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A Theoretical Survey of the Potentialities of Insulation and Internal Cooling for Alleviation of Steady Kinetic Heating

by

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1964

PRICE 3s 6d NET

U.D.C. No. 536.244: 621-71: 533.6.011.6

C.P. No.744

April, 1962

A THEORETICAL SURVEY OF THE POTENTIALITIES OF INSULATION AND INTERNAL COOLING FOR ALLEVIATION OF STEADY KINETIC HEATING

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D. J. McCue

SUMMARY

An aircraft undergoing steady kinetic heating must be cooled to avoid increase of structural temperature. The amount of internal coolant needed during a flight is reduced but not eliminated by the use of external insulation. In a theoretical development it is shown here that under certain conditions, at low altitudes in particular, this combination requires less weight than is necessary using coolant only. This study is a generalisation of earlier work as it includes the effects of radiation and of the variation of thermal conductivity of practical insulating materials.

Replaces R.A.E. Tech.Note No. Structures 312-A.R.C.23723

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1 INTRODUCTION

The kinetic heating of the structure of a high speed aircraft may be reduced by the use of cooling with or without external insulation. Both of these devices involve the addition of weight. Schnitt, Brull and Wolko[1] have investigated the weight of insulation and internal cooling required to limit the temperature of the structure under various flight conditions, optimising the combination at a fixed wall temperature. Taylor[2] has dispensed with the latter restriction, but radiation and insulation effects are considered separately. The present paper extends Taylor's work to include the radiation from the surface together with the variation with temperature of the thermal conductivity of the insulation. The combination of insulation and cooling is optimised to give the minimum weight penalty.

The calculations apply to the steady state cruising conditions over distances of 2,500 and 5,500 miles. Thus no allowances are made for the transient conditions at the beginning and end of the flight. The aircraft structure is assumed to be of aluminium alloy whose temperature is limited to 150°C. Emissivities of 0·3 and 0·8 are considered along with heating rates for Mach numbers between 2·5 and 10·0. The flow is assumed to be turbulent and the representative position is taken as 10 feet from the leading edge. It is suggested that the estimates give the right order of total added weight and of the division of this total between cooling and insulation.

2 AERODYNAMIC RELATIONSHIPS

For the purpose of heat transfer calculations a representative enthalpy i_{wo} for air with a free stream Mach number M and ambient enthalpy i_1 is given by Monaghan[3] as

$$i_{wo} = i_1 (1 + 0{\cdot}178\ M^2) .$$

The factor of 0·178 is derived from experiments on heat transfer by air in turbulent flow. If the enthalpy at the surface is denoted by i_w heat flows from the air to the surface according to the equation

$$Q = h(i_{wo} - i_w) .$$

In this work Q denotes the aerodynamic heat input per unit area and time, and is positive when the flow is towards the surface. (The general heat flux terms which appear subsequently are denoted by q.) The heat transfer coefficient, h, is a useful parameter in incompressible flow theory as it is independent of i_w. For compressible conditions the same heat flow equation may be used if the calculations are made for a suitable mean boundary layer temperature[3]. In this case, however, h depends upon i_w. For the present purpose there is no advantage in defining a rate of heating by the difference of two enthalpy terms multiplied by a function of both. Accordingly a direct relationship is first derived between heat flow, Mach number, distance from leading edge, wall temperature, ambient temperature and density, the latter two being a function of the altitude. It is assumed that at altitudes above 36,000 feet the ambient temperature is -56·5°C. (Taylor[2] assumes the value of -50°C, but for purposes of comparing results the discrepancy is slight.) The density of the air in this region is doubled for every 14,400 feet descent. Turbulent flow is assumed throughout, but the regions of possible laminar flow (i.e. Reynolds number less than 2×10^6) are shown, where possible, in the figures. Results for altitudes above 100,000 feet, where the ambient temperature increases by an amount not yet established, should be regarded as approximations. Fig.1 shows the heating rate plotted against the square root of the absolute surface temperature, for fixed values of other parameters, and Fig.2 gives the conversion factors for various altitudes and distances from leading edge. The difference between results from Monaghan[3] and the linear relationships shown in these graphs is negligible.

