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by

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CABIN AIR REQUIREMENTS FOR CREW COMFORT IN MILITARY AIRCRAFT

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SUMMARY

The Report discusses the effect of various parameters, relating to the crew and aircraft, om cabin air supply requirements for crew comfort. A method of presenting the relationships between the various parameters in the form of 'design curves' is shown. The validity of these is discussed and recommendations made where further confirmatory evidence is required.

Using the 'design curves' and a computer program, the relative importance of factors influencing cabin air requirements for comfort have been examined and recommendations made on how cockpit conditions might be improved.

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* Replaces R.A.E. Technical Report 68304 - A.R.C. 31220

CONTENTS

CONTENTS (Contd.)

1 INTRODUCTION

The aircrew thermal environment in an aircraft cockpit depends on many factors such as the aircraft skin temperature, the degree of wall insulation, the amount and temperature of the cooling air supplies, the amount of solar radiation, and variables associated with the crew. The latter includes the crew's work rate and type of clothing. Because of the number of variables and their interdependence, it is difficult to specify simple design rules to achieve a comfortable environment in the cockpit; in fact, such rules might inhibit the designer rather than help him. However, the basic object of cockpit air conditioning must be met, i.e., maintenance of the pilot or crew member in a state of comfort essential for maximum efficiency. It has been stated by Aero-Medical Authorities[1,2] that a subject is in a state of thermal comfort when his mean skin temperature is 33°C, and this has been used as a basic criterion in this Report.

The Report examines the effect of varying parameters related to the aircraft cabin (wall insulation value, skin temperature, amount of solar radiation etc.,) and to the crew (work rate, clothing insulation, etc.,) on the air supplies necessary to maintain the crew of a military aircraft in a state of thermal comfort. A method of expressing the relationship between the various parameters in the form of 'design curves' is presented, and the experimental evidence and assumptions used are discussed.

A computer program was written to examine the problem in detail and this, together with the design curves, has been used to assess the relative importance of the various factors which influence the cabin air supply required for thermal comfort. Suggestions for obtaining better comfort conditions with an existing air supply are made.

2 PARAMETERS INVESTIGATED

Where appropriate the same nomenclature and units have been used as in Billingham and Kerslake's work[1,2] on thermal comfort. This applies particularly to parameters related to the pilot* and his immediate environment.

2.1 Main parameters relating to the pilot

(a) Pilot's clothing assembly - I_C

The pilot's clothing is defined in terms of its insulation value, I_C ($^oC\ m^2hr/kcal$). Values of I_C for various clothing assemblies (extracted from Ref.2) are included in Table 1. The use of conditioned garments is discussed.

*** Note: In this Report the main argument is based on the pilot. However the conclusions are broadly applicable to any other crew member.**

(b) Pilot's metabolic heat output - H

The pilot's metabolic heat output, which under conditions of comfort is largely sensible heat (H), is a function of his degree of activity. Values of H (kcal/m^2 hr) corresponding to various degrees of activity are given in Table 2 (from Ref.2).

2.2 Main parameters relating to the aircraft

(a) Air supplies (M and T_{in})

The cabin air supplies are defined in terms of the mass flow, M(lb/min) and the temperature at inlet to the cabin, T_{in} (°C).

(b) Cockpit outer skin temperature (T_S)

This parameter is related to the aircraft's speed. An approximation to the value of T_S may be found from the expression

$$T_S = T_A \, (1 + rM^2/5)$$

where T_A = ambient temperature in °abs
M = Mach number
r = recovery factor (usually taken as 0.89)

For detailed treatment, reference should be made to the literature[3].

(c) Cockpit wall insulation (k/ℓ)

In a military aircraft much of the inner surface of the cockpit walls is covered with equipment. In the context of this Report, the wall is considered to include the equipment, and the thermal resistance of the 'wall' includes that of the wall mounted equipment (consoles, etc.), plus any insulation which may be fitted. The 'wall' thermal resistance is expressed as a thermal conductance, k/ℓ (CHU/hr ft^2 °C). This value is assumed to apply to the main homogeneous area, local 'heat leakage' being accounted for separately (see section 3.6).

(d) Solar radiation (S)

The extreme cases of zero solar radiation, and maximum ground level solar radiation intensity (S) are investigated.

(e) Air distribution

Cockpit air distribution affects the relationship between inlet mass flow and the velocity over the pilot and cockpit surfaces and hence the heat transfer processes. It also affects the temperature distribution in the cockpit and hence the relationship between the temperature of the air in the vicinity of the pilot (T_E) and inlet temperature.

(f) Electrical heat load (Q_E)

The method for allowing for the electrical heat load (Q_E) is discussed in section 3.7.

2.3 Other parameters

In the more detailed computer analysis of the effect of varying parameters, wall emissivity (ε_W), pilot's clothing emissivity (ε_ρ) and absorptivity to solar radiation (α_{CS}) have been introduced as variables, and the effect of including a (solar) reflecting layer in the transparencies investigated.

3 THEORY

3.1 Main assumptions

(a) The total surface area of the external walls of the cockpit (i.e. the surfaces at or near T_S - which excludes, for example, the front and rear bulkheads) is assumed to be 60 sq ft, of which 12 sq ft is transparency plan area. The effect on the results of considering different cockpit and transparency areas is discussed in section 6.

(b) Heat flow through inter-compartment 'walls' (e.g. rear bulkheads and floor) is assumed negligible because adjacent compartment temperatures are likely to be similar to cabin temperatures.

(c) It is assumed that the mean conductance of the transparencies is the same as that of the remainder of the cockpit 'walls' as defined above, and that the inner surface temperature is that of the rest of the cockpit.

(d) The air distribution model is that shown in Fig.1. This was developed in a series of tests made at R.A.E. Farnborough[4].

(e) Air leakage from the cabin is assumed to be zero.

(f) As in previous work[2], exposed areas such as the face and possibly the hands are neglected.

(g) Analysis is for a pilot.

The significance of these basic assumptions is discussed in section 6.

3.2 Pilot's heat balance

The basic equation expressing the thermal balance of the pilot is

$$Q_{RP} + Q_M + Q_{SP} = Q_C \qquad (1)$$

i.e. for stability, the heat lost by convection from the surface of the pilot's clothing (Q_C) must equal the heat arriving at the surface. The latter is by radiation from the walls (Q_{RP}) and any solar radiation (Q_{SP}) plus the pilot's metabolic heat conducted through his clothing (Q_M).

As shown in Appendix A, this equation may be expressed (in cgs units) as

$$3{\cdot}41 \times 10^{-8} \varepsilon_{eff} \left(T_W^4 - (T_{PS} - HI_C)^4\right) + H + 0{\cdot}31\, \alpha_{CS}\, \tau S = (T_{PS} - HI_C - T_E)/I_A \qquad \ldots \quad (2)$$

where ε_{eff} = effective emissivity from wall surface to pilot's clothing

T_W = temperature of inner surface of the wall

T_{PS} = pilot's mean skin temperature

T_E = mean temperature of the air in the immediate vicinity of the pilot

τ = mean transmissivity of the transparencies

I_A = air insulation °C m^2 hr/kcal, the reciprocal of the heat transfer coefficient

I_C = clothing insulation value (reciprocal of clothing conductance) °C m^2 hr/kcal

H = pilot's metabolic heat load kcal/m^2 hr

α_{CS} = pilot's clothing absorptivity to solar radiation

S = solar heat flux external to the cockpit.

All temperatures are in °K in this expression.

A relationship between I_A and the mean air velocity over a seated subject is given by Winslow et al.[5], and this relationship has been used in preference to other possible relationships (discussed in section 6) to replace I_A in equation (2) by air velocity.

Assuming a value of unity for the effective emissivity from wall to clothing and 75% transmission (τ) of solar radiation through the transparencies, it is possible to determine T_W for various values of T_E for any given pilot's work rate (H) and clothing assembly (I_C). As an example the relationship between T_E, T_W and the air velocity required to keep lightly clad, resting pilot comfortable (i.e. $T_{PS} = 33°C$) is shown in Fig.2, for the zero solar radiation condition (the remaining relationships shown in this figure are explained in section 3.4).

The relevant part of Fig.2 (re-orientated) is used in the construction of the design curves. Solutions of the equation for other assumed conditions were obtained by using the computer program shown in Appendix B.

3.3 Relationship between 'environmental velocity' and air flow

In the preceding paragraph it was stated that the mean environment temperature required for pilot comfort is a function, among other things, of the mean air velocity over the pilot. The relationship between the cabin inlet temperature and the mean environment temperature is later shown (section 3.7) to be a function of cabin air mass flow. Thus to express pilot comfort in terms of cabin inlet air conditions requires a relationship between cabin air mass flow and mean velocity over the pilot.

Except on the face and other exposed areas of the body it has been found in R.A.E. tests[4] that an air velocity of 600 ft/min is acceptable and that in these tests this limit corresponded to a cabin air mass flow of 24 lb/min.

Assuming that the air distribution scheme is well designed, the air velocity to which any part of the pilot is exposed (with the exception of the face and possibly the hands and ankles) should not depart greatly from the mean value. Also it is reasonable to suppose that this environmental air velocity will change linearly with the total cabin air flow.

An air mass flow scale has therefore been included in Fig.2.

3.4 Heat exchange in the cockpit

In previous work on air distribution in aircraft cockpits[4,6], the heat transfer coefficient (h_{int}) from the cockpit inner surface was determined, and shown to be a function of the cabin air mass flow. This coefficient was defined by the expression:

$$Q = h_{int} A_W (T_W - T_M) \tag{3}$$

where Q = heat flow through cockpit walls excluding leakage heat in CHU/hr

A_W = total surface area of the cockpit (excluding front and rear bulkheads), ft^2

T_M = mean air temperature in the cockpit

= $0 \cdot 5 (T_{in} + T_{out})$, °C

In the present context a heat transfer coefficient h_{WE} from the inner surface of the wall (T_W) to the immediate environment of the pilot (T_E) is required, such that

$$Q = h_{WE} A_W (T_W - T_E) \quad . \tag{4}$$

Combining (3) and (4) gives

$$h_{WE} = h_{int} (T_W - T_M)/(T_W - T_E) \tag{5}$$

(Note that both h_{WE} and h_{int} cover heat lost from the surface by convection and radiation.)

The previous work[4] indicated that the optimum air distribution scheme gave a mean environmental temperature such that

$$T_E - T_{in} = 0 \cdot 75 (T_{out} - T_{in}) \tag{6}$$

Using the data of the reference, values of h_{WE} have been calculated. The variation in h_{WE} with air flow is shown in Fig.3 over the range tested (air flow varied from 8 lb/min to 25 lb/min). Below 8 lb/min it has been assumed that natural rather than forced convection will occur and the heat transfer coefficient will remain approximately constant at 1 CHU/hr ft °C.

Though strictly, the coefficient is a function of velocity rather than mass flow it is evident that they are related, the relationship depending on the dimensions of the cockpit and the method of air distribution. This is briefly discussed in section 6. The mass flow, wall velocity relationship is unlikely to be the same as that relating the mass flow and the velocity in the vicinity of the pilot.

Using the relationship between cabin total air mass flow and h_{WE}, constant q lines (equal heat flow per square foot of insulated surfaces) have been constructed in Fig.2. Constant $(T_W - T_E)$ curves used in their construction are also shown.

The values of T_{out} and T_{in} of equation (6) are simply a function of the total cabin heat pick up and the air mass flow. It will be assumed that if part of the total heat load only is considered, then the value of T_E is unchanged and the cabin outlet and inlet temperatures will be modified to T'_{out} and T'_{in} such that, for example

$$(T_E - T'_{in}) = 0{\cdot}75\,(T'_{out} - T'_{in}) \tag{6a}$$

3.5 Heat flow through the cockpit insulation

With a perfect insulation scheme, the heat flow through the insulation is given by

$$Q = (k/\ell)\,A_W\,(T_S - T_W) \tag{7}$$

or

$$q = (k/\ell)\,(T_S - T_W) \tag{7a}$$

where k/ℓ = the conductance of the insulated wall in CHU/hr ft^2 °C
T_S = the cockpit external skin temperature, which is a function of the flight condition (section 2.2(b)) in °C.

Equation (7a) has been expressed graphically in the related Figs.4a and 4b in which $(T_S - T_W)$ is in each case the base.

3.6 Total heat flow into the cockpit

A method of calculating heat flow into an aircraft cabin, in detail, has been presented by Torgenson, Johnson and Wright[7]. However such calculations require a detailed knowledge of the aircraft structure which is often not available at the stage when design of the air supply system and/or insulation scheme should be initiated. The following approach is therefore more suitable, when initial design data is required.

Experience has shown[4,6,8,9,10], that in practical applications, heat flow through aircraft insulation is invariably greater than would be expected from simple theoretical considerations, due to heat leakage through structural members penetrating, or partly penetrating, the insulation (including the fin effects of bulkheads). This may be expressed as

$$q' = Fq \tag{8}$$

where q' = the heat entering the cockpit in CHU/sq ft hr including heat through heat leakage paths

F = the heat leakage factor.

F is a function of the total air flow (M) through the cockpit (fundamentally of air velocity over the wall), and the relationship between F and M for a simulated cockpit[4,6,8], carefully insulated to have a theoretical wall conductance of 0·24 CHU/hr ft^2 °C between attachment points, is shown in Fig.5. The relationship is linear.

The heat leakage appears to occur through a relatively small total area compared to that covered by the bulk insulation[8], and it is assumed therefore that the higher temperature at the heat leakage paths will have only a minor influence on comfort, but will affect total cabin heat load.

It may be argued that in a nominally uninsulated aircraft, i.e. one relying on the insulating effect of instruments and equipment only, the overall effective wall conductance will be high and the heat leakage factor low. (In the limit, as the wall conductance approaches infinity the heat leakage factor approaches unity.) Also with insulation approaching theoretical perfection, attachment points and hence heat leakage points will still exist and the heat leakage factor will therefore approach infinity.

Using the above arguments, an assumed variation of heat leakage factor with bulk insulation conductance has been constructed in Fig.6 for the simulated cockpit previously discussed[4,6,8] at a cockpit total air flow of 25 lb/min.

Using the assumed values of F at 25 lb/min cabin air flow, Fig.7 has been drawn assuming a linear relationship between F and M for all values of wall conductance.

3.7 Cabin heat pick-up

The total temperature rise of the cabin cooling air, from inlet to exit from the cabin, necessary to remove heat Q' entering the cockpit through the walls, and including heat leakage, may be expressed by

$$FQ = Q' = MC_P\,(T'_{out} - T'_{in}) \tag{9}$$

or

$$A_W\,Fq = A_W\,q' = M\,C_P\,(T'_{out} - T'_{in}) \tag{9a}$$

where C_P = the specific heat of air at constant pressure

T'_{out} = air temperature at exit from the cockpit °C necessary to remove wall heat flow Q'

T'_{in} = the inlet air temperature necessary to remove the heat quantity Q' .

But using equation (6a)

$$FQ = Q' = \frac{4}{3}\,M\,C_P\,(T_E - T'_{in}) \quad . \tag{10}$$

This relationship is shown in Fig.8 for F = 1 (i.e. Q = Q'). The cockpit surface area has been assumed to be 60 sq ft, thus the ordinate q in CHU/hr ft^2 is numerically equal to Q in CHU/min. For values of F other than 1, the air temperature rise necessary to remove the additional heat flow due to leakage is obtained by increasing the basic temperature rise by the value of F appropriate to the air mass flow.

In addition to the cockpit wall heat flow, the cabin conditioning air has to remove the pilot's metabolic heat output (Q_M), any electrical heat load (Q_E), plus any solar radiation entering the cockpit via the transparencies (Q_S), i.e. the total heat pick-up in the cabin,

$$Q_T = Q' + Q_M + Q_E + Q_S \quad . \tag{11}$$

If the additional heat is assumed to be distributed in the same way as the wall heat flow,

$$Q_T = \frac{4}{3} M C_P (T_E - T_{in}) \tag{12}$$

and subtracting (10) from (12)

$$Q_M + Q_E + Q_S = M C_P \frac{4}{3} (T'_{in} - T_{in}) \quad , \tag{13}$$

i.e. at any cabin air mass flow, each additional heat flow necessitates a further reduction in inlet temperature if the pilot's mean environmental temperature, and hence comfort level, is to be maintained.

Q_S, the total solar heat load into the cabin is assumed to be equal to the product of the projected area of the transparencies and the solar intensity (an area of 12 sq ft is assumed).

As an approximation all heat absorbed in the transparency is assumed to enter the cabin by conduction*.

Curves showing the variation of the required decrease in inlet temperature for typical values of Q_M, Q_E and Q_S are shown in Fig.9.

4 COMBINED DIAGRAMS ('DESIGN CURVES')

4.1 Construction

For convenience of use, the relationships discussed above and presented graphically in Figs.2 to 8 may be combined into a single diagram such as Fig.10. In Fig.10, Fig.2 (re-orientated) forms the lower right hand quadrant, Figs.4(a) and 4(b) (re-orientated) form the upper and lower left hand quadrants respectively, while the upper right hand quadrant is composed of Figs.7 and 8.

Using Fig.10 and Fig.9 the cabin air requirements (i.e. mass flow and inlet temperature) can be determined to provide thermally comfortable

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* Note: The proportion of absorbed heat which enters the cabin is in fact a function of the relative thermal resistance to inward and outward flows. A large inward (absorbed) heat flow would raise the canopy inner surface temperature and necessitate a reduction in cabin inlet air temperature to compensate for increased radiation on the pilot. This correction is not applied but some compensation results from assuming that all the absorbed heat contributes to the cabin heat load, necessitating a drop in cabin inlet temperature.

conditions for a pilot in the cockpit under consideration at various cockpit skin temperatures and insulation values. Fig.10 applies to a pilot at rest and wearing lightweight clothing, with no solar radiation. The effect of varying cockpit heat load may be determined by factoring information from Fig.9 appropriately.

Similar families of curves for different pilot work rates and clothing insulation values, with and without solar radiation, are given in Appendix C.

In the composite figures (Appendix C), all except the lower right hand quadrants are identical. Fig.9 giving inlet air temperature reductions necessary to remove the metabolic, electrical, and solar heat loads from the cabin, is common to all the cases considered.

4.2 Use of 'design curves'

An example is given of the manner in which inlet air flow/temperature requirements for comfort in the cockpit specified may be derived from Fig.10.

A vertical line is drawn in the left half of the figure, intersecting the k/ℓ = 1·0 CHU/hr ft^2 °C line at point 'A' corresponding to Q = 50 CHU/hr ft^2 (or 50 CHU/min for a cockpit of 60 sq ft surface area), and intersecting the T_S = 100°C line at 'B' where T_W = 50°C. A horizontal line is drawn from the latter point to intersect the Q = 50 line* in the lower right hand section of the figure at 'C'. This point defines the air mass flow (9.8 lb/min) and the required environment temperature (T_E = 16°C). The vertical line through 'C' intersects the horizontal through 'A' at a point 'D', which defines the inlet temperature (T''_{in}), relative to the environment temperature (T_E), required to remove the basic heat flow through the cockpit walls (16°C in the example). However there is additional heat entering the cockpit by heat leakage, the leakage factor being indicated by point 'E' (in this case 1·10).

Thus the necessary drop in inlet temperature below the environment temperature is 1·10 × 16 = 17·6°C, i.e. the inlet temperature required to remove the total wall heat flow, T'_{in} = 16° - 17·6° = - 1·6°C.

A further reduction in inlet temperature is required to remove the metabolic and electrical heat from the cabin. The appropriate reduction for

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*<u>Note</u>: If the horizontal line fails to cut an appropriate Q line or interpolated line in the lower right hand of the figure then a different position of the vertical line must be tried.

metabolic heat load indicated by point 'F' of Fig.9 is 1·5°C (H = 50 kcal/hr m^2), and for the electrical heat load, indicated by point 'G', 4·9°C (assuming load of 475 watts). The 'corrected' inlet air temperature T_{in} becomes -1·6 - (1·5 + 4·9)°C = -8°C, corresponding to the low mass flow of 9·8 lb/min. Other inlet air mass flow/inlet temperature points may be derived by commencing at a different value of Q. In this way the characteristics shown in Figs.12, 13 and 15 were produced, the points obtained in the above manner being shown.

5 EFFECT OF VARIATION OF PARAMETERS ON CABIN AIR REQUIREMENTS FOR COMFORT

5.1 General

To determine the effects on air supply requirements of varying the numerous parameters, the relationships in sections 3.2 to 3.7 were incorporated in a Computer program (Appendix D). In this way the effects were investigated without the necessity of producing 'design curves' for each of the numerous cases examined. The results of this investigation are illustrated in Figs.11 to 22 and discussed in the following paragraphs, which also include comments on some more general points of significance.

5.2 Effect of wall conductance and aircraft skin temperature on cabin air requirement

The effect of wall conductivity is shown in Fig.11, which gives the cabin air requirements for a skin temperature of 80°C for varying degrees of wall insulation. Solar radiation is assumed. If the minimum air temperature obtainable from the cooling air system is above the requirement for comfort at the particular mass flow, then one way of achieving an improvement in crew comfort is to add insulation. The possible advantage of using wall insulation is more evident at higher skin temperatures, see Figs.12, 13 and 14. These show that the changes in air inlet conditions to maintain crew comfort are smaller in well insulated cockpits. Conversely, if air supplies are constant, the departure from a comfort standard is smaller with changes in skin temperature if the cockpit is well insulated. A further advantage, not evident from the diagrams, stems from the thermal capacity of the insulation (discussed briefly in section 6).

5.3 Effect of clothing insulation and pilot's work rate

The effects on cabin air requirements of clothing insulation and pilot's work rate are shown in Fig.15 for the case of no solar radiation.

Though it is reasonable to suppose that lightweight clothing would be worn in an aircraft designed for the thermal conditions considered, certain roles require that heavier clothing (e.g. pressure suits and immersion suits) be worn. Then, apart from any consideration of sweat removal, personal conditioning may have to be considered.

Under certain conditions, perhaps due to atmospheric conditions, an increase in metabolic rate is unavoidable. However the cockpit layout should be designed to minimise the general level of activity with consequent economy in cabin cooling air.

