LR and CHC become variables instead of constants.

```
LR = (2.2*760.0)/BARO

CHC = CHC*((BARO/760.0)**0.55)
```

Ambient vapor pressure calculation: In Gagge's model, the ambient vapor pressure is read in as one of the input constants; in the KSU-Gagge model, a table of water vapor pressures valid for the temperature range of 5-50^{o}C is read in and then the ambient air temperature (TA) and relative humidity (RH) are supplied as experimental conditions. Using the following relation,

the model then computes the appropriate ambient vapor pressure (PPHG):

```
I = TA/5
PPHG = RH*(P(I) + (P(I+1) - P(I))*(TA-5*I)/5.)
```

Metabolic activity: Gagge's model needs the input of total metabolic activity and the mechanical work done. However, in the KSU-Gagge model the inputs are total metabolic activity (MR), basal metabolic activity (BM), and mechanical efficiency of work done (WE) and the model itself calculates the work output.

```
WK = (MR - BM)*WE
```

Heat of sweat: Gagge has used a constant value of 0.68 W*h/gm as the heat of vaporization of sweat (HVAPS). HVAPS, however, is not a constant but a variable dependent on the skin wettedness (PWET) and skin temperature (TSK). In the KSU-Gagge model HVAPS is calculated at every iteration. Initially, HVAPS is calculated on the assumption that the subject is in a thermoneutral condition and in this condition PWET is equal to 0.06 because of the diffusion loss. HVAPS is calculated by the SUBROUTINE SWVP and the calculations inside the subroutine are:

```
PHIS = PWET + ((1. - PWET)*PPHG)/SVP
K1 = 2806.55 - 762.8*PHIS + 390.2*(PHIS**2.)
K2 = 1.1435 + 1.75*PHIS - 0.6386*(PHIS**2.)
HVAPS = (K1 - K2*(TSK - 30.))*0.0002778
```

where SVP is the saturated vapor pressure at TSK.

Extra outputs: Next, the model computes all the initial definitions dependent variables as done in Gagge's model. However, we have added a few additional outputs. The new outputs are: mean body temperature, cardiac output and heart rate. Cardiac output (CO) is obtained by adding skin blood flow and core blood flow. Heart rate (HEARTR) is obtained by dividing CO with a

constant stroke volume (STROV) of 0.09 liters/stroke. Mean body temperature may be calculated in three ways: a) from thermal capacities, b) from weighted average of temperature increments, and c) from heat storage and specific heat of the body. For conditions (b) and (c), the initial estimates are made from a weighted average of temperatures. Thus, for the initial condition these outputs are calculated as follows:

```
TCCR = (1. - ALPHA)*SPHTB
TCSK = ALPHA*SPHTB
MBT1 = TCR*TCCR/SPHTB + TSK*TCSK/SPHTB
MBT2 = 0.65*TCR + 0.35*TSK
MBT3 = MBT2
CRBF = BCRBF
  CO = CRBF + SKBF
HEARTR = CO/STROV
```

Control actions: The control signals are calculated exactly as they are calculated in the Gagge model. After the control signals have been calculated, the metabolic heat production due to shivering (SHIV) is calculated and then this heat is added to the activity and basal metabolic heat production (MR) to get the total metabolic heat production (RM).

```
SHIV = 19.4*COLDS*COLDC*SA
  RM = MR + SHIV
```

The skin blood flow (SKBF) is computed in the same manner as done in the Gagge model. However, to guard against the calculated SKBF exceeding the physiological limits, the maximum skin blood flow (MAXSBF) is calculated:

```
MAXSBF = 7.0*BSBF
```

where, BSBF is the basal skin blood flow. If the calculated SKBF is greater than MAXSBF, then SKBF is set equal to MAXSBF. Next, the core blood flows (CRBF) are calculated. CRBF consists of the basal core blood flow (BCRBF) plus one liter of blood flow for every watt of metabolic heat produced in excess of the basal level. Thus,

CRBF = BCRBF + (RM - BM - WK)

The maximum physiological limit for the core blood flows (MXCRBF) is calculated as follows:

MXCRBF = BCRBF + 18.0*BBFM

where, BBFM is the basal blood flow to the muscles in the core.

Rate of sweat secretion (REGSW) and skin evaporative heat loss (ERSW) are calculated as outlined in the Gagge model. However, the EMAX calculation is slightly different:

EMAX = SA*LR*CHC*(SVP - PPHG)*FPCL/FACL

In addition to the calculation of PRSW, EDIF and EV, the sweat loss in gm/h (SWEAT) is also calculated; then a cumulative sweat loss (CEVG) for the time of exposure is also calculated. When regulatory evaporative loss (ERSW) is less than EMAX, then

EV = ERES + ERSW + EDIF

SWEAT = (ERSW + EDIF)/HVAPS

However, when ERSW is greater than EMAX, then

DRIP = (ERSW - EMAX)/HVAPS

ERSW = EMAX

SWEAT = DRIP + (ERSW/HVAPS)

Thus,

CEVG = CEVG + SWEAT

External cooling: The calculation of heat storage in the skin shell (HFSK) is slightly modified to account for the cooling effect provided by the use of the dry-ice cooling jacket. First, the heat storage HFSK is calculated as outlined by Gagge. Next, we calculate the cooling effect provided by the dry-ice jacket to the body (COOL) and then subtract this from HFSK to get the adjusted HFSK. As of this stage, our experimental results indicate that the sublimation rate of dry-ice remains fairly constant over the period of exposure; however, it does vary due to pocket location. In our COOL calculation we have provided for variable sublimation rates to be used, if applicable, but in our simulations we use a constant sublimation rate. Thus the adjustments made are:

```
COOL = SUBRAT(K)*0.159*CEFF
```

where, CEFF is the percentage of cooling provided by the jacket that goes directly to the body, 0.159 is the latent heat of sublimation of dry-ice (in W*h/gm), and SUBRAT(K) is the sublimation rate for the period K when the total exposure time is divided into periods of 30 minutes.

Integration step: The calculation of the integration step has been changed; the present form is similar to that of the KSU-Stolwijk model. With the present modification, the integration step is one minute or such that TSK or TCR do not change by an amount greater than $\pm 0.1^{\circ}C$.

```
DTIM = 1./60.
   U = ABS(DTSK)
```

If U*DTIM is greater than 0.1, then set

```
DTIM = 0.1/U
```

and, calculate

U = ABS(DTCR)

If U*DTIM is greater than 0.1, then set

DTIM = 0.1/U

Mean body temperature: In the KSU-Gagge model, the mean body temperature is calculated at every iteration. However, mean body temperature being a concept rather than a measureable variable, considerable disagreement prevails on how to calculate it. Basically, there are three approaches to compute this: 1) mean body temperature (MBT1) from the heat capacitances of various segments and of the total body, 2) from a weighted average of the changes in TCR and TSK (MBT2), 3) from the thermal capacity and heat storages in different segments (MBT3). For approaches 2 and 3, the initial estimate of mean body temperature is made from a weighted average of TCR and TSK in the initial condition. As an academic interest to see how these three approaches to the estimation of supposedly the same quantity vary, we calculated all three of MBT1, MBT2 and MBT3.

MBT1 = TCR*TCCR/SPHTB + TSK*TCSK/SPHTB

DMBT = 0.70*DTCR*DTIM + 0.30*DTSK*DTIM

MBT2 = MBT2 + DMBT

STORE = RM - CRES - WK - EV - DRY - COOL

RTBM = STORE/SPHTB

MBT3 = MBT3 + RTBM*DTIM

If an output is desired at this time, then the program goes on to print the output with various dependent variables.

Since it generally recognized that the normal thermo-regulatory functions of the body fail when the mean body temperature exceeds 41 ^{o}C, the model compares each of MBT1, MBT2 and MBT3 with 41 ^{o}C. If any of

these exceed 41 °C, the simulation comes to a stop. If the limit is not exceeded and the total elapsed is also not more than the specified time for simulation, the model continues on with the simulation.

The simplified flow diagram of the model in Figure 6 and the complete FORTRAN program with the data used in Appendix D will further clarify the KSU-Gagge model.

6. EXPERIMENTAL CONDITIONS

Experimental data used to compare versus the model simulations were gathered at Kansas State University in two series of experiments, one in 1972 and the other in 1974. The 1972 data (Experimental series one) were for a sedentary subject; the 1974 data (Experimental series two) were for two subjects exercising on a bicycle ergometer. In both series of experiments, there were days when the subject(s) did not wear any external cooling device and there were days when the subject(s) did wear an external cooling device. The external cooling device used in both series of experiments were dry-ice cooling jackets; however, the dry-ice cooling jacket designs were drastically different.

Experimental series one: Experimental conditions of this series of experiments have been described in more detail in Konz, Hwang, Perkins and Borell (16). All the experimental sessions took place with a single seated subject. The subject wore shorts (with a clo value of 0.1) and, on days with external cooling, a cooling garment. The experimental environments were 43.3°C dry bulb temperature; relative humidity was 45%; air velocity was 0.1 m/sec. The dry-ice jacket had twelve pockets, each holding a slab of dry ice approximately 80X80X20 mm. For the cooling day's data (August 7) used in this study, the subject had a piece of plastic film with air bubbles pinned to his jacket and he also wore an elbow-length-sleeve poplin jacket over this ensemble (estimated total clo value = 0.4). For each experimental session the subject was weighed and thermistors were taped on at various locations over the body. On days with external cooling, the dry-ice jacket ensemble was then put on and the pockets were held against the body with an EKG strap. After

the subject had entered the experimental chamber, he sat on a stool placed on a scale; he was weighed at intervals while his heart rate and temperatures were recorded. He then measured his own blood pressure. Temperatures were recorded every ten minutes; weights, heart rate and blood pressures were recorded every 20 minutes. The subject normally remained inside the chamber for 120 minutes but on some days he was inside for 100 or 240 minutes. The percentage of cooling provided by the cooling jacket that goes directly to the body (CEFF) has been estimated to be 55% for this series of experiments.

Experimental series two: This series of experiments was conducted in 1974 by Duncan (5) as part of his doctoral dissertation. For the days whose data have been used in this study, the dry bulb environmental temperature was 45°C and the relative humidity was 47%. On the day with external cooling, the surface of dry ice facing the skin was 1600 sq. cm and the insulation between skin and dry ice was low (the conductance was 17.1×10^{-2} Kcal/sec-sq.-cm-°C). The cooling jacket had 12 larger pockets interconnected into four groups of three slabs aligned vertically. Insulation covered the group of three slabs as well as each slab individually. In addition, each pocket was insulated from the environment by the outer garment - composed of a layer of nylon, a layer of nylon polyester insulation, and another layer of nylon. On days with no external cooling, subjects wore a longsleeved shirt, a pair of tennis shoes, socks, undershorts and slacks. This clothing ensemble had a measured clo value of 0.49. On days with dry ice cooling, the long sleeved shirt was replaced by the cooling jacket; this clothing ensemble

had a measured clo value of 0.9. In this series of experiments, there were two subjects, C and J, and they pedalled a bicycle ergometer at a work output of about 64 watts. Temperatures at various locations on the body (as well as in the rectum) was measured at five minute intervals. At the same time, their heart rates were also recorded. After about 30 minutes of exposure to the experimental conditions, their oxygen consumption was measured to calculate the metabolic rate. The subjects were inside the experimental chamber for 45 minutes on non-cooling days and for 60 minutes on days with dry ice cooling. The percentage of cooling provided by the redesigned jacket that goes directly to the body (CEFF) has been estimated to be 90% for the garment.

7. RESULTS

7.1 Without External Cooling:

Two sets of plots have been made for the results where the subject had no external cooling. In the first set, Fig. 7 to 17, the plots are for a sedentary subject. The second set, Fig. 18 to 28, are the plots for the case where two subjects (C and J) were exercising on a bicycle ergometer.

Sedentary: The data of experimental series one (i.e., 1972) are for the case of a sedentary subject. Fig. 7 to 17 show the different plots that have been made for the experimental data and the corresponding simulation results. For the experimental data, plots have been made for one particular day (July 31, 1972); however, the same set of experimental conditions were repeated on two other days (July 5 and July 24). To show the variation on different days for the same set of experimental conditions even with the same subject, on each plot a vertical line has been drawn at each data point showing these deviations. The solid line through the filled circle points indicates the experimental results of July 31, 1972 (and the vertical line showing the deviations on other days). The dotted line through the filled triangle points shows the simulated results of the KSU-Stolwijk model; the dotted line through the filled square points shows the simulation from the KSU-Gagge model.

Fig. 7 to 10 show the plots of skin temperatures of head, trunk, arms and legs for both the experimental data and the KSU-Stolwijk model simulation. Taking into consideration the variation in experimental data

even for the same conditions, we notice a good fit between the data and the simulation both quantitatively and in trend. Fig. 11 shows the weighted mean skin temperature of the experimental data and the simulations from both the models. The KSU-Gagge model seems to give a better fit than the KSU-Stolwijk model. Fig. 12 shows the plot of rectal temperature from experimental data against simulated core temperature from both models; for the KSU-Stolwijk model, it is the trunk core temperature. The KSU-Stolwijk model simulation shows the dip at the beginning and then follows closely for the rest of the exposure time. The KSU-Gagge model simulation does not show this dip, but gradually converges to the experimental data as the exposure time increases. Weighted mean body temperature (Fig. 13) is calculated from experimental data and the model simulations. In case of the KSU-Gagge model, only MBT1 has been plotted; the KSU-Gagge simulation (i.e. MBT1) gives a better fit than the KSU-Stolwijk simulation. Fig. 14 shows the comparison of the results from three approaches used in the KSU-Gagge model to the calculation of mean body temperature. To make the comparison more meaningful, the experimental data and the KSU-Stolwijk simulations have also been plotted. The most striking impression is that MBT3, which was calculated from heat storage in the body and the thermal capacitance, is way-off from other plots. In general, both MBT1 and MBT2 follow the experimental data better.

Fig. 15 shows the evaporated heat loss (EV) predicted by both models; it also shows the amount of sweat that will drip-off because of non-evaporation (DRIP). This quantity is predicted only by the KSU-Gagge model. Since there is no experimental data on EV or DRIP, we have

plotted the model simulations only. Fig. 16 is the plotting of skin blood flow (SKBF) as predicted by both the models. According to the KSU-Gagge model, SKBF reaches the physiological constraint level after 100 minutes of exposure. Finally, Fig. 17 shows the heart rate predicted by the models and the experimental data. The KSU-Stolwijk model simulation follows the experimental data more closely.

Exercising: Fig. 18 to 28 show the same set of plots in the same sequence as those in the case of the sedentary subject. However, in the exercising case, the plots are for two subjects, C and J, and they have been plotted on the same figure to show the between subject variation. In this set of plots, the same convention has been followed as in the case of the sedentary subject; however, here the open circles, triangles and squares refer to the subject C and filled circles, triangles and squares refer to subject J.

From Fig. 18 to 21, the KSU-Stolwijk model predicts quite well the skin temperatures in head and legs while it fails to do so in the case of skin temperatures in trunk and arms after about 20 minutes of exposure. Fig. 22 shows the mean skin temperature plot. For mean skin temperature, the KSU-Gagge model simulation fits better with the experimental data than does the KSU-Stolwijk model simulation. Fig. 23 shows the plot of rectal temperature from experimental data, trunk core temperature for the KSU-Stolwijk model simulation and core temperature from the KSU-Gagge model simulation; we get a mixed result from these plots. The KSU-Gagge simulation fits well for subject J while the KSU-Stolwijk simulation fits better for subject C. The mean body temperature plot, Fig. 24, shows that the KSU-Gagge model gives, in general,

higher values while the KSU-Stolwijk model does just the opposite. Fig. 25 shows the comparison of mean body temperature calculated by different approaches; it shows that MBT1 and MBT2 give, in general, a better fit than MBT3.

The plots of evaporative heat loss (EV) from both the models and unevaporated sweat loss (DRIP) from the KSU-Gagge model are shown in Fig. 26. DRIP is much higher than EV beyond 20 minutes of exposure. Fig. 27 shows the skin blood flow (SKBF) simulated from both the models. According to the KSU-Gagge model, SKBF reaches the physiological constraint by 25 minutes of exposure for subject J and by 20 minutes for subject C. However, according to the KSU-Stolwijk model, SKBF for any of the two subjects never reaches that level. In a heart rate plotting, Fig. 28, the KSU-Gagge model gives a better fit with experimental data for subject J and the KSU-Stolwijk model gives a good fit with the experimental data for subject C.

7.2 With External Cooling:

The next two sets of plots are for the same environmental and experimental conditions as in the last section but in this case the subject(s) was (were) wearing a dry-ice cooling jacket. As explained in the section on experimental conditions, the jacket design is different for the two series of experiments. The plots of this section are for the same subject(s) as in the case where no external cooling was provided. Fig. 29 to 38 are for the case of a sedentary subject and Fig. 39 to 48 are for subjects (C and J) doing exercise on a bicycle ergometer. In

these two sets of plots we have followed the same convention as that used in the case of without external cooling plots.

Sedentary: For the sedentary case, we have plotted the data for August 7, 1972. Fig. 29 to 32 show the plottings of experimental data and the KSU-Stolwijk model simulation of the skin temperatures in head, trunk, arms and legs. In all these plots, the simulated results show the trend in the experimental data and also give a good fit. Mean skin temperature is plotted in Fig. 33; the KSU-Stolwijk model seems to give a better fit than the KSU-Gagge model simulation. Fig. 34 shows the plot of rectal temperature from experimental, trunk core temperature from the KSU-Stolwijk model simulation and core temperature from the KSU-Gagge model. The KSU-Gagge model simulations give a better fit compared to the simulation by the KSU-Stolwijk model. Fig. 35 shows the plot of mean body temperature; MBT2 from the KSU-Gagge model and mean body temperature (TB) from the KSU-Stolwijk model show a very good fit with the experimental data. As before, in this plot also, notice the widely different values for mean body temperature given by different approaches to calculating the supposedly same quantity.

Evaporative heat loss (EV) and unevaporated sweat loss (DRIP) are plotted in Fig. 36. According to the KSU-Gagge model, the skin becomes 100% wet after 20 minutes of exposure while according to the KSU-Stolwijk model EV does not increase beyond the basal level till 30 minutes of exposure. Simulated results for skin blood flow (SKBF) have been plotted in Fig. 37; according to the KSU-Stolwijk model SKBF does not increase above the basal level until after 30 minutes of exposure while according to the KSU-Gagge model it starts increasing as soon as the subject enters

the experimental chamber. Fig. 38 shows the plot of heart rate, both experimental and the simulations. Heart rate simulation from the KSU-Gagge model gives a better fit with the experimental data compared to the simulation from the KSU-Stolwijk model.

Exercising: For the exercising day with external cooling, the same set of plots have been made as those for the sedentary case; but, here plots are for two subjects, C and J, on the same figure. Fig. 39 to 42 show the plot of experimental data and simulations from the KSU-Stolwijk model of the skin temperatures in head, trunk, arms and legs. Except for the trunk skin temperature, simulations from the KSU-Stolwijk model seem to predict well the experimental data. However, the simulations are far off from the experimental data for the trunk skin temperatures. Fig. 43 shows the plottings of experimental data and model simulations of mean skin temperature. For both the subjects, the KSU-Stolwijk model simulation does a better job than the KSU-Gagge model. A similar conclusion can be drawn from the plottings of rectal or core temperatures, Fig. 44. Here again, the simulated values are higher than the experimental data. Moreover, the KSU-Stolwijk model has appropriately shown the initial dip and the later increase in rectal temperature while the KSU-Gagge model has apparently failed to do so. As expected from the results of mean skin and core temperatures, the KSU-Stolwijk model simulation predicts mean body temperature better than the KSU-Gagge model simulation, Fig. 45. In this plotting, MBT1 from the KSU-Gagge model has been plotted as the mean body temperature.

Fig. 46 shows the plot of simulated results of evaporated heat loss (EV) and unevaporated sweat loss (DRIP). DRIP is predicted only by the

KSU-Gagge model. Comparing all the previous sets, we notice a pattern — EV from the KSU-Stolwijk model hs a time lag before it starts increasing above the basal level. Drip as predicted by the KSU-Gagge model seems to be very high. In the plot of skin blood flow (SKBF), Fig. 47, we notice again a result which is very similar to those we have seen in other sets of plots. It seems that SKBF as predicted by the KSU-Gagge model simulation reaches the physiological constraint when the prediction by the KSU-Stolwijk model simulation just increases beyond the basal level. Finally, in Fig. 48 we note that heart rate as simulated by the KSU-Stolwijk model is much closer to the experimental data than the KSU-Gagge model simulation.

8. DISCUSSIONS

The experiments whose data has been used in this study were not designed specifically to compare the models; so, many of the variables were not measured, or even if measured, sometimes they were not done at regular intervals. Notwithstanding this drawback, some meaningful comparisons can be made.

The physiological parameter values vary from day to day even for the same subject and the same experimental conditions; Fig. 7 to 13 and Fig. 17 clearly bring out this fact. On the other hand, given a set of conditions, a model simulation will always give the same result. Thus, when we compare the model simulations with experimental data, we should be aware of this variability in experimental data. In addition, we should also keep in mind the following facts in all such comparisons. First, the clo value of the dry ice jacket ensemble for the experimental series one was not measured; instead, an estimated clo value has been used in the KSU-Gagge model. Second, the experimental mean skin temperatures and the mean body temperatures are not really measured quantities; rather, they are weighted averages of other measured temperatures. The experimental mean skin temperature was obtained by weighing the different skin temperatures with the percentages of the respective skin areas of the total. The experimental mean body temperature was obtained by weighing the rectal temperature 65% and the mean skin temperature 35%. On the other hand, both the models calculate these temperatures by weighing various compartmental temperatures by the proportions of thermal capacity for that compartment.

The effect of clothing can be considered very easily in the KDU-Gagge model; however, there is a catch. When we supply the clo value of the clothing for the KSU-Gagge model, the underlying assumption is that this clo value is distributed evenly over all the skin areas, though this is not mentioned explicitly anywhere in the model. For the dry ice cooling days, when the subject(s) was (were) wearing the cooling garment ensemble, 60% of the skin area was under clothing in experimental series one while for the experimental series two the covered area was about 90%; the rest of the body was nude. This may be partly responsible for the deviations of the KSU-Gagge model simulations from the experimental data.

For the sedentary subject, both with and without external cooling, we see a remarkably good fit between the experimental data and simulations from both the models. In both the cases, the KSU-Stolwijk simulations seem to give a better fit than those from the KSU-Gagge model simulations. However, we should note the exception in case of heart rate. From Fig. 38 we see that for the experimental results, heart rate starts decreasing after 80 minutes of exposure; but, this behavior is not repeated in any of the other experimental results. Thus, if we ignore this drop, we notice that the KSU-Gagge model simulation gives a much better fit for heart rate.

One interesting feature is brought out in Fig. 15 and 36 — they show that the KSU-Gagge model takes into account the fact that not all the sweat secreted is always evaporated. A portion of the sweat might just remain unevaporated bringing no cooling effect for the person. In

the KSU-Gagge model, whenever the regulatory sweating command exceeds the maximum possible evaporation sweat loss, the excess amount is considered as unevaporated sweat loss (DRIP). In the KSU-Stolwijk model when a similar situation arises, the evaporated sweat loss is just set equal to the maximum possible evaporative loss. This is done because the excess unevaporated sweat does not in any way affect the heat balance and the whole model is based on heat balance. Even though the KSU-Gagge model is also based on a heat balance, it recognizes DRIP because it has a physical meaning and is useful in mass-balance calculations.

Fig. 15, 16, 36 and 37 bring out the physiological benefits of using a dry-ice jacket to cool the body in hot environments. Comparing Fig. 15 and 36, we notice that both the models predict a lower evaporative heat loss (EV) in the with cooling condition. We should note here that EV includes, in addition to evaporative sweat loss, the evaporative loss in the respiratory system. For the KSU-Gagge model, EV drops from 200 watts to 165 watts at the end of 120 minutes of exposure to the same environmental condition. Similarly, for the KSU-Stolwijk's model, EV drops from 165 watts to 110 watts. Likewise, DRIP, as predicted by the KSU-Gagge model, drops from 230 watts to 78 watts. A similar benefit is also noticed in the case of skin blow flow (SKBF) simulations. For the KSU-Gagge model, SKBF reaches the physiological constraint level (210 ℓ/hr) within 100 minutes of exposure without external cooling, while with cooling the maximum level reached at the end of 120 minutes of exposure is 125 ℓ/hr. Similarly for the KSU-Stolwijk model, for the day without cooling, SKBF started rising above the basal level after 10 minutes

of exposure and reached a maximum of 130 ℓ/hr at the end of 120 minutes of exposure; for the day with external cooling, SKBF started increasing above the basal level after 30 minutes of exposure and reached a maximum level of 65 ℓ/hr at the end of 120 minutes of exposure.

For the case of exercising clothed subjects, the simulated results are not as satisfactory as in the case of the sedentary semi-nude subject. For the day without cooling, the KSU-Stolwijk model simulations always give a lower value for the skin temperatures (with the exception of leg skin temperature) compared to the experimental data for the subjects. However, for the day with cooling, the simulations fit remarkably well except for the trunk skin temperatures. Thus, here we have an anomaly. There may be three major reasons for this. 1) The percentage distribution of the activity metabolic heat to different segments as given by Stolwijk does not truely represent the case of exercise on a bicycle ergometer. Stolwijk distributes a 30% of the total activity metabolic heat generated to the trunk and a 8% to the arms. But, in a bicycle ergometer exercise, the trunk and the arms are not subjected to that much metabolism. Thus, while Stolwijks distribution may hold good for a walking or jogging case, for exercise on bicycle ergometer then values should reduced while increasing those for legs and feet. 2) Stolwijk's model (and the KSU-Stolwijk model also) has been designed primarily for a nude subject and all the heat transfer coefficients and relations used in the model hold good for such a case. In both the series of experiments, when a dry-ice cooling garment was used, subjects were not nude. In experimental series two, even on the non-cooling day, subjects were wearing clothes with a clo value of 0.49. On days with cooling, about half of

the clo value of the clothing ensemble was in the trunk region. Since we could not estimate the changes in the heat transfer coefficients due to these different clothing ensembles, we have used the same coefficients that are valid for nude body but with inside clothing temperature as air temperature (TAIR). However, we had the inside clothing temperature available for the trunk region only; so we used as TAIR for trunk the average of the temperature inside jacket for the length of the experiment and for the other segments the TAIR used was the same as that of ambient dry bulb air temperature. Thus, we see that there remains a serious drawback in the model which needs to be rectified in future studies. Most of the variation of simulated skin temperatures from the experimental data can be attributed to this drawback. 3) Though not explicitly mentioned anywhere, Stolwijk's model (and this holds good for the Gagge model as well) works well with a fairly uniform temperature distribution in different skin segments. But, on our dry ice cooling days, small portions of the skin area on the trunk were subjected to severe cold (below $10^{o}C$) while other portions were at about normal temperature ranges. Thus, the model could not do very well in simulations may be because in such cases the thermoregulatory relations change from those used in the models.

When comparing the rectal temperature from experimental data to the simulations of core temperatures, we notice that the KSU-Stolwijk model simulations fit very well for the cooling day while the fit is not good at all for the non-cooling day. The reasons for this may be the same ones which have been explained earlier in this section. However, we also note that on both days, the KSU-Gagge simulations are higher than the experimental data, but for the day without cooling the deviations are

very low. The reason for this may be that the Gagge model can take care of "moderate" clothing on persons but the cooling garment used in experimental series two can in no way be described as "moderate".

The effect of the deviations of simulations for the skin temperatures are reflected in the mean body temperature also since the mean body temperature is nothing but a weighted average of all the temperatures. At this stage, we can not pass any judgment about the goodness of fit of the simulated results with those of the experimental data; the reason is the supposedly experimental data is also a calculated average and not a measured quantity. Moreover, the concept of and the mode of calculation of mean body temperature is still a controversial issue. There is no clear cut answer to the question of "what is the mean body temperature?". As described in the section on model description, there are three basic approaches to calculate this quantity and, we get a different value depending on which approach has been used; we do not know, at this stage, which one is the correct approach.

As in the case of the sedentary subject, for exercising subjects also, both models show that due to dry ice cooling there is less strain on the body, physiologically, as indicated by SKBF, EV and DRIP. However, we also notice one interesting difference in the responses of the KSU-Stolwijk model and the KSU-Gagge model. In the simulations of both the series of experimental conditions, SKBF as predicted by the KSU-Gagge model is greater than that by the KSU-Stolwijk; sometimes, the difference between them is quite significant. But for EV, the situation reverses from the sedentary case to the exercising case; in sedentary case, EV as

simulated by the KSU-Gagge model is higher than that by the KSU-Stolwijk model, but, for the exercising case it is just the opposite. There is no real explanation for this behavior. In addition, the KSU-Gagge model activates the control actions as soon as the subject is exposed to the experimental condition while for the KSU-Stolwijk model there is always some time lag. Thus it seems that the KSU-Gagge model is very sensitive and reacts very fast. The regulatory sweating command from the KSU-Gagge model are sometimes so high that it seems improbable that any individual can sweat as much as the model predicts; this is especially significant for exercising subjects. One very informative output from the KSU-Gagge model, however, is that of unevaporated sweat loss (DRIP); DRIP lets us know what percentage of actual sweating is helping the body in cooling.

In exercising subjects, heart rate simulations from the KSU-Stolwijk model give a better fit with the experimental data than those from the KSU-Gagge model. In both the models, the variable part (over time) of the cardiac output is the skin blood flow. Thus, we can infer that the simulations of SKBF by the KSU-Stolwijk are probably nearer to what actually happens in a human body.

From the results and their discussions, we can do nothing but appreciate the basic robustness of both the models. In spite of all their drawbacks, they simulate fairly well all the important physiological variables. They have done a very good job in prediction even in the case of a very severe physiological and experimental conditions (experimental series two) in spite of the very complex nature of human thermoregulation. The KSU-Gagge model is simple and the information provided by it is also limited. Comparatively, the KSU-Stolwijk model is more complex and

it provides a vast amount of information. All this information forces us to look critically at each and every assumption made.

9. SUMMARY AND CONCLUSIONS

A human thermoregulatory model aims to duplicate the thermoregulatory mechanisms of a human body in mathematical form with, of course, simplifications. Gagge's model is simpler in conception than Stolwijk's model and also its information output is not as large. As part of this study, Gagge's model has been adapted for the specific requirements of Kansas State University; Stolwijk's model had already been adapted in this respect earlier. Also, modifications of equations, parameter values and variables have been made for both the models to make them up-to-date and more flexible. Finally, the simulated results from both of the modified models (referred to as the KSU-Gagge and the KSU-Stolwijk models) have been compared with the results of two experimental series, one for a sedentary subject and the other for two exercising subjects.

From the results we can conclude that:

1. Both the models are robust enough to be used for severe physiological and environmental conditions.
2. The heat transfer coefficients in the KSU-Stolwijk model should be made variable with the clothing used (or clo value).
3. The distribution of activity metabolic heat produced to the different segments in the body, as used in the KSU-Stolwijk model, should be made a variable depending on the type of activity done.
4. The coefficient values for vasomotor function and sweating action in the KSU-Gagge model should be rechecked and, possibly, should be reduced with adjustment in other equations to improve the simulation results.

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APPENDIX A

Tables

Table 1. List of Symbols Used in KSU-Stolwijk and Stolwijk Models

Symbol	Definition	Dimensions
BARO	Barometric pressure	mm Hg
BC(N)	Convective heat transfer between central blood and N	W
BF(N)	Total effective blood flow to N	$L.h^{-1}$
BFB(N)	Basal effective blood flow to N	$L.h^{-1}$
C(N)	Heat capacitance of compartment N	$W.h.\ ^{o}C^{-1}$
CCHIL	Shivering from head core	$W\ .\ ^{o}C^{-1}$
CCON	Vasoconstriction from head core	$^{o}C^{-1}$
CDIL	Vasodilation from head core	$L.h^{-1}.\ ^{o}C^{-1}$
CEFF	Percentage of cooling provided by jacket that goes directly to body	N.D*
CEVG	Cumulative evaporative heat loss	gm.
CHILL	Total efferent shivering command	W
CHILM(I)	Fraction of total shivering occuring in muscles of segment I	N.D.*
CO	Cardiac output	$L.min.^{-1}$
COLD(N)	Output from cold receptors in N	^{o}C
COLDS	Integrated output from skin cold receptors	^{o}C
CSW	Sweating from head core	$W.\ ^{o}C^{-1}$
DILAT	Total efferent skin vasodilation command	$L.h^{-1}$
DT	Integration step	h
E(N)	Total evaporative heat loss from N	W

Symbol	Definition	Dimensions
EB(N)	Basal evaporative heat loss from N	W
EG(N)	Total evaporative heat loss from N	$gm.h^{-1}$
EMAX(I)	Calculated maximum rate of evaporative heat loss from segment I	W
ERROR(N)	Output from thermoreceptors in compartment N	^{o}C
EVCP(I)	Heat of vaporization of sweat for segment I	$W.h.gm.^{-1}$
EWET(I)	Skin wettedness for segment I	N.D.*
F(N)	Rate of change temperature in N	$^{o}C.h^{-1}$
H(I)	Total environmental heat transfer coefficient for segment I	$W.^{o}C^{-1}$
HC(I)	Convective and Conductive heat transfer coefficient for segment I	$W.m^{-2}.^{o}C^{-1}$
HEARTR	Heart rate	$Beats.min^{-1}$
HF(N)	Rate of heat flow into or from N	W
HP	Heat production (metabolism + shivering)	W
HR(I)	Radiant heat transfer coefficient for segment I	$W.m.^{-2}.^{o}C^{-1}$
HVP	Heat of vaporization for evaporative loss in respiratory tract	$W.h.gm^{-1}$
INT	Interval between outputs	min.
ITIME	Elapsed time	min.
LR	Lewis relationship	$^{o}C.mmHg^{-1}$
LTIME	Elapsed time	min
P(I)	Vapor pressure table from 5-50^{o}C	mm Hg
PAIR(I)	Vapor pressure in environment (for segment I)	mm Hg
PCHIL	Shivering skin and head core	$^{o}C^{-2}$

Symbol	Definition	Dimensions
PCON	Vasoconstriction from skin and head core	$^{o}C^{-2}$
PDIL	Vasodilation from skin and head core	$L.h^{-1}.^{o}C^{-2}$
PS(I)	Percentage distribution of body surface area to different segments	N.D.*
PSKIN(I)	Saturated water vapor pressure at skin temp.	mm Hg
PSW	Sweating from skin and head core	$W.^{o}C^{-2}$
Q(N)	Total metabolic heat production in N	W
QB(N)	Basal metabolic heat production in N	W
RATE(N)	Dynamic sensitivity of thermoceptors in N	h
RH	Relative humidity in environment	N.D.*
S(I)	Surface area of segment I	m^{2}
SBF	Skin blood flow	$L.min.^{-1}$
SCHIL	Shivering from skin	$W.^{o}C^{-1}$
SCON	Vasoconstriction from skin	$^{o}C^{-1}$
SDIL	Vasodilation from skin	$L.h^{-1}.^{o}C^{-1}$
SKINC(I)	Fraction of Vasoconstriction command applicable to skin of segment I	N.D.*
SKINR(I)	Fraction of all skin receptors in segment I	N.D.*
SKINS(I)	Fraction of sweat command applicable to skin segment I	N.D.*
SKINV(I)	Fraction of vasodilation command applicable to skin segment I	N.D.*
SSW	Sweating from skin	$W.^{o}C^{-1}$
STRIC	Total efferent skin vasodilation command	N.D.*
STROV	Stroke volume	$L.Stroke^{-1}$

Symbol	Definition	Dimensions
SWCG	Sweat command per skin segment	$gm.h^{-1}$
SWEAT	Total efferent sweat command	W
SWPGP	Sweat heat removal command per skin segment	W
T(N)	Temperature of N	^{o}C
TAIR(I)	Effective environment temperature in segment I (dry-bulb)	^{o}C
TB	Mean body temperature	^{o}C
TC(N)	Thermal conductance between N and N+1	$W.^{o}C^{-1}$
TD(N)	Conductive heat transfer between N and N+1	W
TIME	Elapsed time	h
TS	Mean skin temperature	^{o}C
TSETC(N)	"Set point" or reference point for cold for receptors in compartment N	^{o}C
TSETW(N)	"Set point" or reference point for warm for receptors in compartment N	^{o}C
V	Air velocity	$M.sec^{-1}$
WARMS	Integrated output from skin warm receptors	^{o}C
WORK	Total metabolic rate required by exercise	W
WORKM(I)	Fraction of total work done by muscles in segment I	N.D.*
WORKB	Basal metabolism	W
WEFF	Mechanical efficiency of work	N.D.*

*N.D. = Dimensionless

Table 2. List of Symbols Used in KSU-Gagge and Gagge Models

Symbol	Definition	Dimensions	
		KSU-Gagge	Gagge
ALPHA	Ratio of mass skin shell to mass center core	N.D.*	N.D.*
AT	Type of activity: sedentary = 1, Exercise on bicycle ergometer at 50 r.p.m. = 2, Exercise on bicycle ergometer at 60 r.p.m. = 3	N.D.*	
BARO	Barometric pressure for ambient air	mm Hg	
BBFM	Basal blood flow to muscle	$L.h^{-1}$	
BCRBF	Basal core blood flow	$L.h^{-1}$	
BM	Basal metabolic rate	W	
BSBFA	Basal skin blood flow per skin area	$L.h^{-1}.m^{-2}$	
BMSA	Basal metabolic rate per skin area	$W.m^{-2}$	
CEEF	Percentage of cooling provided by jacket that goes directly to body	N.D.*	
CEVG	Cumulative sweat secretion for the time of exposure	gm	
CHC	Convective heat transfer coefficient	$W.^{o}C^{-1}.m^{-2}$	$W.^{o}C^{-1}.m^{-2}$
CHC1	CHC for AT = 1	$W.^{o}C^{-1}.m^{-2}$	
CHC2	CHC for AT = 2	$W.^{o}C^{-1}.m^{-2}$	
CHC3	CHC for AT = 3	$W.^{o}C^{-1}.m^{-2}$	
CHR	Linear radiation exchange coefficient	$W.^{o}C^{-1}.m^{-2}$	$W.^{o}C^{-1}.m^{-2}$
CLO	Intrinsic clothing insulation	clo(=0.155 $m^{2}.^{o}C.W^{-1}$)	clo
CO	Cardiac output	$L.h^{-1}$	

Symbol	Definition	Dimensions	
		KSU-Gagge	Gagge
COLDC	Cold signal from body core	^{o}C	^{o}C
COLDS	Cold signal from skin shell	^{o}C	^{o}C
CRBF	Core blood flow	$L.h^{-1}$	
CRES	Respired convective heat loss	W	$W.m^{-2}$
CRSIG	Signal from body core	^{o}C	^{o}C
CSETC	Core set-point or reference temperature for cold	^{o}C	
CSETW	Core set-point or reference temperature for warmth	^{o}C	
CTC	Combined heat transfer coefficient	$W.^{o}C^{-1}.m^{-2}$	$W.^{o}C^{-1}.m^{-2}$
COOL	Amount cooling provided to the subject by cooling jacket	W	
DILAT	Vasodilation command	$L.h^{-1}.m^{-2}$	$L.h^{-1}.m^{-2}$
DRIP	Unevaporated sweat	$gm.h^{-1}$	$gm.h^{-1}.m^{-2}$
DRY	Total dry heat loss (conduction and convection)	W	$W.m^{-2}$
DTCR	Rate of change in core temperature	$^{o}C.h^{-1}$	^{o}C
DTIM	Incremental time for simulation	h	h
DTSK	Rate of change in skin shell temperature	$^{o}C.h^{-1}$	^{o}C
EDIF	Skin vapor loss by diffusion	W^{-1}	$W.m^{-2}$
EMAX	Maximum possible evaporative heat loss from skin for an environmental condition	W	$W.m^{-2}$
ERES	Respired evaporative heat loss	W	$W.m^{-2}$
ERSW	Skin evaporative heat loss by regulatory sweating	W	$W.m^{-2}$
ETIME	Time to stop simulation	min.	

