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THE THERMAL INSULATION OF AIR GAPS IN THE VERTICAL PLANE

by

J. H. McGuire

Summary

Air gaps are often included in the walls of structures such as buildings, ships, refrigerators and ovens, for the thermal insulation which they provide.

The insulation of an air gap is dependent on the mean temperature of its bounding surfaces and the best effect is achieved when the gap is at the position where it is at the lowest possible mean temperature. The value of the insulation afforded by air gaps under various practical conditions is given graphically.

The expression assumed for convective transfer should only be considered valid when an air gap is at least $\frac{3}{4}$ inch wide.

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1) Introduction

A knowledge of the thermal insulation afforded by an air gap in the wall of a structure such as a building, ship, refrigerator or oven, is important to the designer as this insulation can be superior to that of a similar thickness of solid material and does not generally incur the same weight and cost penalty. This note expresses the thermal insulation of an air gap in terms of the equivalent thickness of concrete (having no thermal capacity) for a range of temperatures of the bounding surfaces.

In deriving the expression for the insulation, or thermal resistance, the width of an air gap has been assumed to be sufficiently great for convective transfer to be considered as natural convective cooling of the warmer surface to a free atmosphere (the air gap) and natural convective warming of the cooler surface by a free atmosphere. Experimental work (1) in the United States of America indicates that this assumption is only valid if the air gap is at least $\frac{3}{4}$ inch wide.

2) Heat transfer across an air gap

The heat transfer across an air gap will be by radiation and convection. The expression for the radiative transfer per unit area of surface (2) is

$$F_R = \frac{\mathcal{E}_1\mathcal{E}_2}{\mathcal{E}_1+\mathcal{E}_2-\mathcal{E}_1\mathcal{E}_2}\,\sigma\left(T_1^4 - T_2^4\right)$$

where $\mathcal{E}_1$ and $\mathcal{E}_2$ are the emissivity (or absorption) factors of the two surfaces, T_1 and T_2 are the absolute temperatures of the surfaces, and σ is Stefan's constant = $1.37.10^{-12}$ cal cm^{-2} sec^{-1} $^{\circ}$C^{-4}.

In Appendix 1 it is shown that an approximation to the above expression, to an accuracy of 1 per cent for all practical conditions, is

$$F_R = \frac{\mathcal{E}_1\mathcal{E}_2}{\mathcal{E}_1+\mathcal{E}_2-\mathcal{E}_1\mathcal{E}_2}\,4\sigma T^3\theta$$

where θ = temperature difference $T_1 - T_2$

and T = mean temperature (absolute) = $\frac{T_1 + T_2}{2}$

Heat flow by convection will be equal to the heat loss by convection from the hotter surface to the air between the surfaces. This will be given, approximately, by

$$F_c = H(T_1 - T)^{1.25}$$

where H is a constant (3) = 4.7×10^{-5} cal cm^{-2} sec^{-1} $^{\circ}$C$^{-1.25}$.

This value of H is intended to apply to vertical surfaces only.

The expression may be rewritten

$$F_c = \frac{H}{2}\left(\frac{\theta}{2}\right)^{\frac{1}{4}}\theta$$

The heat transfer across the gap, which will be by both radiation and convection, will therefore be given by

$$F = F_R + F_c = \left[\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} 4\sigma T^3 + \frac{H}{2}\left(\frac{\theta}{2}\right)^{1/4}\right]\theta$$

This expression is of the same form as the expression for the (steady state) flow of heat per unit area through a slab of material i.e.

$$F = K\theta/x = \theta/R$$

where x = thickness of slab of material
K = thermal conductivity
and R = x/K = resistance (per unit area) of slab of material.

Just as a slab of material has a thermal resistance $R = x/K$ so an air gap has a thermal resistance

$$R = \frac{1}{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} 4\sigma T^3 + \frac{H}{2}\left(\frac{\theta}{2}\right)^{1/4}}$$

Whilst the thermal resistance of a slab of material is dependent on its thickness but independent of the temperature difference across it, the thermal resistance of an air gap is independent of its thickness but dependent both on the mean temperature of the gap and on the temperature difference across it.

