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ON THE FIRE RESISTANCE REQUIREMENTS OF STRUCTURES

by

D. L. Simms and P. G. Smith

Summary

On the assumption that the failure of a structure exposed to a fire, or in a fire resistance test, can be related to the attainment of a certain temperature at some definite point within the structure, it is shown that the failure time is not very sensitive to departures from the standard curve for B.S. 476 and is, within the range of conditions examined, more dependant on the duration of heating than on the temperatures attained.

If a structure is just capable of withstanding some specified temperature-time conditions then whilst a more slowly developing but longer fire will lead to failure within the duration of the fire a shorter but more rapidly developing fire may not.

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1. Introduction

At present, the requirements for the fire resistance of structures are based on the fire load per unit area within the compartment[1] but it is recognised that the air flow and hence the size of the window openings affects both the temperature reached and the duration of the fire[2]. The British Standard[3] for the fire resistance of structures requires that all structures should be exposed in a furnace which follows a standard temperature/time curve regardless of the possible variations in the actual temperature/time curves which would arise from the different fire loads and ventilations in the different buildings in which the structure may be used[4][5][6][7]. Whilst the exposure of any one structure to different fire conditions could result in a range of values of failure time [8][9][10], several temperature/time tests would be costly[9][10] and various suggestions have, therefore, been made to predict the effect of fires with temperature/time curves different from the standard curve[7][8][9][10].

Ingberg[8] introduced the concept of an equivalent fire duration on the assumption that equal areas under different temperature/time curves represented equal severity of exposure (Fig. 1). He also suggested[8] that, in calculating the equivalent fire duration, only the areas of the curves above either 150°C or 300°C need be considered significant. He justified 150°C on the grounds that this was below the "ignition temperature" of most combustible materials and 300°C because it was below the danger level for incombustible materials for fires of relatively short duration. Whilst it is true that only if the temperature of the fire rises above the ignition temperature can the situation be dangerous, the actual temperature of the fire is important in determining the temperatures reached on the unexposed face or even in the centre of the structure. The notion of the equal severity of equal areas has no theoretical basis. Any method of equating the effect of one temperature/time curve with another must be based on some chosen criterion related to temperature, and in addition the thermal properties of the structure which affect both the time taken for the unexposed face to reach a given temperature and the magnitude of the rise[11] are dependant on the actual temperature. If this cannot be done it is difficult to conceive of any method. In practice a failure criterion can be written down for most though not all structures.

If a protected metal structure fails in a fire when the metal reaches a certain fixed temperature, we have a criterion for comparing the effects of different temperature/time curves for such structures. Similarly, where failure is due to the unexposed face of a structure exceeding a certain fixed temperature, the effect of different temperature/time curves can also be related.

The method of calculating these equivalences which in principle depend on the assumed criterion of failure, is described in section 2.

2. Form of temperature/time curves for fires of restricted ventilation

A series of small scale experiments[3][4] has been conducted in which the fire load and ventilation were varied to produce a range of temperature/time curves. Idealised versions of these are shown in Fig. (2). The time to flashover (τ_1) in these tests was approximately 10 min. for all conditions and this is taken as representative of actual fires where it might vary from 5 - 20 min. depending on the nature of the wall lining. In the second stage the temperature rose at an approximately linear rate[3][4] in a way which depended on the fire load and the induced air flow. In the type of building discussed in previous papers[3][4] the maximum temperature reached was about 1200°C. The times (τ_2) to reach this temperature have been taken over the range 30 minutes to 6 hours; this will include the majority of fires. The third stage represents the cooling of a fire and depends on both the air flow and fire load. It has been assumed that the time to cool to 500°C is equal to the time taken for the temperature of the fire to rise from 500°C to 1200°C. While this may not be always a good approximation there are few instances where the form of the cooling curve is relevant to the prediction of failure.

3. Application of "curve follower"

The temperature at any time in a structure exposed to a furnace or fire following any given temperature/time relation may be found by means of an electrical analogue[12][13] of heat conduction in the structure and a curve follower.

The curve follower generates an electric waveform similar in shape to the required temperature/time curve. The waveform is applied to a network of resistors and capacitors representing the electrical analogue of the structure. The shape of the temperature/time curve at any point in the structure can be displayed on a cathode ray tube.