Symbol	Definition	Dimensions	
		KSU-Gagge	Gagge
EV	Total evaporative heat loss	W	$W.m^{-2}$
FCL	Burton clothing thermal efficiency factor	N.D.*	N.D.*
FACL	Factor to increase body surface area due to clothing	N.D.*	N.D.*
FPCL	Nishi permeation efficiency factor for clothing	N.D.*	N.D.*
HEARTR	Rate of heart beats	$Beats.min^{-1}$	
HFCR	Heat storage in body core	W	$W.m^{-2}$
HFSBF	Heat flow from core to skin shell by skin blood flow and conduction	W	
HFSK	Heat storage in skin shell	W	$W.m^{-2}$
HT	Height of subject	cm	
HVAPS	Heat of vaporization of sweat from skin surface	$W.h.gm^{-1}$	
INT	Interval for output printout	min.	
TIME	Elapsed time after last printout	min.	
LR	Lewis relationship	$^{o}C.mm\ Hg^{-1}$	
MAXSBF	Maximum skin blood flow	$L.h^{-1}$	
MBT1	Mean body temperature	^{o}C	
MBT2	Mean body temperature	^{o}C	
MBT3	Mean body temperature	^{o}C	
MR	Metabolic rate (basal and activity)	W	$W.m^{-2}$
MRSA	Metabolic rate (basal and activity) per skin area	$W.m^{-2}$	
MXCRBF	Maximum core blood flow	$L.h^{-1}$	

Symbol	Definition	Dimensions	
		KSU-Gagge	Gagge
P(I)	Vapor pressure table from 5-50^{o}C	mm Hg	
PPHG	Ambient vapor pressure	mm Hg	mm Hg
PRSW	Skin wettedness due to regulatory sweating	N.D.*	N.D.*
PWET	Total skin wettedness	N.D.*	N.D.*
REGSW	Rate of regulatory sweat secretion	$gm.h^{-1}$	$gm.h^{-1}.m^{-2}$
RH	Relative humidity of ambient air	N.D.*	
RM	Total metabolic activity (including shivering)	W	$W.m^{-2}$
RTBM	Rate of change of mean body temperature	$^{o}C.h^{-1}$	$^{o}C.h^{-1}$
SA	Skin surface area	m^{2}	
SBK	Stefan-Boltzman Constant	$W.m^{-2}.{}^{o}K^{-4}$	$W.m^{-2}.{}^{o}K^{-4}$
SKBF	Skin blood flow	$L.h^{-1}$	$L.h^{-1}.m^{-2}$
SKSIG	Signal from skin shell	^{o}C	^{o}C
SPHTB	Specific heat or thermal capacity of subject	$W.h.{}^{o}C^{-1}$	
SPHTBL	Specific heat or thermal capacity of blood	$W.h.L^{-1}.{}^{o}C^{-1}$	
SSETC	Skin set-point or reference temperature for cold	^{o}C	
SSETW	Skin set-point or reference temperature for warmth	^{o}C	
STORE	Rate of body heat storage	W	$W.m^{-2}$
STRIC	Vasoconstriction command	$L.h^{-1}.m^{-2}$	$L.h^{-1}.m^{-2}$
STROV	Stroke volume of heart	$L.stroke^{-1}$	
SUBRAT(I)	Sublimation rate of dry ice per period	$gm.h^{-1}$	

Symbol	Definition	Dimensions	
		KSU-Gagge	Gagge
SVP	Saturated vapor pressure at skin shell temperature	mm Hg	mm Hg
SWEAT	Total sweat loss	$gm.h^{-1}$	
TA	Dry-bulb or ambient air temperature	^{o}C	^{o}C
TCL	Clothing surface temperature	^{o}C	^{o}C
TCCR	Thermal capacity of body core	$W.h.^{o}C^{-1}$	$W.h.^{o}C^{-1}$
TCR	Temperature of body core	^{o}C	^{o}C
TCSK	Thermal capacity of skin shell	$W.h.^{o}C^{-1}$	$W.h.^{o}C^{-1}$
TIM	Elapsed time	h	h
TIME	Elapsed time	min.	
TO	Operative temperature	^{o}C	^{o}C
TR	Mean radiant temperature	^{o}C	^{o}C
TSK	Average temperature of skin shell	^{o}C	^{o}C
WARMC	Warm signal from body core	^{o}C	^{o}C
WARMS	Warm signal from skin shell	^{o}C	^{o}C
WE	Mechanical efficiency of activity metabolism	N.D.*	N.D.*
WK	Work rate accomplished	W	W
WT	Weight of subject	Kg	

*N.D. = Dimensionless

APPENDIX B

Figures

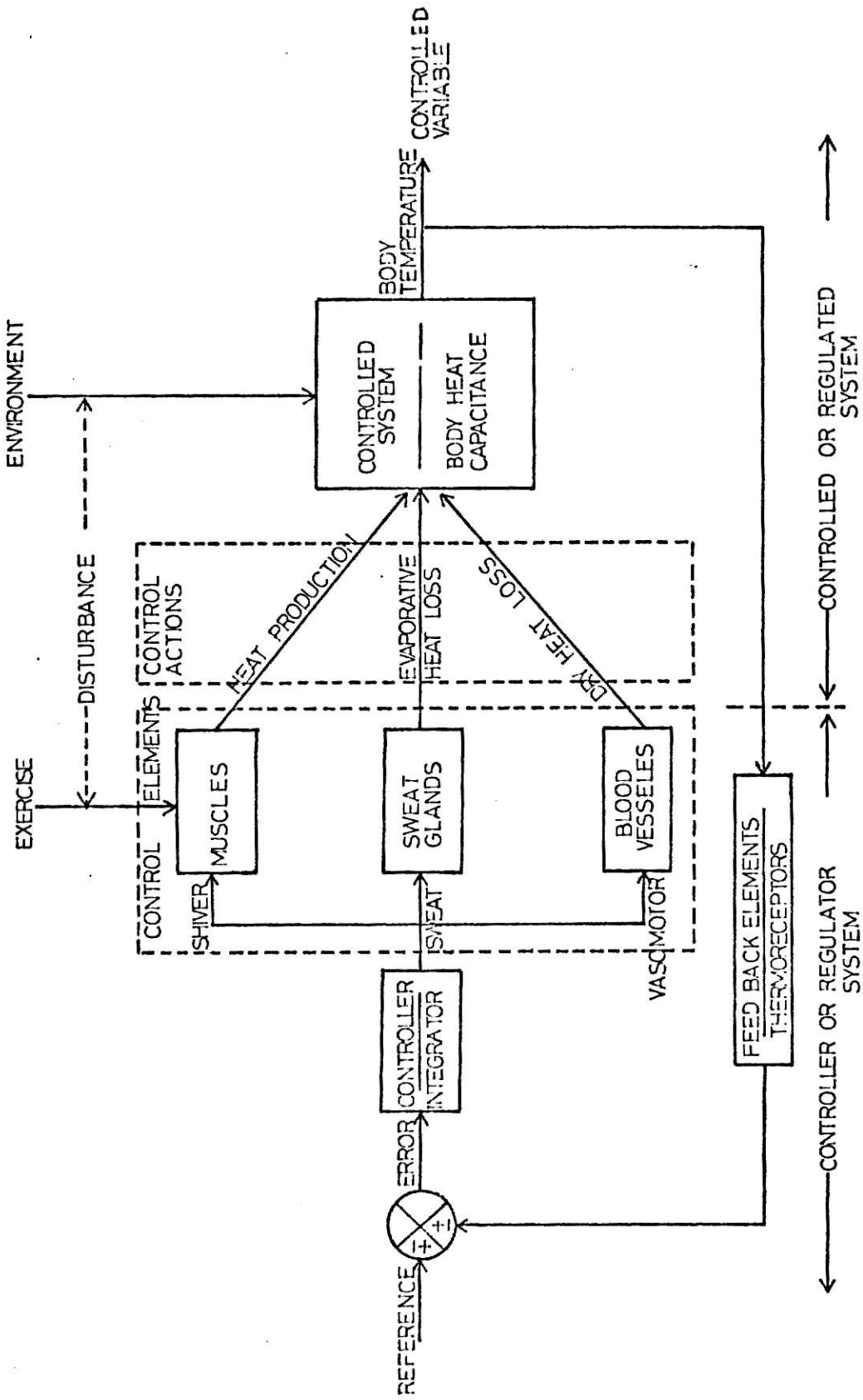


Figure 1. Block Diagram of the Human Thermoregulatory System

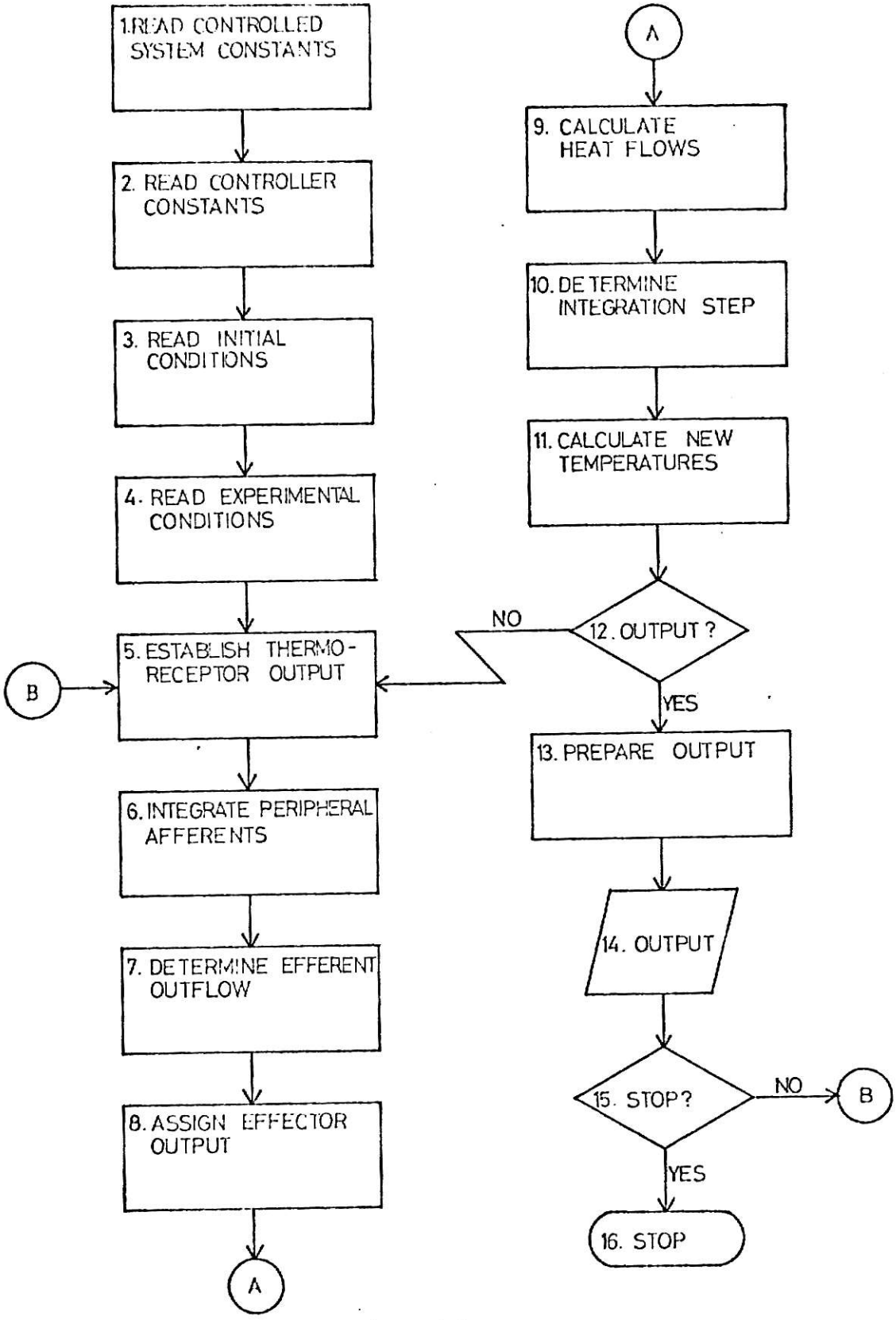
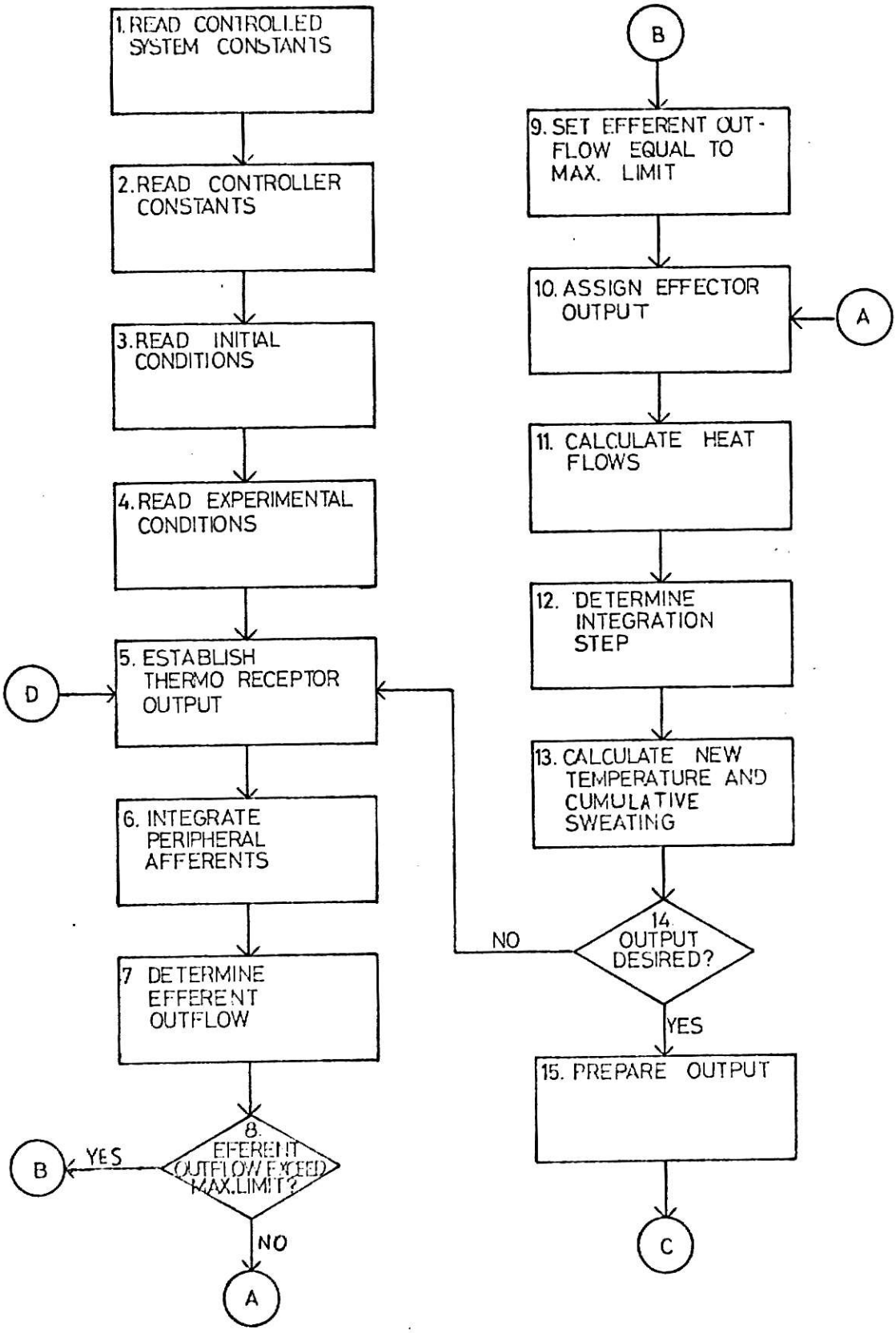


Figure 2. Flow Diagram of Stolwijk's Model


1. READ CONTROLLED SYSTEM CONSTANTS
2. READ CONTROLLER CONSTANTS
3. READ INITIAL CONDITIONS
4. READ EXPERIMENTAL CONDITIONS
5. ESTABLISH THERMO RECEPTOR OUTPUT
6. INTEGRATE PERIPHERAL AFFERENTS
7 DETERMINE EFFERENT OUTFLOW
8. EFFERENT OUTFLOW EXCEED MAX.LIMIT?
YES
NO
B
A
D
9. SET EFFERENT OUT-FLOW EQUAL TO MAX. LIMIT
10. ASSIGN EFFECTOR OUTPUT
11. CALCULATE HEAT FLOWS
12. DETERMINE INTEGRATION STEP
13. CALCULATE NEW TEMPERATURE AND CUMULATIVE SWEATING
14. OUTPUT DESIRED?
NO
YES
15. PREPARE OUTPUT
C

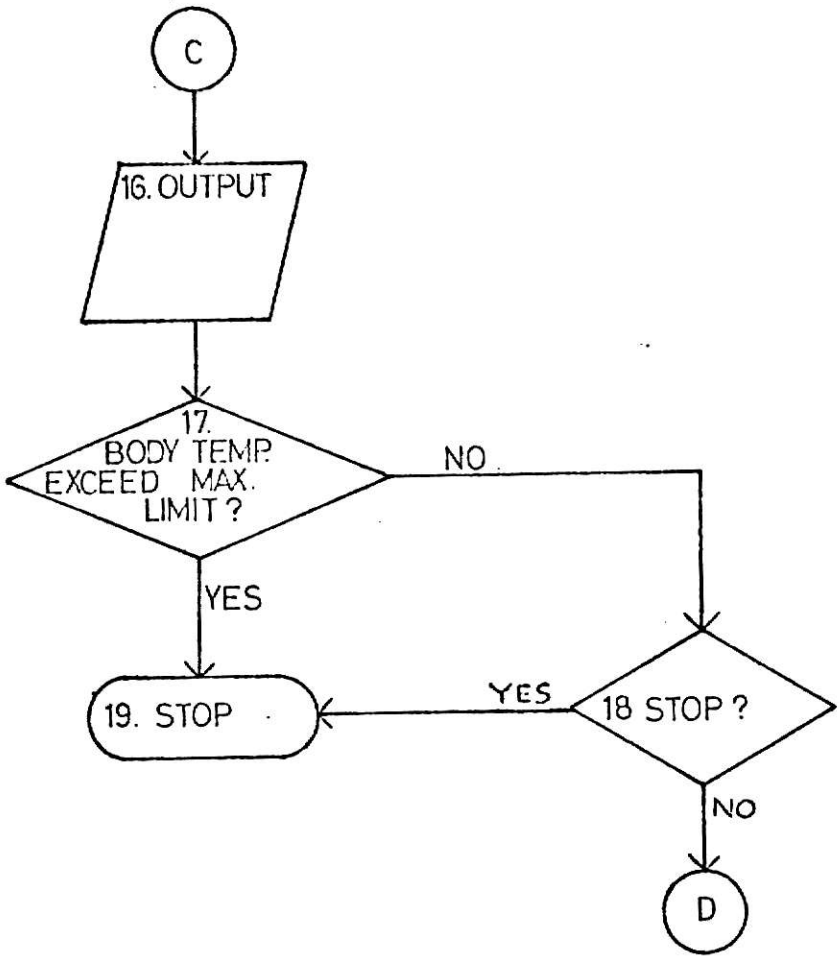


Figure 3. Flow Diagram of KSU-Stolwijk Model

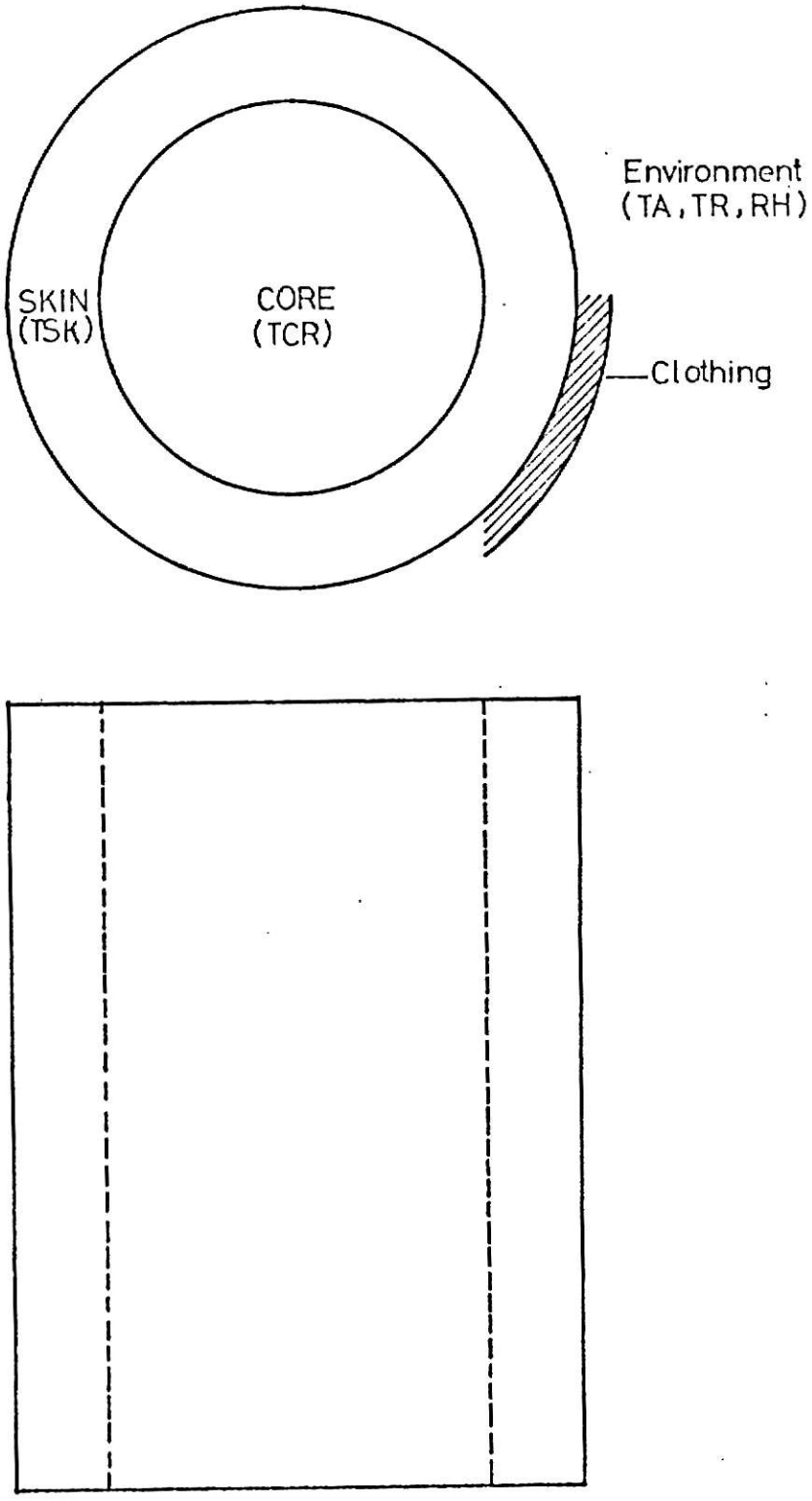


Figure 4. Representation of the Human Body in Gagge's Model

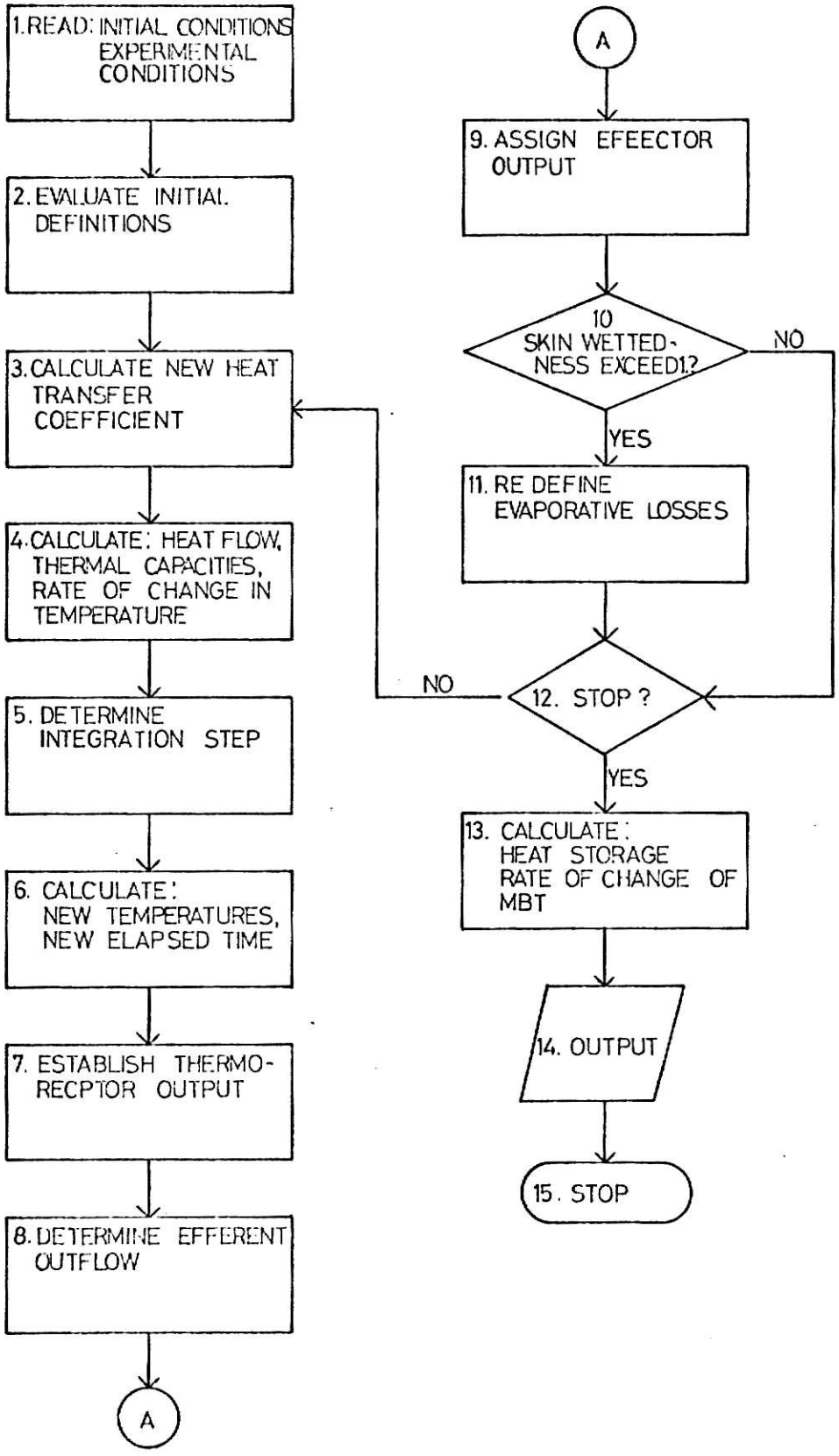
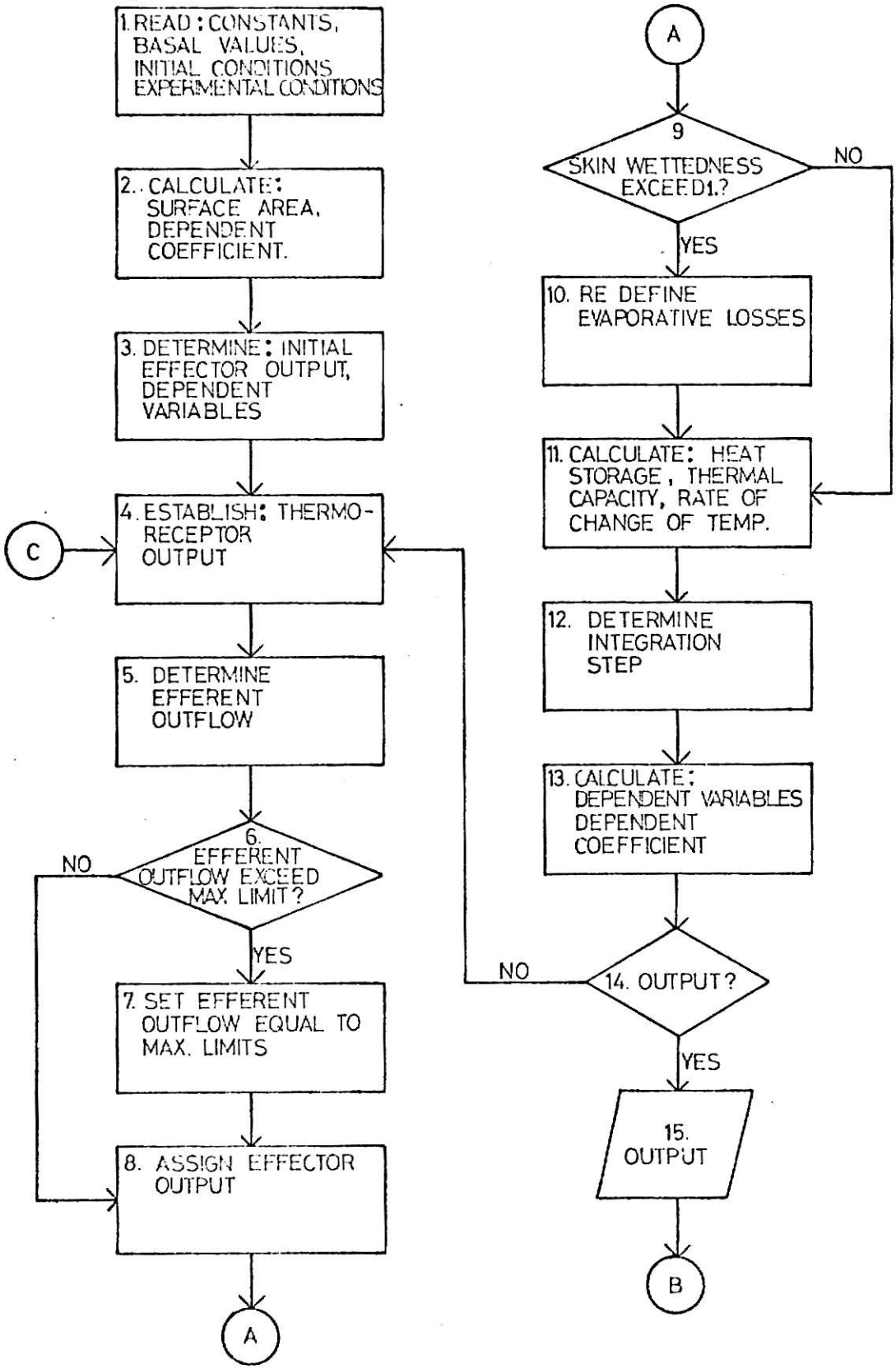


Figure 5. Flow Diagram of Gagge's Model


1. READ : CONSTANTS, BASAL VALUES, INITIAL CONDITIONS EXPERIMENTAL CONDITIONS
2. CALCULATE: SURFACE AREA, DEPENDENT COEFFICIENT.
3. DETERMINE: INITIAL EFFECTOR OUTPUT, DEPENDENT VARIABLES
4. ESTABLISH: THERMO-RECEPTOR OUTPUT
C
5. DETERMINE EFFERENT OUTFLOW
6. EFFERENT OUTFLOW EXCEED MAX LIMIT?
NO
YES
7. SET EFFERENT OUTFLOW EQUAL TO MAX. LIMITS
8. ASSIGN EFFECTOR OUTPUT
A
A
9 SKIN WETTEDNESS EXCEED1.?
NO
YES
10. RE DEFINE EVAPORATIVE LOSSES
11. CALCULATE: HEAT STORAGE, THERMAL CAPACITY, RATE OF CHANGE OF TEMP.
12. DETERMINE INTEGRATION STEP
13. CALCULATE: DEPENDENT VARIABLES DEPENDENT COEFFICIENT
14. OUTPUT?
NO
YES
15. OUTPUT
B

