Fire Research Note
No. 725

FIRE PROTECTION IN THE PROCESS INDUSTRY BUILDING - PLANT AND PLANT STRUCTURES

by

MARGARET LAW, B. Sc.

FIRE
RESEARCH
STATION

Fire Research Station,
Borehamwood,
Herts.
Tel. 01-953-6177

F.R. Note No.725
September, 1968.

FIRE PROTECTION IN THE PROCESS INDUSTRY BUILDING - PLANT AND PLANT STRUCTURES

by

Margaret Law, B.Sc.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

F.R. Note No. 725
September, 1968.

FIRE PROTECTION IN THE PROCESS INDUSTRY BUILDING - PLANT AND PLANT STRUCTURES

by

Margaret Law, B.Sc.

SYNOPSIS

The way fire spreads and the principles of structural fire protection are outlined. The necessity for having fire stops in ventilating systems and in suspended ceilings is shown. The furnace test for building elements specified in B.S. 476 : Part 1 : "Fire tests on building materials and structures" is described.

Fires in flammable liquids, which are different from more conventional building fires and from the furnace test, are discussed. Flame temperatures and the sizes of flames from pools of liquid are described. The rates of heating for structures and storage vessels which may be surrounded by fire or heated by radiation from flames in a nearby bund are given. Methods of estimating the amount of protective material to insulate structures and vessels are provided. This protection is compared with the amount needed in the standard furnace test.

Factors influencing the choice of protective materials are discussed.

KEY WORDS Fire protection, structural elements, equipment, fuel liquid, storage, insulation.

SYMBOLS

A - area cm^2

B - width of column section cm

C - thermal capacity J/deg C

c - specific heat of protective material $\mathrm{J\ g^{-1}\ deg\ C^{-1}}$

c_s - specific heat of steel $\mathrm{J\ g^{-1}\ deg\ C^{-1}}$

D - depth of column section cm

K - thermal conductivity $\mathrm{W\,cm^{-1}\ deg\ C^{-1}}$

k - thermal diffusivity cm^2/s

M - mass of steel g

P - mean perimeter of protective material cm

Q - quantity of heat J

R - thermal resistance deg C/W

t - time s

x - thickness of protective material cm

ρ - density $\mathrm{g/cm}^3$

θ - temperature $^\circ\mathrm{C}$

θ_s - steel temperature $^\circ\mathrm{C}$

θ_f - hot surface temperature, fire temperature or furnace temperature $^\circ\mathrm{C}$

FIRE PROTECTION IN THE PROCESS INDUSTRY BUILDING - PLANT AND PLANT STRUCTURES

by

Margaret Law, B.Sc.

INTRODUCTION

A comprehensive survey of fire spread and structural fire protection cannot be given in a short paper and, in any case, the subjects are dealt with in a number of publications. A very brief survey follows, therefore, but with a list of references,[1] and the paper then discusses the solution of some problems posed to the Fire Research Station recently by chemical manufacturers.

REDUCTION OF FIRE SPREAD

Fires in buildings spread when combustible materials are heated by radiation and convection from flames and hot gases and by heat conducted through poorly insulated walls and ceilings[2,3,4]. The basic way to reduce fire spread is to make fire-tight compartments, with fire-resistant walls and ceilings which by definition are good insulators and remain structurally sound.[5] Fire-resistant doors must also be structurally sound but need not be as well insulated as walls because combustible materials should not be in contact with them in a properly maintained plant. Suitable separation of these materials from such doors can be calculated.[4] If a door in a fire-resistant wall has to be kept open because of the manufacturing process then it should be fitted with, say, a fusible link, so that it closes automatically if a fire starts.

Where trunking for air-conditioning systems passes through a fire-resistant wall or ceiling, gaps round the trunking must be properly sealed (fire-stopped). Unless the trunking can be protected by a fire-resistant enclosure it must also have a damper, operated by a fusible link, at any place where it passes through such walls and ceilings. All ducts for services[6] must be designed carefully otherwise they can spread fire and smoke beyond the compartment containing the original fire.

With any suspended ceiling, the boundary walls of the compartment must extend through the ceiling to make a fire-tight seal with the floor, or roof above, otherwise fire can spread through the ceiling void. A suspended ceiling may or may not contribute fire protection to the floor structure, but any fire which may start in the void should be prevented from spreading by using fire stops. Translucent ceilings (illuminated ceilings) are sometimes installed beneath an automatic sprinkler system and they must either be suitably perforated or else disintegrate at low temperatures, so that they do not interfere with the sprinkler operation.[7,8]

Combustible linings on walls and ceilings can spread fire and it is preferable to use a surface which is non-combustible or classified as of low flame spread.[5] This may affect the choice of material for a roof lining.

In modern factories it is often impractical to divide the building with fire-resistant compartment walls. Within such an open plan quite a small fire can rapidly become large by hot gases spreading to combustible materials, but suitably designed roof venting can restrict the spread of these hot gases.[9,10] Roof screens i.e. truss infillings, increase the venting efficiency, restrict ceiling damage and shield radiation to some extent. The depth of the screen may be limited by the process being carried out and it is usually impractical to have sufficient horizontal spacing of materials on the floor to eliminate the risk of fire spread by radiation. With a partial fire break a line of sprinklers can cool exposed materials, reduce radiation and extinguish flying embers.

PERFORMANCE OF STRUCTURES IN FIRE

Structural fire protection is very frequently achieved by insulating structural elements which would fail if they reached too high a temperature. Steel columns and beams must be protected and the steel reinforcing bars in concrete must stay covered. Apart from the building itself, structures which carry storage vessels must remain intact, especially if the contents of the vessels are flammable.

The performance of various structural elements is tested on full scale in gas-fired furnaces which are controlled, as specified in B.S. 476,[5] so that the temperature rises in a standard way to 927, 1010, 1121 and 1204°C after 1, 2, 4 and 6 h respectively.* No one pretends that this is how a real fire behaves,

---

*This relationship is international.

and indeed no single test could reproduce all possible fire conditions, but the system of grading elements according to the time they perform their function satisfactorily in the standard furnace test, and relating this to the type and size of building,[11,12] has worked reasonably satisfactorily up to now. Changing building methods, new materials and new hazards are leading to a fresh look at the present fire grading of buildings and this is the subject of current fire research. In addition, some of the fire problems of the process industry merit special consideration.

