DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

AND FIRE OFFICES' COMMITTEE

FIRE RESEARCH

SPECIAL REPORT NO.3

Protective Clothing against Flames and Heat

LONDON: HER MAJESTY'S STATIONERY OFFICE

1959

PRICE

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PROTECTIVE CLOTHING AGAINST FLAMES AND HEAT

By

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PREFATORY NOTE

DURING the course of an investigation into the types of clothing required for aircraft rescue teams it was found that there had been no collection of data relative to the use of clothing for protection against heat. This report brings together much of the existing information, some of it in a novel form and it is hoped that this will prove of use to all who are interested in the principles affecting the design of this type of protective clothing.

D.I. LAWSON,

Director of Fire Research

FIRE RESEARCH STATION,
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October, 1959.

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SUMMARY

The conditions in which protective clothing may be used are analysed; the likely effects on the human body and the role of clothing in mitigating or preventing these effects is outlined. Specific points discussed are the differing functions of reflectivity, thermal insulation and thermal capacity in long and short term exposures and the special problems of providing protection for the head, feet, and hands.

INTRODUCTION

Men often have to work in the presence of heat and flames. Every effort should be made to control the environment, but in some operations this is either too difficult or too expensive and protection must be given to the operator himself. In fire-fighting, the very operation is itself an attempt to control the environment and protection must be given to the fire-fighter.

Methods(1)-(10) have been developed to assess the probable protection given by clothing against heat, but this is only part of the problem of designing protective clothing. The note consists largely of information relevant to the physical and physiological aspects of providing protection at high rates of heating; it is complementary, therefore, to other surveys(11)-(14). It does not claim to be exhaustive for other factors must also be considered; people are reluctant to wear clothing even slightly less comfortable than normal(11) (15). Tailoring problems, ease of donning and removal, wearing qualities and price, can modify the choice of garments for any particular application, and many of these factors can only be finally assessed by actual experience under practical conditions.

This paper is divided into two main sections, the first dealing with the degrees of exposure encountered and their effects on the body, and the second with the role of clothing in mitigating adverse effects.

I - HAZARDS

CONDITIONS LIKELY TO BE ENCOUNTERED

TYPES OF HEAT TRANSFER

Operators may be exposed to the three types of heat transfer: radiation, convection and conduction. Near flames, furnaces, and hot bodies heat is transferred by radiation; in direct contact with flames, hot gases or in winds, heat is transferred by convection. With flames, heat transfer by both radiation and convection may be important, radiant heat transfer becoming relatively more important as the flames become thicker. Conductive heat transfer is by direct contact between bodies at different temperatures, being greater with metals, than with wood and brick.

The method of heat transfer influences the means by which protection may be obtained (pp 13-16); the rate and duration of heat transfer determines the protection required (p. 12).

The rate of transfer of heat, or thermal flux, is expressed as the number of calories of heat crossing a surface one square centimetre in area every second* (cal cm^{-2} s^{-1}). 1 cal cm^{-2} s^{-1} is equal to 4.2 W/cm^2 and 13 300 B.t.u. $ft^{-2}h^{-1}$. The heat transfer to an operator is the algebraic sum of the heat transfer by radiation[16] conduction and convection[17]. The convective heat transfer to an operator both in the presence and absence of draughts is shown in Fig.1.

GENERAL CONDITIONS

Conditions which may be encountered fall broadly into two categories: short exposures for a matter of minutes and long exposures which may last for hours. The thermal hazard depends on the rate of heat transfer and the temperature of the respirable air, although the limit of working may be set by other factors such as the toxicity of the local atmosphere.

The actual exposure hazards can sometimes be measured, particularly in industrial conditions but usually they must be estimated. (Tables 1 and 2).

ORDINARY FIRE-FIGHTING

The fireman may normally expect to be exposed to the conditions of temperature and radiation shown in range A of Tables 1 and 2. Occasionally, in rescue work, it is necessary to remain for short periods in an enclosed

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*If the temperatures of the surroundings are approximately uniform, it is possible to use the concept of a mean radiant temperature. A surface at this temperature would radiate at an intensity equal to the mean observed intensity. It is measured by a globe thermometer.[18]

NOTES

Fig. 2 is "Reproduced by courtesy of American Society of Heating & Ventilating Engineers".

Fig. 3 is "Reproduced by courtesy of American Society of Mechanical Engineers".

Fig. 4 is "Reproduced from J. Amer. Med. Assoc., 1950, 144 (9) 723-8.

Fig. 5 is "Reproduced from Amer. J. Path., 1947, 23 695-720.

Table 4 is "Reproduced by courtesy of American Society of Mechanical Engineers".

Table 5 is "Reproduced by courtesy of the National Coal Board".

space which is very near to that stage of a fire known as "flash-over"[19], (range B). More rarely the fireman is exposed to a flash of explosive violence of very short duration[20] (range C).

Protective equipment in normal operational practise is not precluded but is unusual as the protection given by the present uniform seems to be adequate. The main operating dangers[21] appear to be burns to the exposed portions of the skin, cuts and bruises.

RESCUE WORK

Much work on the hazards of the aircraft crash fire has been carried out[22], to examine the problem in terms of how long the occupants of the aircraft can survive. It is estimated that the survival time after a fire has developed cannot greatly exceed 3 min. In slowly developing fires the rescue workers may have longer in which to operate, but the figure of 3 min is a useful basis for estimating the amount of protection required.

Unlike the ordinary fire-fighter who is expected to work fairly steadily over long periods, the rescuer in an aircraft crash fire is only active for short periods. The hazards to which he is exposed depend very much upon the technique adopted in fighting the fire. Both the present procedures[23] [24] require the firemen and rescuers to be kept "at the ready" and this raises problems of ensuring that the perspiration of the body is evaporated during standby periods enabling the metabolic heat to be lost.

The two operating procedures are:

(i) The rescuer[23] is sent into the fire as quickly as possible, whilst the fire is still being "knocked down" and thus may be directly exposed to flames (range D).

(ii) The rescuer waits until the fire is first "knocked down"[24] and does not enter the flame zone. The lower part of the body might be exposed to flames, e.g. pockets of petrol burning in the foam or from burning grass, whilst the rest of the body is exposed to radiation of an intensity of about 0.5 cal $cm^{-2}s^{-1}$ (2 W/cm^2) from flames and hot bodies near him (range E).

In an emergency such as a petrol tank explosion or a flash back, the operator might be immersed in flames with a consequential large increase in radiated and convected heat transfer similar to that given in range C of Tables 1 and 2.

The above discussion is limited to the problem of rescue in aircraft crash fires; similar problems are, however, encountered whenever limited time is available.

INDUSTRIAL WORKING CONDITIONS

Normal working conditions

These are conditions where the operator is expected to work for comparatively long periods, the ambient temperature normally being below 50°C. In some industries operators may have to withstand comparatively high radiation levels, for example, when a furnace is being tapped, and the operator may be exposed to splashes of hot metal.

Emergency conditions

These can only be of short duration[25] where for example operators are required to enter kilns, or other enclosures at high temperatures. Hot air may enter the garments, and there may be high rates of heat transfer by contact with hot objects.

Flash fires

In flash fires, which may occur in factories[26] or in mines[27], workers may be immersed in flames for periods of the order of a second (range C).

Abnormal atmospheres

Occasionally operators have to work in enclosed spaces, for example when welding in tanks, where the oxygen content of the atmosphere is enriched or where compressed air is being used. The likelihood of ignition is then increased.

PHYSIOLOGICAL CONSIDERATIONS AND LIMIT OF HUMAN ENDURANCE

VARIATIONS WITHIN NORMAL CONDITIONS

The human body maintains its deep temperature nearly constant over a very limited range of ambient conditions (about 10°C)[41].

Heat is produced by metabolic processes in the body and this is dissipated by radiation, convection and evaporation (Table 3). Normally the body temperature remains in equilibrium because the various terms in the heat balance compensate by varying with external conditions and the

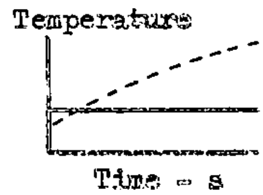
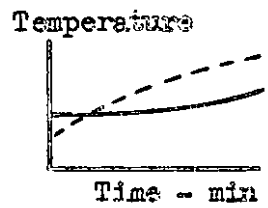
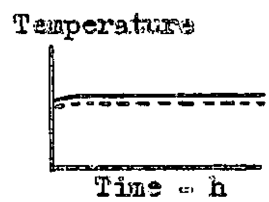
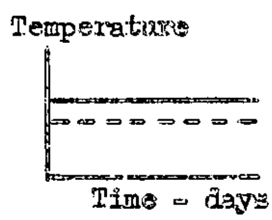
TABLE 3

HEAT BALANCE

Mechanism	Gain or loss of heat	Notes
Metabolic heating	Gain	Depends on work done(41) sitting still 30 cal/s walking 60 cal/s hard work 100 cal/s Increased under hot conditions, much more than 10 per cent for each 1°C rise in body temperature(42)
Radiation	Gain if surrounding objects are above skin temperature Loss if surrounding objects are below skin temperature	Fig. 2(38)
Convection	Gain if air temperature is above skin temperature Loss if air temperature is below skin temperature	Increased by air movement Fig.2.
Evaporation	Loss (except under exceptional circumstances when water vapour may condense on the skin)	Sole means of losing heat if ambient temperature is above skin temperature. Depends on moisture content (relative humidity) of atmosphere. Maximum rate probably about 0.01 cal $cm^{-2}s^{-1}$ (42) (43) or about 700g of perspiration per hour (Fig.2). Under normal conditions about 10 per cent of this is by respiration.

TABLE 4

EFFECT OF DIFFERENT ENVIRONMENTS

Limiting conditions	Tolerance time	Warning symptoms	Skin and body temperatures
Burn	seconds - minutes	pain	
Collapse	minutes - hours	dizziness	
Exhaustion	hours - days	lethargy	
Comfort			

rate of working; occasionally, and for short periods only, it may rise or fall, but no high degree of unbalance can be tolerated for long.

The role of clothing is to provide a comfortable local environment and has little or no effect on the rate of heat transfer into the skin that may be tolerated.

The skin temperature is normally lower than the body temperature so that there is a flow of heat outwards through the skin.

LIMITING CONDITIONS

A worker may be incapacitated by one of several causes(44) which are determined mainly by the rate of heating, the humidity, and the time of exposure as outlined in Table 4(42).

Loss of working efficiency and heat exhaustion

If the temperatures of the air and surroundings rise above that of the skin, heat can only be lost by evaporation. After a time dependent upon the rate of working (Table 3), the rate of entry of heat into the skin and the relative humidity of the atmosphere, the temperature of the body rises. If this condition persists for a long time, the capacity to work decreases, and heat exhaustion and collapse ultimately occur. A man doing hard physical work could, if none of the heat generated were lost, raise his temperature by 1°C in 10 min.* The permissible temperature rise is given variously as 1°C(45) or 2.5°C(38); the difference may be due to men working hard being able to endure a higher temperature rise than those sitting still. Even with such a small temperature rise, the circulation of the blood may be overloaded by vasodilation and collapse result.(46)

A considerable amount of work has been done on the tolerance of men who are resting in hot environments. The results as summarized by Buettner(39) are given in Fig.3.

Results obtained by the National Coal Board Medical Service(47) indicate that for men working in saturated conditions while wearing breathing apparatus, the tolerance times based on a rectal temperature of 38.8°C are much shorter.

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*An average man weighs 75 kg and has a thermal capacity of about 60 kg cal so that at a rate of working of 90 cal/s, (c.$\frac{1}{2}$ h.p.) the body temperature would rise by 1°C every 10 min, if no heat were lost.

TABLE 5

SAFE PERIODS FOR MEN WORKING WHILE WEARING PROTO APPARATUS - MIN.

(Figures in brackets are approximate values of relative humidities)

Dry bulb °F / Wet bulb °F	80	85	90	95	100	105	110	115	120
72.5									59 (9)
75						60 (25)	59 (20)	57 (16)	54 (11)
77.5				60 (45)	56 (37)	54 (30)	53 (23)	52 (19)	48 (15)
80	60 (100)	60 (81)	56 (65)	53 (51)	50 (41)	48 (34)	46 (28)	44 (22)	41 (18)
82.5		50 (90)	49 (73)	46 (59)	44 (48)	42 (40)	40 (32)	38 (27)	36 (20)
85		44 (100)	42 (81)	39 (66)	38 (54)	36 (44)	34 (38)	33 (30)	32 (24)
87.5			27 (91)	26 (74)	25 (60)	24 (49)	24 (41)	29 (35)	28 (29)
90			32 (100)	31 (82)	30 (68)	28 (55)	27 (46)	26 (39)	25 (32)
92.5				27 (91)	26 (75)	25 (62)	24 (51)	24 (41)	22 (36)
95				24 (100)	23 (83)	22 (69)	22 (57)	21 (47)	20 (40)
97.5					22 (91)	20 (76)	19 (64)	19 (53)	
100					19 (100)	less than 20 min.			

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

CORRIGENDUM NO. 1

TABLE 5

SAFE PERIODS FOR MEN WORKING WHILE WEARING PROTO APPARATUS - MIN

Wet bulb °F \ Dry bulb °F	80	85	90	95	100	105	110	115	120
72.5									59
75						60	59	57	54
77.5				60	56	54	53	52	48
80	60	60	56	53	50	48	46	44	41
82.5		50	49	46	44	42	40	38	36
85		44	42	39	38	36	34	33	32
87.5			37	35	34	32	30	29	28
90			32	31	30	28	27	26	25
92.5				27	26	25	24	24	22
95				24	23	22	22	21	20
97.5					22	20	19	19	
100					19	less than 20 min.			

Table 5 gives the maximum safe periods recommended by the National Coal Board Medical Service[47] for fit men wearing Proto (compressed oxygen) apparatus. Even slight unfitness greatly reduced the tolerance to heat and a similar result must be expected with all operators exposed to extreme conditions.

Burns

At high rates of heating the skin temperature rises and this may result in pain and burns. The relationship[37] between the intensity of radiation falling on small areas (about 1–3 cm^2) of bare skin and the time taken to feel pain is shown in Fig.4. The effect of surface cooling is probably negligible for all but the longest times and the average pain threshold is about 45°C. The highest rate at which heat can be absorbed without causing pain is about 0.025 cal $cm^{-2}s^{-1}$; for larger areas this figure may be too high.[48] Above this critical level, a given rate of heating can be tolerated for a time without pain, but once the pain threshold has been passed, the increase in discomfort is likely to be rapid and if a large area of the body is exposed, this may quickly lead to inability to act intelligently. If the skin is initially cool, the time taken for the subject to feel pain is increased; conversely, if it is warm, the time is reduced. Thus the rescue worker should keep as cool as possible beforehand.

The relationship[32] between the temperature of the porcine skin surface and the time taken for a burn is shown in Fig.5; human skin is similar in its reactions. As with pain thresholds, the criterion is not solely that of attaining a given skin temperature, but depends also on the time of exposure. The values of temperature in Fig.5 are actual skin temperatures and apply when a large source of heat such as a mass of hot metal is in firm contact with the skin. Much higher air temperatures may be withstood, particularly if the boundary layer of cool air next to the skin is not disturbed by rapid movement.