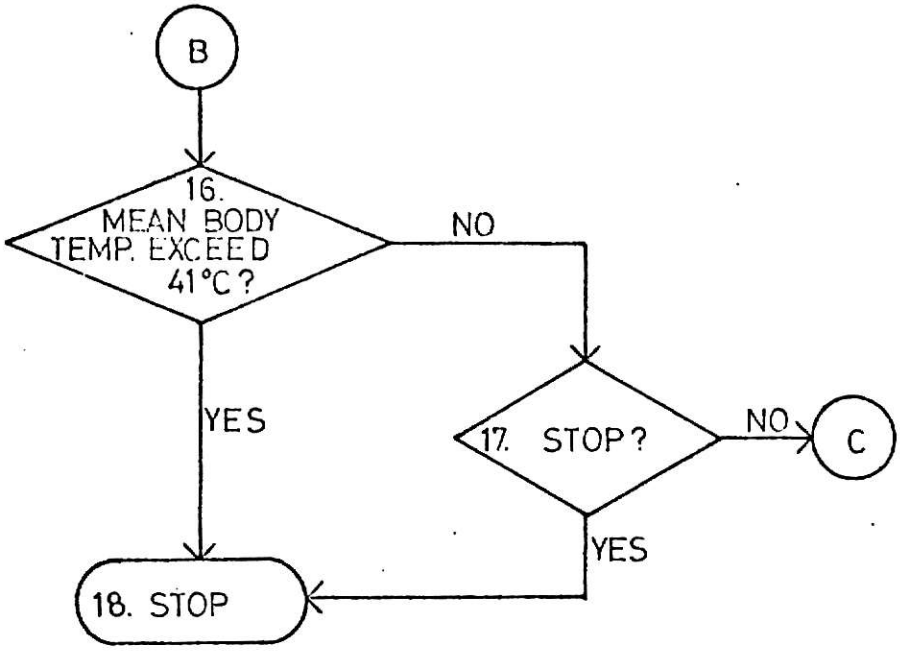


Figure 6. Flow Diagram of KSU-Gagge Model

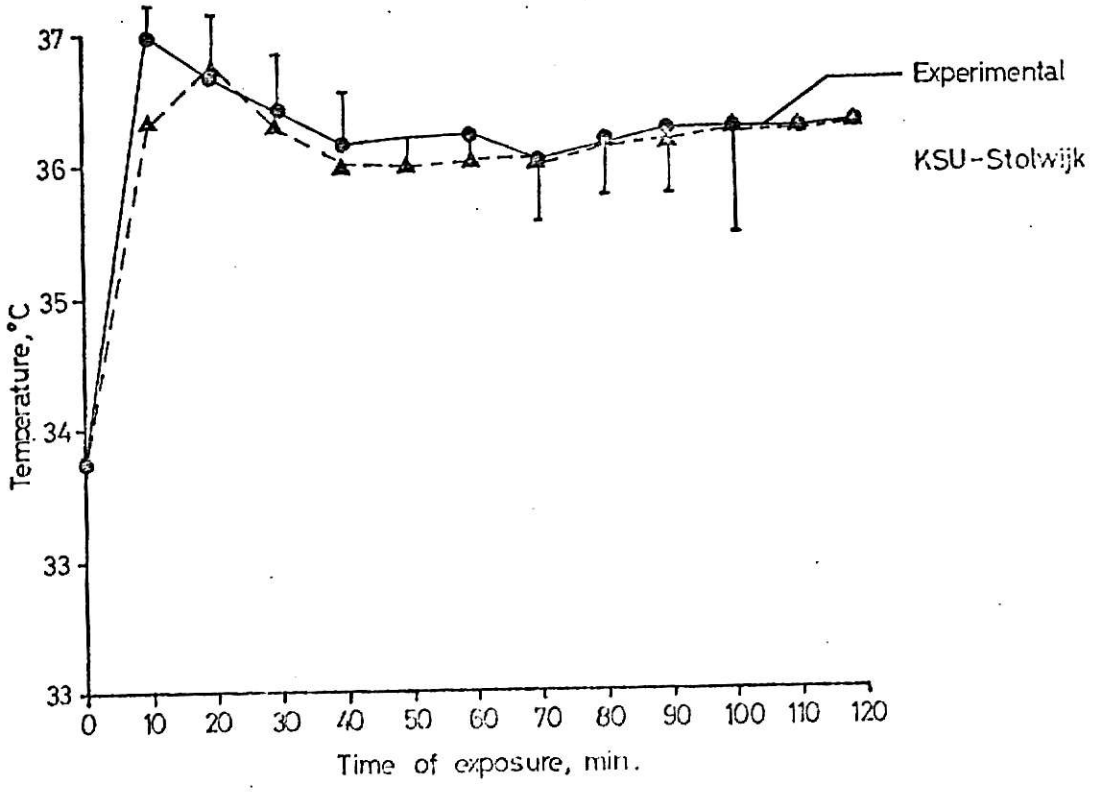


Figure 7. Experimental Head Skin Temperature vs. Simulation (Aug. 31, '72)

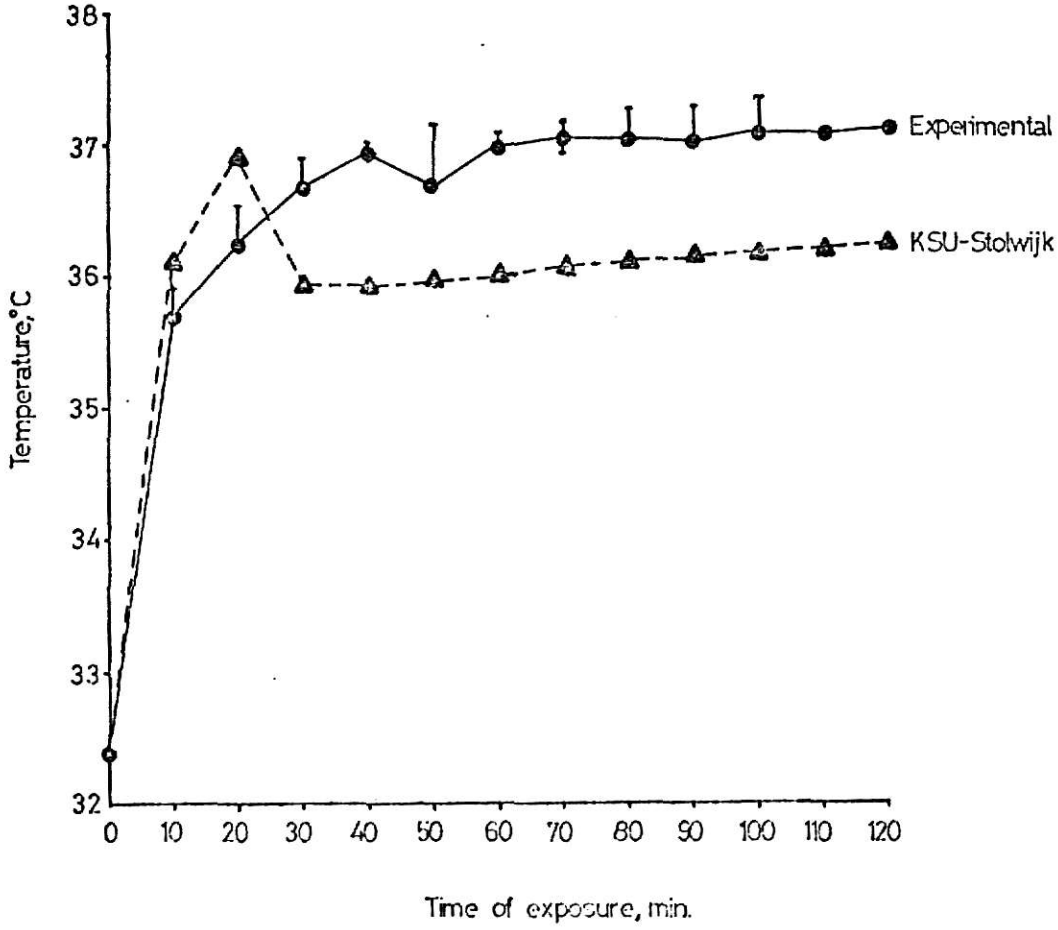


Figure 8. Experimental Trunk Skin Temperature vs. Simulation (Aug. 31, '72)

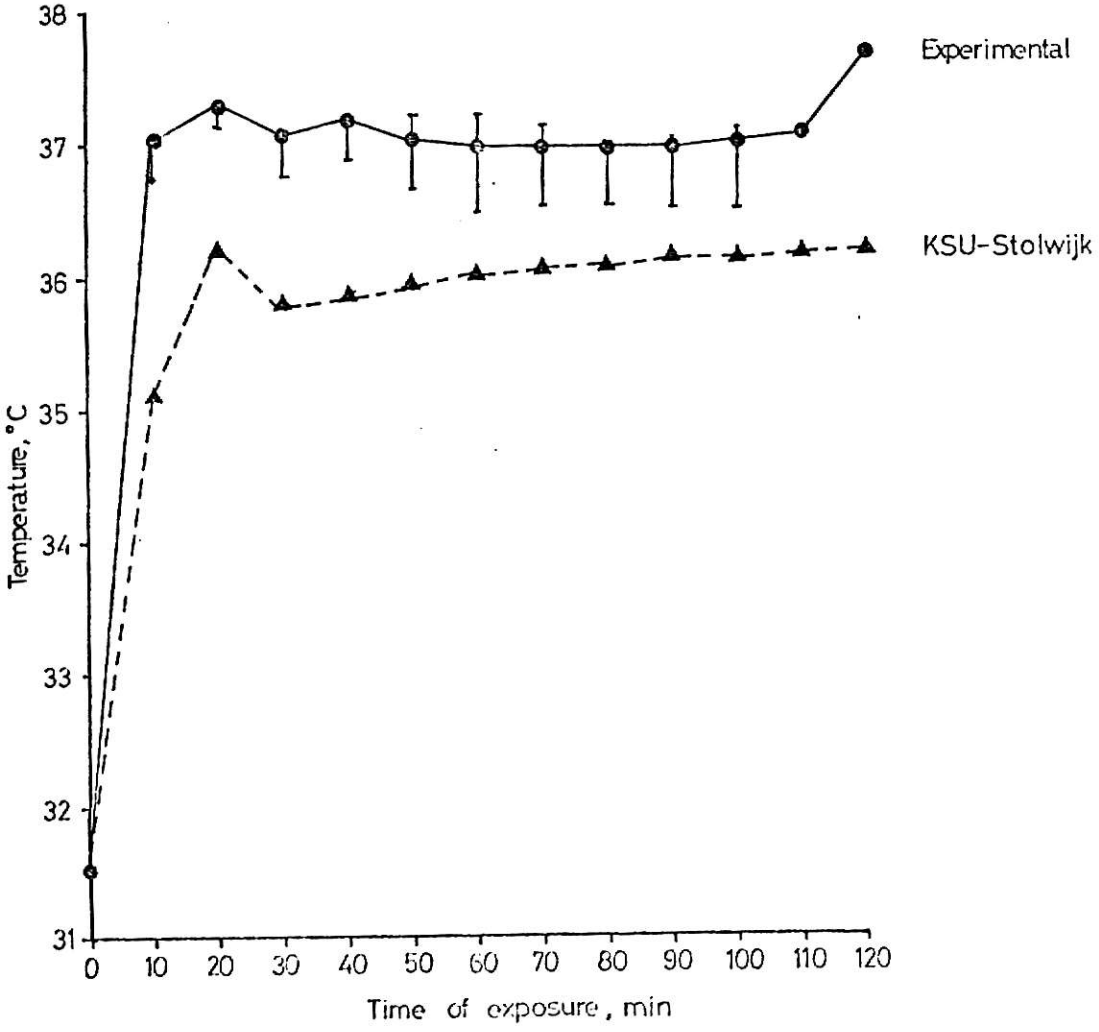


Figure 9. Experimental Arm Skin Temperature vs. Simulation (Aug. 31, '72)

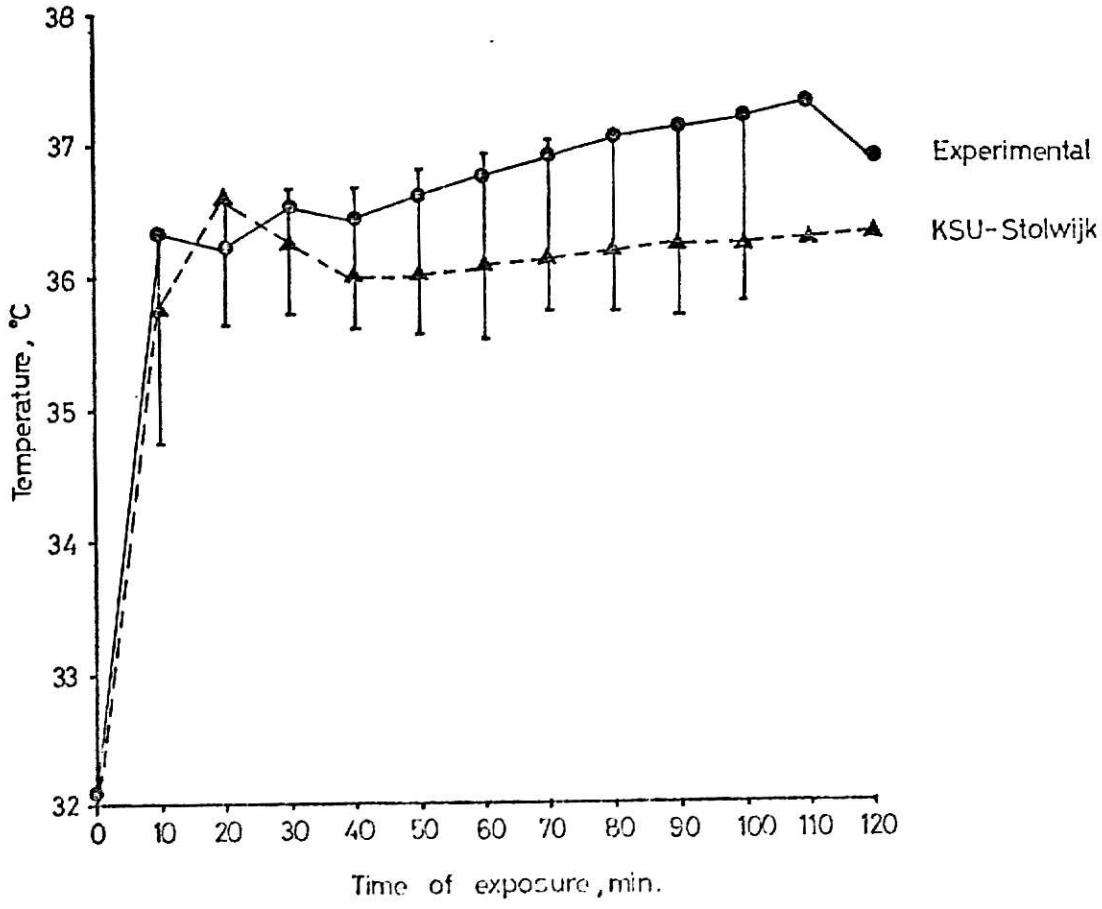


Figure 10. Experimental Leg Skin Temperature vs. Simulation (Aug. 31, '72)

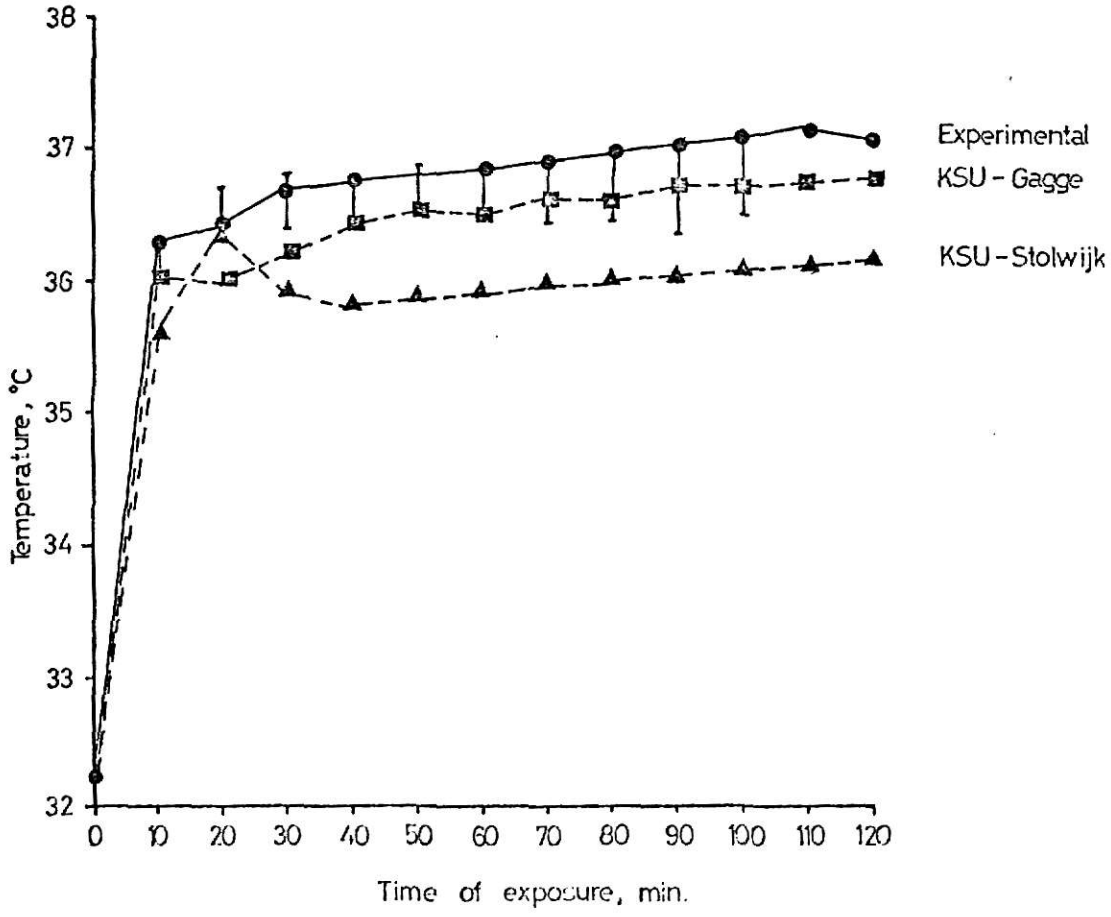


Figure 11. Experimental Mean Skin Temperature vs. Simulation (Aug. 31, '72)

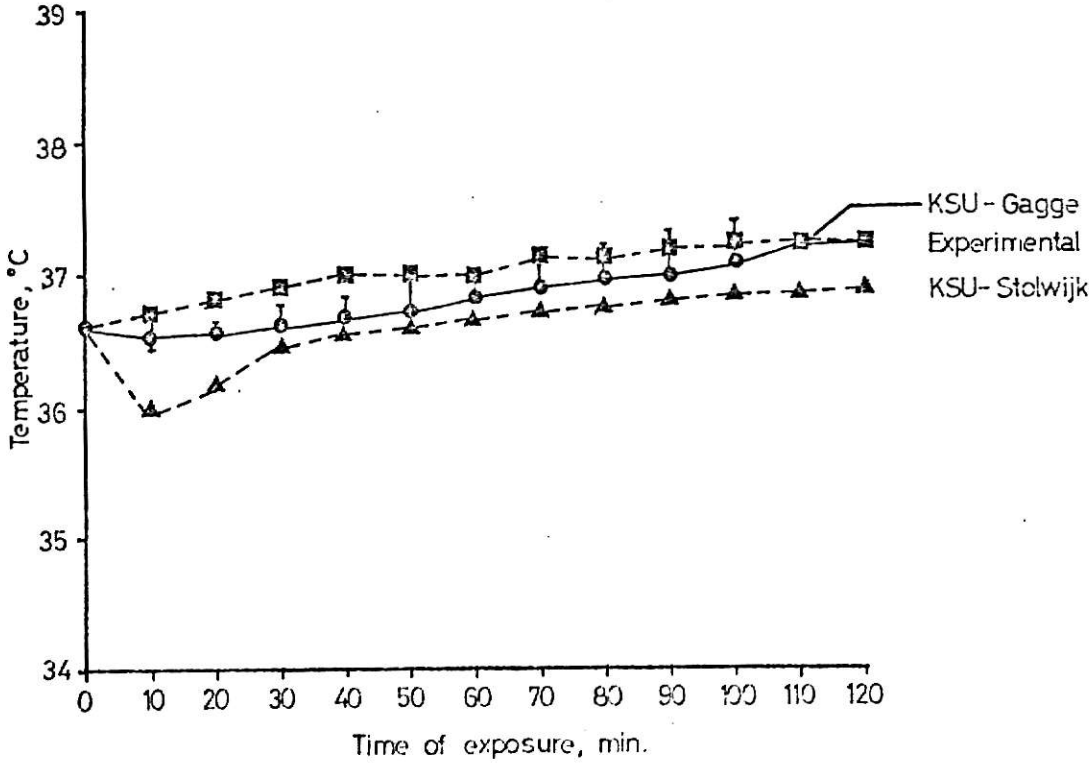


Figure 12. Experimental Rectal Temperature vs. Simulated Core Temperature (Aug. 31, '72)

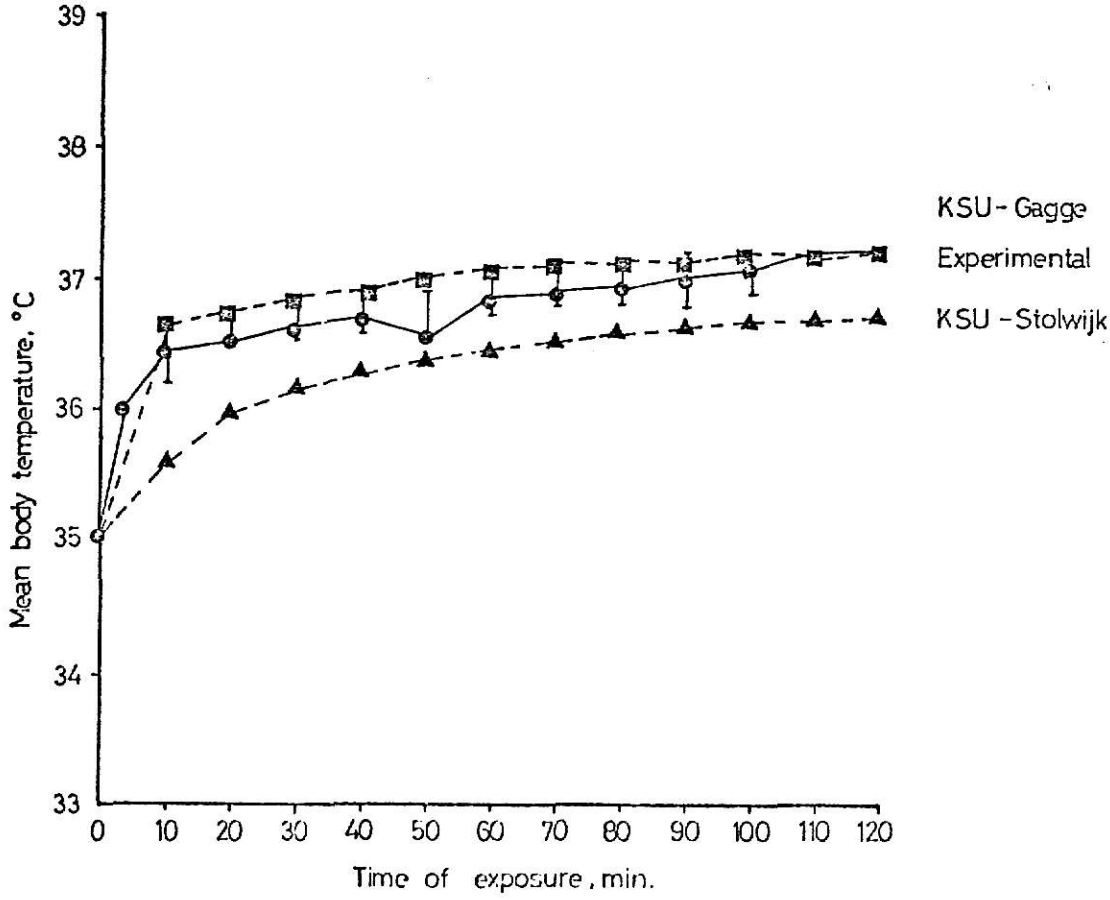


Figure 13. Experimental Mean Body Temperature vs. Simulation (Aug. 31, '72)

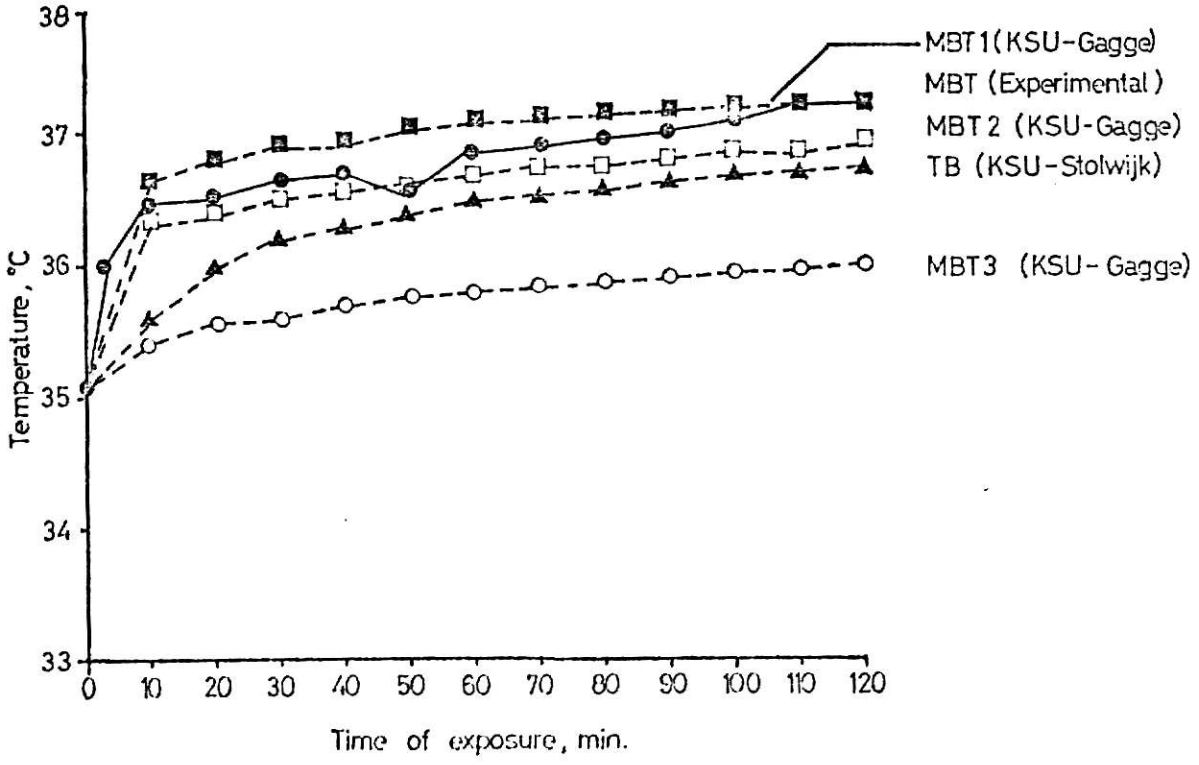


Figure 14. Comparison of Mean Body Temperatures from Alternative Approaches (Aug. 31, '72)

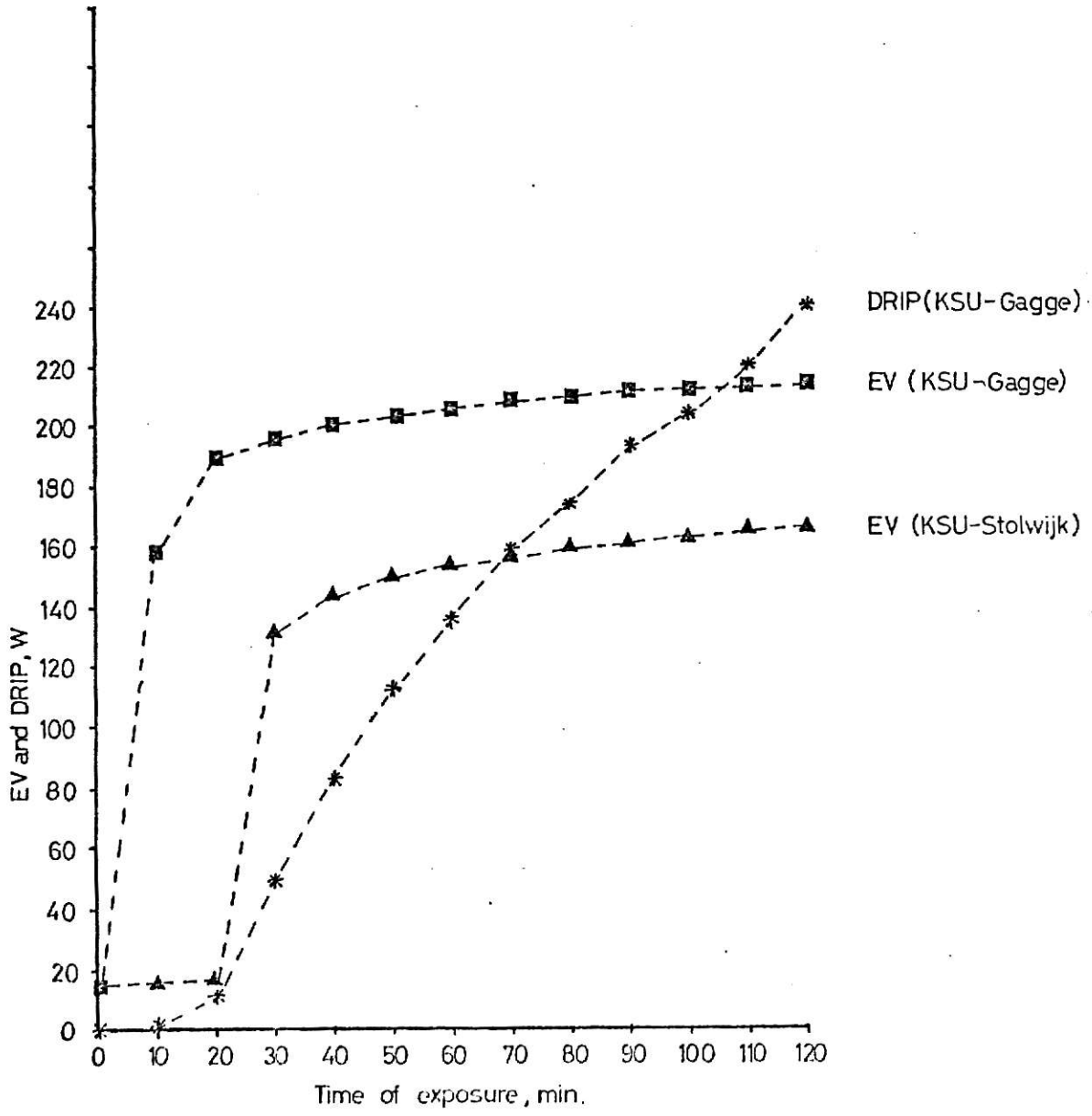


Figure 15. Simulated Evaporated Heat Loss (EV) and Unevaporated Sweat Loss (DRIP) (Aug. 31, '72)

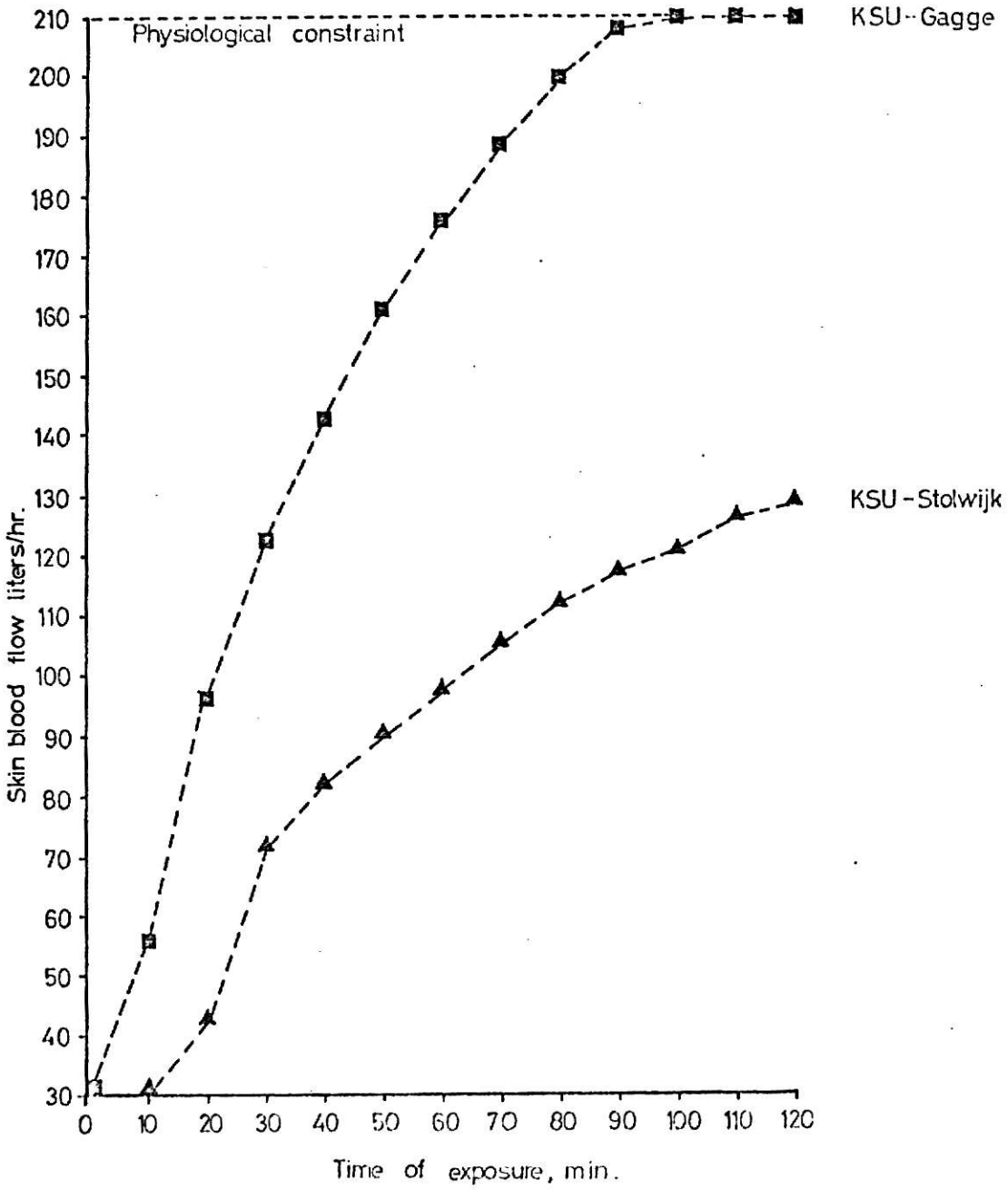


Figure 16. Simulated Skin Blood Flow (Aug. 31, '72)

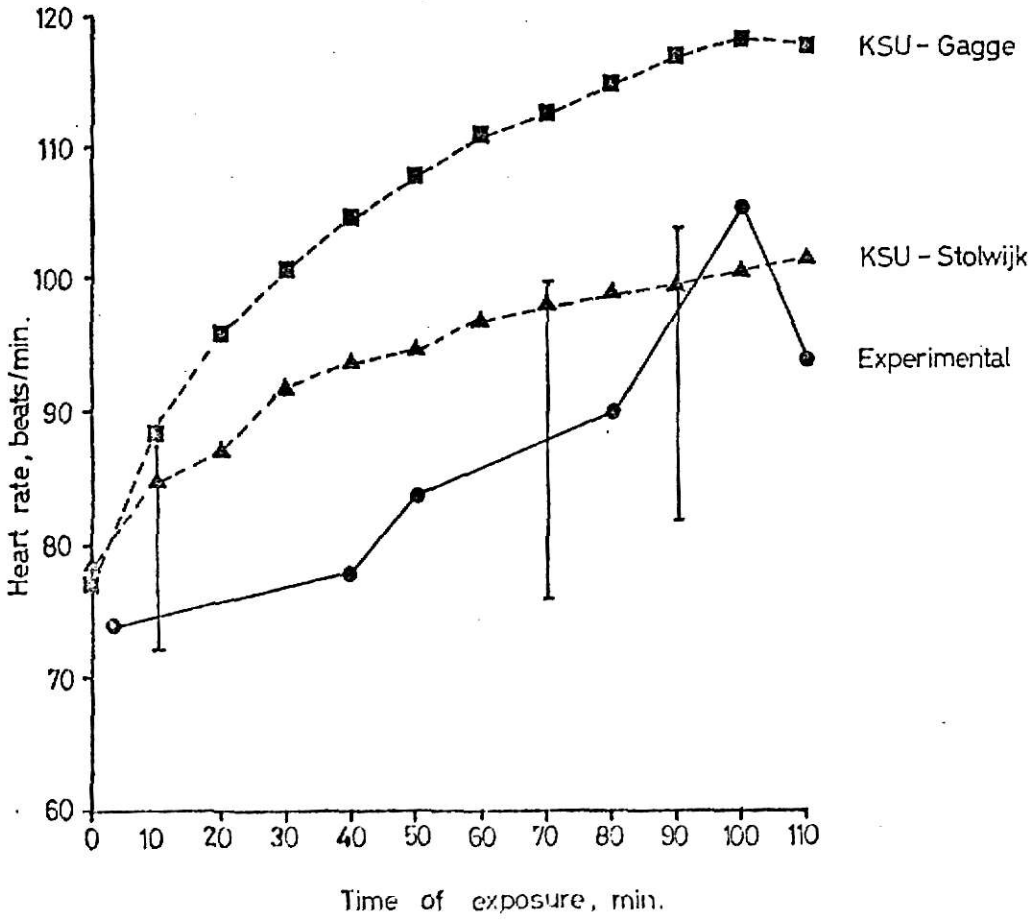


Figure 17. Experimental Heart Rate vs. Simulation (Aug. 31, '72)