4. Structures examined

Two types of structure have been studied with the electrical analogue. In the first, of which a brick wall is an example, the thermal capacity and thermal resistance are uniformly distributed throughout the structure, and the criterion of failure was the attainment of a mean temperature rise of 139°C on the unexposed face.

In the second, of which an insulated steel bulkhead is an example, the insulation has negligible thermal capacity compared with the steel which in turn has negligible resistance. The steel was assumed to fail at 500 - 550°C. The possibility of the overheating of the unexposed face was also considered. Details of the structures examined are given in the Appendix.

Using the electrical analogue the time to fail of the two structures when subjected to the B.S. 476 curve was calculated and the times are given in column B of Tables I and II. Also given, in column A, are the failure times, similarly determined, using a step function ($\tau_2 = 0$).

Lastly the various curves in Fig. 2 were used to calculate the failure times. Fig. 3 shows the failure times for various values of τ_2 for brick walls, etc. using the analogue, and Figs 4 and 5 show the same information for insulated steel bulkheads; failure time being determined by the time to reach a temperature rise of 139°C on the unexposed face and the time for the steel to reach 500°C and 550°C respectively. The value of τ_2 for the curves shown in Fig. 2 arbitrarily equal to the failure time of the structure calculated for the B.S. 476 curve gives a particular failure time. This is shown in column C of Tables I and II. In general these times are very similar to those in column B i.e. they are nearly equal to the failure time under B.S. 476 conditions.

COMPARISON OF FAILURE TIMES USING B.S. 476 CURVE, IDEALISED EXPERIMENTAL CURVE*, AND 1200°C STEP FUNCTION

TABLE I

Failure due to temperature rise of unexposed face

Structure	Time for temperature of unexposed face to rise 139°C - minutes		
	A Step function (1200°C)	B B.S. 476 curve	C Idealised experimental curve*
5 in. Brick wall	100	130	145
7 in. " "	220	250	285
8 in. " "	320	360	455
Insulated steel bulkhead (½ hour	20	30	25
Insulated steel bulkhead (2 hour	60	130	120
Insulated steel bulkhead (4 hour	110	240	245
Insulated steel bulkhead (6 hour	195	360	375
Asbestos board	-	30	30
Plaster partition	-	65	65

TABLE II

Failure due to temperature rise of steel

Structure	Steel failure temp. (°C)	Time for steel to reach failure temperature - minutes		
		A Step function (1200°C)	B B.S. 476 curve	C Idealised experimental curve*
No. 1	500	10	25	20
	550	12	30	25
No. 2	500	20	40	35
	550	25	55	-
No. 3	500	55	125	105
	550	65	170	150
No. 4	500	80	150	145
	550	105	230	-
No. 5	500	125	250	235
	550	210	400	-

* The value of τ_2 for the idealised experimental curve is made equal to the failure time obtained with the B.S. 476 curve.

5. Discussion

The comparison just referred to between columns B and C of Tables I and II shows only that, for the conditions and structures examined, a change in the shape of the temperature /time curve is not of great significance in determining failure time.

From the curves in Figs 3, 4 and 5 it may be seen that if a structure were designed to withstand fires of a certain assumed duration, with a specified safety factor, fires lasting longer than this assumed value, even if having a lower rate of temperature rise, would result either in a lower safety factor or even in failure before the end of the fire.

In the case of fires of shorter duration but with a more rapid rise in temperature the structure fails at a higher exposure temperature or if the fire is short enough, there is no failure.

These conclusions may be summarised by saying that over the range of conditions examined here exposure time is more important than exposure temperature or rate of rise of temperature in determining failure time.

If, as was shown in the experimental work referred to above[3,4], there is a tendency for the maximum temperature to be lower the shorter the fire duration, then the shorter fire is even less likely to cause failure despite any higher rate of temperature rise that there might be.

