Fire and steel construction

Water cooled hollow columns

G.V.L. BOND, B.Sc, MICE, MI Struct E
Oscar Faber & Partners, Consulting Engineers, St Albans, Herts

CONTENTS

Schedule of symbols

A	Area, m^2
A_c	Area of column plate, m^2
A_f	Area of fire, m^2
C_c	Capacity of columns and pipework, m^3
C_l	Experimental constant
C_t	Capacity of tank, m^3
d	Internal pipe diameter, m
E_c	Emissivity of column
E_f	Emissivity of fire
EL	Equivalent length factor, m
F	Factor equal to $\frac{A_f}{A_c} F_{fc}$
F_{fc}	Configuration factor, fire to column
F_{fo}	Configuration factor, fire to air gap
f	Friction factor
G_s	Specific gravity
H	Heat absorption factor, kJ/kg
h_c	Convection factor
K_l	Heat transfer factor, W/m^2
K	Velocity – pressure factor
k	Thermal conductivity of steel, W/m °C
k_s	Surface roughness factor
l	Pipe length, m
M_f	Mass flow rate of fluid, kg/sec
M_l	Mass of water per unit area, kg/m^2
n	Experimental index
P_c	Circulatory pressure, N/m^2
P_z	Pressure under static head, N/m^2
ΔP	Gross pressure loss, N/m^2
Δp	Pressure loss per unit length, N/m^3
P_L	Total pressure loss in circuit, N/m^2
Q	Total heat flow rate per unit area at column surface, W/m^2
Q_c	Heat flow rate per unit area at column surface (convection), W/m^2
Q_r	Heat flow rate per unit area at column surface (radiation), W/m^2
Q'_r	Equal to $\frac{Q_r}{F}$ ($= Q_r$ when $F = 1.0$)
q	Total heat input, W min/m^2
q_r	Heat flow rate (radiation), W
Re	Reynolds number
T_l	Absolute temperature of radiating body, °K
T_o	Absolute temperature of surroundings, °K
T_c	Temperature of fireside column surface, °C
T_f	Temperature of fire, °C
T_i	Temperature of waterside column surface, °C
T_w	Boiling temperature of fluid, °C
ΔT	Temperature range, °C
t	Plate thickness, m
V_w	Volume of water storage, m^3
W_w	Mass of water storage, kg
z	Static head of fluid, m
α	Coefficient of cubical expansion per °C
μ	Absolute viscosity, kg/m.s
ρ	Density, kg/m^3
σ	Stefan's constant

FOREWORD

All structural material can be damaged in severe fire conditions and steel, although non-combustible and making no contribution to fire, can have its function impaired. It is for this reason that the various building regulations and constructional by-laws require it to be protected when used for certain elements of construction in some types of building.
The conventional method of protecting steelwork is by encasing it in fireproof materials such as those described in Constrado Publication 4/74, "Fire and Steel Construction: Protection of Structural Steelwork", August 1974.
An alternative, which can be economical, is to incorporate internal water cooling for the columns. This entails using hollow steel members in the design, possibly in place of the more traditional universal sections. Hollow sections, however, form very efficient columns and there is the added advantage that this method of fire protection allows the steelwork to be freely expressed.
This publication explains the theory involved and makes reference to buildings in North America and Europe where the method has been used. It is now being adopted in Britain where it is expected to arouse widespread interest, in which context the worked example should prove of considerable assistance.

1 INTRODUCTION

1.1 General

The fire protection of hollow steel columns by internal water cooling is an economical alternative to the more conventional method of cladding structural steelwork with fireproof materials. Whereas fireproof cladding delays the passage of heat from the fire to the column, the water in hollow structural steel sections removes the heat as it enters the column. To do this most effectively, the columns are normally interconnected by a piping system which permits gravitational circulation during a fire, the steam generated being vented to the atmosphere and replenishment water being supplied from a storage tank connected to the mains. This system has been used in all the buildings so far constructed with water filled hollow steel sections.
While a system which uses water filled columns without means of replacing evaporation losses (see Appendix) is cheaper and easier to install, it is inherently less capable of providing prolonged fire resistance. Use of the replenishment system is therefore recommended and this publication is consequently based upon it.
The principal advantages of water cooling for *columns* are:

The elimination of external protection results in a reduction in overall column size, thereby providing more floor area.
Potential savings in the cost of fire protection occur, which tend to increase with the size of the building.
The structure of buildings can be more clearly expressed architecturally as the steelwork is exposed.
The columns are more likely to be serviceable after a fire and consequently the insurance cover could be less expensive.

While the fireproofing of *beams* by water cooling is feasible, the advantages to be gained in this case are not so great and there has been only one practical application recorded so far.[1]* This is the four-storey Michelson Building at Newport Beach, California, which utilises a row of water filled rectangular portal frames which straddle the building and from which the floors are hung.

1.2 Historical background

The earliest patent [2] for fireproofing steel columns by water filling was taken out in the USA in 1884. Despite this early concept, the first building in which columns were fireproofed with water, the United States Steel tower block in Pittsburgh, Pennsylvania,[3-5] was not completed until 1970. This 64-storey building is 841 ft high, the external box columns being of welded Cor-Ten steel, unpainted and filled with an aqueous solution. To limit hydrostatic pressure, the columns are divided by means of horizontal diaphragms into four lengths of from 14 to 18 storeys.
The Pittsburgh block is, of course, a unique prestige building, but it has encouraged other designers to use water filled columns in much more modest structures, not only in the USA,[6, 7] but also in Europe.
In France, the first building to use water filled columns is situated in the Champs Elysées.[8] The purpose in this instance was to replace some bulky stone pillars in an existing building by the smallest possible columns. A nine-storey building in Marseilles,[9] uses water cooling in both external and internal columns made from rectangular hollow sections.
The first German building to have been protected in this manner is a new office block in Düsseldorf for the Verein Deutsche Eisenhuttenleute.[10-11] This is a three-storey building with exposed external square hollow columns of Cor-Ten steel. It is interesting to record that, on 28th August 1970, a full scale furnace test was carried out on a one-storey height of one column,[12] providing satisfactory confirmation of the theoretical calculations and, within the limits of the test, proving the efficiency of the system.
Other investigations on column systems have also been performed in Germany[13, 14] and Britain. These show that water cooling can provide excellent fireproofing properties and the results obtained have helped to provide the basis for theoretical calculations.

*Figures in parenthesis refer to items in the Bibliography.

2 BASIS OF DESIGN METHOD

2.1 Assumptions on the behaviour of fire

By its nature, the behaviour of a real fire in a building is haphazard and unpredictable. In arriving at a design method certain simplifying assumptions about the fire must be made which approximate with sufficient accuracy to real conditions and are at the same time amenable to normal design methods and in conformity with building regulations.
Assumptions made in Britain and which are used in the design example for water filled columns in this publication are:

The fire is contained by compartmentation of the building in accordance with the building regulations.
The fire period is in accordance with the relevant building regulation.
The fire intensity is in accordance with the standard time/temperature curve given in BS 476[15] from which the data in Table 1 have been derived.
All the columns within a compartment are simultaneously subject to the same fire intensity.