In further discussions it will be assumed that the cockpit is well designed to minimise crew work and that lightweight clothing is worn.

A method of allowing for cooling loads due to personal conditioning is discussed in section 5.9.

5.4 The effect of solar radiation

Fig.16 compares the cabin air requirements for an insulated cockpit, with alternative transparency areas, with and without solar radiation. The solar radiation intensity assumed is the sea level maximum value of 180 CHU/hr ft^2. At higher altitudes, solar radiation effects would be greater because of the reduced atmospheric absorbtion.

In determining the air requirements with solar radiation, it has been assumed that 25% is absorbed by the transparency material and that the reflectivity of the pilot's clothing is 50% ($\alpha_{CS} = 0.5$). Reflections at the inner, intermediate and outer surfaces of the transparencies have been neglected.

Curve B of Fig.16 represents a 50% solar radiation case. This intermediate value may occur if the sun is at a lower elevation or if thin cloud, etc., causes greater solar absorption. It is assumed that areas of the transparencies, and of the pilot, subjected to solar radiation are constant. It is seen that the cabin air requirements, with and without solar radiation, are widely different and, since solar effects are felt immediately by the pilot, it is evident that ideally a sensor should be positioned in the cockpit to respond to changes in solar intensity and adjust the inlet air supplies appropriately.

The other implication is that since generally only part of the body is subjected to solar radiation, there is an incompatibility between the air supplies required for, say, the lower and upper halves of the body while the sun shines. This effect might be overcome if the sensor were used to bias the air supplies to the upper part of the body when necessary, at the same time reducing inlet temperature if possible.

Fig.17 (Curve B) shows that of the inlet air temperature drop necessary to restore comfort conditions when the sun is shining, approximately one third is required to maintain body heat balance in a state of comfort while the remainder is used to remove the total solar heat load which has entered the cabin while maintaining the same 'environment temperature'.

Fig.17 was constructed using the 'design curves' of Figs.9 and 10 and Appendix C in the manner described in section 4.2. (Comparison of Curves A and C of Figs.16 and 17 shows that this method gives adequate accuracy for determining air flow requirements. Minor differences result from the assumption that the effective emissivity from wall to pilot was unity, in the construction of the design curves and 0·84 in the computer program (section 5.6).)

Methods of reducing solar effects are discussed in sections 5.5 and 5.6.

5.5 Reduction of solar radiation effects

The most direct method of reducing solar radiation effects is to use the minimum transparency area compatible with vision requirements. This primarily affects the heat balance of the cabin rather than that of the pilot. (In the worst case, say with the sun directly overhead, the radiation onto the pilot is likely to be unaltered since it is assumed that there will be a limit to the possible reduction in transparency area.)

On the ground, when cool air supplies may be limited, the use of an external sun shade would considerably improve cockpit conditions.

Solar radiation effects may be reduced by increasing the absorptivity of the glazing material, preferably to infra-red radiation but as little as possible to the visible spectrum. Some of the absorbed heat will enter the cockpit with consequent effects on cabin air requirements (see section 3.7).

Another method of reducing solar radiation through the transparencies is to introduce a reflecting layer in the transparent material, e.g. a very thin gold film[11,12]. The effect of such a reflective layer is shown in Fig.19 where a reflectance of 40% to solar radiation is assumed. It is an advantage to locate this layer near the outer surface; if near the inner surface, the reflected radiation suffers further absorption in the transparency material, a greater part of the absorbed heat tending to enter the cabin by conduction due to the smaller thermal resistance to the inside of the cabin. The major effect in this case is on the crew heat balance.

5.6 Variation of clothing and wall emissivities

In practice it is likely that no change in wall emissivity (ε_W) could be countenanced because of the need to minimise light reflections, and a constant value of 0·9 has been assumed in the investigation of parameter changes. A basic value of 0·85 has been assumed for the emissivity of the pilot's clothing.

The effect of providing the pilot with low emissivity outer clothing (ε_C = 0·2 assumed) is shown in Figs.18a and 18b. Some economy of cooling air is achieved; the advantage is more apparent when the cabin walls have a low insulation value and/or when there is no solar radiation.

Cooling air requirement to compensate for solar radiation would be less severe if the solar absorption of the clothing* could be reduced. (A suitably finished white or aluminised overall might be an advantage.)

5.7 The effect of cabin air distribution

Cabin air distribution has an important bearing on comfort, a fact which is confirmed by the need for 'punkah louvres' which the crew adjust under hot conditions to give maximum local heat transfer, subject to a self imposed limitation of annoyance caused by turbulence, etc. The effect of air distribution has also been clearly demonstrated in R.A.E. tests from which much of the heat transfer information in this Report has been extracted.

It has been assumed that if alteration of the air distribution decreases the convective heat transfer coefficient at the crew there will be a corresponding increase in convective heat transfer from the cabin walls (i.e. including the transparencies), and vice versa. In Fig.20 the cabin air requirements in these two cases have been compared with those for the basic distribution considered in all the previous discussions. (In fact, the possibility of appreciably increasing pilot's heat transfer without producing discomfort is remote with the air distribution arrangement shown in Fig.1, which has been fairly extensively investigated experimentally[4].)

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* Note: The value of clothing and wall emissivities ε_C and ε_W refer to the approximate emissivities at temperature levels appropriate to the cockpit, while α_{CS} refers to the absorptivity of the crew's clothing to solar radiation. ε_C and α_{CS} have been varied independently in the examples in Figs.18a and 18b, though this is unlikely to be the case in practice.

The comparison shows that the air flow requirements for comfort are very dependent on air distribution. It also shows that demisting of transparencies by means of cabin cooling air is positively detrimental to crew comfort, particularly if boosted air flow is obtained at the expense of cooling air flow. Certainly this factor should be taken into account when methods of transparency demisting are being considered.

A second effect of varying cabin air distribution may be to alter the relationship between environmental temperature and the cabin inlet and outlet temperature (equation (6)). Due to entrainment of cabin air by jet action it may not be possible to improve the situation greatly over that expressed by equation (6), but any means of so doing will permit higher air inlet temperatures. This effect is illustrated in Fig.21 which compares the cabin inlet air characteristics for $(T_E - T_{in})/(T_{out} - T_{in})$ values of 0·75 (the case considered throughout) and 0·5. It is assumed that the relationship between mass flow and h_{WE} is unaltered.

5.8 Location of electrical heat loads

In the foregoing work it has been assumed that the distribution of electrical heat loads is such that equation (6) holds true. Ideally however the electrical heat should be removed after the crew has been cooled, as is done when the equipment is incorporated in a bay and cooled by cabin discharge air.

5.9 Personal conditioning

As suggested by Billingham and Kerslake[2], the effect of providing a heat sink adjacent to the skin, in the form of personal conditioning, is to reduce the heat flow through the clothing. In effect, H in equation (2) is replaced by H', the net heat flow through the clothing, which may be negative. Cabin cooling air requirements for values of H' = 50, 0 and -50 kcal/m^2 hr are shown in Fig.22. The appropriate value of H' for any work rate requires that, as well as the work rate, the cooling capacity of the air ventilated suit or water cooled suit be known.

5.10 Typical inlet air characteristics

The general form of the cabin air temperature/flow characteristics (Figs.11 to 22) is similar in all cases. When solar radiation is experienced, the average air conditioning system relying on engine-tapped air is unlikely to meet the cabin air requirements for comfort during ground idle and taxying conditions when the delivered air flow is small and the delivery temperature must be above 0°C to avoid freezing troubles. Then alternative air supplies from a truck for ground running or from an APU will be required. An alternative solution might be to provide personal conditioning, though this might be considered undesirable if required for a ground running condition only.

5.11 Summarised results

Table 3 has been compiled to give a quick indication of the relative importance of various parameters on cabin air requirements. The table shows the cabin air inlet temperature required when certain parameters are altered in value from a basic case. The parameter that has the greatest effect is solar radiation. Other important aircraft parameters are the method of air distribution and the amount of insulation. In the case of the pilot, work rate and clothing assembly (surface finish and the use of personal conditioning) have the greatest effect.

6 VALIDITY OF 'DESIGN CURVES'

The present work may be divided into two parts:

(a) the investigation of the relative effects of various parameters on cabin air requirements for comfort, and

(b) the investigation of a method of presenting the relationship between the various parameters in the form of 'design curves'.

With regard to (a), this study has been based on simple heat transfer considerations and the broad conclusions are not seriously in question. The value of the 'design curves' for precisely defined cockpit air requirements depends on the assumptions made in their construction, and further work is necessary to substantiate certain of the assumptions.

The 'design curves' are considered to be a good approximation for a well-insulated cockpit since they are based on experimental evidence[4,6,8]. For less well-insulated cockpits there is little or no accurate experimental data and information is needed to substantiate the assumptions made for typical heat leakage. Also a realistic insulation equivalent of a cockpit wall with instruments and equipment should be measured since this is the basic case with which other insulated walls should be compared.

The effect of cockpit size on the relationship between cabin cooling air mass flow and the mean effective velocity over the walls and the crew should be investigated. It may then be possible to introduce a cockpit size factor into the relationships between air mass flow and the heat transfer coefficients at the crew and walls. In the present study, a direct relationship between air mass flow and a heat transfer coefficient from the cabin walls to a pilot's environment was determined using experimental results[4,6]. The coefficient includes a radiation component which will vary with wall and clothing surface temperatures. (It is considered that the effective emissivity from wall to clothing will be greater than 0·9 and will have little effect on the radiation component.) It should be noted however that whereas the convective heat flow applies to the whole cockpit surface under consideration, the radiation effect is mainly a function of the surface area of the pilot, and its influence proportionally reduced.

The relationship between mean air velocity over a subject and convective heat transfer from his surface has been investigated by various workers[5,13], including Dr. McK. D. Kerslake of the R.A.F. Institute of Aviation Medicine. There is good agreement between the work of Kerslake (Fig.23) and Nelson et al.[13], while the work of Winslow et al.[5] gave consistently higher values of convection coefficients. This may be due to a degree of turbulence in the latter experiments, and the higher values, used in this present investigation, are possibly more representative of cockpit conditions. However, confirmation under conditions more representative of the cockpit distribution assumed in this Report (see Fig.1) is needed.

In the construction of the 'design curves' a certain relationship between the mean environment temperature (T_E) and the air inlet and outlet temperatures has been assumed. This relationship was based on experimental evidence[4] from a particular cockpit, and, if possible, evidence from other cockpits should be obtained.

7 EVIDENCE FROM FLIGHT TESTS

Flight test records on various aircraft have been examined to provide evidence in support of the present work, but in general it was found that the information was lacking in some respects and was not useable in this context. Very often the information could have been completed with very little additional instrumentation.

In order that maximum value be obtained from future flight trials (particularly those associated with air conditioning system testing), the following measures should be implemented where possible.

(a) A wire suit[14,15], or some other suitable instrument, should be worn to indicate the pilot's mean skin temperature.

(b) Either the cabin air mass flow should be measured during flight or sufficient information given to allow the cabin mass flow to be estimated.

(c) Cabin inlet and outlet air temperatures should be measured.

(d) Whether the sun is shining should be recorded.

(e) Clothing assembly should be noted.

These points are considered essential for theoretical assessment of the cockpit conditioning system, and the following additional information would be of great value.

(f) Cockpit inner surface temperatures. It is suggested that a limited number of thermocouples be attached to surfaces that could be considered typical, in the vicinity of the pilot. Failing this it may be possible to use a portable surface temperature measuring device.

(g) Environment temperature recorded at several positions such as at, say, the head, shoulder, waist and feet. The instrumentation would not necessarily be attached to the pilot and again it is possible that a portable manually operated instrument could be used.

This information would be used to confirm the validity of the assumptions made in preparing the design curves and computer program and for assessing the performance of the wire suit as a method of establishing thermal comfort. Once this has been done flight test measurements would become much simpler and it should only be necessary to measure the mean skin temperature as measured by a wire suit or suitable alternative in order to establish pilot thermal comfort.

8 FURTHER DEVELOPMENTS

Experiments[4] on a simple insulated cockpit, in which no instruments were fitted and solar radiation was not represented, have shown that the air requirements for comfort are a function of the air distribution scheme.

Similar experiments should be conducted with a fully equipped cockpit and better representation of solar radiation, to determine the optimum air distribution. It is considered that such an optimum distribution should apply broadly to all high performance military aircraft, which of necessity are about the same size and shape.

Having established a basic optimum method of air distribution, the additional information referred to in section 6 can be obtained to enable 'design curves' of the type proposed to be of general use in predicting cabin cooling air requirements in the steady state. With more information it may be an advantage to consider heat transfer through the 'walls' and transparencies separately rather than using an average 'wall'.

It is evident that in many cases air conditioning supplies do not meet the requirements for comfort, and it may be argued that to attempt to design a cooling air system to meet all the flight conditions, irrespective of duration, would result in a severe penalty on the aircraft. However it is considered that efficiency or comfort must be a primary consideration and if the crew is thermally uncomfortable during parts of the flight then the integrated effect of this discomfort should be assessed, possibly in terms of a heat storage index. This is a complex physiological subject which includes the effect of evaporation heat loss, not examined in this study. However heat storage and heat stress has been examined by various workers[16,17]. It is suggested that a development of a computer program such as shown in Appendix D might be used to compare the actual and desired environmental temperature over a flight plan and perform the necessary integration of 'heat storage'. Such a program should allow for the heat capacity of the cabin, particularly that of any wall insulation, which would delay subjective effects of certain parameter changes such as the aircraft skin temperature thus possibly relieving conditions in short high speed excursions.

Consideration of cockpit conditions other than comfortable, when evaporative cooling by sweating becomes important, would require that cabin humidity be included as an additional parameter.

9 CONCLUSIONS

Assuming that a mean skin temperature of 33°C indicates thermal comfort, then the heat transfer processes within an aircraft cockpit may be analysed to obtain the required cabin inlet air conditions. Design curves and a computer program, which take account of all the parameters involved, are presented. The information used in preparing the design curves is partly based on experimental evidence from a particular aircraft cockpit: although the cockpit was not fully equipped with instruments, the results are considered to be sufficiently accurate to indicate the relative importance of the various parameters on cabin air supply requirements for comfort.

From this analysis, the following points are evident.

(a) Solar radiation has the greatest effect on the cabin air requirements and measures should be taken to reduce this by keeping transparency areas to a minimum compatible with operational requirements of the aircraft and/or to incorporate methods of reducing the radiation transmission through the transparencies. In any tests to assess the efficiency of a cockpit cooling system, it is essential to simulate solar radiation.

(b) The influence of cabin air distribution on the air requirements for comfort is considerable, and further tests should be made to establish the best distribution system for a representative, fully equipped, cockpit and to confirm the validity of the design curves. Mean skin temperature of the crew should be measured, the relationship between the local environment temperature and the cabin inlet and outlet temperatures confirmed, and the heat transfer process from the cabin walls to the cabin examined. The degree of heat leakage into a cockpit should be investigated and typical heat leakage factors determined for cockpit walls with varying degrees of insulation. The laboratory investigation should be supplemented by flight test information.

(c) Heat transfer from the pilot to the cockpit air is also dependent on distribution and affects the air supply requirements. Heat transfer from a seated human subject has been examined previously but there appears to be some disagreement in the findings of different authorities: information under the more complex flow conditions of an aircraft cockpit is necessary for more accurate predictions to be made.

(d) Other factors which influence cabin air requirements for thermal comfort are the mean work rate of the crew (a factor influenced by cockpit layout) and the clothing assembly, including its surface finish.

Appendix A

HEAT BALANCE OF THE PILOT

(Average) pilot's total surface area[1], A_P = $1 \cdot 8$ m^2

Effective surface area A (i.e. the sum of those areas not in contact with each other or the seat) = $1 \cdot 45$ m^2

Area presented to solar radiation, A_S = $0 \cdot 45$ m^2

Effective area subject to radiation from cockpit wall $= A_R = 0 \cdot 7A$ = $1 \cdot 015$ m^2

The above values are taken from Ref.2.

The basic equation expressing the thermal balance of the pilot is,

$$Q_{RP} + Q_M + Q_{SP} = Q_C \ . \qquad \text{(A-1)}$$

For a body of surface area, A_R (emissivity, ε_C) and at a temperature T_C enclosed by a surface of area A_W (emissivity ε_W) at temperature T_W the radiant heat exchange is given by,

$$Q_{RP} = \sigma \, \varepsilon_{eff} \, A_R \, (T_W^4 - T_C^4) \qquad \text{(A-2)}$$

where the effective emissivity,

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_C} + \frac{A_R}{A_W}\left[\frac{1}{\varepsilon_W} - 1\right]} \qquad \text{(A-3)}$$

σ = Stefans constant
= 10^{-8} CHU/hr ft^2 $^\circ$K^4
= 4.87×10^{-8} kcal/hr m^2 $^\circ$K^4 .

Hence in this context

$$Q_{RP} = 3 \cdot 41 \times 10^{-8} \, \varepsilon_{eff} \, A \, (T_W^4 - T_C^4) \text{ in cgs units} \qquad \text{(A-4)}$$

where T_W = cockpit inner surface temperature $^\circ$K
T_C = clothing surface temperature $^\circ$K
($A_R = 0.7$ A)

Also in cgs units, the metabolic heat output,

$$Q_M = H A \tag{A-5}$$

and the solar heat load of the pilot,

$$Q_S = \alpha_{CS} A_S \tau S \tag{A-6}$$

where S = solar radiation flux per square foot incident on the transparencies at sea level

$S \simeq 180$ CHU/hr ft^2 = 870 kcal/m^2 hr

τ = proportion of solar radiation transmitted by the transparencies, assumed to be 75%

A_S = 0·31 A = area of pilot subject to solar radiation

α_{CS} = absorptivity of clothing, here assumed to be 0·5

$$Q_C = h_C A (T_C - T_E) \quad , \tag{A-7}$$

where h_C = coefficient of heat transfer from the surface of the clothing to ambient

$$= \frac{1}{I_C} .$$

(Note. The relationships between I_A and air velocity over the crew is taken from Ref.5.)

T_E = mean environmental temperature over the man.

Substituting in equation (A-1)

$$\sigma \varepsilon_{eff} 0{\cdot}7 (T_W^4 - T_C^4) + H + \alpha_{CS} \tau \frac{A_S}{A} S = (T_C - T_E)/I_A . \tag{A-8}$$

Part substituting values given above, in cgs units

$$3{\cdot}41 \times 10^{-8} \varepsilon_{eff} (T_W^4 - T_C^4) + H + \alpha_{CS} \tau \frac{A_S}{A} S = (T_C - T_E)/I_A . \tag{A-9}$$

Finally, the clothing temperature (T_C) is related to the skin temperature T_{PS} by,

$$Q_M = (k/\ell)_C \, A(T_{PS} - T_C) \qquad \text{(A-10)}$$

where $(k/\ell)_C$ = the conductance of the clothing assembly

= $1/I_C$

I_C = the clothing insulation value

whence

$$H \, I_C = T_{PS} - T_C$$

and

$$T_C = T_{PS} - H \, I_C \; . \qquad \text{(A-11)}$$

Thus

$$3{\cdot}41 \times 10^{-8} \, \varepsilon_{eff} \, (T_W^4 - (T_{PS} - H \, I_C)^4) + H + 0.37 \, \alpha_{CS} \, \tau \, S = (T_{PS} - H \, I_C - T_E)/I_A \qquad \ldots\ldots \quad \text{(A-12)}$$

Note: A similar equation was used in Ref. 2 in the discussion of globe temperature.

Appendix B

MERCURY COMPUTER PROGRAM FOR SOLUTION OF SIMPLIFIED EQUATION (2)

Assumptions $\varepsilon_{eff} = 1$
$\alpha_{CS} = 0 \cdot 5$
$\tau = 0 \cdot 75$
$S = 870$ kcal/m^2 hr
$T_{PS} = 33^\circ C$

```
TITLE
COMFORT CHARACTERISTICS
TITLE
T L HUGHES    JOB NO2892

CHAPTER 0
D→5
E→6

5)READ(A)                    metabolic heat kcal/m² hr
READ(B)                      clothing insulation °C m² hr/kcal
READ(X)                      0·31 αCS τ S
C=AB
I=0(1)5
READ(DI)                     "Air insulation" at 600, 500 ... 100 ft/min
REPEAT


620,30
620,13

G=33-C                       Clothing surface temp °C
G=G+273
J=0
H=0
READ(E')                     1st environment temperature considered °C
READ(Z)                      Final environment temperature considered °C
READ(V)                      1/3.41 εeff
E=E'
1)E=E+H
JUMP 5, E≥Z
E=E+273

D=G-E

I=0(1)5
EI=D/DI
EI=EI-A-X

EI=VEI
```

```
F=G/100
F=FFFF
EI=EI+F
JUMP 5,0≥EI

EI=ψSQ RT(EI)
EI=ψSQ RT(EI)
EI=100EI
EI=EI-273
REPEAT

620,30
620,13
E=E-273
PRINT(E)2,0                         Environment temperature considered
I=0(1)5
PRINT(EI)3,2                        Wall temperatures for V = 600 - 100 ft/min
REPEAT
H=1

JUMP 1

620,30
620,13
620,13

ψSQ  RT
END
PSA
CLOSE
→
```

Appendix C

DESIGN CURVES

Design curves for the following conditions are presented.