Dangers of breathing hot air

The danger of damage to the lungs from breathing hot, but otherwise respirable air, is less than the danger of damage to exposed portions of the body, especially the face[49]. Nevertheless, the interval between burns occurring on the skin and in the lungs may be short and inspiratory burns are often a complicating factor where burns to the face occur[27]. When the whole body is protected by suitable clothing, inhaling hot air may be the limiting factor and breathing apparatus may then be required. The safe limits of exposure without breathing apparatus may be taken from those given in Fig.4. The highest ambient temperature in which it is safe to remain is not known. There is evidence[35] that the human body can tolerate ambient air temperatures of 130°C (270°F) for over 20 min without injury. Some experiments at the Fire Research Station showed that air at 150°C (300°F) was unpleasant to breathe. In some experiments in Northern Ireland[28], an officer wearing full fire-fighting kit survived exposure in an ambient temperature increasing from 120°C (250°F) to 175°C (350°F) for 3 min, although he had difficulty in breathing. The draft Model Code of Safety Regulations for Factories of the International Labour Office recommends that no person should enter furnaces, kilns or ovens when the temperature exceeds 50°C except in an emergency.

Toxicity of atmosphere

The dangers vary considerably depending upon the situation. In burning buildings the concentration of gases tends to become toxic at about the same time as the air becomes too hot to breathe[36]. There is then a rapid rise in concentration of carbon monoxide and a fall in oxygen concentration of the inspired air[50] [51] and this may be one of the most common causes of death in fires[50].

II - CLOTHING

THERMAL PROPERTIES OF CLOTHING MATERIALS

THERMAL RESISTANCE

Thermal resistance is an inverse measure of the capability of the clothing to transmit heat and may be defined as the ratio of the temperature difference across a material or a clothing assembly to the heat flowing through it.

A unit often used for the thermal resistance of clothing is the "tog" = 240 W^{-1} cm^2 °C = 1000 cal^{-1} cm^2 s °C.

THERMAL CAPACITY

Thermal capacity is a measure of the ability of clothing to store heat and may be defined as the amount of heat required to produce a unit rise in temperature in unit volume. As so defined it is the product of the density and the specific heat.

REFLECTIVITY

When radiation falls on a material, part may be absorbed, part transmitted and the rest reflected. The reflectivity is the ratio of the reflected to the total incident radiation.

EFFECT OF HEAT AND FLAMES ON GARMENTS

DANGERS OF IGNITION

The ignition and continued burning of the garment may increase the amount of heat reaching the body and will almost certainly increase the rate of disintegration. With some materials, such as lasting cloth, the extra heat[52] may be small, but with others, such as rubber-bonded materials, or cotton overalls, it may be large enough to be significant. Rapid spread of flame over the cloth would increase the supply of heat considerably[52] and increase the severity of burns[27].

Most materials used in garments are flammable especially when exposed to flames and to high intensity radiation together, though there are exceptions, such as asbestos and glass fibre.

Flame-retardant treatments may prevent or more probably delay ignition. Their use is justified if the garment would otherwise ignite and then continue to burn after the wearer has retreated from the fire zone.

Most flammable materials burn faster in oxygen enriched atmospheres[53] or compressed air[54] than in the normal atmosphere and some flameproof materials may become flammable.

MECHANICAL FAILURE BY HEATING

A garment, particularly the outer layer, must retain its strength for it to remain in position. Materials made from natural fibres char, whilst most synthetic materials melt[55] often at low temperatures. With woollen materials, tumescence or "frothing" occurs but though this increases the thermal resistance, its appearance means that the fabric has been weakened. Woollen and some synthetic materials when heated to a high temperature often stick to the interlining and may then prevent the complete breakdown of the garment; asbestos cloth which has a cotton base tends to become brittle on heating and glass fibre cloth melts and becomes brittle before 600°C.

Fire-retardant treatments although they increase the resistance to flaming do not prevent disintegration.

PROTECTION BY CLOTHING

ROLE OF CLOTHING

The heat balance of the clothing and the body is controlled by the rate at which external heat is absorbed by the clothing surfaces[*], the thermal properties of the skin and the clothing, and the metabolic heating. As the thermal properties of the body do not vary greatly from operator to operator, for short exposures where metabolic heating may be neglected, the thermal properties of the clothing determine the protection time for a given rate of heating.

If the front surface of a clothing assembly is exposed to a source of heat at a constant temperature, the temperature rise of the skin follows the curve in Fig.6.

For a given rate of heating, the factors determining the time taken to reach a critical level of heat flow and whether this level is reached at all are:

(i) Thermal resistance of the whole thickness of the assembly.

(ii) Thermal capacity of the assembly.

(iii) Reflectivity of the outer surface of the garment.

(iv) Moisture content and moisture permeability of the assembly.

For long exposure times, thermal resistance must provide the protection; for short times where heating rates are likely to be high, thermal capacity is likely to be more important.

If the rate of heating is low enough to be tolerated by the skin for long periods (0.025 cal cm^{-2} s^{-1}), clothing may reduce the tolerance time since it impedes the evaporation of perspiration. Thus, in the conditions outlined in Table 5, the tolerance times would be less if heavy clothing were worn, so that as a general rule as little as possible should be worn.

Perfectly insulated clothing would not allow work being undertaken for periods much in excess of 20 min because there would then be no means of losing body heat.

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[*]The statement which is sometimes made that a suit gives protection against radiation of a particular temperature is by itself meaningless. The correct parameter is the rate at which heat reaches the surface.

PROTECTION BY THERMAL RESISTANCE

After a time which depends on the factors listed above but which is usually of the order of 2 to 3 min, the heat flow into the skin reaches a steady value determined by the thermal resistance and the surface temperature of the assembly. The whole of the clothing contributes to thermal resistance; underwear may be of equal or greater importance than outer garments. The thermal resistance of clothing depends partly upon the resistivity of the fibres, and the radiative transfer between them, but principally upon the still air contained within the fibres and yarns[56]. Its value depends on:

(i) Thickness. This is by far the most important factor; resistance is usually proportional to thickness.

(ii) Density. For a given thickness, the lower the density the greater the resistance, but there is a critical density (about 0.06 g/cm^3) below which convective transfer in the air spaces through the loosely packed fibres becomes important[56].

(iii) Moisture content. The resistance decreases with increasing moisture content.

(iv) Temperature. At 500°C, the resistance may be reduced by as much as a half[42].

(v) The air gap between the fabrics and the body. Increasing this up to a maximum of 0.75 - 1 cm improves the insulation[56]. Even small air gaps have prevented serious burns[27].

(vi) The curvature of the surface. The thickness required to provide a given amount of protection to the fingers may be twice as much as that required elsewhere[14].

In all types of clothing there are bound to be areas where the contact between skin and clothing is good and where the clothing may even be in slight compression, for instance, the shoulders and upper arms, and the front of the thighs, and at these places it is often desirable to provide extra protection. In order to maintain air gaps, in particular those due to bulked fabrics, the material of the garment should be resilient enough to return to its original thickness after compression.

The relationship between the thickness of clothing (at a pressure of 0.001 lb/in^2), its thermal resistance at room temperature[57], the temperature of the outer surface and the heat flow through the clothing corrected for the change in thermal resistance with temperature[42] is shown in Fig.7. The maximum thickness of clothing that can be worn without undue loss of operative power is about 2.5 cm[57]. Thus the maximum feasible thermal resistance is about 6 000 cal cm^{-2} s^{-1} (6 togs) at room temperature, and assuming a heat flow into the skin of 0.025 cal cm^{-2} s^{-1} which might possibly be tolerated for 4 min over the whole body or longer over limited areas, the maximum temperature on the clothing surface that can be tolerated is about 350°C. The actual surface temperature attained depends on the external conditions; where both the air and the surroundings are at the same temperature the surface would eventually acquire this temperature; if the ambient air is cold and the worker is heated by radiation only, the surface of the clothing reaches the temperature given in Fig.8.

PROTECTION BY THERMAL CAPACITY

The reduction in heat flow by thermal capacity is temporary but is important where the rate of heating is high or long term protection is not required. The delay in the establishment of a practically steady temperature gradient in the clothing is shown in Fig.9 and as with thermal resistance the thickness is the most important single factor[(2)x]. Once the condition shown in Fig.9 (third diagram) has been reached, the rise of temperature depends on the thermal constants of skin as well as of the clothing.

There is little difference between the specific heats of textile fabrics although nylon has a slightly higher value than the others[56] and therefore the thermal capacity depends mainly on the density of the material. The density is not usually uniformly distributed and this too influences the rate of rise of temperature of the skin.

Even where the main protection is due to thermal capacity, a high thermal resistance of a protective clothing assembly decreases the maximum possible temperature of the inner surface for a given heating rate, and increases the

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x The time taken for the temperature of the back surface to begin to rise is determined by[58] (thermal resistance) x (thermal capacity) which is proportional to (thickness) x (weight per unit area.)

time taken to reach the critical level (Fig.10).

Protection can be obtained against a rate of heating of 0.5 cal cm^{-2} s^{-1} for a matter of minutes with practical clothing assemblies. The protection afforded by any given assembly can best be estimated by a simple experiment (p. 20).

Protection against flash fires

In the extreme case even light clothing, providing it does not ignite, gives some protection against immersion in flames for times of the order of 1-10s[2] [27] because heat is absorbed by the clothing. If the clothing does ignite the resulting burns may be worse than if no clothing were worn[27]. The ordinary fireman's uniform provides good protection for the area it covers and is difficult to ignite*.

In situations where a flash fire is possible the entire body including the hands and head should be covered with flameproof material.

Limitations of protection by thermal capacity

There is an inherent danger in making use of the storage of heat to obtain protection, because the heat stored in the clothing may only be given up slowly after the wearer has retreated from the source of heat (Fig.11).

Thus even if the rescue worker retreats from the source of heat as soon as he feels pain, his skin temperature does not necessarily fall immediately; it may even continue to rise and maintaining the surface of the skin at a temperature which initially only produces pain or discomfort may, in a short time, produce a burn (p. 9). Thus, the greater the tendency for the inside of the clothing to maintain or increase its temperature, the lower the safety margin given by the first onset of pain. The effect can be minimized by ensuring that the thermal capacity is concentrated in the outer layers of the clothing; to achieve this, the outer layer should be of a dense material and the inner layers of very light open weave materials. Concentrating the thermal capacity in the inner layers would delay the

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*In an explosion[27], workmen wearing cotton dungaree overalls were either killed outright or burnt so severely that they died soon afterwards, whereas firemen standing next to them although badly burnt did survive. The firemen's clothing gave sufficient but only just sufficient protection over most of the body as photographs of the clothing show. Details of the workmen's clothing are not available so that it is not possible to state whether the actual protection afforded by their garments was insufficient or whether the hazard was increased by the flammability.

temperature rise of the inner surface of the assembly but the heat would then tend to flow inwards rather than outwards when the heat source was removed.

PROTECTION BY REFLECTIVITY

Except for polished metallized surfaces the infra-red reflectivities of all textiles likely to be used in protective clothing are very low[59].

It is however possible to design clothing that reflects over 90 per cent of the radiation incident upon it, by having a reflecting layer of aluminium on the outer surface. The protection afforded by this method depends on the conditions encountered.

In an enclosure with the air and walls at the same temperature, a high reflectivity does not affect the final skin temperature, but reduces the rate of rise of temperature. This is useful for rescue work or quick repairs in a kiln. An aluminized surface is more satisfactory as a protection against radiation than flames because it is quickly damaged by the latter. When the air temperature is low and the intensity of radiation fairly high (e.g. near a fire) a high reflectivity not only reduces the rate of temperature rise by a large factor (10 or more) but also reduces the final temperature attained, particularly if there is a wind.

A reflecting layer inside a garment is valueless unless there is an air gap of something like 1 cm in front of it.

<u>Limitations of protection by a highly reflecting surface</u>

A highly reflecting surface reduces both the rate of absorption and emission of radiation by a large factor. Thus the rate of cooling of garments when the wearer has retreated from the heat is reduced by a reflecting surface; this effect is greatest in still air when there is little cooling by convection.

If a reflecting surface becomes dirty or covered with soot its reflecting power is greatly reduced.

EFFECT OF WATER ON PROTECTIVE CLOTHING

The heat lost by perspiration is of great importance in maintaining the heat balance in long term exposure and also in enabling protective garments intended for short term protection to be worn for long periods "at the ready".

Clothing may modify the rate of evaporation considerably. Some of the moisture may be absorbed by the clothing, some may pass through the clothing to be evaporated from the surface, and some may be removed by natural ventilation. The resultant effect can only be determined by wearing the clothing under practical conditions.

Absorption of water by clothing

The moisture in a garment consists of free water between the fibres and absorbed water within the fibres. The amount of free water depends mainly upon the weave, whilst the amount of absorbed water depends on the nature of the fibre and the relative humidity of the atmosphere[(14)]*. Heat is evolved upon wetting at a rate of about 100 cal/g of water[(60)] and is additional to the latent heat evolved when water vapour condenses. Thus, if water vapour evaporates from the skin and is absorbed by clothing, the skin is cooled but the clothing is warmed and more heat is evolved in the clothing than is absorbed from the skin. Although the amount of heat involved is small, it may be desirable for underwear to have a low regain[(61)].

Passage of water through clothing

This occurs either by diffusion through the spaces between the fibres as vapour or along the fibres themselves as liquid by wicking[(61)]. Transmission of water vapour through clothing is analogous to the transmission of heat, both resistance to the passage of water vapour and the capacity to store it being important. The resistance of a material to the passage of vapour through it depends more upon its structure than upon the actual fibre, where the fibre content is less than 30 per cent[(61)].

If the skin and undergarments are wet, some water may pass through the clothing by "wicking"[(62)] to be evaporated from the outer surface. The ease of "wicking" depends mainly upon the nature of the fibre and any treatment it may have received although the fineness of denier and type of weave are also important[(62)].

Water loss by natural ventilation

In conventional clothing, much of the loss of moisture occurs by the evaporation into the air which the movement of the wearer pumps round the edges of

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* The moisture content expressed as a percentage of the dry weight is known as the regain.

the garments and through the interstices of the fabric[61]. The amount depends on the activity of the wearer, the design of the garments and the stiffness and air permeability of the fabrics.

Effect of water on protection

The water content of clothing influences the protection given by:

(i) The cooling effect of the evaporation of water from the surface.

(ii) The heat transfer through the clothing due to the inward diffusion of hot vapour.

(iii) The change of the thermal properties of clothing materials; the thermal resistance may be reduced and the thermal capacity will be increased.

When clothing contains a moisture barrier a large increase in protection is obtained by wetting it. Without a moisture barrier, wet clothing gives less protection against radiant heat than dry clothing because of the inward diffusion of moisture; against flames the protection may be slightly higher for wet clothing than for dry[9]. (Fig.12).

Clothing and comfort

For the wearer to remain comfortable his perspiration must be evaporated. In order to provide protection, it is necessary for clothing to have a high thermal resistance but this is generally associated with a high resistance to the passage of moisture. Many types of reflecting garment are impervious to moisture owing to the continuous layer of aluminium deposited on the surface and are particularly uncomfortable to wear for long periods. For these reasons unless clothing is to be worn in flames or hot gases it should be designed so that the movement of the wearer induces natural ventilation. Openings to allow ventilation which can be quickly closed may be useful.