It is worth noting that this last assumption is particularly severe and that in the more likely event of unequal heating taking place a gravitational circulation of the water would be set up. Some of the thermal capacity in cooler parts of the system would then become available and the effect of this, together with re-radiation from the cooler columns, could well mean that in practice little vaporisation would occur. In buildings with vertical compartmentation it may also be possible to dissipate heat by interconnecting columns in different compartments. When more practical experience of these structures has been gained it may perhaps be possible to modify the assumption.

2.2 Behaviour of a water cooling system in a fire

Cooling can take place in five different ways during a real fire in a building:

(a) By local convection within the column itself, and emission of heat from the parts of the column which are least exposed to the fire.
(b) By convection currents set up in parts of the column and pipe circulation system, in which the cooler columns act as heat sinks and cooling radiators for the hotter columns.
(c) By the initial heating of the water in the columns to boiling point.
(d) By absorption of latent heat of vaporisation when the water is converted to steam.
(e) By heating of the water from the storage tanks which replaces water lost as steam.

Since all the columns in a compartment must be assumed to be heated uniformly and simultaneously and the replenishment water can be heated before it arrives at the affected area, the potential contributions of (a), (b) and (e) are ignored. The design method consequently considers the heat to be removed only by initial heating of the water to boiling point (c) and by evaporation (d).

2.3 Comparison of water filling with conventional fireproofing

Water cooling has the effect of controlling the increase in temperature of the steel column because of the continuous removal of heat and the cooling system can be so designed that, for the requisite fire period, the steel will not reach its critical value (see 2.4). In the Standard Furnace Test, the cooling of the column also effects the temperature of the adjoining fire (because of the comparatively large proportion of the fire chamber occupied by the column) and the heat input to achieve a given temperature is considerably greater than would be the case for a similar column with conventional fireproofing. Thus, design criteria based upon the Standard time/temperature curve are more severe for water filled than for conventionally fireproofed columns.

2.4 Maintenance of steel strength

The successful functioning of a water filled column relies on the steel maintaining its strength during a fire. It has been well established that structural steels at least retain their strength up to about 250°C. Thereafter there is a fairly rapid decline until, at about 550°C, the yield stress is down to normal design stress and any member would not be capable of supporting its full design load beyond that temperature. Consequently, it is commonly accepted practice when designing a system to enable steelwork to withstand the effects of fire to allow for a maximum permissible steel temperature of 550°C.

2.5 Summary

The basic approach is to design the system to pass the BS 476 fire test. Generally, the steel temperature is not a problem; the chief concern is to provide sufficient water storage and adequate pipework for the system to work effectively for the fire period.
The calculations which follow, based as they are on a number of imponderables, should not be regarded as rigorous. It should be emphasized, however, that the method described errs on the conservative side. Furthermore, because the BS 476 fire test is specified by temperature and not by heat flow, the effect of the comparable real fire will not be so severe.

3 PRACTICAL CONSIDERATIONS

3.1 Pipework generally

The basic circulatory system for the cooling water for each piped circuit consists of the following:

A storage tank fed by the mains, the level of the water in the tank usually being controlled by a ball valve.
A replenishment water feed from the storage tank, ideally protected from the fire by being situated inside a column.
A vent from the top of the columns discharging to atmosphere or to the storage tank.
Various valves for testing, isolating and draining down. These should be locked in the correct position when the system is commissioned.
A dry riser for initial filling of the system and for the use of the Fire Brigade in an emergency.

3.2 Circulatory fluid treatment

The water in the columns must be treated in much the same way as that in a central heating system to render it inert and resistant to certain undesirable effects. The chief problems are:

Corrosion
Frost
Biological growth
Scaling

The correct fluid formulation for a particular project is best entrusted to a water treatment specialist. As a guide the following kind of specification, in which the parts are given by weight, has been used in existing buildings:

Desalinated, deoxygenated water	100 parts
Potassium carbonate additive as antifreeze	25 to 60 parts
Potassium or sodium nitrite additive as corrosion inhibitor	1 part

It is desirable that an oil film is maintained on the free surface of the water in the storage tank to inhibit evaporation and to reduce the gradual contamination of the coolant by oxygen, algae, etc.

3.3 Building regulations

Building regulations in Britain require that multi-storey buildings be protected against fire, the extent of protection varying according to such factors as use, height and size of building or compartment. Under certain conditions steelwork external to the fabric of a building may be in no danger from fire and a relaxation of the regulations may be obtained to permit the steelwork to be unprotected. In all other cases any method of providing the appropriate fire protection is acceptable if it is certified as having met the requirements of the Standard Furnace Test (BS 476). Protective cladding materials have no problem in this respect but it is not yet possible to deal with water cooling methods in this way. It is therefore necessary to satisfy the relevant authority that any proposed system of fireproofing columns by water filling will be effective. Features likely to require consideration are:

The installation of devices to give warning of a premature drop in water level.

The possibility of an explosion in a building and its consequences; a column may be removed, or tank supports or pipework damaged.

Arrangements for isolating sections of the system if an accidental breach occurs.

3.4 Patents

Because of its history, the basic idea of fire protection by water cooling is not covered by patents. However, in recent years, some patents (see below) have been taken out for various methods of applying the idea and designers should ensure that they are not unwittingly infringing patent rights.

French Patent	1225209	(June 1960)
USA Patent	3050134	(August 1962)
British Patent	1263567	(February 1972)
British Patent	1265141	(March 1972)

4. THEORY OF HEAT TRANSFER AND REMOVAL

The heat from the fire flows to the column by radiation and to a lesser extent by convection of the hot gases. It then passes through the column plate by conduction. Boiling occurs on the inside of the column plate and heat is transferred to the water by convection and conduction, greatly aided by the mechanical stirring of the bubbling action. This heat is then absorbed chiefly as latent heat when the water is converted to steam and removed from the column by the vent.