As the above expression includes four variables (θ, T, ε_1 and ε_2) presentation of values of R for a range of each of the variables would be cumbersome. In practice the two surfaces bounding an air gap are usually similar and therefore have the same emissivity factor (i.e. $\varepsilon_1 = \varepsilon_2 = \varepsilon$). This condition has been assumed and the following expression computed:-

$$R = \frac{1}{\frac{\varepsilon}{2-\varepsilon} 4\sigma T^3 + \frac{H}{2}\left(\frac{\theta}{2}\right)^{1/4}}$$

Graphs of thermal resistance, in terms of equivalent thicknesses of concrete giving the same thermal resistance, are given in Figs. 1-4.

A nomogram (Fig. 5) is also given to allow conversion of concrete thickness to equivalent thickness of an alternative material of different thermal conductivity.

3) Interpretation of results

Each of Figs. 1-4 includes a number of curves for various values of θ, the temperature difference between the two surfaces bounding the gap. For most practical purposes, however, the temperature difference lies within a particular range for any mean temperature of the air gap and, neglecting the curves for zero temperature difference across the gap, the remainder of each family approximate to one curve.

It will be seen that an air gap provides the greatest thermal insulation when its mean temperature is as low as possible. Thus in a refrigerator the air gap should be located nearest to the inner face of the wall to give maximum effect. In a structure intended to offer maximum fire resistance the gap should be located nearest to the surface least likely to be exposed to the fire. An air gap near to the face exposed to a fire would, after a few minutes of exposure, offer only a small fraction of the thermal resistance afforded at ambient temperature.

Comparing the figures it will be seen that a reduction of ϵ, the emissivity factor of the surfaces, greatly increases the effectiveness of the gap. Treatment of the surfaces bounding the gap, particularly lining with aluminium foil, would therefore prove very effective.

Where a designer needs to predict the thermal insulation of a wall under equilibrium conditions, the effect of an air gap can be calculated quite accurately by one or two successive approximations. Where, however, transient conditions are considered, the more tedious methods of calculation, such as a relaxation method, must be adopted.

Values of thermal insulation, taken from Figs. 1-4, have been found to agree to within ± 10 per cent with values obtained experimentally, over a small range of temperatures, by Wilkes and Peterson (4). The results given in this note refer only to air gaps bounded by vertical surfaces. Those of Wilkes and Peterson indicate that, where the bounding surfaces are horizontal, thermal insulation will be greater where heat flow is downwards and less where heat flow is upwards. The difference only becomes important (i.e. greater than 15 per cent) when the insulation attains a value in excess of an equivalent thickness of 7 inches of concrete.

4) References

1) Wilkes, G. B. "Heat insulation". John Wiley & Sons Inc. p. 112 and 120.

2) McGuire, J. H. "Heat transfer by radiation". Fire Research Special Report No. 2, H.M.S.O. p. 14.

3) "The efficient use of fuel". Min. of Fuel and Power. London 1944. H.M.S.O. p. 130.

4) Wilkes, G. B. and Peterson, C. M. F. "Radiation and convection across air spaces in frame construction". Trans. Amer. Soc. Heat. and Ventil. Engrs. 1937. 43. p. 362

Appendix 1

The accuracy of the approximation $T_1^4 - T_2^4 = 4T^3\theta$

In the expression for the radiative transfer between two surfaces the factor

$(T_1^4 - T_2^4)$ occurs where T_1 and T_2 are in degrees absolute.

