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# The Thermal Assessment of Personal Conditioning Garments

*by*

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# THE THERMAL ASSESSMENT OF PERSONAL CONDITIOMNG GARMENTS

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## SUMMARY

This paper presents a discussion of the thermal behaviour of personal conditioning garments both in theory and practice, A general equation, which is developed for the case of the convective air ventilated suit supplied with cccl sir, is modified for the cases of the water conditioned suit, and the air ventilated suit with warm dry air supplies. Results of past experiments at the Institute of Aviation Medicine and the Royal Aircraft Establishment are reviewed with the aid of this theoretical approach. It is concluded that there is a need for more systematic experimental data on personal conditioning, especially on convective air cooling. The broad outline of a possible experimental. programme is discussed, including certain aspects which requirs new techniques to be developed. The potential performance of convective, evaporative, and liquid conditioning is predicted; but in view of the scarcity of useful data the results, which are presented in graphical form, are considered to be very tentative.

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## CONTENTS

## 1 INTRODUCTION

The purpose of this paper is to contribute to the understanding of the mode of operation of personal cooling systems. There are many situations in industry and in the armed forces where human operators are expected to perform exacting tasks either in hot environments, or when essential protective clothing contributes to a thermal stress on the man. Sometimes this thermal stress is so severe that man's performance is likely to suffer after a relatively short time. In spite of the overriding importance of thermal stress, it appears that in general very little is known about methods of reducing it.

Limited experimental results with some theoretical treatment have been given for air conditioned garments[3,4,5] and water conditioned garments[2] as separate subjects. An attempt is made here to examine the whole field as one and to indicate a method of making valid comparisons between the performances of conditioning garments of different kinds.

The paper begins with a discussion of the physical factors that influence the rate at which heat must be extracted from the vicinity of the skin to produce a state compatible with thermal comfort. A theoretical argument is developed, in support of this discussion, and concludes with equations which describe the behaviour of idealised personal heat exchangers. The inadequacies of this mathematical model are discussed. Although it is to be expected that the mathematical model may lead to inaccuracies due to over simplification, it does indicate the broad outline of a possible experimental method of comparing the thermal performance of existing suits. In addition the theoretical argument is used to analyse existing experimental results for the purpose of predicting the performance limits of an air ventilated suit supplied with cool air, and a liquid conditioned suit supplied with cool water. In spite of the uncertainties of this prediction, it is considered to be a worthwhile exercise, even if its only purpose is to encourage a more determined experimental assault on the problem. The scope of the paper is extended to include, in more detail, the possible form of such an experimental programme. The goal of this programme is firstly to enable designers to choose the most appropriate type of cooling for a particular application, and secondly to aid in the development of particular garments by offering a method of comparing them with other garments.

## 2 DISCUSSION ON IDEALISED PERSONAL COOLING REQUIREMENTS

To cope with the complexities of considering the great number of variables that affect the thermal comfort of a man, interactions between his skin and the environment will be considered in stages.

Discussion begins with a statement of the conservation of energy at the surface of the skin. The fundamental requirement for thermal balance is that, on the average, and in spite of variation of external factors such as clothing, windspeed, air temperature, or radiation, provision should be made for removing heat from the skin at the same rate as it is being generated by metabolic processes. In normal life this thermal balance is not static and there are continuous changes in stored heat within the body. However it is stated that if the time interval, T, as measured from an arbitrary zero, is sufficiently long, then neglecting the production of external mechanical work by the man,

$$\int_0^T (m)\,dt \simeq \int_0^T (h)\,dt \qquad (1)$$

where m is the metabolic heat arriving at the skin at time t
and h is the sum of all heat loses from the skin at time t.
Under ideal steady conditions the average value of the total metabolic rate can be estimated fairly accurately. If there is any external mechanical work done by the man, its value must be subtracted from the total metabolic rate to obtain the heat arriving at the skin. In general, the various components of heat loss from the skin can be split into evaporative and non evaporative portions. The evaporative portion, E, of the heat loss includes a respiratory component whereby the expired air carries water vapour from the lungs. The rest of the evaporative heat loss comes from the skin itself, and varies considerably in magnitude according to whether or not the man is sweating.
The non evaporative heat loss from the skin is more complex, for in general it is composed of conduction, convection, and radiation terms which may vary greatly in magnitude and direction according to conditions outside the skin.
Having considered heat exchange at the skin, let us now include an imaginary uniform clothing layer entirely enclosing the man and an unspecified personal conditioning garment. In order to satisfy equation (1) the amount of heat, Q, to be removed by the personal conditioning garment, must be the sum of the non evaporative component, M-E, of the metabolic rate plus the net heat flow, $H_o$, inwards through the clothing layer from the environment

$$Q = M - E + H_c \,. \qquad (2)$$

Note that if evaporation is not possible, or is chargeable to the conditioning system, E will be zero. Equation (2) can be solved if assumptions are made about the magnitude of the evaporative heat loss, E, from the skin, and provided that the heat flow $H_c$ through the clothing can be estimated. In a particular example of this assumption process the state of comfort, for an average resting subject, can be approximately defined by saying that the mean temperature of the skin is 33°C and the evaporative heat loss, E, totals about 24% of the metabolic rate'. If the clothing layer has a mean thermal insulation of $I_c$, an outer surface temperature of $T_c$, and an inner surface temperature of 33°C, equation (2) becomes

$$Q = (1 - 0{\cdot}24)\, M + \frac{T_c - 33}{I_c} . \qquad (3)$$

It will be shown later that equation (3) can be misleading, as it is in fact a special case because when a personal conditioning garment is being used, the inner surface of the clothing may not be at the temperature of the skin. The third stage in the discussion deals with the conditions outside the clothing layer. These environmental conditions include the ambient temperature of the air which affects convective heat transfer to or from the clothing surface. There is a boundary layer of air associated with the outer surface of the clothing, the effective insulation of which varies with the velocity distribution of the air round the clothing and the geometry of its surface. Hence the prediction of convective heat transfer between the clothing and the ambient air can become very involved mathematically, on account of the inconvenient and variable shape of the clothing, and the consequent velocity distribution around it, The transfer of radiant heat takes place between the clothing surface and other surfaces in the environment. In general, radiant heat transfer can occur directly or by reflection from other surfaces. The prediction of this effect is therefore a geometrical and optical problem which may be of the same order of complexity as the problem of predicting convective heat transfer. If the humidity of the ambient air is low, and the clothing layer is permeable to water vapour, the evaporative loss, E, from the skin is controlled internally by the man's thermoregulatory mechanisms. If the ambient humidity is high or the clothing layer has a low vapour permeability, it may not be possible for the environment to evaporate the amount of water appearing at the skin's surface. The evaporative heat loss may therefore be reduced in magnitude or even reversed in direction, for it is possible that water could condense on the skin from the environment. Humidity is therefore a parameter that affects thermal comfort. The effect becomes more important as humidity rises.

In addition to the inherent difficulties of the theoretical approach when dealing with convection and radiation, it must be borne in mind that in practical situations, distribution of the effects of these environmental factors over the body should be taken into account. For instance, certain areas of the body, namely hands and face, may not be insulated by clothing, and may not be directly cooled or ventilated by a suit. Some areas of the clothing surface may not be exposed directly to the environment, for example because of the seat into which the subject may be strapped.

The discussion, so far, has introduced several physical factors that influence the amount of cooling a man may require for the maintenance of thermal comfort. It has been implied that a theoretical investigation may lack accuracy through over simplification, especially if an attempt is made to determine the heat flow through the clothing layer. The expansion of equation (3) by substituting, for the outer surface temperature of the clothing, a single environmental parameter which allows for the combined effects of air temperature, air velocity distribution, and radiation from external sources, is evidently too involved for a purely theoretical approach.

For the experimental evaluation of various personal conditioning garments, the mean temperature, To, of the outer surface of the clothing can be used as an environmental parameter provided that it can be easily measured. If this parameter is not convenient to measure, then a less general environmental parameter must be used in its place. Under certain conditions, for instance in a climatic chamber, it should be possible to standardise some environmental conditions and use air temperature as the environmental parameter when it is desired to change clothing heat flow.

## 3 PERFORMANCE OF IDEALISED CONDITIONING SYSTEMS

The first stage in an experimental study of personal conditioning is to determine the cooling rates required to keep the man in an acceptable state of thermal comfort over a range of environmental conditions. With any particular clothing insulation it is also necessary to determine the limit of the ability of a particular garment and conditioning system to provide cooling, and the general. relationship between cooling achieved and the quality of the suit input in terms, for instance, of temperature, flow and humidity. Until this is done it will not be possible to specify suit input requirements, and the relative penalties, in terms of system weight, of supporting different types of suit will not be known. Before detailed discussion of a possible experimental. method of evaluating conditioning systems it may be appropriate to classify existing suits into types, and to obtain a partial understanding of the mode of operation of each typo by a physical description and analysis.

## 3.1 Evaporative cooling

Most personal conditioning systems at present in use rely mainly on evaporative cooling. Essentially the suit portion of the system consists of a distribution network of pipes or ducts which release dry air near the skin to facilitate the evaporation of sweat. Such a suit is effective in maintaining thermal balance (equation (1)) both in moderately warm environments, and in situations where a high ambient humidity, or impermeable clothing, would normally prevent evaporation of sweat. If the air supply provides a sufficiently high capacity for evaporation of water, and if the man is sweating, the evaporation rate is controlled automatically by the man's normal thermoregulatory mechanism. Assuming that this control mechanism is such that the secretion of sweat occurs at a rate sufficient to provide thermal balance, an equation can be written down for the necessary continuous sweat rate. The total amount of water to be evaporated is derived from the sum of the metabolic rate and the heat flow inwards through the clothing. Heat removal is assumed to be by evaporation of sweat alone.

$$\eta LS = M + \frac{T_c - T_s}{I_c} \tag{4}$$

where S is the total sweat rate of the man

L is the enthalpy difference between sweat in liquid form at skin temperature and in vapour form at the temperature of the air stream

$\eta$ is the fraction of the sweat that evaporates from the skin surface

$T_c$ is the mean temperature of the clothing outer surface

$T_s$ is the mean temperature of the clothing inner surface

$I_c$ is the thermal insulation of the clothing layer.

Note that the sweating man does not attain true thermal comfort as defined earlier, and that the skin temperature may be higher than 33°C. The ratio, $\eta$, of useful sweating to total sweating could be quite high for a well designed suit when sufficient dry air is distributed evenly over the skin and is made to move at a fairly high velocity to ensure a high mass transfer coefficient (i.e. a high value of evaporation rate per unit vapour pressure difference).