For comfort under hot conditions, materials with a low regain but a large wicking tendency may be preferable to those with a high regain[62].

LIMITS OF PROTECTION

Increased protection for the operator would not increase his danger if he worked for no longer than and in the same conditions as without protection, but it must be expected that he will tend to work for longer periods, probably, in more exposed positions. Should mechanical failure of the clothing occur, however, the operator may be exposed to great danger.

When the air in the immediate vicinity of the skin reaches and rises above the skin temperature, the skin can no longer lose heat by radiation and convection but only by evaporation. The onset of this change may lead to a feeling of panic, but it is not the critical point and does not indicate that the protection time has been exceeded.

It is common experience that the onset of pain may be rapid and occur with little previous sensation of warmth. This is due to the fact that the skin temperature is increasing steadily with time of exposure at temperatures where small increases in temperature produce large effects. The suddenness is due to the properties of the skin (p.9); the reaction is physiological and may be expected with all garments. The effect of the garment is to delay the arrival of the heat (p.12) and although different garments may delay the onset of sensation by different periods, there is little truth in the statement that the heat arrives suddenly with a certain type of garment. The time for which individuals can remain exposed to heat varies considerably. Once pain has been felt, it is advisable to withdraw immediately and in order to minimize the risk of burns through the maintenance of the temperature of the inside of the clothing after removal of the heating source, clothing should be so designed that it can be quickly and easily removed. This is particularly important with garments having highly reflecting outer surfaces.

ARTIFICIAL COOLING OF CLOTHING

Under conditions where there would be no net loss of heat from the body, long term protection (20 min or more) can only be obtained if the garment is cooled by external means.

Spraying with water ("wetting down")

When the temperature of the surface of the clothing is not likely to approach 100°C, "wetting down" increases protection by increasing the thermal capacity of the clothing and by providing evaporative cooling. At higher rates of heating when the surface may exceed 100°C, "wetting down" delays the onset of charring and reduces the tendency of clothing to lose its strength. Under these conditions however, "wetting down" increases protection only if a moisture barrier is included in the clothing; without it, the protection time may be reduced. The danger of scalding from initially wet clothing is much less than from clothing which is wetted when it is hot[9] and thus if there is a danger of accidental wetting, clothing should be "wetted down" before the wearer enters the fire zone, and should not be allowed to dry out.

If the clothing surface has an area of approximately 2 m^2, about 35 c.c. of cold water must be evaporated per second to maintain the surface at below 100°C if the rate of heating is 1 cal cm^{-2} s^{-1}. Thus for 5-min protection at least 10 l. (about 2¼ gal) of water would be required. It is doubtful if such quantities of water could be carried by the rescue worker and it is better to have an external supply. Excess water can then be applied and the external surface of the suit can be kept below body temperature[63].

Ventilation from an external source

This method has been used to cool aircrew in modern high speed aircraft[64]. Its main application seems to be to provide protection against relatively low rates of heating for long periods. Forced ventilation at a low rate could be supplied to an impermeable suit whilst the operator is "at the ready" in hot conditions.

Foam-filled suits

Water-based foams of a reasonably stable nature have a high degree of thermal resistance and even when they do break down, their water content has still to be evaporated.

A suit based on this principle has now been designed[65]. In one form it consists of an inner layer of an impervious fabric and an outer layer through which foam can pass. The space between them is filled with a stable liquid foam about 5 cm thick; this may be supplied continuously from an external source or intermittently by the wearer carrying his own supply.

THERMAL TESTING OF CLOTHING

Broadly, there are two conditions that need to be investigated; those in which only the insulating power of the assembly is important and those in which the thermal capacity is important as well. Where only the insulating power is important, the protection afforded by an assembly at a given rate of heating (Fig.8) may be estimated from the thermal resistances of its parts, making a correction for temperature (Fig.7), and for reflectivity when radiation is the only important heating method. Where the thermal capacity of the clothing is also important, the protection cannot be calculated as all the thermal properties of clothing vary greatly with temperature and the outer surface is often being destroyed. Two laboratory tests have therefore been devised to assess the relative effectiveness of different clothing assemblies and are described in detail in Appendix II. The assembly to be tested is backed by horsemeat to simulate human flesh and the front surface is exposed to radiation or to flames. The temperature of the surface of the horsemeat is measured by a thermocouple and the time taken for its temperature to rise by 25°C is regarded as the protection time. Any tendency for the temperature to continue to rise after the removal of the heating source is noted. The protection given by an assembly cannot be estimated from the protection given by its elements(66); it must be tested as a whole.

LIMITATIONS OF TESTS

(i) A simple criterion of temperature rise is only a crude measure of the limits of physiological endurance.

(ii) The temperature rise of 25°C is an arbitrary one; skin raised in temperature by this amount would signal pain or a burn within a short time. Changing the temperature rise to 15°C does not change the comparative effectiveness of materials. (Fig.13).

(iii) The thermal constants of dead horsemeat and living tissue are not the same but the error introduced is not likely to be large.

(iv) Reasonable repeatability of the results is found only with materials under slight compression; this means that the results are strictly applicable only to the tighter fitting portions of the garments.

OTHER CONDITIONS

The tests were designed to assess the suitability of materials for clothing aircraft crash rescue workers and the rates of heat transfer in these tests are of the order estimated to occur in aircraft crash fires. They may be too high or too low for other conditions where only short periods of work are possible and the level of the radiation test could be changed accordingly; the severity of the flame test can only be increased.

SPECIAL ITEMS

Coverings for the hands, feet and head have to fulfil the same functions as those for the rest of the body to which the discussions on (p.12-18) are relevant, but there are some additional problems.

HAND PROTECTION

The dexterity of the operator must not be unduly reduced by hand protection; this condition may restrict the thickness of gloves or gauntlets that may be used especially on the front of the hand, which means that the thermal resistance may be low especially as the surfaces are convex (p. 13). If hot metal is handled the rate of heat transfer may be high. Under these conditions, it is probably most effective for there to be little thermal capacity in the palm of the gauntlet; the operator will then only hold hot objects until he feels pain and there will be little danger of a burn due to the heat stored in the glove. The glove should be constructed so that the palm can be protected by partially closing the hand. The back of the hand can be provided with a thick layer of insulation and should be aluminized. Tools with insulated handles should be provided so that hot metal need not be handled for long periods.

FOOT PROTECTION

Where boots are likely to be immersed in flames and extinguishing agents, they must be adequately water-repellant and resistant to chemical attack.

An effective type of footwear (Appendix II) consists of an inner and an outer layer of leather with an interlining designed to provide an air gap. Valuable extra protection may also be given by thick woollen socks, which can also absorb a good deal of perspiration.

Although there seems to be no satisfactory alternative to leather, it has the disadvantage that it may shrink sufficiently to cause the footwear to become uncomfortable or even dangerous. Owing to its high thermal capacity the temperature often continues to rise considerably after the footwear is removed from the source of heat (p. 15). Hence it is particularly important that footwear should be designed so that it can be easily removed.

HEAD PROTECTION

Where there is some danger from falling objects a helmet is required. This is commonly adjusted to become a useful shield against radiant heat.

Against higher levels of radiant heat and showers of hot particles from a known direction a simple mask set off from the face is probably adequate. If an area of flame or hot air (above 50°C) has to be entered the entire head must be enclosed. The headgear may be a rigid helmet with a vizor and a neck curtain or a soft hood fitted with a window. Care must be taken to prevent the entry of flames and hot gases into the hood. This, however, is difficult to achieve without limiting the air supply available for breathing to that contained in the headgear. An air vent or openable vizor under the control of the operator is useful when exposure is intermittent; the operator must, however, be trained not to open it when in the fire. The volume of available air may be increased by allowing the wearer to breathe some of the air contained inside his clothing. For long exposures breathing apparatus is necessary.

Helmets

The present test for firemen's helmets(67) was designed as a measure of ignitability and cannot be used as a measure of protection time.

The same considerations apply to the design of a helmet as to other clothing and in addition it should be kept as light as possible. Helmets which enclose the head may consist of a shell of an incombustible material, such as glass fibre, held away from the head. An insulating lining is desirable, particularly a reflecting lining with an air gap inside the helmet(68). Coating the exterior of the helmet with a reflecting material such as aluminium foil may greatly increase the protection provided.

Vizors

Protection must be given to the face without unduly obstructing the vision or breathing. The permissible obstruction to vision depends upon the type of work. Except for rare fires, such as those involving magnesium, glare is not likely to be a problem.

The maximum level of radiation tolerable for long periods is about 0.025 cal cm^{-2} s^{-1} (0.1 W/cm^2) (p. 9). Radiation from most fires and hot bodies is largely in the infra-red region of the spectrum and ideal protection would be given by a vizor which, whilst being transparent to visible radiation, reflects infra-red radiation. Reflection is very much more advantageous than absorption, because although both reduce transmission, the vizor becomes hot by absorption and re-radiates upon the face and the face may come into direct contact with it. In addition, a vizor should not ignite in the most severe exposure conditions; it should not become deformed or lose its optical properties on heating and it must not shatter if it is sprayed with water or foam when it is hot. The actual temperature at which a vizor deteriorates, although important. is not by itself a complete indication of how the vizor will behave in practice; the thermal resistance, capacity, and absorptivity of the material are also important. Two vizors(7) both having the same absorptivity, one of which softened at a given temperature, while the other became opaque at a much higher temperature, deteriorated in about the same time when exposed to radiation with an intensity of 0.5 cal cm^{-2} s^{-1} ($2W/cm^2$). This was because the vizor became opaque when only a small thickness of it reached the required high temperature whereas deformation due to softening did not occur until the entire vizor had reached the softening temperature.

The suitability of a given material is determined by exposing it to radiation of the anticipated intensity and characteristic temperature. The vizor should not deteriorate, e.g. become opaque, break up, seriously deform or transmit too much heat to the face in the time for which it is likely to be required (Appendix III).

A wire gauze conveniently reduces the intensity of variation upon the face(11). If the ambient temperature is low and there is no danger of particles passing through the gauze or of clogging by foam, it may be used by itself. This has the advantage of increasing the ventilation.

BREATHING APPARATUS

Although not strictly protective clothing, breathing apparatus has to be used wherever there are toxic or noxious gases and whenever the ambient temperature is high ($>50^{\circ}C$). Care must be taken that the apparatus and particularly the gas cylinders should not become hot. When high rates of heating are encountered, the apparatus should be provided with an insulating covering; small apparatus may be worn beneath the protective clothing.

Considerable practical experience of their use is summarized elsewhere[69] [70]. Under hot conditions liquid air apparatus is preferable to compressed oxygen since the inspired air is cool[47] and for the same reason open-circuit compressed air apparatus may be preferable to closed-circuit compressed oxygen.

CONCLUSIONS

Each situation in which protective clothing may be used has to be assessed individually because of the wide range and duration of exposures to heat and flames that may be encountered, each demanding different levels of physical work, but there are certain general principles which must be observed (Table 8).

No practical clothing can provide protection for more than a few minutes against high rates of heating without external cooling. Reflecting surfaces provide excellent protection against radiation, but the garments may be uncomfortable to wear for long periods owing to the difficulty of losing body heat by perspiration. Besides this, at the end of the safe-working period, this type of clothing must be removed as quickly as possible because the heat stored within it escapes most easily to the skin. Reflecting surfaces are of little use against flames. Protection in these circumstances is best obtained by using an assembly incorporating an open weave or other type of fabric containing an air gap, which has the advantage of storing little heat. As this type of fabric is also effective against radiation it should be used wherever possible.

If the ambient air temperature is high care must be taken to prevent the hot air entering the garments. If in addition, the atmosphere is noxious or toxic breathing apparatus may have to be worn.

There are limits to the time for which protective clothing may be used without external cooling. The most common way is by "wetting down"; this, to be effective, must be continuous, but where it is not possible a moisture barrier should be incorporated in the garment, otherwise the presence of water may lower the protection considerably.

Materials which may ignite, glow, or continue to burn must not be used.

The extremities, (head, feet, hands) present extra problems because their specialized functions must not be impeded unduly.

Wearing protective clothing does not guarantee safety and does not obviate the need for great care at all times; the importance of regular and frequent practice and careful maintainence of garments cannot be overemphasized.

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APPENDIX I

FLAMMABILITY AND DISINTEGRATION TEST

The British Standard test[71] should be used to measure the flammability of the garments. A strip of cloth, 2 in. wide and 15 in. long is suspended vertically in an incombustible box with a glass front (Fig.14) and a luminous flame from a Bunsen burner applied for 12 s to the lower end. The duration of flaming after the Bunsen flame has been removed is measured and any spread of glowing beyond the area already damaged by flaming is noted. The reduction in rip strength is also measured by the method laid down in British Standard 3119. The material may be called flameproof[72] provided that:

(i) Flaming does not persist for more than 8 s after the removal of the Bunsen burner.

(ii) Glowing does not spread beyond the area already damaged by flaming.

(iii) The length ripped does not extend to within $11\frac{1}{2}$ in. of the unburnt end on any one specimen and to a mean value of $10\frac{1}{2}$ in. for all the samples.

The British Standard test requires the flame to play on both sides of the fabric at once, so that this test cannot be used on the whole assembly and components must be tested individually. For most applications it is probably sufficient for the outer layer to be "flameproof".

APPENDIX II

TESTS TO DETERMINE PROTECTION

DESCRIPTION OF TESTS

Flame test

The apparatus used for these tests is shown in Figs 15 and 16. It was designed to expose the clothing assemblies to flames from a petrol fire. Specimens of the entire assembly are mounted on a metal frame and inserted into a square hole 6.5 cm x 6.5 cm, cut in the asbestos wood shield (a) (Fig.15). The rear of the specimen is protected from flames by the asbestos board (b).

The shield (a) is mounted so that its front face is vertical and 2 in. behind the edge of the tray (c). The petrol fire is obtained by burning about 150 c.c. of petrol floated on water in the metal tray (c). Horsemeat* simulating human tissue is placed in contact with the inner face of the clothing assembly and its surface temperature recorded automatically by a copper disk 1.25 cm in diameter with a 38-S.W.G. copper-constantan thermocouple soldered to the centre of one face. The disk tends to adhere to the surface of the horsemeat ensuring good thermal contact. The time taken for the surface temperature of the horsemeat to rise by 25°C is noted; the petrol flames are then extinguished and any further rise in temperature measured.

Four samples of each assembly are tested.

Radiation test

This is similar to the flame test except that the 6.5 cm x 6.5 cm area of the face of the assembly is exposed to an intensity of radiation of 0.5 cal. cm^{-2} s^{-1} (2 W/cm^2). The specimen is exposed to the radiation until a temperature rise of 25°C is recorded. The radiation is then cut off and any further rise in temperature noted.

TEST CRITERIA

Temperature rise

In the test the time taken for the temperature to rise 25°C is measured; this is an arbitrary figure which is probably greater than that needed to cause severe pain after about 10 seconds (p. 9). The time so measured should not be regarded as the time for which protection may be given, but as the basis for a relative assessment of the protection afforded by different assemblies. In applying the results it must be remembered that the tests were designed for a particular application[(1)-(10)]. In circumstances where there is a long exposure time at a lower rate of heating the relative merits of assemblies may be different, since the protective effect of thermal capacity is reduced, and the ability to transmit perspiration becomes important.

