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THE THERMAL PROPERTIES OF SKIN

by

D. I. Lawson, P. H. Thomas and D. L. Simms

Summary

An apparatus for the study of burns to the human forearm by contact with a heated disk and the theory of the method are described. From some preliminary experiments a mean value of skin thermal conductivity was obtained as $1 \cdot 5 \times 10^{-3}$ c.g.s. units. There is some evidence that restricting the blood circulation may reduce the effective conductivity by about 20 per cent.

November, 1955.

File No. F.1000/12/156
F5/2(P)

Fire Research Station,
Boreham Wood,
Herts.

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1. Introduction

During recent years it has become necessary to simulate the thermal performance of human tissue by physical systems in order to know the degree of protection afforded by clothing in fire fighting. The work also involves the determination of the threshold condition under which burns occur and though a considerable amount of work has been done on the degree of burns caused by different levels of radiation (1, 2, 3, 4, 5, 6, 7) and also by different skin temperatures (8, 9, 10, 11, 12, 20) the lack of knowledge of the inter-relation of heat flux and temperature has limited the use to which the information could be put.

This work has been undertaken with the Burns Research Unit of the Medical Research Council who made available apparatus by which the flow of heat into human tissue could be related to the temperature at the skin interface. Measurements have so far been confined to the temperatures at which pain commences.

2. Experimental method

The apparatus is shown in Figure 1 and Plate 1. Water at a known predetermined temperature is pumped round a closed circuit and heats a disk of tellurium-silver alloy (13, 14). The heat flow through the disk is measured by recording the difference in temperature of two thermocouples attached to the two faces of the disk. An additional thermocouple was attached to the edge of the outer or contact face of the disk for measuring the skin temperature.

The water was first raised to the temperature required for a set of experiments, 55 - 65°C, and the skin was pressed firmly on the disk (Plate 1). The output of the heat flow disk and the thermocouple were recorded automatically. Similar experiments were carried out by four people using the inside of the lower forearm and repeated with the blood flow in the arm arrested by application of pressure in a sphygonometer. The plan of the experiments is shown below in Table 1.

TABLE 1

Plan of experiments

Run No.	Individual	W-with circulation W/O-without circulation	Water temperature °C θ_w	Ambient temperature °C	Initial skin temperature °C θ_s	Duration of exposure Sec.
G	J. B.	W	55	13·5	32·5	122
H	J. B.	W/O	"	"	"	120
I	D. S.	W	"	"	30	144
J	D. S.	W/O	"	"	"	151
K	D. L.	W	"	14·5	31·4	122·5
L	D. L.	W/O	"	"	"	123

Table 1 (contd.)

Run No.	Individual	W-with circulation W/O-without circulation	Water temperature °C w	Ambient temperature °C	Initial skin temperature °C s	Duration of exposure Sec.
A	J. B.	W	60	14	32.4	92
B	J. B.	W/O	"	14.25	"	71
C	D. S.	W	"	13.5	30.5	68
D	D. E.	W/O	"	"	"	62
E	P. T.	W	"	14	32.5	61
F	P. T.	W/O	"	"	"	62
P	D. L.	W	65	14.0	30	33
Q	D. L.	W/O	"	"	"	31
R	D. S.	W	"	"	29	29
S	D. S.	W/O	"	"	"	33
T	J. B.	W/O	"	"	32.8	30.5
U	J. B.	W/O	"	"	"	30.5

The record of any experiment enables the heat flow and skin temperature at any time to be found. Some typical results for heat flow are shown in Figures (2a, b, c) and for skin temperatures in Figures (3a, b, c).

3. Response of apparatus

3.1. Instantaneous constant temperatures

When the heated disk is applied to the skin there is a temperature change at both surfaces since initially they are at different temperatures. At all times continuity of heat flux must exist at the boundary between the heat flow disk and the skin. At the moment of contact and just after, the two bodies may be regarded as semi-infinite in depth, so that, if K is the conductivity, k the diffusivity and $\Delta\theta$ the instantaneous temperature change on the surface, the heat flux Q across the interface is given by (the suffices S and D referring to skin and disk respectively).

$$Q = \frac{K_S \Delta \theta_S}{\sqrt{\pi k_S t}} = \frac{K_D \Delta \theta_D}{\sqrt{\pi k_D t}} \qquad \ldots\ldots (1)$$

Hence if θ_D and θ_S are the disk and skin temperatures before contact and θ_i is the instantaneous contact temperature, it follows from equation (1) that

$$Q = \frac{K_D(\theta_D - \theta_i)}{\sqrt{k_D}} = \frac{K_S(\theta_i - \theta_S)}{\sqrt{k_S}}$$

or $$\sqrt{(K\rho c)_D(\theta_D - \theta_i)^2} = \sqrt{(K\rho c)_S(\theta_i - \theta_S)^2}$$

Although the heat flux is governed by the above equations, the heat flow disk does not give the actual flow because there is not at this time a linear gradient within it. Moreover, the thermocouple used to measure the contact temperature has a time lag, so that little quantitative use can be made of these formulae to determine the skin properties. However, the equation does demonstrate that if the skin temperature is to rise rapidly to the value of the disk temperature the ratio $\frac{(K\rho c)_D}{(K\rho c)_s}$ must be as large as possible.

3.2. Disk response time constant

The time of half response of the centre of a disk to a sudden rise in temperature of its two faces is approximately $0\cdot1\ l^2/k_D$ where l is the thickness and k the diffusivity. If the conductivity of the disk is assumed to be that of tellurium, (0·0144 c.g.s. units), the above time constant is 0·2 seconds. Clearly, even if the conductivity of the disk in these experiments is several times greater than that of pure tellurium the disk may be assumed to be in a quasi-stationary state after the first few seconds. The response time for the boundary layer in the water is neglected. Subsequent experiments showed that the time constant was of the order of 2 seconds.

3.3. Disk area time constant

There is also a second time constant associated with the assembly, namely the time after which heat is lost laterally and the temperature and heat flux characteristics of the small disk heaters are no longer sensibly equal to that of a large heater. This time is greater than (17)

$$T_o = \frac{0\cdot14\ r^2}{k_s} \qquad \ldots\ldots (2)$$

where r is the disk radius.

For the disk used in these experiments, T_o is of the order 100 seconds so that this is the maximum permitted duration of any test.

4. Equations for temperature and heat flow

Within the above limits, it is possible to develop theoretical expressions for the rise in surface temperature and for the heat flux.

In addition to the above notation let

θ_w = circulation of water temperature

θ_s = surface temperature of skin at time t

R = combined thermal resistance of disk and water.

In the skin

$$\frac{\partial^2\theta}{\partial x^2} = \frac{1}{k_s}\frac{\partial\theta_s}{\partial t} \qquad \left(t < \frac{0\cdot14\ r^2}{k_s}\right) \ldots\ldots (3)$$

The above expression assumes that the thermal characteristics K, ρ and c of skin remain constant with temperature, distance and time.