## 3.2 Convective cooling

The fact that evaporative suits used in hot environments do not provide true thermal comfort has led to tha suggestion that air could be used for cooling the body directly, provided that it was supplied to the suit at a temperature lower than that of the skin. For the purposes of an elementary physical analysis, the air stream is considered to be flowing in a duct bounded by one surface representing the man's skin, and another surface representing the inner face of the clothing assembly. It is assumed that betwsen the skin and the gas stream there is a heat transfer coefficient, $U_s$, which includes the boundary layer of air associated with the skin. Between the gas stream and the outer surface of the clothing assembly there is assumed to be another heat transfer coefficient, Uc; which includes the static outer clothing insulation and the boundary layer of air on its inner surface. These heat transfer coefficients are based on a reference area, A, considered as the area ventilated by the gas stream. At this stage the radiation heat transfer, across the air gap between the skin and the inner surface of the clothing, is neglected so as to render the analysis more manageable. The analysis, which appears in Appendix A, derives a gas temperature distribution along the duct described above, and concludes with an expression for the suit inlet temperature required, at a given flow and environmental condition, to maintain the man's thermal balance by non-evaporative means. This expression for the performance of a hypothetical air cooled suit is of the form:

$$\dot{m}\, C_p\, \Delta T_{IN} = \left[\frac{1}{1 - \exp\left\{\dfrac{-A(U_s + U_c)}{\dot{m}\, C_p}\right\}}\right]\left\{Q_s\left(1 + \frac{U_c}{U_s}\right) + X A U_c\right\} - \frac{X \dot{m}\, C_p}{1 + \dfrac{U_s}{U_c}} \qquad (5)$$

where $\dot{m}$ is the suit mass flow

$C_p$ is the specific heat of air at constant pressure

$\Delta T_{IN}$ is the difference between air inlet temperature and mean skin temperature

$U_s, U_c$ are heat transfor coefficients as defined above and based on a reference area A

A is the area being ventilated by the air stream

$Q_s$ is the non-evaporative component of the metabolic rate

X is the mean difference between clothing outer surface temperature and skin temperature.

The quantity $\dot{m}\ Cp\ \Delta T_{IN}$ can be considered as the potential cooling capacity of the air stream supplied to the suit, neglecting evaporation Of sweat. This cooling capacity is required in order to maintain a non-evaporative heat loss of $Q_s$ from the skin to the gas stream. Note that if the outer clothing surface temperature is equal to skin temperature, i.e. $X = 0$, the ratio of potential cooling supplied to cooling achieved at the skin is:

$$\frac{\dot{m}\ C_p\ \Delta T_{IN}}{Q_s} = \left[\frac{1}{1 - \exp\left\{\frac{-A(U_s + U_c)}{\dot{m}\ C_p}\right\}}\right]\left\{1 + \frac{U_c}{U_s}\right\}. \qquad (6)$$

This ratio, which always exceeds unity, can be regarded as an inverse thermal efficiency for the suit/clothing system (see end of Appendix A).

The first term, i.e.

$$\left[\frac{1}{1 - \exp\left\{\frac{-A(U_s + U_c)}{\dot{m}\ C_p}\right\}}\right]$$

represents the temperature effectiveness of the suit, by allowing for the fact that the outlet air has not yet reached a stable temperature. If realistic values are substituted for heat transfer coefficients, and reference area, this effectiveness term is approximately unity at low flows. The second term, i.e. $(1 + U_c/U_s)$ represents the correction factor for heat flowing inwards through the clothing from ambient to the gas stream. This term is often a greater source of inefficiency than the first one and shows the shortcomings of assuming that the inner clothing surface is at skin temperature. Note that if the mass flow is very small equation (5) reduces to the form associated with normal unconditioned clothing the heat transfer coefficient of which is $\left(\frac{U_s + U_c}{U_s\ U_c}\right)$

$$- X = \frac{Q_s}{A\left(\frac{U_s\ U_c}{U_s + U_c}\right)} = \frac{Q_s}{A\ I_c}$$

where Ic represents the insulation between the skin and the outer surface of the clothing.

Also in equation (5) note that there will normally be some evaporative cooling, so that $Q_s = M - \eta LS$.

In the analysis presented in the Appendix it is shown that if the heat-exchange area is large enough the gas stream ultimately reaches a temperature which lies somewhere between skin temperature and clothing outer surface temperature. This stable or equilibrium temperature is given by

$$\Delta T = \frac{X}{1 + \frac{U_s}{U_c}} .$$

If this equilibrium temperature is substituted for $\Delta T_{IN}$ into equation (5) the gas temperature does not change through the suit, and the result is an equation mathematically similar to that for evaporative cooling (equation (4)).

### 3.3 Liquid cooling

The analysis for a liquid conditioned suit system is similar to that for an air ventilated suit with convective cooling. With present British designs of liquid conditioned suits, that are relatively close fitting, the fraction of the skin area covered by pipes is small. The conductance of the skin is much higher than that of the clothing. In this case it has been assumed as a crude first approximation that the inner surface of the clothing is effectively at the same temperature as the skin, and that the cooling rate required for comfort is therefore given by equation (3) provided that the clothing layer is vapour-permeable, and the ambient humidity is low.

$$Q = (1 - 0{\cdot}24)\, M + \frac{T_c - 33}{I_c} . \qquad (3)$$

The assumption that the inner surface of the clothing is at skin temperature will be examined in para 6.

It was suggested, as a result of the experiments reported in Ref.2, that the cooling rate of a liquid conditioned suit at a given mass flow was approximately proportional to the difference between inlet temperature and skin temperature.

$$Q = \dot{m}\, C_p\, \varepsilon(33 - T_{IN}) .$$

The constant of proportionality or effectiveness, $\varepsilon$, was found to be fairly consistent with a constant value of the heat transfer coefficient between the skin and the water stream. It was found that over the useful range of mass flow the effectiveness, $\varepsilon$, was given by

$$\varepsilon = 1 - \exp\left(-\frac{A\,U_s}{\dot{m}\,C_p}\right).$$

The complete performance equation for the liquid conditioned suit expressed in the same form as equation (5) is therefore

$$\dot{m}\,C_p\,\Delta T_{IN} = \left[\frac{1}{1 - \exp\left(-\frac{A\,U_s}{\dot{m}\,C_p}\right)}\right] \left\{M(1 - 0{\cdot}24) + \frac{X}{I_{c3}}\right. . \qquad (7)$$

## 4 LIKELY DIFFERENCES BETWEEN THEORY AND PRACTICE

The equations presented above and derived in Appendix A are, of course, only as accurate as the basic simplifying assumptions made in the first instance. In spite of the limitations imposed by those assumptions, it is felt that such a discussion is worthwhile, in that it serves to suggest appropriate experimental methods. The empirical approach demands that experiments are performed under conditions such that the basic unknown heat transfer coefficients could be evaluated if required. In view of the difficulty of applying these equations "in reverse" to the experimental data, and in view of the possibly important discrepancies between the simplified mathematical model and the real suit/man/clothing system, it is not recommended that suit performance be routinely described in terms of basic heat transfer coefficients. The discussion will now concentrate on the expected deficiencies of the mathematical model.

For the air conditioned suit the value of $U_s$, the heat transfer coefficient of the boundary layer between the skin and the air stream, is a function of the local Reynolds number, and would therefore be sensitive to flow and changes in geometry of the flow pattern such as would be caused by the varying fit of different clothing assemblies. The quantity $U_c$ which is the heat transfer coefficient between the air stream and the outer surface of the clothing includes a similar boundary layer at the clothing inner surface, and is subject to similar variations. In addition, it is to be expected that the value of $U_c$ would differ considerably according to whether or not the outer clothing is porous enough to allow gas to seep through it. When it is porous, the change of Uc due to air flow through the material is known as the Dynamic Insulation effect[3]. In addition, as has already been pointed out, the effects of radiation between the skin and the inner clothing surface have been neglected. The effective radiant heat transfer across this air gap may well be of the same order as other heat flows estimated in the analysis.

For the liquid conditioned suit the situation is, in many ways, simpler. The heat transfer coefficient between the liquid and the skin is flow dependent but the analysis presented in Ref.2 indicated that the most important component of the coefficient is the thermal resistance of the skin itself. For the range of flow normally used in liquid conditioned suits it was found experimentally that the variations of heat transfer coefficient with flow are small and to neglect them would not incur serious error. There is also no possibility of effects due to dynamic insulation.

The apparent shortcomings of the analysis may lead one to ask why the attempt was made at a theoretical approach, since the equations are unwieldy and their applicability is suspect.. The primary reason for the analysis is that it does indicate the type of effect expected when the most important parameters are varied, and hence it suggests the basis of a sound comparative experimental programme, end methods of presenting experimental results.

## 5 EXISTING EXPERIMENTAL RESULTS

### 5.1 System of *units*

One of the problems associated with work on thermal conditioning is the confusion often caused by the use of different systems of units in the disciplines of engineering and physiology. In general, physiological information tends to be presented in a metric system of units based on kilogram calories, metres, hours and centigrade degrees. Use of this information by 'engineers may involve conversion of these quantities into other systems of units. In the following analyses of experimental results the metric system is retained. Figs.1 and 2 make use of a flow parameter which is the product of mass flow $\Theta\ \frac{kg}{hr}$ and specific heat $\left(\frac{KAL}{kg\,^{\circ}C}\right)$ divided by a reference ventilated area of $1{\cdot}45$ metres$^2$. This flow parameter can be converted into more 'conventional engineering units.. For instance a flow of 1 lb/min of air is equivalent to approximately $4{\cdot}5\ \frac{KAL}{M^2\ hr\ ^{\circ}C}$ and a flow of 1 lb/min of water is equivalent to approximately $18{\cdot}8\ \frac{KAL}{M^2\ hr\ ^{\circ}C}$. Figs.2 and 3 show heat transfer coefficients based on the same reference area of 1-45 $M^2$. For conversion of heat transfer coefficients to British units note that $1\ \frac{KAL}{M^2\ hr\ ^{\circ}C}$ IO.205 $\frac{BTU}{ft^2\,hr\ ^{\circ}F}$.

The reciprocal of a heat transfer coefficient represents an absolute unit of insulation. Conversion is as follows for units of insulation.

$$1\ \frac{M^2\ hr\ ^\circ C}{KAL} = 4{\cdot}88\frac{ft^2\ hr\ ^\circ F}{BTU} = 5{\cdot}55\ \text{Clo units.}$$

## 5.2 Air ventilated suit

The most comprehensive results of experiments on convective air cooling that could be found were in Ref.4. Several types of Air Ventilated Suit (A.V.S.) were evaluated in the climatic laboratory at the R.A.F. Institute of Aviation Medicine, and it was decided to concentrate on results from the Mk.3 A.V.S. which "... is the only practical suit which provides a good (skin) temperature distribution with a cool air supply". Since the exercise was done for the purposes of comparing the performances of different suits, the experiments were performed on a thermal analogue rather than a living subject. In addition the experiments were restricted to one outer clothing assembly, which happened to be fairly thick and also permeable to air flow. Only one environmental air temperature, namely 33°C, was used for the tests. The experiments consisted essentially of a flow traverse, in which the suit mass flow was varied over a range, whilst inlet temperature was adjusted to a value such that the 'skin' temperature of the dummy was maintained at 33°C, and the heat loss from its skin was maintained at approximately 55 $\frac{KAL}{M^2\ hr}$. The experiments were therefore done under conditions compatible with a constant state of 'thermal comfort' throughout the traverse. Referring to the analysis in the Appendix of this paper, when the environmental air temperature is the same as mean skin temperature, equation (6) should apply, it being understood that if sir temperature is used instead of clothing surface temperature, the clothing thermal properties must include the insulation of an air boundary layer.

$$\frac{\dot{m}\ C\ \Delta T_{IN}}{Q_s} = \left[\frac{1}{1 - \exp\left\{-\frac{A(U_s + U_c)}{\dot{m}\ C_p}\right\}}\right]\left\{1 + \frac{U_c}{U_s}\right\} . \qquad (6)$$

Note that there is an analysis in Ref.4 of the same form, but by assuming an inner clothing surface temperature of 33°C, the clothing heat flow is neglected, and the second term $\left\{1 + \frac{U_c}{U_s}\right\}$ is missing, viz

$$\frac{\dot{m}\ C_p\ \theta_1}{H} = \left[\frac{1}{1 - \exp\left(\frac{-K}{\dot{m}\ C_p}\right)}\right] \qquad \text{(Ref.4)}$$

The experimental results from Ref.4 are reproduced in Table 1 below, and plotted in Fig.1 together with a possible representative curve for the Mk.3 A.V.S. under the test conditions.