Fig.C1	Lightweight clothing assembly (I_C = 0·1 °C m^2 hr/kcal) Pilot at rest (H = 50 kcal/m^2 hr) Solar radiation at ground level intensity (180 CHU/hr ft^2) Absorption of solar radiation by transparencies 25% Absorption of solar radiation by clothing 50% Effective wall to clothing emissivity 1.
Fig.C2	Heavier clothing (I_C = 0·2°C m^2 hr/kcal) No solar radiation Otherwise as for Fig.C1.
Fig.C3	As for Fig.C2 but with solar radiation.
Fig.C4	Lightweight clothing (I_C = 0·1°C m^2 hr/kcal) Pilot doing moderate amount of work (H = 100 kcal/m^2 hr) No solar radiation.
Figs.C5 to C7	As for Figs.C1 to C3 respectively but with pilot doing moderate amount of work (H = 100 kcal/m^2 hr)

Appendix D

MERCURY COMPUTER PROGRAM TO DETERMINE CABIN AIR SUPPLIES FOR PILOT'S COMFORT

Assumptions: Cabin "exposed" surface 60 sq ft including transparencies.
Transparency "plan" area 12 sq ft

```
TITLE
CABIN AIR REQUIREMENTS
TITLE
T.L. HUGHES 16/4/68          30/8/68
CHAPTER 0
E→7
X→2
V→2

Z→1

7)READ(A)                    Metabolic rate  kcal/m^2 hr
READ(B)                      Clothing insulation °C m^2 hr/kcal
READ(C)                      Clothing absorption of solar radiation
READ(X)                      Solar intensity
READ(Y)                      Absorption of solar radiation by transparencies
READ(Z)                      Reflectance included in transparencies
READ(G')                     G' = 2 if reflecting layer on inside: outside
READ(V1)                     εC, clothing emissivity                 G' = 0
READ(V2)                     εW, wall surface emissivity

READ(A')                     Wall conductance (ideal) k/ℓ CHU/hr ft^2 °C
READ(F')                     Max heat leakage factor for given k/ℓ
READ(C')                     Electrical heat load CHU/min
READ(B')                     Cockpit outer skin temperature °C

READ(H')                     Factor to test the effects of varying heat
Y=1-Y                                                  transfer coefficients
Z1=1-Z
X1=XYZ1

X1=0.31CX1

Y=ψLOG(Y)
Y=G'Y
Y=ψEXP(Y)
X2=X-XYZ

V1=1/V1
V2=1/V2
V=V1+0.11666V2-0.011666      Calculation of 1/εeff.  Assuming effective
                                                   area of man of 10 sq ft
V=0.293V
F'=F'-1
```

```
C=AB                          Temperature differential over clothing
620,30
620,13
620,13

G=33-C                        Clothing surface temperature
G=G+273
H=0

READ(E')                      "Starting" environment temperature °C

2)READ(X')                    Air flow lb/min (for JUMP 7 make M = 0)
JUMP7,X'=0
E=E'
1)E=E+H
E=E+273
D=G-E

D'=0.416X'
D'=ψSQRT(D')
D'=5.86D'

D'=H'D'

E1=DD'

E1=E1-A-X1
E1=VE1
F=G/100
F=FFFF
E1=E1+F
E1=ψSQRT(E1)
E1=ψSQRT(E1)
E1=100E1
E1=E1-273

E=E-273

V'=0.21X'-0.58
W=E1-E
W=WV'/H'
W'=B'-E1
W'= A'W'
CHECK(W',W,0.1,5)
JUMP3,H=1
JUMP4,H=0.1

JUMP8, H=0.01

JUMP9, H=0.001
```

```
H=1
JUMP1
3)JUMP1, W>W'
E=E-H
H=0.1
JUMP1
4)JUMP1, W>W'

E=E-H
H=0.01

JUMP1

8)JUMP1, W>W'

E=E-H
H=0.001
JUMP1
9)JUMP1, W>W'

5)U'=X'F'/25
U'=1+U'

E2=3.11U'W/X'
H=0

PRINT(X')2,1          Air mass flow lb/min
PRINT(E1)2,2          Cockpit inside surface temperature °C
PRINT(E)2,2           Air temperature immediately
                      surrounding pilot (environment temperature) °C
E2=E-E2
PRINT(E2)2,2          Cabin air inlet temperature for comfort neglecting
                      effects on the total cabin heat load of solar,
                      metabolic and electrical heat

E3=0.2055A/X'
E3=E2-E3
PRINT(E3)2,2          E2 corrected for metabolic heat load
E4=3.12C'/X'
E4=E3-E4
PRINT(E4)2,2          E3 corrected for electrical heat load
E5=0.129X2/X'
E5=E4-E5
PRINT(E5)2,2          Fully corrected inlet temperature, i.e.
                      E4 corrected for solar heat
PRINT(W)2,2           Basic heat flow through walls - not factored for heat
                      leakage

620,30
620,13

I=0(1)10
620,0
REPEAT
JUMP2
```

```
ψSQRT
ψLOG
ψEXP
END
PSA
CLOSE
→
```

Table 1

CLOTHING INSULATION VALUES

(Data from Ref. 2)

Clothing assembly	Clothing insulation I_C at ground level
	°C m² hr/kcal
Shirt and slacks	0·1
Battle dress	0·2
Partial pressure assembly	0·4
Heavy cold weather assembly	0·8

Table 2

METABOLIC HEAT PRODUCTION

(Data from Ref. 2)

Activity	Metabolic heat production H
	kcal/m² hr
Sleeping	40
Sitting still	50
Mild physical work	75
Working heavy controls, maintaining posture in bumpy conditions and during combat sorties	100

Table 3

RELATIVE EFFECTS OF VARIOUS PARAMETERS ON REQUIRED CABIN INLET TEMPERATURES

Required inlet air temperatures for crew comfort are shown for a cabin air flow of 25 lb/min. The 'basic case' is defined as follows:-

Total cockpit (outside) surface area	60 sq ft
Cockpit skin temperature	100°C
Cockpit wall insulation value	0.3 CHU/hr/ft^2 °C
Cockpit wall surface emissivity	0.9
Clothing insulation	0.1 °C m^2 hr/kcal
Clothing absorptivity to solar radiation	0.5
Clothing surface emissivity	0.85
Pilot work rate (effective)	50 kcal/m^2 hr
Transparency plan area	12 sq ft
Transparency transmittance	75%
Solar intensity	180 CHU/hr ft^2
Electrical heat load	475 watts

In the table below, examples of effect of altering the value of some individual parameters from the basic value, is shown:-

Condition	Required cabin inlet temp. for comfort °C		Remarks
	No solar radiation	Solar radiation	
(a) Basic	15.2	5.5	Section 5.4 and Fig.16
(b) Transparency area 20 sq ft	15.2	2.5	Section 5.5 and Fig.16
(c) Reflective layer in transparency	15.2	10.8-9.2	Section 5.5 and Fig.19
(d) Clothing absorptivity (solar) 0.2	15.2	8.7	Section 5.6 and Fig.18a
(e) Clothing emissivity 0.2	15.7	5.6	Section 5.6 and Fig.18a *
(f) Wall insulation 1.0 CHU/hr ft^2 °C	12	1.5	Section 5.2 and Figs.12 and 14
(g) Cockpit skin temperature 120°C	12.5	-	Section 5.2 and Fig.13
(h) Work rate 100 kcal/m^2 hr	6.5	-	Section 5.3 and Dig.15
(i) Clothing insulation 0.2°C m^2 hr/kcal	10.0	-	Section 5.3 and Fig.15
(j) Electrical heat 1000 watts	13.1	3.4	Section 3.7
(k) Air distribution (decreased velocity over crew)	13.3	0	Section 5.7 and Figs.20 and 21
(l) Air distribution (temperature effect)	-	10.7	
(m) Personal conditioning extracting 210 watts	-	22.5	Section 5.9 and Fig.22

* **Note:** The benefit of low emissivity clothing is more apparent when the wall insulation is low, as shown by Fig.18b.

SYMBOLS

A_P = total surface area of average pilot = 19.4 sq ft (1.8 sq m)

A = crew effective surface area for heat exchange = 15·6 sq ft (1·45 sq m)

A_S = area of pilot presented to solar radiation = 4.95 sq ft (0.45 sq m)

A_R = area of pilot subject to radiation from cockpit walls = 0.7 A = 10·9 sq ft (1·015 sq m)

A_W = total surface area of cockpit excluding front and rear bulkheads - sq ft

A_C = total presented area of transparencies - sq ft

H = effective metabolic heat load per sq ft of pilot's surface area kcal/m^2 hr

H' = net heat flow through clothing kcal/m^2 hr

= H - cooling load of personal conditioning per sq ft of pilot area

h_{int} = heat transfer coefficient from wall surface to cabin mean temperature CHU/hr ft^2 °C

h_{WE} = heat transfer coefficient from wall surface to pilot's environmental temperature CHU/hr ft^2 °C

h_C = heat transfer coefficient from surface of pilot's clothing CHU/hr ft^2 °C

I_A = insulation value of air passing over pilot (reciprocal of convective heat transfer coefficient) °C m^2 hr/kcal

I_C = clothing insulation value (reciprocal of clothing conductance) °C m^2 hr/kcal

(k/ℓ) = ideal cockpit wall conductance CHU/hr ft^2 °C

M = cabin total air flow lb/min (M = Mach number in section 2.2 only)

q = rate of heat flow per sq ft (into cockpit by conduction) of cockpit walls, excluding heat leakage CHU/hr ft^2

Q = total heat entering cockpit by conduction through walls excluding heat leakage = $q\ A_W$ CHU/hr*

q' = rate of heat flow by conduction into cockpit per sq ft of cockpit walls, including heat leakage CHU/hr ft^2

Q' = total heat entering cockpit by conduction through walls including heat leakage = $q'\ A_W$ CHU/hr*

Q_C = heat lost by convection from surface of clothing. CHU/hr (kcal/hr in Appendix A and section 3.2)

Q_E = electrical heat load within cockpit CHU/hr

---

* **Note:** For $A_W = 60$ sq ft, Q and Q' in CHU/min are numerically equal to q and q' in CHU/hr ft^2 °C.

SYMBOLS (Contd.)

Q_{RP} = total radiation heat load from cockpit walls to pilot - CHU/hr (kcal/hr in Appendix A and equation 2)

Q_M = total metabolic heat load - CHU/hr (kcal/hr in Appendix A and section 3.2)

Q_{SP} = solar radiation load on pilot CHU/hr (kcal/hr in Appendix A and section 3.2)

Q_S = solar radiation heat load into the cabin CHU/hr

S = solar heat flux external to the cockpit CHU/hr ft^2

T_A = ambient temperature outside the aircraft °C

T_S = cockpit mean outer skin temperature °C

T_{in} = cabin air inlet temperature °C (allowing for heat leakage and cabin heat loads)

T'_{in} = cabin inlet air temperature required to remove total wall heat flow (allowing for heat leakage)

T''_{in} = cabin inlet air temperature required to remove basic heat flow through walls

T_{out} = cabin exit air temperature °C

T'_{out} = cabin exit air temperature corresponding to T'_{in}

T_M = cabin mean air temperature °C

T_E = mean temperature of the air in the immediate vicinity of the pilot °C

T_{PS} = pilot's mean skin temperature °C

T_C = temperature of external surface of clothing °C

T_W = cockpit inner surface temperature °C

C_P = specific heat of air

α_{CS} = clothing absorptivity to solar radiation

ε_{eff} = effective emissivity from wall surface to clothing surface

ε_W = wall inner surface emissivity

ε_C = clothing emissivity

τ = proportion of solar radiation transmitted by transparencies

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13	N. Nelson L. W. Eichna S. M. Horvath W. B. Shelley T. F. Hatch	Thermal exchanges of man at high temperature. Am. J. Physiol, 151 (1947)
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16	William C. Kaufman	Human tolerance limits for thermal environments of aerospace. AMRL Memo M-27, February 1963
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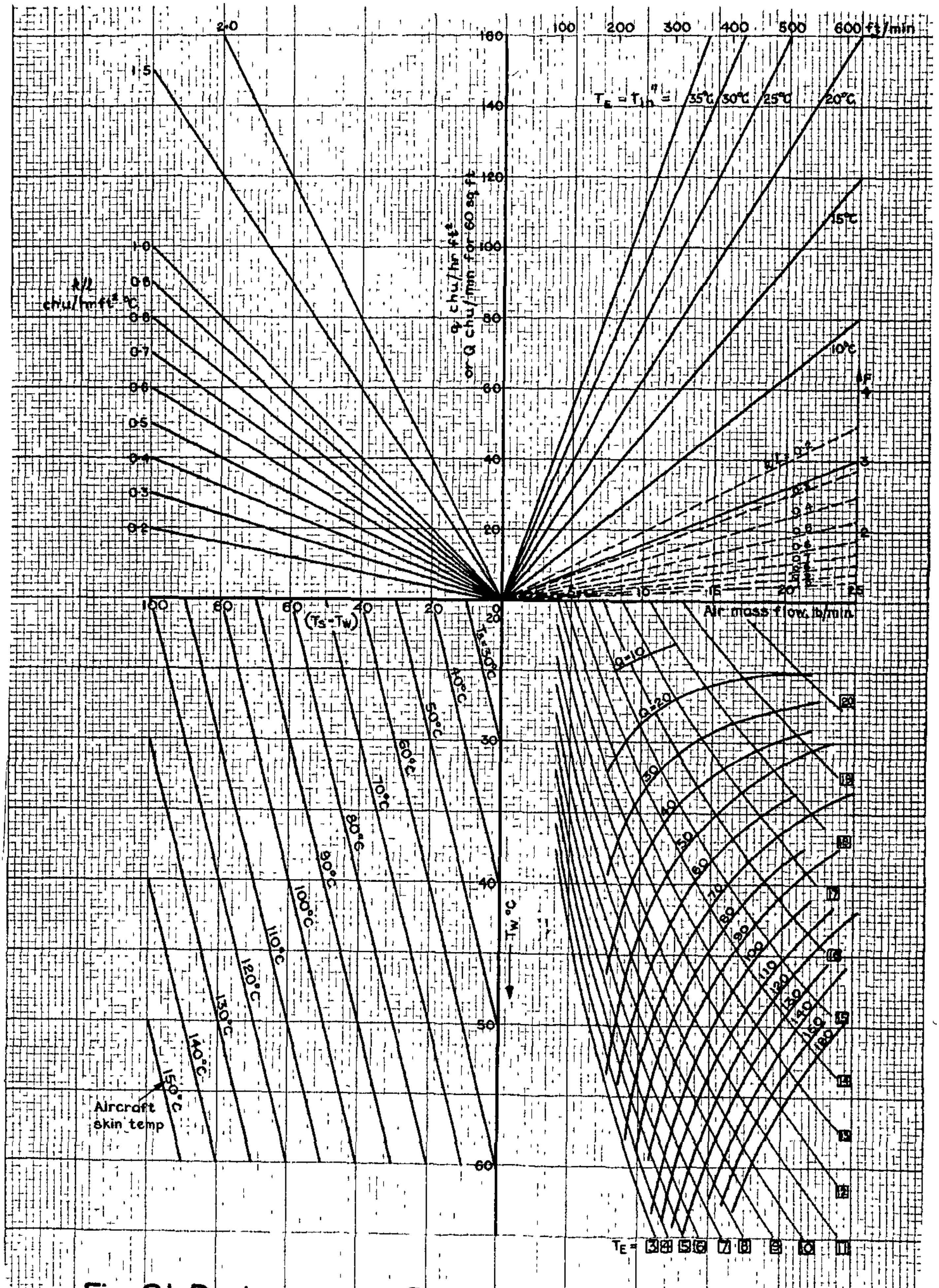