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*In place of the horsemeat any incombustible solid having approximately similar thermal characteristics may be used. An asbestos insulating material has been substituted in later experiments. The protection times can be related by a simple factor determined by comparative tests.

Further temperature rise

With most materials, the temperature rise after the source of heat has been removed is small. However, with those materials that ignite or glow liberating considerable quantities of heat, the further temperature rise may be large (>25°C). These materials may be dangerous in practice and should be rejected.

Time of further temperature rise.

For those materials which neither ignite nor glow, the time during which the temperature continues to rise is principally a measure of the radiative cooling constant of the surface and to a lesser extent of the heat capacity of the assembly. Assemblies fall into two classes: those with aluminized surfaces where the times for continued rise of temperature tend to be very long (p. 16), and the non-aluminized surfaces where the times are short. Within this second class, those assemblies with an inner lining of low thermal capacity tend to cool more quickly. These differences should influence the choice of assembly for different applications.

COMMENTS

Relation between tests

The protection times against flames are compared with the protection times against radiation in Fig.17. The points are distributed with a large scatter about a straight line of slope 0.8. The mean heat transfer in the radiation test is about 0.5 cal cm^{-2} s^{-1} (2 W/cm^2). It follows, therefore that the mean heat transfer from the flames is about 0.6 cal cm^{-2} s^{-1} (2.5 W/cm^2), so that except for materials having a high reflectivity the two tests are of approximately the same severity.

Effect of combustibility of garments

The tests may not show whether the materials have ignited as the extra heat produced by combustion may be quite small; for this reason, fire-retardant treatments may make little difference to the protection time[2].

APPENDIX III

TESTS TO DETERMINE PROTECTIVE VALUE OF VIZORS

DESCRIPTION OF TESTS

Thermal transmission test

The apparatus used and the method of test is similar to the radiation test described in Appendix II. except that the entire vizor is subjected to radiation and the heat it transmits is measured.

A total radiation radiometer is placed 2.54 cm behind a point where the intensity of radiation is 0.5 cal cm^{-2} s^{-1} (2 W/cm^2) and the intensity of radiation recorded. The vizor is then placed 2.54 cm in front of the radiometer and left in position for 2 min. The reduction in thermal transmission caused by the vizor is then measured.

Thermal shock test

At the end of 2 min a jet of water at a rate of flow 2.80 c.c./min (0.5 pints/min) is directed against the front surface of the vizor for 10 seconds.

TEST CRITERIA

The vizor should not crack, seriously deform, or cease to be transparent during the test, nor should it shatter or crack when the jet of water is directed upon it.

The heat that is transmitted should not exceed 0.025 cal cm^{-2} s^{-1} (0.15 W/cm^2).

TABLE I
LIKELY AMBIENT TEMPERATURES

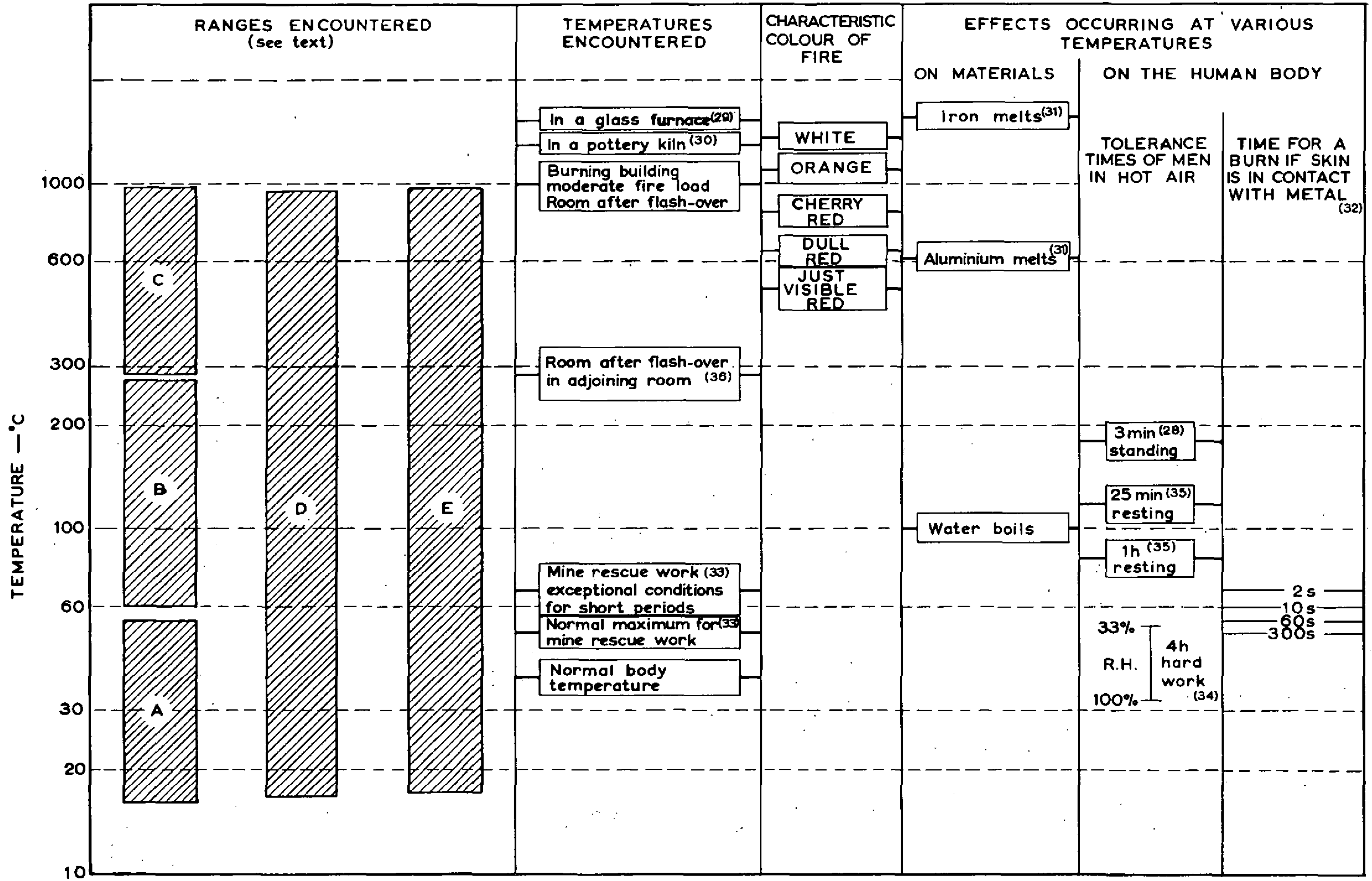


TABLE 2
LIKELY RADIATION EXPOSURES

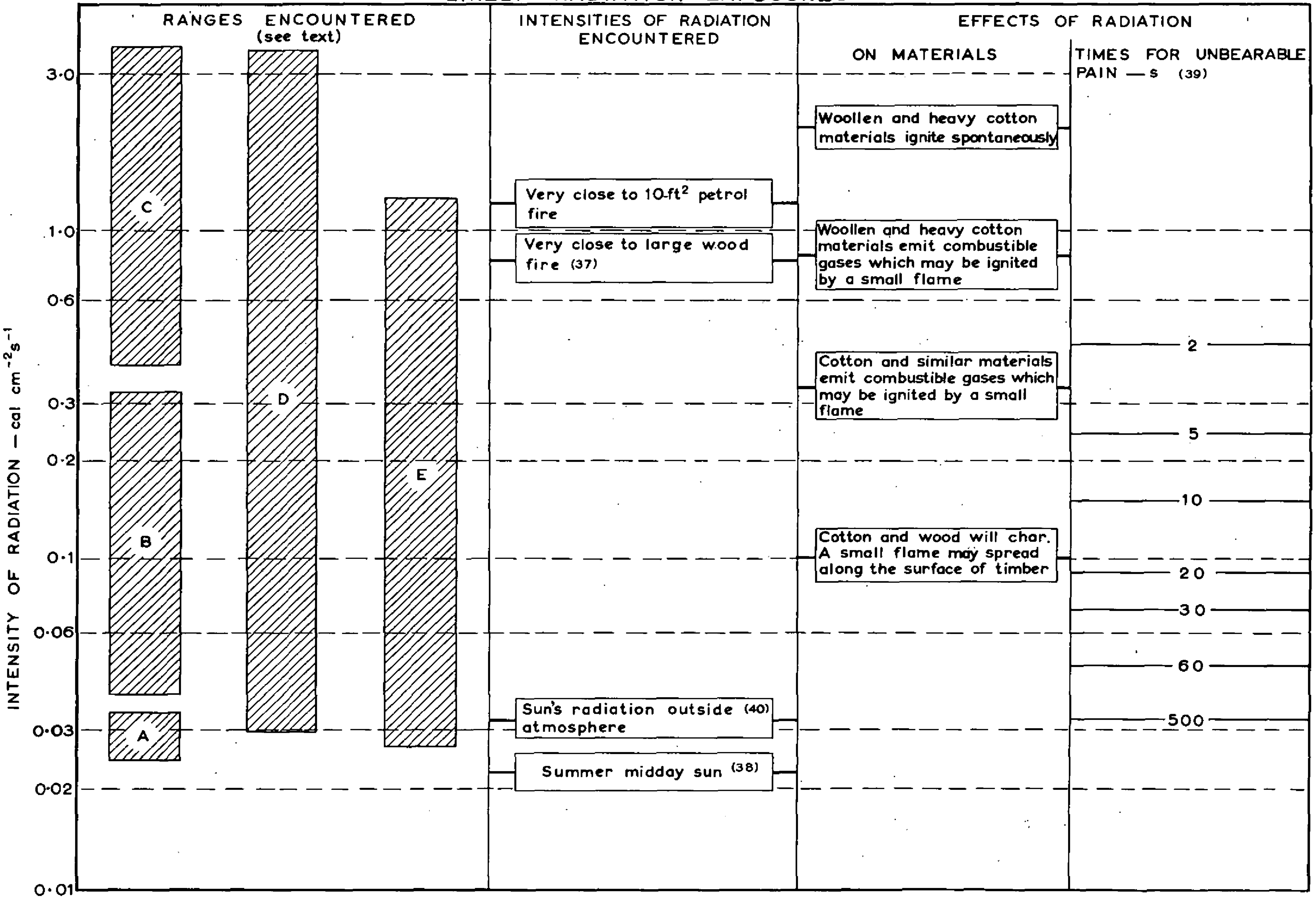


TABLE 6

RESULTS OF TESTS ON SOME SUITINGS, FOOTWEAR AND GAUNTLETS

Materials				Flame tests			Radiation tests			
Outer	Interlining	Lining	Underwear	Time for 25°C temperature rise s	Further temperature rise °C	Additional time for further temperature rise - s	Time for 25°C temperature rise s	Further temperature rise °C	Additional time for further temperature rise - s	Remarks
SUITS										
White lasting cloth	Wool pile	Cotton poplin	None	49	2	8	76	5	15	Lasting cloth tends to char away exposing interlining
	"	"	String vest	78	2	11	not tested			
	Open mesh fabric (two layers)	"	None	64	4	21	83	3	24	
Blue lasting cloth (flameproofed)	Wool pile	Cotton poplin	None	58	2	9	53	3	7	ditto
Fearnought	None	Cotton poplin	None	34	2	8	53	2	9	When heated Fearnought swells to form brittle mass of frothy carbonaceous material
	Wool pile	"	"	82	1	26	110	3	25	
	"	"	String vest	142	1	22	not tested			
Asbestos cloth	Wool pile	Cotton poplin	None	37	5	11	62	3	17	
Aluminized asbestos	Open mesh fabric	Cotton poplin	"	27	7	44	460	5	550	
Khaki serge	None	None	None	15.5	2.5	2	not tested			
			Woollen knitted	13	5	6.5				
FOOTWEAR										
White chrome leather	Open weave asbestos cloth + aluminium vynide laminate	White goatskin	None	155	20	165	"	"	"	
			Two layers of sock	180	12	60	"	"	"	
	Open weave asbestos cloth	White goatskin	Two layers of sock	185	12	150	"	"	"	
	Expanded rubber	Natural kip	None	No results obtained			"	"	"	Rubber ignited and burnt persistently
	Expanded neoprene	"	"	167	16	150	"	"	"	
	Chrome split	"	"	64	18	170	"	"	"	
Service boot leather	Expanded neoprene	"	"	185	12	36	"	"	"	
GAUNTLETS										
Asbestos cloth	Jute canvas	Cotton material	"	23	6	8	65	2.5	15	
Aluminium-faced asbestos cloth	None	Brushed knitted cotton	"	28	4	19	645	0	None	
	"	Linen canvas	"	19	10	16	270	0	None	

TABLE 7

RESULTS OF TESTS ON VIZORS

Vizor	Transmission of radiation by vizors: Infra-red heat radiation from a fire: Transmittance Initial value - per cent	Effective transmittance (including re-radiation) after 1 min - per cent	Visible radiation transmittance - per cent	Ratio of visible transmittance to infra-red transmittance	Time for serious distortion at 0.5cal $cm^{-2}s^{-1}$ ($2W/cm^2$) - s	Notes
Perspex	10	10.5	95	9.5	90	After 120 s bubbles formed in perspex. Vizor sagged inwards
Wire gauze backed perspex	7	8	45	6.5	70	Perspex badly distorted but not wire gauze
Tinted perspex	12.5	16.5	20	1.5	75	
Perspex with semi-reflecting aluminium coating	3	4	45	15	90	Unlacquered coating darkened, lacquered coating became translucent
Laminated glass	22	-	95	4.5	-	After 105 s bubbles appeared between laminations. Application of jet of water after 120 s resulted in front lamination being badly cracked but rear lamination remained intact
Composite vizor (Two sheets of glass with a semi-reflecting layer of copper between them and separated by an air gap from a plastic sheet)	1.7	1.7	30	17.5		Application of jet of water after 120 s had no effect. Vizor was irradiated at 3 W/cm^2 for a further 60 s. Plastic sheet became deformed and touched glass and opaque blister formed. Jet of water was again directed at front face. Front lamination cracked but rear glass lamination remained intact
Thermosetting plastic	10.2	15.2	91	8.9		After 90 s vizor surface became "crazed" and by 120 s was opaque and breaking up