A number of processes involve the use and storage of flammable liquids. Protection is needed for structures exposed to fires in these liquids, which burn somewhat differently from the more conventional building fire with a mainly cellulosic fire load (like a wood fire). They burn even more differently from the gas-fired furnace, but normally the only precise information on the fire behaviour of structures is given by the results of furnace tests. What protection is needed then for structures and storage vessels exposed to fires in flammable liquids; and how can the performance of various protective materials in these fires be predicted from the results of standard furnace tests[11,12,13]? The remainder of this paper discusses these problems and gives some rules of thumb which it is hoped will be useful to fire protection engineers.

BEHAVIOUR OF FIRES IN FLAMMABLE LIQUIDS

The problem is considerably simplified because for our purpose we can say that fires in organic liquids are like petrol ones.

Tanks and supporting structures can be surrounded by flames from spilt liquid fuel within the same bund or heated by radiation from flames in an adjoining bund or ruptured tank.

The burning liquids will have flame temperatures of the order 1100°C.[14] (Much higher theoretical flame temperatures are often quoted but these are for premixed flames). The flame emissivity depends on the thickness but over about 1.5 m their emissivity can be taken as unity, giving a radiating intensity of about 17 W/cm^2.

Measurements in the United States and United Kingdom of heat input to a tank surrounded by petrol flames in a bund gave values of 6.3 to 8.8 W/cm^2 for uncooled tanks[15,16]. Since in this situation the flames, being thin, would not be highly emissive these values are consistent with a flame temperature of order 1100°C.

For radiant heating by flames in a separate bund or tank it is more reasonable to assume the flames are thick and radiate 17 W/cm^2. The radiation received then depends on the area of the flames and their distance away[17,18].

Russian experiments[19] on the natural burning of liquid petroleum products in open pans showed that for pan sizes ranging from 1 to 30 m in diameter the flame height is between one and two diameters. The shape of the flames tends to be narrower at the top but for simplicity they can be assumed of uniform width.

At a given distance from the flames, a vertical surface facing the centre of the radiating area receives most radiation. The intensity of radiation received at this and other positions is illustrated in Fig. 1.

STORAGE TANKS IN BUILT-UP AREAS

In some situations storage tanks could be exposed to radiation from fires in nearby buildings. The levels of radiation to be expected from these fires are discussed in detail elsewhere,[20,21] but it may be assumed that each window of a burning building can emit an intensity of 17 W/cm^2. Tanks should therefore be spaced accordingly or protected. The maximum intensity of radiation which can safely be accepted on the face of a building which may be exposed to fire, is also discussed elsewhere,[20] but should normally be taken as 1.25 W/cm^2.

PROTECTION OF TANKS AND STEELWORK

Structural steel supporting its design load will normally fail if its temperature exceeds 550°C. The permissible temperature for a storage tank usually depends on the nature of its contents but normally, to prevent undue pressure rises or ignition of flammable vapours, it will need to be considerably below 550°C. For both structure and vessel, therefore, protective material must be used to keep the steel below hazardous temperatures.

The most vulnerable part of a tank is above the liquid level where the internal surface of the wall is not cooled by the liquid. If cooling of the internal surface is negligible then all the heat which flows through the protective material is soaked up by the steel wall which acts as a heat sink (See Fig. 2).

There is a similar situation with a protected steel column surrounded by fire, where all the heat which flows through the protective material goes to the heat sink which is provided by the steel (See Fig. 3).

Protective materials are generally of low density and offer high resistance to flow of heat. Steel is of high density and offers very little resistance to flow of heat. The steel temperature can therefore be estimated using the following approximation:

Consider an idealised situation of protective material with resistance but no heat capacity and steel with heat capacity but no resistance. The standard equation for one-dimensional heat conduction

$$\frac{dQ}{dt} = KA\frac{d\theta}{dx}$$

can be re-written

$$Mc_s \frac{d\theta_s}{dt} = KA\frac{(\theta_f - \theta_s)}{x} \qquad (1)$$

where dQ/dt is rate of heat flow

K is thermal conductivity (of protective material)

A is area through which heat flows

$d\theta/dx$ is temperature gradient

M is mass of steel

c_s is specific heat of steel

θ_s is temperature of steel

t is time

θ_f is temperature of heated surface of protective material

x is thickness of protective material

Putting

$$R = \frac{x}{KA} \qquad (2)$$

$$C = Mc_s$$

$$\theta_f = \text{constant}$$

the solution of equation (1) is

$$\frac{\theta_s}{\theta_f} = 1-\exp(-t/RC) \qquad (3)$$

Equation (3) is analogous to the familiar electrical circuit equation for the charging of a condenser, with a time constant RC; it is plotted in Fig. 4.

For a denser protective material, with a significant amount of heat capacity, a good approximation[26] is to add half the value of its heat capacity to the capacity of the steel.

i.e.
$$C = Mc_s + \tfrac{1}{2} x A \rho c \qquad (4)$$

where ρ is the density of the protective material
c is the specific heat of the protective material.

The diameter of a storage tank is normally large enough for heat flow to be considered one-dimensional (see Fig. 2) and can be calculated for unit area putting $A = 1$.

Columns are long enough for end effects to be negligible, and the heat flow can be calculated for unit column length putting A equal to the mean perimeter P of the protective material.

Two main methods of column protection are used: hollow encasement and encasement following the profile of the column. P is therefore calculated in two ways as shown in Fig. 3 (the resistance and capacity of the cavity in the hollow encasement can be ignored).

The heat flow to a beam can also be calculated for unit length, putting A equal to the mean perimeter of the heated part of the protective material.

These approximations should suffice for most types of construction but accurate solutions to heat flow problems for a variety of situations are given elsewhere[22].

EXPOSED SURFACE TEMPERATURE

Equation (3) assumes a constant temperature on the exposed surface of the protective material. An insulating material exposed to a fire in a flammable liquid will soon reach the fire temperature on its exposed surface and therefore it should be assumed that the surface is at fire temperature from the start : this assumption errs on the safe side.

