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THE ESTIMATION OF FIRE-RESISTANCE

by

J. H. McGuire

Summary

Expressions have been derived from which the fire-resistance of certain kinds of structure, for thermal failure, may be evaluated either by comparison with a test result on a similar structure or from the thermal properties of the component materials.

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1. Introduction

The fire-resistance of a structure is the time for which it will comply with the following requirements when subjected to a test in accordance with B.S. 476:-

(a) It shall not collapse under its design load.

(b) For all elements of structure intended to separate spaces and to resist the passage of fire from one space to another, cracks, etc., through which flame can pass, shall not develop.

(c) For certain elements of structure, intended to separate spaces and to resist the passage of fire from one space to another, the average temperature of the unexposed surface shall not rise by more than 139 Centigrade degrees (250 Fahrenheit degrees); nor shall the temperature of any point on this surface exceed 221°C (430°F) or rise by more than 180 Centigrade degrees (325 Fahrenheit degrees) whichever is the less.

The third requirement is purely concerned with temperature and in many cases the same may be said of collapse. Thus with loaded, protected, steel or aluminium columns or bulkheads failure by collapse generally occurs when the metal attains a temperature at which it begins to yield substantially.(1)(2) For protected steel columns, for example, this temperature is in the region of 500°C - 600°C dependent on the stresses in the steel member. The same is also true of the failure of the cable in prestressed concrete beams(3) although the failing temperature for a cold drawn steel prestressing tendon is 100°C or so lower than that for the steel member of a column, principally because much greater stresses are involved.

As a general rule, therefore, provided requirement (b) above may be neglected and provided such phenomena as the spalling of concrete do not occur, a fire resistance problem may be treated as a heat flow problem in which the time to attain a specified temperature at some point within the structure is to be determined.

Even when the heat flow is purely a process of heat conduction, fire resistance problems are almost always intractable analytically and this note is intended to show how approximate solutions can generally be obtained by one of two methods.

The first method, of which there is more than one form, is a scaling method depending, for its use, on the existence of an experimental result for a similar structure. The second method is a prediction of the fire-resistance from the relevant heat conduction equations or approximations to them.

The first method will solve problems involving structures with negligible cooling to the atmosphere. The second method will solve column, beam and bulkhead problems where the thermal capacity of the insulating material is small compared with that of the metal core and also problems involving walls and floors where the thermal capacity is small.

The whole of the note is concerned with temperature and unless the contrary is stated, the origin of the scale is taken as an ambient temperature of 17°C. Examples of observed and predicted values of fire resistance are given to illustrate the usefulness of the various methods.

2. The scaling of fire-resistance problems

An electric analogue of heat conduction(4) has been used to predict the times at which a specified temperature would be attained at corresponding points in a number of columns which are scale replicas of each other (dimensions being the only scaled quantities). It was found that both for homogeneous and for protected metal-cored columns, these times are proportional to D^n where D is the dimensional scale factor and n is slightly dependent on time but approximates to 1.6. The reason why this differs from the square law implicit in the Fourier number kt/l^2 where k is thermal diffusivity, l is a linear dimension, and t is time, is that scaling is complicated by the fact that the standard temperature-time curve itself is not scaled. The 1.6 law is thus peculiar to this curve and is empirical. The relationship covers the conditions in which the time exceeds 30 minutes and the temperature is less than 600°C.

Only dimensions in which there is a component of heat flow influence the relationship. Thus in a column problem, the height of the column provided it is substantially greater than the transverse dimensions, will not influence the temperature distribution within the column.

The above scaling relationship was derived by treating a fire-resistance problem as one of heat conduction. In practice however, additional factors, such as the presence of water, affect fire-resistance times. The extent of the application of the scaling relationship has been described elsewhere(5)(6) and the following conclusions have been drawn.

One of the effects resulting from the presence of water not invalidating the scaling relationship, is the absorption of heat both as the temperature of the water (or moisture) rises and as it vaporizes. A second effect, the migration of moisture and vapour, should not affect the validity in so far as migration follows diffusion laws. For equal moisture contents, therefore, this scaling law is used unaltered.

Where cavities exist in a structure, scaling is not applicable excepting where, from the geometry of the structure, it can be seen that the cavities do not play a substantial part in the heat transfer.

Cooling to the atmosphere involves processes which do not scale according to D^n and it is therefore not wise to use this scaling relationship for wall or bulkhead problems, where surface cooling plays an important role.

Unfortunately it is not possible at present to say how the accuracy of predictions regarding concrete structures will be affected by spalling.

The accuracy to be expected from scaling according to the 1.6 power law is illustrated by Table 1 which gives predictions and test results for a series of prestressed concrete beams. Failure occurred when the tensile strength of the prestressing wires fell off substantially due to high temperature and, since the temperature in this region was not appreciably influenced by the cooling to the atmosphere of the top surface of the beam, this factor did not invalidate the use of the scaling law.