The surface boundary condition is given by the heat flux Q across the interface

$$Q = -K_s\left(\frac{\partial\theta_s}{\partial x}\right)_0 = \frac{\theta_w-\theta_s}{R} \;\ldots\ldots\; (4)$$

$$t > 0, \quad x = 0$$

At time zero the distribution of temperature in the skin is assumed to be represented by (Appendix I)

$$\theta_x = \theta_s + \theta_i\left(1-e^{-\alpha x}\right) \;\ldots\ldots\; (5)$$

where θ_1 is the difference between the skin and body temperature 37°C and α is a constant.

The effect of the instantaneous rise in surface temperature on contact is neglected, as this is only important at very short times.

Applying the Laplace Transformation to equations (3) and (4),

$$\frac{d^2\bar\theta_s}{dx^2} = {}^{p}\!/_{k_s}\,\bar\theta_s - \frac{\theta_i}{k_s}\left(1-e^{-\alpha x}\right) - {}^{\theta_s}\!/_{k_s} \;\ldots\ldots\; (6)$$

$$Q = -K_s\left(\frac{d\bar\theta_s}{dx}\right)_0 = \frac{1}{R}\left(\frac{\theta_w}{p} - \bar\theta_s\right) \;\ldots\ldots\; (7)$$

$$t > 0, \quad x = 0$$

The solution to equations (6) and (7) is

$$\bar\theta_s = \frac{\theta_w}{p(1+qK_sR)} + \frac{(\theta_s+\theta_i)}{p}\,\frac{qK_sR}{(1+qK_sR)} - \frac{\theta_1 K_s R}{k_s(q+\alpha)(1+qK_sR)} \;\ldots\ldots\; (8)$$

The heat flow Q is obtained from equations (7) and (8)

i.e.

$$\bar Q = \left[\frac{\theta_w}{p} - \frac{(\theta_s+\theta_1)}{p}\right]\frac{K_s q}{(1+qK_sR)} + \frac{K_s\theta_1}{k_s(q+\alpha)(1+qK_sR)} \;\ldots\ldots\; (9)$$

Inverting the transform in equation (9)

$$\frac{Q\,R}{\theta_w - \theta_s} = e^{\tau}\operatorname{erfc}\sqrt{\tau} - \frac{\theta_1}{(\theta_w - \theta_s)}\frac{\alpha K_s R}{(\alpha K_s R - 1)}\left[e^{\tau}\operatorname{erfc}\sqrt{\tau} - e^{(K_s \alpha R)^2 \tau}\operatorname{erfc}\alpha K_s R\sqrt{\tau}\right] \qquad \ldots\ldots(10)$$

and

$$\tau = \frac{t}{(K\rho c)_s\, R}$$

Hence the resistance of the apparatus controls the time response of skin temperature at short times.

The correction for the fact that the bulk of the skin is not at the skin surface temperature depends on the values of α, an approximate value for which is 3·0 which gives a value for α K_sR of 0·5 (Appendix I).

5. Approximate equations

If the second term in equation (9) is assumed negligible, i.e., the times considered are small enough for heating not to have penetrated to a region where the skin temperature is sensibly greater than the normal surface temperature, then from equation (10)

$$\frac{Q\,R}{(\theta_w - \theta_s)} \doteqdot e^{\tau}\operatorname{erfc}\sqrt{\tau} \qquad \ldots\ldots(11)$$

If $\frac{kt}{(KR)^2} >> 1$ equation (11) reduces to

$$Q \doteqdot (\theta_w - \theta_s)\sqrt{\frac{(K\rho c)_s}{\pi t}} \qquad \ldots\ldots(12)$$

i.e. a graph of $\frac{1}{Q}$ against $\sqrt{t}$ tends to linearity with a slope of $\frac{\sqrt{\pi}}{(\theta_w - \theta_s)}\frac{1}{\sqrt{(K\rho c)_s}}$. Actually a graph of $\frac{1}{Q}$ against $\sqrt{t}$ will behave as the function $(e^{x^2}\operatorname{erfc} x)^{-1}$ behaves as a function of x, and this is nearly linear in the range considered (Figure 4).

Using a value of α RK equal to 0·5, the value of $\frac{1}{Q}$ as a function of $\sqrt{t}$ is also shown in Figure 4. In equation (10) the coefficients of the correction term involve θ_s, θ_1 and θ_w. The corrected curve shown in Figure 4 strictly refers to a water temperature of 60°C only, the middle value of the experimental range, but this is considered to be sufficient in view of the approximate derivation of the correction. The best approximation to equation (11) for the range of values

$$2 < \frac{\theta_w - \theta_s}{Q\,R} < 4$$ in Figure 4 is

$$\frac{\theta_w - \theta_s}{Q\,R} = 0{\cdot}75 + \frac{1{\cdot}85}{R}\sqrt{\frac{t}{(K\rho c)_s}} \qquad \ldots\ldots(13)$$

The factor 1·85 replaces $\sqrt{\pi}$ for the slope as given by equation (12) and therefore gives values of $(K\rho c)_s$ which are 8 per cent higher. Equation (13) is also shown in Figure (4).

6. Determination of $K_s\rho_s c_s R$ and effective water temperature θ_w

The experimental data are plotted as $\frac{1}{Q}$ against $\sqrt{t}$ (Figure 5a-c). This curve approximates to a straight line in the range 2-4 times the intercept and its slope, if values for θ w and θ s are known, enables the values of $K_s\rho_s c_s$ to be calculated. These are shown in Table 2. It does not assume that R is the same for different experimental runs but only that R is constant during any one run.

R could be found by extrapolating the line to the axis of $\frac{1}{Q}$ and using the same values of θ w and θ' s, but a method making use of equation (4) is more direct and thus preferable. The measured heat flow and the corresponding measured skin temperature at any time are plotted against one another (Figures 6a-c) and the slope of the line is a measure of R. The results for R obtained by this method are also shown in Table 2. In addition to giving values of R, equation (4) enables the applied water temperature to be calculated. This is given by the intercept on the temperature axis for zero heat flow. These values are also listed in Table 2.

TABLE 2

Values of $(K\rho c)_s$ R, and effective water temperatures calculated from experiments

Run	Actual water temperature °C	Calculated water temperature °C	(1) R cgs units	(2) $K\rho c$ cgs units x 10^{-3}	Circulation
G	55	54·0	158	2·03	W
H		53·7	168	0·95	W/O
I		51·9	162	1·38	W
J		52·4	168	1·35	W/O
K		50·4	129	2·81	W
L		51·4	153	0·96	W/O
A	60	60·5	189	1·70	W
B		57·5	156	1·64	W/O
C		56·7	148	1·75	W
D		56·0	140	1·23	W/O
E		55·7	127	1·77	W
F		56·0	128	1·20	W/O
P	65	58·5	126	1·06	W
Q		58·2	133	1·63	W/O
R		57·5	133	1·52	W
S		55·8	121	1·50	W/O
T		58·5	137	1·36	W
U		57·5	130	1·30	W/O

Key (1) by heat flow method (equation (4)). (2) by equation (13) using nominal applied temperature for θ w.