The surface exposed to radiant heating from a distant source will eventually reach an equilibrium temperature depending on how it is cooled and on its emissivity. Equilibrium temperatures for a black vertical surface, with an emissivity of unity, cooled by radiation and natural convection are given in Table 1. (A black surface, being a perfect absorber of radiation, represents the most hazardous condition). As an approximation it can be assumed that these give the temperature of the exposed surface from the start : this assumption errs on the safe side.

Table 1

Assumed surface temperature of protective material exposed to radiation

Intensity of radiation on surface W/cm^2	Surface temperature ^oC
0.15	100
0.4	200
0.9	300
1.5	400
2.5	500
4.0	600
6.0	700
8.5	800
12.5	900
15.5	1000

THERMAL PROPERTIES OF MATERIALS

The specific heat of most insulating materials can be taken as 0.84J g^{-1} deg C^{-1}. The specific heat of steel varies with temperature but a representative value of 0.50 J g^{-1} deg C^{-1} may be taken. The thermal conductivity of most insulating materials[25] increases with temperature and an average value must be assumed.

Information about thermal conductivity, especially its variation with temperature, is very sparse but it may often be estimated from the results of furnace tests, using equation (3). The furnace temperature θ_f is not constant but an equivalent constant temperature for different periods of the test has been derived[26] and suitable values for our problem are given in Table 2.

Table 2

Equivalent constant temperature for furnace test

Time h	Equivalent constant temperature °C
1	840
2	930
3	1000
4	1050
6	1120

EXAMPLE

It is proposed to use 3.8 cm ($1\frac{1}{2}$ in) thickness of vermiculite cement, of 0.43 g/cm^3 (27 lb/ft^3) density, on a 2.75 m (9 ft) diameter cylindrical tank made of 1.6 cm ($\frac{5}{8}$ in) steel. What is the steel temperature after 1 h and 2 h exposure to a fire in a flammable liquid? The same thickness of this type of vermiculite cement provided 3 h fire-resistance when applied as a hollow encasement to a 20.3 cm x 20.3 cm x 52 kg/m run (8 in x 8 in x 35 lb/ft run) Universal column.

(a) Estimation of K

The result of the furnace test can be used to estimate a value of the time constant, RC, of the encased column and hence a value of thermal conductivity, K, for the vermiculite cement. Since the column had 3 h fire-resistance this means that the steel did not reach its failure temperature, 550°C, until 3 h exposure in the furnace test.

$$\frac{\theta_s}{\theta_f} = 1 - \exp(-t/RC) \qquad (3)$$

When $t = 3 \times 3.6 \times 10^3$ s

$\theta_f = 1000^\circ C$ (from Table 2)

Taking $\theta_s = 550^\circ C$ (failure temperature for steel)

gives $\frac{t}{RC} = 0.80$ (from Fig. 4)

and $RC = 13.5 \times 10^3$ s

Consider unit length of the column i.e. A = P :

$$R = \frac{x}{KP} \qquad (2)$$

$$C = Mc_s + \tfrac{1}{2}xP\rho c \qquad (4)$$

Putting $x = 3.8$ cm
$P = 2(D + B + 2x)$ (from Fig. 3)
$B = D = 20.3$ cm
$P = 96.4$ cm
gives $R = \frac{0.0395}{K}$ cm deg C W^{-1}

Putting $M = 520$ g/cm
$c_s = 0.50$ J g^{-1} deg C^{-1}
$\rho = 0.43$ g/cm^3
$c = 0.84$ J g^{-1} deg C^{-1}
gives $C = 260 + 66 = 326$ J cm^{-1} deg C^{-1}
Hence $K = \frac{0.0395 \times 326}{13.5 \times 10^3} = 9.5 \times 10^{-4}$ W cm^{-1} deg C^{-1}

(b) Estimation of tank temperature

Since the diameter of the tank is large, heat flow can be taken as one-dimensional. Consider unit area of the portion above the liquid (see Fig. 2):

$$R = \frac{x}{KA} \qquad (2)$$

$$C = Mc_s + \tfrac{1}{2}xA\rho c \qquad (4)$$

Putting $x = 3.8$ cm
$K = 9.5 \times 10^{-4}$ W cm^{-1} deg C^{-1}
$A = 1.0$ cm^2
gives $R = 4.0 \times 10^3$ degC/W

For unit area of steel, 1.6 cm thick, of density 7.8 g/cm^3

putting $M = 12.5$ g

$c_s = 0.50$ J g^{-1} deg C^{-1}

$\rho = 0.43$ g/cm^3

$c = 0.84$ J g^{-1} deg C^{-1}

gives $C = 6.95$ J/deg C

Thus $RC = 27.8 \times 10^3$ s

For $t = 3.6 \times 10^3$ s, $t/RC = 0.13$ giving $\Theta_s/\Theta_f = 0.12$ (fig. 4)

$t = 7.2 \times 10^3$ s, $t/RC = 0.26$ giving $\Theta_s/\Theta_f = 0.23$ (fig. 4)

Taking Θ_f as 1100°C gives a tank wall temperature of 135°C after 1 h and 255°C after 2 h.

CHOICE OF PROTECTIVE MATERIAL

No one protective material is suitable for all situations. For example, sprayed asbestos, vermiculite plaster, vermiculite cement, mineral wool and concrete can all be used for insulation but some of these might get damaged too easily and others might add too much weight. Fixing and reinforcement are very important factors and should be discussed carefully with the manufacturer. In explosive atmospheres some fixing methods cannot be used at all. For pipework it may be convenient to use a mineral wool wrapping rather than a solid encasement.

It may be necessary to check that the material performs satisfactorily when subjected to the high temperatures which are attained so much more rapidly in a flammable liquid fire than in the furnace test.

PROTECTION OF REINFORCED CONCRETE

Reinforced concrete will normally fail when the steel reinforcing bars reach temperatures of about 550°C and prestressed concrete when the bars reach about 400°C. There must be sufficient concrete cover on the bars to keep them cool and it is usual to incorporate some kind of mesh to prevent the concrete spalling and exposing the bars to fire. Because concrete is a comparatively dense material, and the bars are relatively small, equation (1) cannot be used, but the bar temperature can be estimated approximately by neglecting the effect of the bars themselves on the heat flow and calculating the concrete temperature at the depth of the bars.