3 ALLEVIATION OF HEATING

3.1 Radiation

Some of the heat received from the air is returned by radiation and an aircraft surface of high emissivity ε is therefore advantageous. The rate of emission from unit area is given by the equation

$$q = -\varepsilon \sigma T_w^4$$

where T_w is the surface temperature, σ the Stefan-Boltzmann constant and q the heat flux, using the positive-inwards sign convention. The emissivities of 0·3 and 0·8 used in these calculations are a typical value for polished metal and an upper limit for durable matt surfaces respectively. If the structure at 150°C receives heat via a layer of external insulation the outer surface is at a higher temperature and radiation is correspondingly greater. No account is taken of solar radiation in this work.

3.2 Cooling

If the equilibrium temperature of the aluminium structure in the foregoing conditions is greater than 150°C then artificial cooling must be employed. Attention is devoted here to internal cooling. A suitable circulating fluid carries the heat from the structure to a heat exchanger, where the coolant, water at 15°C, is converted into steam at 100°C. A cooling rate of 1 kilowatt is taken to require a coolant disposal rate of 3 lb per hour. The weight of coolant fluid per square foot of surface, W_c, used on a flight is proportional to the distance D and inversely proportional to the Mach number M. The rate of cooling under ideal conditions is thus

$$q = \frac{A\,M\,W_c}{D}$$

where A is a coolant efficiency parameter which has the value, at $-56{\cdot}5°C$ ambient temperature, of 221 kW mile lb^{-1} M^{-1}. (Taylor's value of 225 is derived from an ambient temperature of -50°C.) Only at constant ambient temperature is it convenient to use this parameter, instead of the more usual kW hours per lb.

3.3 Insulation

In certain flight conditions, especially at low altitude, some of the additional weight may be used more effectively as insulation than as coolant. The latter must still be used if the structure is not to reach adiabatic wall temperature. The incidental benefit of increased radiation has been mentioned in para 3.1. The resistance to heat flow of an ideal insulator is proportional to its thickness, as is its weight. For a material of thermal resistivity 1000°C per inch for each kilowatt per square foot, and a specific gravity of 0·5 the insulation efficiency B is 385°C kW^{-1} ft^4 lb^{-1}. This value is used by Taylor[2] and is assumed to include the weight of the supporting structure. In the present paper the insulation efficiency for a small temperature difference between faces has a value of 400 units at 150°C and this efficiency is halved for each 400°C rise in temperature, in accordance with an empirical law derived from the data of Bishop and Rogers[5]. For an ideal insulation

$$q = \frac{T_W - T_s}{B\,W_I}$$

where T_s is the structural temperature, 150°C in this case, and W_I the weight of insulation per square foot of surface. In the real insulation, considered here, $(T_W - T_s)/B$ must be replaced by the effective value for finite temperature difference which is

$$\left[\frac{T_W - T_s}{B}\right]_{\text{effective}} = \frac{1}{0{\cdot}693}\left\{\exp\ 0{\cdot}693\,\frac{(T_W - T_s)}{400} - 1\right\} \text{kW lb ft}^{-4} .$$

This quantity is denoted in subsequent calculations by F. Its differential coefficient with respect to T_W, which occurs in the minimum weight derivation is

$$\frac{d}{dT_W}\left[\frac{T_W - T_s}{B}\right]_{\text{effective}} = \frac{dF}{dT_W} = \frac{1}{400}\exp\ 0{\cdot}693\,\frac{(T_W - T_s)}{400}\ \text{kW lb ft}^{-4}\,{}^{\circ}\text{C}^{-1} .$$

4 DERIVATION OF EQUATIONS

The steady state equation expresses the fact that the heat removed by the coolant is equal to the difference between aerodynamic and radiant heat, thus:-

$$q = \frac{A\,M\,W_c}{D} = Q - \varepsilon\,\sigma\,T_W^4 . \tag{1}$$

This is also the quantity of heat flowing through the insulation and so

$$q = \frac{A\,M\,W_c}{D} = \frac{F}{W_I} . \tag{2}$$

For given flight conditions the structural temperature requirement is satisfied by using any quantity of coolant with the appropriate amount of insulation, because F and Q are functions of T_W and the latter can be eliminated from (1) and (2) leaving a single equation relating W_c and W_I. It is the purpose of this work to find the combination of weights satisfying this single equation and also giving minimum total weight. This is satisfied when

$$\delta W_c + \delta W_I = 0 .$$

It can be shown that in practice this condition gives a minimum and not a maximum, but in some cases W_I is negative. In such instances coolant only should be used. A small variation of F derived from equation (2) with $-\delta W_c$ substituted for δW_I may be written as

$$\delta F = \frac{AM}{D} (W_c \, \delta W_I + W_I \, \delta W_c) = \frac{AM}{D} (W_I - W_c) \, \delta W_c \ .$$