Table 1

| Flow<br>$\frac{\dot{m}\,C_p}{A}$ $\frac{KAL}{M^2\ hr\ °C}$ | Potential. cooling rate of air supply<br>$Q_{IN} = \frac{\dot{m}\,C_p}{A}(\Delta T_{IN})$<br>$KAL/M^2\ hr$ | Heat loss from dummy<br>QS $\frac{KAL}{m^2 hr}$ | &IN<br>QS |
|---|---|---|---|
| 3·58 | 87·0 | 55·9 | 1·56 |
| | | | 1·64 |
| 4'21 | 93·0 | 58·4 | 1·60 |
| 4.36 | 82·8 | 52·3 | 1·59 |
| 5·14 | 83·3 | | 1·60 |
| 5·64 | | 52·0 | |
| 6·03. | 89·9 | 5653·8. | 1·67 |
| 6·44 | 90.8 | 53·1 | 1·71 |
| 7·26 | 101·6 | 53·3 | 1·91 |
| 7·26 | 95.5 | 54·7 | 1·75 |
| 7·68 | 111·4 | 52·3 | 2·14 |
| 8·40 | 107·5 | 53·6 | 1·01 |
| 9·08 | 105·3 | 52·1 | 2·02 |
| 10·67 | 127·0 | 52·0 | 2·45 |

The initial slope of equation (6) with respect to mass flow is zero (see representative curve in Fig.1).

Using equation (6) tho ratio of $U_c$ to $U_s$ at zero flow can be obtained from Fig.1, namely

$$\left(\frac{Q_{IN}}{Q_s}\right)_{m=0} = 1 + \frac{U_c}{U_s} = 1{\cdot}54 .$$

The insulation of the clothing of the dummy, as quoted by Kerslake, was 2·8 clo units or, in metric units of insulation, 0·504 $\frac{°C\ M^2\ hr}{KAL}$.

In order to make use of this quantity to find $U_s$ end $U_c$ in equation (6) clothing outer surface temperature must be replaced by ambient air temperature. The clothing insulation must therefore be increased by an amount representative of the boundary layer on the outer surface of the clothing. The ambient air velocity in the experiments was quoted as 350 ft/min, which gives an air boundary layer insulation of $0{\cdot}1 \dfrac{^\circ C\ M^2\ hr}{KAL}$ (Ref.5). The insulation of the clothing between skin and ambient at zero suit flow is therefore $0{\cdot}504 + 0{\cdot}1 \dfrac{^\circ C\ M^2\ hr}{KAL}$.

Now

$$0{\cdot}604 = \frac{1}{U_s} + \frac{1}{U_c}$$

$$0{\cdot}604 = \frac{1}{U_c}\ (1.54) \text{ from Fig.1}$$

then

$$U_c = 2{\cdot}55 \frac{KAL}{M^2\ hr\ ^\circ C}$$

and

$$U_s = 4{\cdot}72 \frac{KAL}{M^2\ hr\ ^\circ C}.$$

Knowing that the outer clothing is ventile, and assuming that all the gas flow escapes through the clothing, the value of Uc as a function of mass flow can be obtained from Ref.3 which allows us to estimate the effects of dynamic insulation. One of the assemblies tested in Ref.3 has heat transfer properties at zero flow approximately representative of the clothing assembly of the dummy man (as calculated above). The result has been used as an assumed heat transfer coefficient Uc and is presented in Fig.2 as a function of mass flow. The curve for the heat transfer coefficient $U_s$ between the skin and the gas stream has been derived from the dummy man experiments using the assumed values of Uc end equation (6).

The shape of the resulting curve of Us against mass flow is not of the form normally associated with convective heat transfer. It is likely that air flow over the 'skin' in Kerslake's experiments could be generally laminar in structure at low flows, with a transition to turbulent flow at high flows. In addition there may also be changes in geometry of the flow path at higher flows caused perhaps by a lifting of the clothing assembly from the skin.

In some other unpublished experiments a Mk.3 A.V.S. was worn under a Frankenstein Full Pressure Suit at an environmental temperature of 65°C. The true state of thermal comfort was not attained because the resulting sweat rate of 66 $gm/M^2hr$ was higher than that expected for comfort (about 20 $gm/M^2hr$), and the mean skin temperature as recorded by a knitted wire suit on the skin was a little high (35°C). The suit inlet conditions were 28 cubic feet/min at 15°C. Assuming a metabolic rate of 50 KAL/$M^2$ hr, a partial solution to equation (5) was found. Neither $U_c$ *nor* Us can be fixed in value, but the relationship between Us and $U_c$ required to satisfy equation (5) CM be found, and is plotted in Fig.3. It is not possible with the information available to decide where, on this curve, the operating point should be. Presumably the skin side heat transfer coefficient of an air ventilated. suit would bo higher undor a full pressure suit than under a ventile assembly because the gas is constrained to move over the skin on its way to the outlet valves of tho pressure suit. A value for $U_s$ ‘of about 6 KAL/$M^2$ hr °C, and a corresponding $U_c$ of 7·5 KAL/$M^2$ hr °C may define a representative operating point. The overall heat transfer coefficient between the skin and the environment is given by $\frac{U_s U_c}{U_s + U_c}$ = 3·335 KAL/$M^2$ hr °C. In terms of insulation value this is equivalent to 1·67 clo units (1 clo unit = 0·18 $\frac{M^2 \text{ hr } ^\circ C}{KAL}$). Note that Fig.3 merely shows a family of possible solutions to equation (5) at one flow rate. It is therefore not compatible with Fig.2.

### 5.3 Liquid *conditioned* suit

Results of a number of live tests with the liquid conditoned suit developed at R.A.E. are given in Ref.2. They were obtained under conditions such that the subject was allowed to select and adjust his own suit inlet temperature to maintain as near as possible the best state of subjective thermal comfort. The heat transfer coefficient between the liquid and the skin was referred, for the purposes of analysis, to a reference area which was that of the inside curved surface of the pipes. Experimental values were not referred to this area, but appear as values of conductance, $AU_s$. The average experimental value of this conductance, or thermodynamic size, was 36·8 CHU/hr °C for the suit used in the experiments. The corresponding figure *in the* system of units adopted in this paper is referred to a skin area of 1·45 $M^2$ covered by clothing, and its value is therefore $\frac{6\ 36}{2\cdot 2 \times 1\cdot 45} = 11\cdot 55 \frac{KAL}{M^2 \text{ hr } ^\circ C}$.

As a result of simplifications made to the analysis in Appendix A the performance equation for the liquid cooled suit is given by equation (7)

$$\dot{m}\, C_p\, AT_{IN} = \left[\frac{1}{1 - \exp \frac{-AU_s}{\dot{m}\, C_p}}\right] \left\{M(1 - o{-}24) + \frac{X}{I_0}\right\} \qquad (7)$$

for thermal comfort in a ventile outer clothing assembly. For non-ventile clothing assemblies note that if there is no provision for removing water vapour, the entire metabolic rate M is used in the equation for required suit inlet conditions.

## 6 DEDUCTIONS FROM EXISTING RESULTS

The analytical model presented in Appendix A was an attempt to describe the behaviour of various types of personal conditioning garment in terms of basic heat transfer coefficients. The results of analysing the available experimental data may shed more light on some of the assumptions already made. It has been assumed as a result of experimental evidence in Ref.2 that for a liquid conditioned suit the heat transfer coefficient between the liquid and the skin is not very sensitive to flow over the useful range of mass flows. An additional assumption, as yet unverified, was that the direct heat transfer between the ambient and the liquid stream is negligible compared with the heat transfer between the ambient and the skin. This assumption will be examined in the light of experimental evidence from Ref.2.

Consider the heat transfer properties of a layer of normal clothing having an insulation value of 1 Clo unit or $0{\cdot}18 \frac{M^2 \text{ hr } {}^\circ C}{KAL}$ and an area of $1{\cdot}45 \text{ M}^2$. The heat picked up by the skin at 33°C from clothing whose outer surface temperature is (say) 45·5°C, is about 100 KAL/hr. This is of the same order as the metabolic rote for a resting man, so that tho assumed heat pickup of the liquid is 200 KAL/hr (say).

Experimentally, the conductance between a liquid conditioned suit and the skin was 16·75 KAL/hr °C, so the mean temperature of the liquid must be lower than skin temperature by the amount $\frac{200}{16{\cdot}75}$, or about 12 deg. C. The direct heat flow between the clothing outer surface and the liquid is given approximately by the clothing heat transfer coefficient, the effective area of the pipes, and the overall temperature difference (in this case 24·5 deg. C). This quantity, expressed as a fraction of the heat flow from the clothing outer surface to the skin, is of the order of twice the fraction of skin area covered by pipes. The assumption, that direct heat transfer to the liquid is negligible, is therefore not valid except for a suit with a very small contact area.

For the case of the air conditioned suit supplied with cool air it was assumed that the flow path completely covers the skin beneath the clothing. Suit behaviour is therefore more complex than with a liquid conditioned suit because all clothing heat flow is assumed to enter the air stream directly, even the radiation to the skin across the air gap being neglected. This is probably also a rather extreme assumption and may lead to substantial errors in computing heat transfer coefficients. It is thought that the useful flow range for convective cooling includes the laminar as well as the turbulent types of flow pattern. Existing results indicate that with high flows there may be some changes in geometry of the flow path caused by significant pressure differences within the clothing. The heat transfer coefficient between the skin and the gas stream is probably a fairly complex function of flow and its determination is highly empirical. The heat transfer coefficient between the gas stream and the environment may be complicated by the effects of dynamic insulation, although existing results have not indicated the order of this effect.

## 7 SUGGESTED EXPERIMENTAL TECHNIQUES

### 7.1 General difficulties

The fact that subjects differ considerably from each other in every respect, and that a given subject's thermal characteristics change with time, can introduce a large amount of experimental scatter into any quantitative results. It must not be expected, therefore, that the same experiment performed on two different occasions would give the same quantitative result owing to the number of important variables beyond the control of the experimenter. Subject variance can be affected by the immediate or long term thermal history of the subject. The general health, acclimatisation, and state of heat storage of a subject at the beginning of an experiment are examples of common causes of subject variance. Many other causes of experimental scatter may be partly psychological in nature, such as the sweating that often accompanies apprehension. Although scatter will be present in operational situations, and its magnitude is of importance to the designer of personal cooling equipment, its avoidance in early laboratory investigations is desirable.