TABLE 1

Predicted failure times and test results for prestressed concrete beams

Scale of beam	Actual fire-resistance time (minutes)	Fire-resistance time predicted from ½ scale result (minutes)
4/5	165	226
1/2	100	-
3/8	65	63
1/4	38	33

The predictions were based on the $\frac{1}{2}$ scale result and whilst they were quite accurate in the case of the 3/8 and 1/4 scale beams the prediction in the case of the 4/5 beam was grossly inaccurate. During the test on this beam, severe spalling occurred. It did not occur in the other specimens and it has now been suggested that with this type of structure, spalling will occur if the unreinforced concrete cover to the prestressing wires exceeds two inches.(7)

3. The evaluation of thermal resistance and capacity

The use of a scaling law, when the structures considered are not scale replicas of each other, or the use of a calculation method, require the evaluation of the thermal resistance and capacity of component elements of structures. These may be derived from the thermal conductivities (K), densities (ρ) and specific heats (s) of the materials involved.

(a) Thermal resistance

The thermal resistance of a small element in the direction of heat flow, is given by:-

$$R = \frac{\ell}{AK} \qquad \text{................ (1)}$$

where ℓ is the length of the element in the direction of heat flow and A is the cross-sectional area through which heat is flowing. Dimensionally

$$(R) = \frac{(\ell)}{(A)\ (K)} = \frac{(L)}{(L^2)\ (QL^{-1}\,\theta^{-1}T^{-1})} = \frac{\theta}{Q/T}$$

so that thermal resistance = $\frac{\text{Temperature difference}}{\text{rate of flow of heat}}$ and is analogous

to electrical resistance = $\frac{\text{potential difference}}{\text{rate of flow of charge}}$

It should be noted that thermal resistance is quite different from fire-resistance which, by definition, has the dimension time.

Equation (1) applies to large elements of constant cross-section A provided the heat flow is unidirectional. It may be used directly to evaluate the thermal resistance of a thin layer of insulation following the contour of a column, as illustrated in Fig. 1. If unit height is considered, the mean cross-sectional area through which the heat is flowing numerically equals the periphery P and the expression reduces to

$$R = \frac{x}{PK} \qquad \text{................ (2)}$$

With radially symmetrical columns the insulation constitutes an annulus and the area through which the heat flows is a function of the radius. The resulting expression for R is

$$R = \frac{1}{2\pi K h} \log_e r_2/r_1 \qquad \text{................ (3)}$$

where r_2 is the external radius of the annulus

r_1 is the internal radius of the annulus

and h is the height of the column.

The choice of a self-consistent system of units for K, ℓ, r, etc. in the above expressions is discussed in Appendix 1.

Some structures include air gaps for which the thermal resistance is a function of the absolute temperature of the bounding surfaces. If the gap is near to the furnace the thermal resistance is low and may generally be neglected. In other cases an assessment of the resistance may be obtained by reference to graphs of resistance against temperature given elsewhere.(8)

(b) Thermal capacity

The thermal capacity of an element is given by

$$C = V \rho s \qquad \text{..............} \quad (4)$$

where V is the volume of the element. The expression applies directly to all geometrical configurations.

(c) The effect of variation of the thermal properties

The thermal conductivity (K) of a material is frequently a function of temperature and in an extreme case the ratio of the conductivities at 1000°C and ambient temperature has been found to be as high as 6. The effect of this variation can usually be taken into account by using a mean value of K. Where a steady state unidirectional heat flow problem is being considered and K is a function of temperature, the effect will be accurately allowed for by using, in expression (1), the arithmetic mean value of K for the temperature range in the slab of the material involved. If the effect of this variation in K is large the method of estimation of the temperature-time distribution becomes one of successive approximations.

Where a transient heat flow problem is being considered the effect can be taken into account, to a first approximation, by attributing to a material in a particular structure a value of K appropriate to the mean temperature of the material over the whole of the fire resistance time. Since the dependence of conductivity on temperature is widely different for different materials and since the effect of this variation will itself depend on the nature of the structure, it is not possible to be specific as to the error which might arise due to an inaccurate assessment of a suitable value of K. The order of error likely to be introduced in any one problem is best assessed by evolving solutions for different values of K. The same may be said of the product ρ s but this is generally not liable to such great variation.

4. Columns and beams in which the insulation follows the contour of the core

It is now possible to discuss structures which are not scale replicas of each other and to discuss the assumptions which must first be made in applying either a modification of the scaling method described above or a direct calculation method.

To make a prediction of the fire resistance of a protected column (or beam) the properties of resistance and capacity should be attributed to all the component materials. Where, however, the core of a column is of metal, its thermal conductivity is so high compared with that of the protective covering that it may be considered infinite.

A further assumption is necessary to reduce the problem to simple terms and it is that the capacity of the protecting material may be neglected. The extent to which this is justified has been investigated theoretically. From solutions obtained by the electric analogue (Figs. 2 and 3) it can be seen that, in the region of the failing temperature for steel (500°C - 600°C), the error in time introduced by neglecting the thermal capacity of the protection will be 12 per cent and 20 per cent where the capacity neglected amounts to 25 per cent and 50 per cent respectively, of the capacity of the metal core. To a first approximation the effect of the thermal capacity which is distributed throughout the protection may be represented by half this value of thermal capacity considered to be located at the centre of column. Calculation has also shown that the use of this representation reduces the errors referred to above by a factor of at least four.

Making these assumptions a column may be considered to be merely a thermal resistance followed by a thermal capacity as illustrated in Fig. 1. We now discuss the two approaches in turn.