Substituting $T = \frac{T_1 + T_2}{2}$ and $\theta = T_1 - T_2$ this factor may be written

$$\left(T + \frac{\theta}{2}\right)^4 - \left(T - \frac{\theta}{2}\right)^4 = T^4\left[\left(1 + \frac{\theta}{2T}\right)^4 - \left(1 - \frac{\theta}{2T}\right)^4\right]$$

$$= 4T^3\theta\left[1 + \left(\frac{\theta}{2T}\right)^2\right]$$

The fractional error in approximating this expression to $4T^3\theta$ is therefore $\left(\theta/2T\right)^2$

If θ be considered as large as 100°C and T be as low as 290°K (17°C, i.e. normal ambient temperature) then the error is only 3 per cent and with the values of θ and T used in this note the error is always less than 1 per cent.

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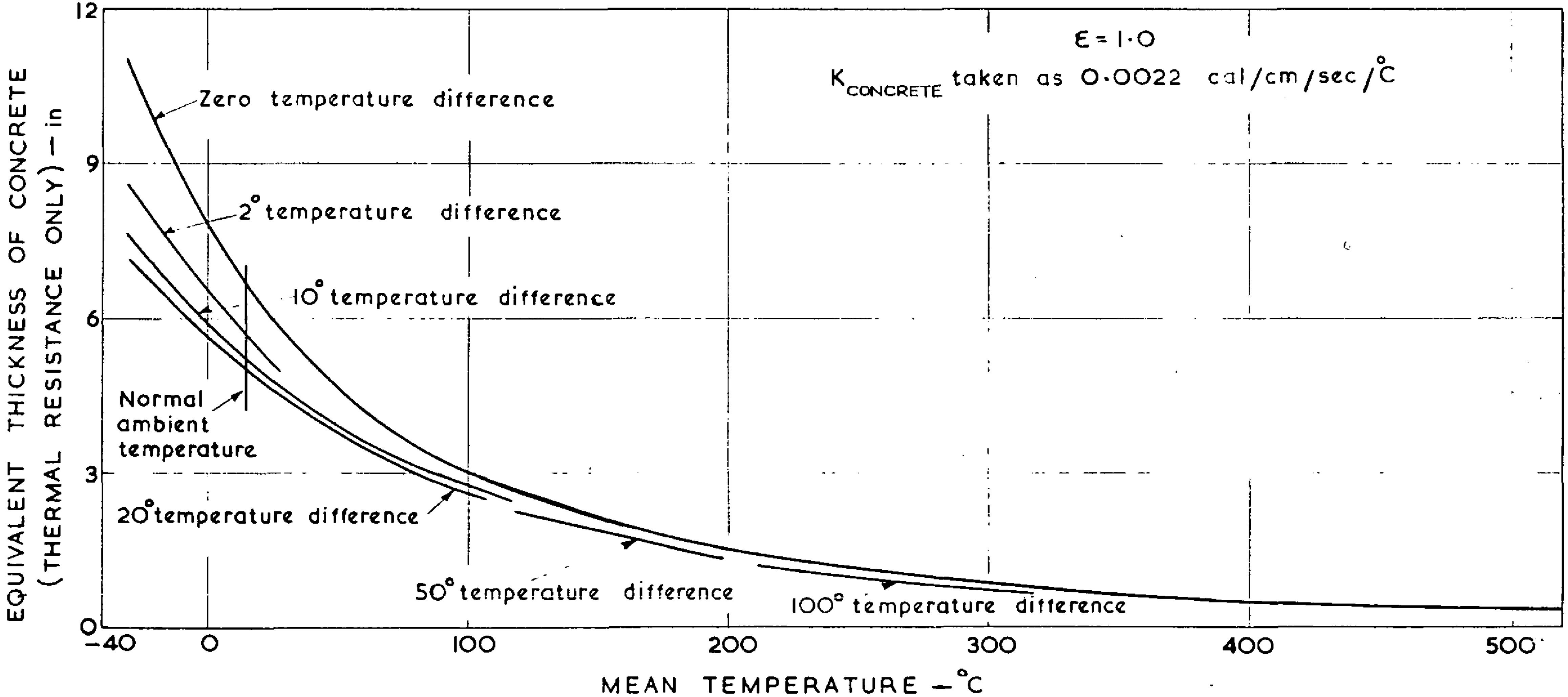