Much attention is paid to small differences between the different standard curves of various countries which, while justified from the point of view of standardisation, is of little consequence in terms of representing the fire. This is illustrated by the following example: A 5 in. brick wall subjected to the B.S. 476 curve has a calculated fire resistance of 130 minutes, the time to fail when τ_2 is 130 minutes is 145 minutes, a relatively small difference. Results of this kind for the structures examined in this report, are shown in Tables I and II. The use of a step function which is an extreme distortion of the standard curve, has a marked effect, but for the curves with a linear rise from 500 - 1200°C the discrepancy is only significant for the 7 in. and 8 in. brick walls.

6. Conclusion

Given the fire resistance criterion for a particular structure, or type of structure, the variation of failure time in different fire situations can be calculated, and while calculations require assumptions about the thermal properties of the structure which can only be approximate, such calculations can be normalised to a fire resistance measured in the B.S. 476 or similar standard test.

Further work in this field of calculation is not a profitable undertaking until the role of the elements of structure in the heat balance of the fire and the other factors affecting temperature and duration of fires have been evaluated in more detail for the reason that the temperature/time curve of a fire is not strictly independent of the composition and design of the containing walls, floors etc. as has been assumed here for a first approximation.

Nevertheless the qualitative results of this analysis although not new do emphasize the view that:

(1) the fire resistance for a particular structure is not very sensitive to changes in the shape of the applied temperature/time curve unless these are extreme, and

(2) the duration of a fire is more important than temperature in determining the required fire resistance of a structure.

<u>References</u>

(1) Fire grading of buildings. Post War Building Studies No. 20. H.M. Stationery Office, London 1946.

(2) Model bye-laws. Ministry of Housing and Local Government. Series IV. Buildings 1953.

(3) Fire tests on building materials and structures. British Standards Institution. B.S. 476/1953.

(4) SIMMS, D.L., HIRD, D., and WRAIGHT, H.G.H. The temperature and duration of fires, Part I. Some experiments with models. <u>Joint Fire Research Organization F.R. Note</u> No. 412/1960.

(5) SIMMS, D.L. and WRAIGHT, H.G.H. Ibid. Part II. Analysis of some full scale results. <u>Joint Fire Research Organization F.R. Note</u> No. 413/1959.

(6) WEBSTER, C.T., WRAIGHT, H.G.H. and THOMAS, P.H. The burning of fires in rooms, Part I. Small scale tests with cribs with high ventilations. <u>Joint Fire Research Organization F.R. Note</u> No. 398/1959.

(7) WEBSTER, C.T. and RAFTERY, MONICA. Ibid. Part II. Tests with cribs and high ventilations on various scales. <u>Joint Fire Research Organization F.R. Note</u> No. 401/1959.

(8) INGBERG, S.H. Tests of severity of building fires. <u>National Fire Protection Association</u> Quarterly <u>Vol. 22</u> No. 1. July 1928.

(9) KAWAGOE, K. Fire behaviour in rooms. <u>Building Research Institute</u> Report No. 27. Ministry of Construction, Japan, September 1958.

(10) MOURACHEV, V.J. Methods adopted in the Soviet Union for the studies of the fire resistance of structural elements and some results obtained - Russia, <u>Academy of Building and Construction</u>.

(11) CARSLAW, H.S. and JAEGER, J.C. Conduction of heat in solids, Oxford, 1947, Clarendon Press.

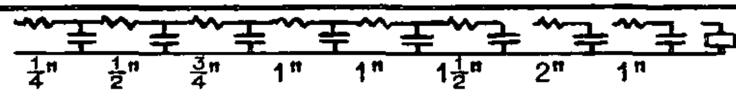
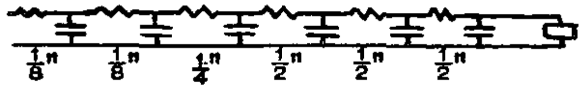
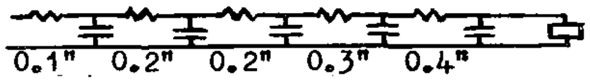
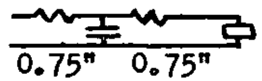
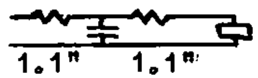
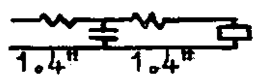
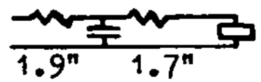
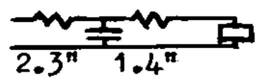
(12) LAWSON, D.I. and McGUIRE, J.H. The solution of transient heat - flow problems by analogous electrical networks. <u>Proc. Inst. Mech. Engrs</u> (a) 1953, <u>167</u> No. 3, 275-290.