(a) Scaling method

The results of calculations on an analogue have shown(6) that the fire-resistance times t_1 and t_2 of two columns of similar construction but not of complete geometric similarity will be related by the expression

$$\frac{t_1}{t_2} = \left(\frac{R_1C_1}{R_2C_2}\right)^{0.8} \qquad \text{..................(5)}$$

or on substituting for R and C in the case where the capacity of the insulation may be neglected

$$\frac{t_1}{t_2} = \left(\frac{x_1\, A_1\, P_2}{x_2\, A_2\, P_1}\right)^{0.8} \qquad \text{..................(6)}$$

where x = thickness of insulation
P = mean periphery
and A = cross sectional area of metal column.

Considerations of temperature, thermal conductivity (K) and thermal capacity per unit volume have thus been eliminated. Where the thermal conductivity of the material nearest to the furnace is very dependent on temperature the fact that long fire-resistance tests involve higher temperatures should strictly be taken into account. Neglect of this factor does not, however, generally introduce appreciable errors.

The fire-resistance of a metal cored column can be predicted from a test result on a column with a different core provided the latter has a higher failure temperature. Thus the fire-resistance of an aluminium cored column can be predicted from a test result on a steel cored column but not vice versa. The yield temperature of the metal core of the first column, in this example aluminium, must be known and the time at which the steel attained this temperature in the test found from the test record. The expression for t_1/t_2 will now involve the products (ρ s) for the two metals and will be

$$\frac{t_1}{t_2} = \left(\frac{x_1\, A_1\, \rho_1\, s_1\, P_2}{x_2\, A_2\, \rho_2\, s_2\, P_1}\right)^{0.8} \qquad \text{..................(7)}$$

Where the capacity of the insulation must be taken into account the expression must, of course, be modified.

Although equation (7) formally reduces, for structures of similar shape and materials, to the scaling law described in Section 2. it is likely to be less accurate, in general.

To illustrate the versatility of the approach, a series of predictions has been made (see Table 2), not on columns in which the insulation follows the contour of the core but on steel H members in solid concrete encasements.

TABLE 2

Predictions concerning rectangular encasements

Type of Column	Fire-resistance Time (by test)	Predicted fire-resistance time*
8" x 6" x 35 lb R.S.J. 2" cover	3 hrs 40 mins	-
- ditto -	3 hrs 7 mins	-
6" x 4.5" x 20 lb R.S.J. 2" cover	3 hrs 8 mins	3 hrs 4 mins ± 14 mins
4" x 3" x 10 lb R.S.J. 2" cover	3 hrs - mins	2 hrs 42 mins ± 12 mins
4" x 3" x 10 lb R.S.J. 1" cover	1 hr 30 mins	1 hr 13 mins ± 5 mins
4" x 3" x 10 lb R.S.J. 4" cover	6 hrs - mins	7 hrs 3 mins ± 33 mins

* The quoted tolerance is derived from the variation in the first two tests.

Failure was assumed to occur when the steel flange attained a certain temperature and only the flow of heat through a face adjacent to one flange was considered. To a first approximation the thermal resistance of this path is proportional to the thickness of the concrete cover and to the reciprocal of the mean cross sectional area of the cover over the flange.

The capacity of the protection is not negligible for these columns and as described above the effect of the thermal capacity of the concrete cover was represented by half its value added to that of the flange, which was calculated to be 0.3 of the total thermal capacity per unit length of the steel member.

The predictions were based on the column for which two results were available. In view of the difference of over half an hour between these two test results and of the fact that the application of the method has been considerably extended to cover this class of problem, the agreement is considered satisfactory. The tendency to over-estimate long times and under-estimate short times is presumed to be a result of the extension of the application of the method.

Excepting where the cover on the flange is exceptionally thick, the effect on scaling of the heat sink provided by the concrete surrounding the inner portion of the flange has been neglected. The amount of this concrete which will constitute a heat sink is itself a function of time and hence has been assumed to scale in accordance with the value of $(R\,C)^{0.8}$ where R and C are derived as stated above. The relative dimensions of the last column listed in Table 2 make the assumption invalid in this case. This is no doubt the principal reason why the fire-resistance of the column was not as long as was predicted. Other factors which would have influenced the accuracy of the results were the effects of water and the cracking of the concrete.

(b) Calculation method

The fire-resistance of columns with different protective materials could in theory be obtained in a similar way but it is quicker and probably just as accurate to derive a solution from the following formula which predicts the temperature at the centre of a column given a fixed temperature imposed at the surface.

$$\Theta = \Theta_o \left(1 - e^{-\frac{t}{RC}}\right) \quad \text{................ (8)}$$

where R and C are the thermal resistance and capacity as previously defined

Θ is the temperature (rise) of the metal core

and Θ_o is the temperature (considered constant) imposed on the exterior surfaces of the column.

Since in a B.S. 476 test the surface temperature is not constant, a value of Θ_o must be used in the calculations which will produce the same value of Θ as the B.S. 476 time-temperature curve. By considering columns which reach their failure temperature at selected times the electrical analogue of heat conduction has been used to calculate appropriate values of Θ_o. These are given in Table 3.

TABLE 3

Step function equivalent of B.S. 476 Furnace time-temperature curve (columns)

Failure time	Equivalent Step Function Θ_o (temp. rise)
$\frac{1}{2}$ hr	745°C
1 hr	845°C
2 hrs	935°C
4 hrs	1,050°C

A graph of expression (8) in terms of Θ/Θ_o against t/RC is given in Fig. 4.