For these calculations the time constant of the concrete is used and for a thickness of x

$$R = \frac{x}{KA}$$

$$C = x A \rho c$$

giving $$RC = \frac{x^2 \rho c}{K} = \frac{x^2}{k}$$

k is known as the thermal diffusivity and it is conventional to give the concrete temperatures as function of $x/\sqrt{(kt)}$ (where $x^2/kt = RC/t$). The functions are usually more complicated than equation (3), so the solutions only will be given here.

For a slab heated on one surface, with bars at depth x,

$$\frac{\theta_s}{\theta_f} = F_1\left(\frac{x}{\sqrt{(kt)}}\right) \qquad (5)$$

and the solution[23] is given in Fig. 5. This is based on the assumption that heat loss from the unheated surface of the slab is negligible, an assumption which is justifiable for slab thicknesses exceeding $3x$. (Appendix)

For columns, heated on all surfaces, the column size is also a factor and

$$\frac{\theta_s}{\theta_f} = F_2\left\{\frac{x}{l}, \frac{l}{\sqrt{(kt)}}\right\} \qquad (6)$$

where l is the depth of the centre of the column from the heated surface i.e. the column thickness is 2 l. (For circular columns l is the radius). The solution[24] is given in Fig. 6.

For beams, heated on three sides only, the solution is complex but in many cases it is sufficiently accurate to use the solution for columns, putting l equal to the depth of the centre line of the beam as shown in Fig. 6.

Concrete normally contains moisture which has the effect of delaying temperature rise until the water has boiled. From the results of furnace tests a value of 1.5×10^{-3} cm^2/s for effective thermal diffusivity* has been derived.

---

* Portland cement, river sand and gravel.

EXAMPLE

A reinforced concrete column of 25 cm (10 in) square section, with 2.5 cm (1 in) cover to the main bars may be exposed to a petrol fire for 1 h. From Fig. 7. What will be the temperature of the reinforcement?

$$x = 2.5 \text{ cm}$$

$$l = 12.5 \text{ cm}$$

$$\frac{x}{l} = 0.2$$

$$t = 3.6 \times 10^{3} \text{ s}$$

$$k = 1.5 \times 10^{-3} \text{ cm}^2/\text{s}$$

$$\frac{l}{\sqrt{(kt)}} = 5.3$$

From Fig. 6:

$$\frac{\theta_s}{\theta_f} = 0.51$$

$$\theta_f = 1100^\circ\text{C}$$

Therefore $\theta_s = 560^\circ\text{C}$

Since the temperature of the reinforcing bars will just exceed 550°C the column may fail.

CONCLUSIONS

Fire spread should be restricted as much as possible by fire-resistant walls and floors, with all openings protected by automatically closing dampers or shutters. When this is not possible, smoke and hot gases may be removed by roof vents, with heated materials cooled by sprinklers.

Fires in flammable liquids are a special hazard, somewhat different from conventional building fires, but it is possible to estimate their heating effect and so calculate temperature rises in exposed structures, using the results of standard furnace tests to estimate the behaviour of various protective materials.

ACKNOWLEDGMENT

The paper is Crown Copyright, reproduced by permission of the Controller, H.M. Stationery Office. It is contributed by permission of the Director of the Fire Research Station of the Ministry of Technology and Fire Offices' Committee.

REFERENCES

1. A guide to fire prevention in the chemical industry. British Chemical Safety Council of the Chemical Industries Association Limited 1968. This guide was prepared in collaboration with the Fire Protection Association. It gives a general survey, a list of the relevant legislation and a bibliography.
   A British Standard Code of Practice for chemical plant fire precautions is in preparation.

2. THOMAS, P.H. Fire spread in factories. Fire Prot. Rev., 1963, 26 (267) 37-9.

3. LANGDON THOMAS, G.J. Fire in your factory. Industr. Archit., 1963, 46 (5) 352-9.
   These give a general discussion of fire spread in factories and the function of roof vents.

4. ASHTON, L.A. Fire protection. Specification 1967 London. The Architectural Press. This is a review of fire protection in all types of buildings.

5. Fire tests on building materials and structures. British Standard No. 476 : Part 1 1953. Part 6 : 1968.

6. A revised British Standard Code of Practice for ducts for services is in preparation.

7. O'DOGHERTY, M.J. and NASH, P. Suspended translucent ceilings - effect on operation of automatic sprinklers. Ind. Archit., 1966, 9 (2), 76-9.

8. A British Standard Code of Practice for suspended ceilings and linings is in preparation.

9. THOMAS, P.H. and HINKLEY, P.L. The design of roof venting systems for single-storey buildings. Fire Research Technical Paper No. 10. London, 1964. H.M. Stationery Office,
   This gives the theory of roof venting.

10. LANGDON THOMAS, G.J. and HINKLEY, P.L. Fire venting in single storey buildings. Fire Note No. 5. London, 1965. H.M. Stationery Office.
    This is a plain man's guide to the design of roof venting.

11. The Building Standards (Scotland) Regulations 1963. House of Commons S.I. No. 1963 : 1897. London, 1963. H.M. Stationery Office.

12. The Building Regulations 1965. House of Commons S.I. No. 1965 : 1373. London, 1965. H.M. Stationery Office.
These contain Schedules which describe a number of constructions deemed to satisfy the fire-resistance requirements of the Regulations.

13. ASHTON, L.A. and SMART, P.M.T. Sponsored fire-resistance tests on structural elements. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization. London, 1960. H.M. Stationery Office.
This gives the results of some fire-resistance tests using proprietary materials. Information is also supplied directly by manufacturers.

14. RASBASH, D.J., ROGOWSKI, Z.W. and STARK, G.W.V. Properties of fires of liquids. Fuel. Lond., 1956, 35 (1) 94-107.

15. DUGGAN, J.J., GILMOUR, G.H. and FISHER, P.F. Venting of tanks exposed to fire. Natn. Fire Prot. Ass. Q., 1943, 37 (2) 132-53.
This summarizes some American work.

16. BRAY, G.A. Fire protection of liquid petroleum gas storage tanks. 101st Annual General Meeting The Institution of Gas Engineers 1 - 5 June 1964.
This paper gives measurements of heat input to a tank, temperature measurements of metal targets heated by flame radiation and it reports further American work.

17. Fire Research 1965. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization London, 1966. H.M. Stationery Office.