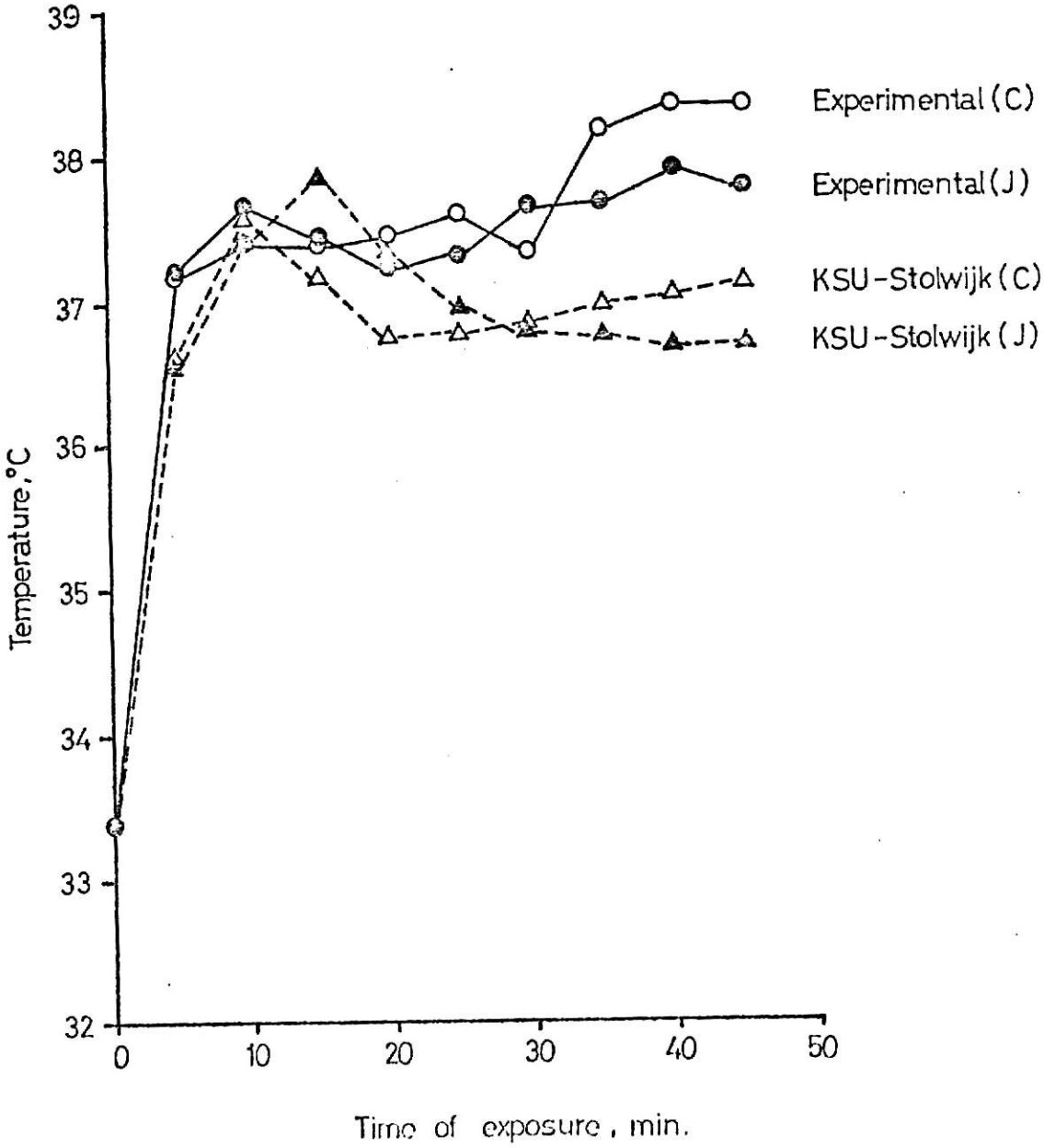


Figure 18. Experimental Head Skin Temperature vs. Simulation (Oct. 29, '74)

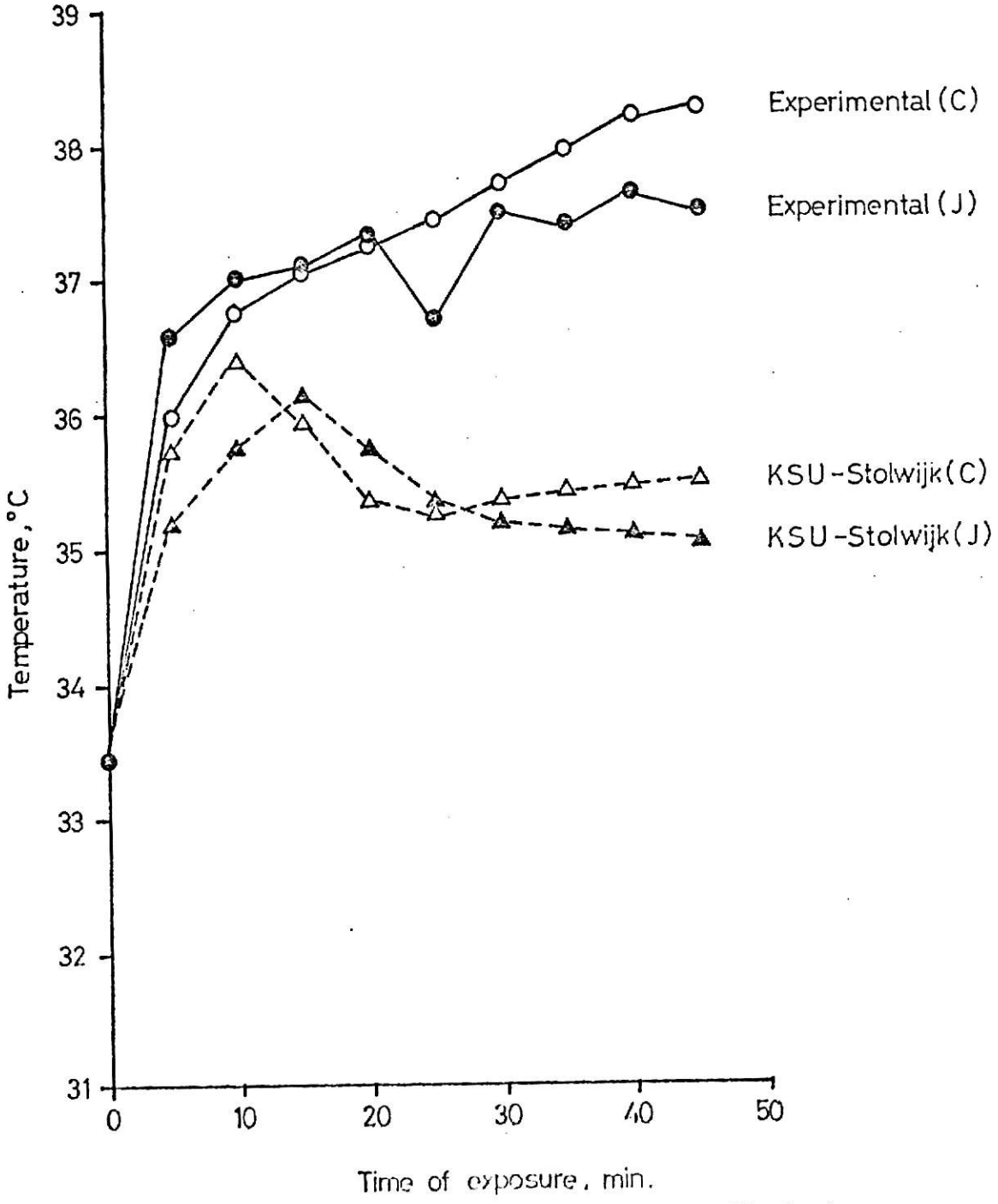


Figure 19. Experimental Trunk Skin Temperature vs. Simulation (Oct. 29, '74)

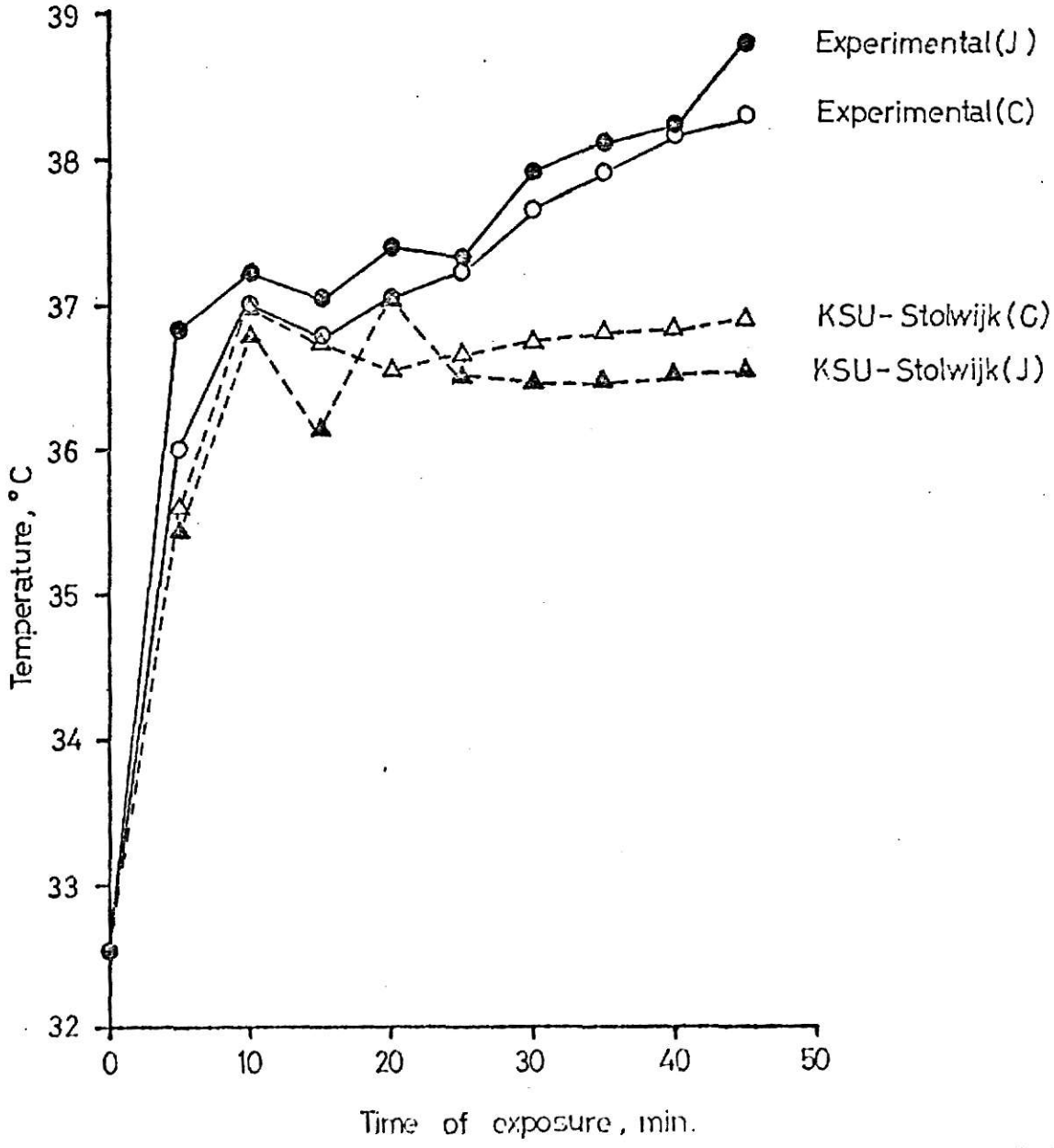


Figure 20. Experimental Arm Skin Temperature vs. Simulation (Oct. 29, '74)

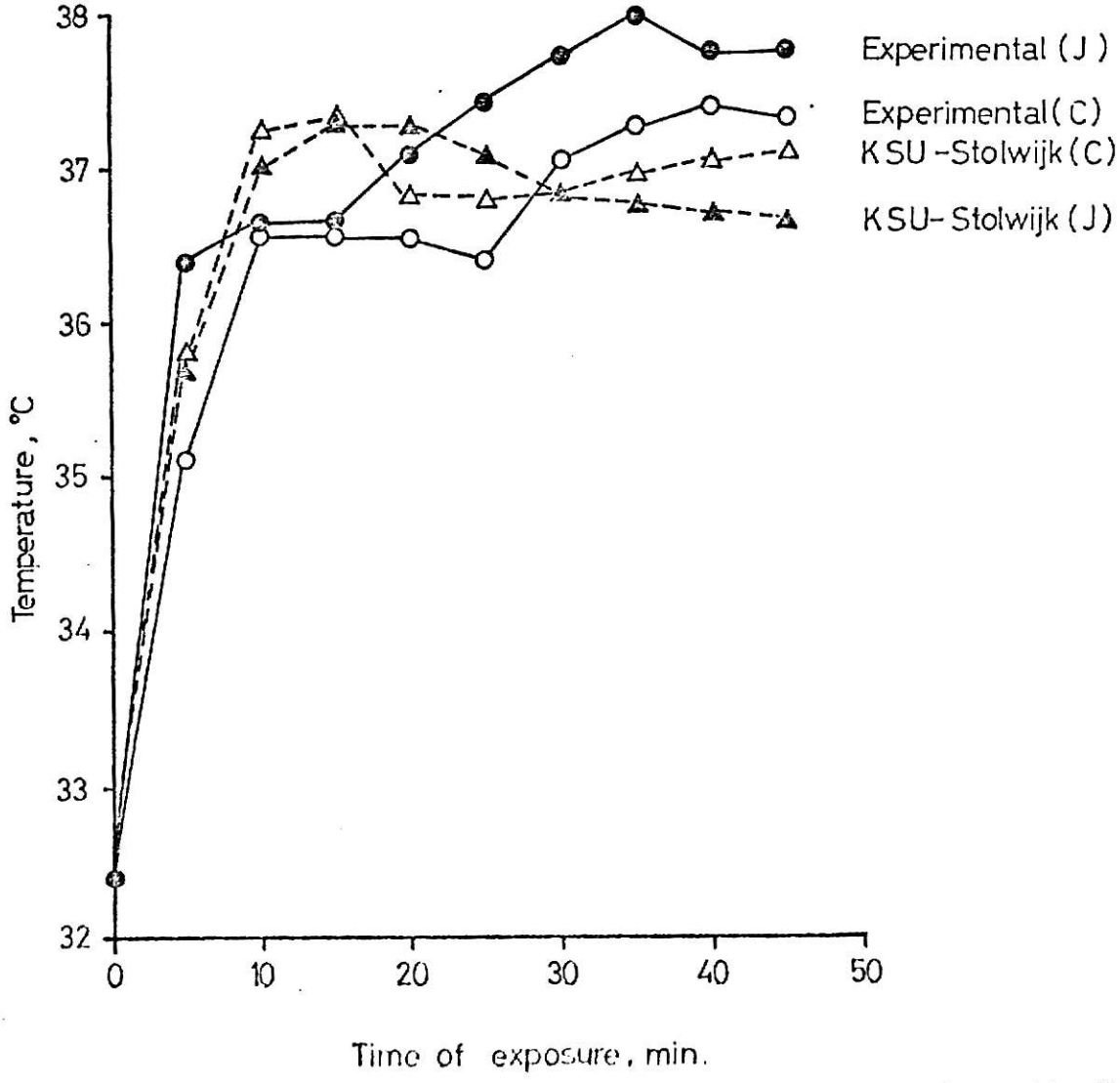


Figure 21. Experimental Leg Skin Temperature vs. Simulation (Oct. 29, '74)

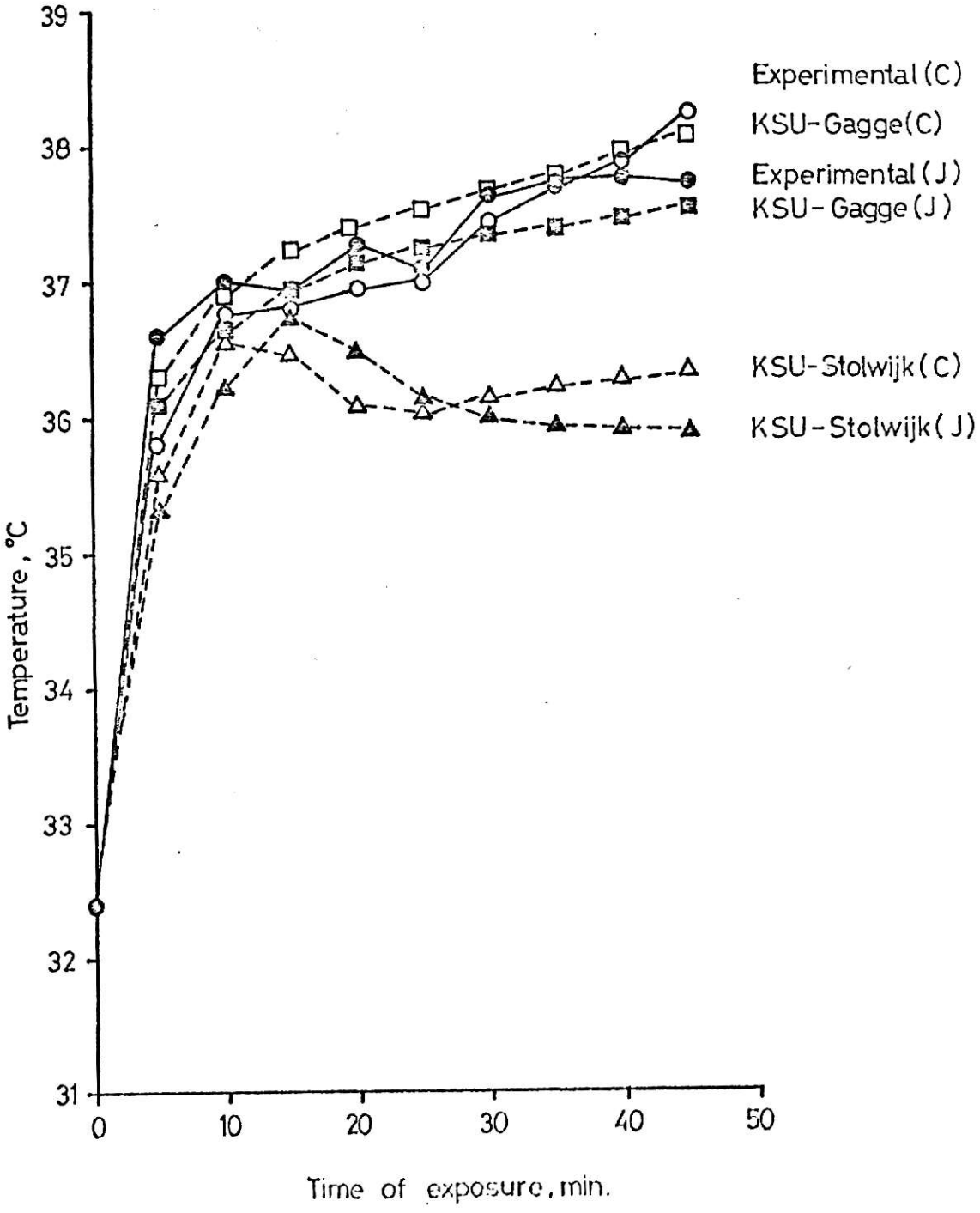


Figure 22. Experimental Mean Skin Temperature vs. Simulation (Oct. 29, '74)

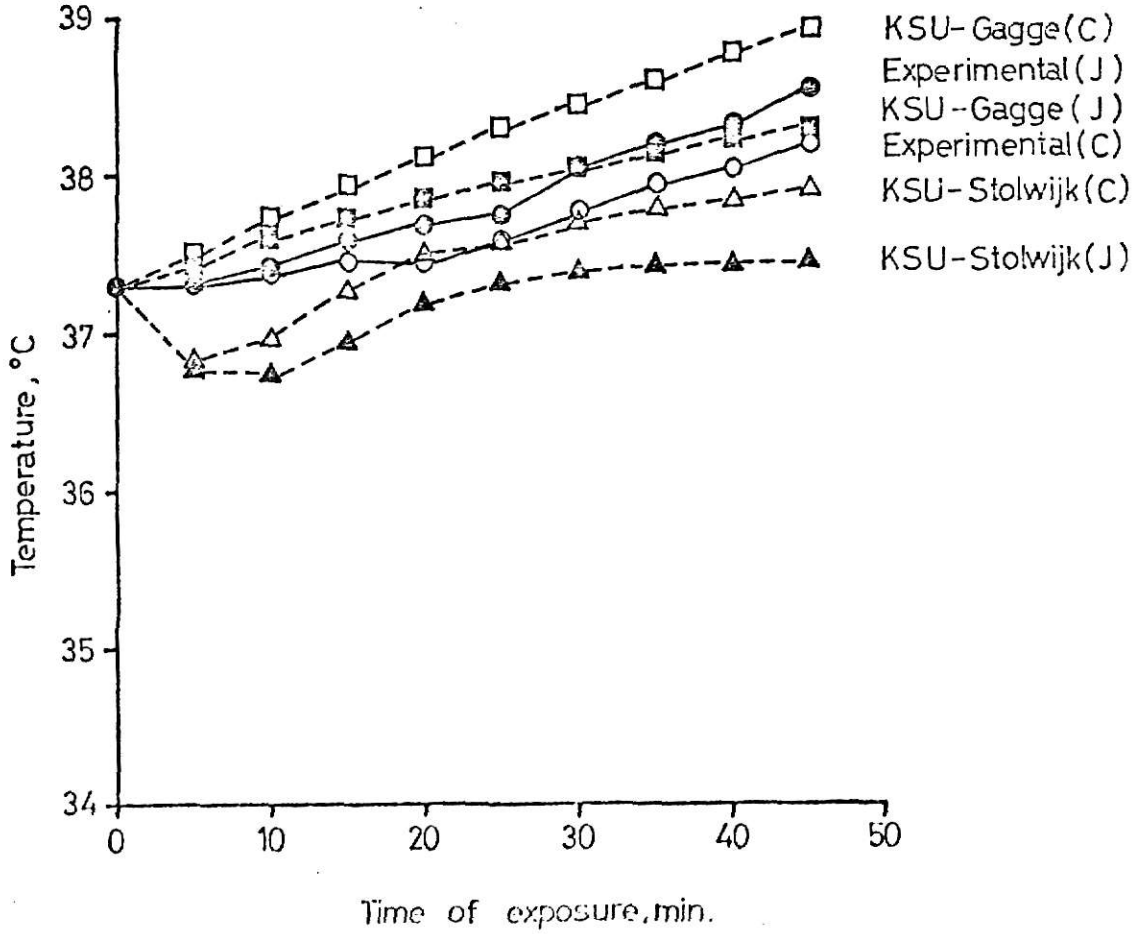


Figure 23. Experimental Rectal Temperature vs. Simulated Core Temperature (Oct. 29, '74)

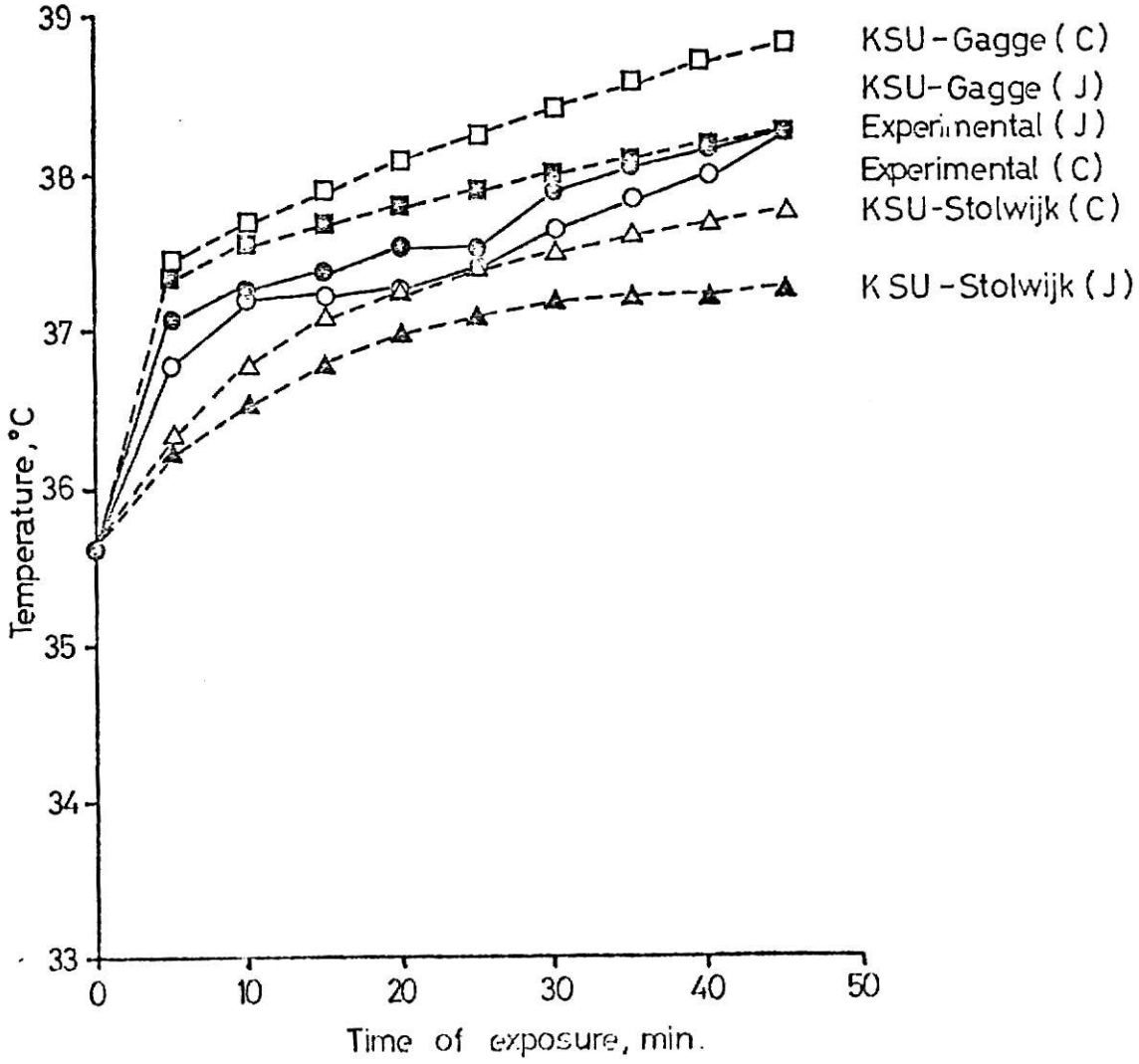


Figure 24. Experimental Mean Body Temperature vs. Simulation (Oct. 29, '74)

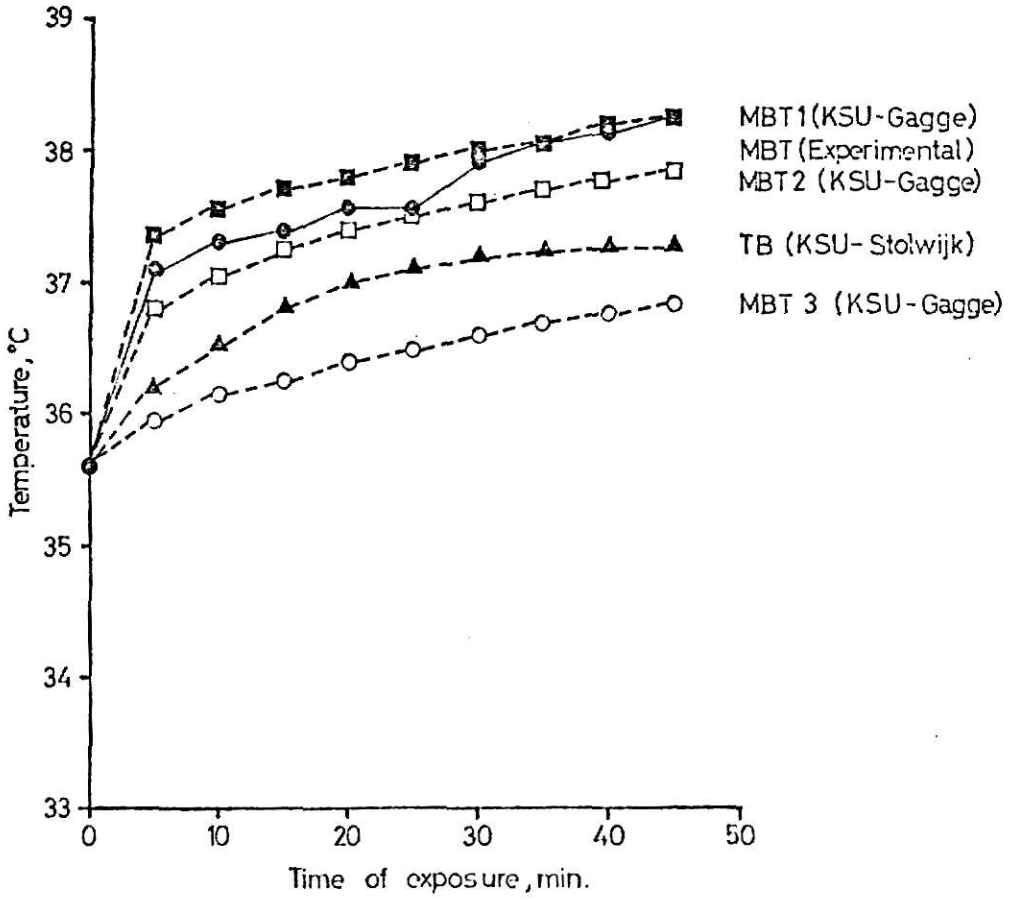


Figure 25. Comparison of Mean Body Temperatures from Alternative Approaches (Oct. 29, '74)(Subject J)

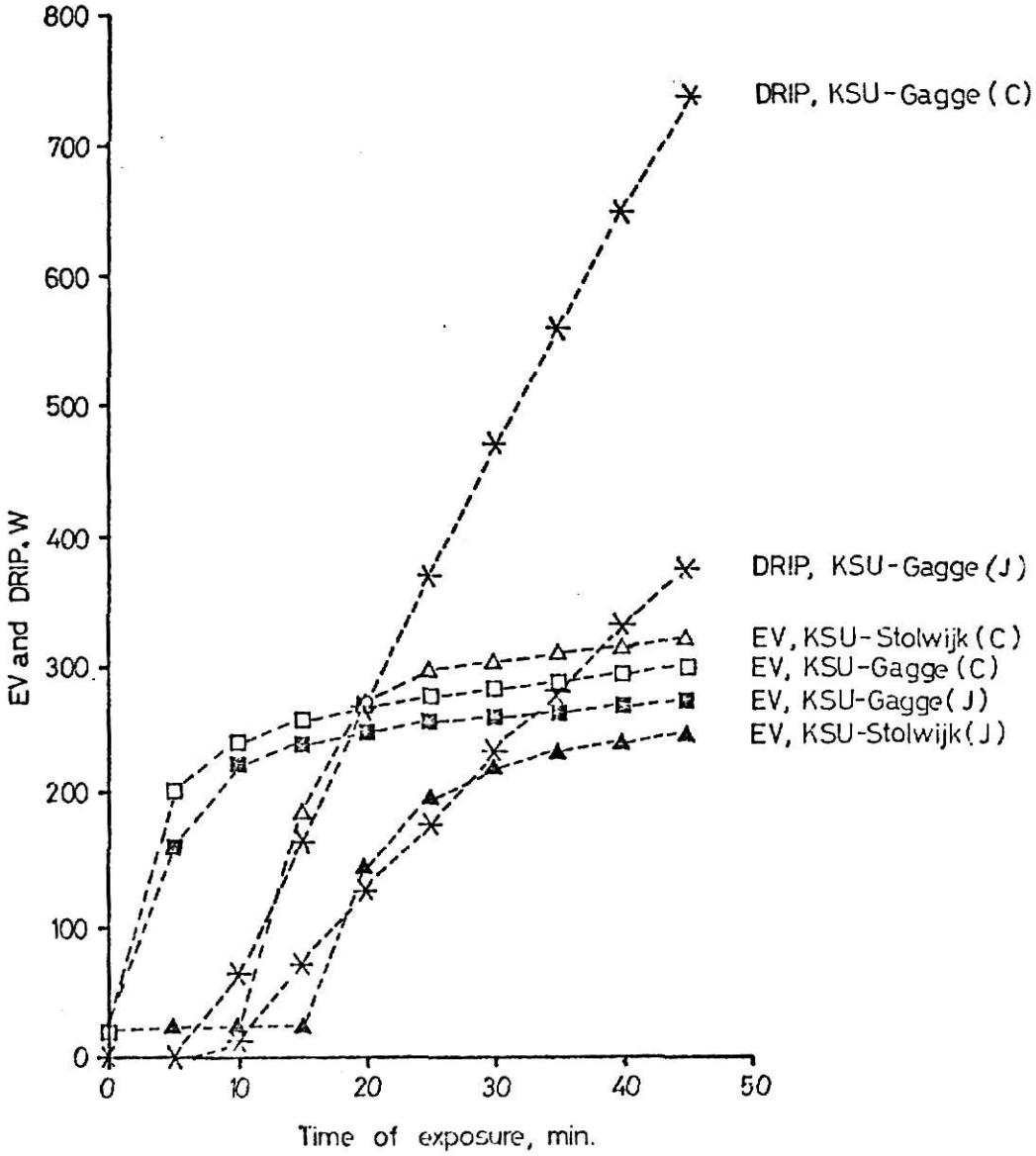


Figure 26. Simulated Evaporative Heat Loss (EV) and Unevaporated Sweat Loss (DRIP) (Oct. 29, '74)