7. Discussion of results

7.1. Discussion of results for R

Typical graphs of heat flow against skin temperature are shown in Figures (6a-c). They are straight lines curving at the extremeties. The reasons for this have already been discussed (Sections 3.2. and 3.3.). Analysis shows that the value of R, the combined thermal resistance of disk and water, obtained from the slope of the line may depend upon the applied temperature but that the variation is much greater than the minimum value predicted for the variation in water resistance (Appendix II).

7.2. Discussion on effective water temperature

The values of the effective water temperature are seen to be as much as 7°C lower than the nominal values. This implies that the heat capable of being absorbed by the skin, is greater than the source can supply, and that the actual applied temperature varies in the initial stages of the experiment.

7.3. Discussion of results for $K\rho c$

In Table 2 values of $K\rho c$ are given using only the nominal values of θ w. The scatter amongst individual results is too large to permit satisfactory analysis, but a partial analysis of the results obtained using the nominal water temperature suggest that there might be a reduction in $K\rho c$ when the circulation is restricted. The magnitude of the reduction, if real, would be from 1.6×10^{-3} C.G.S. units to $1{\cdot}3 \times 10^{-3}$ C.G.S. units. Using the calculated values of water temperature gives somewhat higher values of $K\rho c$, but since these may be shown to be correlated with R it follows that errors in estimating R effect the values of $K\rho c$ and this method is therefore to be rejected. Assuming that ρc is unity, gives a mean value for K for all results of $1{\cdot}5 \times 10^{-3}$ C.G.S. units compared with a value of $0{\cdot}6 - 1 \times 10^{-3}$ C.G.S. units given by Reader (18).

A probable reason for this difference is the variation in the pressure with which the arm is brought into contact with the disk. This has been noted by Moritz and Henriques (9).

8. General discussion

The results using the apparatus in its present form are not likely to be accurate since:-

(a) the thermal resistance between the water, the disk and the skin means that the heat flow to the skin is not necessarily characteristic of the nominal water temperature (Appendix II). This raises some doubt as to the correct value of the effective water temperature. This phenomena has been reported by other investigators (9).

(b) the skin temperature may be being measured at a different point from where the heat flow is being measured (Appendix III).

(c) the pressure with which the skin was pressed against the disk was uncontrolled and this seems a likely cause of variation in the value obtained for $K\rho c$. Although Moritz and Henriques (9) do not claim that there is an effect due to compression of the skin, they tried to avoid it during their experiments. They do not report any increase in burn severity with compression.

9. Design of new apparatus

Since the damage to the skin varies markedly with temperature in this range of experiments, it is necessary to know the skin temperature with some accuracy. Both the heat flow and skin temperature vary during the course of an experiment with the present apparatus and some modification would appear to be necessary.

For periods of heating longer than 100 seconds a disk of larger area will be necessary. Two important constants of the disk are unknown, thermal conductivity, and thermo-electric output of the junction; a slight modification of the electrical system introducing extra thermocouples would enable these quantities to be measured, and check the accuracy of the system. The pressure with which the skin is applied to the heat disk is applied needs to be controlled. A check on the accuracy of the method can be obtained by using a material of known $K\rho c$. This would also enable the importance of the term due to heat flow from the blood out to the skin to be estimated. It should also be possible to use the apparatus in reverse to examine low temperature values of K, ρ and c. If cold water flows through the tube and extract heat from the skin, the effect of the initial conditions will have vanished by equilibrium, and the difficulties in interpreting the results will be correspondingly reduced.

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APPENDIX I

The temperature distribution within the skin is assumed to take the form

$$\theta_x = \theta_s + \theta_1 \left(1 - e^{-\alpha x}\right) \quad \ldots\ldots \text{(1A)}$$

This expression would give $\theta_x = \theta_s + \theta_1$ (the body temperature) when the exponent term is small i.e. at large depths. The value of α must be determined from the boundary conditions.

The heat flux across the surface x = o is

$$Q = -K \left(\frac{\partial \theta}{\partial x}\right)_0 = K \alpha \theta_1 \quad \ldots\ldots \text{(2A)}$$

Q is also given by.

$$Q = H \theta_s \quad \ldots\ldots \text{(3A)}$$

where H is the heat transfer coefficient at the skin surface to the surrounding air.

Hence from (2A and 3A)

$$\alpha = \frac{H}{K} \frac{\theta_s}{\theta_1} \quad \ldots\ldots \text{(4A)}$$

For a black body at 30°C H is approximately 0·00046 C.G.S. units.

Since the correction term is small, approximate values for $K\rho c$ and R may be assumed

viz. $K \doteqdot 1 \times 10^{-3}$ C.G.S. units

$\rho \doteqdot 1$ c.g.s. unit

$c \doteqdot 1$ c.g.s. unit

$\theta_s \doteqdot 31{\cdot}5°C$

$\theta_1 \doteqdot 37 - 31{\cdot}5 = 5{\cdot}5°C$

R = 170 C.G.S. units.

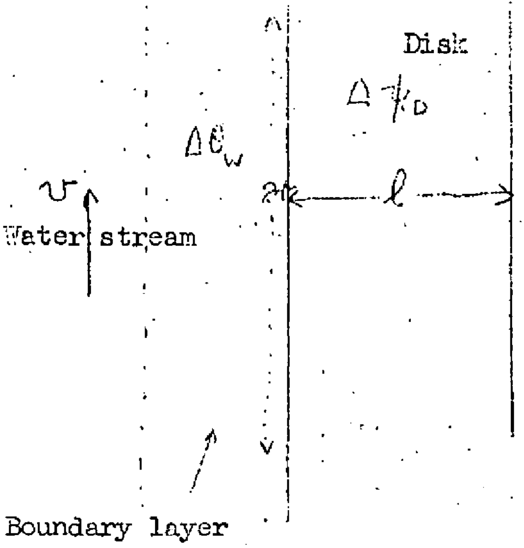
α is then found to be approximately 3 cm^{-1}.

A value of 3 for α implies that the skin temperature at 8 mm depth is 36·5°C, within ½°C of the bulk body temperature.

APPENDIX II

Effect of thermal resistance of disk and water

The amount of heat being taken from the water system is comparatively large and the resistance in the boundary layer is high, so that the amount of heat passing through the disk may not be characteristic of the temperature of the main stream of water. An approximate calculation of the comparative resistance to heat flow of disk and water may be made as follows.



The heat flux Q through the boundary layer is

$$Q = H_w \Delta\theta_w \qquad \text{......} \; (1)$$

where H_w is the heat transfer coefficient across the water boundary layer and $\Delta\theta_w$ is the temperature drop in this layer.

The heat flow through disk is given by

$$Q = \frac{K_D}{l} \Delta\psi_D \qquad \text{......} \; (2)$$

where $\Delta\psi$ is the temperature drop across the disk and l is its thickness.