18. THOMAS, P.H. and LAW, MARGARET. Fire protection of liquid fuel storage tanks. Joint Fire Research Organization F.R. Note No. 609/1965.
The heating, venting, spacing and cooling of petrol storage tanks is discussed in this note.

19. BLINOV, V.I. and KHUDIAKOV, G.N. Certain laws governing diffusive burning of liquids. Dokl. Akad. Nauk. S.S.S.R., 1957, 113 1094-8; Fire Res. Abstr. Rev., 1959, 1 (2) 41-4.

20. LAW, MARGARET. Heat radiation from fires and building separation. Fire Research Technical Paper No. 5. London, 1963. H.M. Stationery Office.

21. LAW, MARGARET. Radiation from fires in a compartment. Fire Research Technical Paper No. 20. London, 1967. H.M. Stationery Office.

22. CARSLAW, H.S. and JAEGER, J.C. Conduction of heat in solids. Second edition, Oxford University Press, 1959.

23. Ibid. page 60 equation (10).

24. Ibid. page 199 equation (10).

25. Tables of thermal conductivity for building, miscellaneous and proprietary materials. The Institution of Heating and Ventilating Engineers. 1955.

26. McGUIRE, J.H. The estimation of fire resistance. Joint Fire Research Organization F.R. Note No. 348/1958.

APPENDIX

Effect of neglecting heat loss from unheated face of reinforced concrete slab.

Consider a concrete slab of thickness l, with one surface maintained at a temperature θ_f and the other surface cooling to the atmosphere. Reinforcing bars are at a depth x from the heated surface and are assumed to be at the same temperature as the concrete at the depth x. The analytical solution to this heat flow problem allowing for cooling is complex, but if, at the time the bars reach their failure temperature, the cool face temperature is negligible then the calculation may be made assuming that the slab is semi-infinite in thickness. A simple analytical solution exists for a semi-infinite solid.

For a semi-infinite solid with the surface maintained at a temperature θ_f, the temperature θ at a depth x after a time t is given by[23]

$$\frac{\theta}{\theta_f} = 1 - \operatorname{erf} \frac{x}{2\sqrt{(kt)}}$$

where erf denotes the normal error integral.

Taking $\frac{\theta}{\theta_f} = 0.36$ for a rod failure temperature of 400°C

$\frac{\theta}{\theta_f} = 0.50$ for a rod failure temperature of 550°C

the corresponding values of $\frac{x}{2\sqrt{(kt)}}$ are 0.64 and 0.48

The temperature at depth l at the same time t is given by

$$\frac{\theta}{\theta_f} = 1 - \operatorname{erf} \frac{l}{2\sqrt{(kt)}}$$

If $l = 3x$

$$\frac{\theta}{\theta_f} = 1 - \operatorname{erf} \frac{3x}{2\sqrt{(kt)}}$$

$= 0.007$ and 0.042 respectively.

These values are small and cooling therefore should be negligible.

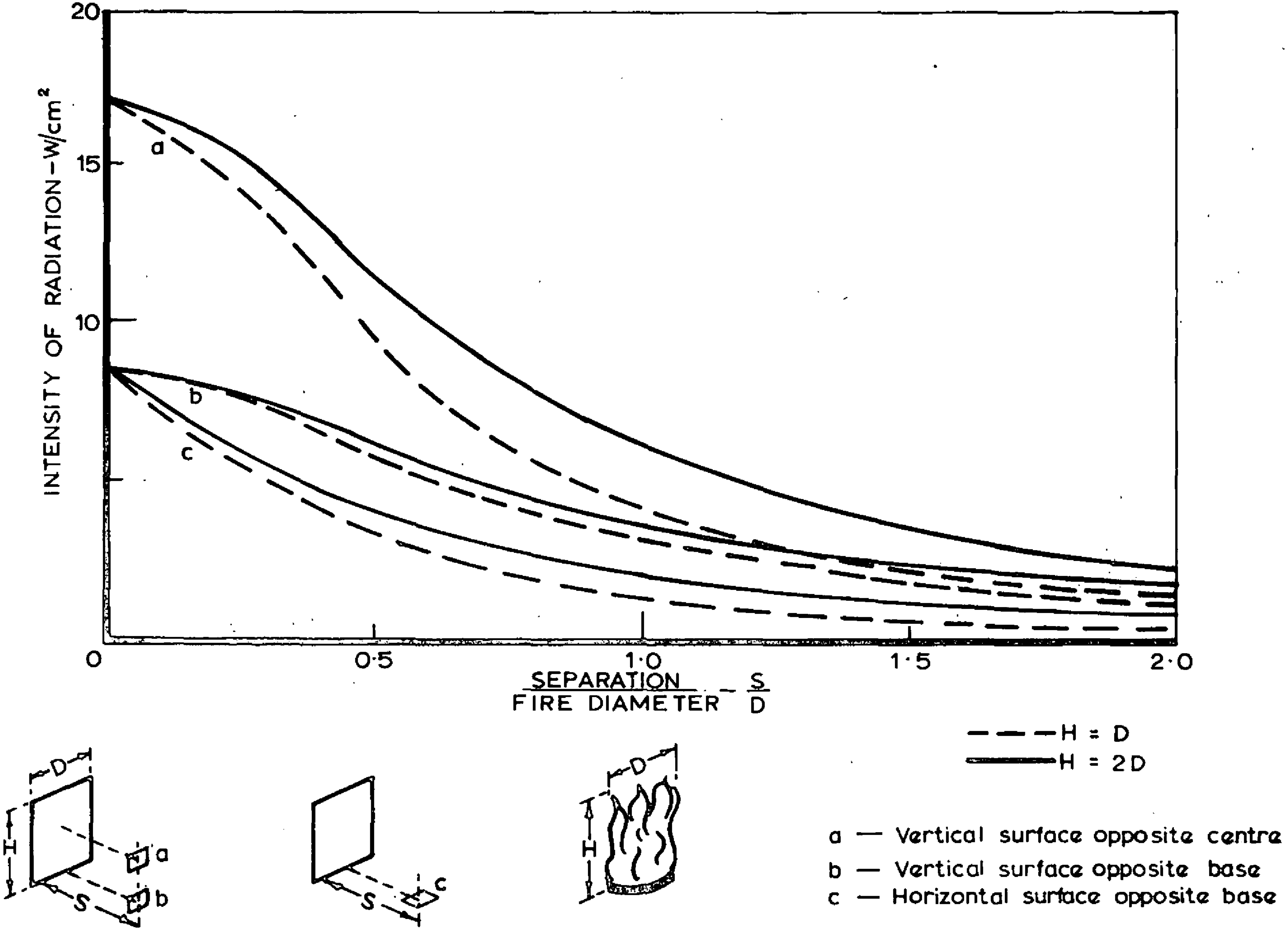


FIG.1. RADIATION FROM FLAMES OF BURNING LIQUIDS RECEIVED ON SURFACES AT VARIOUS POSITIONS.