Expression (8) is essentially in terms of temperature and in order to derive a fire-resistance time a value must be attributed to the failure temperature of the metal core. This will, of course, depend on the nature of the metal but will also depend on the stresses in the member. A suitable temperature is thus best ascribed by an examination of previous test records. Since the gradient of the core temperature/time curve (see Fig. 4) exceeds half its value at the origin for the range of temperatures which will be involved, errors in the specification of the core failure temperature will not produce substantially greater errors in the predicted fire resistance time.

The order of accuracy to be expected in using expression (8) is illustrated by the following example. In a fire-resistance test the mean steel temperature rise, after 1 hour, of an 8 in. x 6 in. x 35 lb steel column protected by a 5/16 in thickness of spray asbestos, was 550°C. Expression (8) with a value of 1.8×10^{-4} c.g.s. units for the thermal conductivity of spray asbestos gives a prediction of 600° rise.

The use of expression (8) can be extended to give predictions of the fire-resistance of a column consisting of an H member in a solid lightweight encasement, an example of which is illustrated in Fig. 5. To simplify the method of solution, only the heat flowing through one end face is considered. As discussed above (see p. 6) only 0.3 of the total thermal capacity of the steel is taken into account. In the example illustrated in Fig. 5, the effective mean cross sectional width of the area through which heat is flowing to the flange was taken as 7 inches and the predicted temperature rise of the steel was 160°C after 1 hour and 350°C after 2 hours. In a fire-resistance test the temperature rises attained were 170°C and 390°C after 1 and 2 hours respectively.

5. Floors, walls and bulkheads

Cooling to the atmosphere plays a part in the fire-resistance of walls, bulkheads and floors and hence it is unwise to apply the scaling relationship described in Section 2.

The thermal resistance of many walls, bulkheads and floors is so great that, even if their thermal capacity were negligible, cooling to the atmosphere would ensure that the temperature of the unexposed surface (or in fact of any other critical point) would not rise above the prescribed level.

It is possible to predict rapidly the equilibrium temperatures of the unexposed surface so that as a first approach to this class of problem it is advisable to determine the temperature which would be attained at the specified point in the structure, at the specified time, if the effect of thermal capacity were neglected. For the unexposed surface of the structure this is given by expression (9) and for any other point in the structure by expression (10).

$$\Theta = \frac{\Theta_o R_c}{R + R_c} \qquad \text{..............} (9)$$

$$\Theta' = \frac{\Theta_o (R_c + R_a)}{R + R_c} \qquad \text{..............} (10)$$

where Θ is the temperature at the unexposed surface;

Θ' is the temperature at any prescribed point;

Θ_o is the furnace temperature (rise) at the time considered (see Fig. 6)

R_c is the equivalent resistance representing cooling to the atmosphere at the unexposed surface;

R_a is the thermal resistance between the unexposed surface and the point at which the temperature is required;

and R is the thermal resistance of the structure.

In evaluating R only unit area of the structure need be considered so that the expression for R reduces to $R = l/K$ where l is the thickness of the structure. Where a structure is composed of laminae of different materials

$$R = l_1/K_1 + l_2/K_2 + l_3/K_3 \text{ etc.}$$

where l_1 and K_1 are the thickness and thermal conductivity of the first lamina, etc.

R_c is slightly dependent on temperature. For unexposed surface temperature rises of the order of 140°C it may be taken as 2,400 sec °C cal^{-1} for walls and bulkheads and 2,100 sec °C cal^{-1} for floors where the area considered is one square centimetre.

A furnace test on a structure consisting of a steel bulkhead faced with a 1½ in. of insulating material gave a temperature rise of 123°C at the unexposed face, the steel being nearest to the furnace. Expression (3) gives a predicted temperature rise of 107°C. Since the neglect of thermal capacity gives a conservative approximation the predicted temperature rise should exceed the test value. The example is thus one in which the value given for the thermal conductivity (K) of the material involved was measured under laboratory conditions which were not appropriate to a fire-resistance test. For the solution of fire-resistance problems it is most important, where values of K are required, that the dependence of K on absolute temperature be determined or that a value based on the result of a previous test be used.

If the temperature rises predicted by the above method are higher than permitted by the B.S. 476 criteria of failure it is necessary to take into account the thermal capacity. It does not necessarily follow that the structure considered would fail in an actual test as the effect of thermal capacity might produce much lower temperatures. An analysis, referring to homogeneous walls has been made by C. F. Fischl(9) and it may also be taken as applicable to floors, so that only bulkheads need be discussed here. Solutions can be obtained for problems involving lightweight protected steel or aluminium bulkheads where, as with metal cored columns, the resistance of the metal may be neglected and the capacity of the protection may be considered to be zero, or, better still, lumped with the bulkhead capacity. The representation of such a bulkhead is shown in Fig. 7. Only unit area of the bulkhead need be considered and thus the expression for the capacity of the metal reduces to $\ell \rho s$ where ℓ is the thickness of the metal bulkhead. The expression for the capacity of a thickness (ℓ_1) of insulation, either side of a bulkhead is $C_1 = 2 \ell_1 \rho_1 s_1$ and this value should be added to the value of the capacity of the bulkhead proper. To date the only problems considered have involved bulkheads in which the thermal capacity of the insulation has not exceeded 30 per cent of the thermal capacity of the bulkhead proper. No statement can therefore be made, at present, as to whether lumping the capacities will introduce appreciable errors where higher capacity insulation is involved.