Fig. C1 Design curves $I_C = 0·1$ H=50 Solar radiation

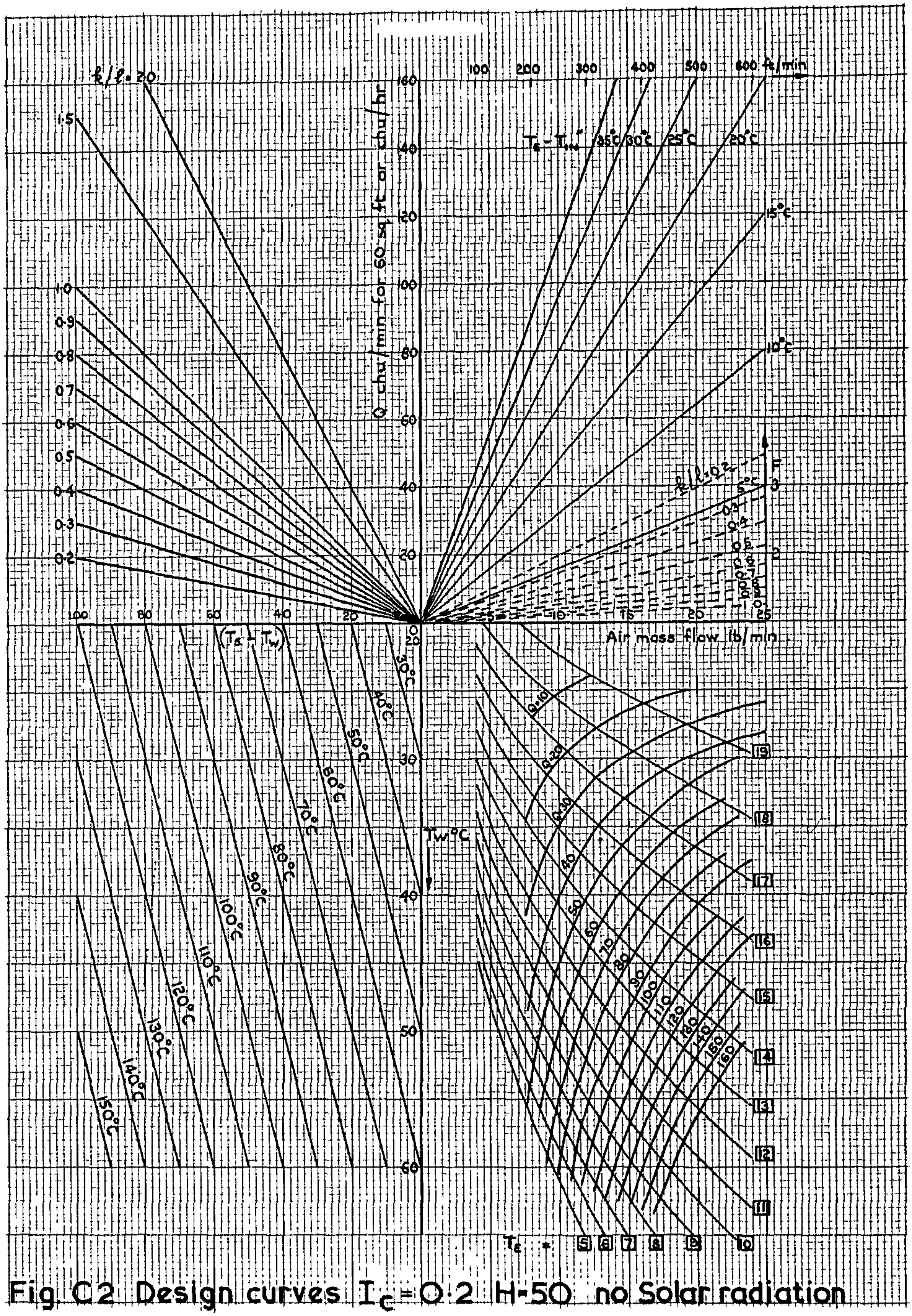


Fig C2 Design curves $I_C = 0.2$ H-50 no Solar radiation

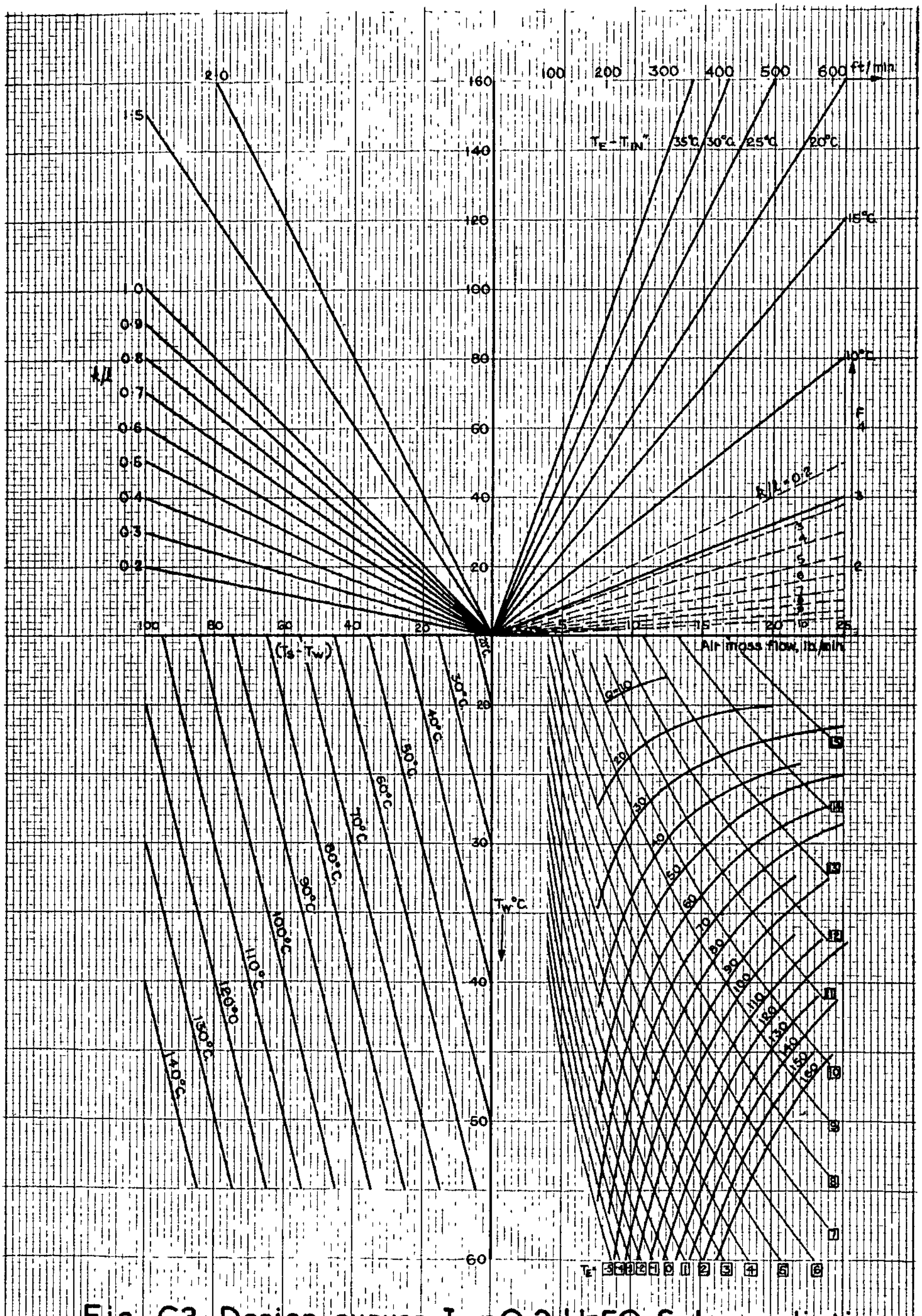


Fig. C3 Design curves $I_c = 0.2$ $H = 50$ Solar radiation

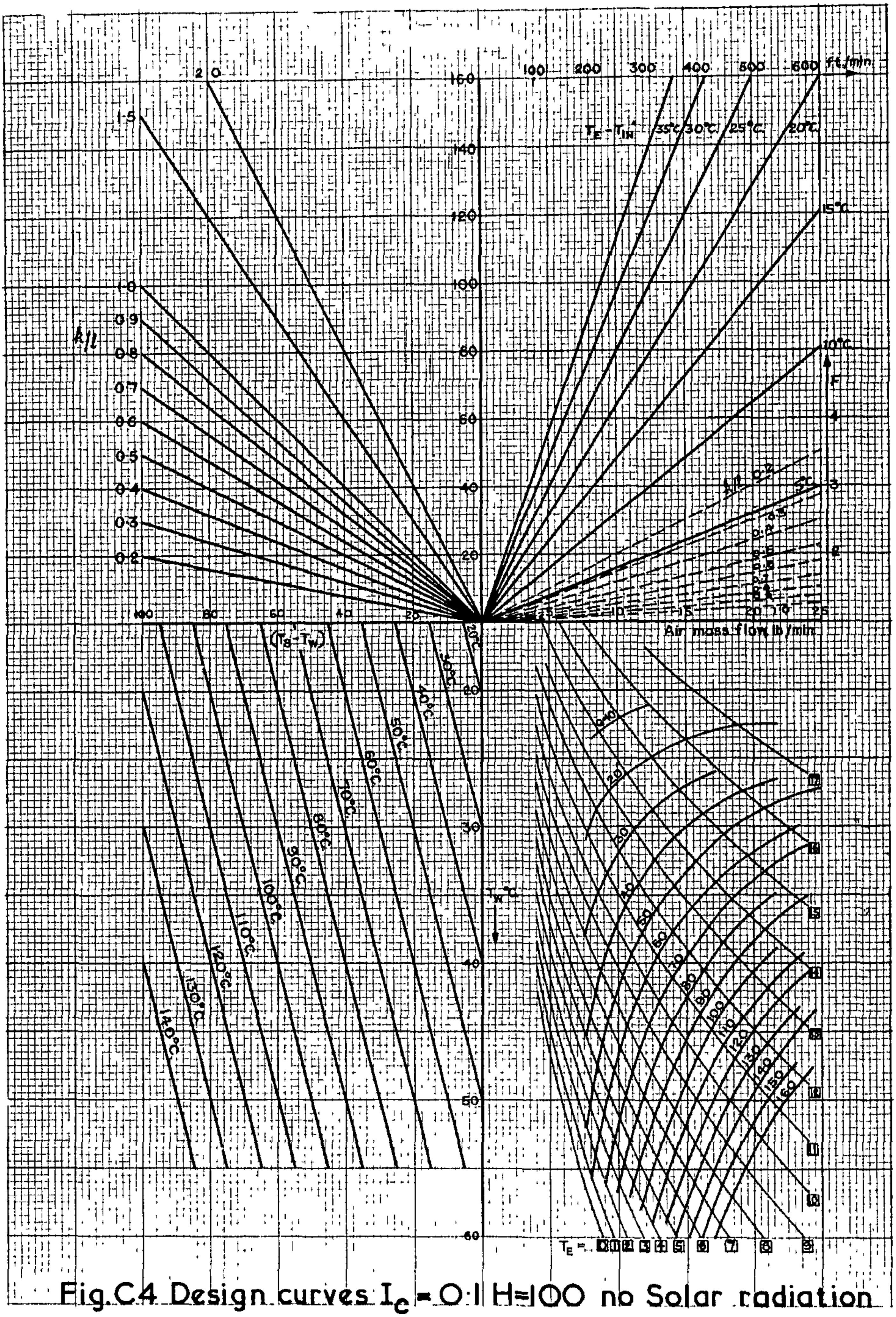


Fig.C4 Design curves I_c = 0·1 H=100 no Solar radiation

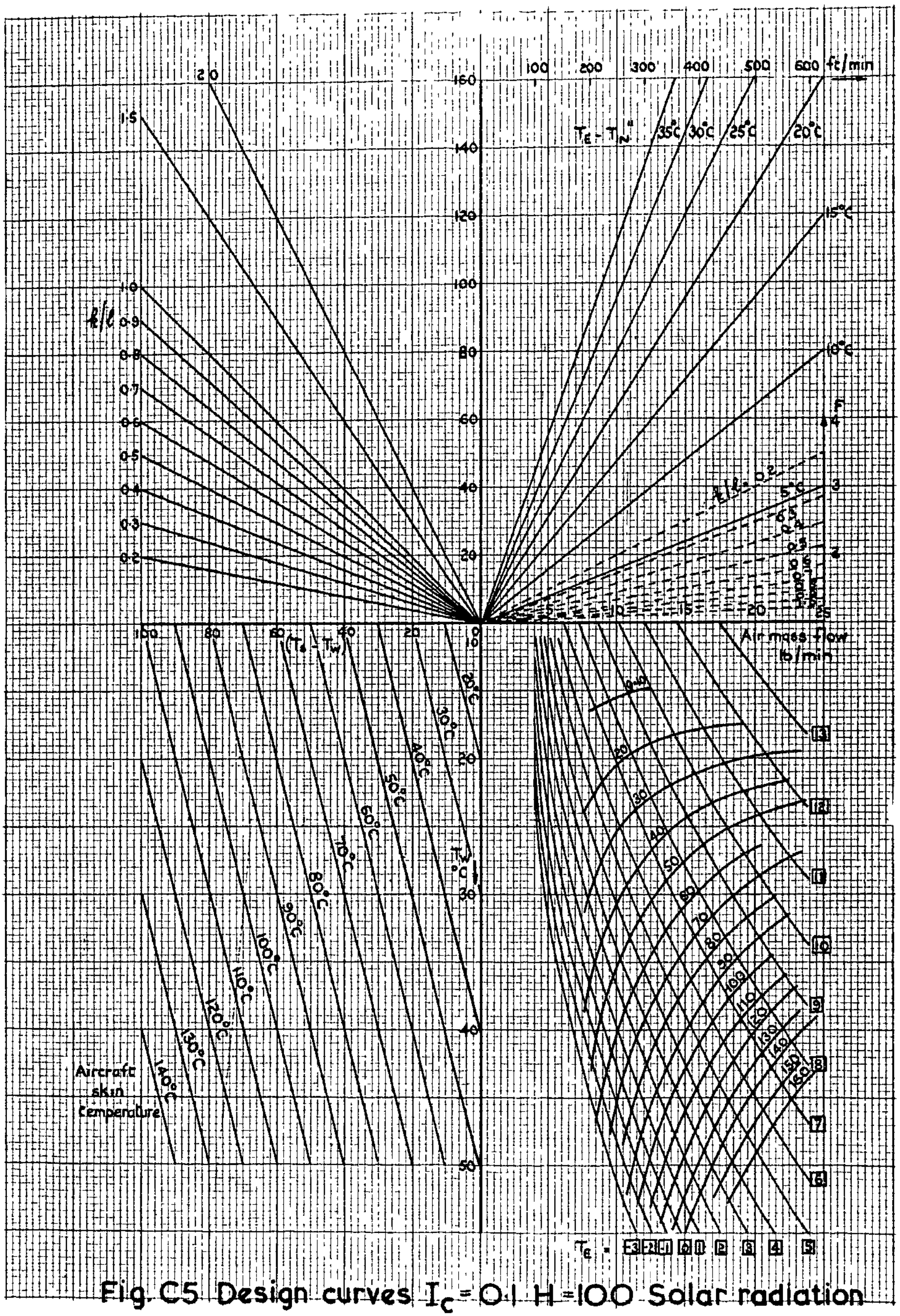


Fig. C5 Design curves I_c = 0·1 H = 100 Solar radiation

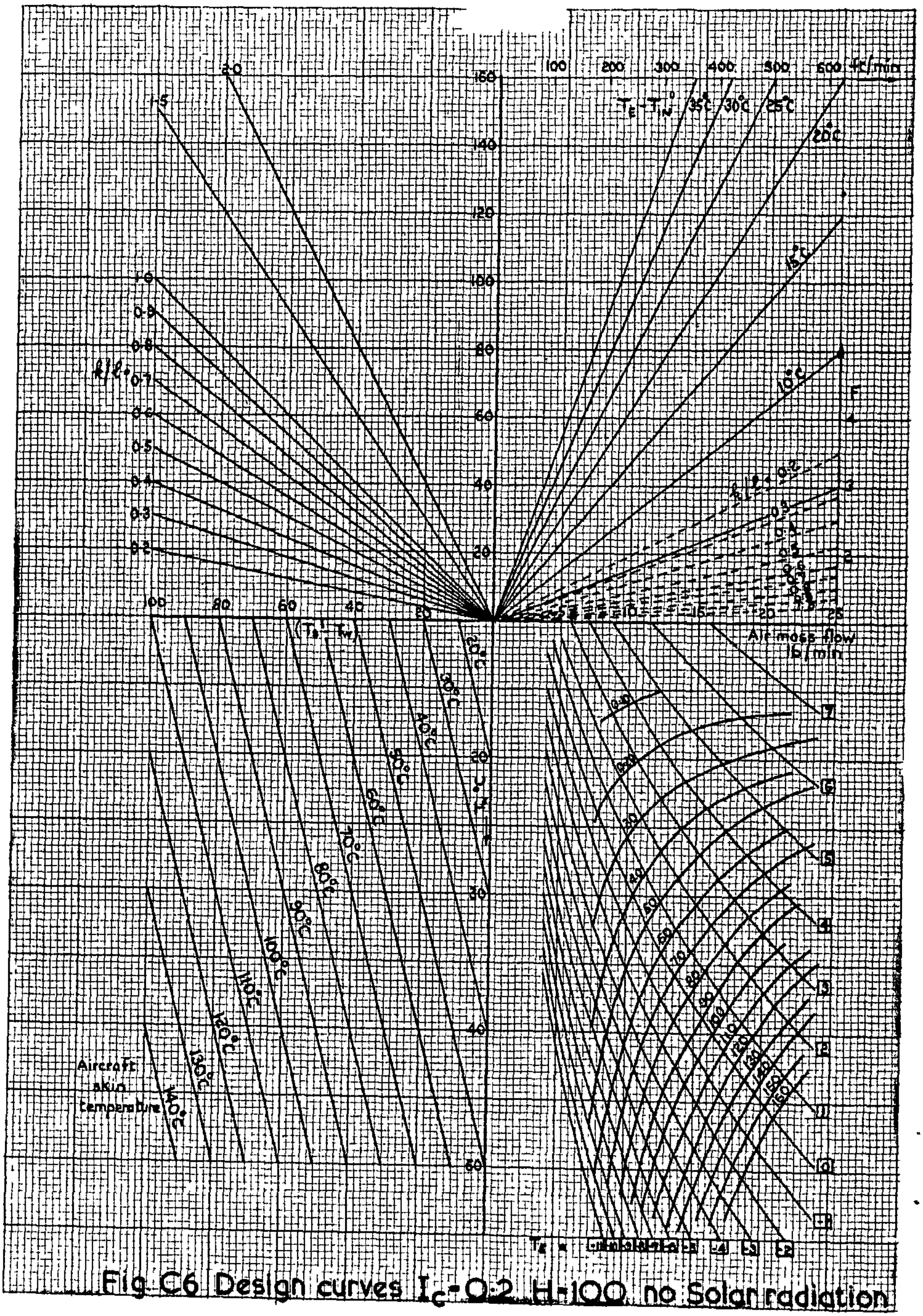


Fig C6 Design curves $I_C = 0{\cdot}2$ $H = 100$ no Solar radiation

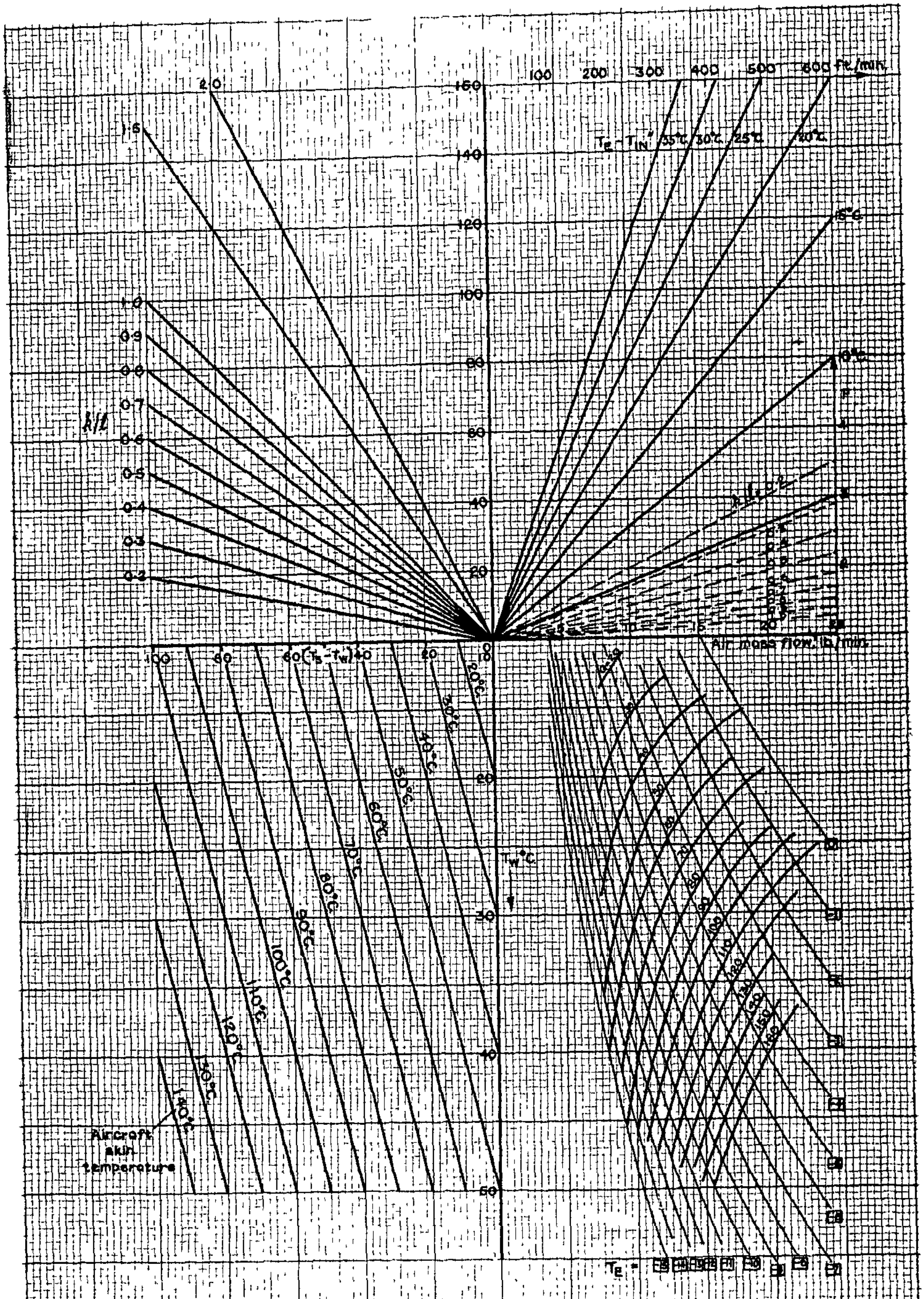


Fig. C7 Design curves I_c = 0·2 H=100 Solar radiation

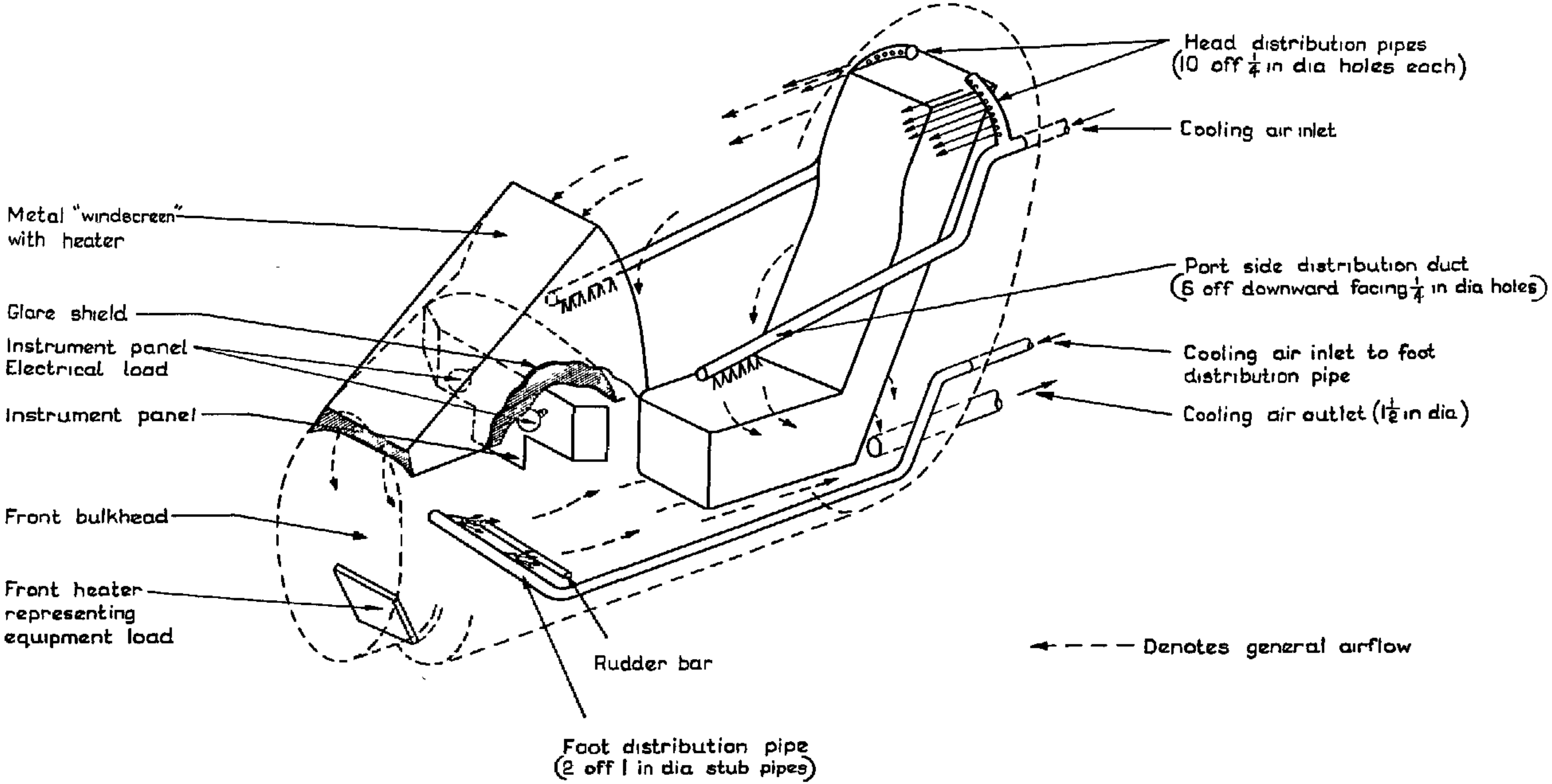


Fig. 1 Final version of cockpit cooling arrangement (consoles omitted)