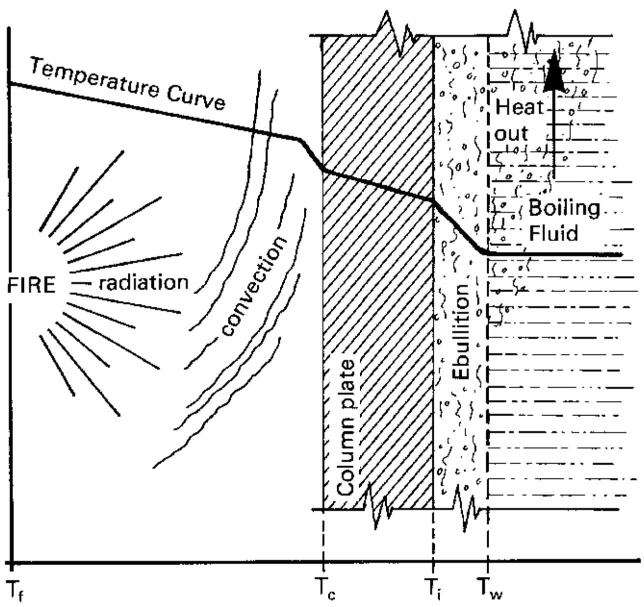


FIGURE 1

4.1 Radiation

The Stefan-Boltzman law gives the general relationship for ideal black body radiation:

$$q_r = A\,\sigma\,(T_i^4 - T_o^4)$$

where q_r = heat flow rate in Watts
A = surface area of radiating body
σ = Stefan's constant
T_i = absolute temperature of radiating body in °K
T_o = absolute temperature of surroundings in °K

In practice, radiation is an exchange between two 'grey' bodies and the equation is modified to:

$$Q_r = \frac{A_f}{A_c} F_{fc} E_f E_c \sigma \left[(T_f + 273)^4 - (T_c + 273)^4\right] \ldots 1$$

where Q_r = heat flow rate per unit area of column plate in W/m²
A_f = area of fire in m²
A_c = area of column plate in m²
F_{fc} = configuration factor, fire to column
E_f = emissivity of fire
E_c = emissivity of column
T_f = temperature of fire in °C
T_c = temperature of column surface in °C

The various parameters used are defined in detail below:

Stefan's constant, σ

This has a value of 5.66×10^{-8} W/m² °K^{-4} for ideal black body radiation.[16]

Configuration factor, F_{fc}

This factor is the fraction of radiant energy leaving the emitter which arrives at the receptor. It is a dimensionless quantity related to the geometric configuration of the two bodies. A useful property of configuration factors is that for the same aspect they are additive (see Graph 1).

Accurate calculation of F_{fc} is not a simple matter, because of the various imponderables, and standard textbooks[17, 18] should be consulted for comprehensive treatment. Fortunately, it is not necessary to make a rigorous evaluation of the configuration factor. The highest theoretical value it can have is A_c/A_f which gives an upper bound solution. Table 2 gives recommended values of F_{fc} for certain standard situations.

Emissivity of fire, E_f

This factor is introduced because the BS fire test furnace does not radiate as a perfect black body. E_f depends to some extent on the operating temperature and on the surface finish of the furnace wall. Its value lies between 0·75 and 0·97 for normal materials and may be taken as 0·85 for design purposes.[14]

Emissivity of column, E_c

This factor (which is the same as absorptivity) takes account of the column not being a perfect receptor of radiation. Its value depends chiefly on the surface finish of the steel and lies between 0·7 and 0·97. Since columns are likely to become soot blackened during a fire, it is prudent to assume a high value, say 0·95.[14]

Temperature of fire, T_f
This is selected from the BS 476 time/temperature curve, the maximum temperature being determined by the period of fire resistance required. Intermediate values will usually be needed for calculation of water storage. Commonly used values are given in Table 1. The calculations are based on a furnace starting temperature of 40°C, the most severe condition given in BS 476.

Temperature of column, T_c
This is the temperature of the fireside surface of the column. Its value is related to the boiling temperature of the circulatory fluid and to the thickness of the steel plate. T_c will usually be found to lie in the range 120 to 320°C. This temperature must not exceed that critical for steel (about 550°C – see 2.4).
Substituting in equation 1 for σ, E_f and E_c, and rearranging gives:

$$Q_r = 4.6 \frac{A_f}{A_c} F_{fc} \left[\left\{ \frac{T_f + 273}{100} \right\}^4 - \left\{ \frac{T_c + 273}{100} \right\}^4 \right] \quad ..2$$

4.2 Convection

Heat transfer by convection is not susceptible to rigorous analysis but the following simplified equation for natural convection at a vertical surface in air has been arrived at experimentally.[19]

$$Q_c = h_c (T_f - T_c) \quad \ldots\ldots 3$$

where Q_c = heat flow per unit area due to convection in W/m²
h_c = convection factor (see below)

Convection factor, h_c
This factor is related to the Grashof, Prandtl and Nusselt numbers for the gas concerned, and can be expressed in the form

$$h_c = C_l (T_f - T_c)^n$$

where n is about 0.25
and C_l is an experimental constant.
A value of h_c = 29 W/m² °C can be used for design purposes.[10]
Substituting in equation 3 gives:

$$Q_c = 29 (T_f - T_c) \quad \ldots\ldots 4$$

4.3 Total heat flow, fire to column

Equation 2 can be written:

$$Q_r = F Q'_r$$

where $F = \frac{A_f}{A_c} F_{fc}$

Thus total heat flow, fire to column, per unit area of column is thus:

$$Q = Q_r + Q_c = FQ'_r + Q_c \quad \ldots\ldots 5$$

Values of Q, Q'_r and Q_c when F = 1.0 are given in Table 3. When $F \neq 1$ its value may be found by using Graph 1 (see 4.6 for determination of Q).

4.4 Conduction through column plate

This obeys a simple straight line relationship (originally proposed by Fourier in 1822):

$$Q = \frac{k}{t} (T_c - T_i) \quad \ldots\ldots 6$$

where $Q = Q_r + Q_c$ in W/m²
k = thermal conductivity of steel (see below)
t = plate thickness in m
T_i = temperature of waterside surface of column in °C.

Thermal conductivity, k
This varies both with steel composition and with temperature. For structural steels the value is about 55 W/m°C at room temperature and about 40 W/m°C at 300°C.

*Graph 3 shows $T_i - T_W$ plotted against heat flow per unit area for two potassium carbonate solutions and pure water.

4.5 Heat flow across bubble layer

The rate of flow of heat across the bubble layer is **not** easily defined and is dependent on a number of factors. Bubble vaporisation can be assumed to occur,[13] but the heat transfer coefficient is dependent on the hydrostatic pressure and Q, the heat flow per unit area.
There are no suitable theoretical analyses but there have been several experimental approaches. McAdams[20] quotes the following empirical relationship for boiling water under pressure in a vertical tube:

$$e^n (T_i - T_W) = 0.79 Q^{\frac{1}{4}} \quad \ldots\ldots 7$$

where $n = \frac{z + 10.3}{840}$
z = head of water in m
T_W = boiling point of fluid in °C for head z (Graph 2).