(13) Fire Research, 1954 p.24. H.M. Stationery Office. London 1955.

APPENDIX

Details of structures considered

(1) failure due to temperature rise of unexposed face

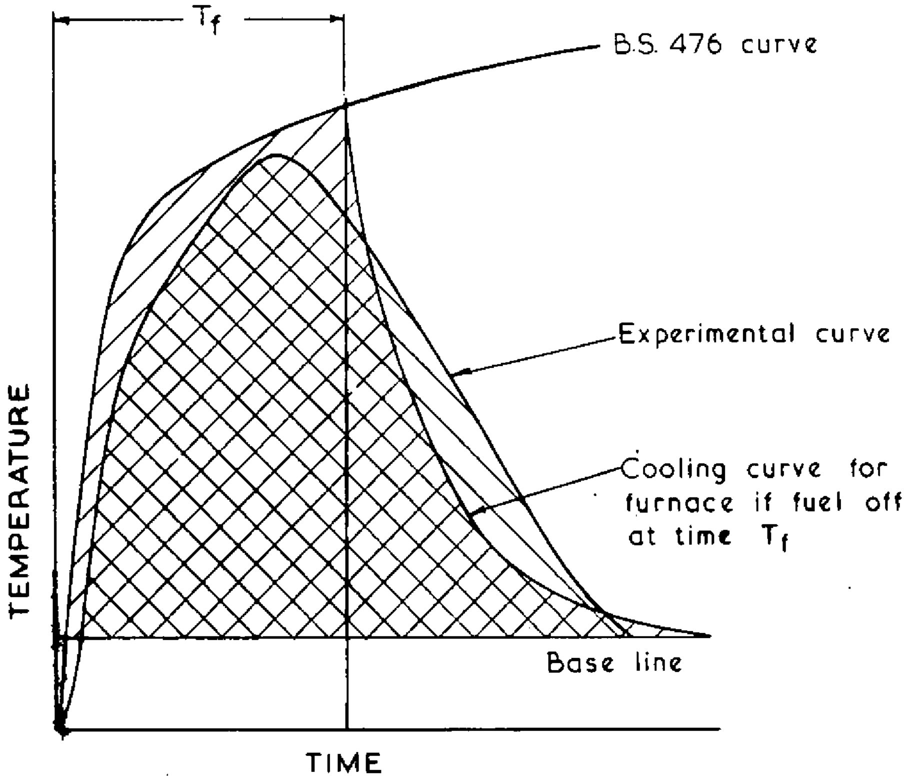
STRUCTURE	THERMAL PROPERTIES: Thermal conductivity (cal/cm/s/°C)	Density (g/cm³)	Specific heat (cal/g/°C)	ELECTRICAL REPRESENTATION	
Brick wall	$1.88 \cdot 10^{-3}$	1.73	0.2		Non-linear cooling resistance in parallel with final capacitor.
Plaster partition	$5.16 \cdot 10^{-4}$	0.88	0.25		Non-linear cooling resistance.
Asbestos ships board	$2.75 \cdot 10^{-4}$	0.61	0.2		Non-linear cooling resistance.
Insulated steel bulkhead: Steel	0.11	7.8	0.12	½ hour ¼" steel bulkhead 	Non-linear cooling resistance.
Insulated steel bulkhead: Insulation (plaster)	$5.16 \cdot 10^{-4}$	0.88	0.25	1 hour ¼" steel bulkhead 	Non-linear cooling resistance.
				2 hour ¼" steel bulkhead 	Non-linear cooling resistance
				4 hour ¼" steel bulkhead 	Non-linear cooling resistance.
				6 hour ¼" steel bulkhead 	Non-linear cooling resistance.