TABLE 8

OUTLINE OF PROTECTIVE CLOTHING AGAINST FLAMES AND HEAT

Exposure	Protection required against: Heat	Ambient temperature °C	Effect of relative humidity of atmosphere	Examples	Flame-resistance rating	Type of protection required	Fitting of suit	Suitable type of material	Head protection
Short term exposure (s - m)	1 Radiant heat	50	Negligible (except that moisture content of garment may be changed) unless garments are to be worn at "the ready" for long periods in which case may lead to discomfort	Close approach to fires and furnaces	All garments and especially the outer garment must have a high flame-resistance rating	Highly reflecting surfaces, high thermal resistance, for high rates of heating, thermal capacity may be necessary	Free ventilation desirable to allow evaporation and prevent local heating - complete cover may be unnecessary	Reflecting outer garment with open mesh underwear or interlining of wool pile	Face shield wire gauze or clear window
	2 Radiant heat	50		Inside kilns - close approach to fires in mines inside burning compartments		As 1 - care necessary to ensure that perspiration is absorbed, the sole means of losing heat. Heat transfer by conduction dangerous	As little entry of air as possible - but as much flow inside as possible - breathing apparatus may be necessary	As 1 - but wool pile useful to absorb perspiration - open mesh type underwear	Helmet - as 1
	3 Radiant heat and pockets of flame	50		Aircraft crash rescue work - oil fires - fireman rescue work		Reflecting surfaces useful against radiant heat - thermal resistance as high as possible in order to rely on thermal capacity as little as possible	As 1	Heavy woollen blanket weave cloth effective - top garment may be aluminized if flames unlikely to reach it	Helmet as 1 <u>but</u> impenetrable material necessary to prevent foam and water from reaching vizor
	4 Immersion in flames	1000		<u>Emergencies</u>	As above but outer garment should be incombustible	Reflecting surfaces of great value outside if not soot covered, also useful inside suit, continuous wetting down may be necessary - breathing apparatus essential	Total exclusion of air essential	Heavyweight asbestos fabrics - aluminised garments probably useful	Helmet as 3 but airtight
Long term exposure (m - h)	5 Radiant heat	50 (dry air)	Reduces maximum tolerable air temperature to less than 33°C at saturation	General fire-fighting operations - furnaces - kilns	As 1	As 1 - limit set by thermal resistance	As 1 - free ventilation essential	As 1	Helmet as 1
	6 Radiant heat	50	Difficulty of protection increased at high humidities	As 2 - aircraft at high speeds	As 4	As 5 - all parts protected - forced ventilation or wetting down essential	As 2 - breathing apparatus almost certainly essential	As 2	Helmet as 1

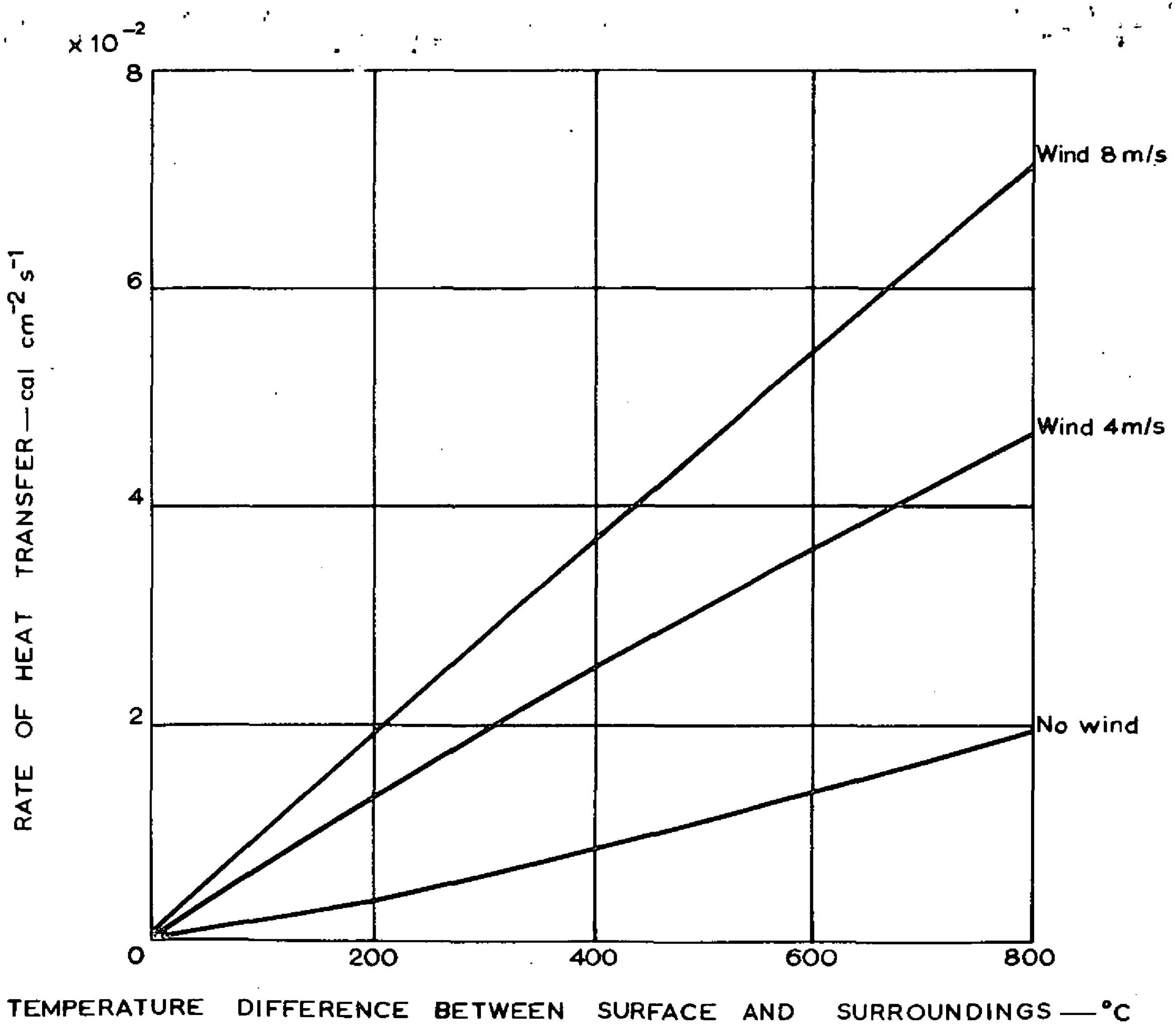


FIG. 1. HEAT TRANSFER BY CONVECTION FROM DIFFERENT AMBIENT TEMPERATURES

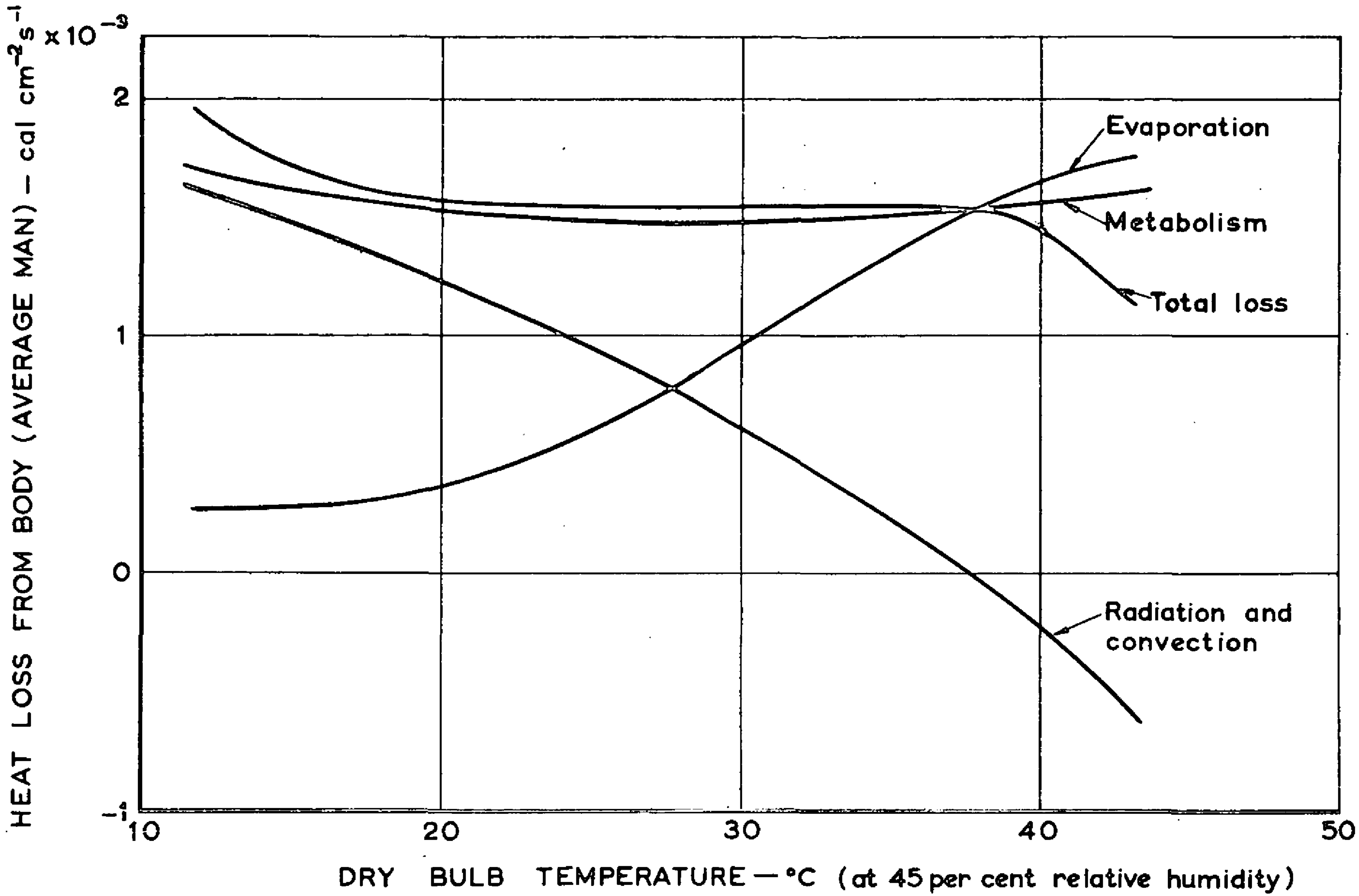
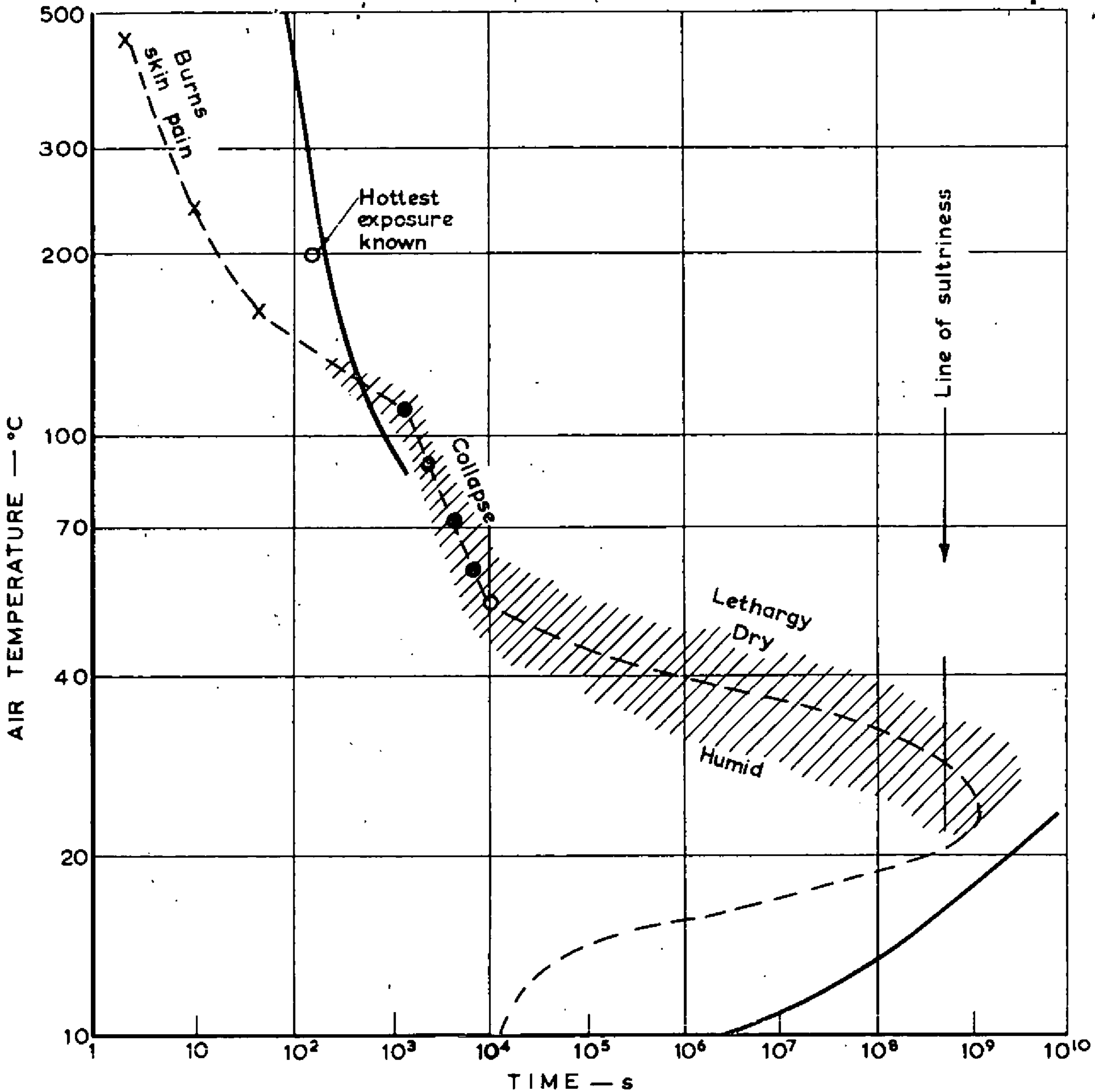