### 7.2 Parametric investigation

During the early stages of an investigation into suit behaviour it may be useful to alter the relevant dependent variable over a fairly large range in one sitting. For instance a given subject could be dressed in the assembly under test and allowed to equilibrate in the climatic chamber under conditions compatible with thermal comfort. When conditions are steady the surface temperature of the clothing could be increased in stages over a large range by heating the environment, whilst simultaneously adjusting the suit inlet temperature to keep the subject in the same thermal state throughout the traverse. The physical analysis already performed will help in this situation because if the mass flow is kept constant for the duration of the experiment the heat transfer coefficients in the assembly will not alter very much. The required cooling rate should therefore increase approximately linearly with the clothing surface temperature. Another important quantity that can be varied in this way is the mass flow. A mass flow traverse would be done at a constant clothing surface temperature and metabolic rate, whilst adjusting suit inlet temperature to maintain a constant condition of thermal comfort. In this case the analysis would suggest that the required cooling rate would be a fairly complex function of flow rate. By dint of much arithmetical manipulation, the heat transfer coefficients, if required, could be extracted graphically as empirical functions of the flow rate. The usefulness of such an exercise, however, is rather doubtful. A range of metabolic rates could also be investigated in this may whilst adjusting the inlet temperature of the suit to maintain comfort.

When the fundamental part of the investigation is fairly complete it is still necessary and important to determine the amount of scatter that can be expected when a number of subjects are exposed, in turn, to a given thermal situation.

## 7.3 Experimental end points

### 7.3.1 Subjective end point

The experimental relation between cooling requirement for comfort, and the clothing surface temperature is a fundamental pre-requisite for gaining predictive information on clothing assemblies. The experimental technique for performing a suitable clothing temperature traverse may be difficult to develop because the cooling rate of the personal conditioning system must be adjusted to keep the man in a constant, state of thermal comfort throughout the traverse.

It is the opinion of the author that the most realistic end point in work on personal conditioning is obtained by allowing the subject to select and adjust his own cooling rate to maintain a constant subjective impression of comfort. This type of experiment is realistic in the sense that it will simulate an operational situation, where cooling rate is likely to incorporate either a full manual control, or a manual override if the control loop is automatic. For experiments where cooling control is subjective, the response of the system to a change in demand by the subject should be sufficiently fast to avoid serious overshoots. Ref.2 gives some data from experiments using a liquid conditioned suit under subjective control. It was found that most subjects were able to reach their desired cooling rate in a short time, and without large overshoots. The response speed of the system was such that the full hot condition could be changed to full cold in approximately 30 seconds.

The main disadvantage found with this method was that subjects differed very considerably in their demands for cooling rate in a given thermal situation. For instance, when 20 subjects were exposed in turn to a constant environment of 45°C globe temperature, at rest, wearing a lightweight flying assembly, the subjectively chosen cooling rates were distributed over a range of about 5:1. The investigation of this scatter may form the most important part of the intended experimental programme. Evidently those subjects who found full sensible cooling disagreeable with the liquid conditioned suit could have made up their heat balance with some evaporation of sweat through the ventile outer clothing. There is also some tolerance to being slightly out of thermal balance before a given cooling rate is adjusted by the subject, so that there may have been considerable heat storage taking place. Individual scatter may be reduced by performing experiments of longer duration than the 1 hour exposures previously used.

### 7.3.2 Sweat rate end point

A physical or physiological end point for thermal comfort could presumably be maintained during an experiment, perhaps at the expense of 'losing some of the realism of allowing subjective control. It would appear that the most sensitive single parameter related to thermal stress is the sweat rate. An experimental technique could be evolved whereby the cooling rate was controlled either by an observer, or suitable automatic mechanism, with the aid of a signal related to the sweat rate. From the preceding paragraph it would be deduced that subjectively, different people may show preference for slightly different levels of evaporative cooling, hence the variable results in Ref.2. However it is possible that, for a given individual at rest, the subjective choice of cooling rate may be consistent with a given rate of evaporative cooling.

Since subjective comfort can be maintained, say in normal office life, over a range of environmental conditions without any conscious control there must be a significant band of tolerance compatible with subjective thermal comfort. If experiments of sufficient duration are performed, there should be a corresponding range of sweat rates within which no conscious feelings of heat or cold would be apparent. It follows that if low sweat rates could be easily measured, they may provide a more sensitive guide to the thermal state of the man than subjective impressions alone. The globe temperature traverses attempted in Ref.2 could form the basis of a useful experimental technique if the maintenance of a constant sweat rate within the 'comfort band' reduced the within-subjects variance, and provided some measurable reasons for between-subjects variance. Clothing surface temperature rather than globe temperature would be preferred as the environmental parameter.

An experimental technique of this type will be tried within M.E. Department in the near future. The cooling rate will be controlled to give a constant sweat rate for a complete traverse of any importance parameter. The sweat rate for the experiment will be overridden by the subject himself so as to place the 'set point' within his comfort tolerance. If the stability of the control system, whether automatic or manual, can be made satisfactory it is hoped to increase the sensitivity of the experiments without losing realism. In addition it may be possible to investigate situations at states other than thermal comfort by using sweat rate as an independent variable.

If a fixed flow of dry air is passed over the skin, the outlet humidity of the air from the suit will be proportional to the sweat rate. If this outlet humidity is measured, in terms of dewpoint temperature, a sensitive indication of low sweat rates is possible (see Fig.&). It may be difficult to apply this technique to clothing assemblies that do not easily allow for the collection of suit outlet air.

### 7.3.3 Other end points

The use of various body temperatures to indicate the thermal state of the subject appears to be fundamentally sound. The deep body temperature of a man under most conditions covers a comparatively small range, and the instrumentation must be fairly sensitive to be of use. The large thermal capacity of the body suggests that rates of change of deep body temperature are usually very low, and hence because of the low rate at which information is gained from measuring deep temperature, it is probably more of academic interest than of use as a control signal.

The measurement of skin temperatures in conjunction with deep temperature, is said to be very useful as these quantities can be interpreted in terms of heat storage and the activity of the body's thermoregulatory mechanism'. Any state incompatible with thermal comfort causes redistribution of blood flow to the skin which is reflected by changes in skin temperature and its regional distribution. Skin temperature levels must be measured accurately at as many sites as possible. Temperature measurements on surfaces are subject to appreciable errors, however, especially if the thermal properties of the sensor are different from those of the surface itself. The temperature recorded by a sensor depends to some extent on its size, shape, method of attachment, conductivity of wires, and the thermal microclimate of the surface. A few badly-positioned local skin sensors, if the subject is wearing a liquid conditioned suit, would give very little indication of the true mean skin temperature on account of the skin temperature variations near the pipes.

Some idea of the mean akin temperature can actually be inferred from the behaviour of the liquid conditioned suit itself. In a clothing surface temperature traverse at constant mass flow and metabolic rate with a given clothing assembly, the liquid inlet and outlet temperatures would probably bear an almost linear relationship with the clothing surface temperature. At the clothing surface temperature which requires the cooling rate to be zero the liquid temperatures going into and emerging from the suit will coincide. This temperature can be interpreted as a mean skin temperature but its value is subject to the same errors as that from any other type of sensing device.

As a concluding paragraph on experimental end points it would seem of value to emphasize again that the subjective impression Of the wearer, as far as thermal comfort is concerned, is of overriding importance. The cooling rate of an operational personal. cooling system is almost certain to be controlled manually via the subjective impression of the wearer. For experimental work within the comfort tolerance it would be desirable to effect small adjustment of cooling rate to keep some physical quantity, such a3 body sweat rate, at a constant level. Further investigations of a more fundamental physiological nature could investigate the limits of the comfort band, and extend to severe discomfort if necessary. It would be of interest to find out whether, for a given person, the subjective comfort state is compatible with a given level of sweating. If it is, there may be a case under certain circumstances, for incorporating an automatic control system which is driven by a sweat rate signal such as the outlet dew point temperature of an air ventilated suit. The system would automatically compensate for changes in environmental temperature, mass flow, or clothing assembly. It would of course still incorporate a manual override so that the subject could initially select his own sweat rate for comfort, Such a mechanism may over-compensate for a change in work rate, because the preferred sweat rate may rise with metabolic rate.

### 7.4 Effects of altitude

In the later stages of a general investigation on personal cooling, another variable that must be investigated is the effect of ambient pressure. In general the Reynolds number for a fluid flowing in a duct is given by:

$$Re = \rho \frac{VD}{\mu}$$

where p = fluid density
V = average velocity through duct
D = a characteristic dimension of the duct, such as diameter
$\mu$ = absolute viscosity

From the continuity equation for a duct of cross section area A

$$\dot{m} = \rho A V$$

so that

$$Re = \frac{\dot{m} D}{A \mu}$$

and for circular tubes

$$Re = \frac{4\dot{m}}{\pi D \mu} .$$

This quantity is independent of altitude if D is constant, so that the internal heat transfer coefficients of the suit should not change with altitude. The pressure drop through a duct with turbulent flow is approximately proportional to the dynamic head: i.e.

$$\Delta P \propto \rho V^2 \quad \text{or} \quad \Delta P \propto \frac{\dot{m}^2}{\rho A^2} .$$

To maintain a constant mass flow, therefore, the suit pressure drop must be increased approximately as the inverse of the density. The working fluid of a liquid conditioned suit should not need increased inlet pressure at altitude, the density of liquids being relatively constant. The air ventilated suit, however, would require larger inlet pressures at altitude to maintain a given mass flow through the system. There is a possibility that the larger pressure differences at altitude could induce changes in geometry of the clothing, and hence alter Reynolds numbers and heat transfer coefficients by changing the clearance between the skin and the first layer of clothing.

## 7.5 Subjective assessment

An investigation of the gross thermal performance of a cooling garment may be useful, but by itself it could be misleading as far as development of hardware is concerned. Comparative assessment of a family of prototype designs may indicate certain features that can be associated with a high thermal performance and hence low total system weight. The criterion for the acceptance or rejection of any item of personal equipment is ultimately a subjective choice. In any experimental investigation of a personal conditioning suit, therefore, it will be extremely relevant to record as much subjective information as possible. Of particular importance is the subjective impression of pooling distribution. For example with an air ventilated suit running on cold air it is likely that the very features that promote high heat transfer coefficients may result in regions of high local cooling which would be subjectively unacceptable. In common with most development work, a compromise must always be reached between pure efficiency and other important factors such as bulk, weight, discomfort due to cold spots, etc. The proposed experimental investigation into the thermal aspects of personal cooling suits should make use of a scoring system, by which the subjective state of areas of the body can be assessed.

## 8 COMPARISON OF VARIOUS CONDITIONING SYSTEMS

It has been pointed out that there is a serious lack of experimental information on convective cooling. Such information as is available has served only to indicate that the thermal behaviour of personal conditioning systems supplied with cold air is likely to be fairly complex. It is therefore necessary to emphasise that, at the present state of knowledge, any predictions of the necessary suit inlet conditions required in a given situation must be tentative in the extreme. The following comparison of various conditioning systems must therefore be regarded only as a determination of the orders of magnitude involved, since it relies directly on the validity of the mathematical model in Appendix A.. Results will be presented for a representative standard man at rest whose metabolic rate is 50 KAL/M$^2$ hr. The outer clothing assembly has an insulation value of 1 clo unit ($I_c$ = 0·18 °C M$^2$hr/KAL).