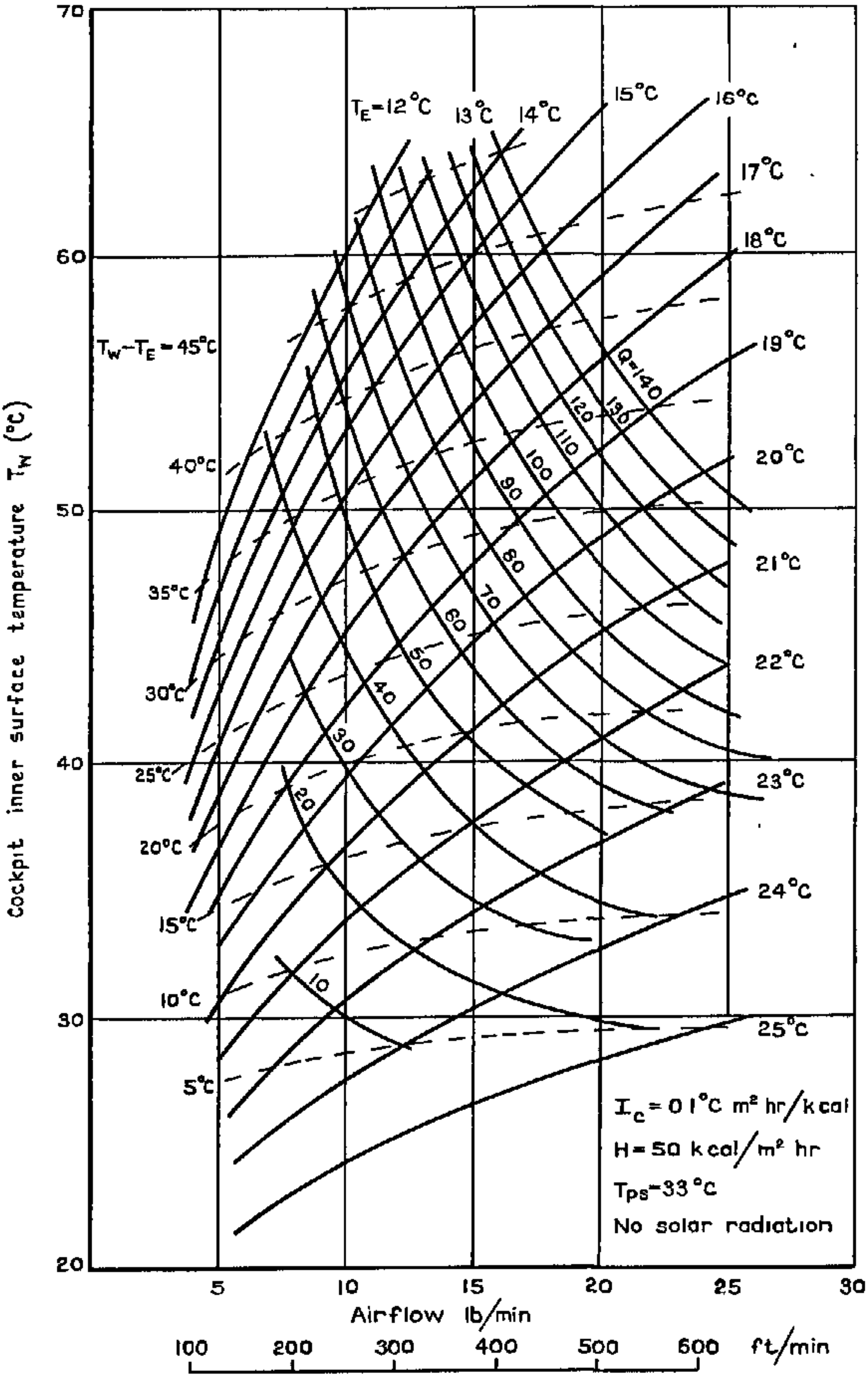
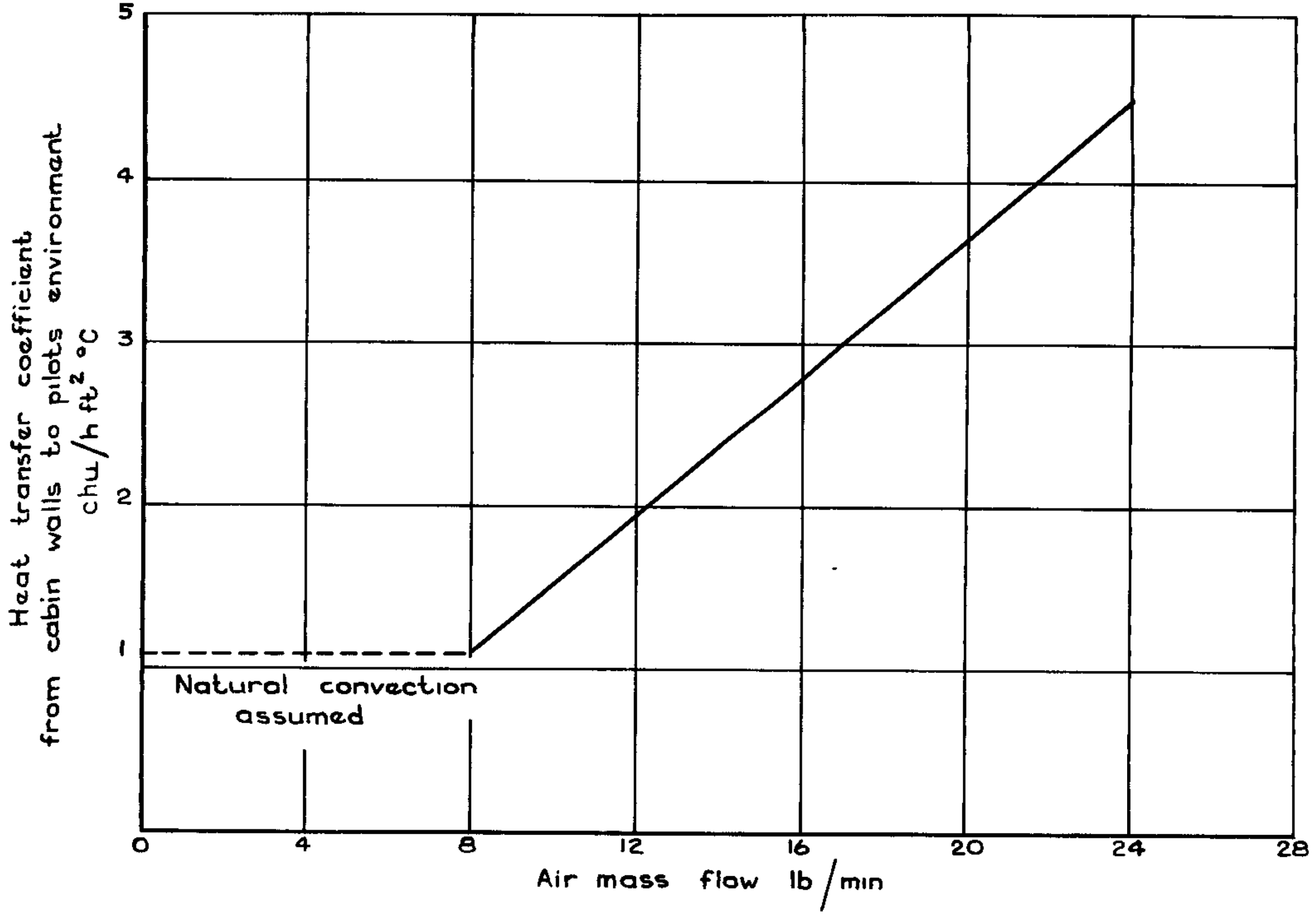
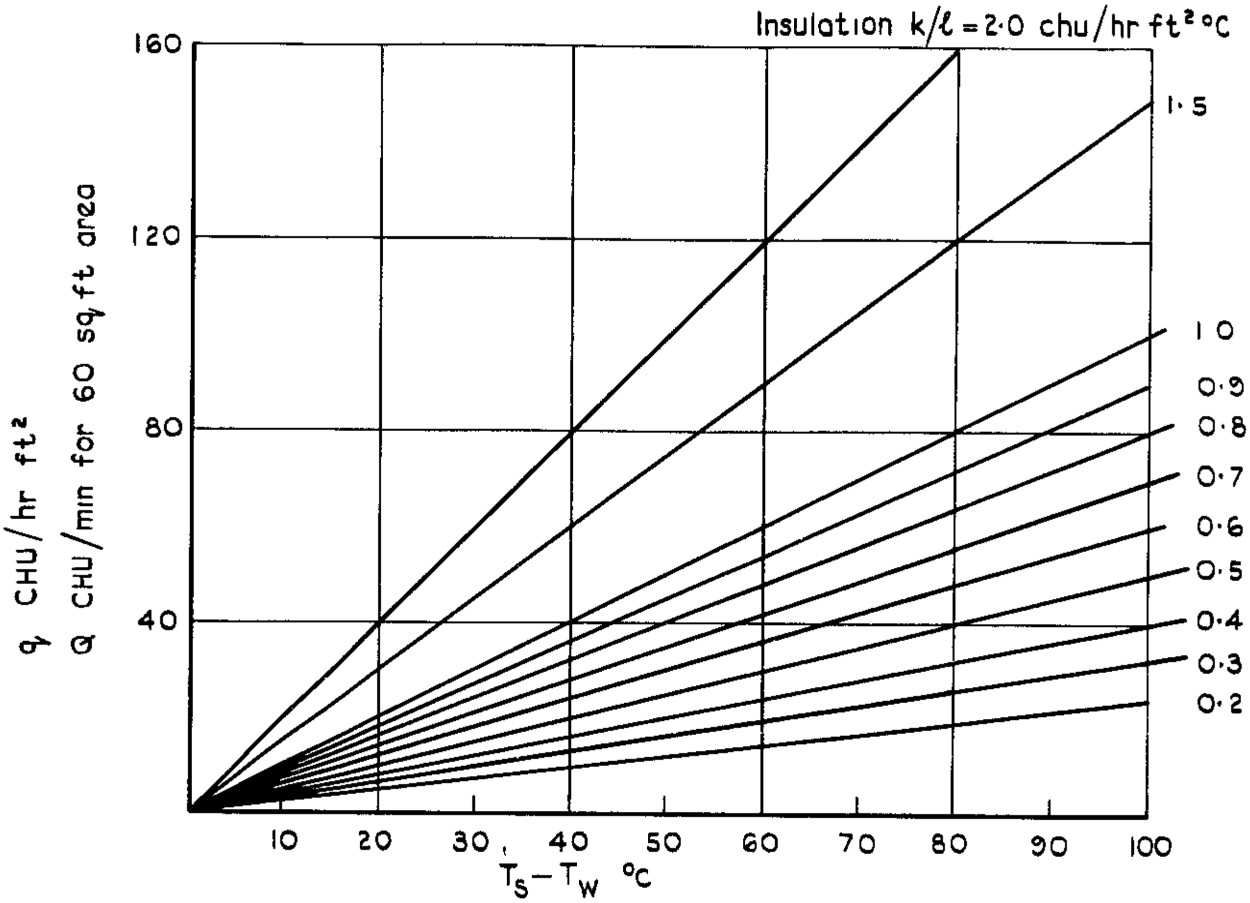