FIG. 2. HEAT BALANCE FOR A CLOTHED SUBJECT



— — — Body nude or parts exposed

——— Clothed 1 cm thick

Experimental points

X Body or parts exposed

⊛ Lightly clothed

O Clothed, face bare

FIG.3. TOLERANCE TIMES OF RESTING MEN

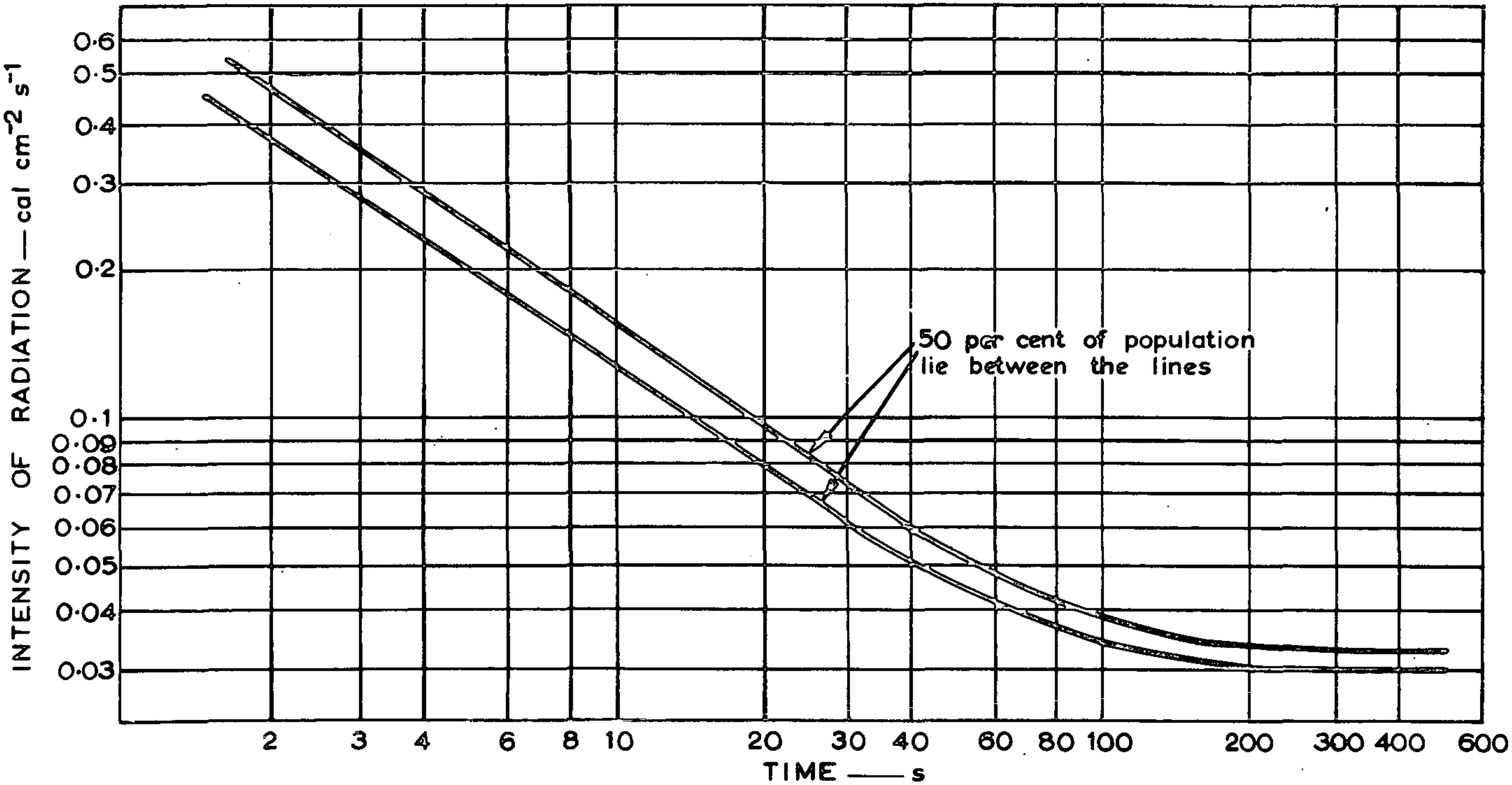


FIG. 4. TIME FOR UNBEARABLE PAIN

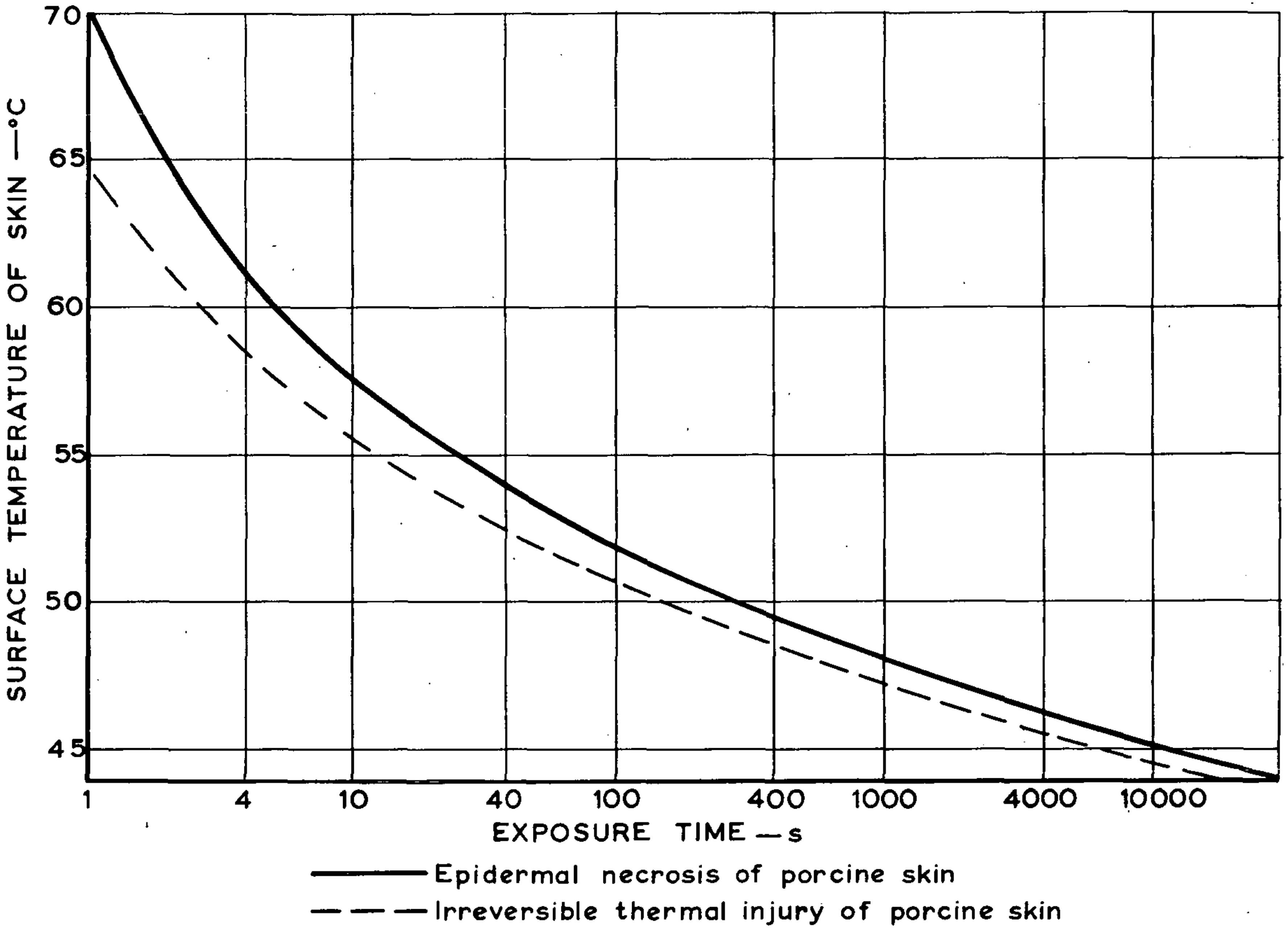


FIG. 5. TIME AT WHICH CUTANEOUS BURNING OCCURS

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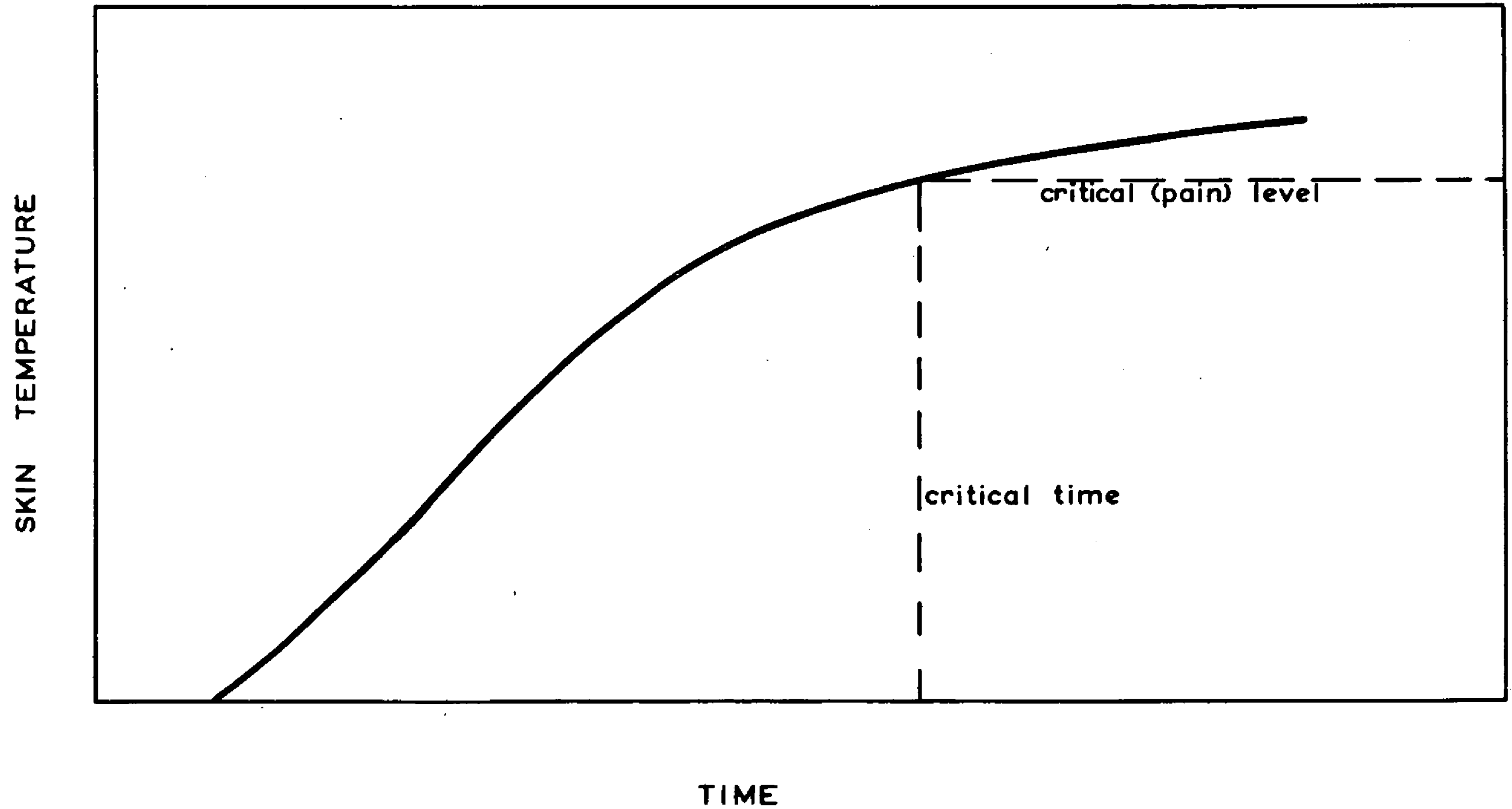

FIG. 6. TEMPERATURE OF SKIN BEHIND CLOTHING

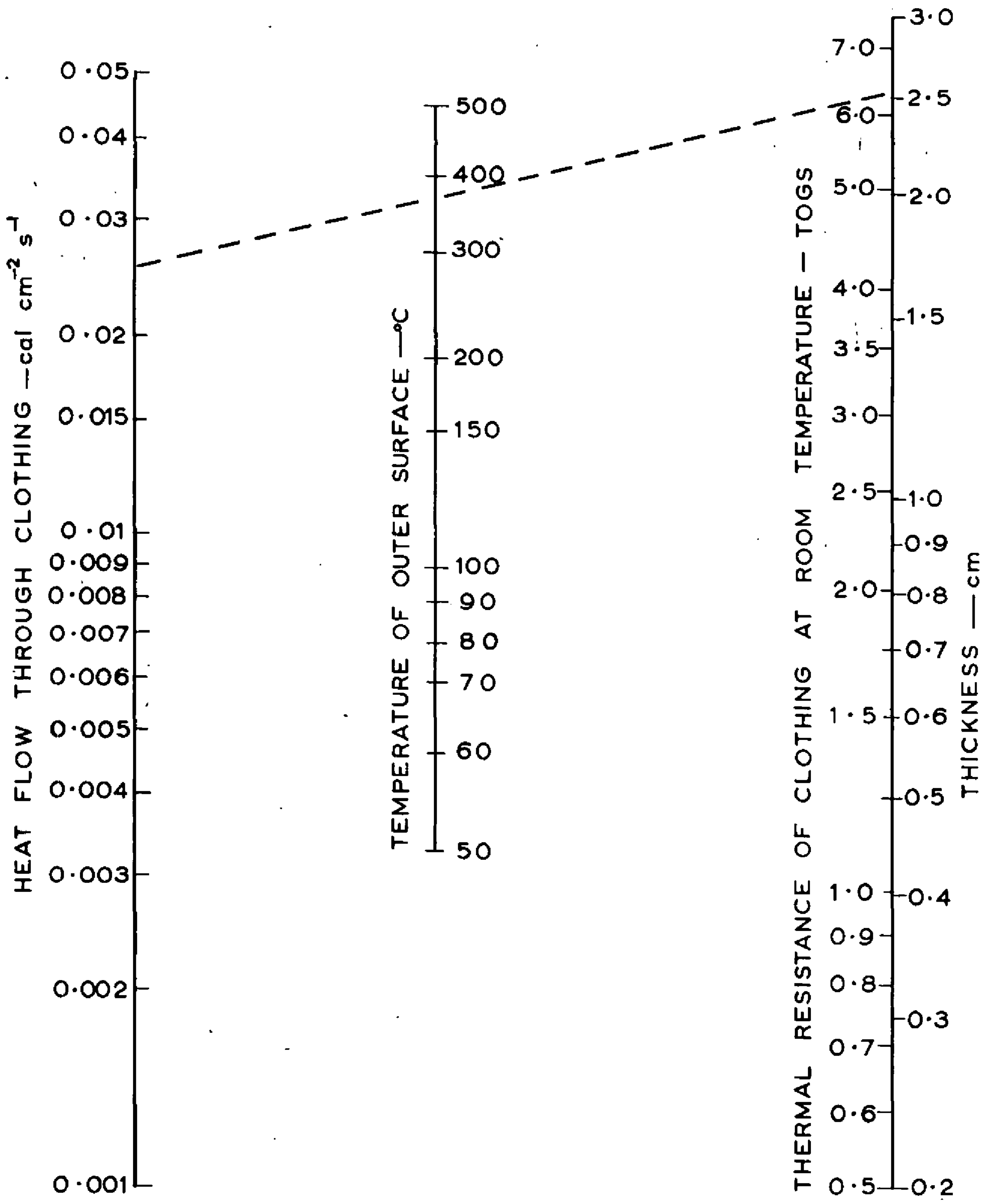

FIG.7. NOMOGRAM FOR HEAT FLOW THROUGH CLOTHING (STEADY STATE)