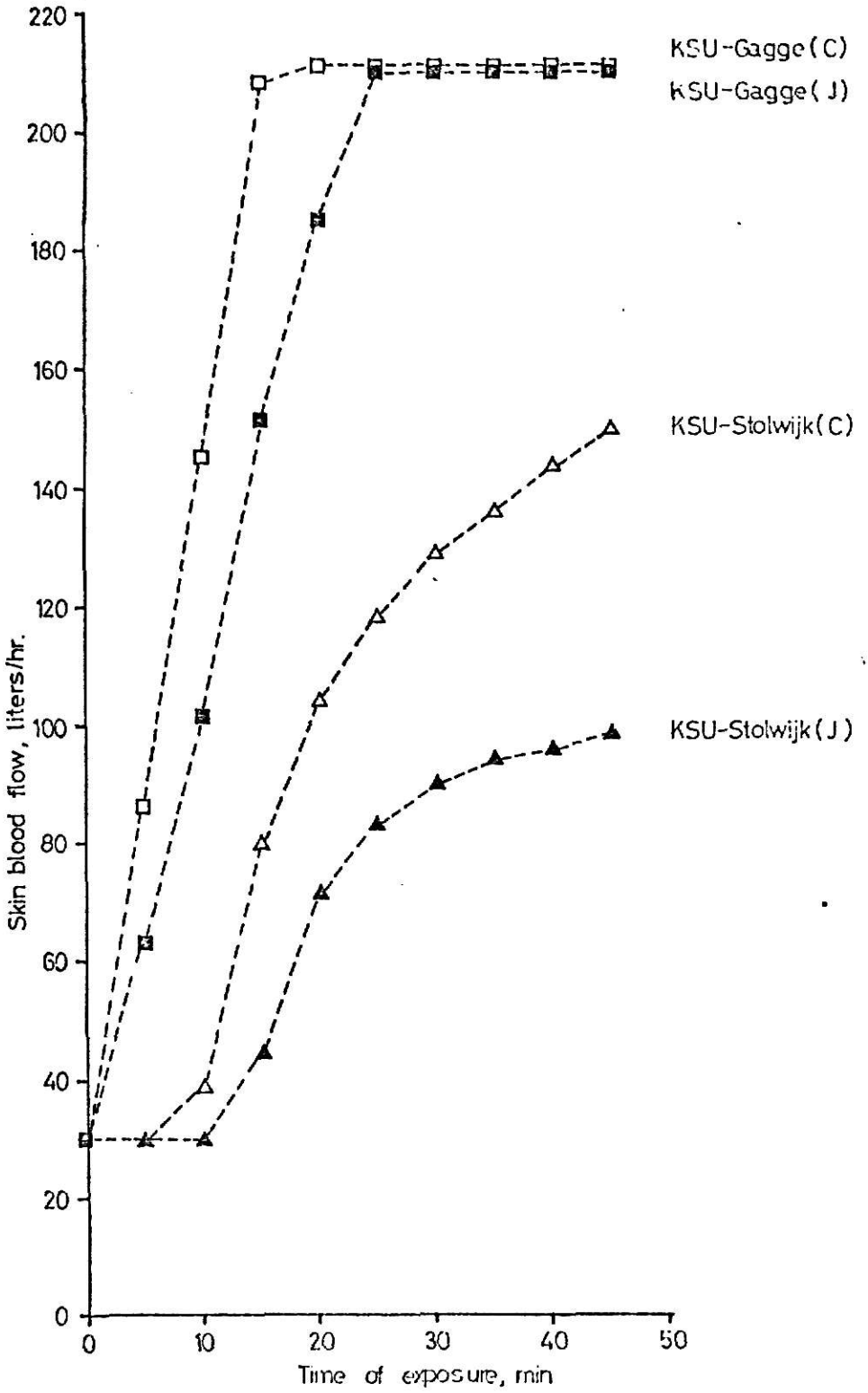


Figure 27. Simulated Skin Blood Flow (Oct. 29, '74)

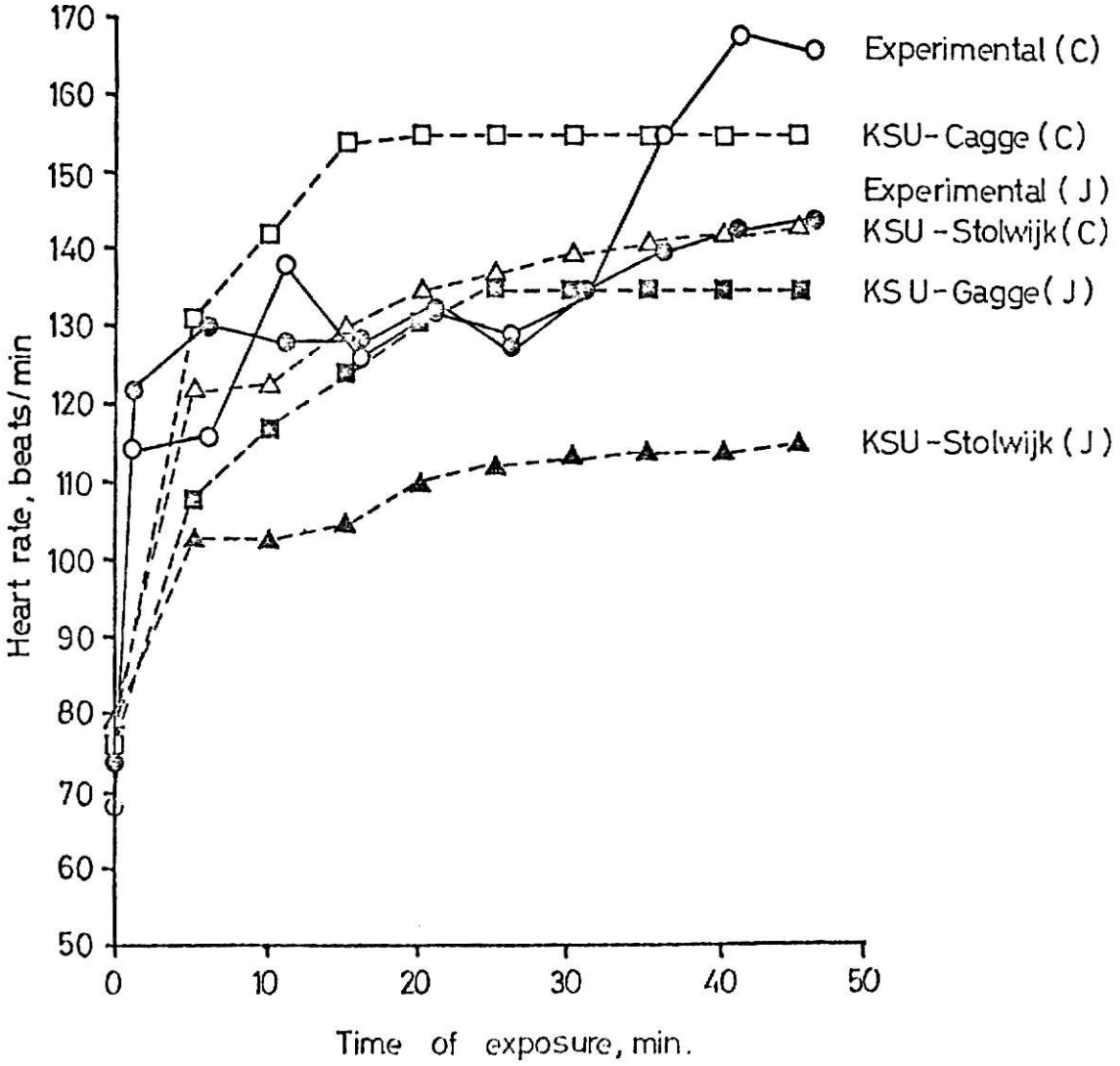


Figure 28. Experimental Heart Rate vs. Simulation (Oct. 29, '74)

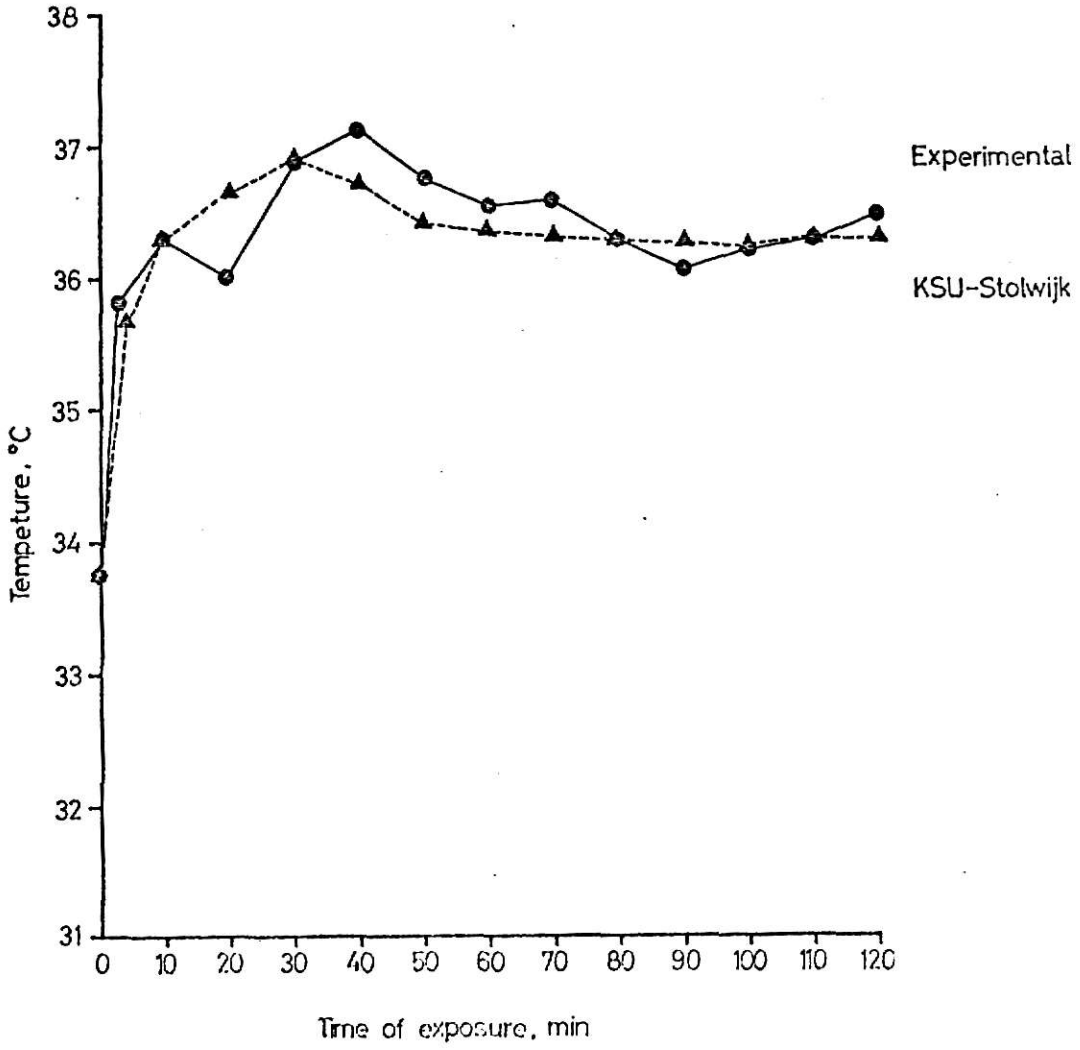


Figure 29. Experimental Head Skin Temperature vs. Simulation (Aug. 7, '72)

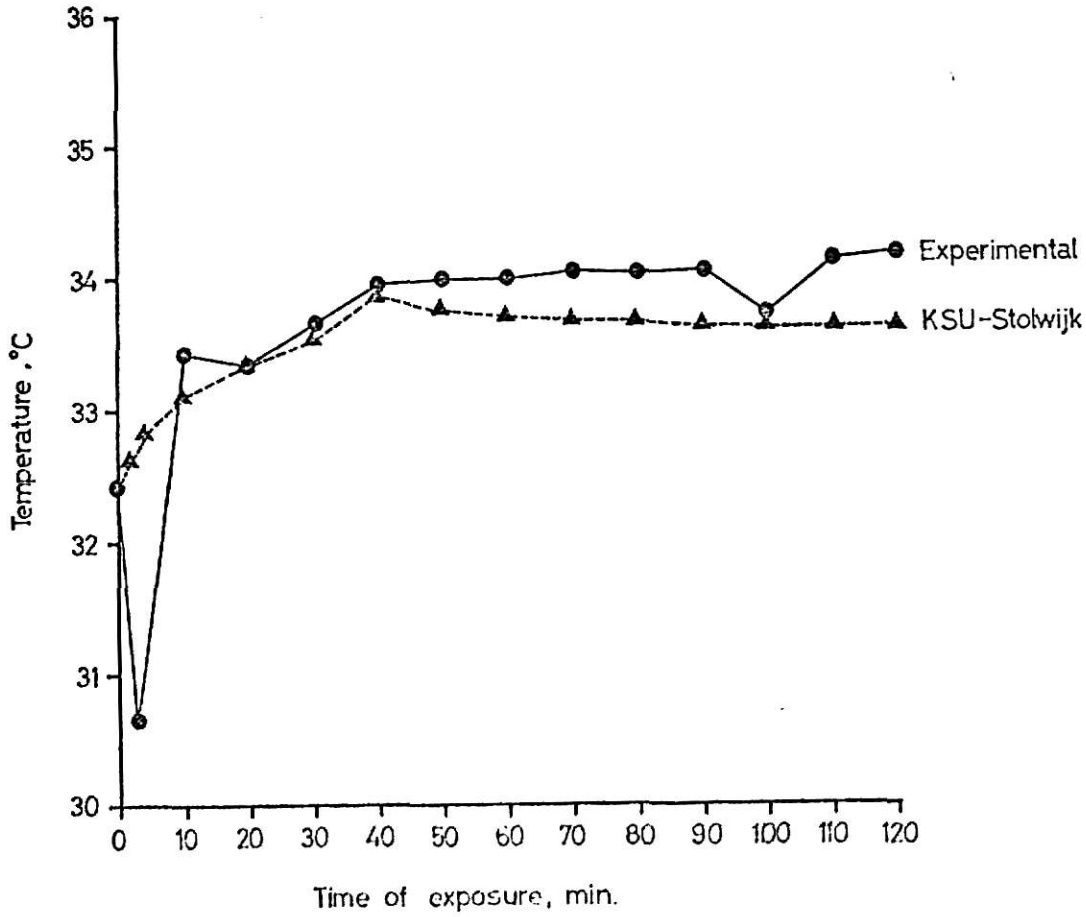


Figure 30. Experimental Trunk Skin Temperature vs. Simulation (Aug. 7, '72)

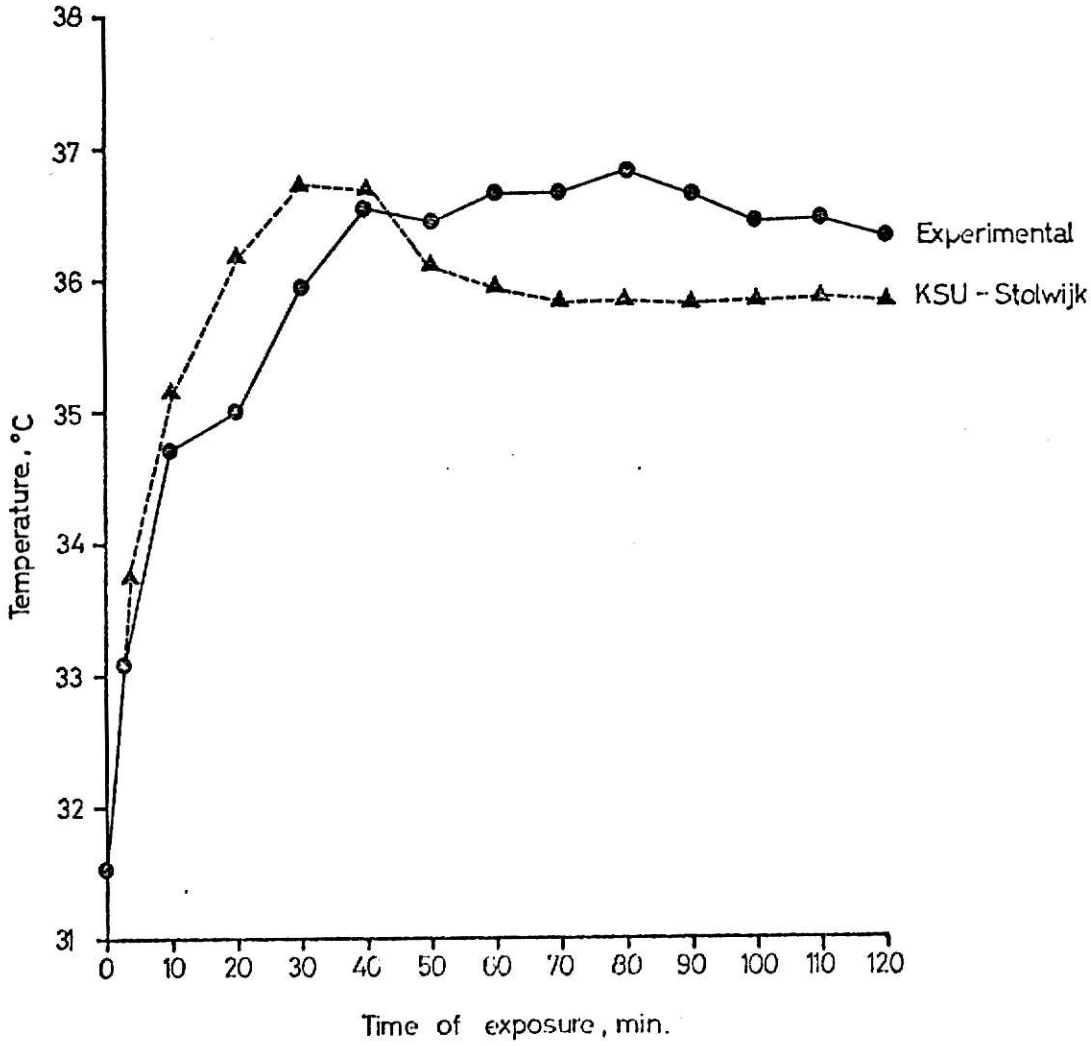


Figure 31. Experimental Arm Skin Temperature vs. Simulation (Aug. 7, '72)

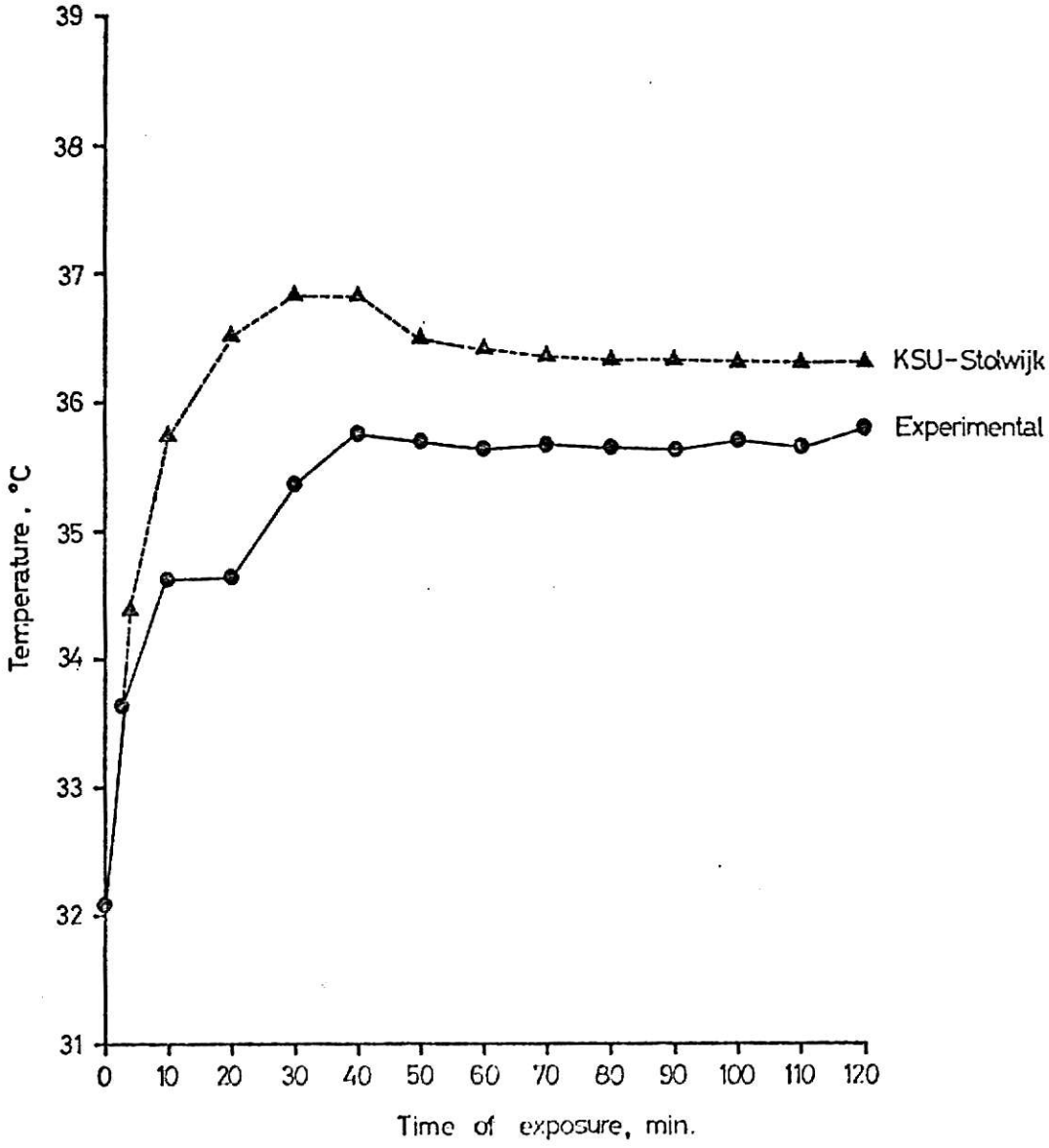


Figure 32. Experimental Leg Skin Temperature vs. Simulation (Aug. 7, '72)

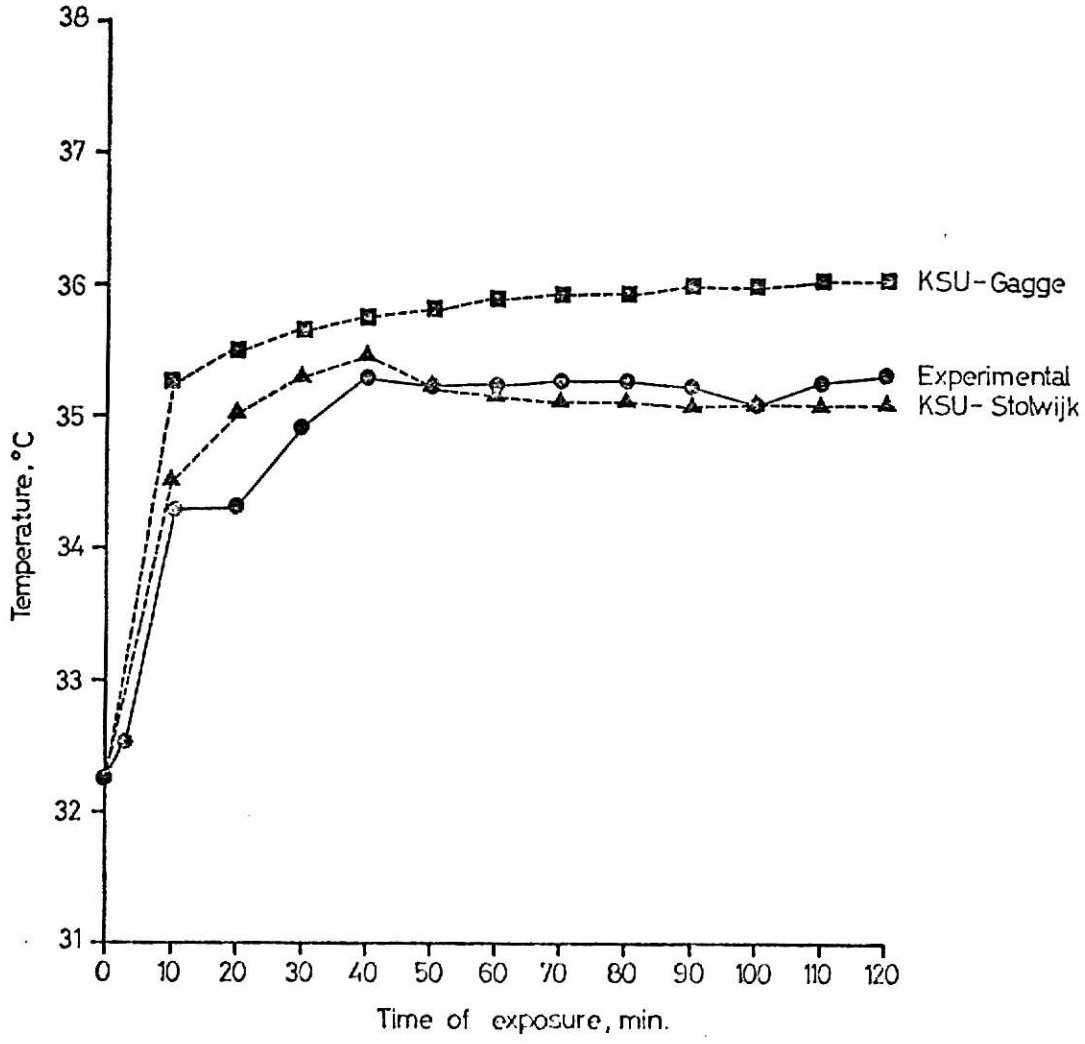


Figure 33. Experimental Mean Skin Temperature vs. Simulation (Aug. 7, '72)

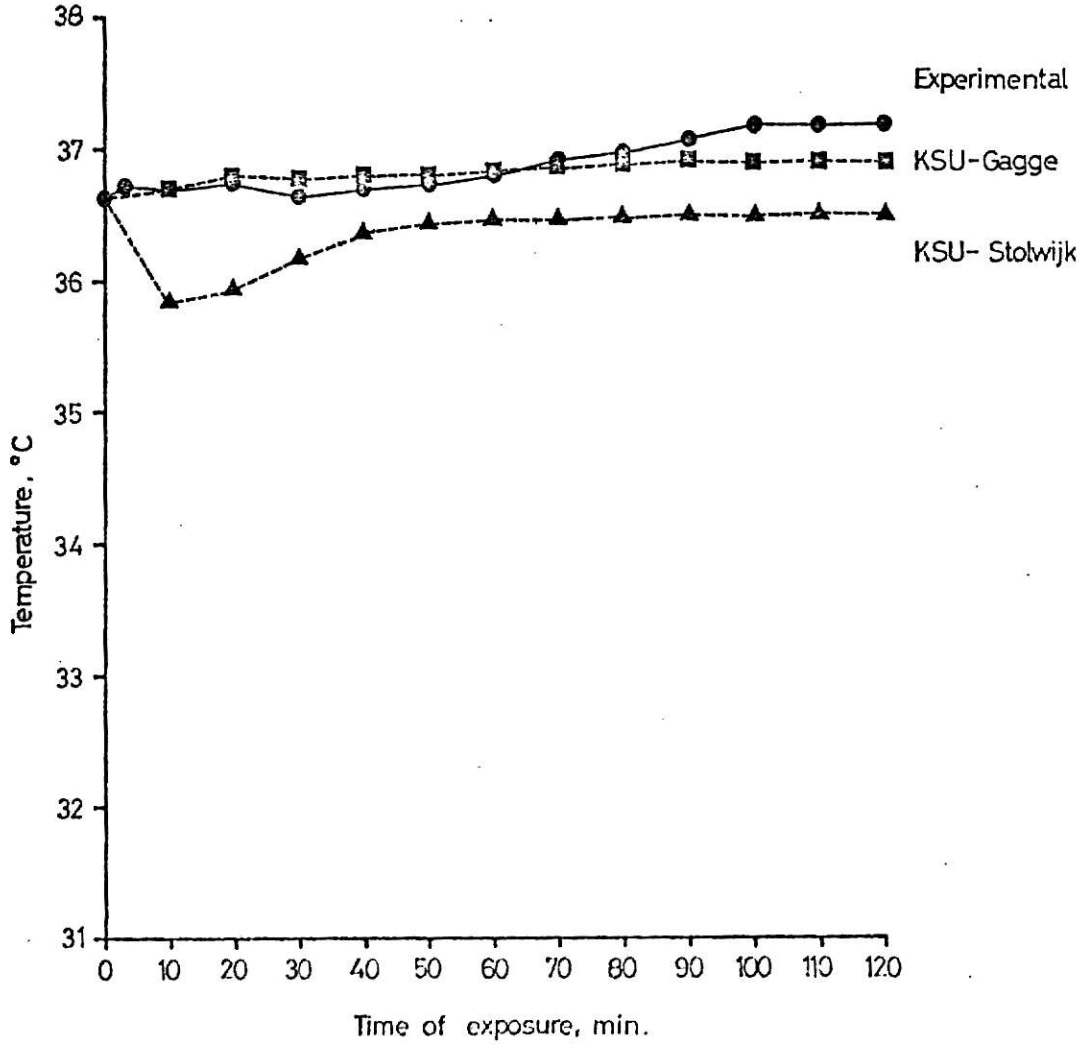


Figure 34. Experimental Rectal Temperature vs. Simulated Core Temperature (Aug. 7, '72)

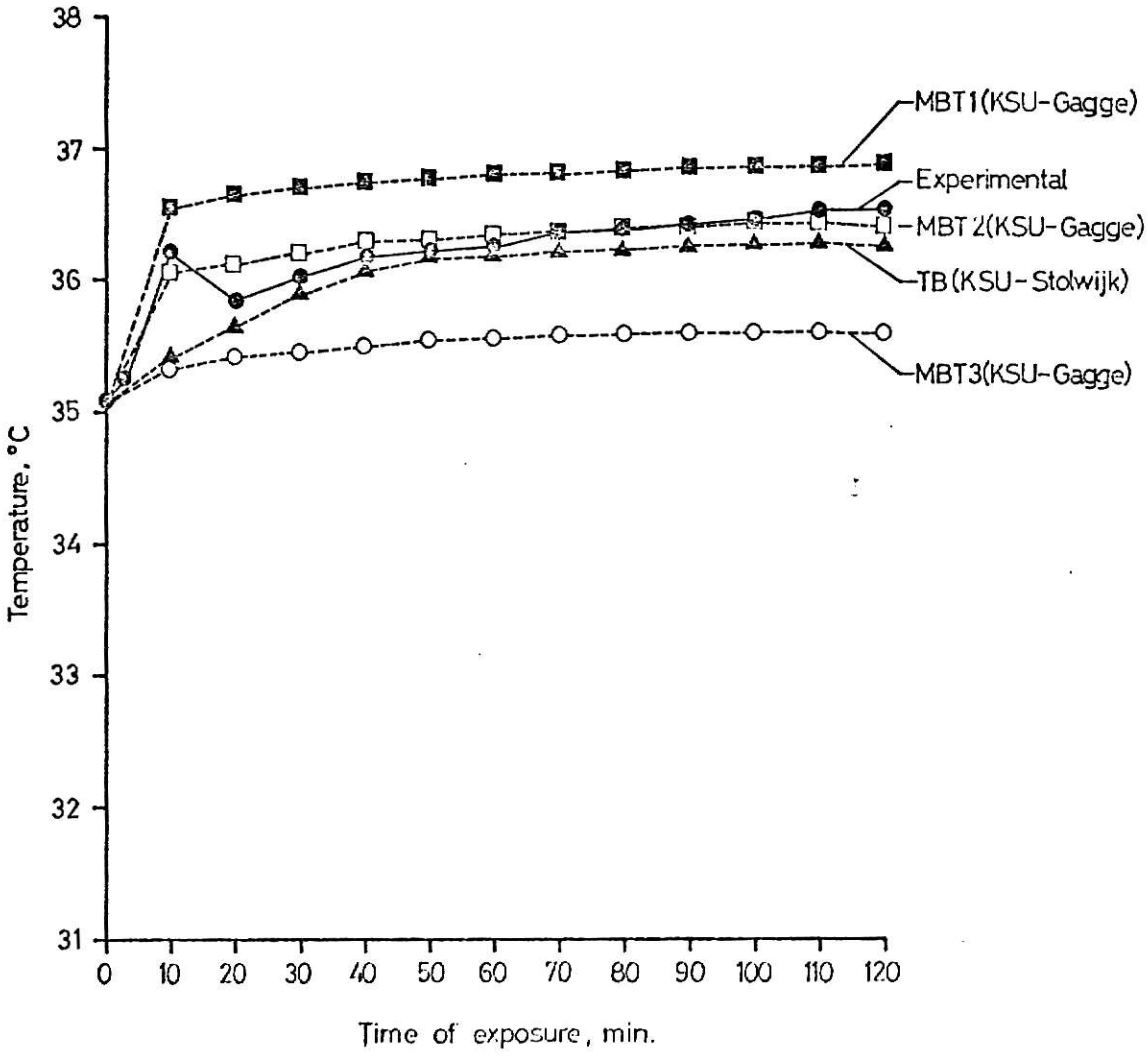


Figure 35. Experimental Mean Body Temperature vs. Simulation (Aug. 7, '72)

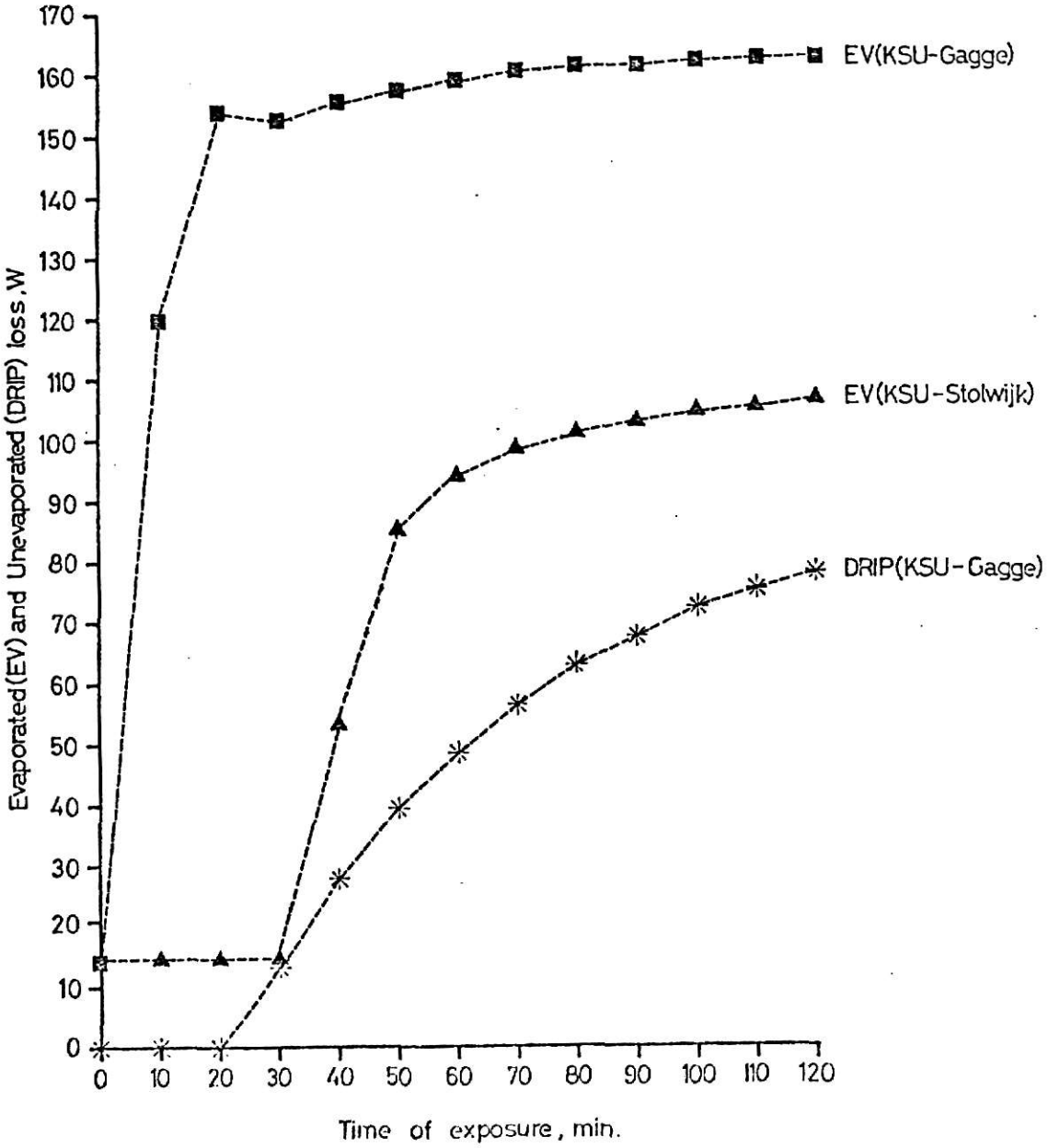


Figure 36. Simulated Evaporated Heat Loss (EV) and Unevaporated Sweat Loss (DRIP) (Aug. 7, '72)