Piret and Isbin[21] have performed tests on water and potassium carbonate solutions boiling at atmospheric pressure in a vertical tube. Some of their results for heat transfer properties are presented in Table 4. An approximate relationship, using their values of the heat transfer factor, K_l, is given by:

$$Q = K_l (T_i - T_W) \quad \ldots\ldots 8$$

Piret and Isbin's results do not cover the high heat flow densities likely to be encountered but their extrapolated results* for a flow of 150 000 W/m² °C correlate well with Ehm and Bongard's [13] recommended values for K_l of approximately 8000 W/m² maximum. The type of circulatory fluid has a considerable influence on the thermal properties and should be taken into account. The heat flow calculation does not have an accuracy better than ±15% but since $T_i - T_W$ is unlikely to exceed 20° the effect of this on the analysis will be small. Equation 8 is recommended where the effect of hydrostatic pressure is not great, i.e. for z less than 30m. If equation 7 is used, a suitable allowance must be made for the fact that it relates only to pure water. For example, the 50% potassium carbonate solution has a heat transfer coefficient about 30% less than that for water. This implies a corresponding increase in the value of $T_i - T_W$.

4.6 Solution of heat flow equations

The total heat flow per unit area, as given in equation 5, is:

$$Q = FQ'_r + Q_c$$

This equation is dependent on the ultimate value of T_c but, as will be seen from Table 3, the variation in Q is so small that, for practical purposes, it can be considered independent of T_c. It will also be noted that Q decreases as T_c increases. In determining Q, therefore, it is advisable to assume a conservative value for T_c. Table 3 gives values of Q, Q'_r and Q_c for various points on the BS time/temperature curve for the case when F = 1.0. Under this condition, therefore, Q can be read directly from the table.
When F has a value other than 1.0, the values of Q'_r and Q_c in Table 3 can be used to determine Q from equation 5 after finding F from Graph 1 (see Section 6 – worked example).
If a knowledge of the column temperature, T_c, is required, this value of Q may be used to determine a value for T_i from equation 7 or 8. This may then be substituted in equation 6 to find T_c. A more precise value for T_c may be determined by iteration of this process but convergence is rapid and the value already found will be near the optimum even if it does not agree closely with the original assumed value. As the calculation for T_c is not very accurate but gives safe answers, there is no point in further iteration.

4.7 Removal of heat by water

The cooling water absorbs heat in two phases, firstly by a rise from initial temperature to boiling point and secondly by conversion to steam and the consequent storage of latent heat. The relative quantities of heat absorbed are:

1. 1 kg of water raised 1°C absorbs 4·187 kJ of heat. In a typical fire, with a temperature rise of, say, 75°C, 1 kg of water absorbs 314 kJ.

2. Latent heat of vaporisation varies slightly with temperature but it can be taken as 2150 kJ/kg.

Comparing, it can be seen that the first phase, i.e. raising the temperature of the water to boiling point, absorbs only about 15% of the heat absorbed during vaporisation. Furthermore, the specific heat of the fluid used will be rather less than that for water. It is therefore recommended that the value of the constant, H, representing the overall heat absorption per unit mass of cooling water should be taken as 2200 kJ/kg.
The thermal capacity of the column plate is usually ignored as being insignificant. With relatively thick column plates, however, a small saving in storage capacity may be made by considering this point (specific heat of steel = 0·48 kJ/kg). See also Appendix.

4.8 Water storage requirement

The water storage required is calculated from the total heat input, q, for the fire period considered. A curve is drawn showing the variation of heat input, Q, with time and the area under the curve gives q, in W min/m² units. The mass of water storage required per m² of column surface is then:

$$M_l = \frac{60q}{1000H}\ \text{kg/m}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

and the total volume of water storage required is:

$$V_W = \frac{M_l A}{1000}\ \text{m}^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

where A is the total area of column surface in the fire compartment and this depends on the number, size and height of the columns therein.
For the case when F = 1·0 and H = 2200 kJ/kg values of M_l may be interpolated directly from Table 5.

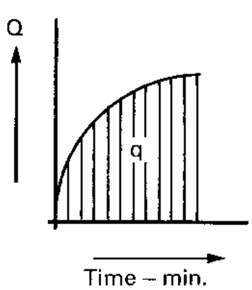


FIGURE 2

4.9 Tank capacity

The tank capacity, C_t, must be sufficient for the volume of water, V_W, given in 4.8 plus the volume of water, C_c contained in columns and pipework, and it must also allow for expansion and contraction. If the climatic temperature range is ΔT and the coefficient of cubical expansion of the fluid is α, then the tank capacity must be:

$$C_t = V_W + (V_W + C_c)\Delta T\alpha\ \text{m}^3. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

Some relief from the expansion effect is afforded by the thermal expansion of the columns themselves.

5. DESIGN OF PIPEWORK

5.1 General

As previously stated, it is assumed that all the columns in a fire compartment are simultaneously subject to the same temperature. This means that ordinary gravitational circulation is unlikely to occur until vaporisation develops. The motive force is then related to the density difference between the head of water in the cold feed and the column of steam present in the vent pipe.
The design of the pipework follows conventional lines. When the required rates of flow in the columns have been calculated, the head loss for a given pipe diameter can be read directly from tables in the IHVE Guide [22], or from Graphs 4 and 5. Although these are related to the flow of pure water, they are suitable for most aqueous solutions (see 5.4). The total head loss in any circuit, including allowance for pipe fittings, must be less than the circulation head. Some problems arise over the question of the transition from fluid to steam phase. The first steam generated will condense in the vent pipe but eventually sufficient steam will form to eject this water into the storage tank or to atmosphere. Ultimately pure steam will be flowing through the vent pipe but prior to this some form of two-phase flow [23] will probably occur which is virtually incalculable. For this reason the vent pipe design should err on the generous side. It will generally be found that losses in the fluid part of the circuit are insignificant compared with those in the vent pipe.

5.2 Pipe sizing

(a) WATER PIPE

The maximum water mass flow rate, M_f, to any one column is calculated from the value of Q at the end of the fire period and the exposed area, A, of column. It is given by:

$$M_f = \frac{QA}{H} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

where H = 2200 kJ/kg.
Using this value for M_f and an estimated size of pipe, Graph 4 is entered to find the head loss/m of pipe, Δp, and the factor EL. EL is the number which when multiplied by the factor, K, for a pipe fitting represents the head loss through the fitting as an equivalent length of pipe. Values of K are given in Table 6.
The head loss, ΔP, through a circuit is then given by:

$$\Delta P = \Delta p\ (l + K.EL)\ \text{N/m}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 13$$

where l = pipe length in m.

(b) STEAM PIPE

Steam flow is handled in similar fashion. Using the value of M_f and an estimated size of pipe, Graph 5 is used to find Δp and EL. (Graph 5 has been drawn assuming that the steam is vented to atmosphere.)

5.3 Circulatory pressure

The circulatory pressure, P_c, is calculated from the least available head of fluid converted into pressure units, P_z (Table 7).
This head is measured from the lowest allowable boiling surface to the underside of the storage tank (the tank will be just empty) and multiplied by the specific gravity, G_s, of the fluid. Then:

$$P_c = G_s\, P_z\ \text{N/m}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 14$$

This circulatory pressure must be greater than the sum of head losses in the circuit for sufficient flow to take place.