Fig.2 Pilots heat balance

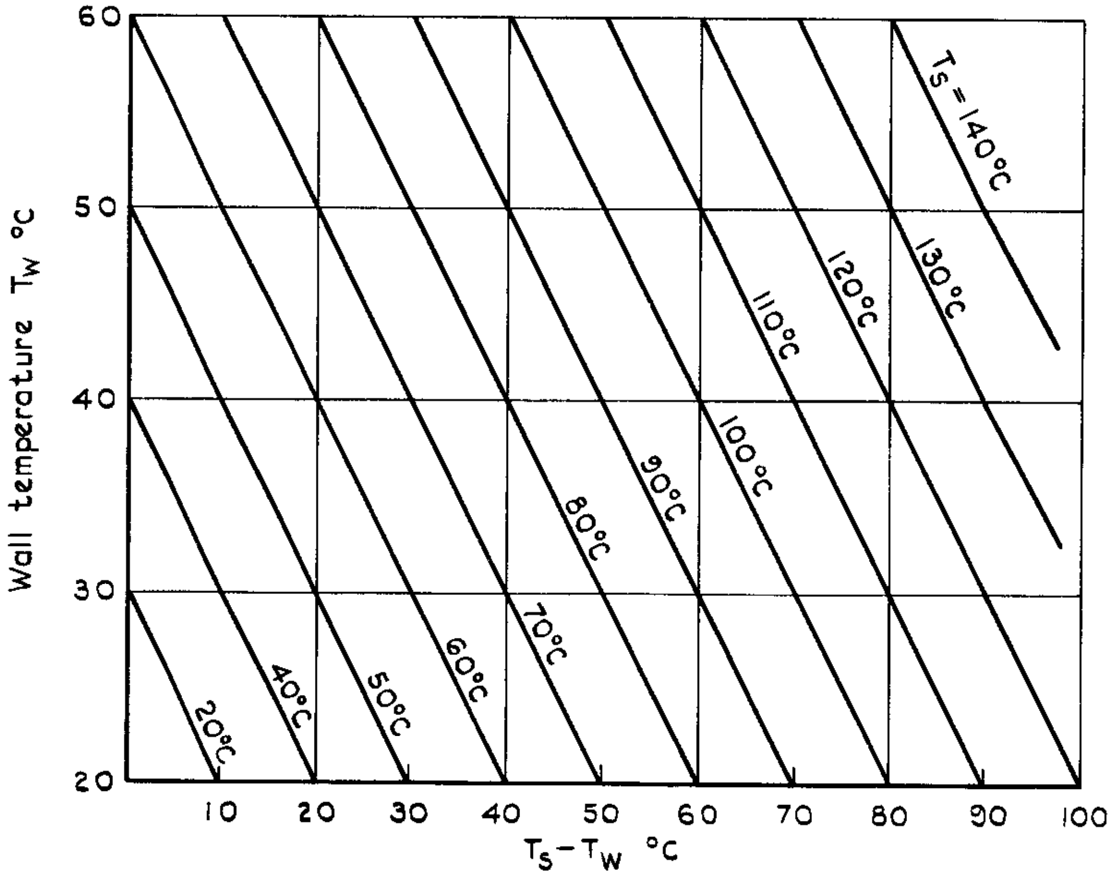


Data extracted from ref 4

Fig. 3 Heat transfer coefficient from walls to pilots environment

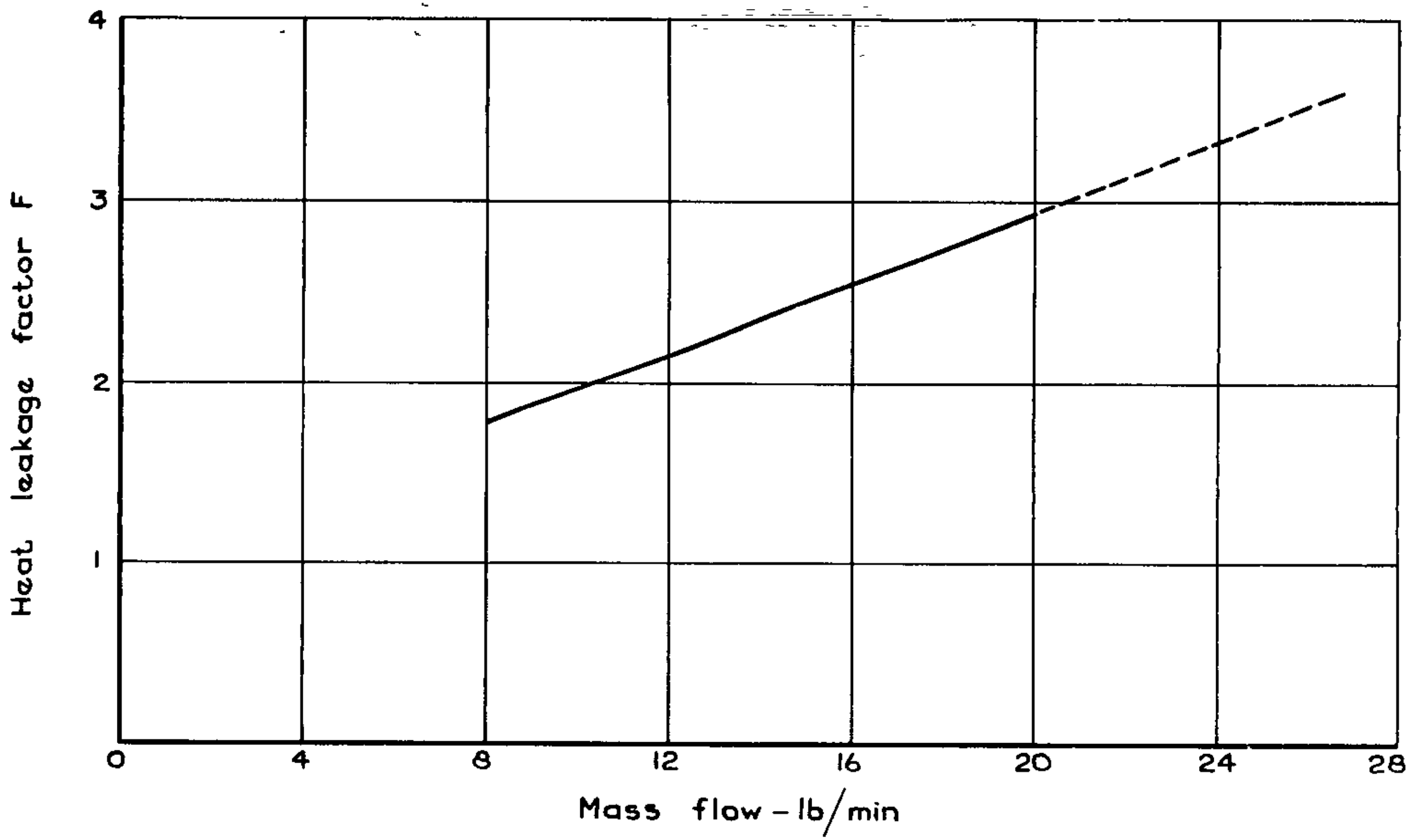


a Basic insulation heat flow v wall differential temp



b Wall temp v wall differential temp

Fig 4 a & b Wall heat flow and surface temperature



Data from ref 6

Fig.5 Heat leakage factor v mass flow

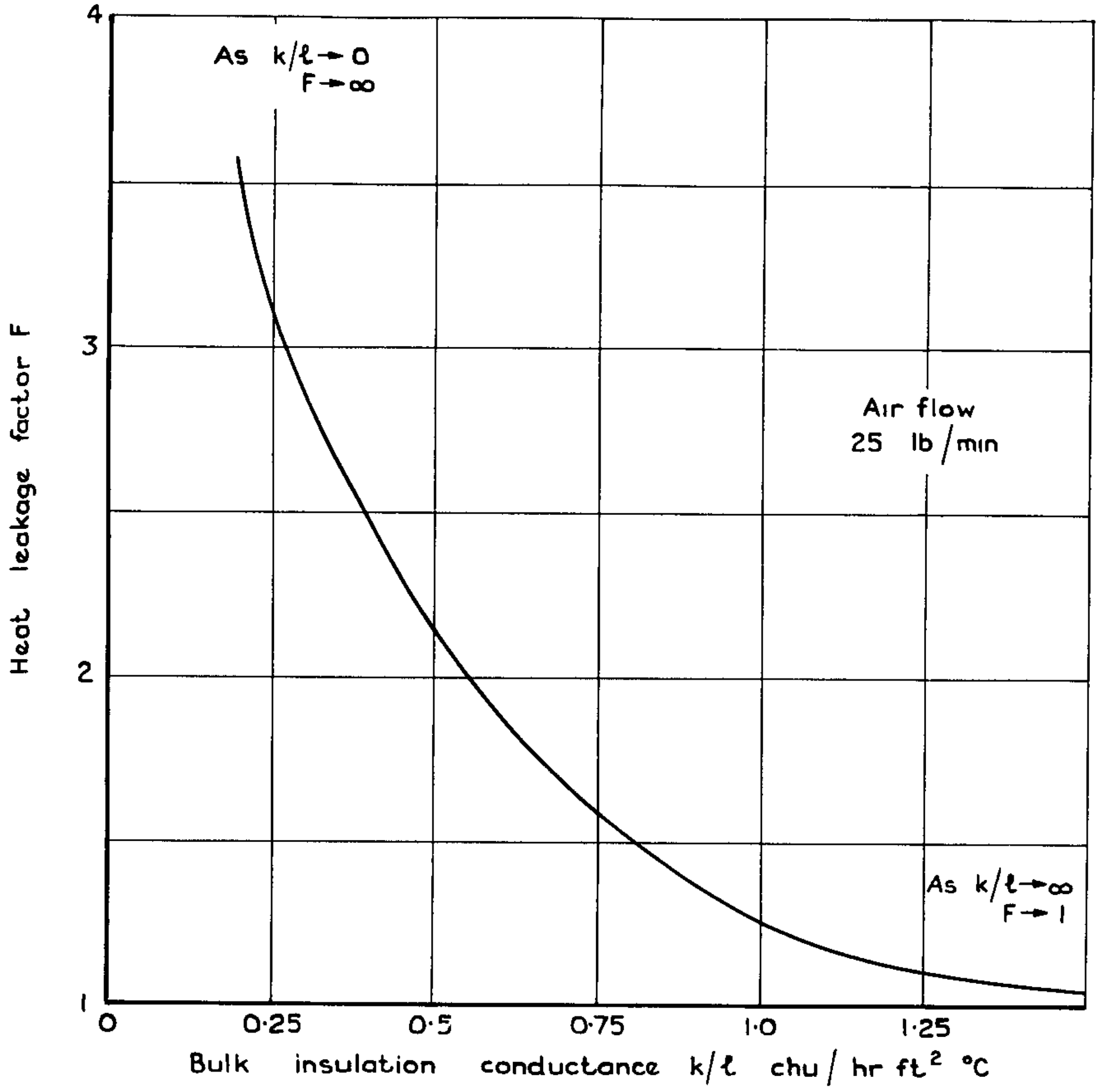


Fig 6 Assumed values of "maximum" heat leakage factors

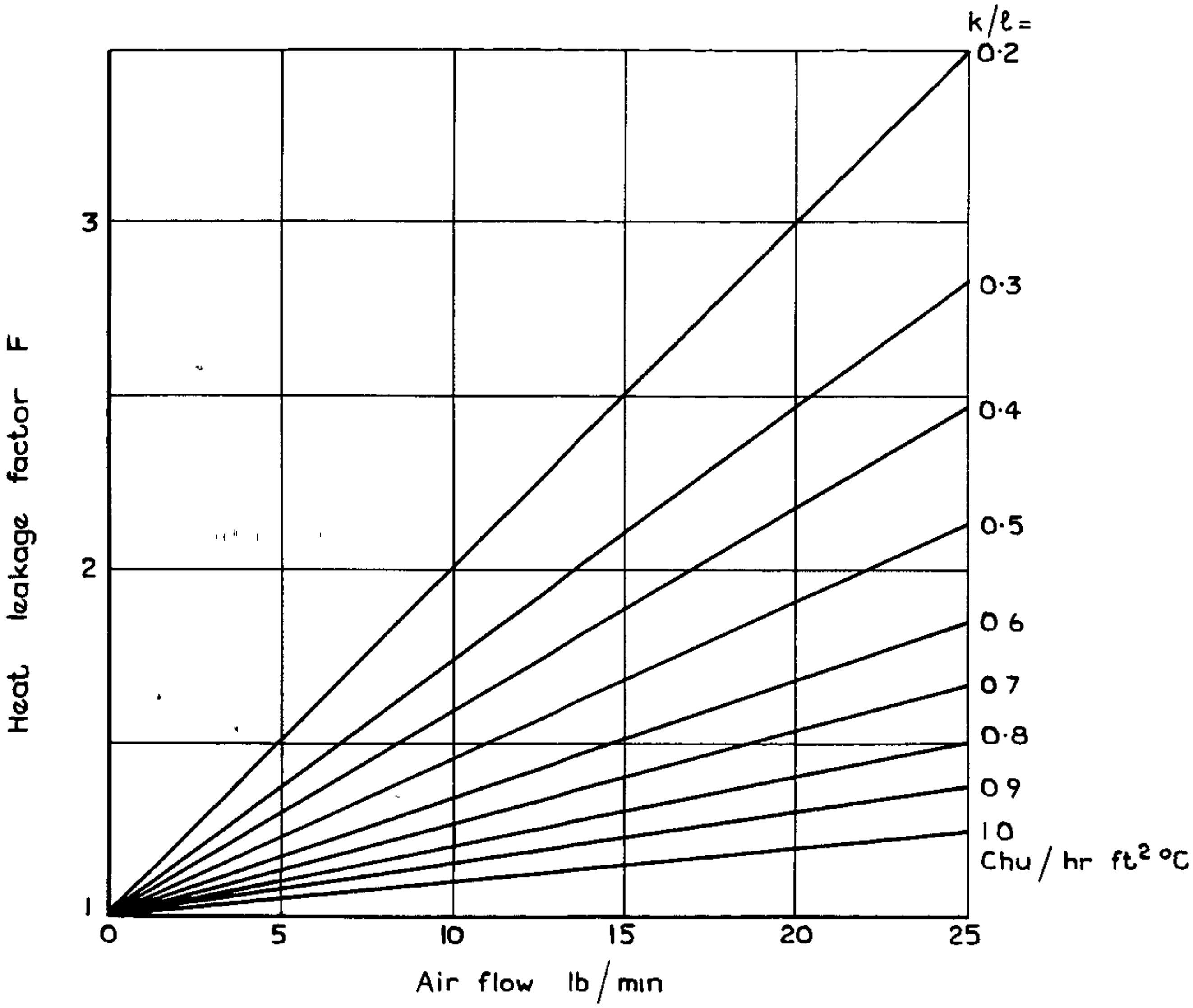
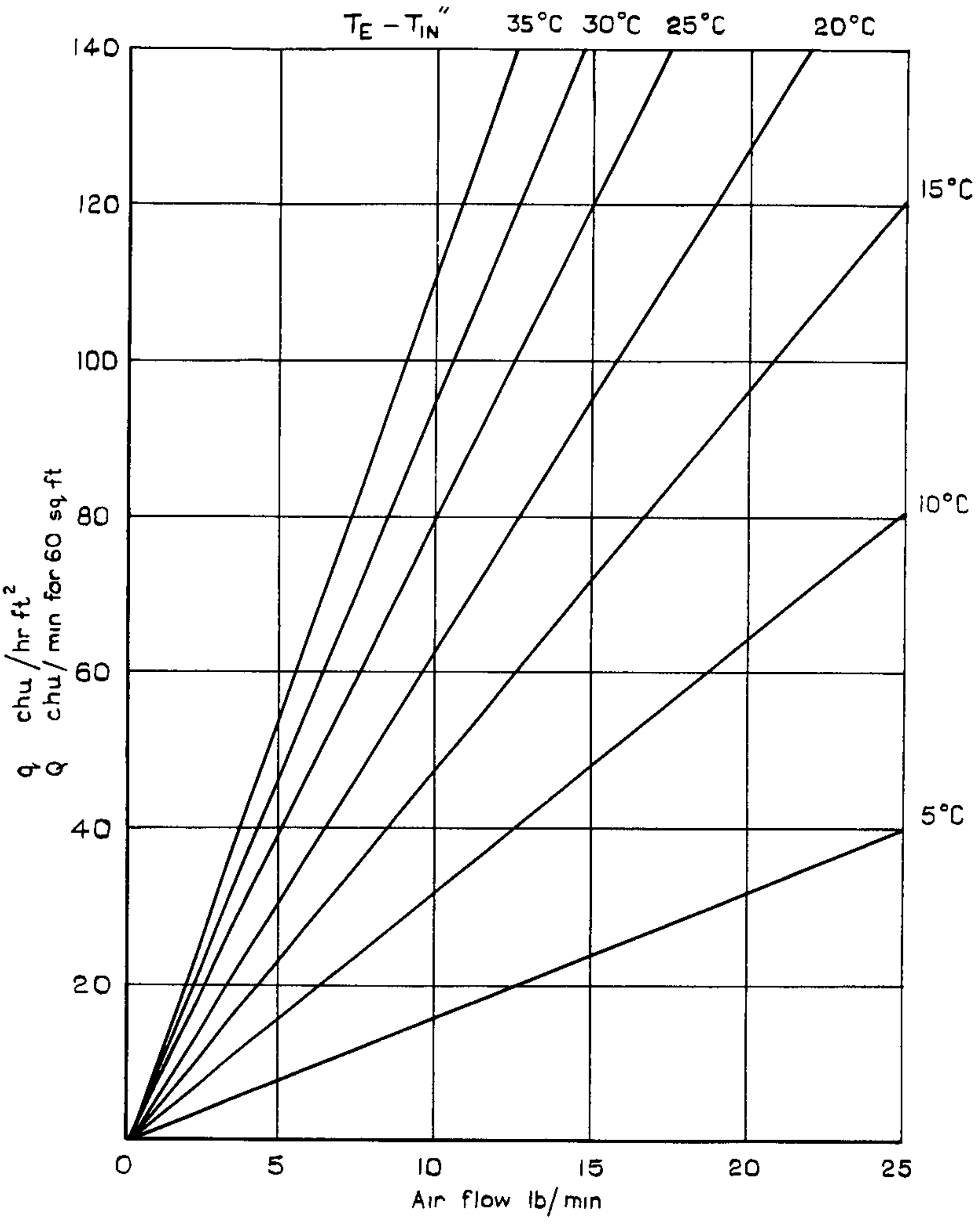


Fig. 7 Assumed values of heat leakage factor



$$q = Mc_p \frac{4}{3} \left(T_E - T_{IN}''\right)$$

Fig 8 Neccesary reduction in inlet temperature to remove unfactored heat flow through insulation

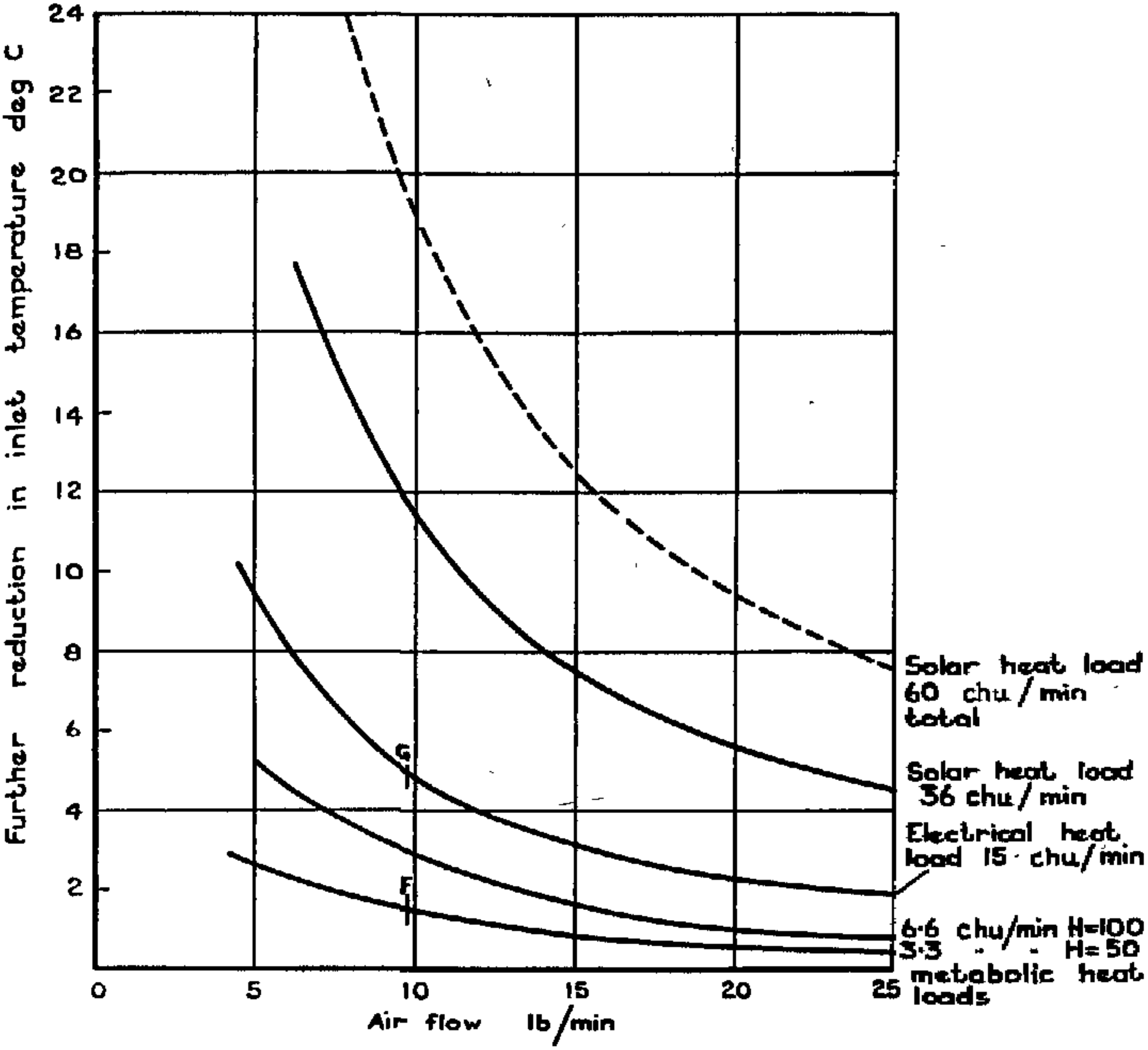


Fig. 9 Further reduction in inlet temperature to remove additional heat loads

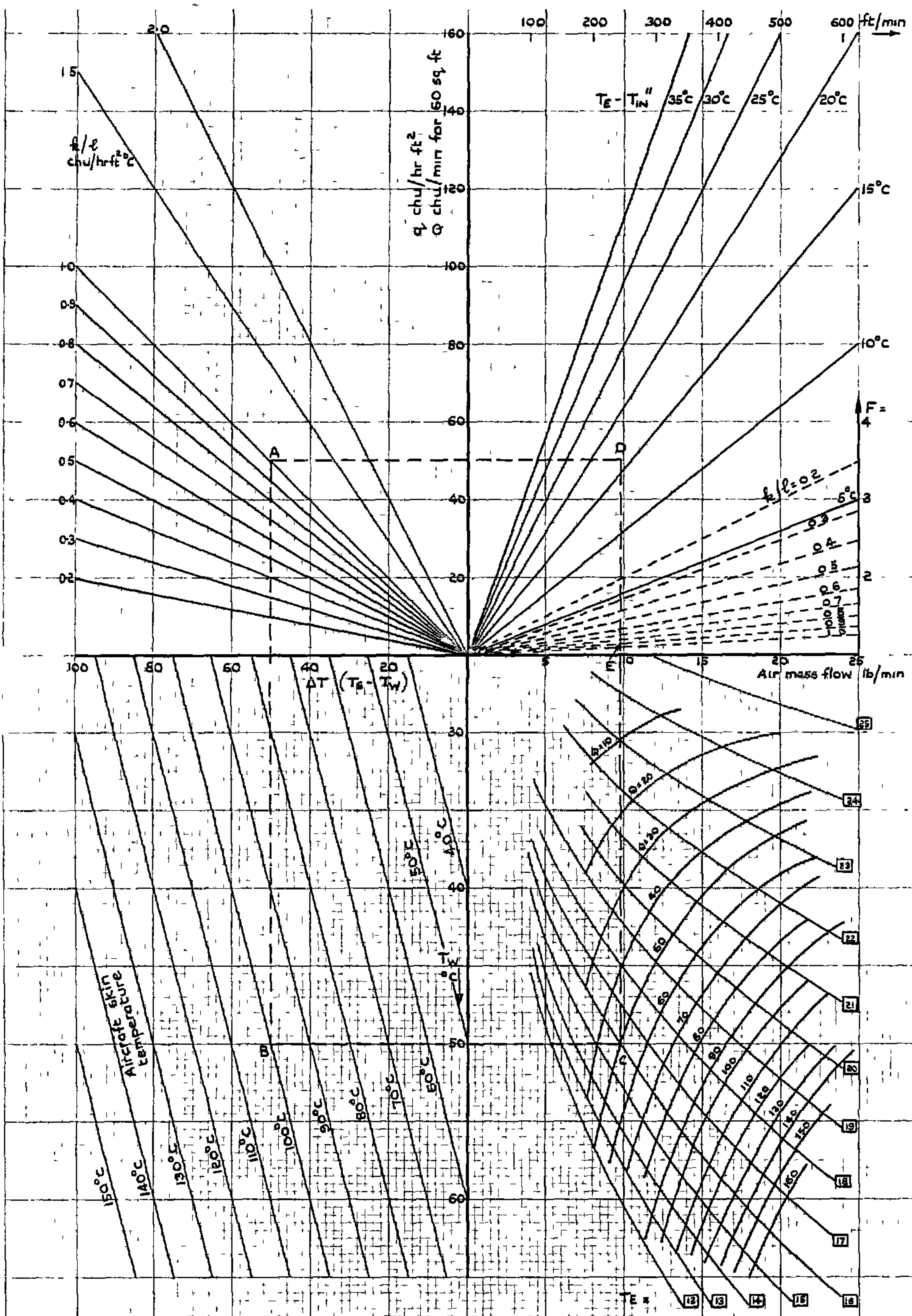


Fig. 10 Design curves

Pilot at rest (H = 50 K cal / m² hr)

Lightweight clothing (I_c = 0·1 °C m² hr/K cal)