Subjecting equation (1) to a variation, and substituting the above value of δW_c,

$$\frac{AM}{D} \delta W_c = \delta Q - 4 \, \varepsilon \sigma \, T_W^3 \, \delta T_W = \frac{\delta F}{W_I - W_c} \ .$$

Hence, in the limit,

$$W_c - W_I = \frac{dF/dT_W}{4 \, \varepsilon \sigma \, T_W^3 - dQ/dT_W} \tag{3}$$

This is the auxiliary equation which enables optimum values of W_c and W_I to be found.

5 METHOD OF CALCULATION

Four values of T_W are assumed, 150°C (where insulation thickness is zero), 400°C (softening point of glass fibre), 600°C (an estimated limit for synthetic resins), and 1000°C which is an estimate of the maximum allowable temperature for use of insulation based on silica or asbestos fibres.

Having assumed T_W the necessary degree of freedom is restored by making Q the other unknown. It is evident from Fig.2 that the aerodynamic heating is very sensitive to changes in altitude, and therefore a wide range of heating rates obtained from equations (1), (2) and (3) can be accommodated in the practically relevant altitude range. From Fig.2 it is seen that dQ/dT_W is proportional to Q regardless of altitude and so the auxiliary equation (3) can be expressed in terms of Q. This means that cubic equations in W_c, W_I and Q must be solved, and there is found to be only one positive root for each. On plotting Mach number against altitude for fixed surface temperature T_W, interpolation is necessary to obtain lines of constant W_c and W_I. This gives a complete picture of the requirements and limitations of the use of coolant and insulation. Calculations for two values of flight distance provide diagrams Figs.3-5. If the distance from the leading edge is other than 10 feet, the change in aerodynamic heating rate may be found from Fig.2.

6 DISCUSSION OF RESULTS

The salient features of these calculations can be summarised without detailed reference to the values of the various parameters. Altitude is predominant in determining the order of magnitude of kinetic heating, the latter being halved for an increase in height of between 17,000 and 18,000 feet. Distance from the leading edge has little influence and to halve the heating rate this distance must be increased by a factor of over 30, which is in most cases well outside the region of investigation.

A study of equation (3) reveals that as Q decreases with increasing temperature the right hand side expression is positive and so W_c is always greater than W_I. Two extreme cases are noteworthy. At low altitude we find that the optimum condition requires the insulation weight to be nearly equal to the coolant weight. Taylor[2] refers to this effect which is independent of the magnitude of radiation. At high altitude the optimum weight of insulation may be predicted as an essentially negative quantity, and so the other extreme occurs when $W_I = 0$ and consequently $T_w = T_s$. Between these extremes lie all cases of practical interest in steady state problems. A direct comparison of the results with those of Taylor[2] is only enlightening in the case of zero insulation, where the effect of emissivities 0, 0·3 and 0·8 can be seen. The relative importance of different radiation intensities becomes obscured in other cases because the behaviour of the insulating materials is not ideal.

7 CONCLUSION

Steady flight conditions and structural temperature requirements can be related to the necessary weight penalty per square foot of aircraft surface. The laws of heat flow give one relation between the amounts of coolant and insulation. An equation which holds for optimum conditions only can be used, in addition, to determine each part of the weight penalty. When this calculation results in the appearance of negative insulation weight coolant only should be used, and in regions beyond the limit of surface temperature of insulation this temperature must be assumed in the calculation. The equation for optimum conditions may only be used between these extremes. The results show that the altitude is the most important factor in determining the usefulness of insulation. At high altitude coolant only is needed whereas at low altitude the weights of coolant and insulation are approximately equal. It must be noted that in no optimum conditions does the insulant weight exceed the coolant weight, but in transient heating, not considered here, the insulation assumes a greater relative importance.

LIST OF SYMBOLS

i_{wo}	enthalpy of air corresponding to adiabatic wall temperature
i_1	enthalpy of air under ambient conditions
i_w	enthalpy of air at wall
M	free stream Mach number
$\dot{Q}$	heat flow into aircraft skin per unit area and time (kW ft^{-2})
h	heat transfer coefficient $q/(i_{wo} - i_w)$
ε	emissivity
σ	Stefan-Boltzmann constant (kW ft^{-2} $^{o}K^{-4}$)

LIST OF SYMBOLS (Contd.)