For sweating conditions, the rise of skin temperature with sweat rate is considered negligible when compared with the useful range of clothing outer surface temperature. For all conditions, therefore, it is assumed that the skin temperature will be 33°C. The sweating level at comfort, including respiratory water losses, is assumed to be 12 KAL/M$^2$ hr or 20·7 gm/M$^2$ hr. For air ventilated suits which rely wholly or in part on evaporation of sweat it is assumed that all of the sweat is actually evaporated at the skin surface ($\eta$ [illegible] its latent heat of evaporation is 0·58 KAL/gm, and its rate of secretion is just sufficient to maintain thermal balance; It is assumed that the outer clothing is not ventile, so that there will be no effects of dynamic insulation with air ventilated suits, and there will be no evaporation of sweat from the skin with liquid conditioned suits. If the liquid suit does not provide sufficient cooling to maintain a comfort condition, it is assumed that the sweat rate will increase indefinitely until an arbitrary tolerance limit of $300\ gm/M^2\ hr$ is reached. The skin-side heat transfer coefficient of the sir ventilated suit is assumed to be $6{\cdot}0\ \frac{KAL}{M^2\ hr\ ^{\circ}C}$, and for the liquid conditioned, suit running on water, $II\text{-}55\ \frac{KAL}{M^2\ hr\ ^{\circ}C}$ based on a conditioned skin area of $1{\cdot}45\ M^2$.

The results of the comparison are derived from the basic equations developed in the analyses, and are presented in two forms. The first comparison shows combinations of inlet temperature and mass flow required for the liquid and air conditioned suits to maintain thermal comfort at various clothing surface temperatures. The results are presented in Fig.5 in which mass flow and inlet temperature are coordinates, and clothing surface temperature is a parameter. In comparing the suits in Fig.5 on an engineering basis it must be remembered that although both suits are assumed to be doing an adequate job of keeping the hypothetical man in thermal comfort, the weights of their support systems may differ considerably. The pumping power penalty for providing say 1 lb/min of air is inherently much higher than that for providing 1 lb/min of water, even though its potential cooling capacity is less. The weight penalty for providing a given rate of cooling at a given temperature is probably of the same order regardless of the type of fluid from which the heat is to be extracted, although heat exchanger weight may be less for a dense working fluid such as mater. The second comparison is shown on Fig.6 for suits that do not provide thermal comfort, or that are operating beyond the limit of true comfort. In Fig.6, three types of cooling are compared by means of a tradeoff between the operating clothing surface temperature, and the discomfort of the man in terms of his sweat rate intensity. Each line represents a constant suit inlet condition except for the one labelled PURE EVAPORATIVE COOLING, where the inlet temperature is adjusted accordingly (para. 3.2). It has been assumed that a sweating intensity of $300\ gm/M^2\ hr$ represents a safety limit, end would feel very uncomfortably hot. A sweating intensity of up to $30\ gm/M^2\ hr$ would probably feel very comfortable if no important anomalies of skin temperature were produced by the suits. Sweating between these limits would indicate subjective states ranging from slightly warm to very hot.

## 9 GENERAL CONCLUSIONS

There are many potential applications, both in industry and in the fighting forces, where human subjects working in hot environments would benefit considerably from some form of personal cooling. The maintenance of heat balance by evaporation of sweat, is a powerful human thermoregulatory mechanism, which can be exploited by providing a stream of dry air over the man's skin. Garments which actively use dry air or oxygen for evaporative cooling of the skin are at present in use in aircraft and spacecraft. Their main disadvantage is that in hot environments or at high metabolic rates a high continuous sweat rate must be maintained. Such a situation is at best uncomfortable to the unacclimatised wearer, and may approach the limits of tolerance and safety. The maintenance of thermal comfort by direct cooling of the skin is a relatively recent proposal and determination of the behaviour of personal heat exchangers demands new experimental techniques.

Owing to the obvious difficulties of a purely theoretical approach, and of the problems associated with interpretating ad hoc experimental data, it was decided that a systematic experimental programme should be planned. Fairly crude analyses of suit behaviour indicate that the temperature of the fluid entering the suit can be considered as the basic dependent variable. The suit inlet temperature should depend on a number of import&t parameters, some of which can be varied systematically during an experiment. Such independent variables that can be investigated parametrically are: mass flow, metabolic rate, and clothing surface temperature. The use of clothing surface temperature as an experimental variable should take into account the environmental effects that influence clothing heat flow, provided that the outer clothing assembly is effectively wind proof. If clothing surface temperature can be conveniently measured it would therefore be a useful combined indication of the severity of the environment. The effect of separate environmental' components such as radiation, air temperature, and air movement, on the clothing surface temperature of a thermally conditioned subject could almost form a separate and self-contained investigation. It must be remembered that'the severity of the environment can also be influenced by the ambient humidity because it reduces the ability of the man to evaporate moisture from his skin.

In order to preserve some semblance of realism, the suit inlet temperature should be adjusted during traverses of an independent variable so as to maintain the man in a constant state of thermal comfort, as he would probably attempt to do manually with an operational system. The simplest way of ensuring thermal comfort in the subjective sense is to allow the man to control the inlet temperature himself. Owing to large differences in comfort preference, and a certain amount. of human tolerance, this method of controlling suit inlet temperature, although psychologically satisfactory, may introduce large amounts of experimental scatter. Although this scatter must be evaluated and allowed for in an operational system, its avoidance in early experimental work would be an advantage.

It is suggested that the experimental scatter may be reduced by controlling inlet temperature to give a constant rate of evaporation of sweat, at a level compatible with subjective comfort. The determination of sweat rate by monitoring the outlet dewpoint of a known flow of dry air over the man's skin may be a promising way of achieving a sensitive, quantitative indication of the man's thermal. state. Experiments at states other than thermal comfort could be done if sweat rate itself were used as an additional independent variable.

An experimental programme of this type would be of considerable value in comparing existing types of personal conditioning both from a subjective point of view, and from the point of view of the designer of a cooling system for supporting a particular suit in an aircraft or space vehicle, For instance it may well be found that, with the ideal cold air supply, an air ventilated suit may be subjectively superior to its liquid-cooled counterpart, but it may be rejected on the grounds that because of its high consumption of pumping power, and requirements for low inlet temperatures, its associated cooling and pumping system would incur too high a weight penalty, especially at altitude.

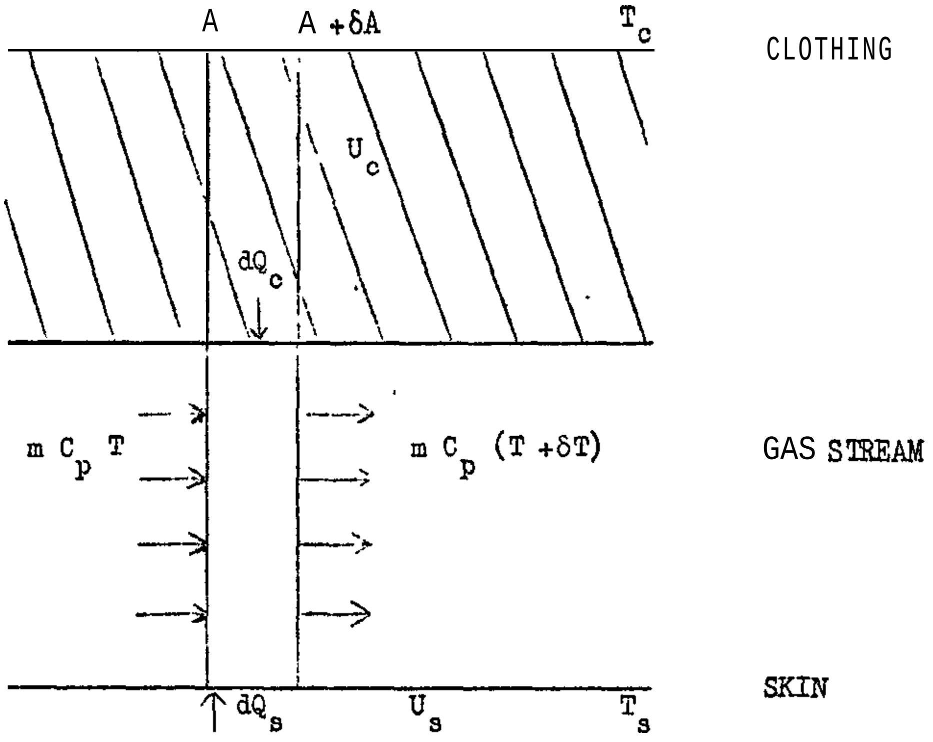
In view of the serious thermal problems that nearly always confront air-crew operating in the tropics; the equally serious thermal problems of some future manned space flight operations, and the very great scarcity of experimental data on the general subject of personal conditioning; the importance of gaining information in this field can hardly be overemphasised.

## Appendix A

## ANALYSIS OF THE THERMAL PERFORMANCE OF AN IDEALISED AIR VENTILATED SUIT

The air stream is considered to flow within a duct bounded by one surface representing the man's skin, and another surface representing the inner face of the clothing assembly. The boundary layer of air next to the skin is assumed to have a uniform heat transfer coefficient $U_s$, and the layer of clothing with its associated boundary layer on the inner face is assumed to have a uniform heat transfer coefficient $U_c$. The radiant heat transfer between the skin and the inner surface of the *clothing is* neglected for reasons of convenience.

Consider the heat flow into an elementary length of this duct whose heat transfer area is SA. Heat from the environment passes through a clothing layer of overall heat transfer coefficient $U_c$, and heat from the skin passes through a boundary layer of heat transfer coefficient $U_s$.



Heat flow from environment is $dQ_c = U_c\ dA\ (T_c - T)$ (8)

Heat flow from skin is $dQ_s = U_s\ dA\ (T_s - T)$ (9)

Heat gained by gas is $dQ = \dot{m}\ C_p\ \delta T$ (10)

From equations (8), (9), (10) the conservation of energy implies that:

$$U_c \, dA \, (T_c - T) + U_s \, dA \, (T_s - T) = \dot{m} \, C_p \, \delta T \qquad (11)$$

and the temperature rise of the gas is

$$\delta T = \frac{dA}{\dot{m} \, C_p} \left\{ U_c \, (T_c - T) + U_s \, (T_s - T) \right\} \qquad (12)$$

or

$$\delta T = \frac{dA}{\dot{m} \, C_p} \left\{ Us \, (T_s - T) + Uc \, (T_s - T + T_c - T_s) \right\} . \qquad (13)$$

If $T_s$ and To are constants, then

$$d(T_s - T) = - \delta T, \qquad (14)$$

Equation (13) can be written:

$$\frac{d(T_s - T)}{U_s \, (T_s - T) + Uo \, (T_s - T + T_c - T_s)} = - \frac{dA}{\dot{m} \, C_p} . \qquad (15)$$

For convenience we write

$$(T_s - T) = AT$$

and

$$(T_c - T_s) = X .$$

Then equation (15) becomes

$$\frac{d(\Delta T)}{\Delta T + \frac{U_o}{U_s} (\Delta T + X)} = - \frac{dA \, U_s}{\dot{m} \, C_p} . \qquad (16)$$

We are now in a position to integrate this expression to find the temperature distribution of' the gas along the duct provided that $\frac{U_s}{\dot{m} \, C_p}$, $\frac{U_c}{U_s}$, and X, are constant over the duct length. Thus:

$$\int_{\Delta T_{IN}}^{\Delta T} \frac{d(\Delta T)}{\left(1 + \frac{U_c}{U_s}\right)\Delta T + \frac{U_c}{U_s} X} = - \frac{U_s}{\dot{m}\, C_p} \int_0^A dA \, . \qquad (17)$$