5.4 Circulatory fluid properties

It will generally be found that, within the limit of accuracy of the calculations as a whole, the water and the steam tables can be used for the flow calculations. The head loss/m for the fluid can, if desired, be compared with that for pure water using the d'Arcy equation:

$$\Delta p = \frac{f \pi M_f^2}{d^5 \rho} \quad \ldots\ldots 15$$

where f = friction factor
d = internal pipe diameter in m
ρ = density in kg/m³

The friction factor is a function of the Reynolds Number and the relative roughness of the internal surface of the pipe.

Reynolds Number, $R_e = \frac{1 \cdot 27 + M_f}{d\mu}$

where μ = absolute viscosity in kg/m.s (Table 4)

Relative roughness $= \frac{k_s}{d}$

where k_s = surface roughness factor.

Values of relative roughness are given in Table C4.3 in the IHVE Guide and, knowing the Reynolds Number, the friction factor, f, can be read from Figure C.4.1 in the IHVE Guide. Substitution for f in equation 15 gives Δp.

If this calculation is performed both for pure water and the circulatory fluid and the two results are in close agreement, the conventional water flow tables can be used.

Since, in general, most aqueous solutions have similar flow properties and, in any case, the fluid losses are usually insignificant compared with the steam losses, this analysis is rarely necessary.

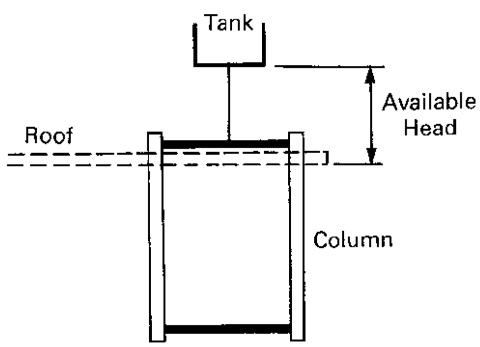


FIGURE 3

6. WORKED EXAMPLE

6.1 Description

Figures 4, 5 and 6 show the basic structural arrangement for a steel framed building. The columns are welded hollow box sections, fireproofed by internal water cooling. The column plates are 15 mm thick at the top storey and 40 mm thick at the bottom. The beams are fireproofed by conventional means. The floors are of reinforced concrete and the walls are of brickwork or blockwork suitably tied to the structural frame, with full length windows along line A (see Figures 4 and 5). The columns on grid A are set outside the building to provide a visual feature. They are of weathering steel and will be left unpainted.
The building is divided horizontally into compartments by the floors. The water cooling system can therefore be designed on the assumption that a major fire will be restricted to one floor for the requisite fire period which has been established at 1 hour.
The circulatory fluid is a nominal 35% solution of potassium carbonate with 1% potassium nitrite (see 3.2).

6.2 Calculation

The worst case for water storage and pipe design occurs when a fire breaks out on the top floor.
This is because the storage tank has in this case to provide the whole of the replenishment fluid and because only a small pressure head can be developed in the pipework.
The worst case as regards column temperature occurs on the ground floor. This is due to the thicker column plates at this level and to the higher boiling point of fluid under pressure. In this case, however, replenishment fluid is also available from the columns in the upper storeys and the pressure head is consequently greater.
If there were a basement this would have to be considered as the worst case regarding column temperature. The fire resistance requirement would also be greater (1½ hour). However, as can be seen from 6.2 (f), the system designed in the following would be more than adequate.
The calculation process is illustrated by Flow Charts 1, 2 and 3.

(a) HEAT FLOW

Columns on Grid A

As these columns are set outside the building the factor F (see 4.3) is different for each column plate.

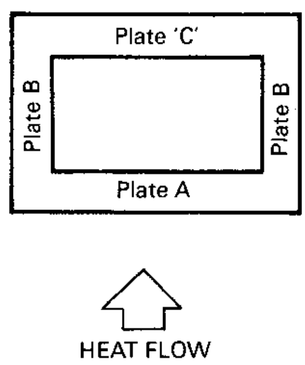
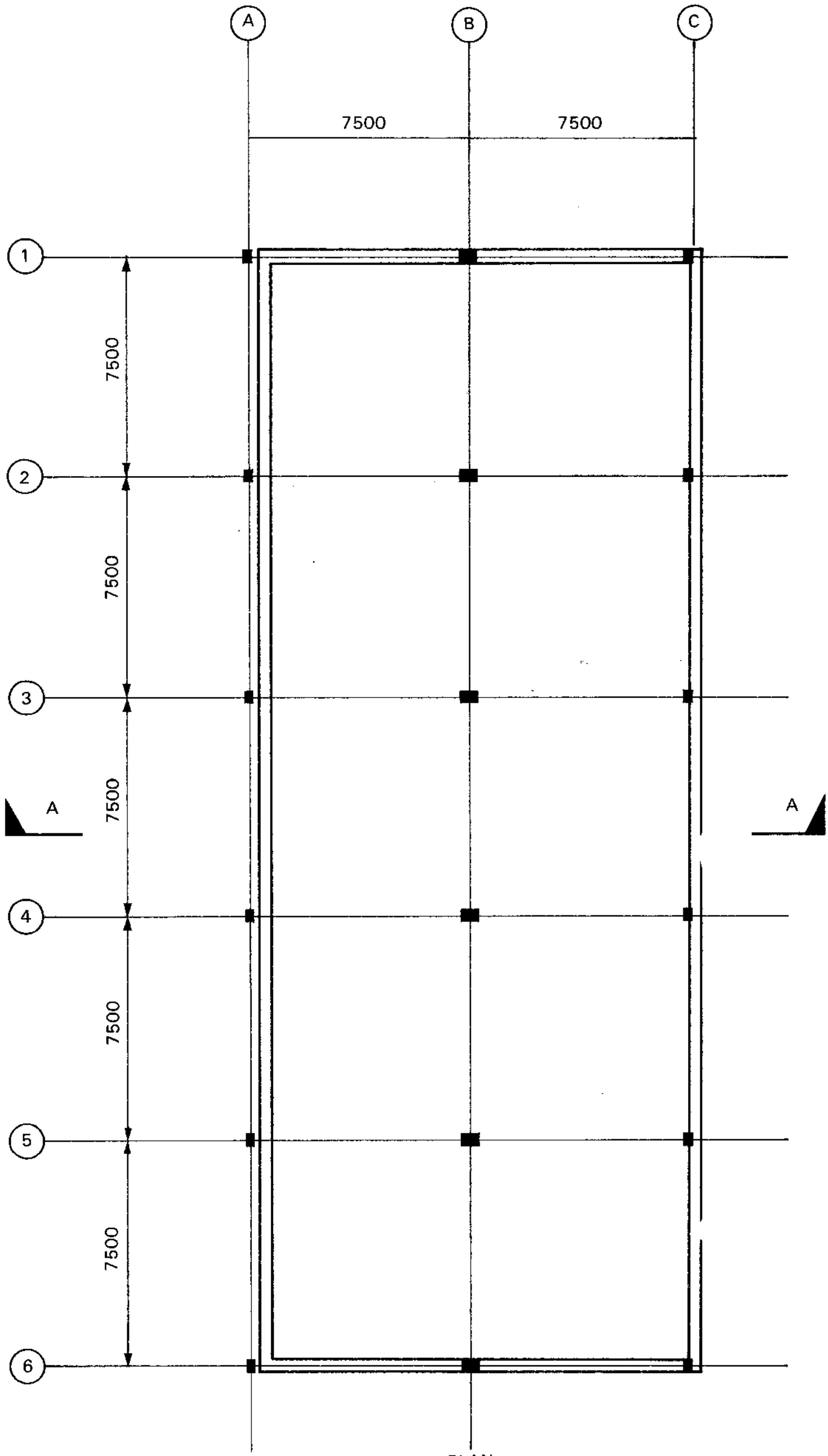