T_w	wall temperature (°K)
T_s	structural temperature (°K)
A	coolant efficiency parameter (kW mile lb^{-1} M^{-1})
B	insulation efficiency parameter (°C kW^{-1} ft^4 lb^{-1})
D	flight distance (miles)
W_c	weight of coolant per unit area (lb ft^{-2})
W_I	weight of insulation per unit area (lb ft^{-2})
F	heat flux through unit surface density of insulation

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Printed in England for Her Majesty's Stationery Office by
the Royal Aircraft Establishment, Farnborough. W.T.60.K4

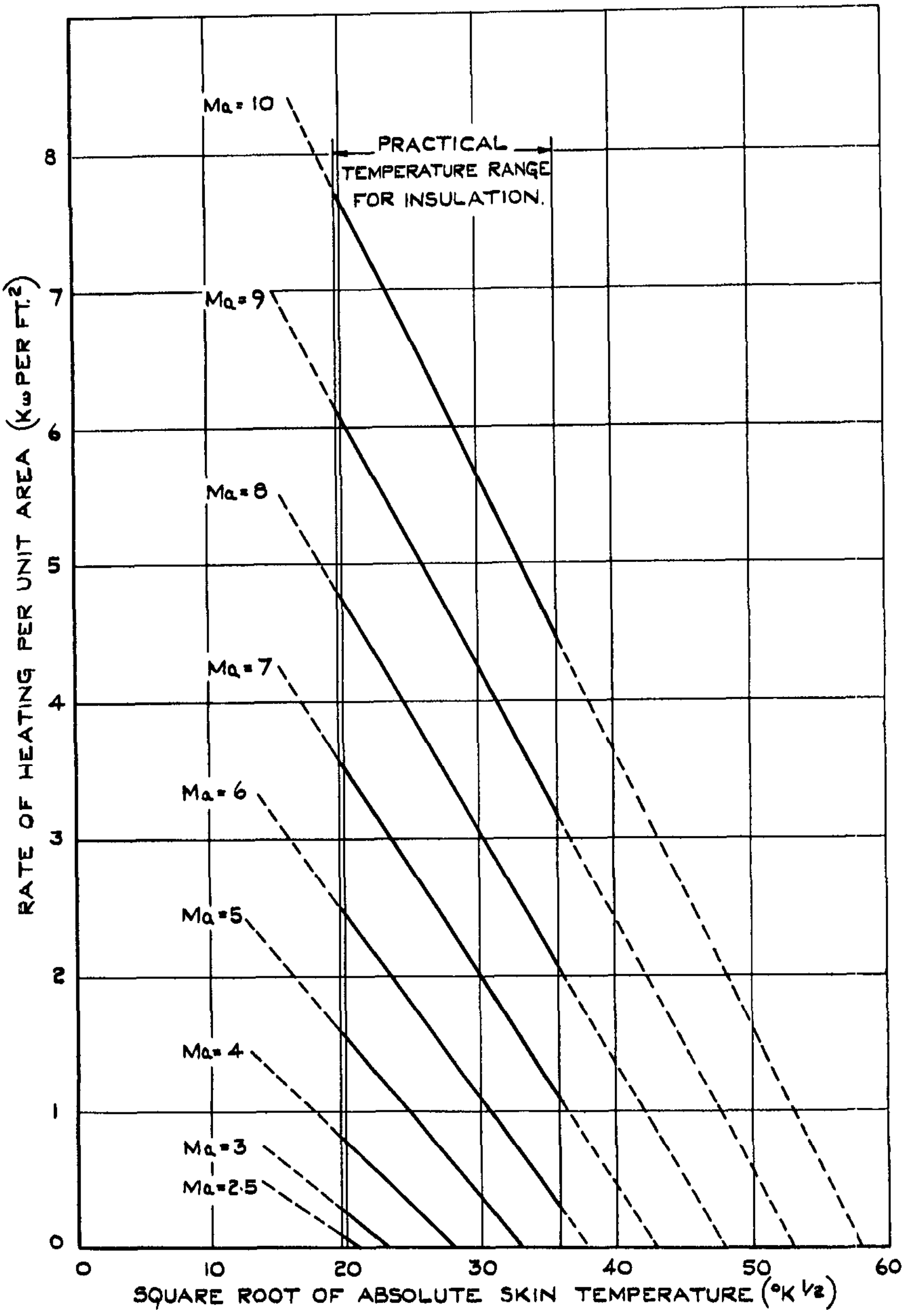


FIG.1. KINETIC HEATING AT 100,000 FT. ALTITUDE & 10 FT. FROM LEADING EDGE FOR VARIOUS VALUES OF MACH. Nº & SKIN TEMPERATURE.