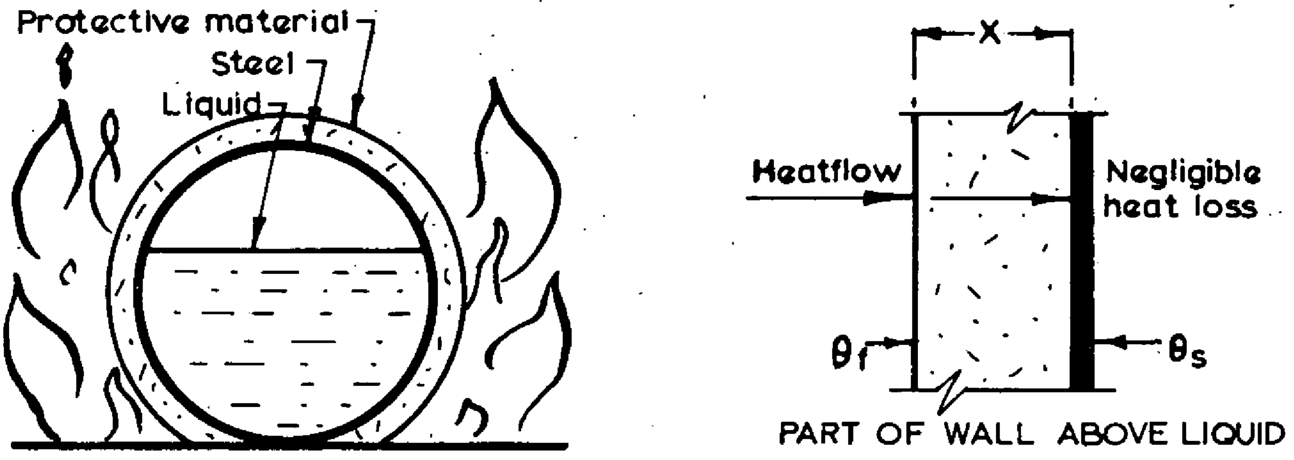
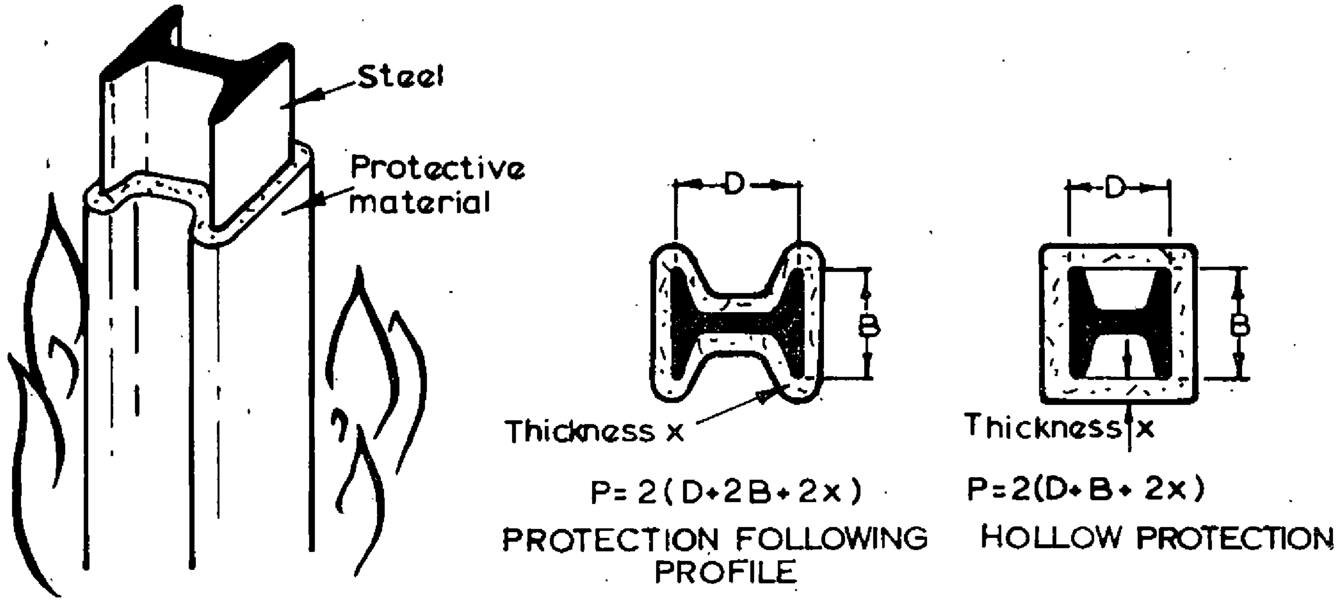