FIG.1. THE THERMAL RESISTANCE OF AN AIR GAP (IN INCHES OF CONCRETE)

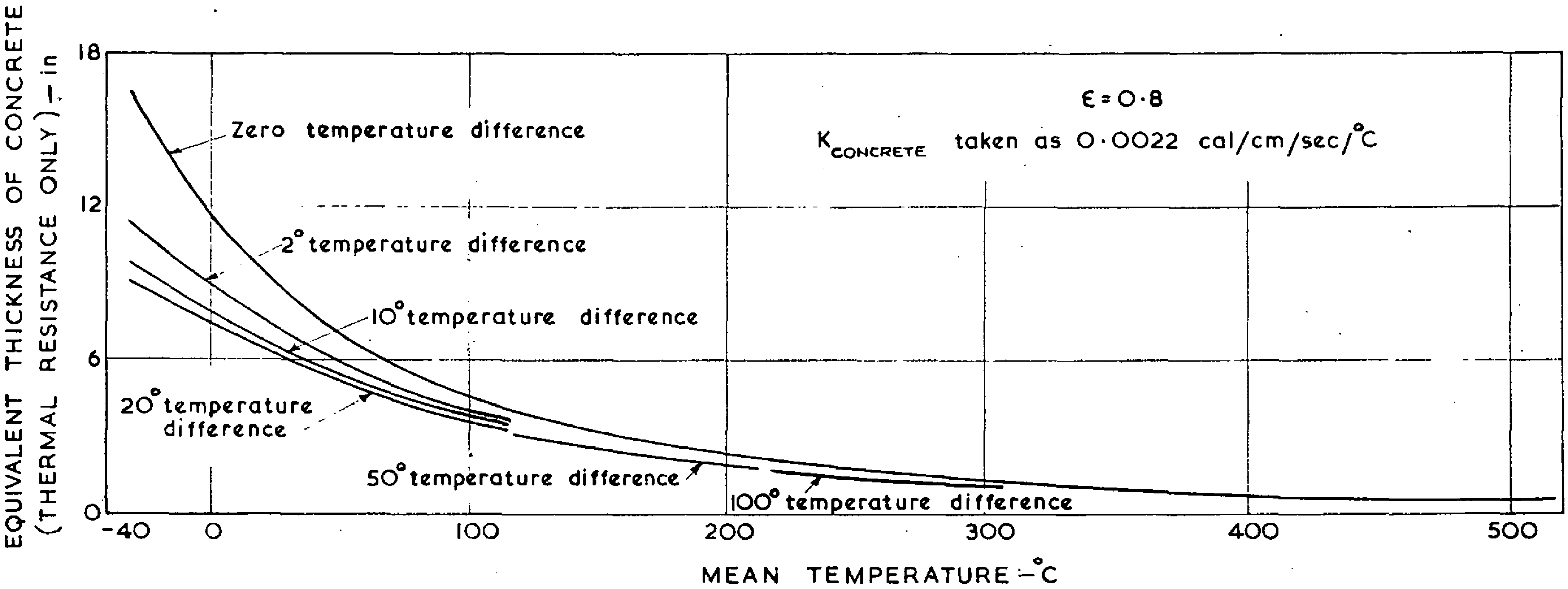

FIG.2. THE THERMAL RESISTANCE OF AN AIR GAP (IN INCHES OF CONCRETE)