APPENDIX

Details of structures considered

(2) failure due to temperature rise of steel

STRUCTURE		THERMAL PROPERTIES: Thermal conductivity (cal/cm/s/°C)	THERMAL PROPERTIES: Density (g/cm^3)	THERMAL PROPERTIES: Specific heat (cal/g/°C)	ELECTRICAL REPRESENTATION
Insulated steel bulkhead	Steel	0.11	7.8	0.12	No. 1 ¼" steel bulkhead  Non-linear cooling resistance.
	Insulation (plaster)	$5.16.10^{-4}$	0.88	0.25	No. 2 ¼" steel bulkhead  Non-linear cooling resistance.
					bulkheads No. 3, 4 and 5 are identical to the 2, 4 and 6 hour bulkheads respectively which are described in Appendix (1).



T_f is defined by equal areas under the two curves

FIG. 1. DEFINITION OF EQUIVALENT FIRE DURATION (INGBERG)

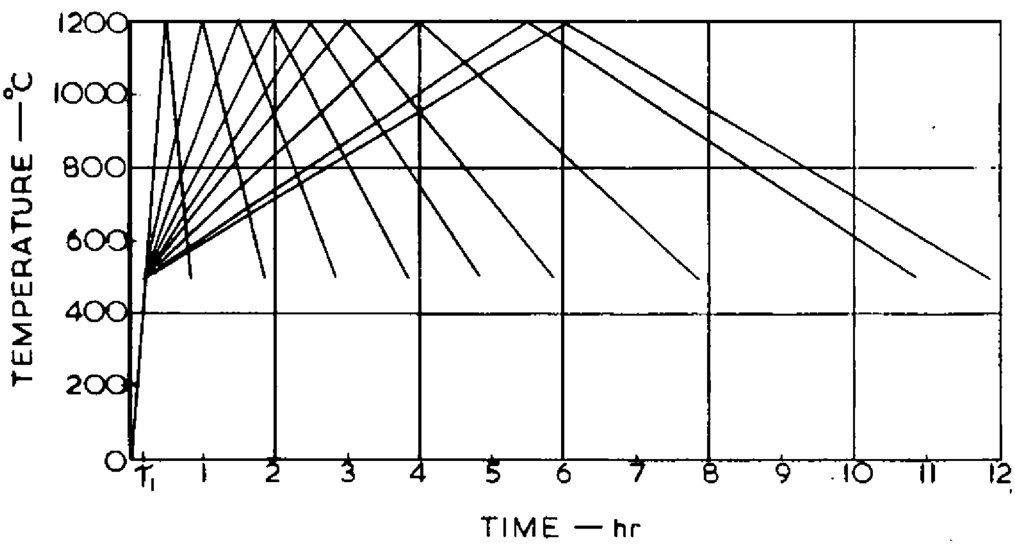


FIG. 2. IDEALISED EXPERIMENTAL CURVES

F.R. 447