FIG.2. TANK CONTAINING LIQUID FUEL



$P = 2(D + 2B + 2x)$
PROTECTION FOLLOWING PROFILE

$P = 2(D + B + 2x)$
HOLLOW PROTECTION

FIG.3. PROTECTED STEEL COLUMN

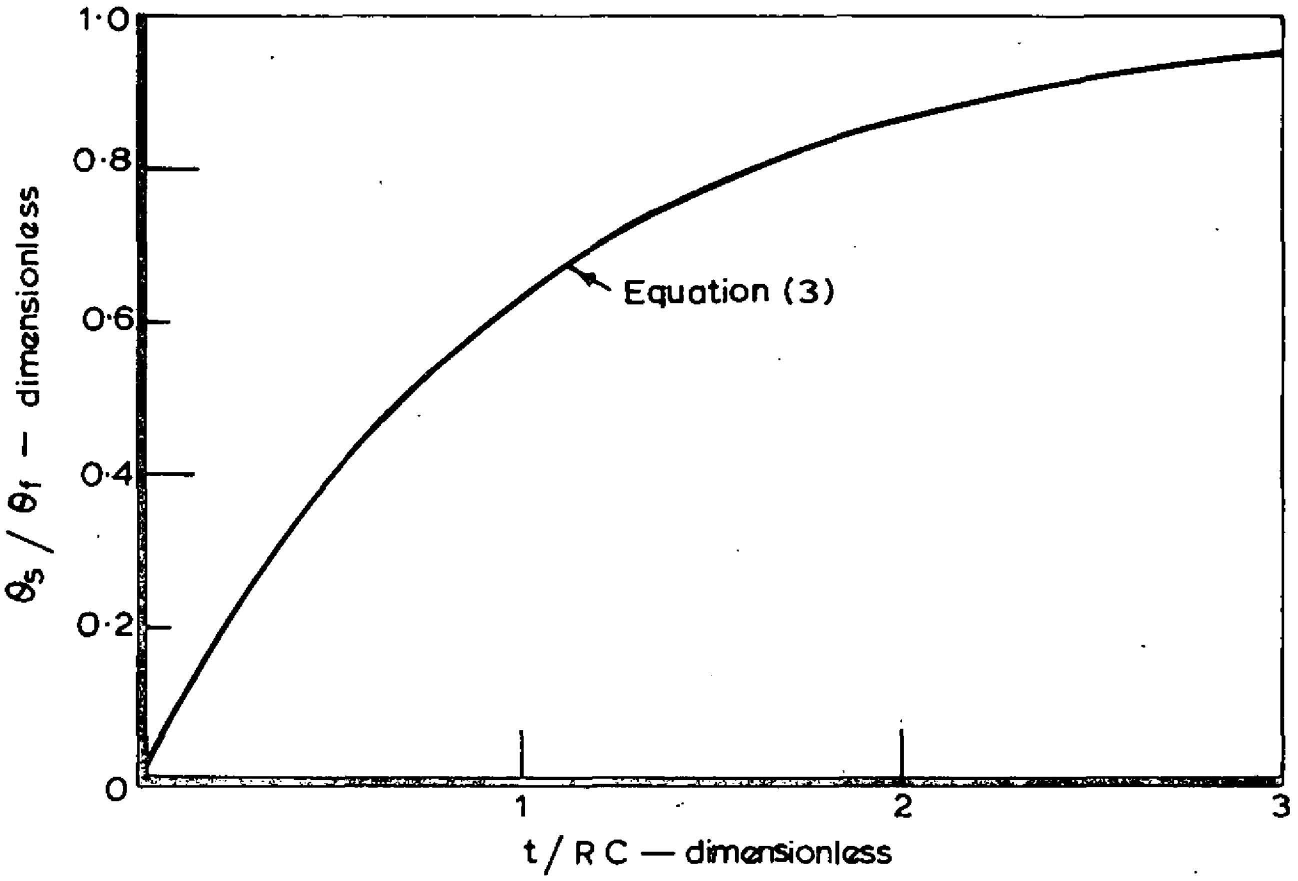


FIG. 4. STEEL TEMPERATURE θ_s WHEN EXPOSED SURFACE OF PROTECTIVE MATERIAL IS AT TEMPERATURE θ_f

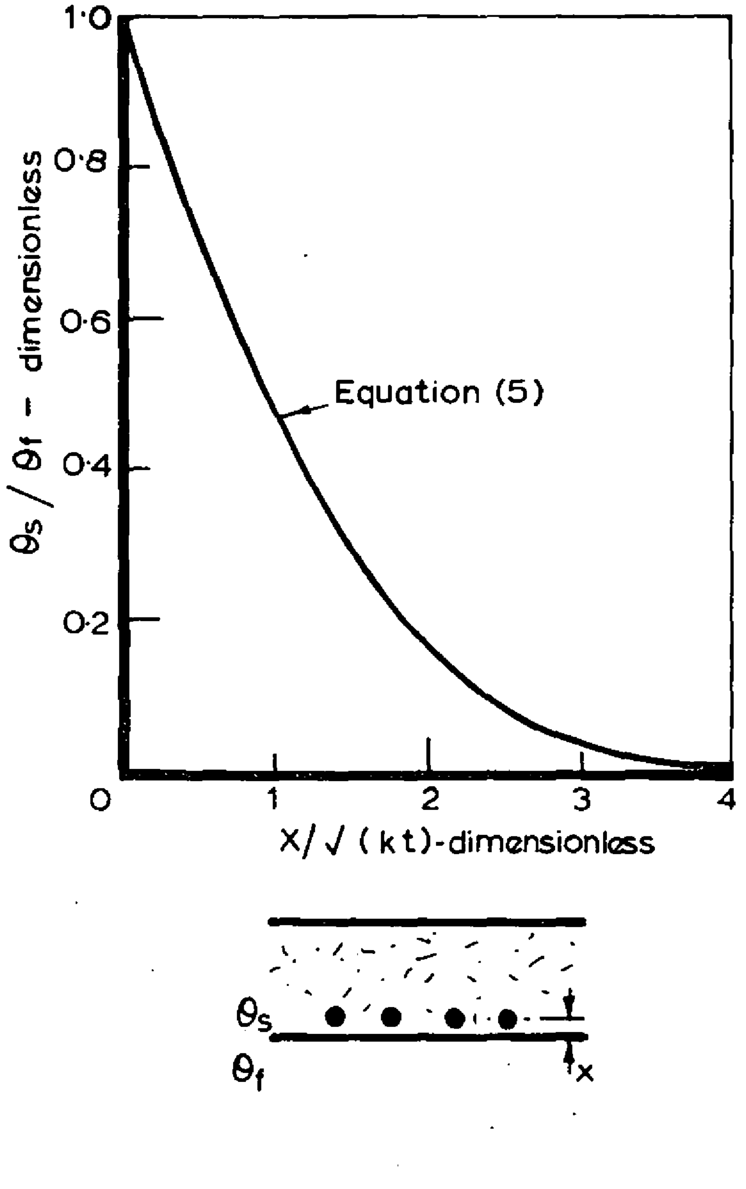