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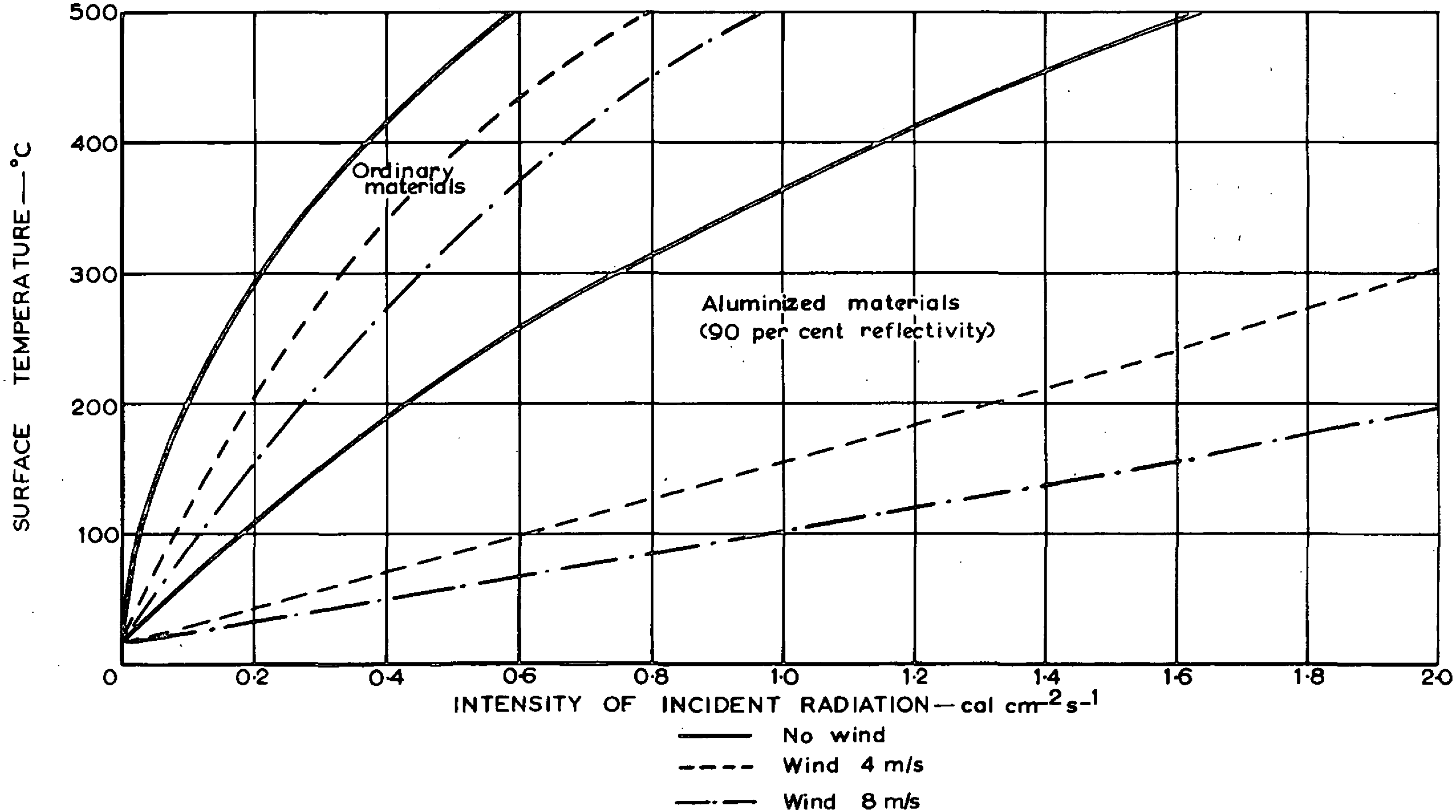
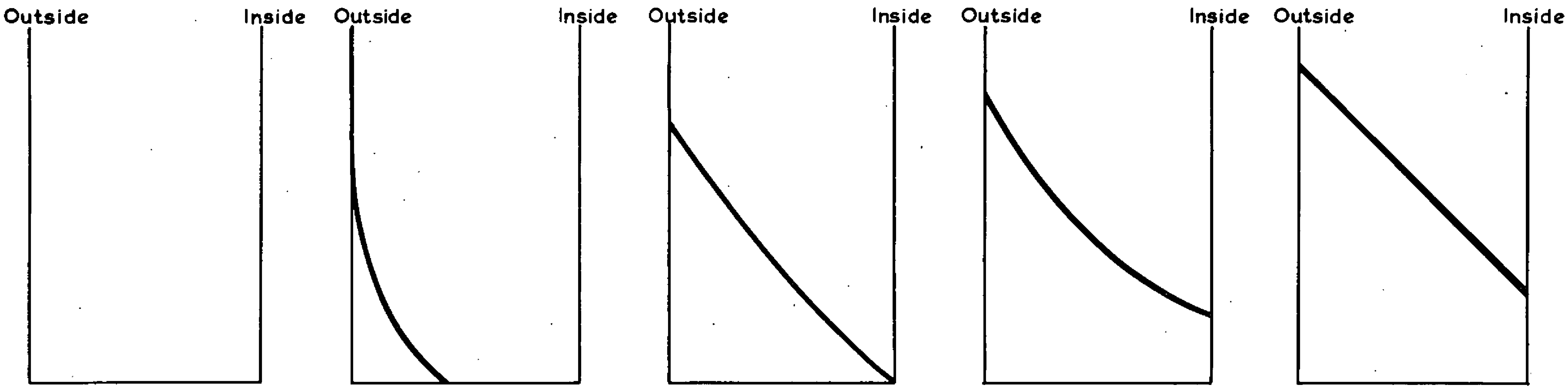


FIG. 8. SURFACE TEMPERATURE OF CLOTHING EXPOSED TO RADIATION (AIR TEMPERATURE = 15°C)



(a) No heat applied

(b) No temperature rise on inner surface

(c) Inner surface temperature rises

(d) Pain threshold exceeded on inner surface

(e) Steady state

(a)–(e) Show the temperature distribution through the material at different times after application of heat

FIG.9. TEMPERATURE DISTRIBUTION THROUGH MATERIAL DURING HEATING

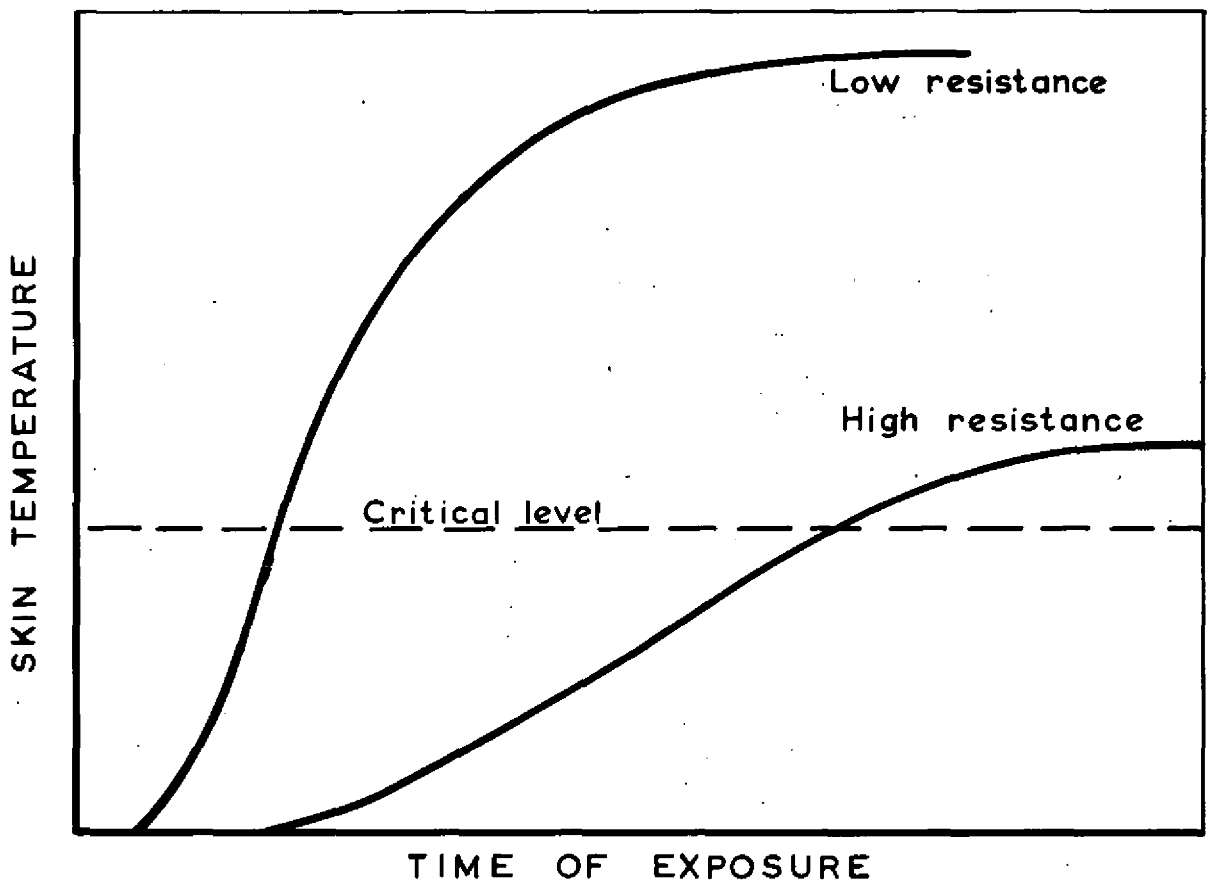
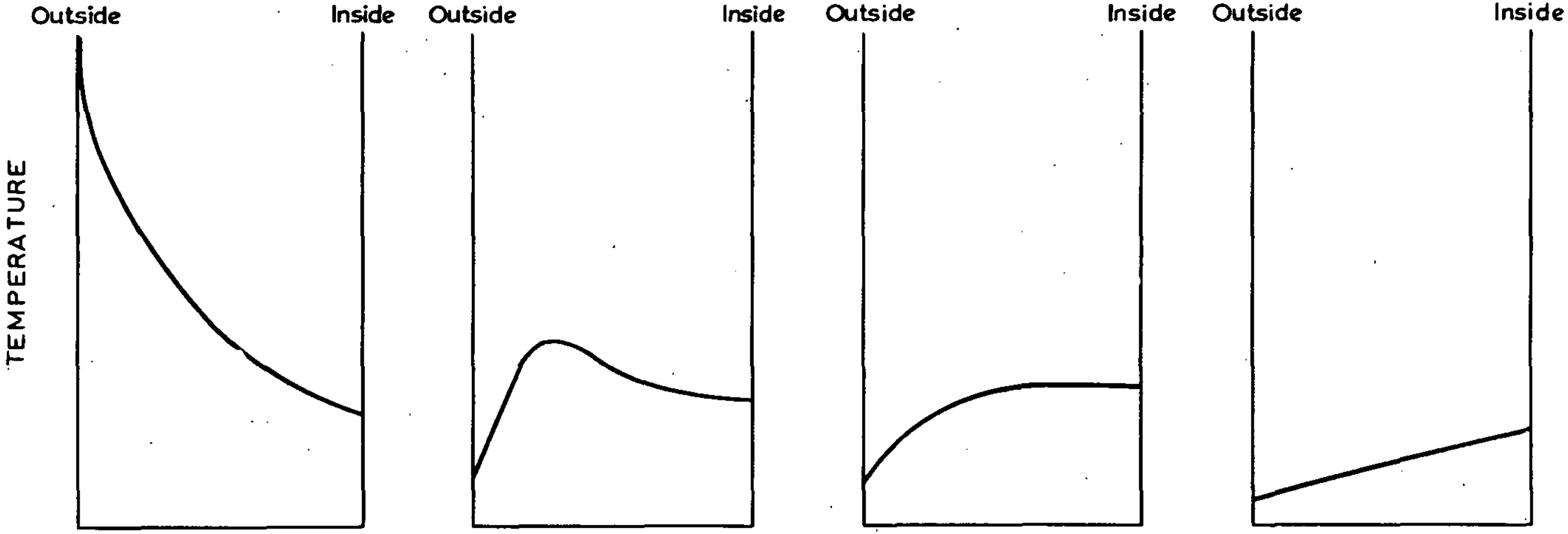


FIG. 10. EFFECT OF THERMAL RESISTANCE ON PROTECTION TIME FOR A GIVEN THERMAL CAPACITY



a. Immediately before removal of heat source

b. Inner surface temperature continues to rise

c. Inner surface temperature steady

d. Inner surface temperature falling

a—d show the temperature distribution through the material at different times after removal of heat source