From (1) and (2)

$$H_w \Delta\theta_w \doteq {}^{K_D}/_{l}\, \Delta\psi_D \text{......} \; (3)$$

The value of H_w depends upon the local velocity of the water and the geometry of the apparatus. If it can be assumed that the local velocity 'v' is the same as in the main stream, i.e. 100 cm/sec, a maximum value for H_w may be calculated which is appropriate to a short plate of the same length "L" as the disk, 1 cm in a free stream of water.

The Reynolds number is

$$N_{Re} = \frac{v \cdot L}{\nu}$$

where ν is the kinematic viscosity of water at 60°C,

hence $N_{Re} = 20,000.$

For this value of the Reynolds number the boundary layer is laminar. The heat transfer coefficient is then obtained from (19)

$$\frac{H_w L}{K} = 0 \cdot 66 \left(N_{Re}\right)^{1/2} \left(\frac{\nu}{k_w}\right)^{1/3}$$

where K_W is the thermal conductivity of water and k_W is its thermal diffusivity.

At 60°C

$$H_W = 0 \cdot 2 \text{ c.g.s. units.}$$

The disk is 1 mm thick and if the thermal conductivity of the disk is assumed to be 0·0144 cal/cm/sec/°C equation (3) gives

$$K_D/_l = 0 \cdot 144 \text{ cal/cm/sec/°C}$$

$$\therefore \frac{\Delta \theta_w}{\Delta \psi_D} = 0 \cdot 72$$

The boundary layer resistance is therefore important since the temperature drop across it is comparable with the temperature drop across the disk.

$\Delta \psi_D$ is of the order 8°C and θ_W will then be of the order 6 °C H_W may be less than the value calculated above and K_D may be larger than the value for pure tellurium, this would increase the estimate of $\frac{\Delta \theta}{\Delta \psi}$. The Reynolds number and the Prandtl number (ν / k_w) are temperature dependent and since they control H_W, the resistance to heat flow is temperature dependent. From the data on these physical properties of water, H_W should decrease by about 8 per cent in the range 55°-65° and this would alter the resistance of the water and disk by at least 4 per cent.

Leach, Peters, and Rossiter (10) describe experiments using a metal chamber the base of which was held in contact with the skin of guinea pigs. Moritz and Henriques (9) have examined the water flow in a similar chamber and have discovered that the temperature of the stream of hot water flowing through the upper and midportions of the metal chamber was significantly and variably higher than that of the underlying skin. They comment that there are two hindrances to the conduction of heat between the site of the measured temperature and the surface of the skin, the metallic base of the chamber and the layer of quiet fluid above it.

Moritz and Henriques (9) do not give details of the thickness of the chamber or state the metal they or Leach, Peters, and Rossiter (10) used for it. Assuming it to be copper and to be 1 mm thick,

the thermal conductance is $\frac{0\cdot93}{0\cdot1} = 9\cdot3$ C.G.S. units

and $$\frac{\Delta \theta_w}{\Delta \psi_D} = \frac{9\cdot3}{0\cdot2} = 45$$

The thermal resistance of the water boundary layer is thus much more important than the thermal resistance of the metal.

Moritz and Henriques claim to have eliminated the static layer of water by the use of a brass cup, the base of which was open so that water in direct contact with the skin. In fact, their system and the earlier system could only remove the laminar boundary layer if eddies were deliberately introduced. The fact that their thermocouple did measure the same temperature as the water may have been due to its creating eddies in the water.

So far as the experiments described in this paper are concerned, the high resistance of the boundary layer will not affect the results obtained provided that the resistance is linear with temperature and that sufficient heat can be obtained from the water.

APPENDIX III

Uneven temperature of disk

The temperature rise at the edge of a uniformly heated disk in equilibrium on a semi-infinite solid may be 40 per cent below the temperature rise at the centre (17). The difference between the central and the edge disk temperatures has been measured for different water temperatures (Figure 7); since the temperatures are less than 40 per cent different the heat flux must be greater towards the edge of the size than at the centre, but this difference may vary with the conductivity of the object in contact with the disk. The different form of the time-temperature curve near the beginning of the experiment is due to the different time constants of the thermocouples.