No solar radiation

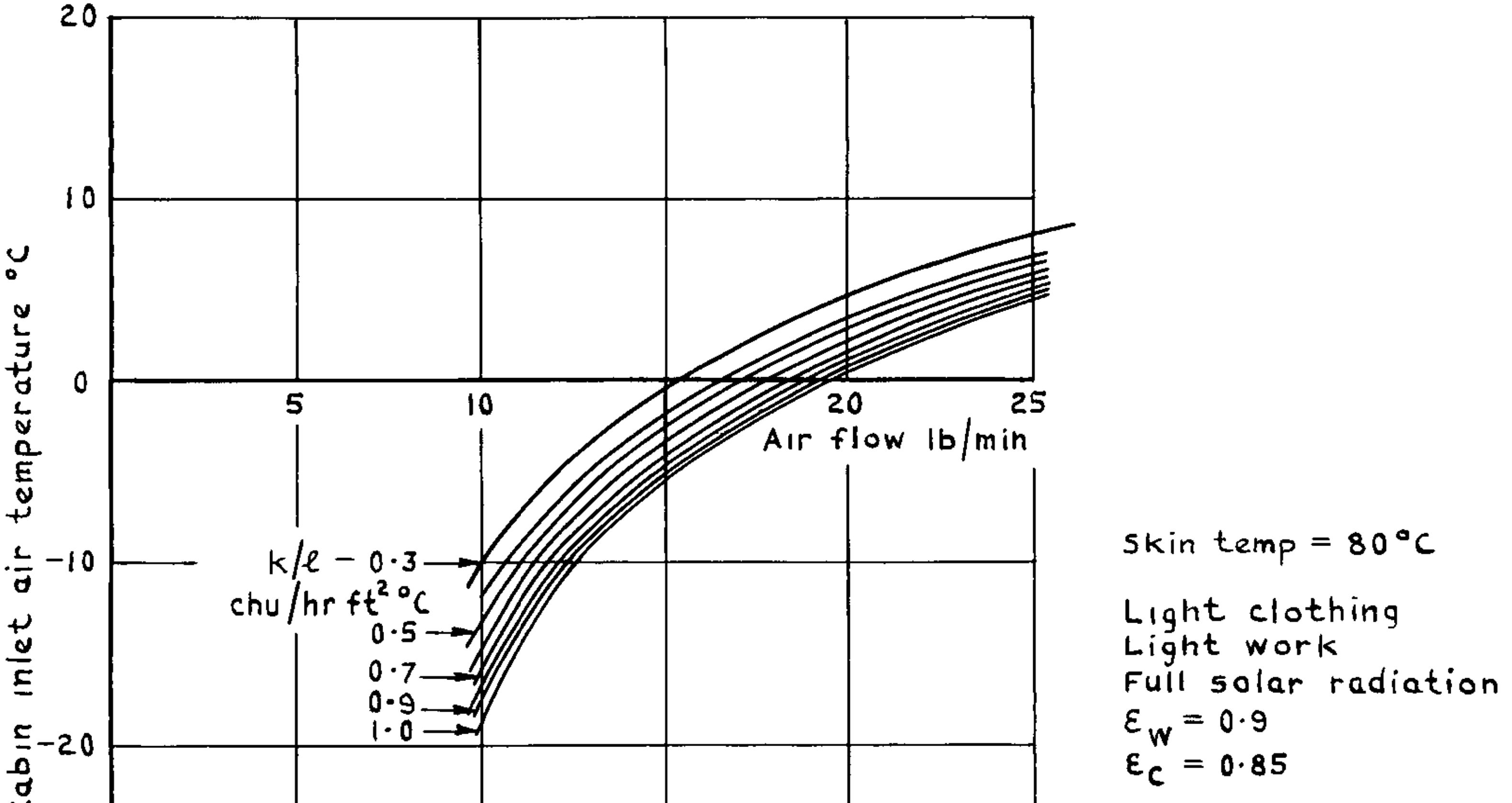


Fig. 11 **Effect of cabin air insulation on cabin air requirements**

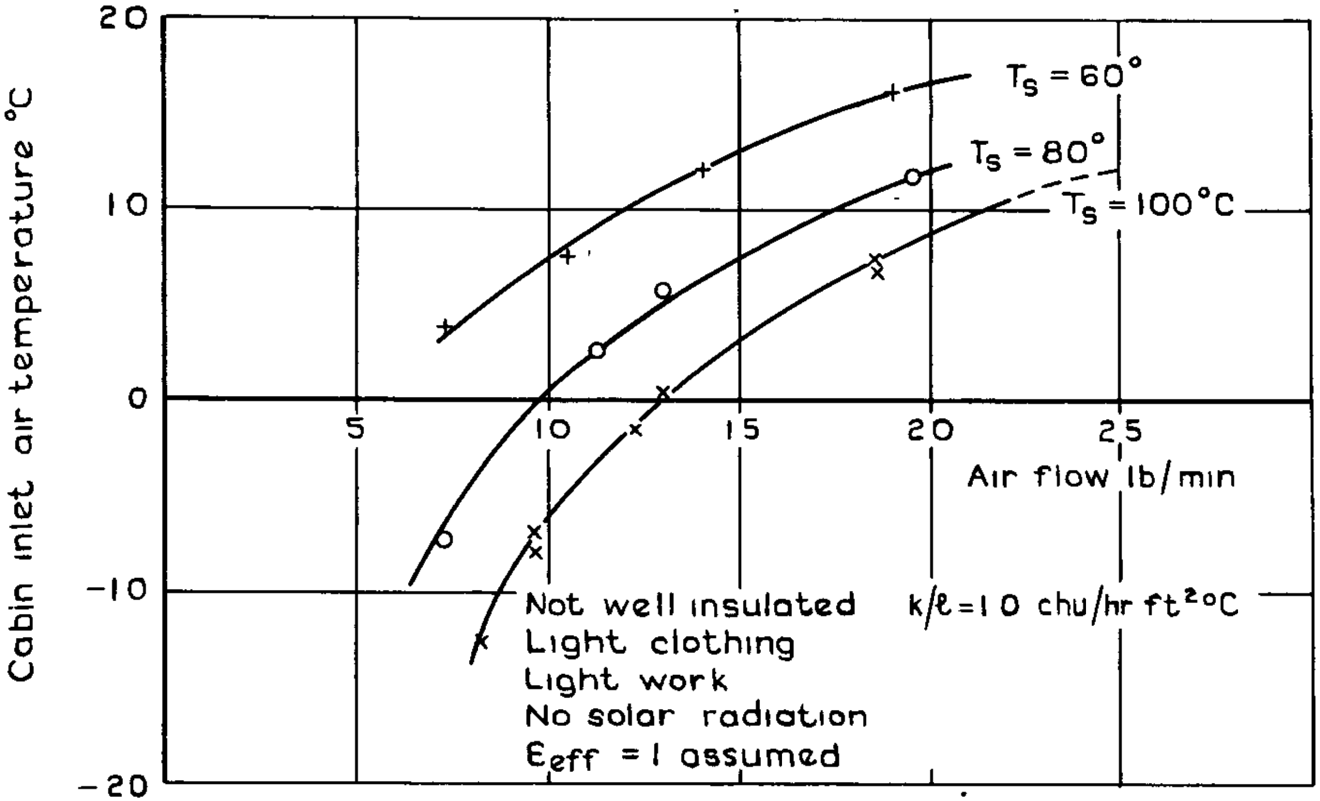


Fig. 12 Inlet air flow/temperature requirements – "uninsulated" cockpit

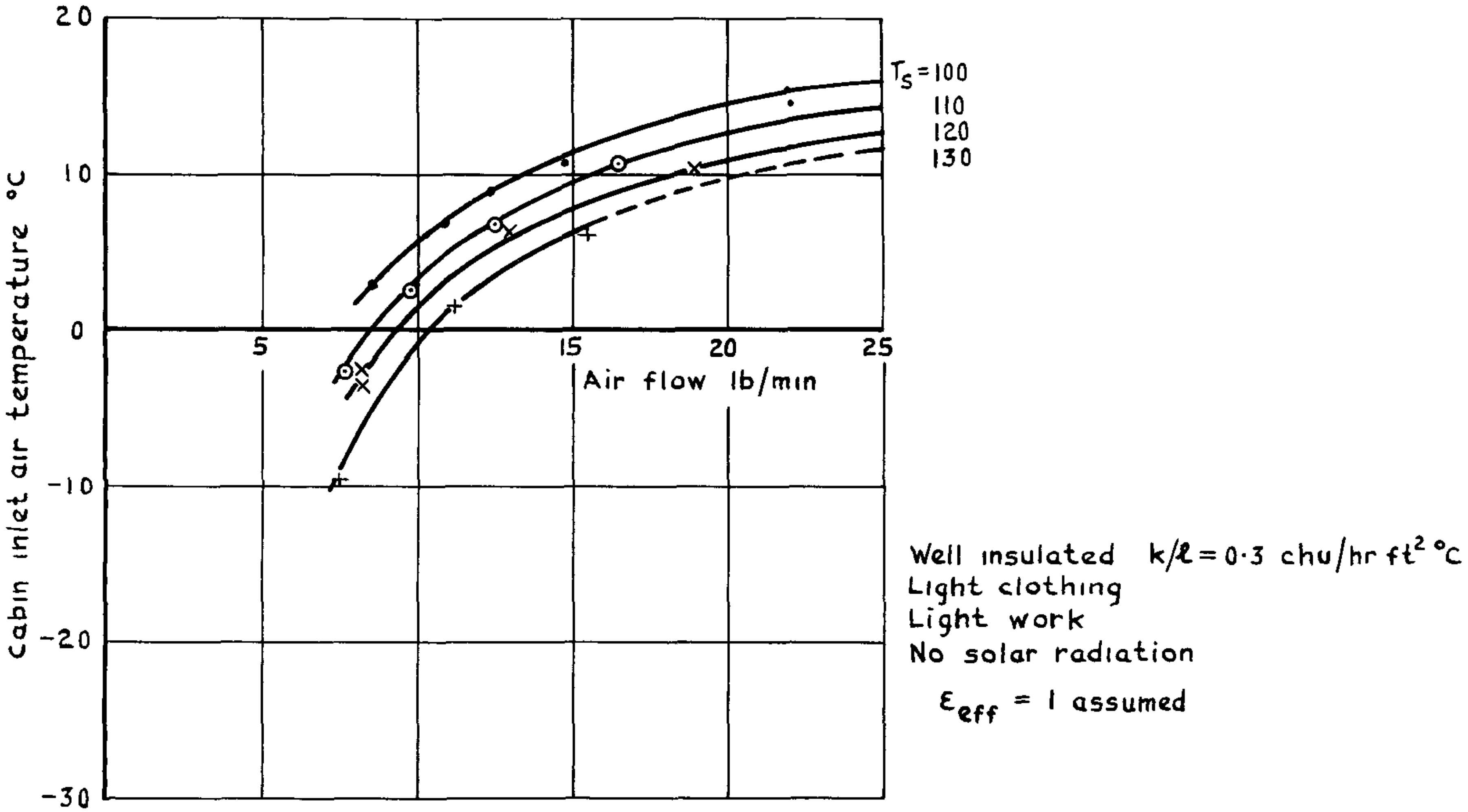


Fig.13 Inlet air flow / temperature requirments–insulated cockpit

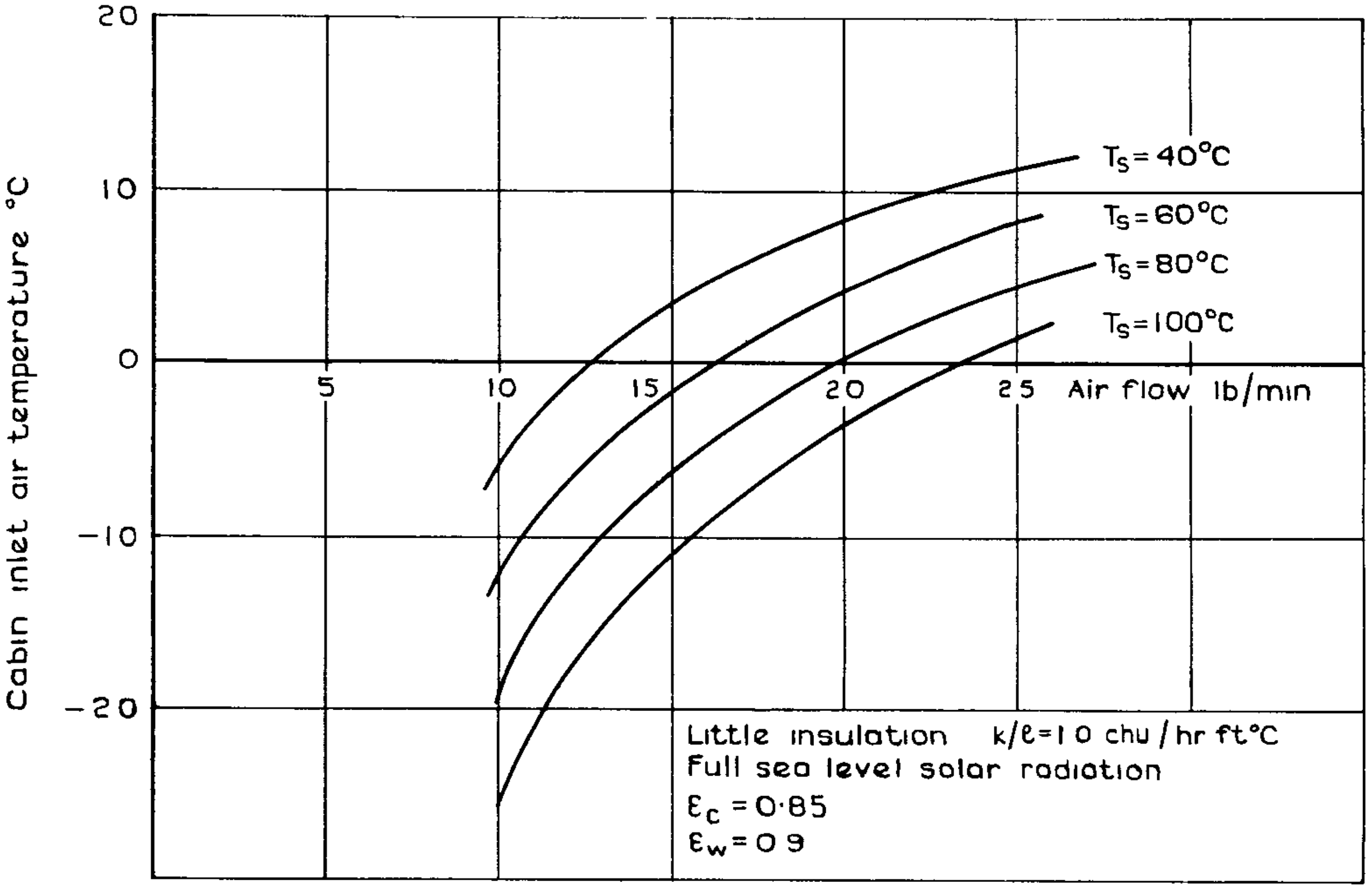


Fig 14 Effect of aircraft skin temperature on cabin air requirements

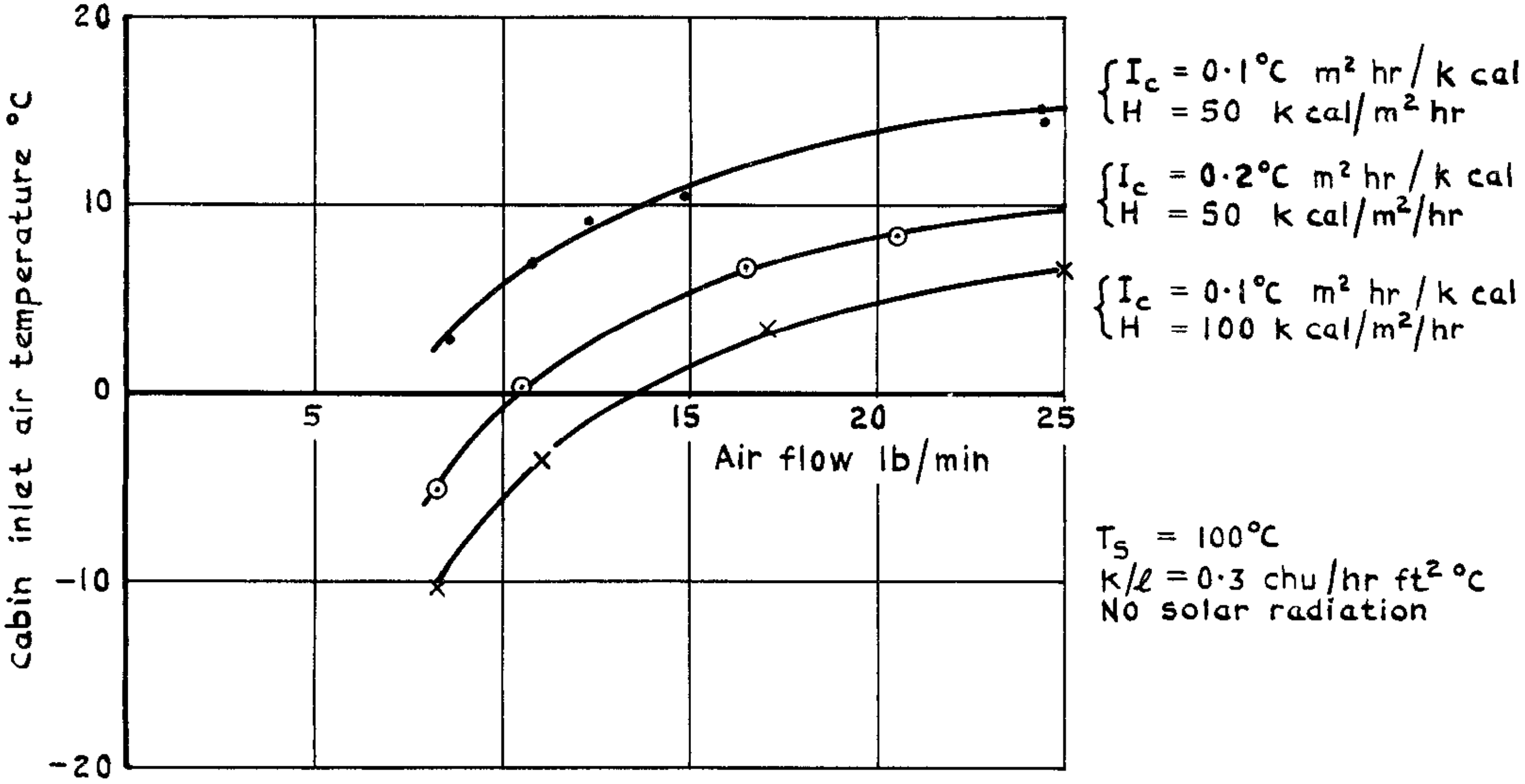


Fig. 15 Effect of work rate and clothing insulation on cabin air requirements

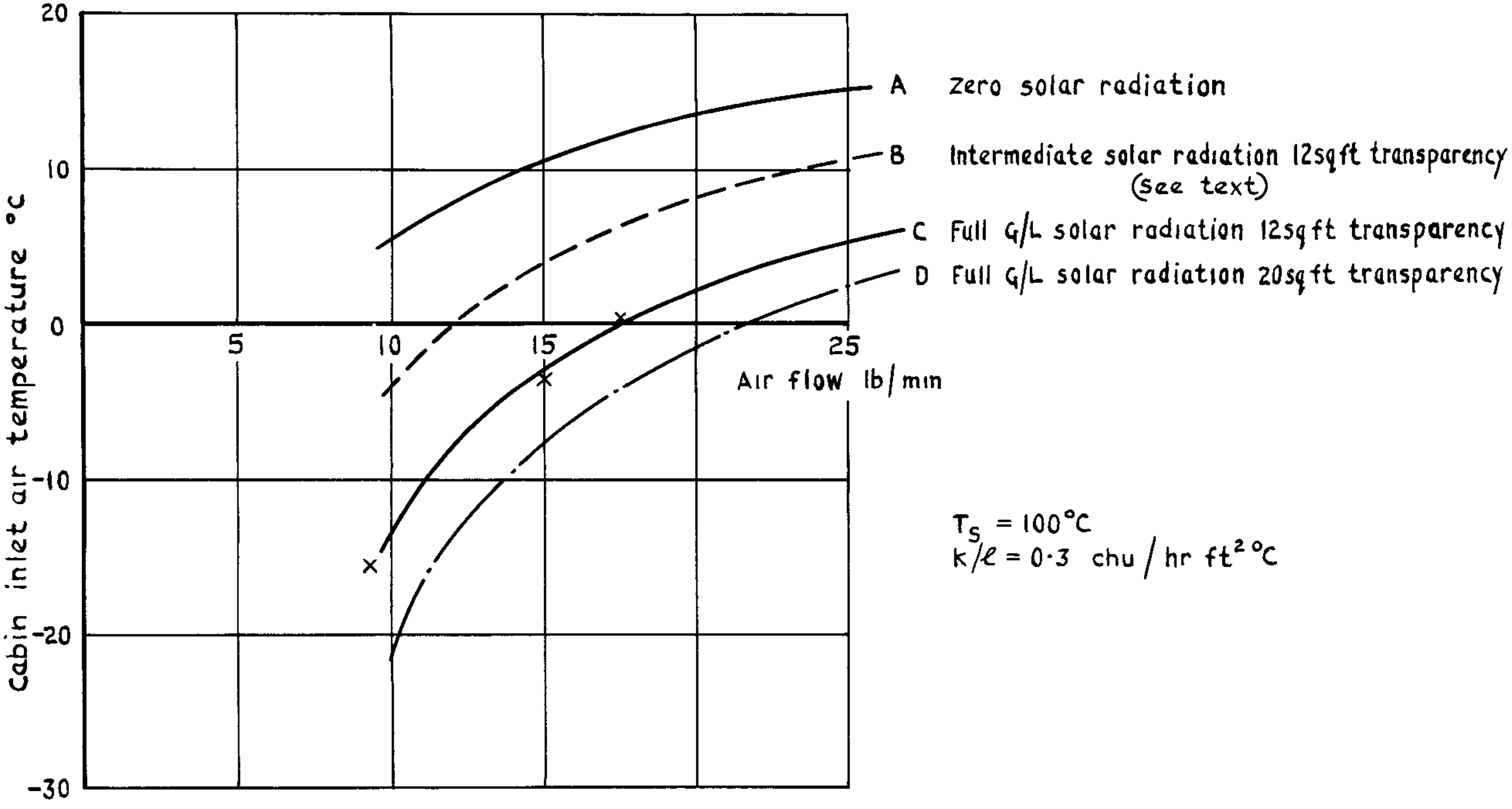


Fig. 16 Effect of solar radiation on cabin air requirements

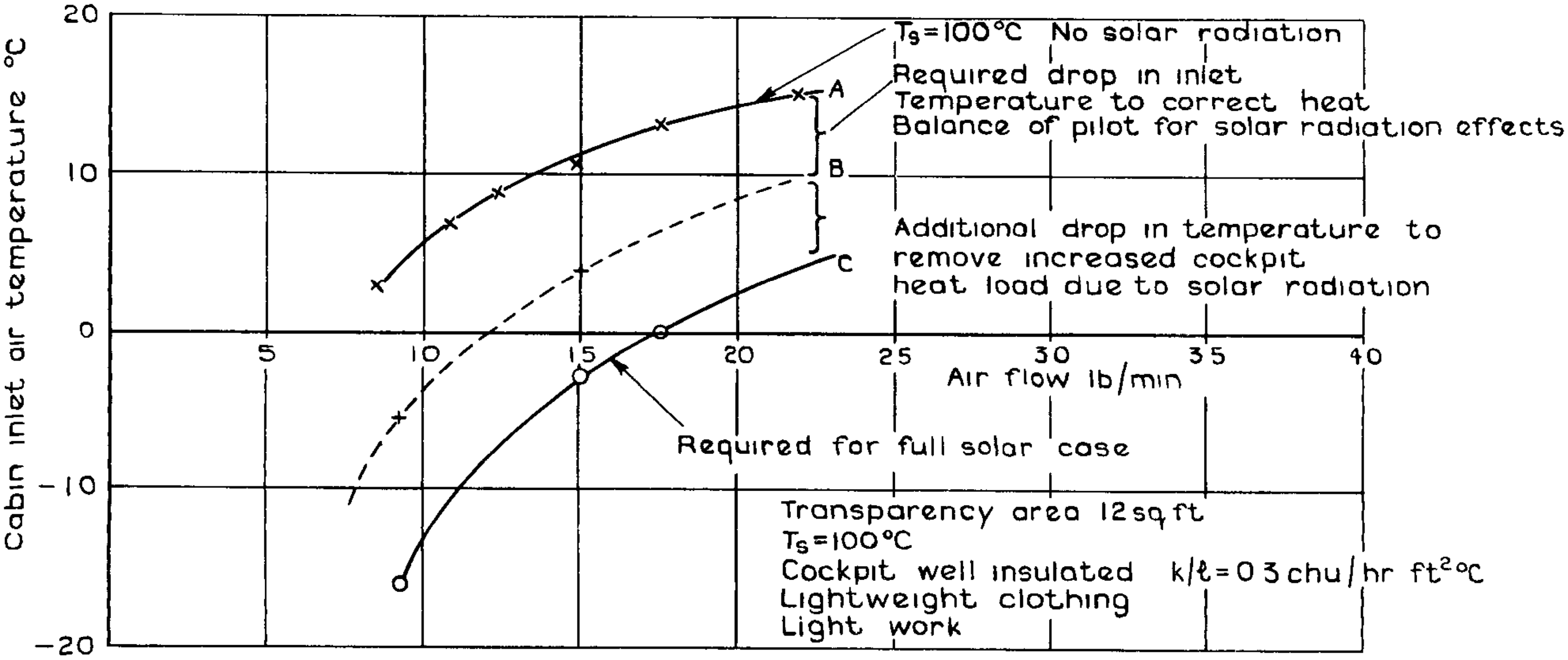


Fig 17 Comparative effects of solar radiation on pilot and cabin

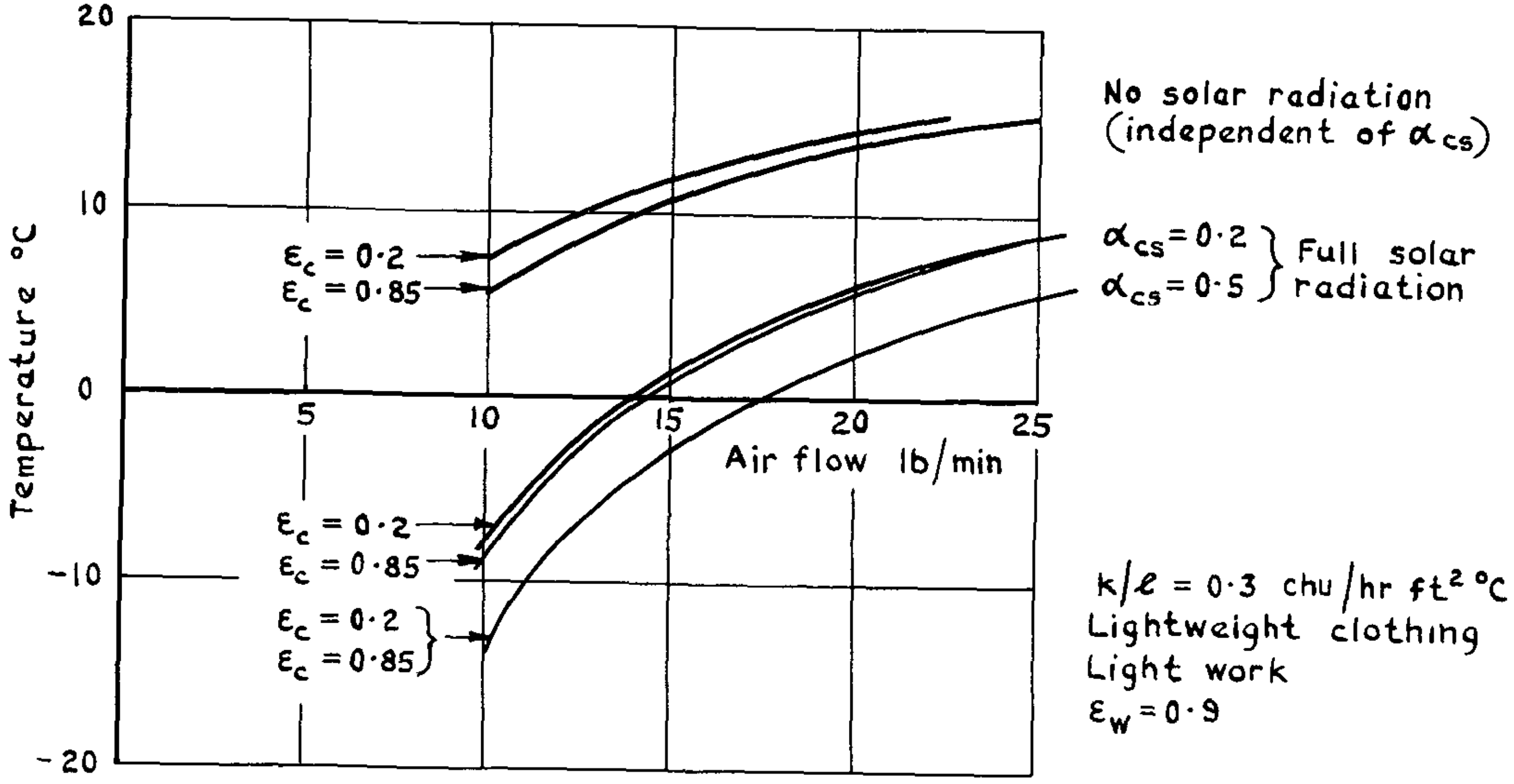


Fig.18 a Influence of clothing emissivity on cabin air requirements

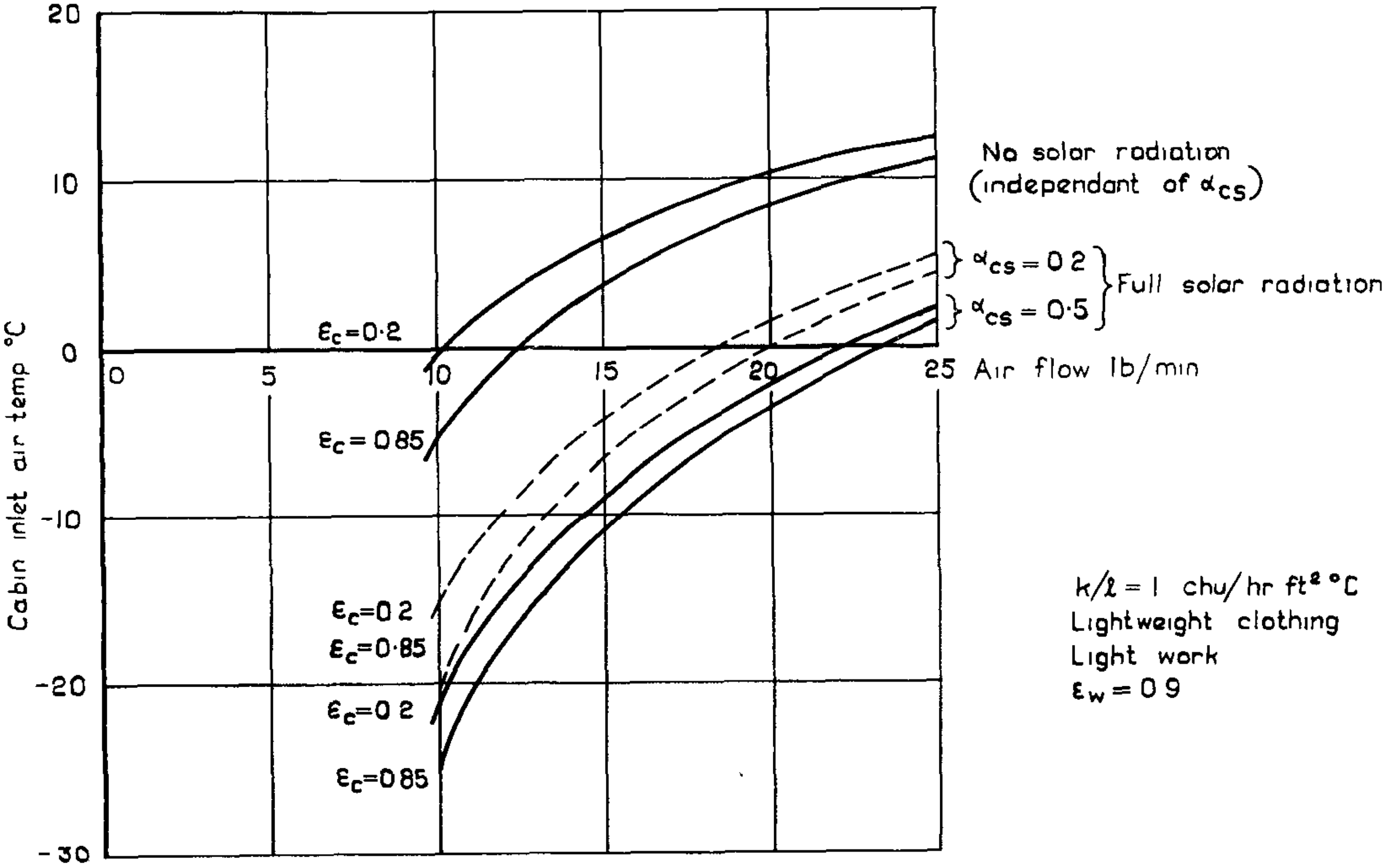


Fig. 18 b Influence of clothing emissivity of cabin air requirments