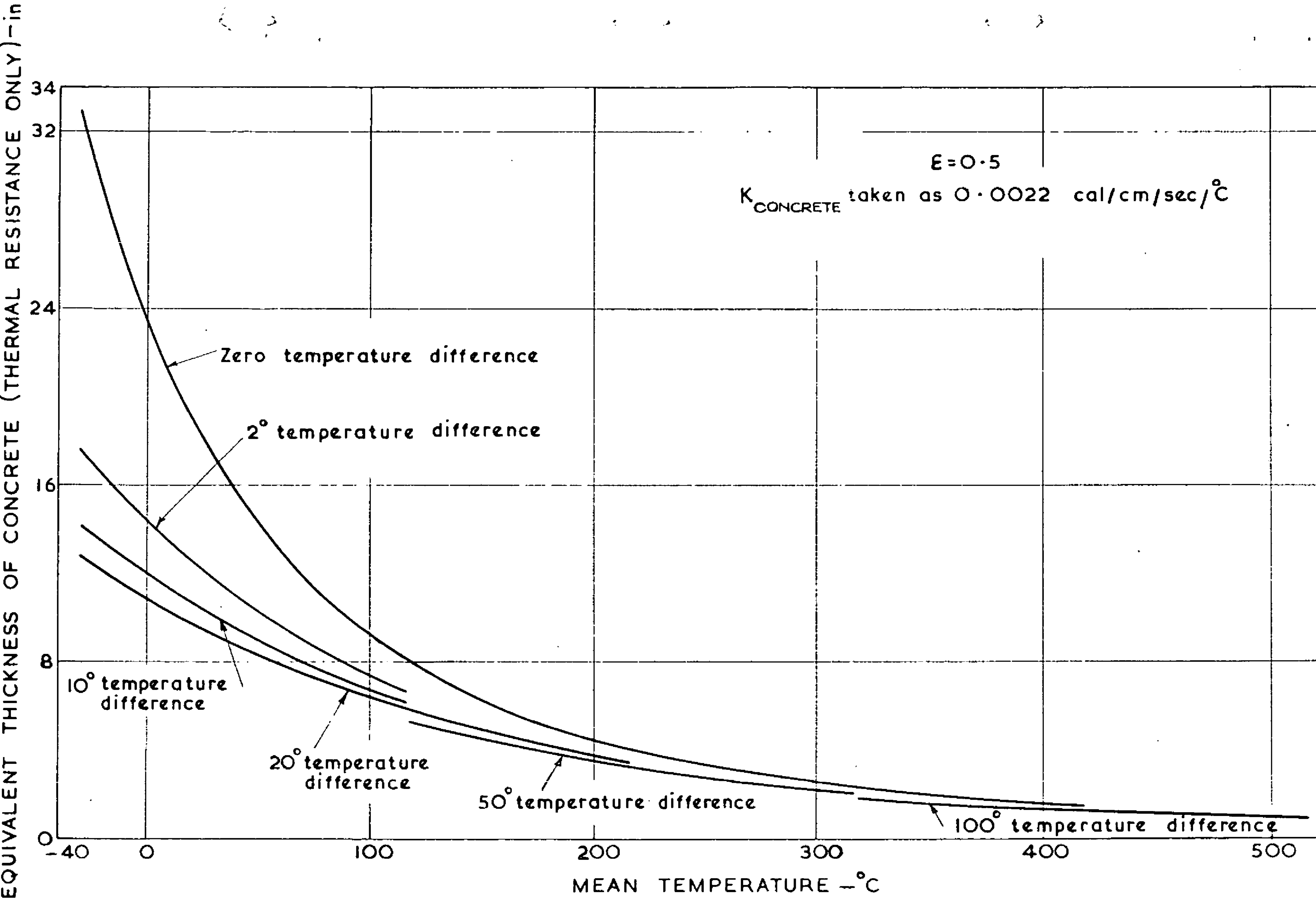

FIG. 3. THE THERMAL RESISTANCE OF AN AIR GAP (IN INCHES OF CONCRETE)