As given earlier in this paragraph the expression for R reduces to $1/K$. The thermal conductivity (K) of the protection will probably be a function of temperature and in evaluating R_1 and R_2, the resistances of the insulation, it will probably be necessary to use two different values of K.

Expression (11) and (12) relate the temperatures of the bulkhead to R_1, R_2 and C and are exactly analogous to expression (8) given in para. 4.

$$\theta' = \frac{\theta_o (R_2 + R_c)}{R_1 + R_2 + R_c} \left[1 - e^{-t\frac{(R_1 + R_2 + R_c)}{R_1 (R_2 + R_c) C}} \right] \qquad (11)$$

$$\theta = \frac{\theta_o R_c}{R_1 + R_2 + R_c} \left[1 - e^{-t\frac{(R_1 + R_2 + R_c)}{R_1 (R_2 + R_c) C}} \right] \qquad (12)$$

where θ' is the temperature rise (above ambient) of the metal bulkhead;

θ is the temperature rise (above ambient) of the unheated surface of the bulkhead;

θ_o is the temperature rise (considered constant) imposed on the heated surface (see Table 4);

R_c is the equivalent resistance representing cooling to the atmosphere at the unexposed surface;

and R_1, R_2 and C are defined in Fig. 7.

The value adopted for R_c should be a mean of the values it would assume during the course of a test. For walls and bulkheads it may be taken as 2,800 sec °C cal^{-1} and for floors 2,450 sec °C cal^{-1}.

TABLE 4

Step Function Equivalent of B.S. 476 Furnace Time-temperature Curve - Bulkheads

Failure Time	Equivalent Step Function θ_o (temp. rise)	
½ hr.	745°C	
1 hr.	845°C	
2 hr.	975°C (1)	935°C (2)
4 hr.	1,100°C (1)	1,050°C (2)

(1) Failure criterion: temperature rise of 139°C on unexposed face.
(2) " " : temperature rise of order 550°C on protected metal.

Since the expressions are based on the quantities K, ρ and s they are valid only where heat flow is by conduction. The order of accuracy which can be achieved by the application of expressions (11) and (12) is illustrated by the predictions and test results given in Table 5. The close agreement between most of the predictions and the test results is probably unusual and in general the effects of water or poor thermal diffusivity data will give greater inaccuracies.

TABLE 5

Temperature predictions for bulkheads

Structure	Time	Test Results (temp. rise)		Predicted Results (temp. rise)	
		Unexposed face	Steel	Unexposed face	Steel
¼" steel bulkhead protected on both sides by ¾" of insulating material	1 hr	54°C	322°C	55°C	325°C
¼" steel bulkhead protected on furnace side only by 1" of insulating material	1 hr	113°C	-	115°C	-
⅜" steel bulkhead protected on both sides by ¾" of insulating material	2 hrs	120°C	-	135°C	-

A further prediction has been made to illustrate the accuracy to be expected in the combined use of expressions (9) and (12). A steady state test result on a slab of insulating material was available and from expression (9) a value of the thermal conductivity of the material was calculated. Using this value in expression (12) gave a predicted temperature rise of 71°C after 1 hour at the unexposed face of a bulkhead protected on both sides by this material. The corresponding test result was 62°C rise.

6. Discussion

Temperature-time predictions for columns subjected to B.S. 476 fire-resistance tests are theoretically possible assuming that spalling of concrete is not involved, by means of (a) a scaling method, where a test result on a similar column exists, (b) by direct calculation from the basic data (K, ρ and s).

The scaling method for identical structures (scale replicas) is in principle the most accurate since the effects of using the B.S. 476 furnace curve and of variation of thermal properties with temperature and most of the effects of water are all taken into account. The scaling method applied to structures which are not replicas of each other takes into account the use of the B.S. 476 curve and to an approximation the effect of the variation of thermal properties with temperature, but it may introduce errors where water has considerable influence and where the relative proportions of protection and core are quite different. The calculation method takes into account, to an approximation, the effects of using the B.S. 476 curve and of variations of thermal properties with temperature but completely neglects the effects of water and demands either direct knowledge of the thermal properties or effective values obtained from previous tests.

A simple method of predicting the steady state temperature of walls and bulkheads is given, with the comment that on occasions the steady state conditions will meet fire-resistance requirements. So far as transient conditions are concerned (i.e. including the effect of capacity) homogeneous walls are not considered in this note having been discussed elsewhere[9] by C. F. Fischl. A method is given for the determination from basic data of the temperature within and on the unheated surface of a bulkhead and it has the same limitations as the analogous method applied to column problems.

No simple satisfactory comparative method exists as yet for solving bulkhead problems.