FIG.5. BAR TEMPERATURE θ_s AT DEPTH X IN CONCRETE SLAB WITH SURFACE AT TEMPERATURE θ_f

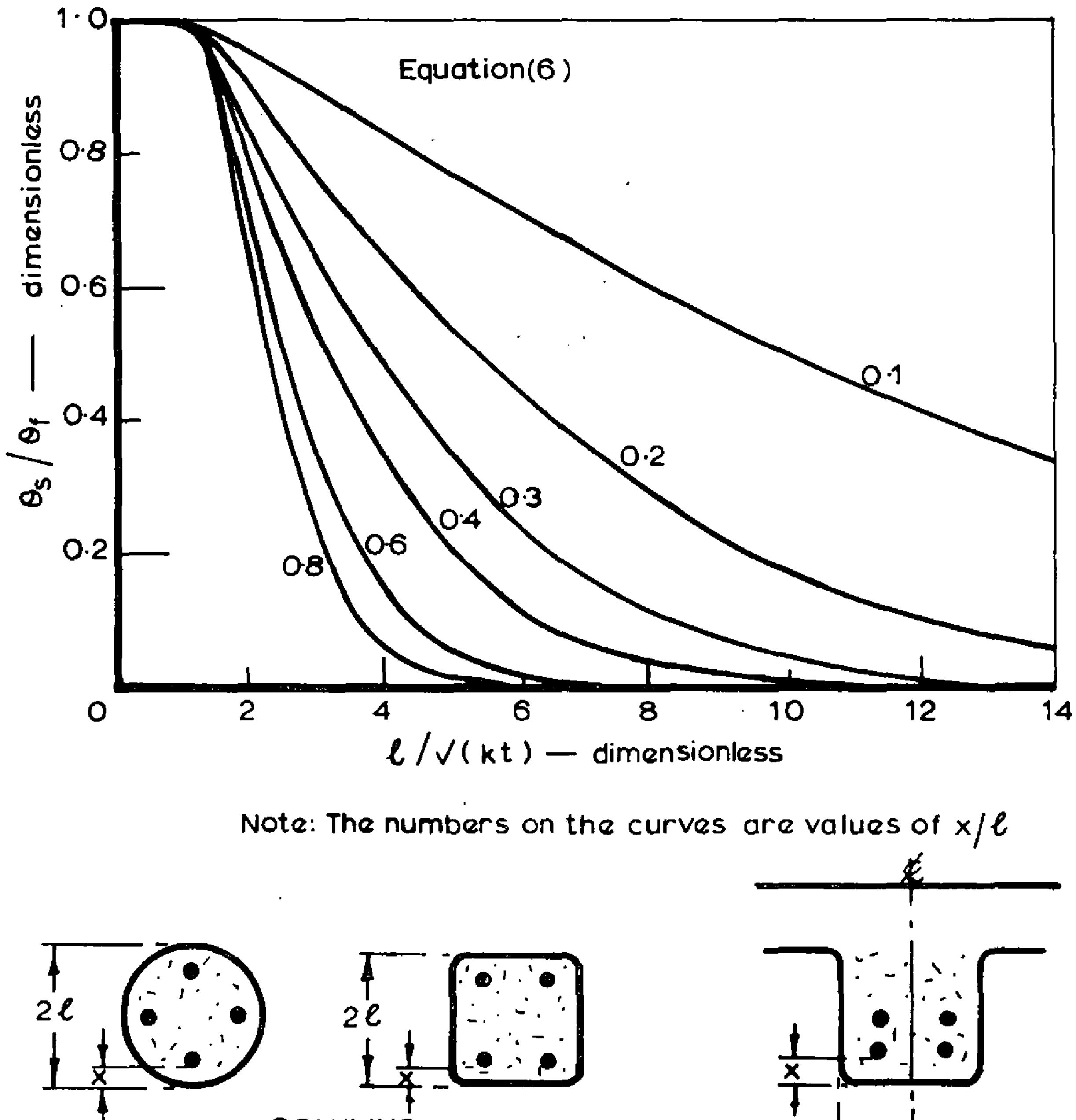


FIG.6. BAR TEMPERATURE θ_s AT DEPTH X IN CONCRETE COLUMN OR BEAM OF THICKNESS 2ℓ WITH SURFACE TEMPERATURE θ_f

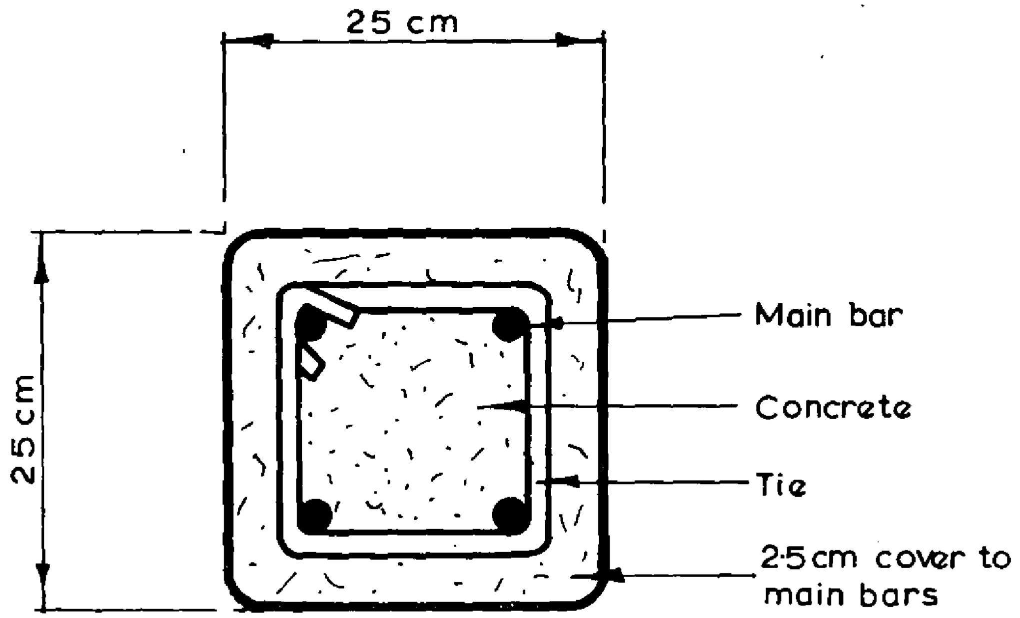


FIG.7. REINFORCED CONCRETE COLUMN
(WORKED EXAMPLE)