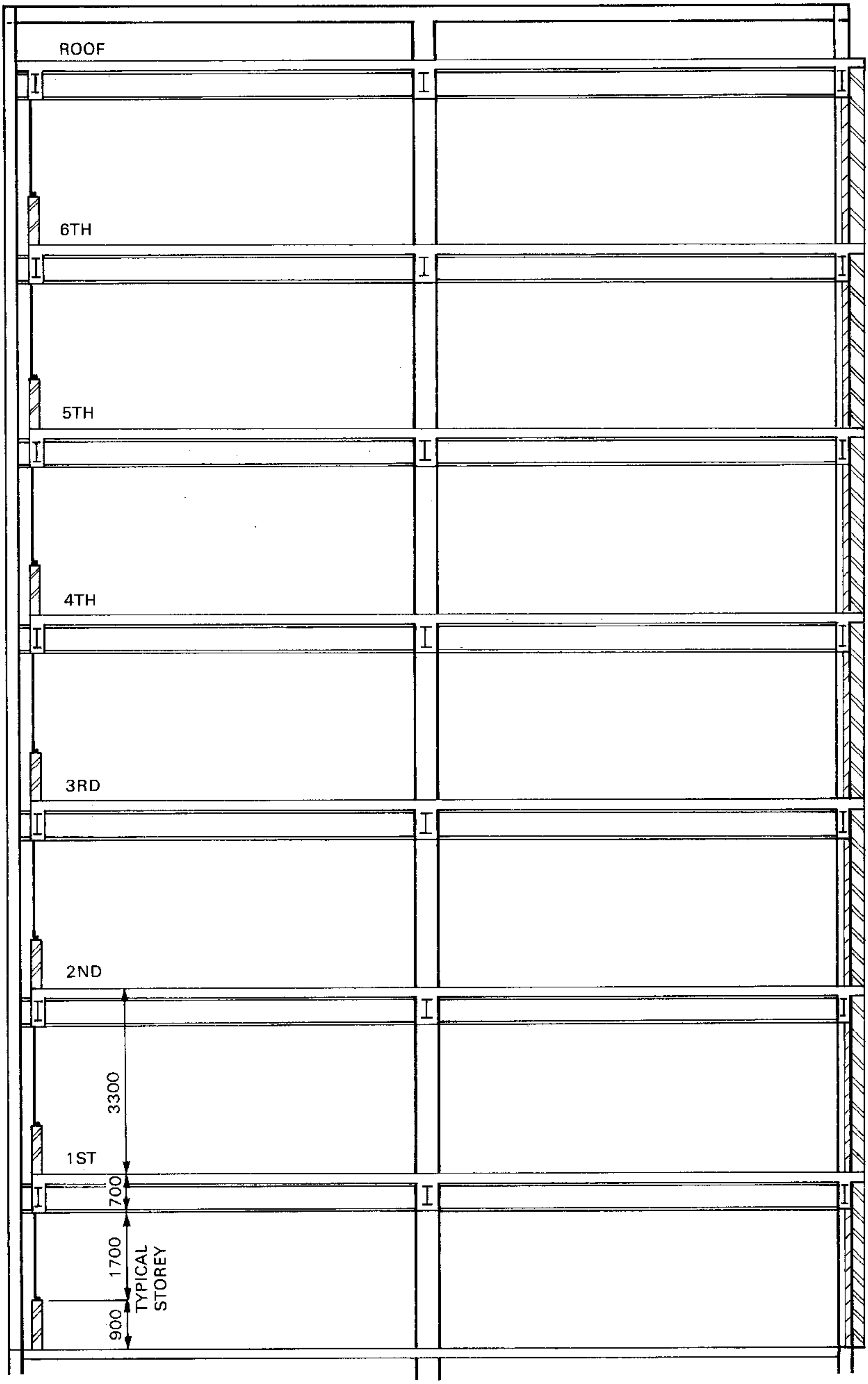
FIGURE 7

The basic equation for the total heat flow per unit area, equation 5, is:

$$Q = FQ'_r + Q_c$$

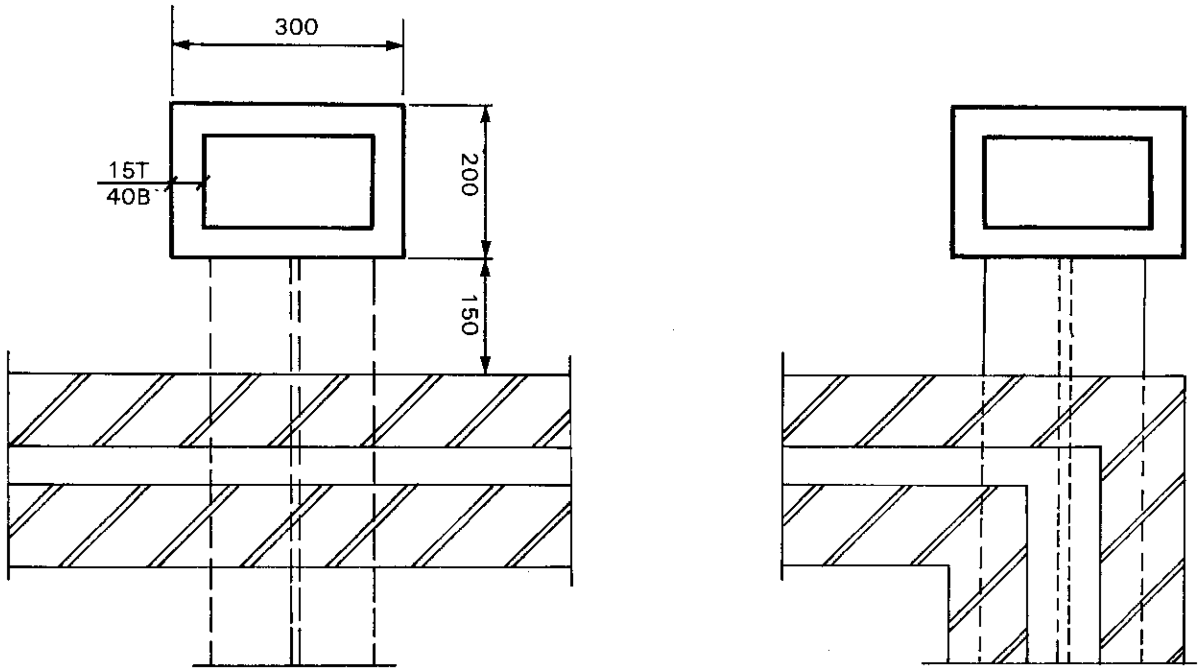


PLAN
FIGURE 4

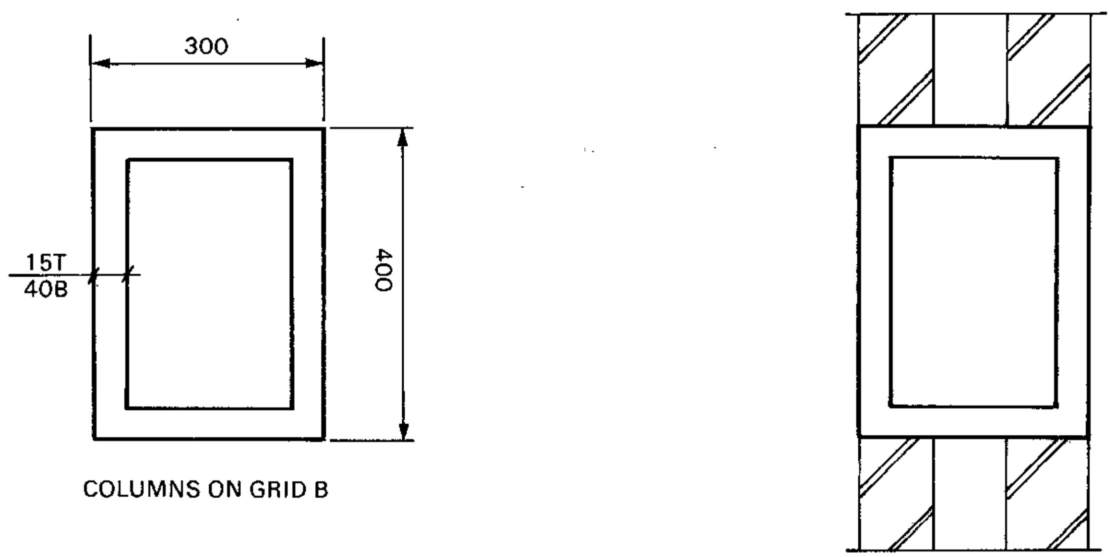


SECTION A-A

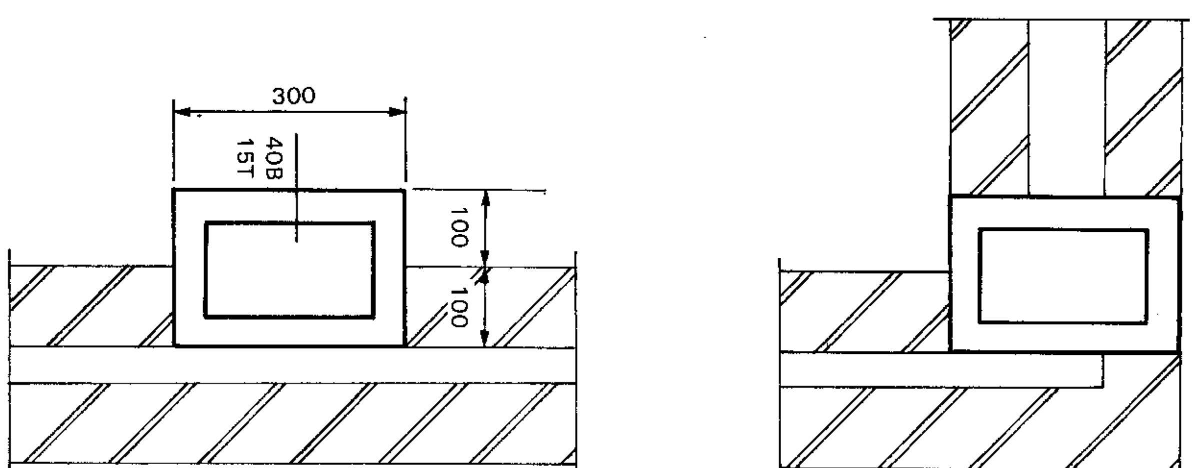
FIGURE 5



COLUMNS ON GRID A



COLUMNS ON GRID B



COLUMNS ON GRID C

NOTE T = TOP STOREY
B = BOTTOM STOREY

FIGURE 6

Plates A
From Table 2, $F = 1.0$
Assume a value of $T_c = 140°C$ for the temperature of the plate
Then, from Table 3, $Q = 130.6\ kW/m^2$ at 1 hour

Plates B

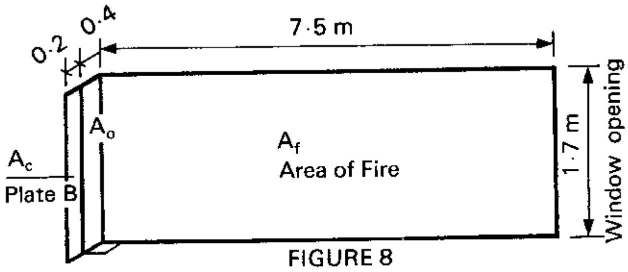


FIGURE 8
(see also Graph 1)

In this case, $F \neq 1.0$ and it must be determined from

$$F = \frac{A_f}{A_c} F_{fc}$$

Here $F_{fc} - F_{(fc+fo)} - F_{fo}$
where F_{fc} = Configuration factor for fire to column
and F_{fo} = Configuration factor for fire to air gap
$F_{(fc+fo)}$ and F_{fo} are determined from Graph 1.

$F_{(fc+fo)}$: $C = \frac{c}{a} = \frac{0.6}{1.7} = 0.35$

$B = \frac{b}{a} = \frac{7.5}{1.7} = 4.41$

Then from Graph 1, $F_{(fc+fo)} = 0.03$

F_{fo}: $C = \frac{0.4}{1.7} = 0.24$

$B = \frac{7.5}{1.7} = 4.41$

Then from Graph 1, $F_{fo} = 0.02$
Hence, $F_{fc} = 0.03 - 0.02 = 0.01$
and $F = 0.01 \times \frac{7.5 \times 1.7}{0.2 \times 1.7} = 0.4$ approx.
Heat flow when $F = 0.4$ and $T_c = 140°C$:
From Table 3:
At 10 min.: $Q'_r = 39.7\ kW/m^2$
$Q_c = 16.2\ kW/m^2$
$\therefore Q = 0.4 \times 39.7 + 16.2 = 32.1\ kW/m^2$
At $\frac{1}{2}$ hour: $Q'_r = 69.5\ kW/m^2$
$Q_c = 20.3\ kW/m^2$
$\therefore Q = 0.4 \times 69.5 + 20.3 = 48.1\ kW/m^2$
At 1 hour: $Q'_r = 106.7\ kW/m^2$
$Q_c = 23.9\ kW/m^2$
$\therefore Q = 0.4 \times 106.7 + 23.9 = 66.6\ kW/m^2$

Plates C
No heat flows to these plates.