7. References

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8. Acknowledgment

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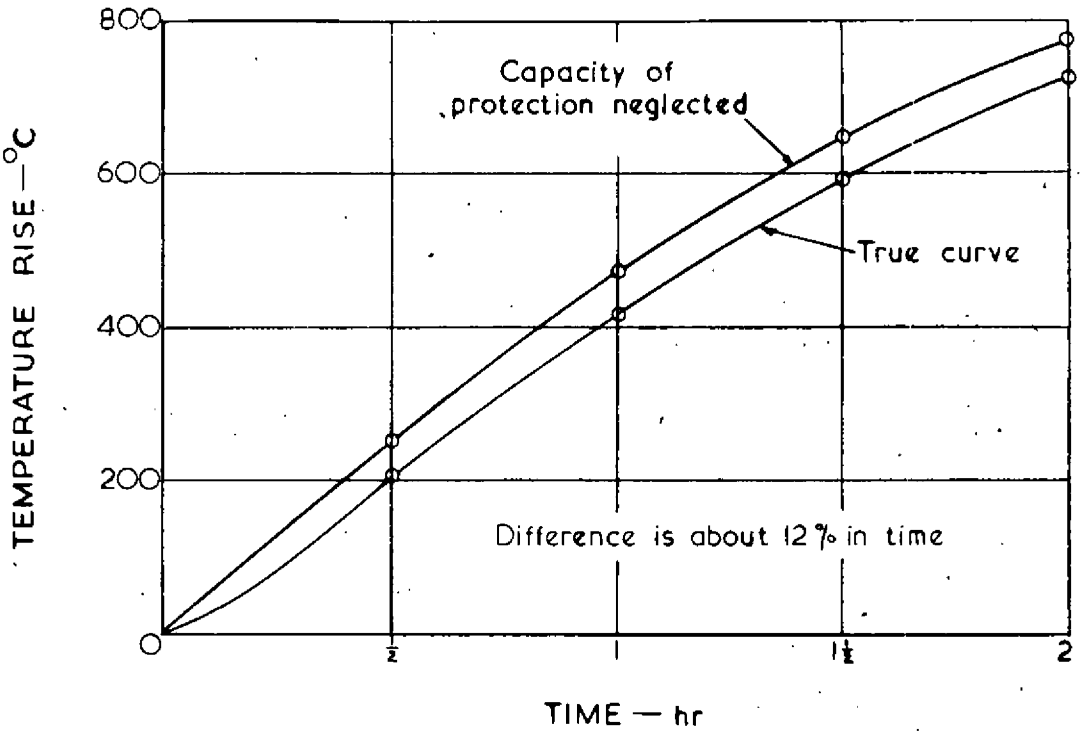