Integrating along the flow path

$$\frac{1}{1 + \frac{U_c}{U_s}} \log \left[ \left(1 + \frac{U_c}{U_s}\right)\Delta T + \frac{U_c}{U_s} X \right]_{\Delta T_{IN}}^{\Delta T} = - \frac{U_s A}{\dot{m}\, C_p} \, . \qquad (18)$$

On substituting *limits* $\Delta T_{IN}$ and $\Delta T$

$$\log \left[ \frac{\left(1 + \frac{U_c}{U_s}\right)\Delta T + \frac{U_c}{U_s} X}{\left(1 + \frac{U_c}{U_s}\right)\Delta T_{IN} + \frac{U_c}{U_s} X} \right] = \frac{-A(U_s + U_c)}{\dot{m}\, C_p} \qquad (19)$$

which may be written as

$$\frac{\left(1 + \frac{U_c}{U_s}\right)\Delta T + \frac{U_c}{U_s} X}{\left(1 + \frac{U_c}{U_s}\right)\Delta T_{IN} + \frac{U_c}{U_s} X} = \exp \left\{ \frac{-A(U_s + U_c)}{\dot{m}\, C_p} \right\} \qquad (20)$$

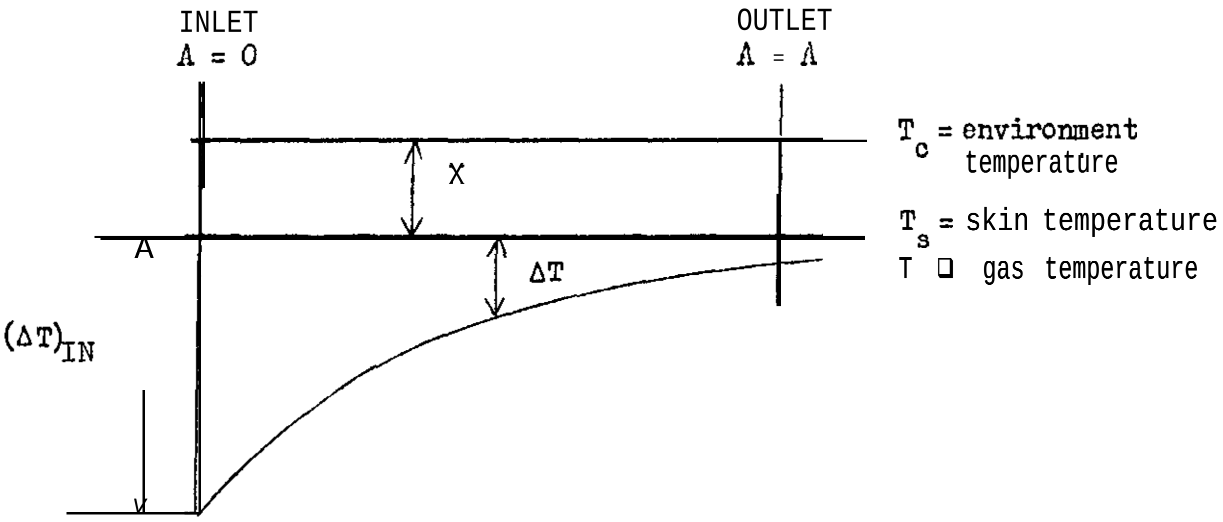
hence

$$\left(1 + \frac{U_c}{U_s}\right)\Delta T + \frac{U_c}{U_s} X = \left[ \left(1 + \frac{U_c}{U_s}\right)\Delta T_{IN} + \frac{U_c}{U_s} X \right] \exp \left[ \left( \frac{-A(U_s + U_c)}{\dot{m}\, C_p} \right) \right] \qquad \ldots. \quad (21)$$

from which $\Delta T$ may be isolated,

$$\Delta T = \left[ \Delta T_{IN} + \frac{X}{1 + \frac{U_s}{U_c}} \right] \exp \left[ \frac{-A(U_s + U_c)}{\dot{m}\, C_p} \right] - \frac{X}{1 + \frac{U_s}{U_0}} \qquad (22)$$

This is the theoretical temperature distribution along the duct and is of the form shown below in the diagram below.



As a check let us assume a very large heat transferring area (A → ∞). Then

$$AT = -\frac{X}{1+\frac{U_s}{U_c}} .$$

For large outer clothing insulation (Uc → 0), AT vanishes and the gas emerges from the suit at skin temperature. For large insulation between the skin and the gas stream ($U_s \to 0$), AT → -X, and the gas emerges at the temperature of the clothing outer surface. With a known gas temperature distribution along the duct we can find the total heat transfer from the 'man's skin' to the gas stream. By definition from equation (9)

$$Q_s = U_s \int_0^A AT \, dA .$$

By substituting equation (22) for AT and integrating along the duct length, the total heat loss from the skin becomes:

$$Q_s = U_s\left[\frac{-\dot{m}\,C_p}{U_s+U_c}\left(\Delta T_{IN} + \frac{X}{1+\frac{U_s}{U_c}}\right)\exp\left\{\frac{-A(U_s+U_c)}{\dot{m}\,C_p}\right\} - \frac{XA}{1+\frac{U_s}{U_c}}\right]_0^A \qquad \ldots\ (23)$$

which, on substitution of the limits becomes

$$Q_s = U_s\left[\left\{\frac{-\dot{m}\,C_p}{U_s + U_c}\left(\Delta T_{IN} + \frac{X}{1 + \frac{U_s}{U_c}}\right)\exp\left(\frac{-A(U_s + U_c)}{\dot{m}\,C_p}\right)\right]\right.$$

$$\left. - \frac{-\dot{m}\,C_p}{U_s + U_c}\left(\Delta T_{IN} + \frac{X}{1 + \frac{U_s}{U_c}}\right) - \frac{XA}{1 + \frac{U_s}{U_c}}\right] \quad (24)$$

which gives

$$Q_s = \frac{-\dot{m}\,C_p\,U_s}{U_s + U_c}\left(\Delta T_{IN} + \frac{X}{1 + \frac{U_s}{U_0}}\right)\exp\left[\frac{-A(U_s + U_c)}{\dot{m}\,C_p} - 1\right] - \frac{X\,A\,U_s}{1 + \frac{U_s}{U_c}}. \quad (25)$$

This is the skin cooling effect of a stream of gas initially cooler than the skin by the amount $\Delta T_{IN}$. If the quantity $Q_s$ is made equal to the non-evaporative component of the man's metabolic rate, he will lose heat to the gas stream at the correct rate to ensure heat balance.

$$Q_s + \frac{X\,A\,U_s}{1 + \frac{U_s}{U_c}} = \frac{\dot{m}\,C_p}{1 + \frac{U_c}{U_s}}\left(\Delta T_{IN} + \frac{X}{1 + \frac{U_s}{U_c}}\right)\left\{1 - \exp\left(\frac{-A(U_s + U_c)}{\dot{m}\,C_p}\right)\right\} \quad (26)$$

which may be rearranged

$$\left(Q_s + \frac{X\,A\,U_s}{1 + \frac{U_s}{U_c}}\right)\left(\frac{1 + \frac{U_c}{U_s}}{\dot{m}\,C_p}\right)\left\{\frac{1}{1 - \exp\frac{-A(U_s + U_c)}{\dot{m}\,C_p}}\right\} = \Delta T_{IN} + \frac{X}{+\frac{U_s}{U_c}} \quad (27)$$

**from which**

$$T_{IN} + \frac{X}{1 + \frac{U_s}{U_c}} = \left\{\frac{Q_s}{\dot{m}\,C_p}\left(\frac{U_c}{U_s} + 1\right) + \frac{X\,A\,U_c}{\dot{m}\,C_p}\right\}\left[\frac{1}{1 - \exp\left\{\frac{-A(U_s + U_c)}{\dot{m}\,C_p}\right\}}\right] \quad (28)$$

**Thus**

$$\dot{m}\,C_p\,\Delta T_{IN} = \left[\frac{1}{1 - \exp\left\{\frac{-A(U_s + U_0)}{\dot{m}\,C_p}\right\}}\right]\left\{Q_s\left(1 + \frac{U_c}{U_s}\right) + X\,A\,U_c\right\}\frac{-X\,\dot{m}\,C_p}{1 + \frac{U_s}{U_c}} \quad (29)$$

This expression gives the potential cooling capacity required to be supplied to the suit to maintain a sensible heat loss of $Q_s$ from the akin to the gas stream. Note that if the ambient temperature is equal to skin temperature, i.e. X □ 0, the ratio of cooling supplied to cooling achieved is

$$\frac{\dot{m}\ C\ \Delta T_{IN}}{Qa} = \left[\frac{1}{1 - \exp\dfrac{-A(U_s + U_o)}{\dot{m}\ C_p}}\right]\left\{1 + \frac{U_o}{U_s}\right\}. \qquad (30)$$

This is the ratio of potential cooling to useful cooling for a given suit/clothing system where outer surface temperature is at mean akin temperature, The ratio always exceeds unity, and its rociprocal can be regarded as an overall efficiency.

Experimentally the ratio of potontial_aooling Supplied, to useful_cooling achieved, could be found in laboratory teats. Its usefulness as a performance parameter does not rest directly on the validity of the mathematical model, which may of itself have important deficiencies due to the simplified treatment.

The derived expression is a linear function of clothing surface temperature and it is expected that in spite of the idealised analysis, presentation of experimental results in this form would also give a linear result when plotted against clothing surface temperature.

If the ratio of potential. cooling supplied to useful cooling achieved is plotted against flow rate, the results of live experiments should yield a curve of the same form as Fig.1.