1/3903

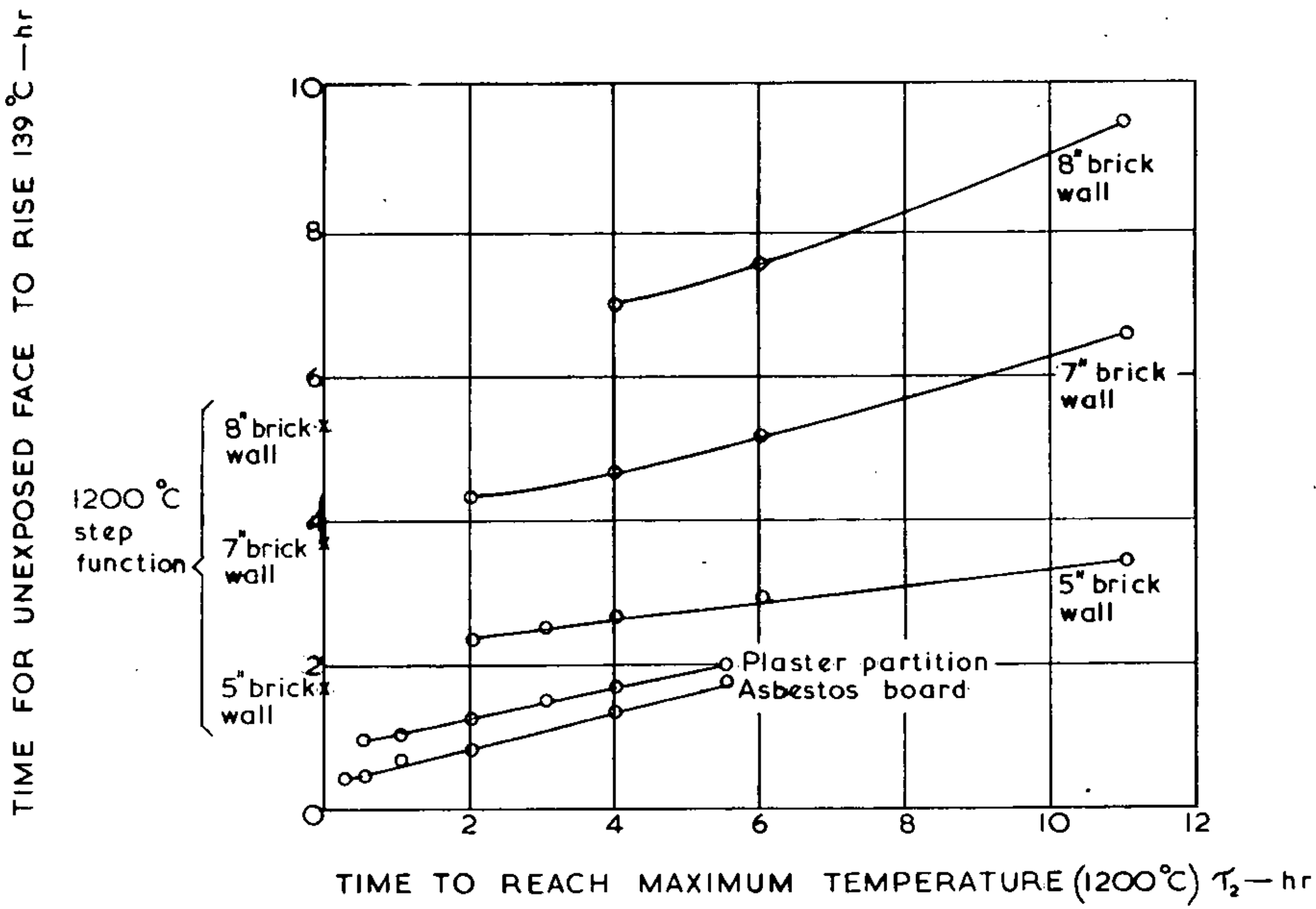


FIG. 3. BRICK WALLS, ETC — FAILURE DUE TO TEMPERATURE RISE OF UNEXPOSED FACE

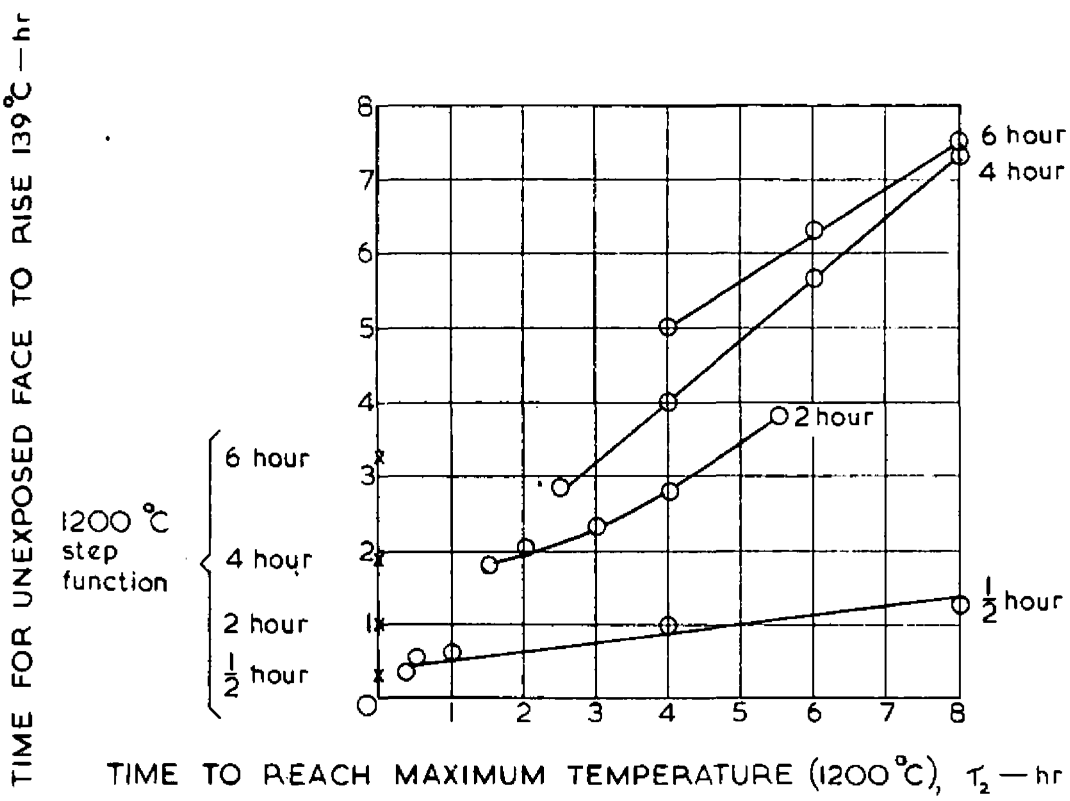


FIG. 4. INSULATED STEEL BULKHEADS — FAILURE DUE TO TEMPERATURE RISE OF UNEXPOSED FACE

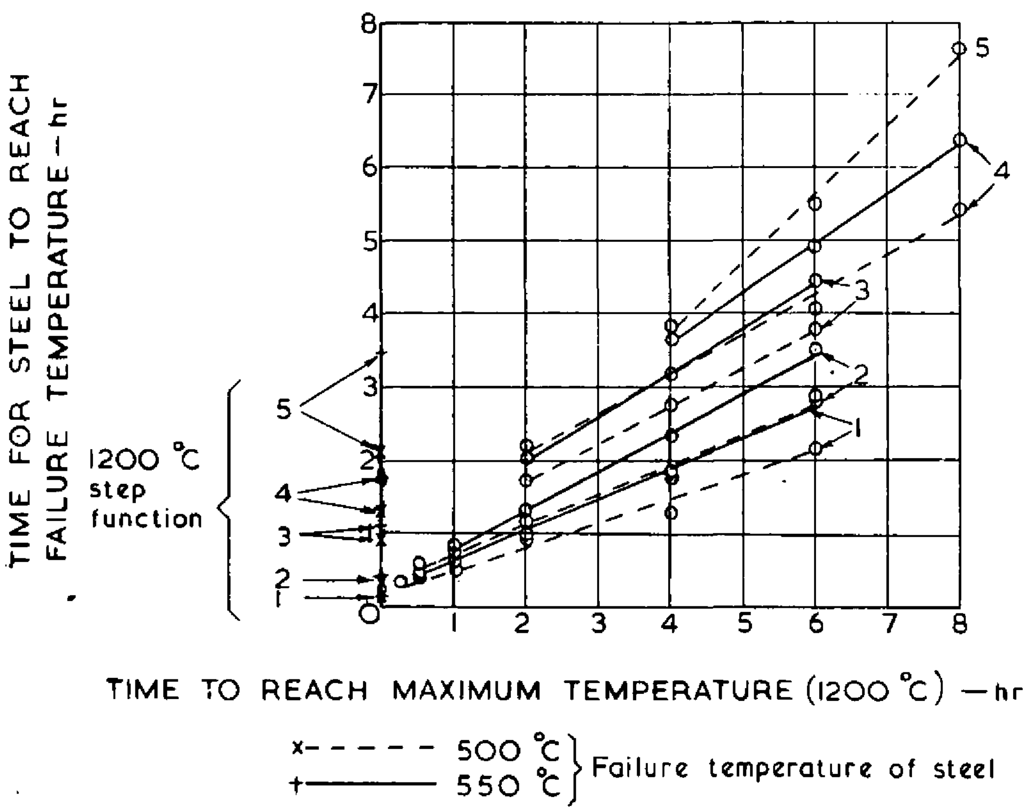


FIG. 5. INSULATED STEEL BULKHEADS FAILURE DUE TO TEMPERATURE RISE OF STEEL

F.R. 447

1/3905