FIG. 2. EFFECT ON COLUMN TEMPERATURE OF NEGLECTING THERMAL CAPACITY OF MATERIAL PROTECTING THE COLUMN

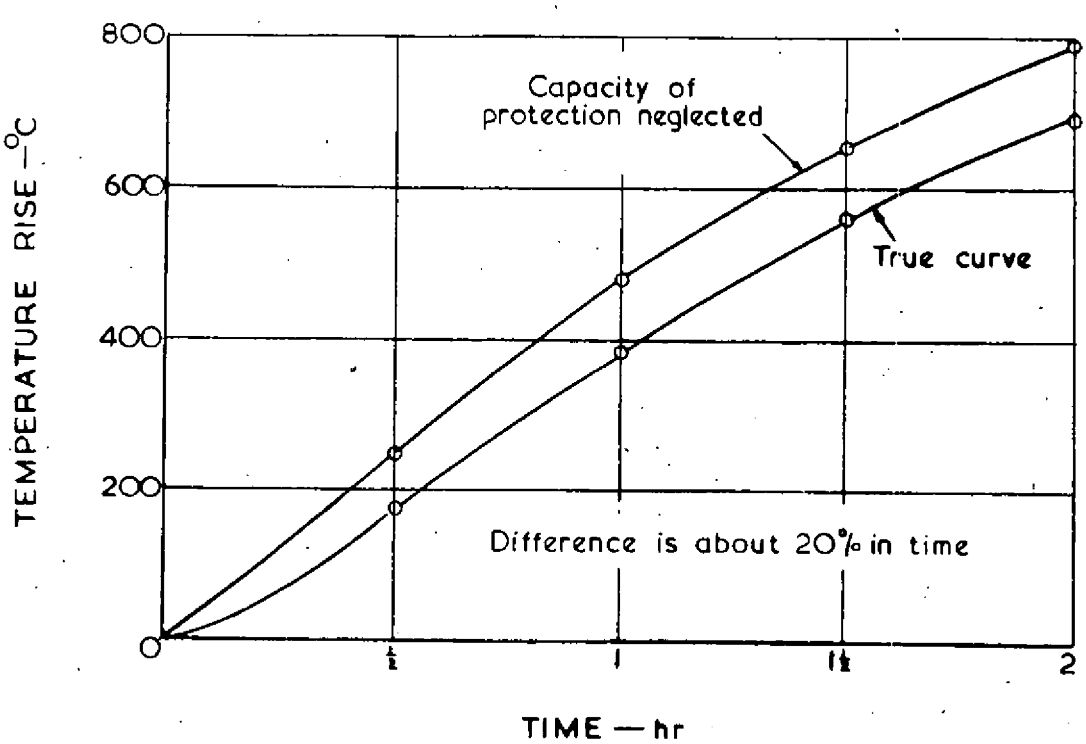

FIG. 3. EFFECT ON COLUMN TEMPERATURE OF NEGLECTING THERMAL CAPACITY OF MATERIAL PROTECTING THE COLUMN

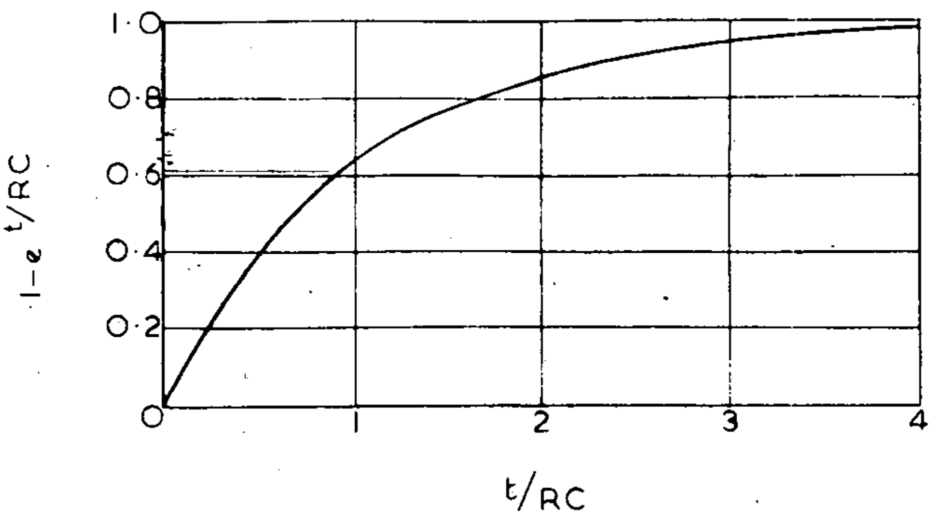

FIG. 4. THE EXPONENTIAL FUNCTION $(1-e^{-t/RC})$

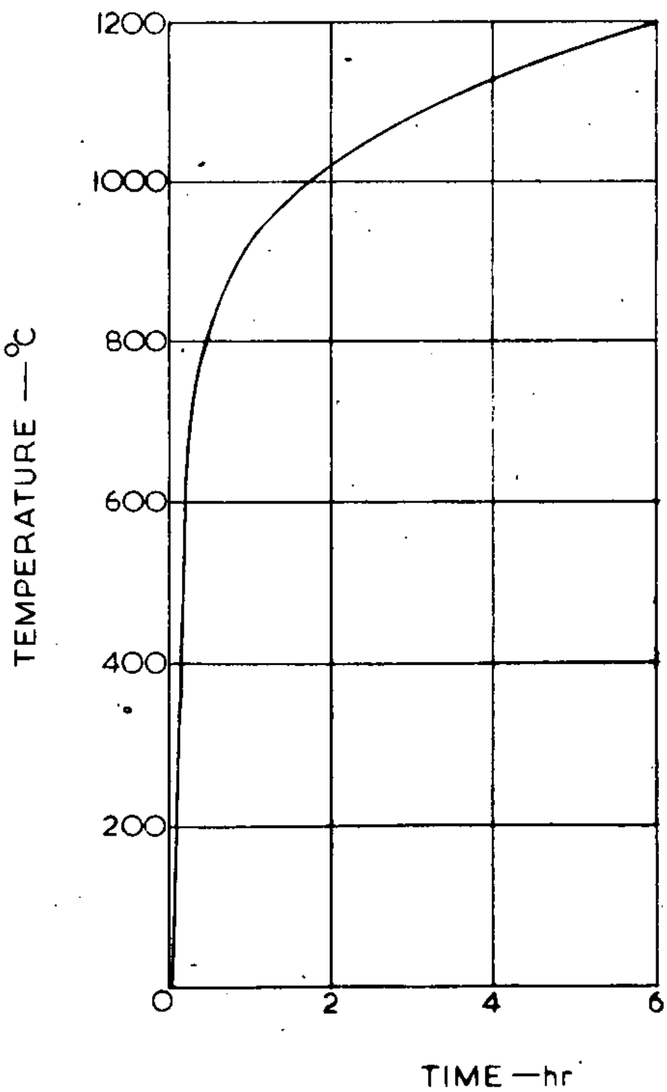

FIG. 6. B.S. 476. FURNACE CURVE

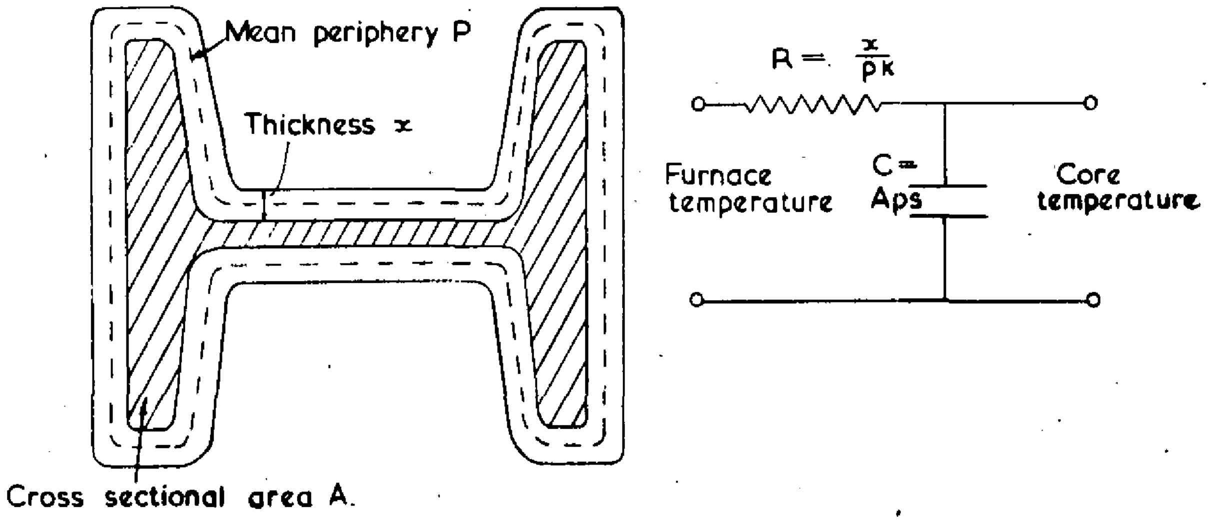

FIG.1. THE THERMAL REPRESENTATION OF A PROTECTED COLUMN. (CAPACITY OF PROTECTION NEGLIGIBLE)