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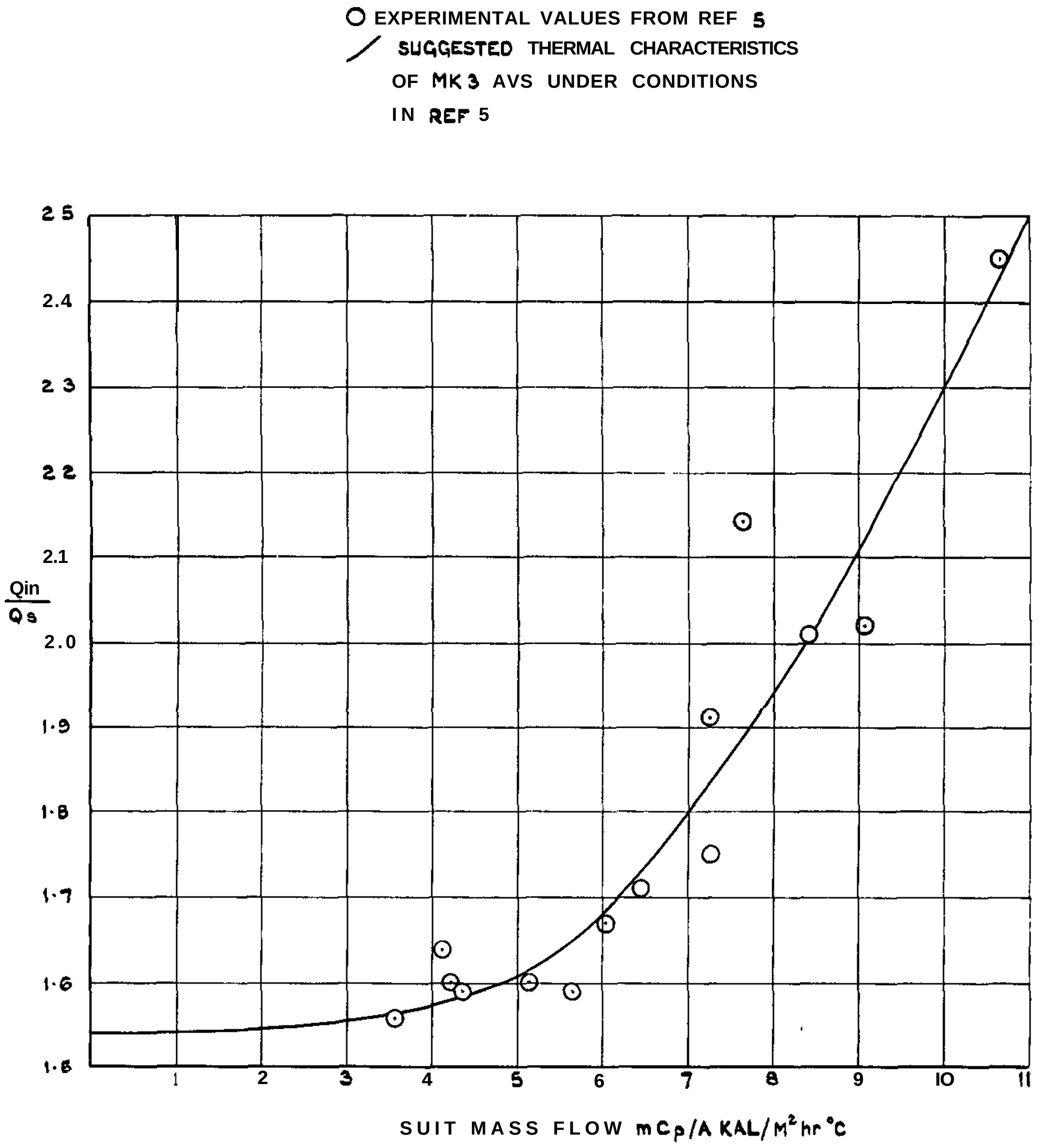

FIG. I THERMAL CHARACTERISTICS OF MK 3 A.V.S. ON DUMMY MAN. RATIO OF POTENTIAL COOLING SUPPLIED TO ACTUAL COOLING ACHIEVED, PLOTTED AGAINST FLOW RATE

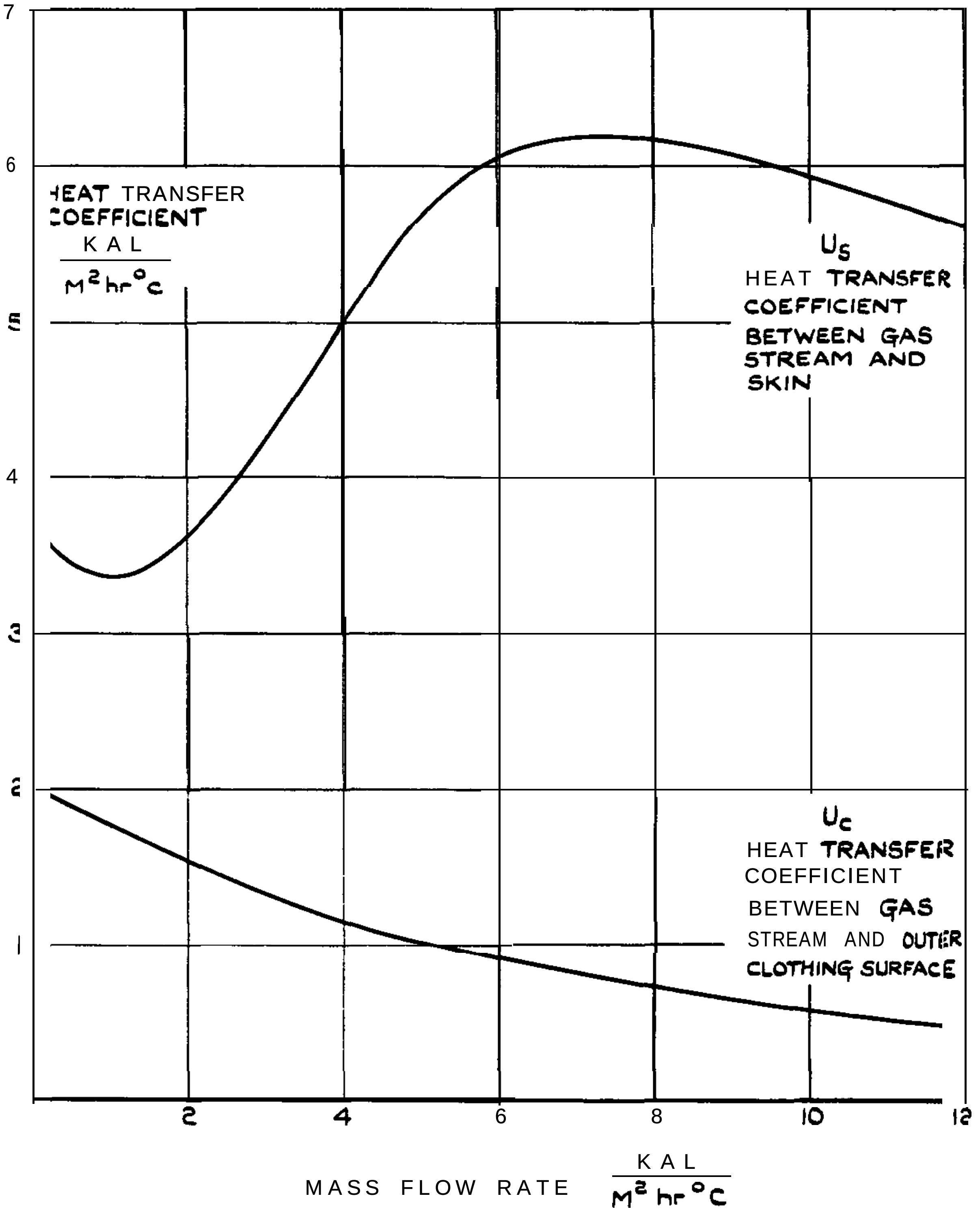

FIG.2 DERIVED HEAT TRANSFER COEFFICIENTS FOR THE MK.3 AIR VENTILATED SUIT (FROM EXPERIMENTS IN REFS.3 AND4) AS FUNCTIONS OF MASS FLOW

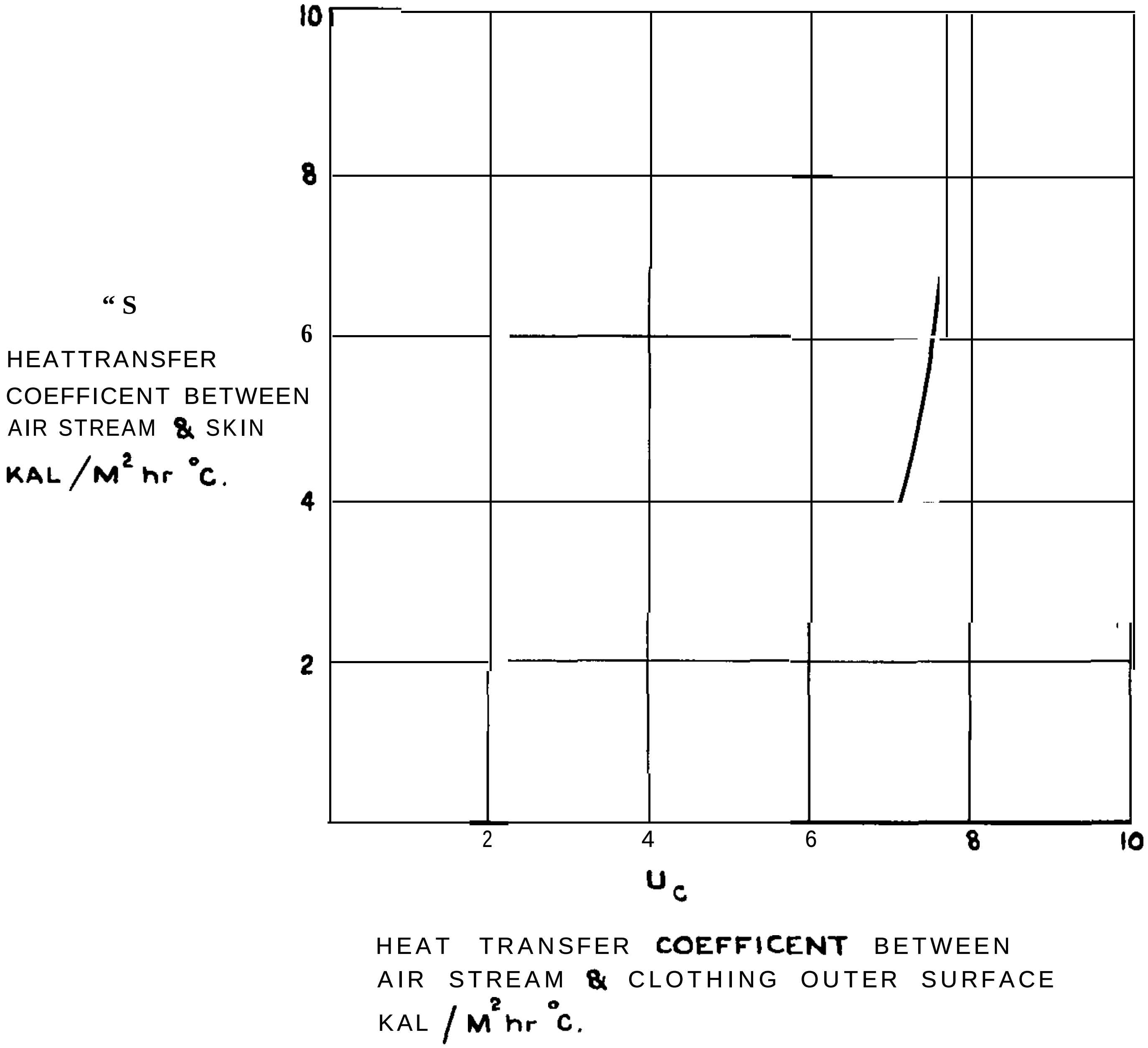

FIG 3. POSSIBLE VALUES OF HEAT TRANSFER COEFFICIENTS DERIVED FROM AN EXPERIMENT (UNPUBLISHED) FOR MK.3 AIR VENTILATED SUIT WORN UNDER A FULL PRESSURE SUIT,