FIG. 11. DELAYED COOLING DUE TO THERMAL CAPACITY

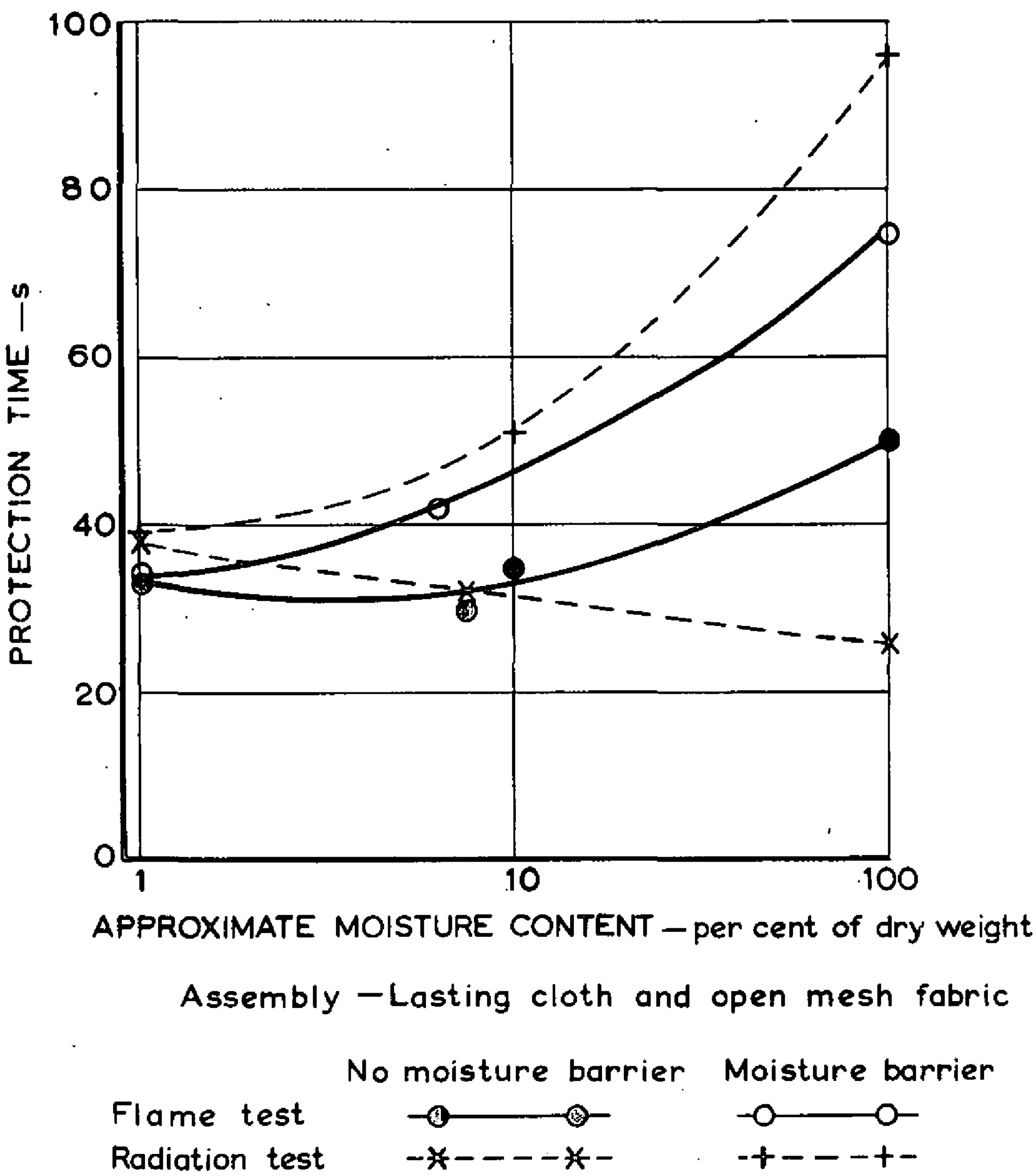


FIG.12. VARIATION IN PROTECTION TIME WITH MOISTURE CONTENT

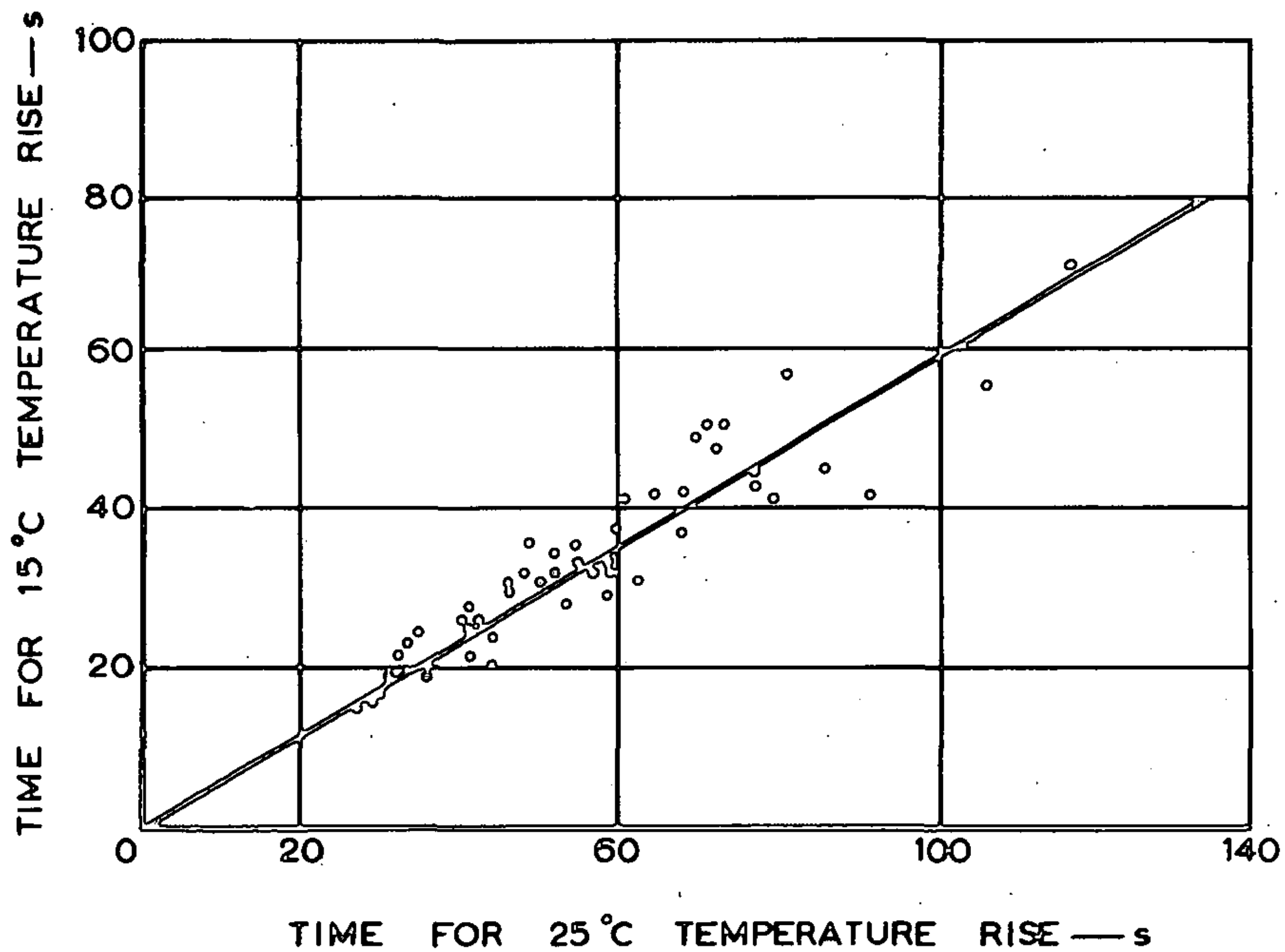


FIG. 13. COMPARISON OF PROTECTION TIMES FOR TWO DIFFERENT TEMPERATURE RISES

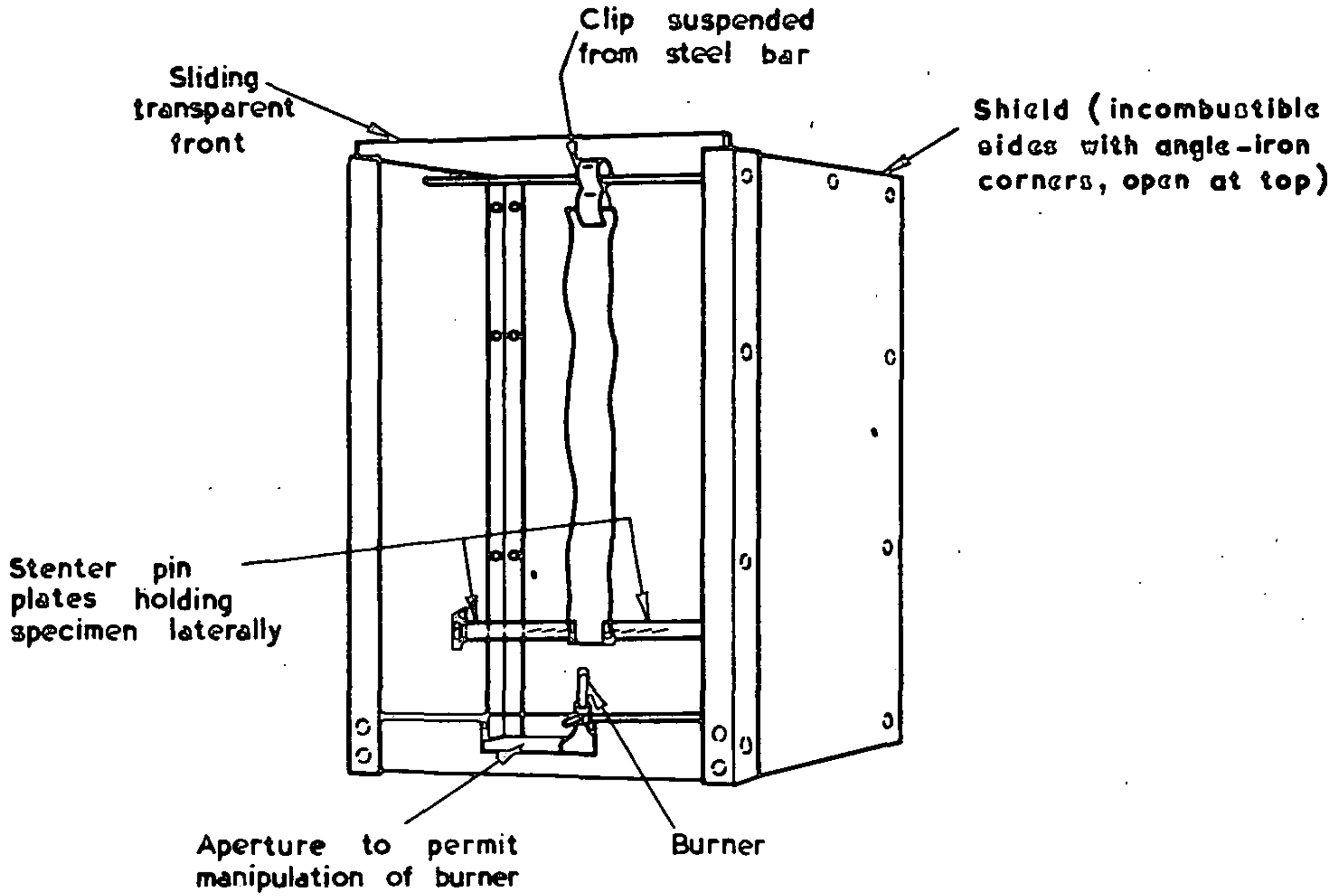


FIG. 14. APPARATUS FOR TESTING FLAMEPROOF MATERIAL

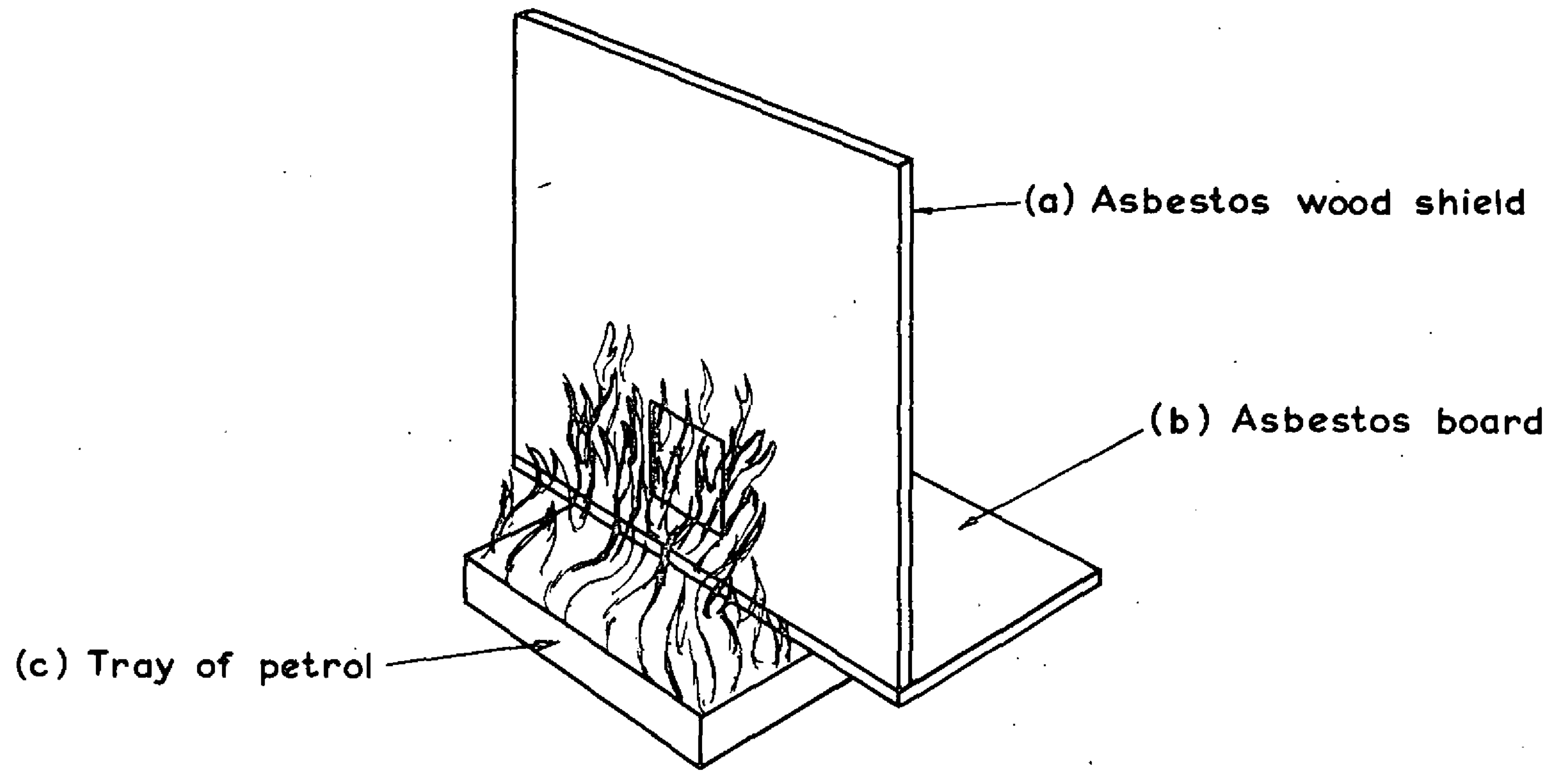


FIG. 15. FLAME TEST APPARATUS

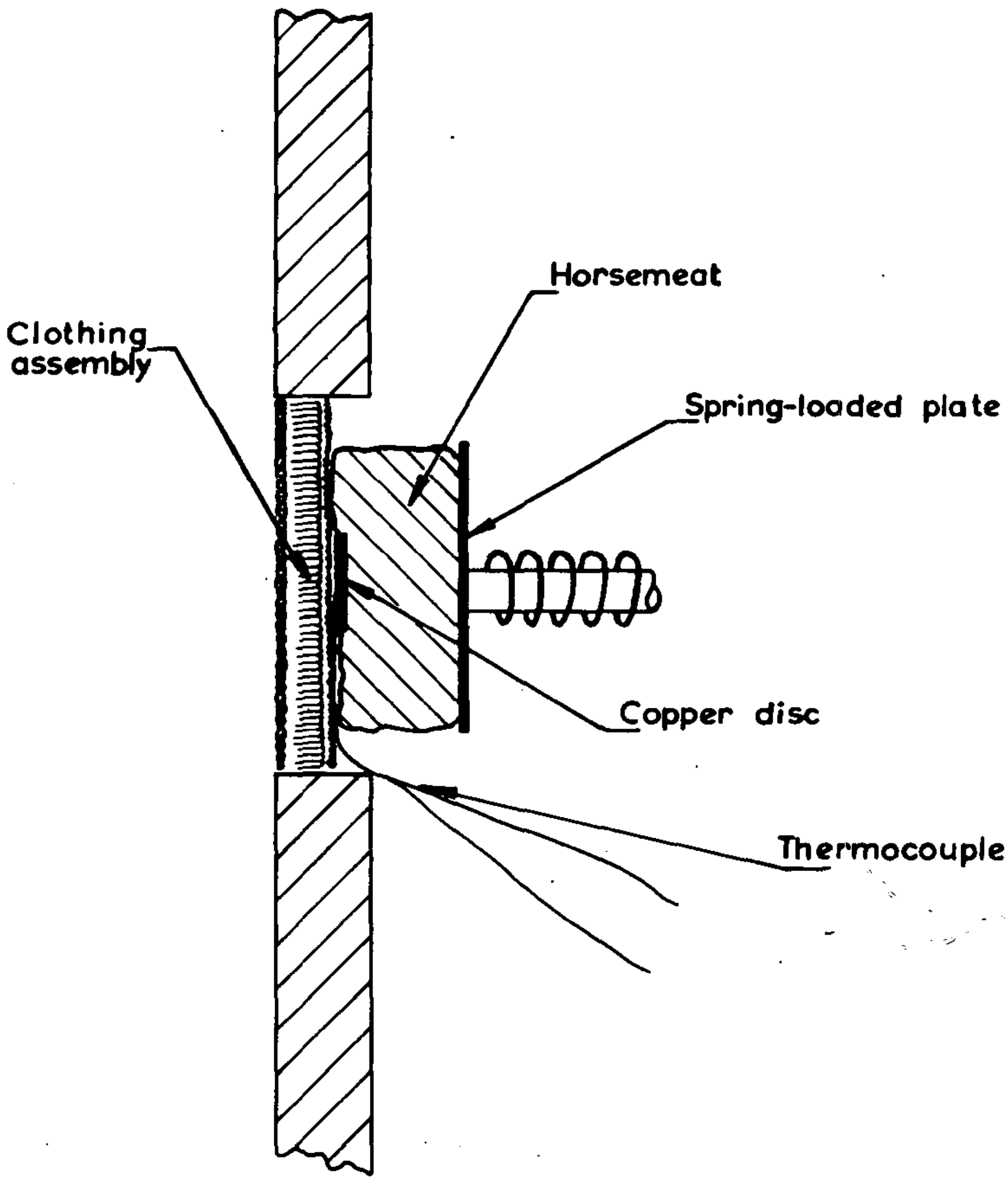


FIG. 16. CLOTHING ASSEMBLY MOUNTED

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