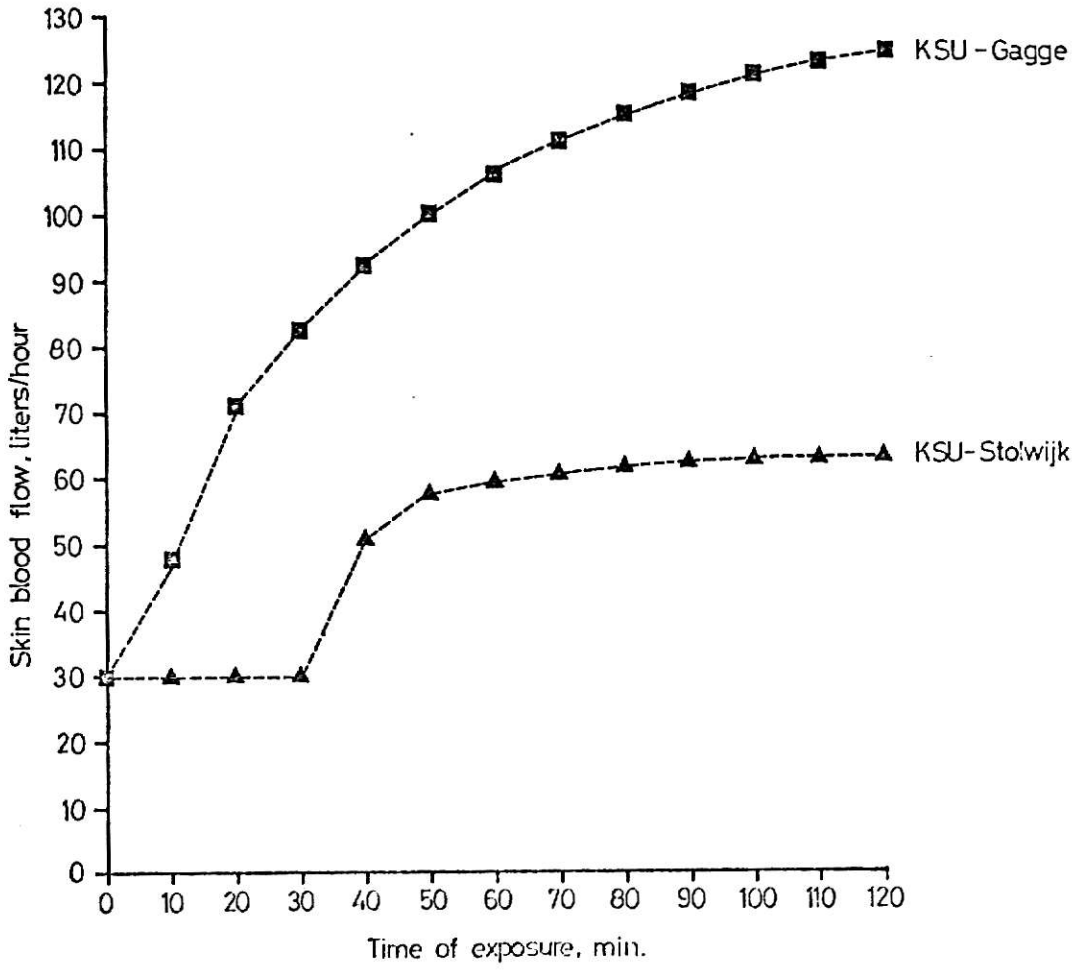


Figure 37. Simulated Skin Blood Flow (Aug. 7, '72)

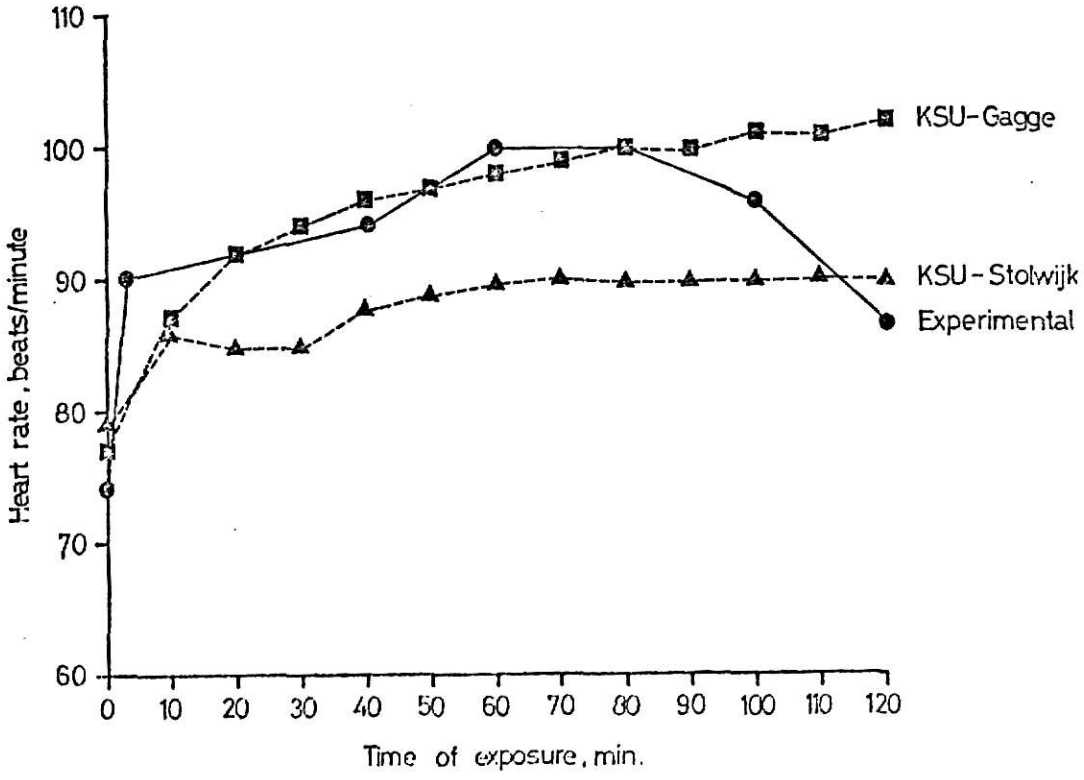


Figure 38. Experimental Heart Rate vs. Simulation (Aug. 7, '72)

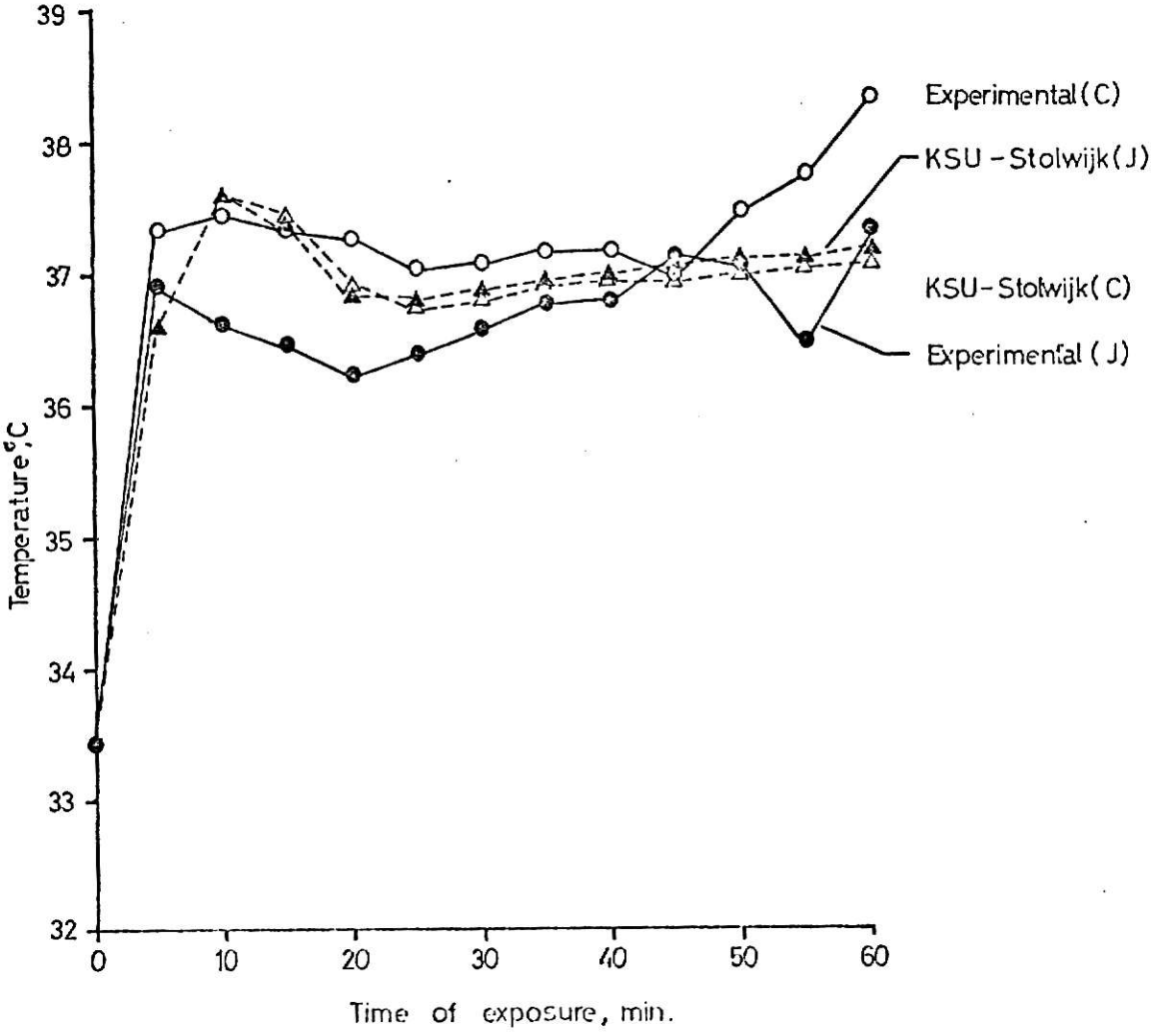


Figure 39. Experimental Head Skin Temperature vs. Simulation (Nove. 6, '74)

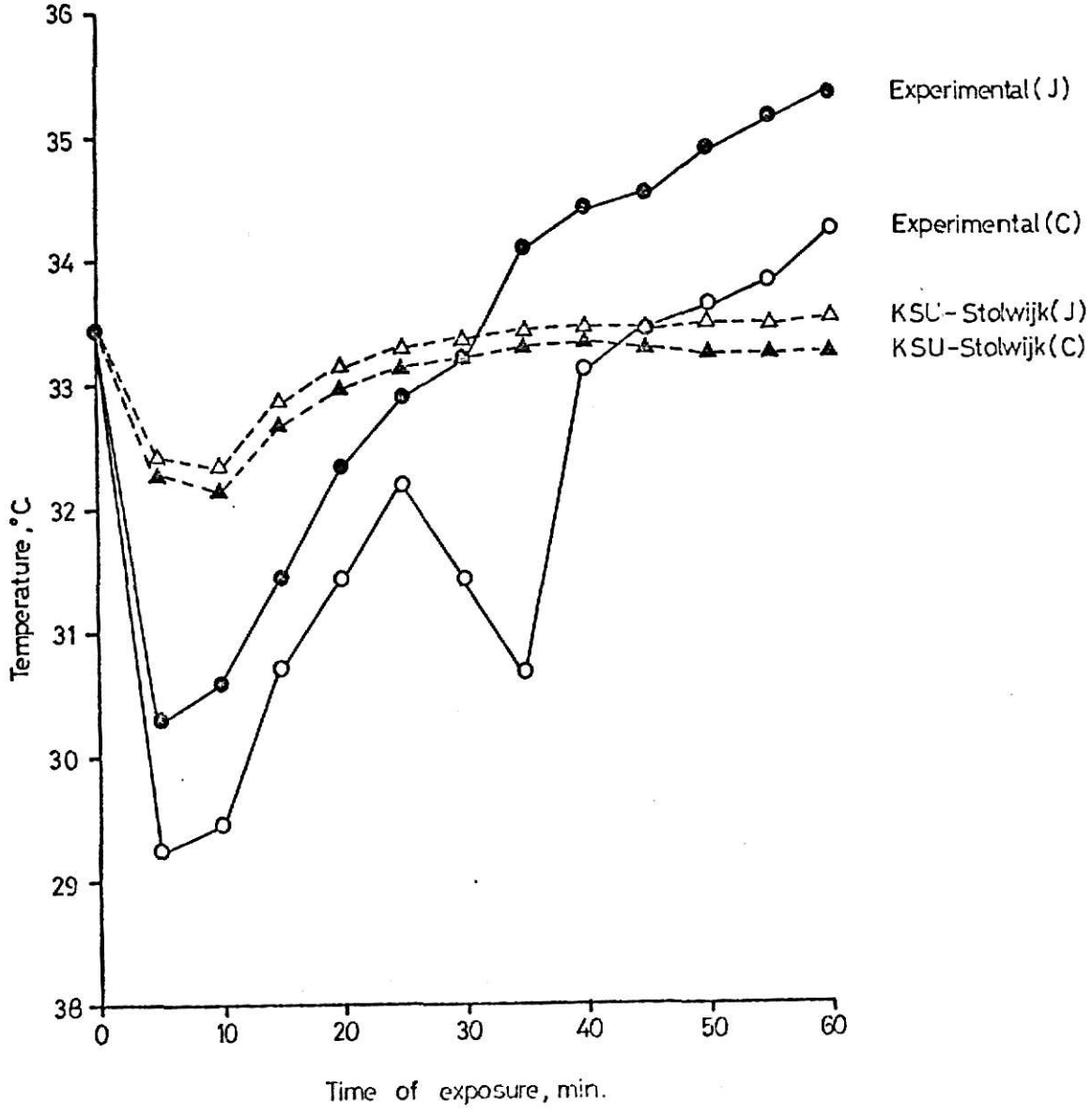


Figure 40. Experimental Trunk Skin Temperature vs. Simulation (Nov. 6, '74)

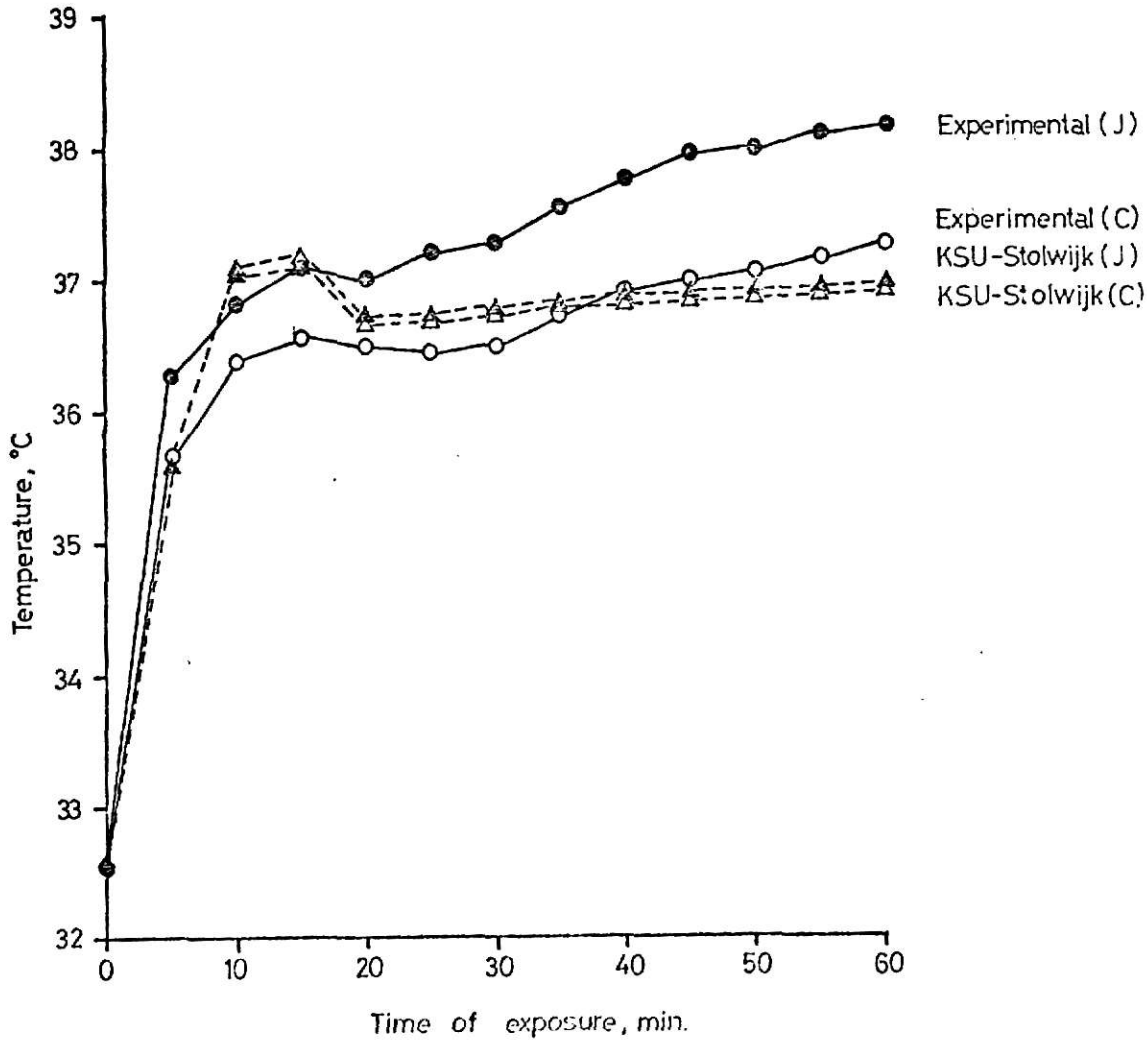


Figure 41. Experimental Arm Skin Temperature vs. Simulation (Nov. 6, '74)

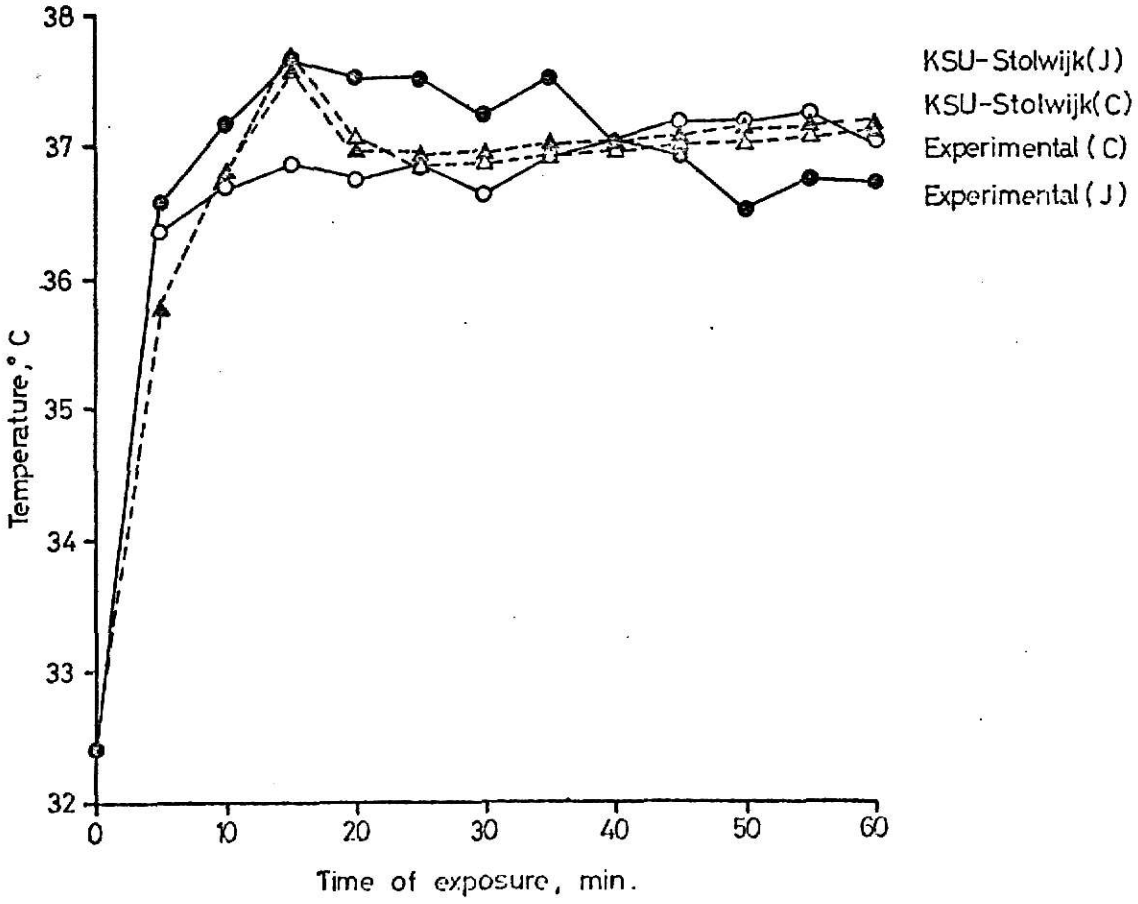


Figure 42. Experimental Leg Skin Temperature vs. Simulation (Nov. 6, '74)

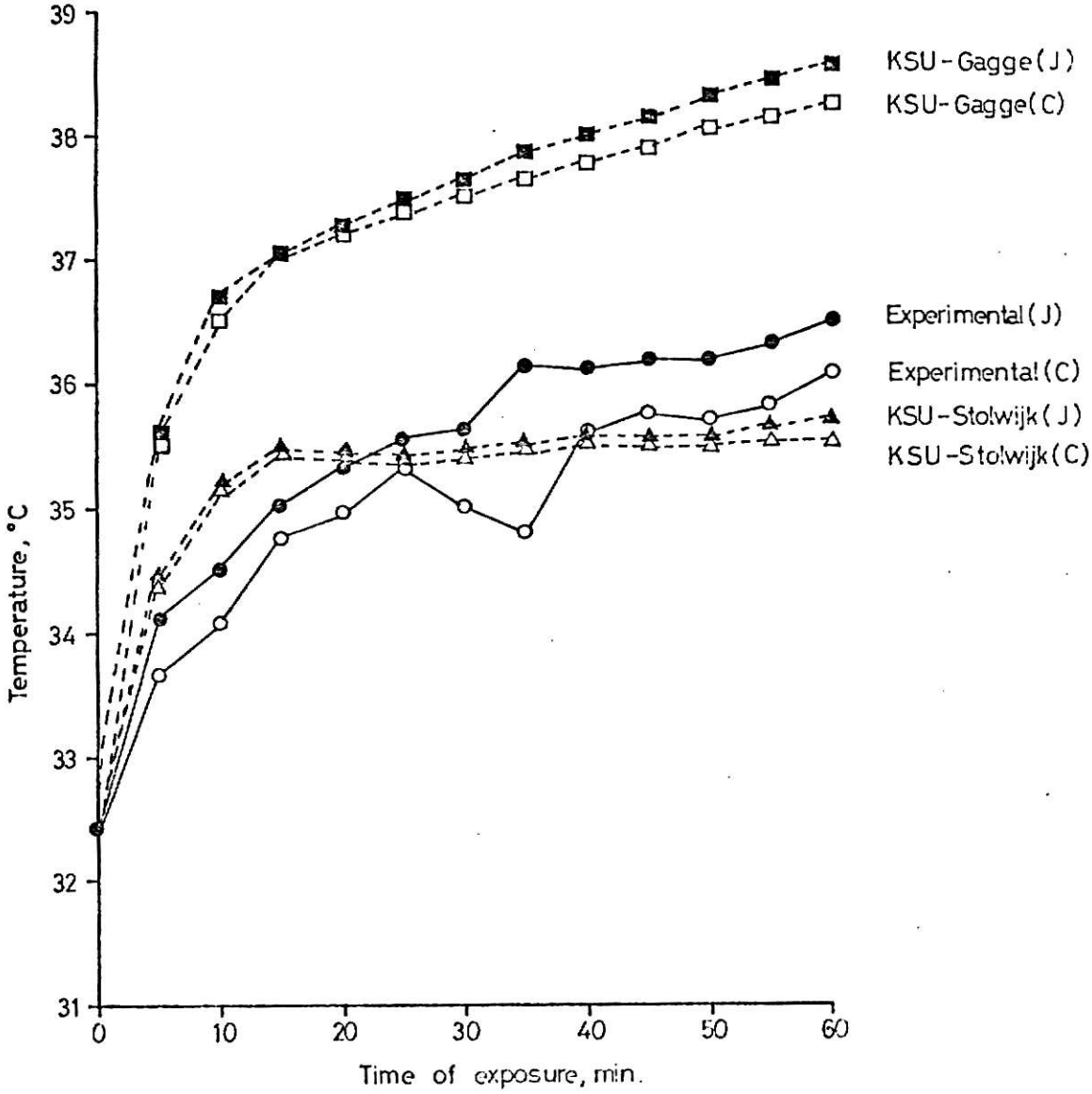


Figure 43. Experimental Mean Skin Temperature vs. Simulation (Nov. 6, '74)

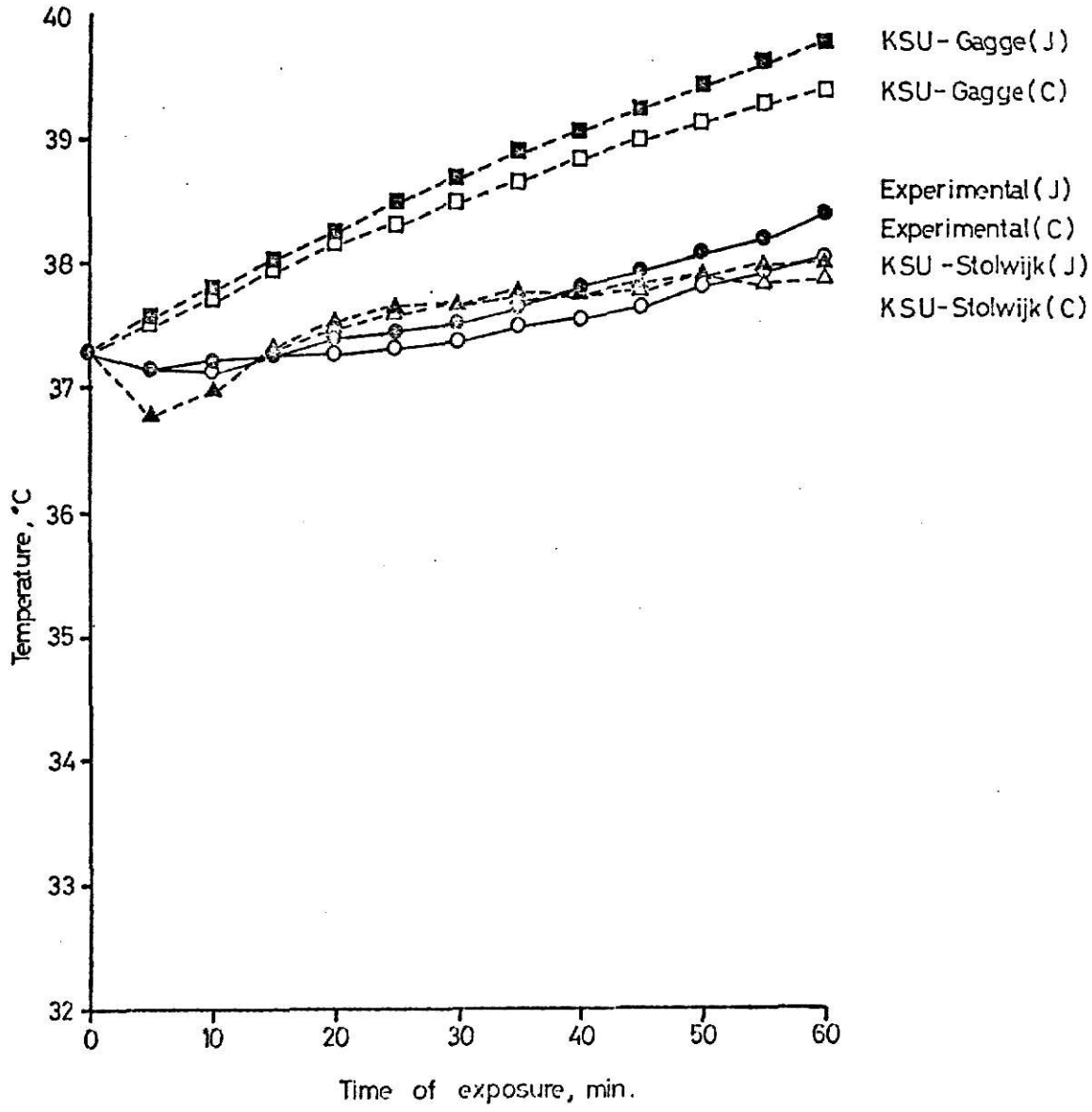


Figure 44. Experimental Rectal Temperature vs. Simulated Core Temperature (Nov. 6, '74)

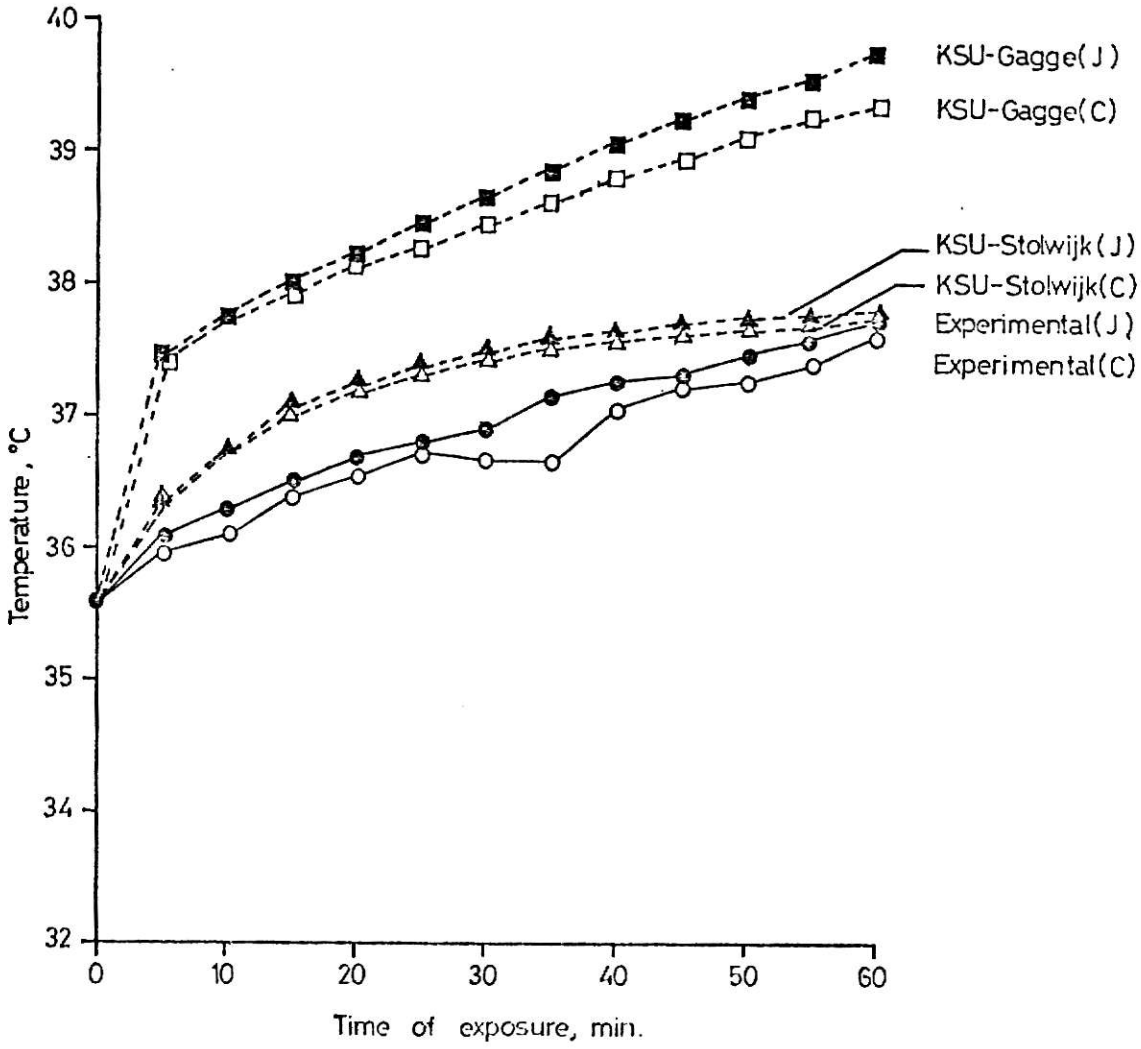


Figure 45. Experimental Mean Body Temperature vs. Simulation (Nov. 6, '74)

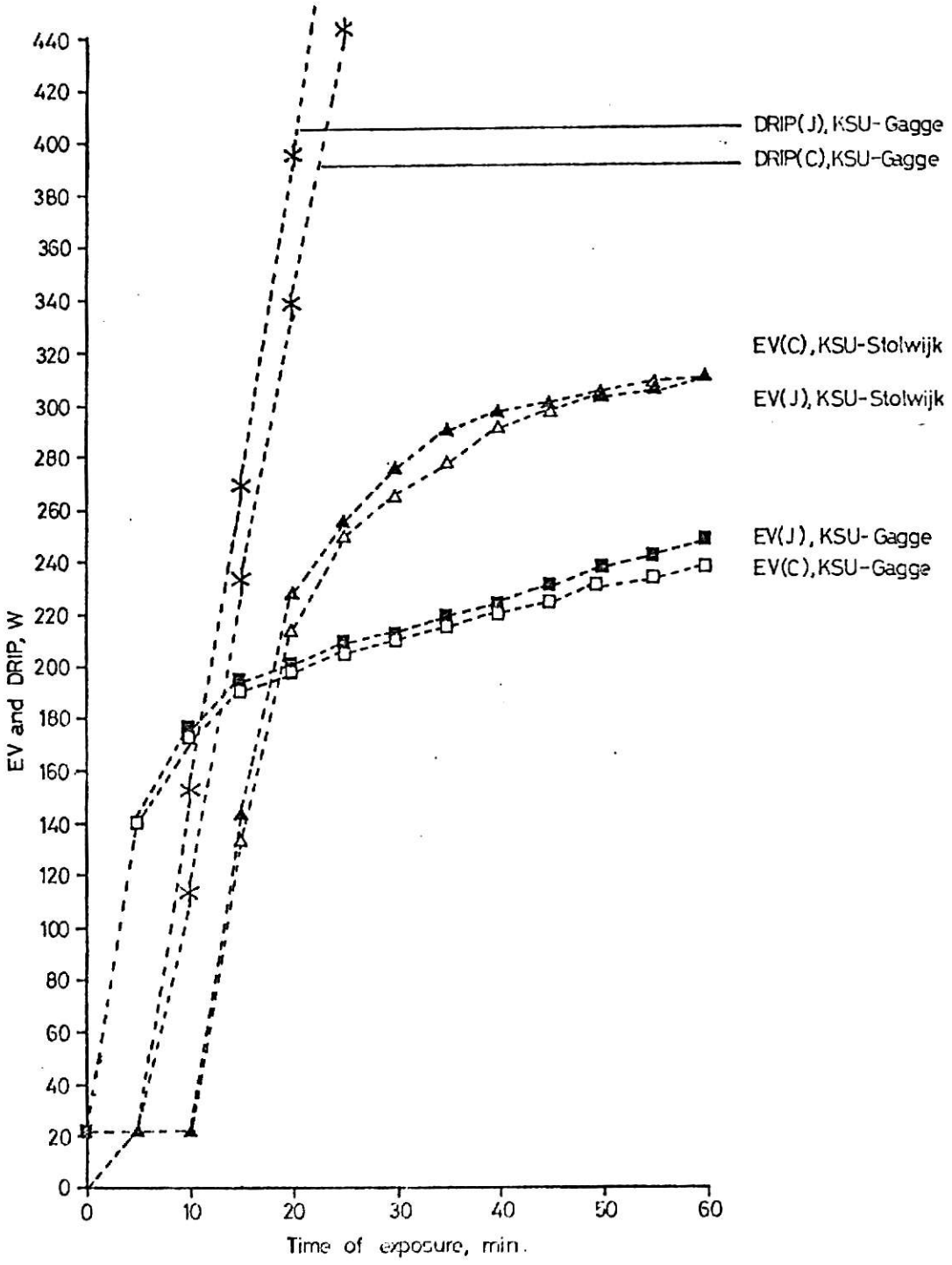


Figure 46. Simulated Evaporated Heat Loss (EV) and Unevaporated Sweat Loss (DRIP) (Nov. 6, '74)