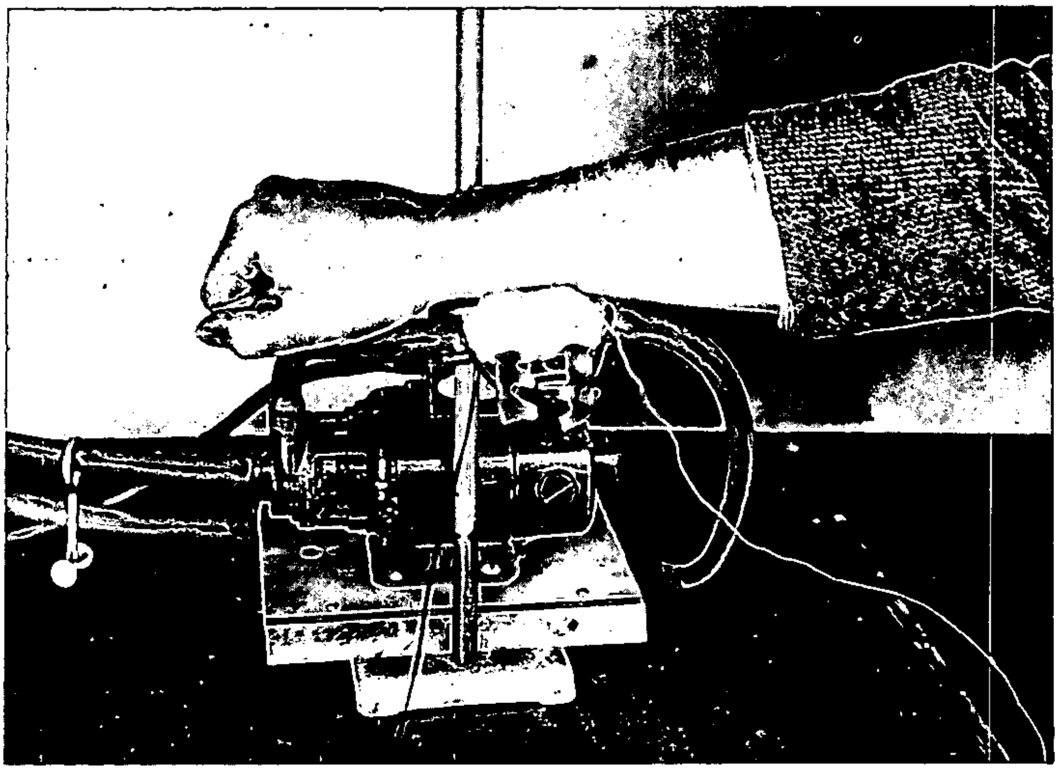


PLATE.1. APPARATUS IN USE

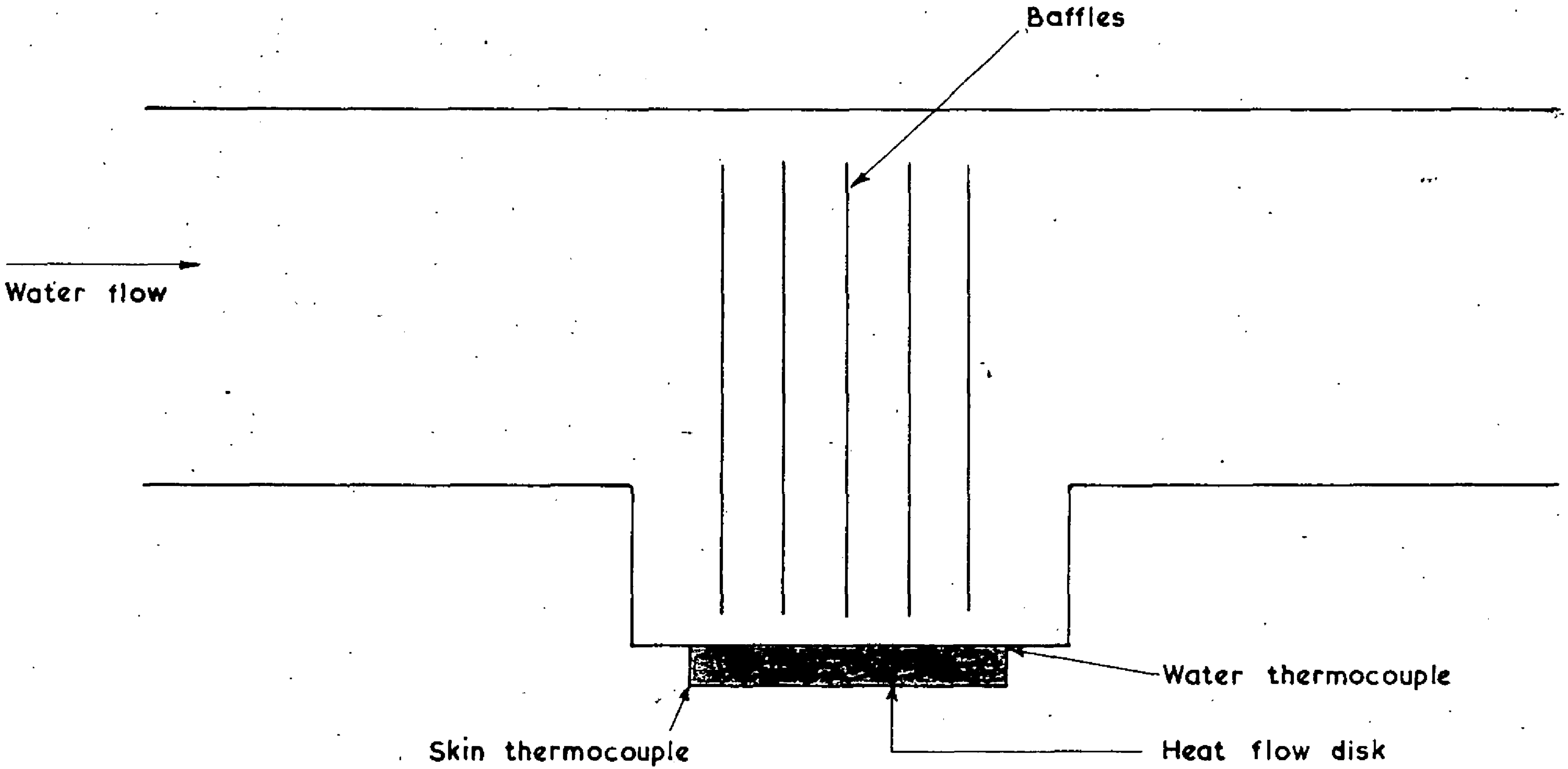


FIG. 1. DIAGRAM OF APPARATUS

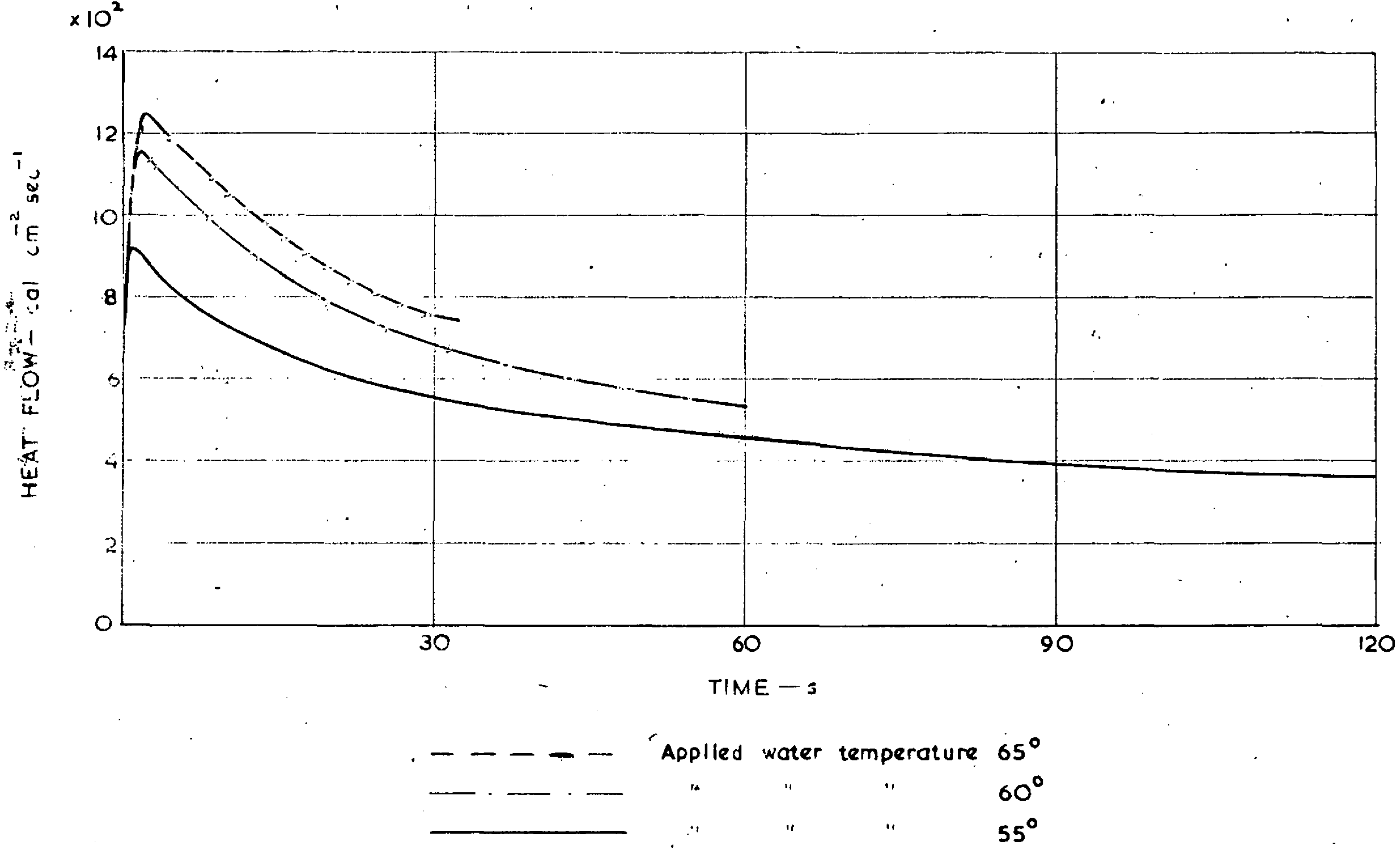


FIG. 2 HEAT FLOW INTO SKIN AS A FUNCTION OF TIME