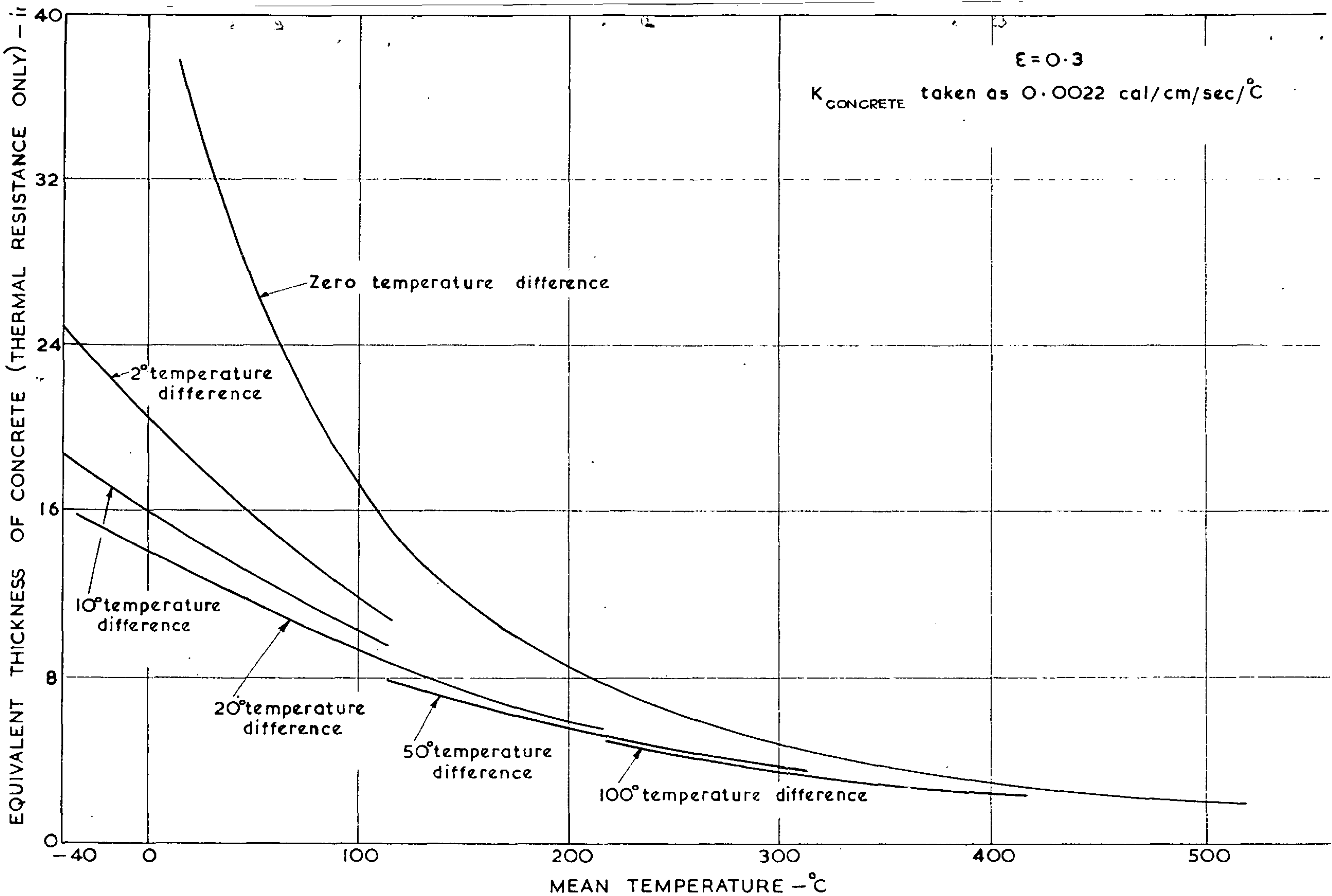

FIG. 4. THE THERMAL RESISTANCE OF AN AIR GAP (IN INCHES OF CONCRETE)