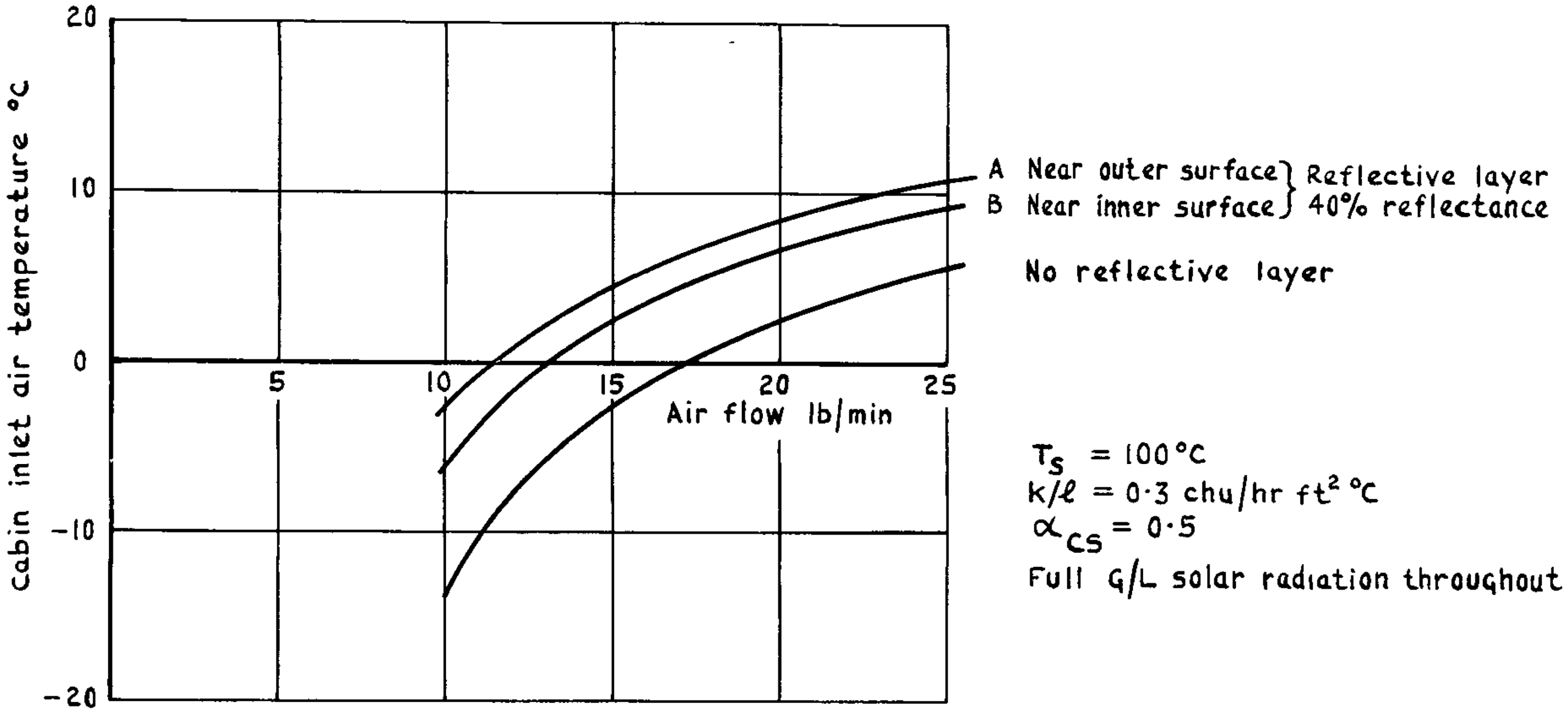
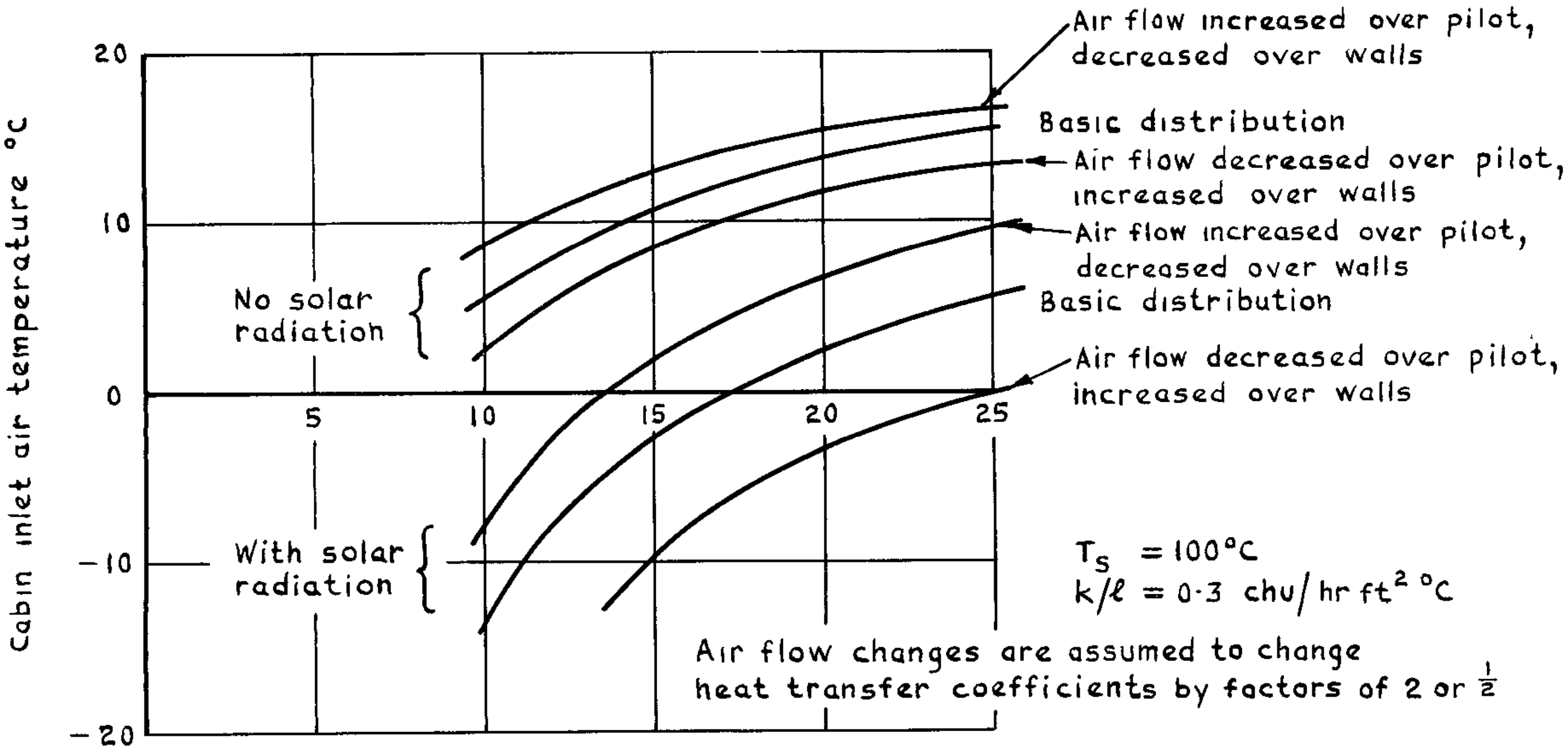


Fig. 19 The effect of reflecting layer in transparency on cabin air requirements



Air flow increased over pilot, decreased over walls

Basic distribution

Air flow decreased over pilot, increased over walls

Air flow increased over pilot, decreased over walls

Basic distribution

Air flow decreased over pilot, increased over walls

$T_S = 100°C$
$k/\ell = 0{\cdot}3$ chu/hr ft^2 °C

Air flow changes are assumed to change heat transfer coefficients by factors of 2 or $\frac{1}{2}$

Fig.20 Influence of air distribution on cabin air requirements

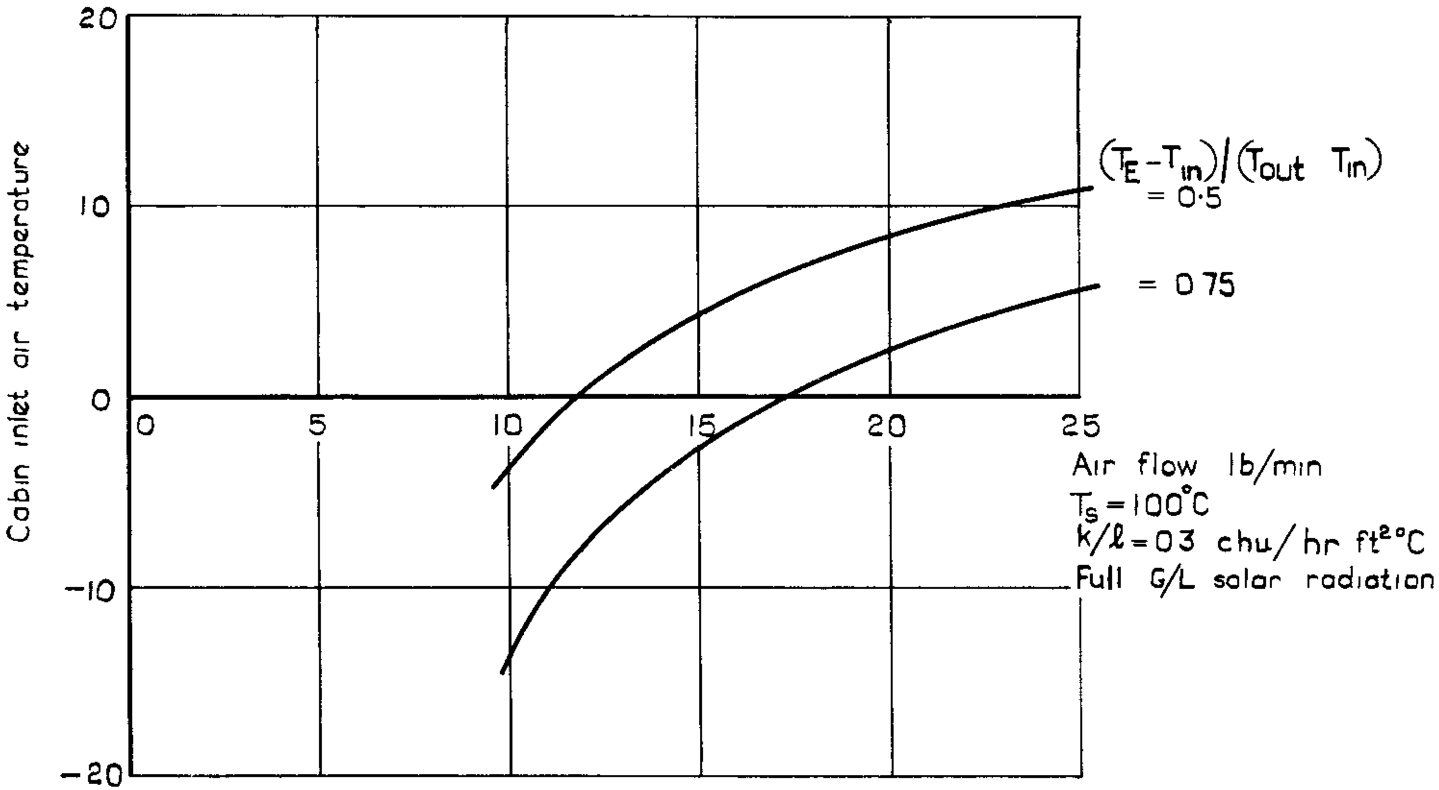


Fig. 21 Influence of temperature distribution on cabin air requirments

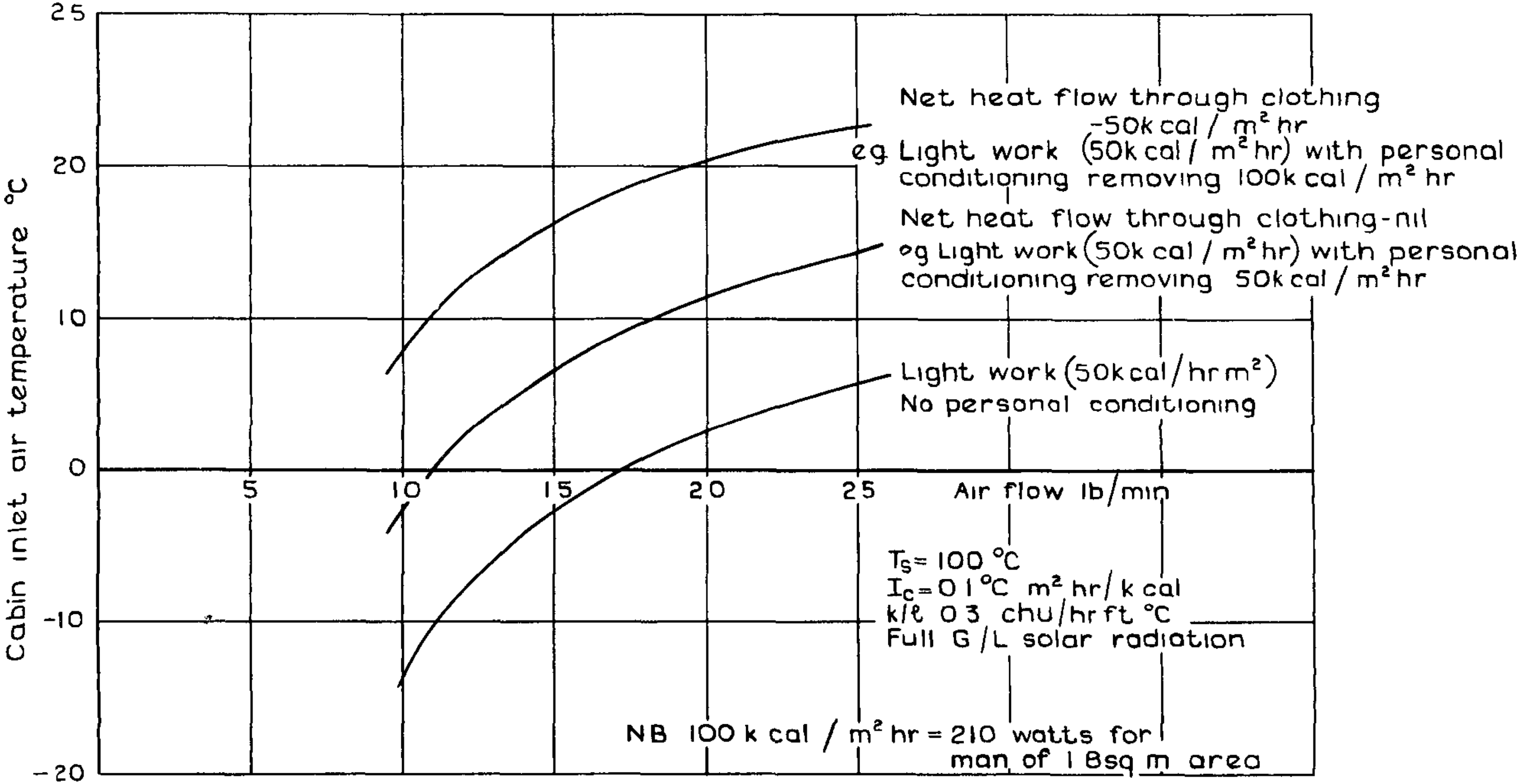


Fig. 22 Effect of personal conditioning (and work rate) on cabin air requirements

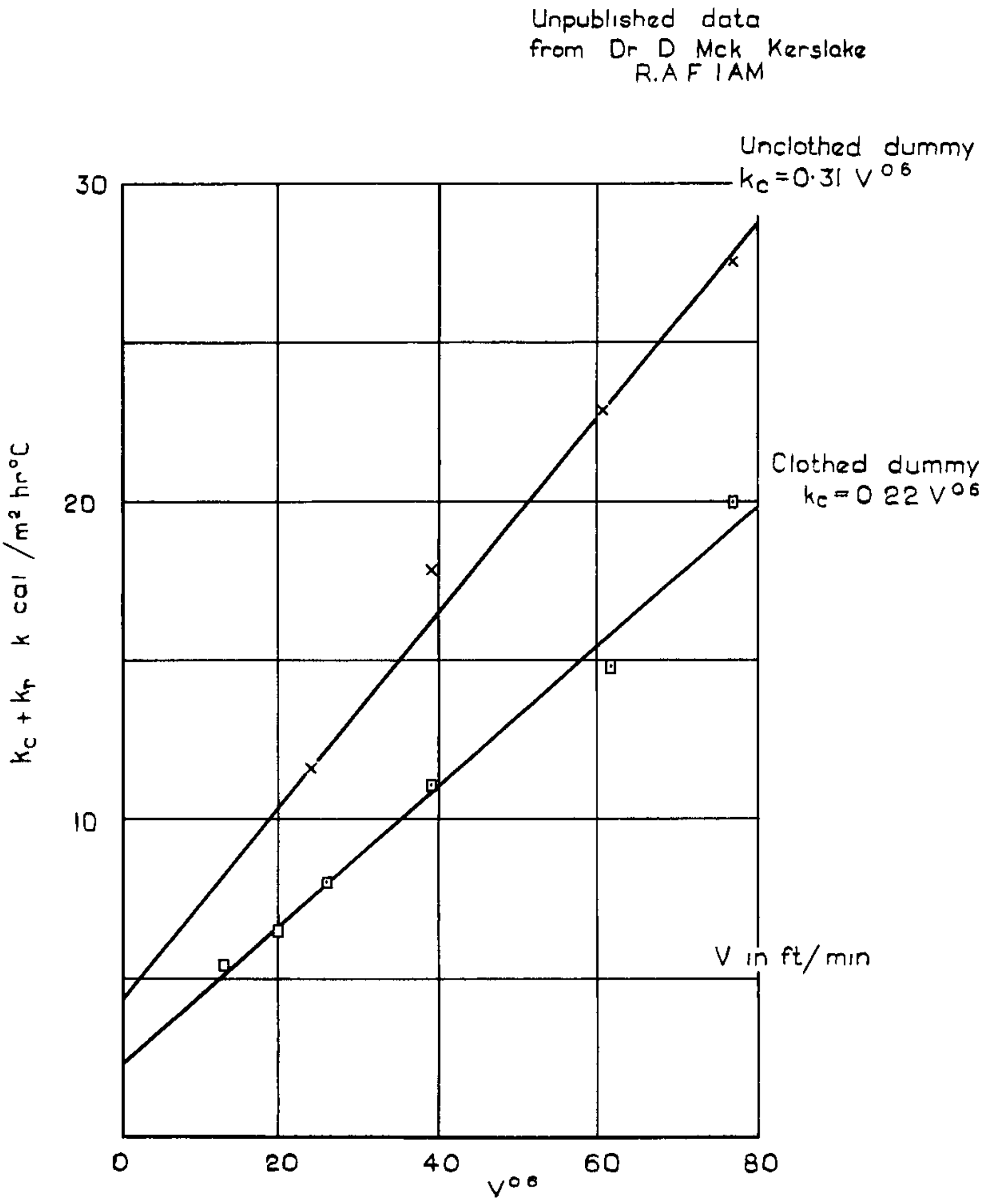


Fig. 23 Data on convective cooling of seated dummy

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