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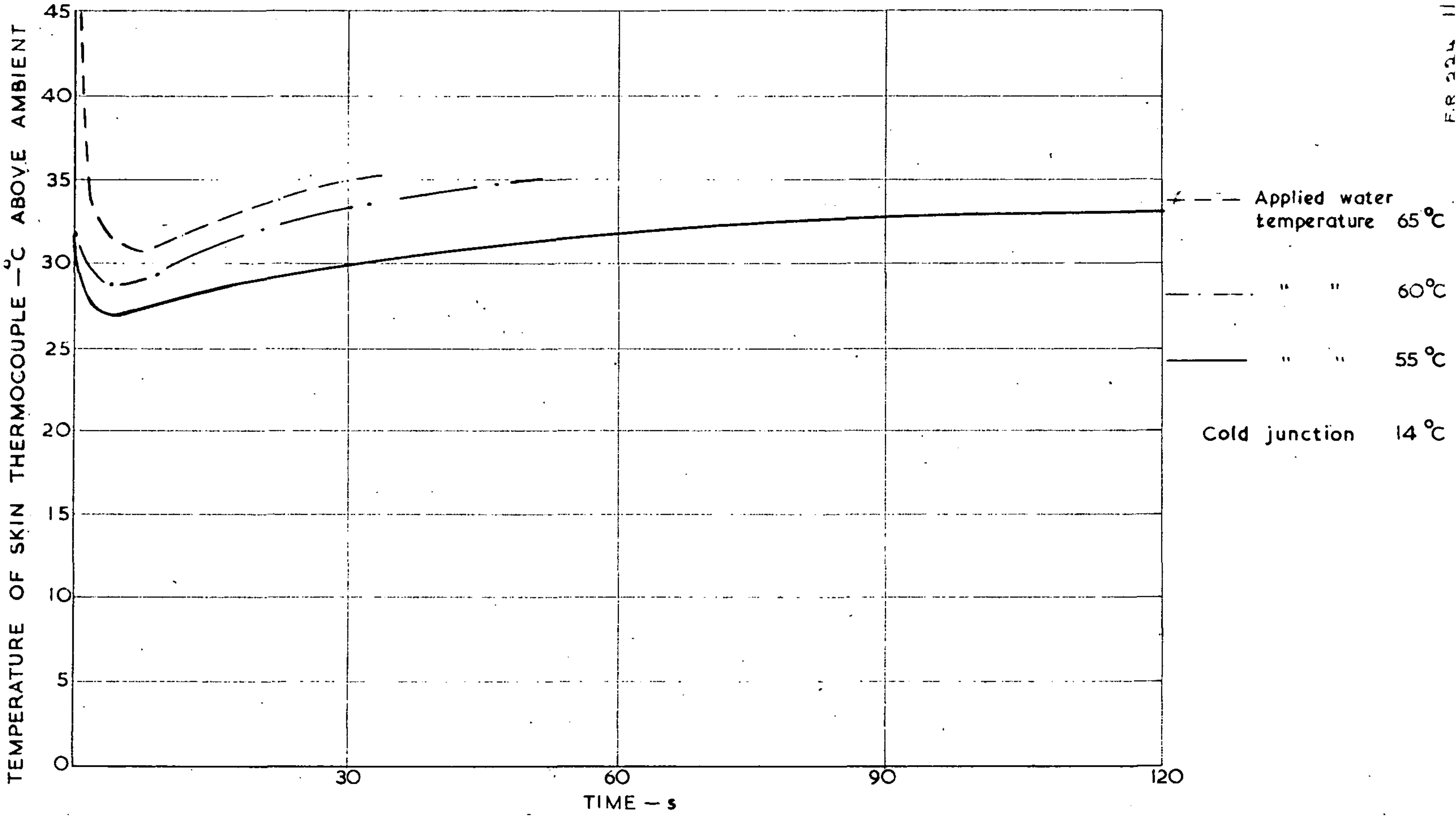

FIG. 3. CHANGE IN TEMPERATURE OF SKIN THERMOCOUPLE WITH TIME

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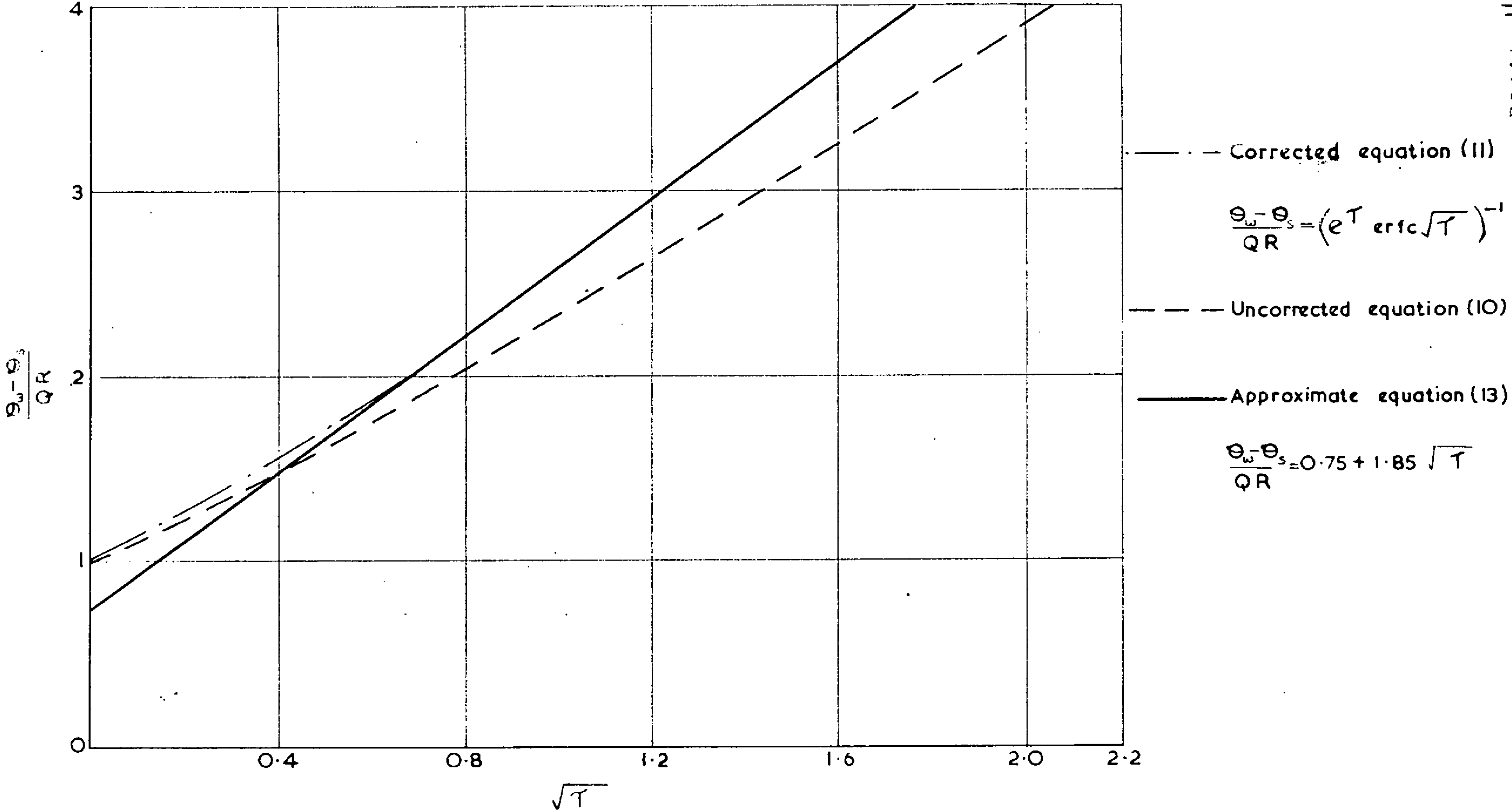