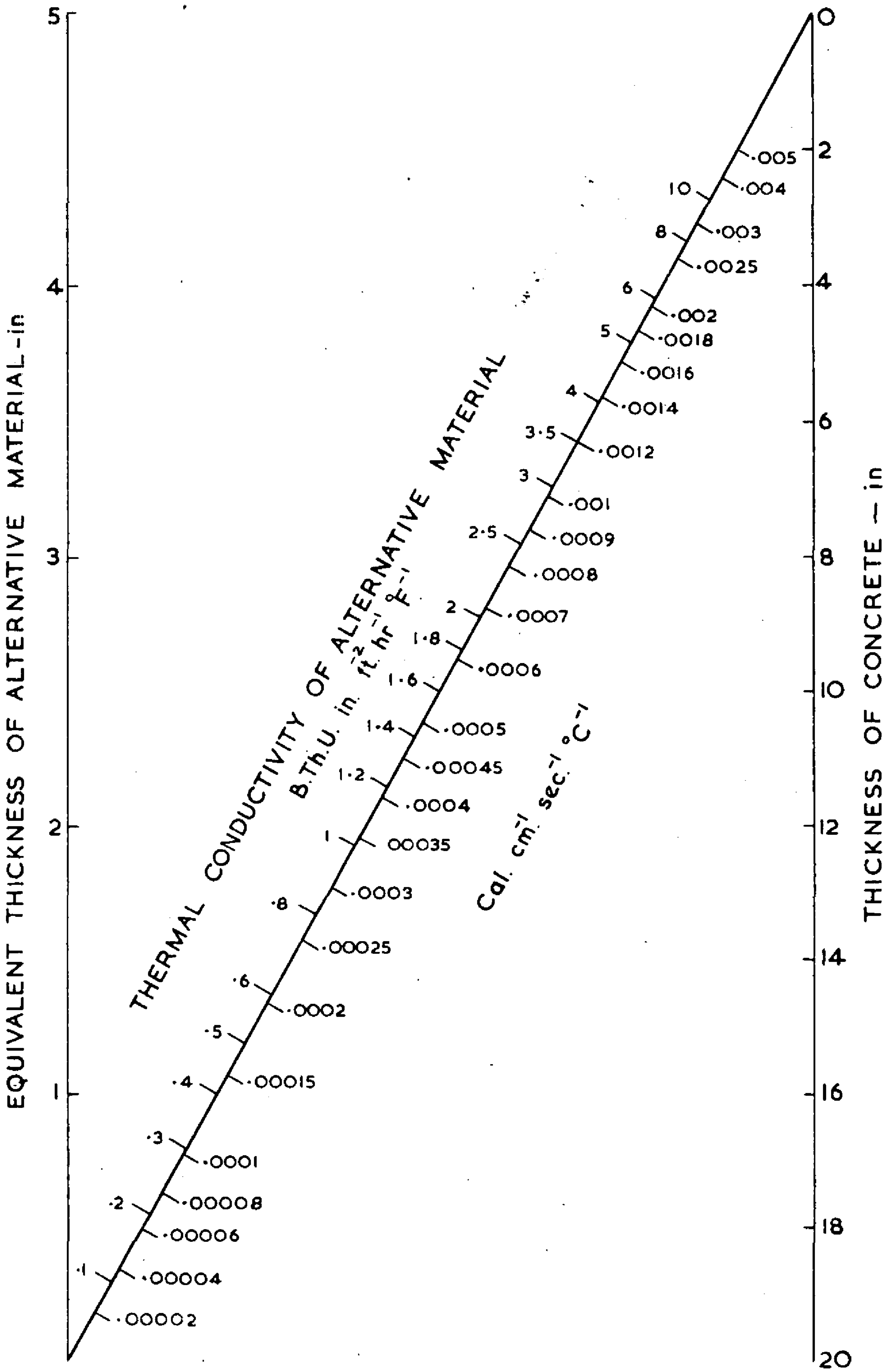

FIG.5. EQUIVALENT THICKNESSES OF ALTERNATIVE MATERIAL