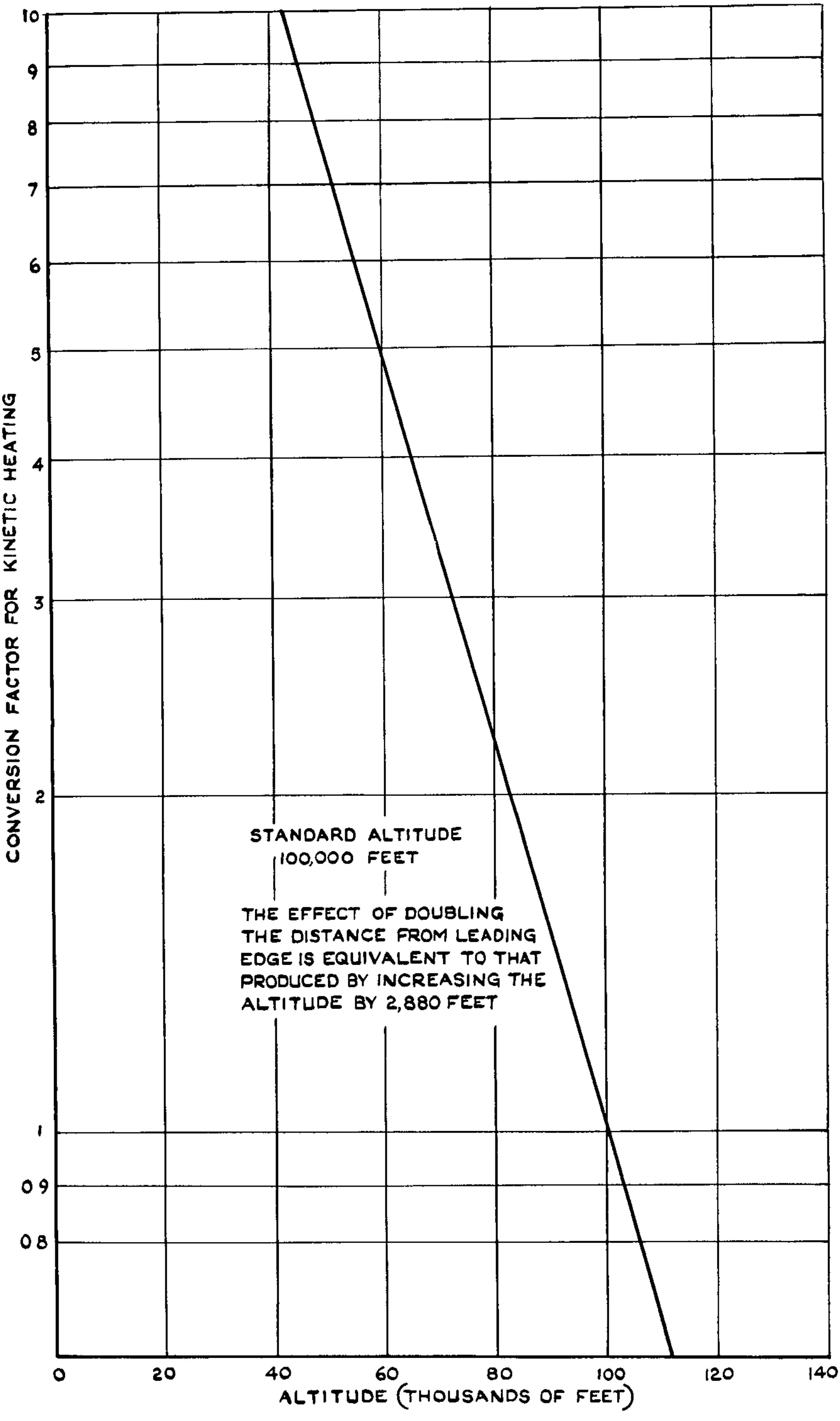