FIG. 4. THEORETICAL RELATION BETWEEN HEAT FLOW AND TIME, UNCORRECTED AND CORRECTED FOR INITIAL TEMPERATURE GRADIENT IN SKIN

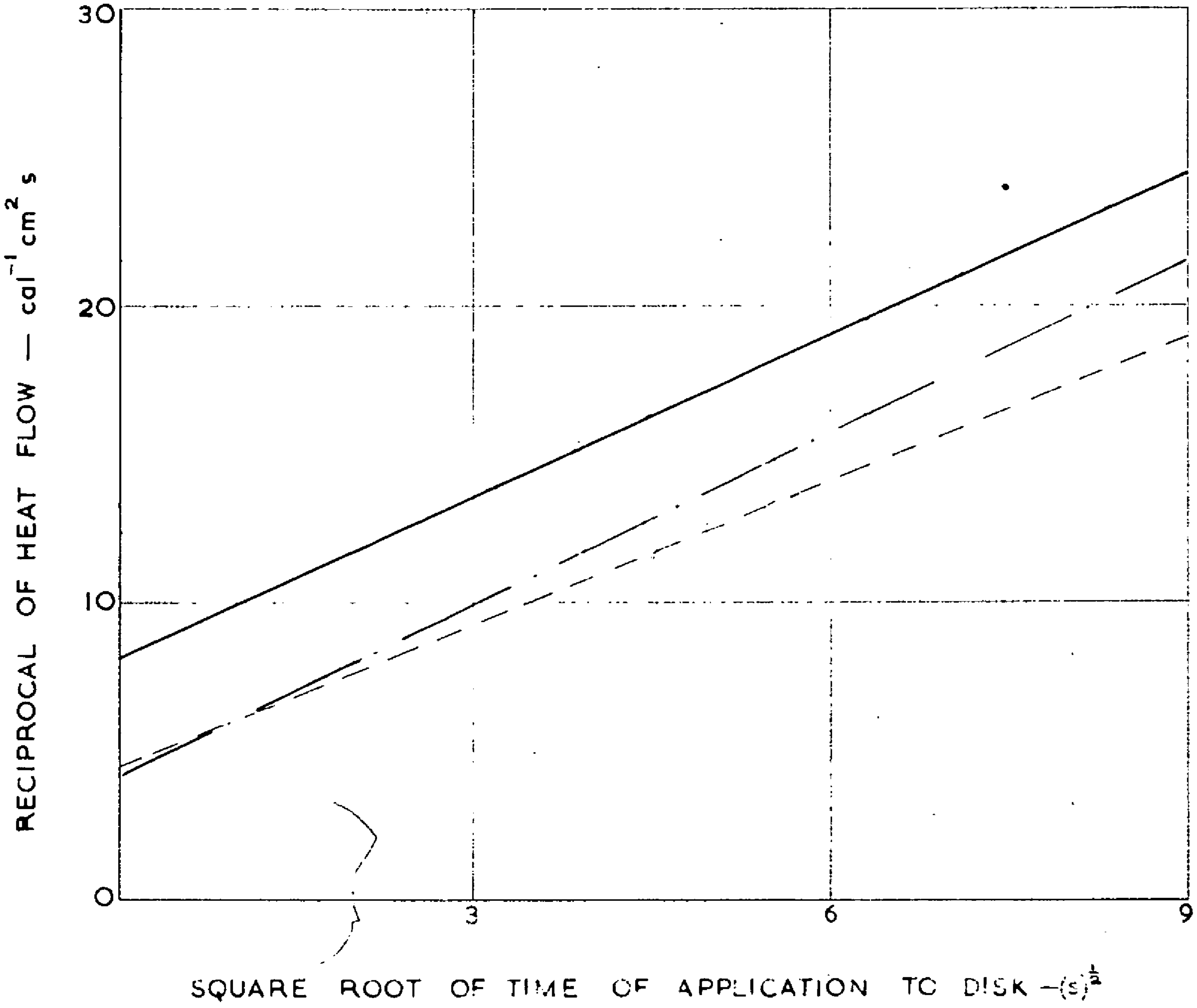

FIG.5. RELATION BETWEEN RECIPROCAL OF HEAT-FLOW AND SQUARE ROOT OF TIME OF APPLICATION TO DISK.