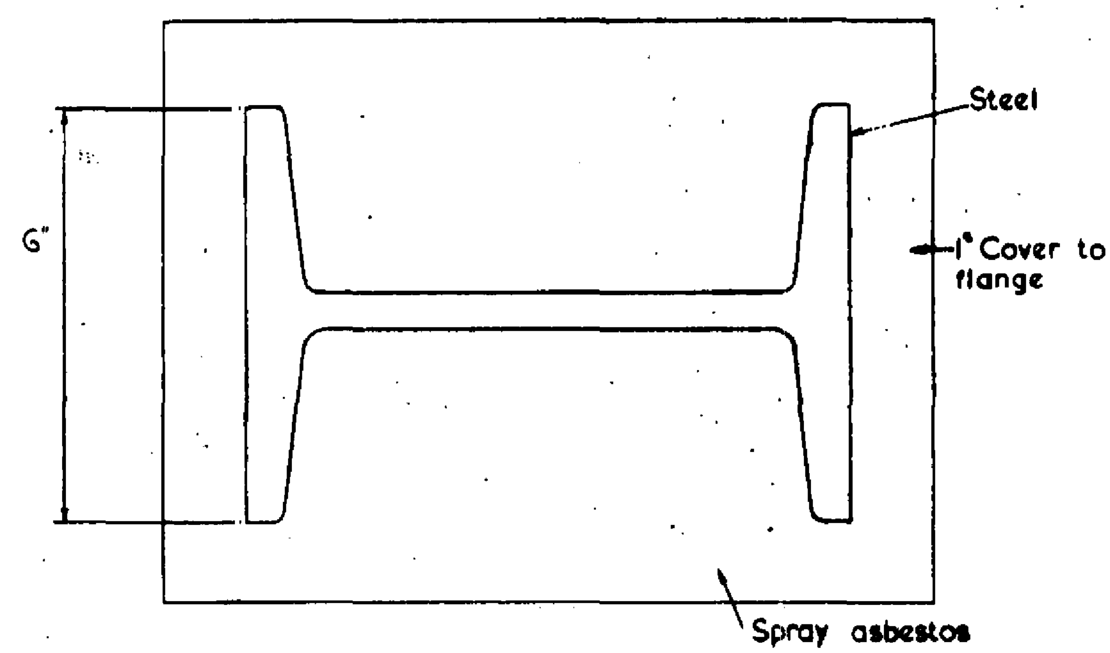

FIG. 5. A TYPICAL EXAMPLE OF A SOLID ENCASEMENT

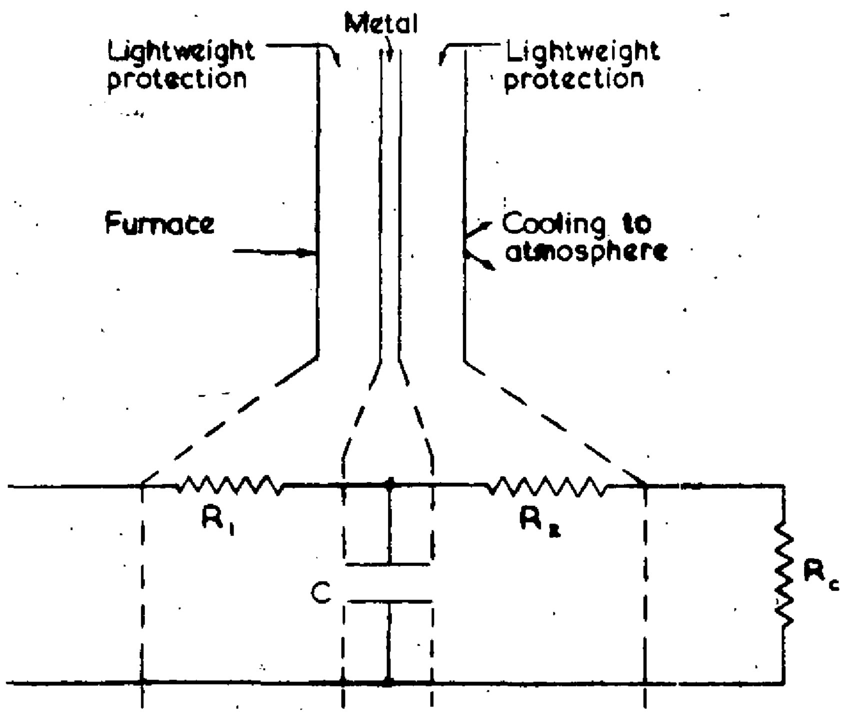

FIG. 7. REPRESENTATION OF A LIGHTWEIGHT PROTECTED METAL BULKHEAD