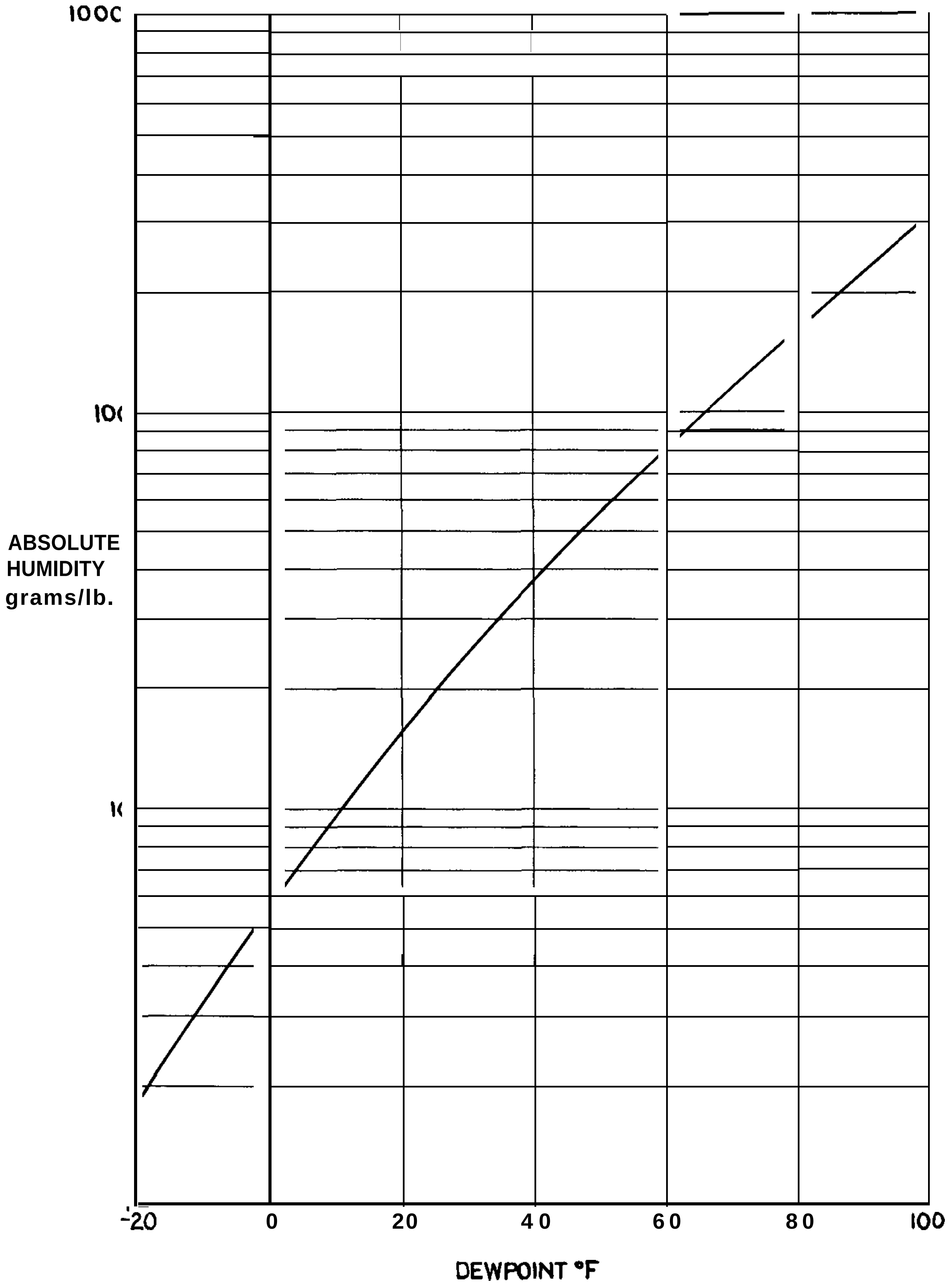

FIG. 4 RELATION BETWEEN ABSOLUTE HUMIDITY AND DEWPOINT TEMPERATURE

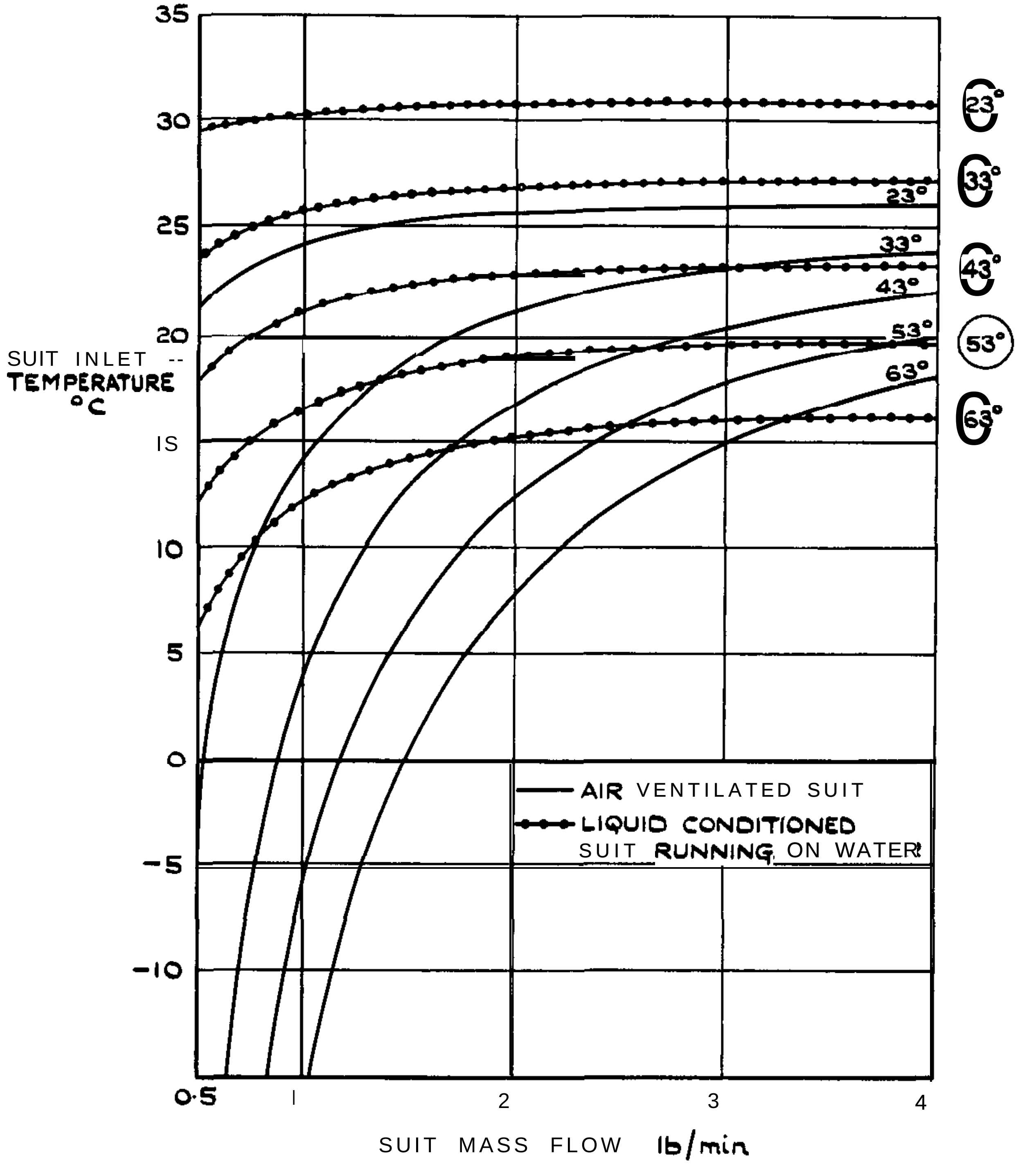

FIG.5 PREDICTED COMPARISON OF PERSONAL CONDITIONING SYSTEMS. INLET TEMPERATURE Vs FLOW FOR COMFORT AT SEVERAL CLOTHING SURFACE TEMPERATURES

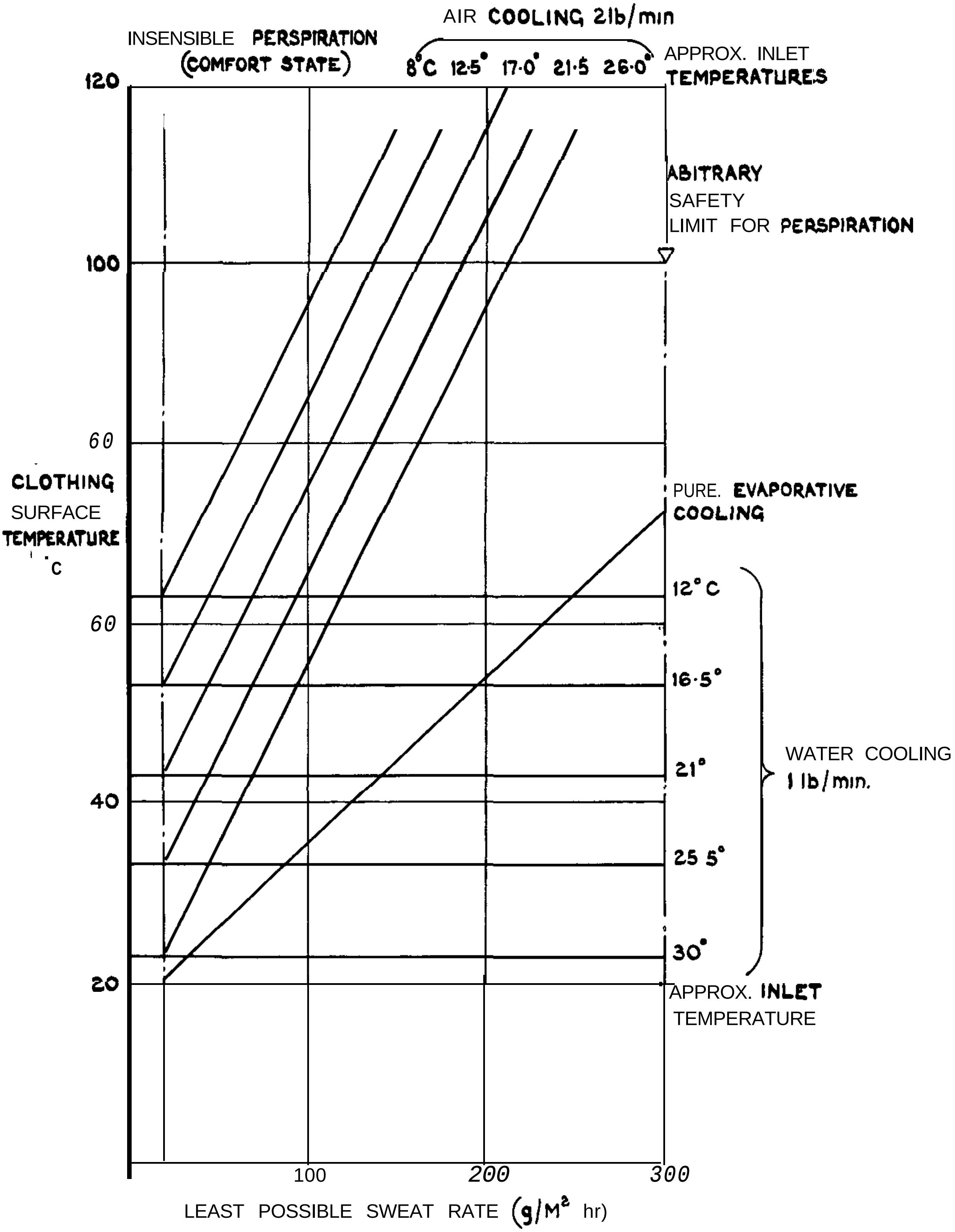

FIG. 6 PREDICTED COMPARISON OF PERSONAL CONDITIONING SYSTEMS. CLOTHING SURFACE TEMPERATURE $V_S$ SWEAT RATE FOR VARIOUS SUIT INLET CONDITIONS

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