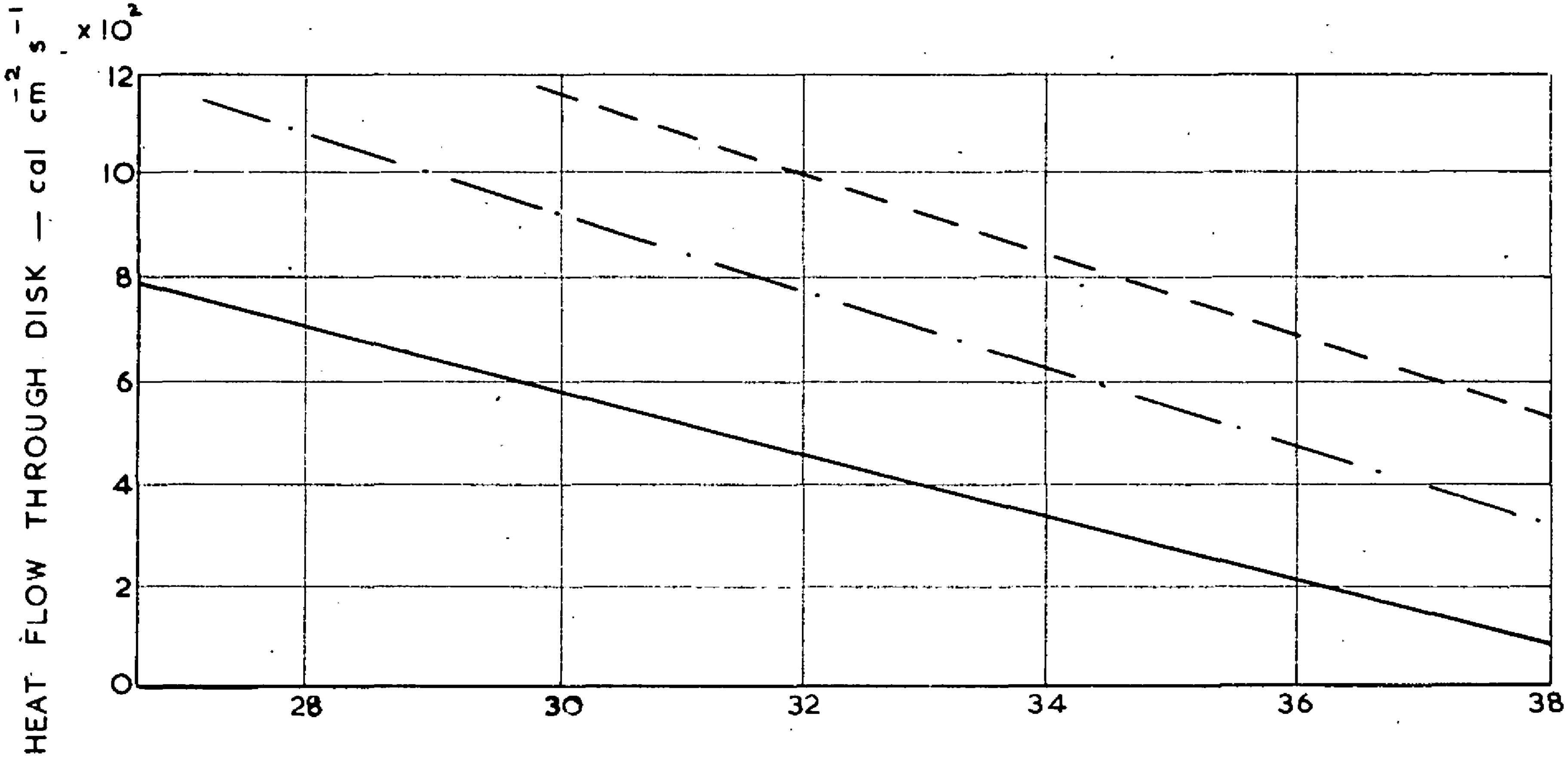

FIG.6. RELATION BETWEEN HEAT FLOW ACROSS DISK AND SKIN THERMOCOUPLE READING

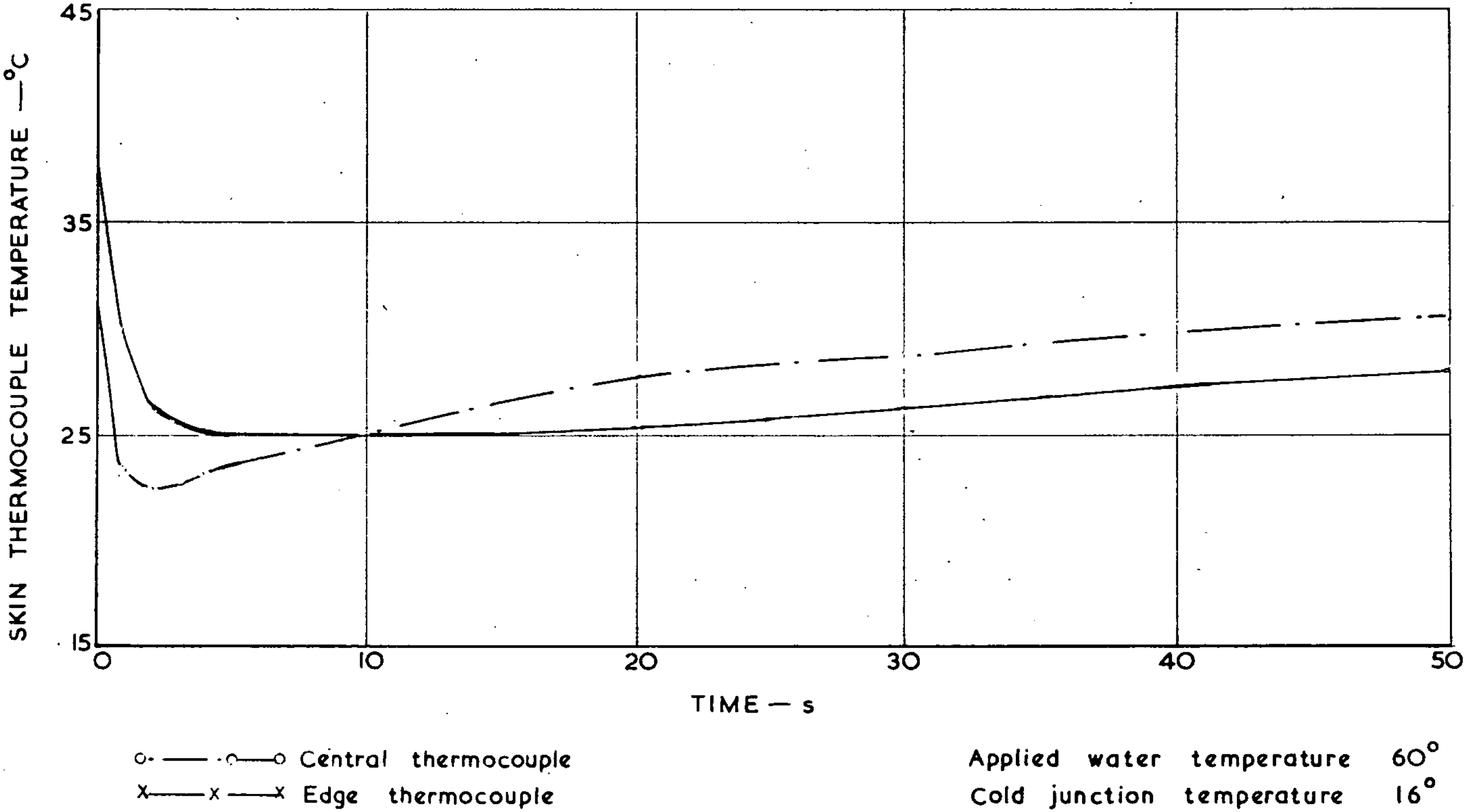

FIG. 7. DIFFERENCE IN TEMPERATURE BETWEEN CENTRAL AND EDGE OF DISK

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