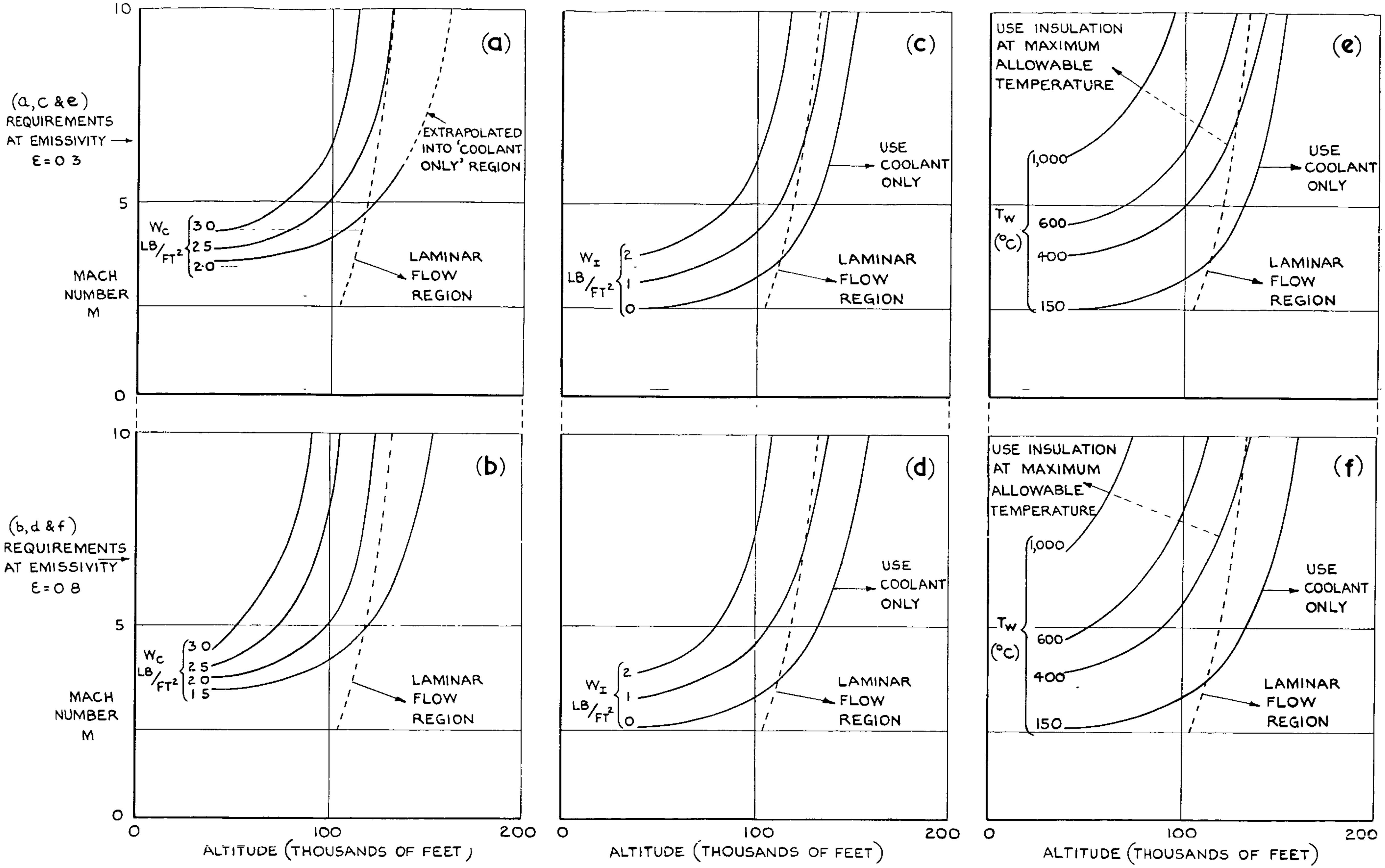