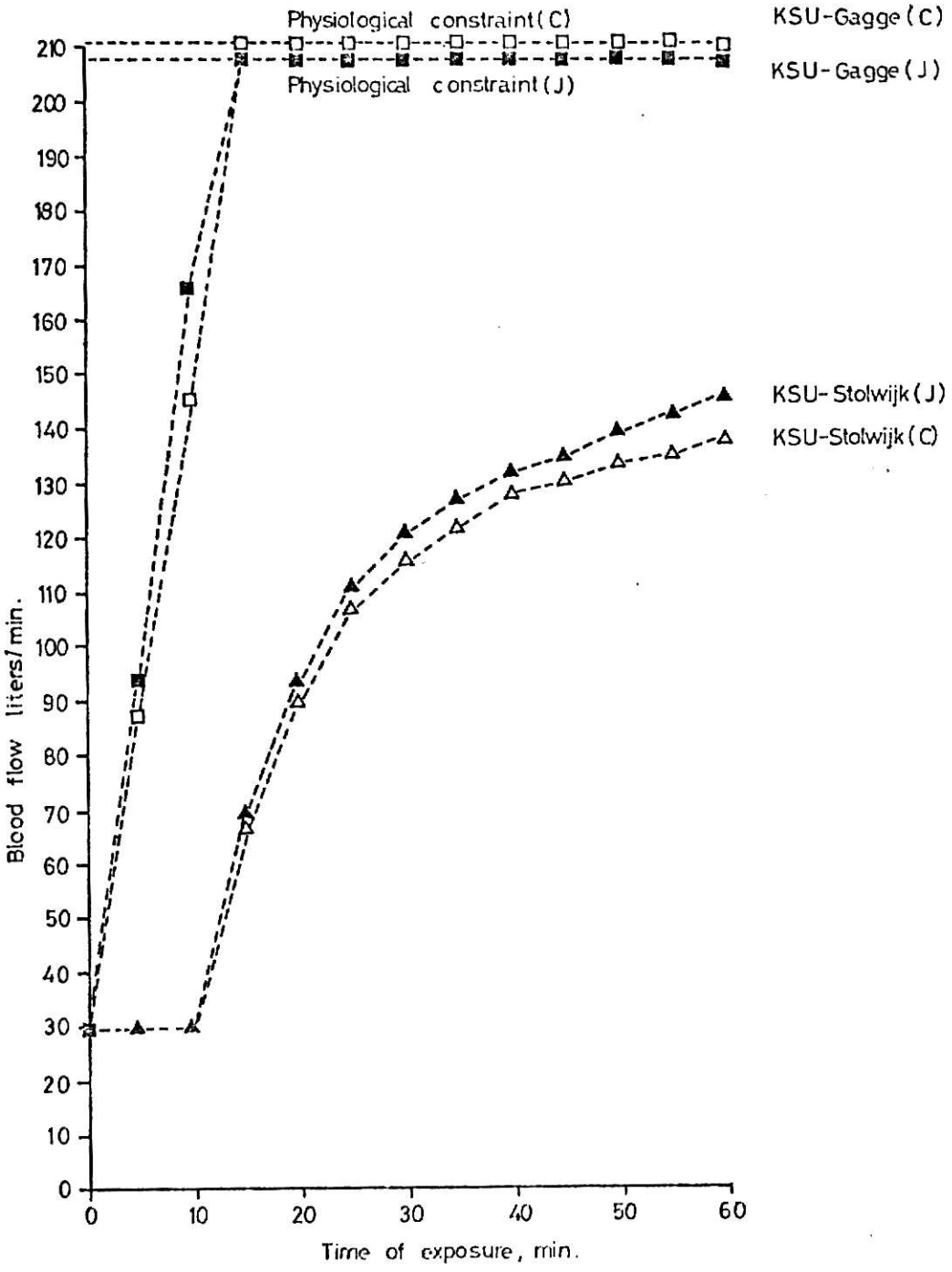


Figure 47. Simulated Skin Blood Flow (Nov. 6, '74)

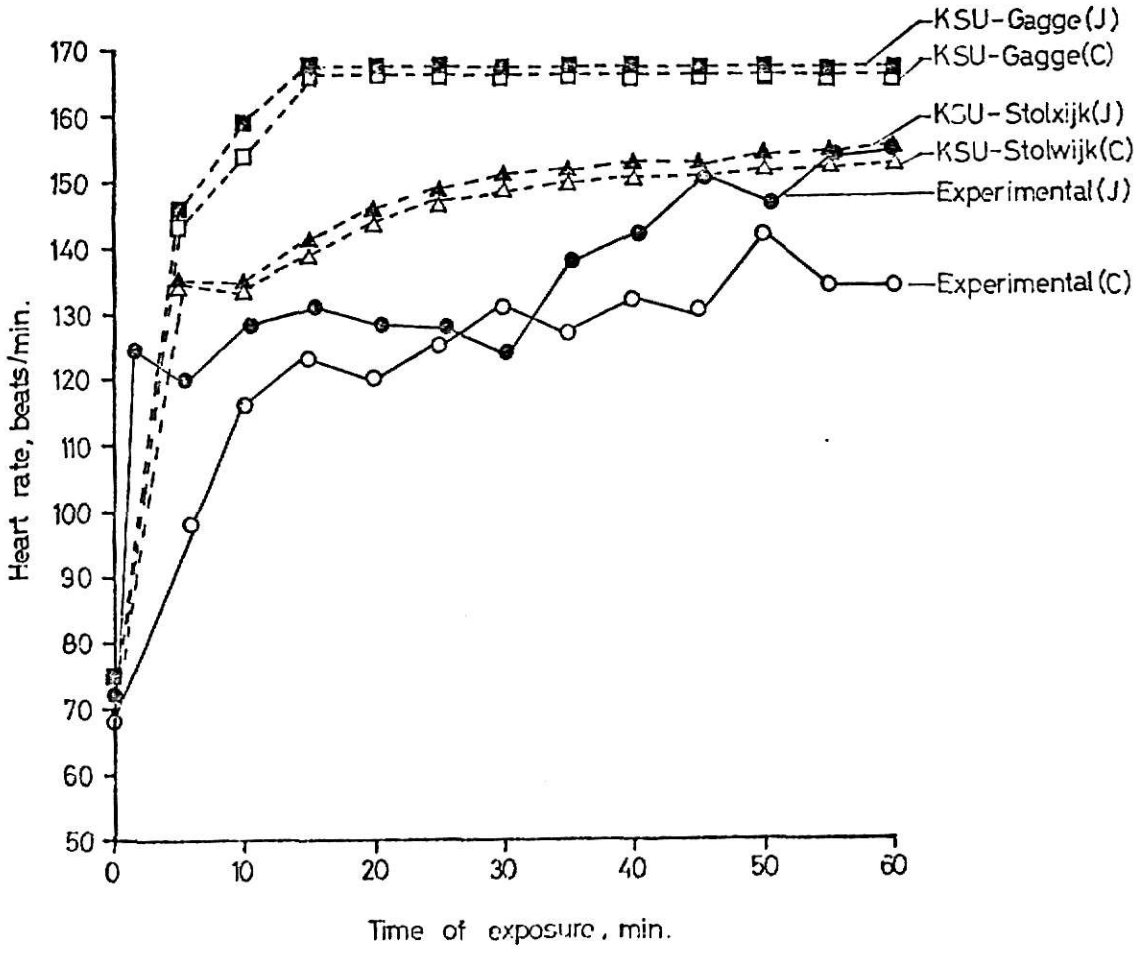


Figure 48. Experimental Heart Rate vs. Simulation (Nov. 6, '74)

APPENDIX C

FORTRAN Program of KSU-Stolwijk Model with Data Used

```
      DIMENSION C(25),T(25),F(25),HF(25),TC(24),TD(24),CB(24),Q(24),
     1EB(24),E(24),BFB(24),RF(24),BC(24),HC(6),S(6),HR(6),H(6),P(10),
     2EMAX(6),TSETW(25),ERROR(25),RATE(25),CCLD(25),WARM(25),SKINR(6),
     3SKINS(6),SKINV(6),SKINC(6),WORKM(6),CHILM(6),TI(25),PSKIN(6),
     4SWPCP(6),TAIR(6),PAIR(6),TSETC(25),PCT(75)
      DIMENSION SUBRAT(14),PS(6),EVG(25)
      DIMENSION SWCG(6),EG(25),EWET(6),EVCP(6)
      REAL MAXBF(24)
      REAL LTIME,ITIME,LR
      REAL K1,K2
   10 FORMAT(1HO,4X,'S(I)= SURFACE AREA OF EACH SEGMENT',/,4X,'HR(I)= RA
     1DIANT HEAT TRANSFER COEFFICIENT',/,4X,'HC(I)= CONVECTIVE AND CONDU
     2CTIVE HEAT TRANSFER COEFFICIENT',/,4X,'SKINR(I)= FRACTION OF ALL S
     3KIN RECEPTORS IN EACH SEGMENT',/,4X,'SKINS(I)= FRACTION OF SWEATIN
     4G COMMAND APPLICABLE TO EACH SKIN SEGMENT',     /,4X,'SKINV(I)= FR
     5ACTION OF VASODILATION COMMAND APPLICATION TO EACH SKIN SEGMENT',/
     6,4X,'SKINC(I)= FRACTION OF VASOCONSTRICTION COMMAND APPLICATION TO
     7 EACH SKIN SEGMENT',/,4X,'WORKM(I)= FRACTION OF TOTAL WORK DONE BY
     8 MUSCLE IN EACH SEGMENT',/,4X,'CHILM(I)= FRACTION OF TOTAL SHIVERI
     9NG OCCURING IN EACH SEGMENT')
   11 FORMAT(1HC,4X,'CUMULATIVE EVAPORATIVE HEAT LOSS,CEVG=',F9.3,' GM')
   12 FORMAT(1HO,4X,' HEART RATE, HEARTR= ',F9.3,'  BEAT/MT')
  100 FORMAT(14F5.2)
  200 FORMAT(I2)
  505 FORMAT(1HO,4X,'WEIGHT OF THE SUBJECT,WT=',1X,F6.2)
  506 FORMAT(1HC,4X,'SPECIFIC HEAT OF FAT,SHF=',1X,F6.2)
  507 FORMAT(1HC,4X,'SPECIFIC HEAT OF BONE,SHB=',1X,F6.2)
  508 FORMAT(1HC,4X,'SPECIFIC HEAT OF TISSUE,SHT=',1X,F6.2//)
  509 FORMAT(1HC,4X,'HEIGHT OF THE SUBJECT,HT=',1X,F6.2)
  510 FORMAT(1HO,4X,'SURFACE AREA OF THE SUBJECT,SA=',1X,F6.2)
  531 FORMAT(1HC,4X,'TC(I),  THERMAL CONDUCTANCE BETWEEN ADJACENT ELEMEN
     1TS,  W/DEG C ')
  575 FORMAT(7F10.2)
  585 FORMAT(1HC,21X,'CORE',9X,'MUSCLE',9X,'FAT',9X,'SKIN'/3X,'HEAD
     1',4(5X,F9.3)/3X,'TRUNK    ',4(5X,F9.3)/3X,'ARMS  (2)',4(5X,F9.3)/
     23X,'HANDS (2)',4(5X,F9.3)/3X,'LEGS  (2)',4(5X,F9.3)/3X,'FEET  (2)'
     3,4(5X,F9.3))
  710 FORMAT(12F6.3)
  715 FORMAT(1HO,4X,'TSETC(I),  SET POINT FOR RECEPTORS FOR COLD CONDITI
     2ON, DEG C ')
  750 FORMAT(' ',4X,'TOTAL METABOLIC ACTIVITY=',F8.2,' W ')
  890 FORMAT(1HO,4X,'INITIAL INPUT TEMPERATURES, DEG C')
  893 FORMAT(1HO,4X,'TIME=0.0  ************************************')
  894 FORMAT(1HO,4X,'AIR VELOCITY=',F8.2,'  M/SEC')
  896 FORMAT(1HC,4X,'RELATIVE HUMIDITY=',F8.2)
  898 FORMAT(1HO,4X,'OUTPUT INTERVAL=',I2,'  MINUTES')
  900 FORMAT(1HO,4X,'METABOLIC HEAT PRODUCTION,Q,   W ')
  901 FORMAT(1HC,4X,'BLOOD FLOWS,BF,LITERS/HR')
  902 FORMAT(1HC,4X,'CONVECTIVE HEAT TRANSFER BETWEEN CENTRAL BLOOD AND
     XELEMENTS,BC, W ')
  903 FORMAT(1HO,4X,'CONDUCTIVE HEAT TRANSFER BETWEEN SUCCESSIVE ELEMENT
     XS,TD, W ')
  904 FORMAT(1HO,4X,'RATE OF HEAT FLOW INTO OR FROM AN ELEMENT,HF, W ')
  905 FORMAT(1HO,4X,'RATE OF CHANGE OF TEMPERATURE OF AN ELEMENT,F,DEG C
     X/HR')
  906 FORMAT(1HC,4X,'EVAPORATIVE HEAT LOSS, E,  W ')
  907 FORMAT(1HO,4X,'SKIN BLOOD FLOWS,SBF = ',F9.3,'LITERS/MT ')
  911 FORMAT(1HO,4X,'CONSTANT DATA  ************************************')
```

```
931 FORMAT(1HO,4X,'TEMPERATURES,T,DEG C')
940 FORMAT(F5.4)
941 FORMAT(1HC,////////'      TIME=',F8.0,' MINUTES')
942 FORMAT(' ',4X,'COOLING EFFICIENCY OF JACKET=',F5.4)
943 FORMAT('0',4X,'SUBLIMATION RATE OF DRY-ICE FOR EACH PERIOD OF 30 M
   UINUTES,GM/HR'//4X,14(F6.2,2X))
944 FORMAT(' ',4X,'BASAL METABOLISM = ',F8.2,' W ')
945 FORMAT(' ',4X,'MECHANICAL EFFICIENCY = ',F5.3)
946 FORMAT(' ',4X,'BAROMETRIC PRESSURE = ',F5.1,'MMHG')
947 FORMAT(1HO,4X,'PS(I)    ',6(1X,F8.4))
948 FORMAT(' ','****EB(5),THAT IS RESPIRATORY HEAT LOSS IS NOT CONSTAN
   1T.SO,IT HAS BEEN INITIALIZED AS ZERO')
950 FORMAT(1HO,4X,'CARDIAC OUTPUT,CO=',F9.3,'LITERS/MINUTE')
951 FORMAT(1HO,4X,'HEAT PRODUCTION(METABOLISM+SHIVERING),HP=',F9.3,' W
   X ')
952 FORMAT(1HC,4X,'TOTAL EVAPORATIVE HEAT LOSS,EV = ',F9.3,' W')
953 FORMAT(1HO,4X,'MEAN SKIN TEMPERATURE,TS=',F9.3,' DEG C')
954 FORMAT(1HO,4X,'MEAN BODY TEMPERATURE,TB=',F9.3,' DEG C')
958 FORMAT(1HO,21X,'CORE',22X,'MUSCLE',22X,'FAT',24X,'SKIN'/13X,
   1'FAT',6X,'BONE',3X,'TISSUE',5X,'FAT',6X,'BONE',3X,'TISSUE',5X,
   2'FAT',6X,'BONE',3X,'TISSUE',5X,'FAT',6X,'BONE',3X,'TISSUE'/T14,
   322('_'),T41,22('_'),T68,22('_'),T95,22('_')/3X,'HEAD ',12(3X,F6.2)
   4/3X,'TRUNK',12(3X,F6.2)/3X,'ARMS ',12(3X,F6.2)/3X,'HANDS',
   512(3X,F6.2)/3X,'LEGS ',12(3X,F6.2)/3X,'FEET ',12(3X,F6.2)/3X,
   6'CENTRAL BLOOD',1(3X,F6.2),1X,'TISSUE')
959 FORMAT(1HC,17X,'CORE',9X,'MUSCLE',9X,'FAT',9X,'SKIN'/3X,'HEAD ',4(
   15X,F9.3)/3X,'TRUNK',4(5X,F9.3)/3X,'ARMS ',4(5X,F9.3)/3X,'HANDS',4(
   25X,F9.3)/3X,'LEGS ',4(5X,F9.3)/3X,'FEET ',4(5X,F9.3))
960 FORMAT(1HC,17X,'CORE',9X,'MUSCLE',9X,'FAT',9X,'SKIN'/3X,'HEAD ',4(
   15X,F9.3)/3X,'TRUNK',4(5X,F9.3)/3X,'ARMS ',4(5X,F9.3)/3X,'HANDS',4(
   25X,F9.3)/3X,'LEGS ',4(5X,F9.3)/3X,'FEET ',4(5X,F9.3)/3X,'CENTRAL B
   3LOOD')
961 FORMAT(1HC,15X,'HEAD',5X,'TRUNK ',3X,'ARMS',5X,'HANDS',4X,'LEGS',6
   1X,'FEET',4X,'TOTAL',2X,'UNITS    ')
962 FORMAT(1HO,4X,'PSKIN    ',6(1X,F8.3),9X,' MM HG  ')
963 FORMAT(1HC,4X,'EMAX     ',6(1X,F8.3),9X,' W ')
964 FORMAT(1HO,4X,'SWPCP    ',7(1X,F8.3),' SWEAT,HEAT REMOVAL COMMAND/S
   XKIN SEGMENT , W ')
965 FORMAT(1HO,4X,'H(I)     ',6(1X,F8.3),9X,' W/DEG C ')
966 FORMAT(1HO,4X,'S(I)     ',6(1X,F8.4),' SQ. M ')
967 FORMAT(1HC,4X,'HR(I)    ',6(1X,F8.3),' W/SQ.M/DEG C ')
968 FORMAT(1HC,4X,'HC(I)    ',6(1X,F8.3),' W/SQ.M/DEG C ')
970 FORMAT(1HC,4X,'SKINR(I)',6(1X,F8.3))
971 FORMAT(1HC,4X,'SKINS(I)',6(1X,F8.3))
972 FORMAT(1HC,4X,'SKINV(I)',6(1X,F8.3))
973 FORMAT(1HC,4X,'SKINC(I)',6(1X,F8.3))
974 FORMAT(1HC,4X,'WORK%(I)',6(1X,F8.3))
975 FORMAT(1HO,4X,'CHILM(I)',6(1X,F8.3))
976 FORMAT(1HO,4X,'TAIR(I) ',6(1X,F8.2),' DEG C ')
979 FORMAT(1HO,4X,'PCT(I),      % DISTRIBUTION, BY WEIGHT, OF DIFFERENT
   1 TISSUE TYPES')
980 FORMAT(1HC,4X,'C(I),  HEAT CAPACITANCE,  W*HR/DEG C ')
981 FORMAT(1HO,4X,'QB(I),  BASAL METABOLIC HEAT PRODUCTION,  W ')
982 FORMAT(1HC,4X,'EB(I),  BASAL EVAPORATIVE HEAT LOSS,  W ')
983 FORMAT(1HC,4X,'BFB(I),  BASAL EFFECTIVE BLOOD FLOW,  LITRES/HR ')
985 FORMAT(1HO,4X,'TSETW(I),  SET POINT FOR RECEPTORS FOR WARM CONDITI
   2ON, DEG C ')
986 FORMAT(1HC,4X,'RATE(I), DYNAMIC SENSITIVITY OF THERMORECEPTORS ')
991 FORMAT(1HC,4X,'SWCG     ',7(1X,F8.3),' SWEAT,HEAT REMOVAL COMMAND/S
   XKIN SEGMENT , GM/HR ')
```

```
  992 FORMAT(1HO,4X,'TOTAL EVAPORATIVE  HEAT LOSS,TEVG = ',F9.3,'GM/HR')
  993 FORMAT(1HO,4X,'EVAPORATIVE  HEAT LOSS, EG ,  GM/HR  ')
  995 FORMAT(1HO,15X,'HEAD',5X,'TRUNK ',3X,'ARMS',5X,'HANDS',4X,'LEGS',6
     1X,'FEET',2X,'UNITS      ')
  101 CONTINUE
C           READ CONSTANTS FOR CONTROLLED SYSTEM
      READ(5,100)SHF
      READ(5,100)SHB
      READ(5,100)SHT
      READ(5,100)(PCT(I),I=1,73)
      READ(5,100)(QB(I),I=1,24)
      READ(5,100)(EB(I),I=1,24)
      READ(5,710)(BFB(I),I=1,24)
      READ(5,100)(TC(I),I=1,24)
      READ(5,100)(PS(I),I=1,6)
      READ(5,100)(HR(I),I=1,6)
      READ(5,100)(HC(I),I=1,6)
      READ(5,100)(P(I),I=1,10)
C           READ CONSTANTS FOR THE CONTROLLER
      READ(5,100)(TSETH(I),I=1,25)
      READ(5,100)(TSETC(I),I=1,25)
      READ(5,100)(RATE(I),I=1,25)
      READ(5,100)CSW,SSW,PSW,CDIL,SCIL,PCIL,CCON,SCON,PCON,CCHIL,SCHIL,
     XPCHIL
      READ(5,100)(SKINR(I),I=1,6)
      READ(5,100)(SKINS(I),I=1,6)
      READ(5,100)(SKINV(I),I=1,6)
      READ(5,100)(SKINC(I),I=1,6)
      READ(5,100)(WORKM(I),I=1,6)
      READ(5,100)(CHILM(I),I=1,6)
C                 READ INITIAL CONDITIONS
      READ(5,100)WT
      READ(5,100)HT
      READ(5,100)WORKB
      READ(5,100)(T(I),I=1,25)
C     CALCULATION OF HEAT CAPACITANCE,C(I),W*HR/C
      DO 703 I=1,6
      J=4*I-3
      K=12*(I-1)+1
      C(J)=(WT*SHF*PCT(K)+WT*SHB*PCT(K+1)+WT*SHT*PCT(K+2))/100
      C(J+1)=(WT*SHF*PCT(K+3)+WT*SHB*PCT(K+4)+WT*SHT*PCT(K+5))/100
      C(J+2)=(WT*SHF*PCT(K+6)+WT*SHB*PCT(K+7)+WT*SHT*PCT(K+8))/100
      C(J+3)=(WT*SHF*PCT(K+9)+WT*SHB*PCT(K+10)+WT*SHT*PCT(K+11))/100
  703 CONTINUE
      C(J+4)=(WT*SHT*PCT(73))/100
      SA=.208+.945*(.007184*(HT**.725)*(WT**.425))
      DO 406 I=1,6
      S(I)=PS(I)*SA
  406 CONTINUE
      WRITE(6,911)
      WRITE(6,893)
      WRITE(6,505)WT
      WRITE(6,509)HT
      WRITE(6,510)SA
      WRITE(6,506)SHF
      WRITE(6,507)SHB
      WRITE(6,508)SHT
      WRITE(6,979)
      WRITE(6,958)(PCT(I),I=1,73)
      WRITE(6,980)
```

```
      WRITE(6,960)(C(I),I=1,25)
      WRITE(6,981)
      WRITE(6,959)(QB(I),I=1,24)
      WRITE(6,982)
      WRITE(6,955)(EB(I),I=1,24)
      WRITE(6,948)
      WRITE(6,983)
      WRITE(6,959)(BFB(I),I=1,24)
      WRITE(6,531)
      WRITE(6,959)(TC(I),I=1,24)
      WRITE(6,985)
      WRITE(6,960)(TSETW(I),I=1,25)
      WRITE(6,715)
      WRITE(6,960)(TSETC(I),I=1,25)
      WRITE(6,986)
      WRITE(6,960)(RATE(I),I=1,25)
      WRITE(6,995)
      WRITE(6,947)(PS(I),I=1,6)
      WRITE(6,966)(S(I),I=1,6)
      WRITE(6,967)(HR(I),I=1,6)
      WRITE(6,968)(HC(I),I=1,6)
      WRITE(6,970)(SKINR(I),I=1,6)
      WRITE(6,971)(SKINS(I),I=1,6)
      WRITE(6,972)(SKINV(I),I=1,6)
      WRITE(6,973)(SKINC(I),I=1,6)
      WRITE(6,974)(WCRKP(I),I=1,6)
      WRITE(6,975)(CHILM(I),I=1,6)
      WRITE(6,890)
      WRITE(6,960)(T(I),I=1,25)
      DO 102 N=1,25
      F(N)=0
  102 CONTINUE
C                 READ EXPERIMENTAL CONDITIONS
  103 CONTINUE
      READ(5,100)(TAIR(I),I=1,6)
      READ(5,100)V
      READ(5,100)RH
      READ(5,100)WORK
      READ(5,100)WEFF
      READ(5,100)BARC
      READ(5,200)INT
      READ(5,100)(SUBRAT(I),I=1,14)
      READ(5,940)CEFF
      WRITE(6,976)(TAIR(I),I=1,6)
      WRITE(6,894)V
      WRITE(6,896)RH
      WRITE(6,750)WCRK
      WRITE(6,944)WCRKB
      WRITE(6,945)WEFF
      WRITE(6,946)BARC
      WRITE(6,858)INT
      WRITE(6,943)(SUBRAT(I),I=1,14)
      WRITE(6,942)CEFF
C  ******   LR= LEWIS RELATION
      LR=2.2*(760./BARC)
      DO 202 J=1,6
      H(J)=(HR(J)+3.16*HC(J)*V**0.5)*S(J)
      I=TAIR(J)/5
      PAIR(J)=RH*(P(I)+(P(I+1)-P(I))*(TAIR(J)-5*I)/5.)
  202 CONTINUE
```

```
C     CALCULATION OF RESPIRATORY HEAT LOSS.
      RDRY=0.0014*WORK*(34.-TAIR(1))
      RWET=0.0023*WORK*(44.-PAIR(1))
C     PAIR(1) AND TAIR(1) HAS BEEN USED FOR AMBIENT ATMOS. CONDITIONS
      EB(5)=RWET
      IF(WORK-WORKB)104,104,105
  104 WORK=0.
      GO TO 106
  105 WORK=(WORK-WORKB)*(1.-WEFF)
  106 CONTINUE
      AEWET=0.0
      DO 451 I=1,6
      N=4*I-3
      K=T(N+3)/5
      PSKIN(I)=P(K)+(P(K+1)-P(K))*(T(N+3)-5*K)/5.
      EMAX(I)=(PSKIN(I)-PAIR(I))*LR*(H(I)-HR(I))*S(I))
      EWET(I)=EB(N+3)/EMAX(I)
      AEWET=AEWET+EWET(I)*(S(I)/SA)
      PPHG=PSKIN(I)
      SVP=EMAX(I)
      PWET=EWET(I)
      TEMP=T(N+3)
      CALL SHVP(PWET,PPHG,SVP,TEMP,HVAPS)
      EVCP(I)=HVAPS
      EG(N+3)=EB(N+3)/EVCP(I)
  451 CONTINUE
C     FOR EVAPORATION DUE TO RESPIRATION,WE CONSIDER THE RESPIRATORY
C     TRACT AS 100 PERCENT WET AND CALCULATE HVP=EVCP(TRUNK CORE) AS:
      HVP=(2433.95-2.2549*(T(5)-30.))*0.0002778
      EG(5)=EB(5)/HVP
C               ESTABLISH THERMORECEPTOR OUTPUT
      TIME=0.
      ITIME=0.
      CEVG=0.0
  301 CONTINUE
      DO 302 N=1,25
      ERROR(N)=0.
      WARM(N)=0.
      COLD(N)=0.
      IF(T(N).GT.TSETW(N))ERROR(N)=T(N)-TSETW(N)+RATE(N)*F(N)
      IF(T(N).LT.TSETC(N))ERROR(N)=T(N)-TSETC(N)+RATE(N)*F(N)
C     TSETW(N)=SET TEMPERATURE ABOVE WHICH SWEATING AND VASODILATION
C     TAKE PLACE
C     TSETC(N)=SET TEMPERATURE BELOW WHICH SHIVERING AND
C     VASOCONSTRICTION TAKE PLACE
      IF(ERROR(N))303,302,304
  303 COLD(N)=-ERROR(N)
      GO TO 302
  304 WARM(N)=ERROR(N)
  302 CONTINUE
C                 INTEGRATE PERIPHERAL AFFERENTS
      WARMS=0.0
      COLDS=0.0
      DO 305 I=1,6
      K=4*I
      WARMS=WARMS+WARM(K)*SKIN(I)
      COLDS=COLDS+COLD(K)*SKIN(I)
  305 CONTINUE
C                 DETERMINE EFFERENT OUTFLOW
      SWEAT=CSW*ERROR(1)+SSW*(WARMS-COLDS)+PSW*ERROR(1)*(WARMS-COLDS)
```

```
      DILAT=CDIL*ERROR(I)+SDIL*(WARMS-COLDS)+PDIL*WARM(I)*WARMS
      STRIC=-CCON*ERROR(I)-SCON*(WARMS-COLDS)+PCON*COLD(I)*COLDS
      CHILL=-CCHIL*ERROR(I)-SCHIL*(WARMS-COLDS)+PCHIL*ERROR(I)*(WARMS-CO
     XLDS)
      IF(SWEAT)1500,1500,1501
 1500 SWEAT=0.0
 1501 CONTINUE
      IF(DILAT)1502,1502,1503
 1502 DILAT=0.0
 1503 CONTINUE
      IF(STRIC)1504,1504,1505
 1504 STRIC=0.0
 1505 CONTINUE
      IF(CHILL)1506,1506,1507
 1506 CHILL=0.0
 1507 CONTINUE
C                 ASSIGN EFFECTOR OUTPUT
  400 CONTINUE
      DO 401 I=1,6
      N=4*I-3
      BF(N)=BFB(N)
      Q(N)=QB(N)
      E(N)=EB(N)
      Q(N+1)=QB(N+1)+WORKM(I)*WORK+CHILM(I)*CHILL
      E(N+1)=0
      BF(N+1)=BFB(N+1)+Q(N+1)-QB(N+1)
      Q(N+2)=QB(N+2)
      E(N+2)=0
      BF(N+2)=BFB(N+2)
      Q(N+3)=QB(N+3)
      E(N+3)=EB(N+3)+SKINS(I)*SWEAT*2.**((T(N+3)-TSETW(N+3))/4.)
      BF(N+3)=(BFB(N+3)+SKINV(I)*DILAT)/(1.+SKINC(I)*STRIC)
      K=T(N+3)/5.
      PSKIN(I)=P(K)+(P(K+1)-P(K))*(T(N+3)-5*K)/5.
      EMAX(I)=(PSKIN(I)-PAIR(I))*LR*(H(I)-HR(I)*S(I))
      IF(EMAX(I)-E(N+3))402,403,403
  402 E(N+3)=EMAX(I)
  403 CONTINUE
  401 CONTINUE
      SWEAG=0.0
      AEWET=0.0
      DO 405 I=1,6
      N=4*I-3
      SWPCP(I)=SKINS(I)*SWEAT
      EWET(I)=E(N+3)/EMAX(I)
      AEWET=AEWET+EWET(I)*(S(I)/SA)
      PPHG=PSKIN(I)
      SVP=EMAX(I)
      PWET=EWET(I)
      TEMP=T(N+3)
      CALL SWVP(PWET,PPHG,SVP,TEMP,HVAPS)
C     EVCP=EVAPORATIVE SPECIFIC HEAT, W*HR/GM
      EVCP(I)=HVAPS
      EG(N+3)=E(N+3)/EVCP(I)
      SWCG(I)=SWPCP(I)/EVCP(I)
      SWEAG=SWEAG+SWCG(I)
  405 CONTINUE
      HVP=(2433.95-2.2549*(T(5)-30.))*0.0002778
      EG(5)=E(5)/HVP
      EG(25)=0.0
```

```
C ** THESE CARDS ARE PLACED HERE TO LIMIT MAXIMUM BLOOD FLOW  *****
      DO 704 I=1,6
      MAXBF(4*I-3)=BFE(4*I-3)
      MAXBF(4*I-2)=BFB(4*I-2)*18.
      MAXBF(4*I-1)=BFE(4*I-1)
      MAXBF(4*I)=BFB(4*I)*7.
  704 CONTINUE
      DO 706 I=1,24
      IF(BF(I).GT.MAXBF(I))BF(I)=MAXBF(I)
  706 CONTINUE
C ** THESE CARDS WERE PLACED HERE TO LIMIT MAX BLOOD FLOW **
C                 CALCULATE HEAT FLOWS
      DO 499 I=1,6
      TD(4*I-3)=TC(4*I-3)*(T(4*I-3)-T(4*I-2))
      TC(4*I-2)=TC(4*I-2)*(T(4*I-2)-T(4*I-1))
      TD(4*I-1)=TC(4*I-1)*(T(4*I-1)-T(4*I))
      TD(4*I)=0.
  499 CONTINUE
      DO 500 K=1,24
      BC(K)=BF(K)*(T(K)-T(25))
  500 CONTINUE
      DO 501 I=1,6
      K=4*I-3
      HF(K)=Q(K)-E(K)-BC(K)-TC(K)
      HF(K+1)=Q(K+1)-BC(K+1)+TD(K)-TC(K+1)
      HF(K+2)=Q(K+2)-BC(K+2)+TC(K+1)-TD(K+2)
      HF(K+3)=Q(K+3)-BC(K+3)-E(K+3)+TD(K+2)-H(I)*(T(K+3)-TAIR(I))
  501 CONTINUE
      HF(5)=HF(5)-RDRY
C *** NEXT FOUR CARDS ARE PLACED TO ACCOUNT FOR VARIABLE SUBLIMATION
C     RATE AND COOLING EFFECT OF DRY-ICE.IF MORE THAN 14 PERIODS,CHANGE
C     DIMENSION AND READ STATEMENTS FOR SUBRAT     **********
      PER=ABS((ITIME-0.0001)/3C.)
      JPER=PER
      K=JPER+1
      HF(8)=HF(8)-(SUBRAT(K)*.159*CEFF)
      HF(25)=0.0
      DO 502 K=1,24
      HF(25)=HF(25)+BC(K)
  502 CONTINUE
C                 DETERMINE OPTIMUM INTEGRATION STEP
      DT=1./60.
      DO 600 K=1,25
      F(K)=HF(K)/C(K)
      U=ABS(F(K))
      IF(U*DT-0.1)600,600,601
  601 DT=0.1/U
  600 CONTINUE
C                 CALCULATE NEW TEMPERATURES
      DO 700 K=1,25
      T(K)=T(K)+F(K)*DT
      EVG(K)=EG(K)*DT
      CEVG=CEVG+EVG(K)
  700 CONTINUE
      TIME=TIME+DT
      LTIME=60.*TIME
      IF(LTIME-INT-ITIME)301,701,701
  701 CONTINUE
      ITIME=ITIME+INT
      WRITE(6,941)ITIME
```

```
      WRITE(6,961)
      WRITE(6,962)(PSKIN(I),I=1,6)
      WRITE(6,963)(EMAX(I),I=1,6)
      WRITE(6,964)((SWPCP(I),I=1,6),SWEAT)
      WRITE(6,951)((SWCG(I),I=1,6),SWEAG)
      WRITE(6,965)(H(I),I=1,6)
      WRITE(6,921)
      WRITE(6,960)(T(K),K=1,25)
      WRITE(6,901)
      WRITE(6,959)(BF(I),I=1,24)
      WRITE(6,900)
      WRITE(6,959)(C(N),N=1,24)
      WRITE(6,906)
      WRITE(6,959)(E(N),N=1,24)
      WRITE(6,953)
      WRITE(6,959)(EG(N),N=1,24)
      WRITE(6,902)
      WRITE(6,959)(BC(K),K=1,24)
      WRITE(6,903)
      WRITE(6,959)(TC(K),K=1,24)
      WRITE(6,904)
      WRITE(6,960)(HF(K),K=1,25)
      WRITE(6,905)
      WRITE(6,960)(F(K),K=1,25)
C                     PREPARE FOR OUTPUT
      CO=0.
      HP=0.
      EV=0.
      TEVG=0.0
      TS=0.
      TB=0.
      HFLOW=0.
      SBF=0.
      CT=0
      CN=0
      DO 800 N=1,24
      CO=CO+BF(N)/60.
      HP=HP+C(N)
      EV=EV+E(N)
      TEVG=TEVG+EG(N)
  800 CONTINUE
C   ***    CALCULATION OF  HEART RATE,HEARTR, BEAT/MIN
C   ***      STROV = STROKE VOLUME, LITER/STROKE
      STROV=.09
      HEARTR=CO/STROV
      DO 804 I=1,6
      CT=CT+C(4*I)
  804 CONTINUE
      DO 802 I=1,6
  766 TS=TS+T(4*I)*C(4*I)/CT
      SBF=SBF+BF(4*I)/60.
  802 CONTINUE
      DO 805 N=1,25
      CN=CN+C(N)
  805 CONTINUE
      DO 801 N=1,25
      TB=TB+T(N)*C(N)/CN
      HFLOW=HFLOW+HF(N)
  801 CONTINUE
      WRITE(6,950)CO
```

```
      WRITE(6,12)HEARTR
      WRITE(6,907)SBF
      WRITE(6,951)HP
      WRITE(6,952)EV
      WRITE(6,997)TEVG
      WRITE(6,11)CEVG
      WRITE(6,953)TS
      WRITE(6,954)TB
      IF(TB.GT.41.0)GO TO 803
      IF(ITIME-120)301,803,803
  803 CONTINUE
      STOP
      END
      SUBROUTINE SWVP(PWET,PPHG,SVP,TSK,HVAPS)
      REAL K1,K2
C     SUBROUTINE TO CALCULATE THE HEAT OF VAPORIZATION OF SWEAT
C     FROM SKIN IN W*HR/GM
      PHIS=PWET*((1.-PWET)*PPHG)/SVP
      K1=2806.55-762.8*PHIS+390.2*(PHIS**2.)
      K2=1.1435+1.75*PHIS-0.6386*(PHIS**2.)
      HVAPS=(K1-K2*(TSK-30.))*0.0002778
      RETURN
      END
```

DATA TO BE USED IN KSL-STOLWIJK MODEL:

FOLLOWING DATA CARDS ARE COMMON

```
0.698                                                                                                                  SHF    01
0.582                                                                                                                  SHB    02
1.047                                                                                                                  SHT    03
0.   2.14 2.13 0.   0.   0.51 0.50 0.   0.   0.   0.   0.36 0.   3.30                                                PCT    04
12.150.   0.   24.359.60 0.   0.   0.   0.   1.82 0.   2.02 1.0  0.                                                  PCT    05
0.   4.58 1.30 0.   0.   0.   0.   0.65 0.   0.31 0.04 0.   0.   0.91                                                PCT    06
0.19 0.   0.   0.   0.   0.26 0.   6.73 2.64 0.   0.   13.823.23 0.                                                  PCT    07
0.   0.   0.   1.62 0.   0.50 0.07 0.   0.   0.09 0.29 0.   0.   0.                                                  PCT    08
0.   0.34 2.55                                                                                                         PCT    09
14.95.12  .13  .09  52.605.81 2.49 .47  .82  1.11 .20  .15  .09  .23                                                  QB     10
.03  .06  2.59 3.32 .50  .37  .15  .02  .05  .08                                                                      QB     11
0.00 0.00 0.00 .81   0.0 0.00 0.00 3.78 0.00 0.00 0.00 1.40 0.00 0.00                                                  EB     12
0.00 0.52 0.00 0.00 0.00 3.32 0.00 0.00 0.00 0.72                                                                     EB     13
45.0002.475 0.765 3.633 210.0058.4104.5355.298 0.84  11.1541.989 1.263                                                BFB    14
0.1   0.264 0.306 5.046 2.69  33.9244.896 7.191 0.16  0.264 0.459 7.569                                                BFB    15
1.61 13.2516.100.0  1.59 5.53 23.080.0  1.40 8.90 30.500.0  6.40 11.20                                                TC     16
11.500.0  10.5014.4074.500.0  16.3020.6016.400.0                                                                     TC     17
                                                                                                                       PS     18
0.07 .39  .131 .049 .296 .064                                                                                          HR     19
4.80 4.80 4.20 3.60 4.20 4.0                                                                                           HC     20
3.0  2.10 2.1  4.0  2.1  4.0                                                                                           P      21
6.54 9.20512.7817.5123.6931.7142.0255.1371.6692.30                                                                     RATE   26
0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.                                                  RATE   27
0.   0.   0.   0.   0.   0.   0.   0.   0.   0.   0.                                                                CONT   28
372. 33.7 0.00 136. 17.0 0.00 10.8 10.8 0.00 13.0 0.40 0.00                                                            SKINR  29
0.21 0.42 0.10 0.04 0.20 0.03                                                                                          SKINS  30
0.0810.4810.1540.0310.2180.035                                                                                         SKINV  31
0.1320.3220.0950.1210.2300.100
```

```
0.01 0.05 0.19 0.20 0.20 0.35                                                  SKINC 32
0.    .3    .09   .01   .60   .01                                             WORKM 33
0.02 0.85 0.05 0.00 0.07 0.00                                                  CHILM 34

      FOLLOWING ARE THE DATA FOR INDIVIDUAL EXPERIMENTAL CONDITIONS ---

      DATA FOR JULY 31,1972
36.6634.3634.0433.7636.5935.8133.5632.3935.2432.9432.0831.5235.1234.85  TSETW 22
34.1233.3935.5234.8732.3532.0834.8534.6633.1132.9936.41                  TSETW 23
36.6634.3634.0433.7636.5935.8133.5632.3935.2432.9432.0831.5235.1234.85  TSETC 24
34.1233.3935.5234.8732.3532.0834.8534.6633.1132.9936.41                  TSETC 25
77.23                                                                          WT    35
177.0                                                                          HT    36
93.70                                                                          WORKB 37
36.6634.3634.0433.7636.5935.8133.5632.3935.2432.9432.0831.5236.1234.85  INIT  38
34.1233.3935.5234.8732.3532.0834.8534.6633.1132.9936.41                  INIT  39
43.3043.3043.3043.3043.3043.30                                                 TAIR  40
0.1                                                                            V     41
0.45                                                                           RH    42
129.5                                                                          WORK  43
0.0                                                                            WEFF  44
740.0                                                                          BARO  45
10                                                                             INT   46
0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0    SUBRAT47
0.0                                                                            CEFF  48

      DATA FOR AUGUST 7,1972
36.6634.3634.0433.7636.5935.8133.5632.3935.2432.9432.0831.5235.1234.85  TSETW 22
34.1233.3935.5234.8732.3532.0834.8534.6633.1132.9936.41                  TSETW 23
36.6634.3634.0433.7636.5935.8133.5632.3935.2432.9432.0831.5235.1234.85  TSETC 24
34.1232.3935.5234.8732.3532.0834.8534.6633.1132.9936.41                  TSETC 25
76.3                                                                           WT    35
177.0                                                                          HT    36
93.70                                                                          WORKB 37
36.6634.3634.0433.7636.5935.8133.5632.3935.2432.9432.0831.5235.1234.85  INIT  38
34.1233.3935.5234.8732.3532.0834.8534.6633.1132.9936.41                  INIT  39
43.3035.4043.3043.3043.3043.30                                                 TAIR  40
0.1                                                                            V     41
0.45                                                                           RH    42
129.5                                                                          WORK  43
0.0                                                                            WEFF  44
740.0                                                                          BARO  45
10                                                                             INT   46
53373533735337353373533735337353373533735337353373533735337353373533735337353373  SUBRAT47

      DATA FOR OCTOBER 29,1974 (SUBJECT C)
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60  TSETW 22
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                  TSETW 23
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60  TSETC 24
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                  TSETC 25
75.21                                                                          WT    35
180.34                                                                         HT    36
82.57                                                                          WORKB 37
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60  INIT  38
35.0434.4936.2235.5032.6932.3935.5435.3232.4533.3137.13                  INIT  39
45.0045.6145.0045.0045.0045.00                                                 TAIR  40
0.4                                                                            V     41
0.47                                                                           RH    42
380.3                                                                          WORK  43
```

```
0.21                                                                                    WEFF  44
735.0                                                                                   BARO  45
05                                                                                      INT   46
0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0                   SUBRAT47
0.0                                                                                     CEFF  48

      DATA FOR OCTOBER 29,1974 (SUBJECT J)
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                TSETW 22
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                TSETW 23
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                TSETC 24
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                TSETC 25
75.99                                                                                  WT    35
177.8                                                                                  HT    36
107.0                                                                                  WORKB 37
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                INIT  38
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                INIT  39
45.0037.0745.0045.0045.0045.00                                                         TAIR  40
0.4                                                                                    V     41
0.47                                                                                   RH    42
302.4                                                                                  WORK  43
0.32                                                                                   WEFF  44
735.0                                                                                  BARO  45
05                                                                                     INT   46
0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0                   SUBRAT47
0.0                                                                                    CEFF  48

      DATA FOR NOVEMBER 6,1974 (SUBJECT C)
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                TSETW 22
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                TSETW 23
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                TSETC 24
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                TSETC 25
75.7                                                                                   WT    35
18034                                                                                  HT    36
82.57                                                                                  WORKB 37
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                INIT  38
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                INIT  39
45.0036.1145.0045.0045.0045.00                                                         TAIR  40
0.4                                                                                    V     41
0.47                                                                                   RH    42
441.9                                                                                  WORK  43
0.17                                                                                   WEFF  44
745.0                                                                                  BARO  45
05                                                                                     INT   46
720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0                 SUBRAT47

      DATA FOR NOVEMBER 6,1974 (SUBJECT J)
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                TSETW 22
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                TSETW 23
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                TSET3 24
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                TSETC 25
74.45                                                                                  WT    35
177.8                                                                                  HT    36
107.0                                                                                  WORKB 37
37.3834.2333.8033.4237.3136.5934.5333.4635.9433.8533.0632.5635.8135.60                INIT  38
35.0434.4936.2235.5032.6932.3935.5435.3233.4533.3137.13                                INIT  39
45.0036.9645.0045.0045.0045.00                                                         TAIR  40
0.4                                                                                    V     41
0.47                                                                                   RH    42
478.0                                                                                  WORK  43
0.18                                                                                   WEFF  44
745.0                                                                                  BARO  45
05                                                                                     INT   46
720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0720.0                 SUBRAT47
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APPENDIX D

FORTRAN Program of KSU-Gagge Model and Data Used

```
      DIMENSION P(10),SUBRAT(14)
      REAL ITIME,INT,MR,MHT,MBT1,MBT2,LR,MRSA,MAXSBF,MXCRBF,MBT3
      REAL K1,K2
C     SIMULATION OF A HUMAN THERMOREGULATORY SYSTEM BASED ON GAGGE
C     MODEL( AS MODIFIED AT KANSAS STATE UNIVERSITY)
  701 FORMAT(10F7.2)
  702 FORMAT(14F5.2)
  703 FORMAT(F13.11)
  800 FORMAT('-',5X,'INITIAL CONDITIONS AT TIME=0.0')
  801 FORMAT(' ',4X,'TA,C = ',F8.3/5X,'TR,C = ',F8.3/5X,'TO,C = ',F8.3/5
     1X,'TCR,C = ',F8.3/5X,'TSK,C = ',F8.3/5X,'TCL,C = ',F8.3/5X,'MBT1,C
     1 = ',F8.3/5X,'MBT2,C = ',F8.3/5X,'MBT3,C = ',F8.3/5X,'CSETC,C = ',
     1F8.3/5X,'CSETW,C = ',F8.3/5X,'SSETC,C = ',F8.3/5X,'SSETW,C = ',F8.
     13/)
  802 FORMAT(' ',4X,'RH = ',F8.3/5X,'BARO,MMHG = ',F8.3/5X,'WE = ',F8.3/
     25X,'ALPHA = ',F8.3/)
  803 FORMAT(' ',4X,'MR, W =      ',F8.3/5X,'BM, W =      ',F8.3/5X,'WK,
     3 W =      ',F8.3/5X,'CLO = ',F8.3/5X,'AT = ',F8.3/5X,'LR,C/MMHG =
     3 ',F8.3/)
  804 FORMAT(' ',4X,'WT,KG = ',F8.3/5X,'HT,CM = ',F8.3/5X,'SPHTB,W*HR/KG
     4/C = ',F8.3/5X,'SPHTBL,W*HR/L/C = ',F8.3/5X,'TCCR,W*HR/C = ',F8.3/
     45X,'TCSK,W*HR/C = ',F8.3/)
  805 FORMAT(' ',4X,'SA,SQ.M = ',F8.3/5X,'CHC, W/SQ.M/C =       ',F8.3/
     55X,'CHR, W/SQ.M/C =       ',F8.3/5X,'CTC, W/SQ.M/C =       ',F8.
     53/5X,'FCL =',F8.3/5X,'SBK, W/SQ.M/K4 =       ',F13.11/5X,'FACL =
     5',F8.3/5X,'FPCL = ',F8.3/)
  806 FORMAT(' ',4X,'ERES, W =      ',F8.3/5X,'CRES, W =      ',F8.3/5X,
     6'EV, W =      ',F8.3/5X,'HVAPS,W*HR/GM = ',F8.6/5X,'PWET = ',F8.3/
     65X,'SVP,MMHG = ',F8.3/5X,'PPHG,MMHG = ',F8.3/)
  807 FORMAT(' ',4X,'SKBF,L/HR = ',F8.3/5X,'CRBF,L/HR = ',F8.3/5X,'CO,L/
     7HR = ',F8.3/5X,'HEARTR,BEATS/MIN = ',F8.2/)
  808 FORMAT(' ',4X,'SUBRAT,GM/HR =  ',8(2X,F8.2)/20X,8(2X,F8.2)/)
  809 FORMAT(' ',4X,'CEFF = ',F8.3/)
  900 FORMAT('1',4X,'SIMULATION OF A HUMAN THERMOREGULATORY SYSTEM BASED
     9 ON KSU-GAGGE MODEL'/////)
  901 FORMAT('1',5X,'ELAPSED TIME AFTER THE START OF SIMULATION,MIN= ',F
     15.1/)
  902 FORMAT(' ',4X,'TCL,C = ',F8.3/5X,'FACL = ',F8.3/5X,'CHR, W/SQ.M/C
     2 =       ',F8.3/5X,'CHC, W/SQ.M/C =       ',F8.3/5X,'CTC, W/SQ.M/
     2C =      = ',F8.3/5X,'FCL = ',F8.3/)
  903 FORMAT(' ',4X,'DRY, W =      ',F8.3/5X,'HFCR, W =      ',F8.3/5X,'
     3HFSK, W =      ',F8.3/5X,'TCCR,W*HR/C = ',F8.3/5X,'TCSK,W*HR/C = '
     3,F8.3/5X,'DTCR,C/HR = ',F8.3/5X,'DTSK,C/HR = ',F8.3/5X,'DTIM,HR =
     3',F8.3/)
  904 FORMAT(' ',4X,'TSK,C = ',F8.3/5X,'TCR,C = ',F8.3/5X,'SKSIG,C = ',F
     48.3/5X,'CCLDS,C = ',F8.3/5X,'WARMS,C = ',F8.3/5X,'CRSIG,C = ',F8.3
     .4/5X,'CCLDC,C = ',F8.3/5X,'WARMC,C = ',F8.3/5X,'STRIC = ',F8.3/5X,'
     4DILAT = ',F8.3/)
  905 FORMAT(' ',4X,'SKBF,L/HR = ',F8.3/5X,'MAXSBF,L/HR = ',F8.3/5X,'CRB
     5F,L/HR = ',F8.3/5X,'MXCRBF,L/HR = ',F8.3/5X,'CO,L/HR = ',F8.3/5X,'
     5HEARTR,BEATS/MIN = ',F8.2/)
  906 FORMAT(' ',4X,'REGSW,GM/HR = ',F8.3/5X,'ERSW, W =      ',F8.3/5X,'
     6FPCL = ',F8.3/5X,'EMAX, W =      ',F8.3/5X,'PRSW = ',F8.3/5X,'PWET
     6 = ',F8.3/5X,'EDIF, W =      ',F8.3/5X,'EV, W =      ',F8.3/5X,'SW
     6EAT,GM/HR = ',F8.3/5X,'DRIP,GM/HR = ',F8.3/5X,'HVAPS,W*HR/GM = ',F
     68.6/5X,'PPHG,MMHG = ',F8.3/5X,'SVP,MMHG = ',F8.3/)
  907 FORMAT(' ',4X,'ALPHA = ',F8.3/5X,'RM, W =      ',F8.3/5X,'STORE,KC
     7AL/HR = ',F13.3/5X,'PTBM,C/HR = ',F8.3/5X,'MBT1,C = ',F8.3/5X,'MBT
```

```
72,C = ',F8.3/5X,'MBT1,C = ',F8.3/5X,'TO,C = ',F8.3/)
      READ(5,701)TA,TCR,TSK,TR,BARO
      READ(5,702)RH,WE,ALPHA
      READ(5,702)WT,HT
      READ(5,702)(P(I),I=1,10)
      READ(5,702)MR,BM,CLO,AT
      READ(5,702)CHC1,CHC2,CHC3,CHR,BSBFA,EVA
      READ(5,702)INT,ETIME
      READ(5,703)SBK
      READ(5,702)CSETC,CSETW,SSETC,SSETW,BCRBF,BBFM
      READ(5,702)(SUBRAT(I),I=1,14)
      READ(5,702)CEFF
C     INITIAL DEFINITIONS,TIME=0.0
C     SA=BODY SURFACE AREA,M**2
      SA=0.202+0.945*(0.007184*(HT**0.725)*(WT**0.425))
      SPHTB=0.91*WT
      SPHTBL=1.08
      MRSA=MR/SA
      BMSA=BM/SA
      IF(AT.EQ.1.)CHC=CHC1
      IF(AT.EQ.2.)CHC=CHC2
      IF(AT.EQ.3.)CHC=CHC3
      CHC=CHC*((BARO/760.)**0.55)
      BSBF=BSBFA*SA
      EV=EVA*SA
C     LR=LEWIS RELATION
      LR=(2.2*760.)/BARO
      I=TA/5.
C     PPHG=AMBIENT VAPOR PRESSURE FOR TA & RH,MMHG
      PPHG=RH*(P(I)+(P(I+1)-P(I))*(TA-5*I)/5.)
      PWET=0.06
C     SVP=SATURATED VAPOR PRESSURE AT TSK,MMHG
      FSVP=18.66855-(4030.1825/(TSK+235.))
      SVP=EXP(FSVP)
      CALL SWVP(PWET,PPHG,SVP,TSK,HVAPS)
C     RM=TOTAL METABOLIC ACTIVITY=BASAL+ACTIVITY+SHIVERING, W
      WK=(MR-BM)*WE
      RM=MR
C     ERES=RESPIRED EVAPORATIVE HEAT LOSS, W      (FANGER,1970)
      ERES=0.0023*RM*(44.-PPHG)
      EV=EV+ERES
C     RESPIRED CONVECTIVE HEAT LOSS, W      (FANGER,1970)
      CRES=0.0014*RM*(34.-TA)
C     CTC=COMBINED HEAT TRANSFER COEFFICIENT, W/SQ.M/DEG C
      CTC=CHC+CHR
C     FCL=BURTON CLOTHING EFFICIENCY FACTOR
      FCL=1./(1.+0.155*CTC*CLO)
C     FACL=FACTOR TO INCREASE BODY SURFACE AREA DUE TO CLOTHING(FANGER,
C     1970)
      FACL=1.+0.15*CLO
C     FPCL=NISHI PERMEATION EFFICIENCY FACTOR FOR CLOTHING
      FPCL=1./(1.+0.143*CTC*CLO)
C     TO=OPERATIVE TEMPERATURE,C (GAGGE,STOLWIJK,NISHI,1971)
      TO=(CHR*TR+CHC*TA)/CTC
C     TCL=CLOTHING SURFACE TEMPERATURE,C
      TCL=TO+FCL*(TSK-TO)
      TCCR=(1.-ALPHA)*SPHTB
      TCSK=ALPHA*SPHTB
      MBT1=TCR*TCCR/SPHTB+TSK*TCSK/SPHTB
      MBT2=0.65*TCR+0.35*TSK
```

```
      MBT3=MBT2
C     SKBF=SKIN BLOOD FLOW,L/HR
      SKBF=BSKBF
C     CRBF=BLOOD FLOW TO CORE AREAS,L/HR
      CRBF=BCRBF
C     CO=CARDIAC OUTPUT,L/HR
      CO=CRBF+SKBF
      STROV=0.05
      HEARTR=CO/(STROV*60.)
      WRITE(6,900)
      WRITE(6,800)
      WRITE(6,801)TA,TR,TO,TCR,TSK,TCL,MBT1,MBT2,MBT3,CSETC,CSETW,SSETC,
     1SSETW
      WRITE(6,802)RH,BARO,WE,ALPHA
      WRITE(6,803)MR,BM,WK,CLO,AT,LR
      WRITE(6,804)WT,HT,SPHTB,SPHTBL,TCCR,TCSK
      WRITE(6,805)SA,CHC,CHR,CTC,FCL,SBK,FACL,FPCL
      WRITE(6,806)ERES,CRES,EV,HVAPS,PWET,SVP,PPHG
      WRITE(6,807)SKBF,CRBF,CO,HEARTR
      WRITE(6,808)(SUBRAT(I),I=1,14)
      WRITE(6,809)CEFF
C     SIMULATION STARTS HERE
      TIM=0.0
      ITIME=0.0
      CEVG=0.0
  100 CONTINUE
C     CALCULATE CONTROL SIGNALS ******
      CALL SIGNAL(TSK,TCR,CSETC,CSETW,SSETC,SSETW,SKSIG,CRSIG,COLDS,WARM
     1S,CCLDC,WARMC)
C     CALCULATE REGULATORY CONTROLS ******
C     SHIV=SHIVERING ACTION, W
      SHIV=19.40*COLDS*CCLDC*SA
      RM=MR+SHIV
      STRIC=0.5*CCLDS
      DILAT=150.*WARMC
C     ABOVE COEFFICIENT VALUES OF 0.5 & 150. MAY VARY DUE TO
C     ACCLIMATIZATION
C     SKIN BLOOD FLOWS
      SKBF=((BSBFA+DILAT)/(1.+STRIC))*SA
      MAXSBF=7.*BSBF
      IF(SKBF.GT.MAXSBF)SKBF=MAXSBF
C     CHANGE IN ALPHA VALUE DUE TO CHANGE IN SKBF(ASHOFF,1956)
      ALPHA=0.0442+(0.3509/((SKBF/SA)-0.01386))
C     CORE BLOOD FLOWS
      CRBF=BCRBF+(RM-BM-WK)
      MXCRBF=BCRBF+18.*BSBF
      IF(CRBF.GT.MXCRBF)CRBF=MXCRBF
C     SWEATING IS CONTROLLED BOTH BY MBT(SNELLEN,1966) AND TSK(NADEL,
C     BULLARD AND STOLWIJK,1971)
C     REGSW=RATE OF SWEAT SECRETION ,GM/HR
      REGSW=(250.*(ALPHA*SKSIG+(1.-ALPHA)*CRSIG)*EXP(SKSIG/10.7))*SA
      IF(REGSW)45,45,50
   45 REGSW=0.0
   50 CONTINUE
C     ERSW=SKIN EVAPORATIVE HEAT LOSS BY SWEATING, W
      ERSW=REGSW*HVAPS
C     SVP=SATURATED VAPOR PRESSURE AT TSK,MMHG
      FSVP=18.6685-(4030.1825/(TSK+235.))
      SVP=EXP(FSVP)
C     EMAX=MAXIMUM POSSIBLE EVAPORATIVE HEAT LOSS, W
```

```
      EMAX=SA*LR*CHC*(SVP-PPHG)*FPCL/FACL
C     PRSW=SKIN WETTEDNESS DUE TO SWEATING
      PRSW=ERSW/EMAX
C     PWET=TOTAL SKIN WETTEDNESS
      PWET=0.06+0.94*PRSW
      CALL SWVP(PWET,PPHG,SVP,TSK,HVAPS)
      ERSW=REGSW*HVAPS
C     EDIF=SKIN VAPOR LOSS BY DIFFUSION, W
      EDIF=PWET*EMAX-0.94*ERSW
C     EV=TOTAL EVAPORATIVE HEAT LOSS, W
      EV=ERES+ERSW+EDIF
C     SWEAT=TOTAL SWEAT LOSS,GM/HR
      SWEAT=(ERSW+EDIF)/HVAPS
      IF(PWET.LE.1.)GO TO 60
   65 EV=ERES+EMAX
      EDIF=0.0
      PRSW=1.0
      PWET=1.0
      CALL SWVP(PWET,PPHG,SVP,TSK,HVAPS)
      ERSW=REGSW*HVAPS
C     DRIP=UNEVAPORATED SWEAT,GM/HR
      DRIP=(ERSW-EMAX)/HVAPS
      ERSW=EMAX
      SWEAT=DRIP+(ERSW/HVAPS)
   60 CONTINUE
      CEVG=CEVG+SWEAT
C     HEAT FLOWS, W
C     DRY=R+C+K=TOTAL DRY HEAT LOSS, W
      DRY=CTC*FCL*(TSK-TO)*SA
C     HFCR=HEAT STORAGE IN BODY CORE,W
      HFSBF=(5.28*SA+SPHTBL*SKBF)*(TCR-TSK)
      HFCR=RM-ERES-CRES-WK-HFSBF
C     HFSK=HEAT STORAGE IN SKIN SHELL,W
      HFSK=HFSBF-DRY-(EV-ERES)
C     NEXT FIVE CARDS ARE PLACED TO ACCOUNT FOR VARIABLE SUBLIMATION
C     RATE AND COOLING EFFECT OF DRY-ICE.IF MORE THAN 14 PERIODS,CHANGE
C     DIMENSION AND READ STATEMENTS FOR SUBRAT.
      PER=ABS((ITIME-0.0001)/30.)
      JPER=PER
      K=JPER+1
      COOL=SUBRAT(K)*0.159*CEFF
      HFSK=HFSK-COOL
C     TCCR=THERMAL CAPACITY OF BODY CORE,W*HR/C
      TCCR=(1.-ALPHA)*SPHTB
C     TCSK=THERMAL CAPACITY OF SKIN-SHELL,W*HR/C
      TCSK=ALPHA*SPHTB
C     CTCR=RATE OF CHANGE IN CORE TEMPERATURE,C/HR
      CTCR=HFCR/TCCR
C     DTSK=RATE OF CHANGE IN SKIN-SHELL TEMPERATURE,C/HR
      DTSK=HFSK/TCSK
C     ITERATION WILL BE AT ONE MINUTE INTERVAL OR CORE OR SKIN-SHELL
C     TEMPERATURE CHANGE NOT GREATER THAN +/- .1C
      CTIM=1./60.
      U=ABS(DTSK)
      IF(U*DTIM-0.1)5,10,10
   10 DTIM=0.1/U
    5 CONTINUE
      U=ABS(CTCR)
      IF(U*DTIM-0.1)105,110,110
  110 DTIM=0.1/U
```

```
  105 CONTINUE
C     CALCULATE NEW VALUES
      TIM=TIM+DTIM
      TIME=60.*TIM
      TSK=TSK+DTSK*DTIM
      TCR=TCR+DTCR*DTIM
      TO=(CHR*TR+CHC*TA)/CTC
      TCL=TC+FCL*(TSK-TO)
C     'CHR' VARIES WITH 'TSK' OR 'TCL' DURING REGULATION
      CHR=4.*SBK*(((TCL+TO)/2.+273.)**3.)*FACL*0.72
      CTC=CHC+CHR
      FCL=1./(1.+0.155*CTC*CLO)
C     STORE=RATE OF BODY HEAT STORAGE, W
      STORE=RM-CRES-WK-EV-CRY-WHEAT-COOL
C     RTBM=RATE OF CHANGE MBT,C/HR
      RTBM=STORE/SPHTB
      MBT1=TCP*TCCR/SPHTB+TSK*TCSK/SPHTB
      CMBT=0.70*DTCR*DTIM+0.30*DTSK*DTIM
      MBT2=MBT2+CMBT
      MBT3=MBT3+RTBM*DTIM
      CO=CRBF+SKBF
      HEARTR=CO/(STROV*60.)
      IF(TIME-INT-ITIME)100,201,201
  201 CONTINUE
      ITIME=ITIME+INT
      WRITE(6,901)ITIME
      WRITE(6,902)TCL,FACL,CHR,CHC,CTC,FCL
      WRITE(6,903)DRY,HFCR,HFSK,TCCR,TCSK,DTCR,DTSK,DTIM
      WRITE(6,904)TSK,TCR,SKSIG,COLDS,WARMS,CRSIG,COLDC,WARMC,STRIC,DILA
     4T
      WRITE(6,905)SKBF,MAXSBF,CRBF,MXCRBF,CO,HEARTR
      WRITE(6,906)REGSW,ERSW,FPCL,EMAX,PRSW,PWET,EDIF,EV,SWEAT,DRIP,HVAP
     6S,PPHG,SVP
      WRITE(6,907)ALPHA,RM,STORE,RTBM,MBT1,MBT2,MBT3,TO
      IF(MBT1.GT.41.)GO TO 301
      IF(MBT2.GT.41.)GO TO 301
      IF(MBT3.GT.41.)GO TO 301
      IF(ITIME-ETIME)100,301,301
  301 CONTINUE
      STOP
      END
      SUBROUTINE SIGNAL(TSK,TCR,CSETC,CSETW,SSETC,SSETW,SKSIG,CRSIG,COLD
     1S,WARMS,COLDC,WARMC)
C     SUBROUTINE FOR CALCULATION OF CONTROL SIGNALS
C     CALCULATION OF CONTROL SIGNALS FROM SKIN,SKSIG,C
      SKSIG=0.0
      COLDS=0.0
      WARMS=0.0
      IF(TSK.LT.SSETC)SKSIG=TSK-SSETC
      IF(TSK.GT.SSETW)SKSIG=TSK-SSETW
      IF(SKSIG)15,15,20
   15 COLDS=-SKSIG
      GO TO 25
   20 WARMS=SKSIG
   25 CONTINUE
C     CALCULATION OF CONTROL SIGNALS FROM CORE,CRSIG,C
      CRSIG=0.0
      COLDC=0.0
      WARMC=0.0
      IF(TCR.LT.CSETC)CRSIG=TCR-CSETC
```

```
      IF(TCR.GT.CSETW)CRSIG=TCR-CSETW
      IF(CRSIG)30,30,35
   30 COLDC=-CRSIG
      GO TO 40
   35 WARMC=CRSIG
   40 CONTINUE
      RETURN
      END
      SUBROUTINE SWVP(PWET,PPHG,SVP,TSK,HVAPS)
      REAL K1,K2
C     SUBROUTINE TO CALCULATE THE HEAT OF VAPORIZATION OF SWEAT
C     FROM SKIN IN W*HR/GM
      PHIS=PWET+((1.-PWET)*PPHG)/SVP
      K1=2806.55-762.8*PHIS+390.2*(PHIS**2.)
      K2=1.1435+1.75*PHIS-0.6386*(PHIS**2.)
      HVAPS=(K1-K2*(TSK-30.))*0.0002778
      RETURN
      END
```

DATA TO BE USED IN KSU-GAGGE MODEL :

```
      DATA FOR JULY 31,1972
43.3   36.59  32.22  42.8   740.                                                    GDATA  1
0.45 0.0  0.1                                                                      GDATA  2
77.23177.0                                                                         GDATA  3
6.54 9.2C512.7817.5123.6931.7142.0255.1371.6692.30                                 GDATA 04
129.593.7C0.1  1.                                                                  GDATA  5
2.9  5.4  6.C  5.0  14.715.17                                                      GDATA  6
10.  120.                                                                          GDATA  7
0.0C00CC05735                                                                      GDATA 08
36.5936.5932.2232.223882310649                                                     GDATA  9
0.0  0.0  0.0  C.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0        GDATA 10
0.0                                                                                GDATA 11

      DATA FCR AUGUST 7,1972
43.3   36.59  32.22  42.8   740.                                                    GDATA  1
0.45 0.0  0.1                                                                      GDATA  2
76.30177.0                                                                         GDATA  3
6.54 9.20512.7817.5123.6931.7142.0255.1371.6692.30                                 GDATA 04
129.593.700.4  1.                                                                  GDATA  5
2.9  5.4  6.C  5.0  14.715.17                                                      GDATA  6
10.  120.                                                                          GDATA  7
0.CC00C005735                                                                      GDATA 08
36.5936.5932.2232.22388231C649                                                     GDATA  9
533735337353373533735337353373533735337353373533735337353373533735337353373     GDATA 10

      DATA FCR CCTOBER 29,1974 (SUBJECT C )
45.0   37.31  32.41  45.0   735.                                                    GDATA  1
0.47 0.21 0.1                                                                      GDATA  2
75.2118034                                                                         GDATA  3
6.54 9.2C512.7817.5123.6931.7142.0255.1371.6692.30                                 GDATA 04
380.382.570.49 3.                                                                  GDATA  5
2.9  5.4  6.0  5.0  14.715.17                                                      GDATA  6
5.   65.                                                                          GDATA  7
C.00000005735                                                                      GDATA 08
37.3137.3132.4132.413882310649                                                     GDATA  9
0.0  0.0  0.0  C.0  0.0  0.0  C.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0        GDATA 10
0.0                                                                                GDATA 11
```

```
      DATA FCR CCTOBER 29,1974 (SUBJECT J )                                                  GDATA  1
45.0    37.31  32.41  45.0   735.                                                           GDATA  2
0.47 0.32 0.1                                                                               GDATA  3
75.99177.8                                                                                  GDATA 04
6.54 9.20512.7817.5123.6931.7142.0255.1371.6692.30                                          GDATA  5
302.4107.00.49 3.                                                                           GDATA  6
2.9  5.4  6.0  5.0  14.715.17                                                               GDATA  7
5.   65.                                                                                    GDATA 08
0.CC00C005735                                                                               GDATA  9
37.3137.3132.4132.41388231C649                                                              GDATA 10
0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0                  GDATA 11
0.0

      CATA FCR NCVEMBER 6,1974 (SUBJECT C )                                                 GDATA  1
45.0    37.31  32.41  45.0   745.                                                           GDATA  2
0.47 0.17 0.1                                                                               GDATA  3
75.7018C34                                                                                  GDATA 04
6.54 9.20512.7817.5123.6931.7142.0255.1371.6692.30                                          GDATA  5
441.582.570.9  3.                                                                           GDATA  6
2.9  5.4  6.0  5.0  14.715.17                                                               GDATA  7
5.   65.                                                                                    GDATA 08
0.0C00CCC5735                                                                               GDATA  9
37.3137.3132.4132.41388231C649                                                              GDATA 10
720.0720.0720.0720.0720.C720.0720.0720.0720.0720.0720.0720.0720.0720.0                      CEFF  48
0.90

      CATA FCR NCVEMBER 6,1974 (SUBJECT J )                                                 GDATA  1
45.0    37.31  32.41  45.0   745.                                                           GDATA  2
0.47 0.18 0.1                                                                               GDATA  3
74.45177.8                                                                                  GDATA 04
6.54 9.20512.7817.5123.6931.7142.0255.1371.6692.30                                          GDATA  5
478.0107.00.9  3.                                                                           GDATA  6
2.9  5.4  6.0  5.0  14.715.17                                                               GDATA  7
5.   65.                                                                                    GDATA 08
0.00000C005735                                                                              GDATA  9
37.3137.3132.4132.41368231C649                                                              GDATA 10
720.C720.C720.C720.C720.C720.C720.0720.0720.C720.0720.0720.0720.0720.0720.0                CEFF  48
0.90
```

COMPARISON OF TWO HUMAN THERMOREGULATORY MODELS

by

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1975

ABSTRACT

Both Stolwijk's and Gagge's models aim at duplicating the human thermoregulatory mechanisms in mathematical form. Gagge's model, simpler in construction than Stolwijk's, also has a smaller output. As part of this study, Gagge's model was adapted for specific requirements of Kansas State University; Stolwijk's model had already been adapted. Also, modification and addition of equations, parameter values and variables have been made for both the models. Finally, the simulated results from both modified models were compared with experimental values (both with and without external cooling; one for a sedentary subject and the other for two exercising subjects).

Neither model is clearly superior in predictive power. Both are robust enough to be used for severe physiological and environmental conditions. From the KSU-Gagge model we get the minimum of basic physiological information. The KSU-Stolwijk model predicts more information and thus forces us to critically examine each and every assumption.