FIG. 2. VARIATION OF KINETIC HEATING WITH ALTITUDE AND DISTANCE FROM LEADING EDGE.

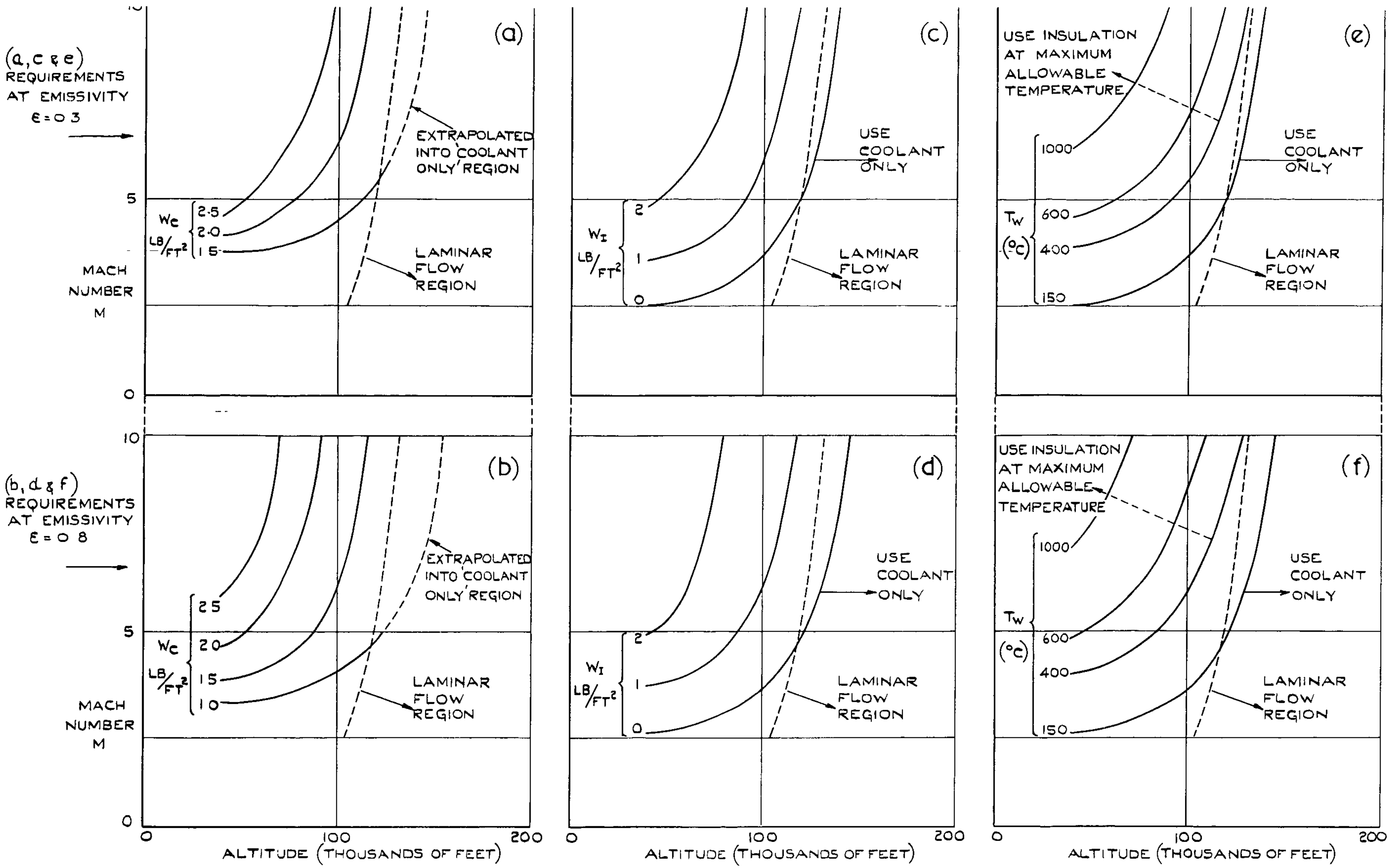


(a & b) LB. WEIGHT OF COOLANT PER FT^2 OF SURFACE.

(c & d) LB WEIGHT OF INSULATION PER FT^2 OF SURFACE

(e & f) SURFACE TEMPERATURE °C.

FIG. 4 (a-f). COOLANT, INSULATION AND TEMPERATURE REQUIREMENTS FOR A STEADY FLIGHT OF 5,500 MILES (STRUCTURAL TEMPERATURE 150°C., DISTANCE FROM LEADING EDGE 10 FT.)

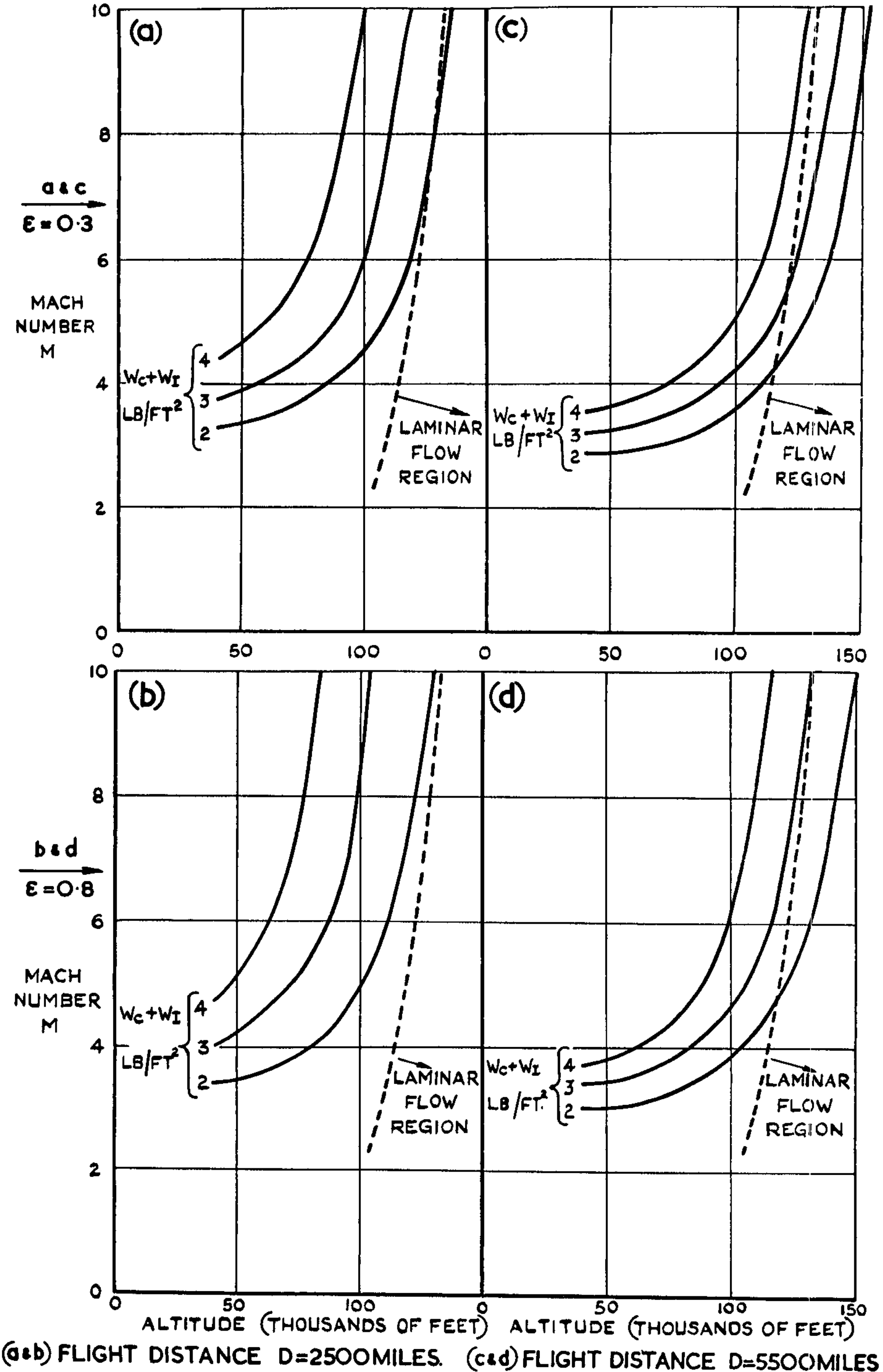


(a & b) LB WEIGHT OF COOLANT PER FT² OF SURFACE.

(c & d) LB WEIGHT OF INSULATION PER FT.² OF SURFACE

(e & f) SURFACE TEMPERATURE °C

FIG. 3. (a - f) COOLANT, INSULATION AND TEMPERATURE REQUIREMENTS FOR A STEADY FLIGHT OF 2,500 MILES. (STRUCTURAL TEMPERATURE 150 °C., DISTANCE FROM LEADING EDGE 10FT.)



(a & b) FLIGHT DISTANCE D=2500 MILES. (c & d) FLIGHT DISTANCE D=5500 MILES

FIG. 5. (a–d) COOLANT PLUS INSULATION WEIGHT. (STRUCTURAL TEMP. 150°C DISTANCE FROM L.E. 10 FT.)

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