Columns on Grid B
From Table 2, $F = 1.0$
Again assuming $T_c = 140°C$
from Table 3, $Q = 130.6\ kW/m^2$ at 1 hour

Columns on Grid C
From Table 2, $F = 1.0$
Again assuming $T_c = 140°C$
from Table 3, $Q = 130.6\ kW/m^2$ at 1 hour

(b) WATER REQUIREMENTS
Columns on Grid A
Plates A
Total exposed area (6 plates) $= 0.3 \times 1.7 \times 6 = 3.06 m^2$
From Table 5 (since $F = 1.0$),
$M_l = 137.4\ kg/m^2$ at 1 hour
$\therefore$ mass of water required for Plates A
$= 137.4 \times 3.06 = 421 kg$
Plates B
Total exposed area (10 plates) $= 0.2 \times 1.7 \times 10 = 3.4 m^2$

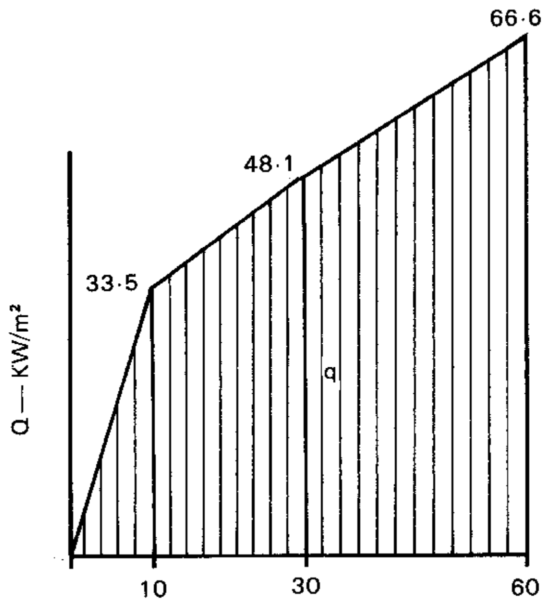


FIGURE 9

Area under curve (Figure 9),

$$q = \frac{32.1 \times 10}{2} + \frac{(32.1 + 48.1)20}{2} + \frac{(48.1 + 66.6)30}{2}$$

$= 160.5 + 802 + 1720.5 = 2683$ kW min.
Then mass of water required

$$= \frac{2683 \times 60 \times 3.4}{2200} = 249 \text{ kg}$$

Columns on Grid B
Total exposed area $= (0.3 \times 8 + 0.4 \times 10)\, 3.3$
$= 21.12 m^2$
From Table 5 (since $F = 1.0$),
$M_l = 137.4\ kg/m^2$ at 1 hour
$\therefore$ mass of water required $= 137.4 \times 21.12 = 2902$ kg

Columns on Grid C
Total exposed area $= (0.3 \times 4 + 0.1 \times 10)\, 3.3$
$= 7.26 m^2$
Here again $F = 1.0$ and $M_l = 137.4\ kg/m^2$ at 1 hour
$\therefore$ mass of water required $= 137.4 \times 7.26 = 998$ kg

Total water requirements, W_w

Summing the parts calculated above,
$W_w = 421 + 249 + 2902 + 998 = 4570$ kg

The volume of water storage is thus $V_w = \frac{4570}{1000} = 4.6 m^3$

The calculations thus far are summarized in tabular form below:

Element	Grid A			Grid B	Grid C
	Plate A	Plates B	Plate C	All Plates	Exposed Plates
F	1.0	0.4	0	1.0	1.0
T_c °C	140	140	—	140	140
Q kW/m²					
at 10 min	—	32.1	0	—	—
at 30 min	—	48.1	0	—	—
at 60 min	130.6	66.6	0	130.6	130.6
q kWmin/m²	—	2683	0	—	—
ΣA m²	3.06	3.4	—	21.12	7.26
W_w kg	421	249	0	2902	998
				ΣW_w – 4570	

(c) CIRCULATORY FLUID

Approximate capacity of columns and pipework (see Figure 10) assuming 100 mm internal diameter pipes is:

$$C_c = 6 \times 3.3 \times 7\ (2 \times 0.27 \times 0.17 + 0.27 \times 0.37) + \frac{\pi \times 0.1^2}{4} \times 200$$

$= 29\ m^3$ approx.

The density of the 35% solution, from Table 8, is 1.355 g/cc. For all intents and purposes, however, the addition of salt to pure water, while increasing the density, does not increase the volume.

(d) TANK CAPACITY

This is given by equation 11:

$C_t = V_W + (V_W + C_c)\ \Delta T\ \alpha$

In this case, $V_W = 4.6\ m^3$

$C_c = 29\ m^3$

$\Delta T = 35°C$ (say)

$\alpha = 21 \times 10^{-5}$ per °C

Hence, $C_t = 4.6 + (4.6 + 29)\ 35 \times 21 \times 10^{-5}$

$= 4.85\ m^3$ (minimum)

(e) COLUMN TEMPERATURE

As explained previously, the worst case in respect of column temperature occurs on the ground floor but a check will also be made on the assumed value of $T_c = 140°C$ for the top storey.

Top Storey

The internal columns, with all plates under the same temperature conditions, give the worst case. Then:

$T_W = 100°C$

$Q = 130.6\ kW/m^2$

and $T_i\text{-}T_W = 19°C$ (from Graph 3)

$\therefore T_i = 119°C$

Equation 6 gives $Q = \frac{k}{t}(T_c\text{-}T_i)$

In this case, t = 0.015m and k may be assumed to be 45 W/m.°C (see 4.4)

Hence, $T_c = \frac{Qt}{k} + T_i = \frac{130.6 \times 1000 \times 0.015}{45} + 119$

$= 163°C$ (i.e. greater than 140°C assumed)

Ground Floor

Here $T_W = 135°C$ (from Graph 2)

$Q = 130.6\ kW/m^2$

and $T_i\text{-}T_W = 19°C$ (from Graph 3)

$\therefore T_i = 154°C$

From equation 6, in which t = 0.04 m,

$T_c = \frac{130.6 \times 100 \times 0.04}{45} + 154$

$= 270°C$ (again greater than 140°C)

A local peak temperature will occur at the column corners where $t = 0.04\sqrt{2} = 0.056$ m.

Using this value in equation 6 gives $T_c = 317°C$.

It will be noted that although the heat flow calculations have been based on an assumed value of $T_c = 140°C$, the calculated values of the column temperature are all greater than this. However, since the heat flow requirements lessen as T_c increases, a conservative value of T_c was purposely assumed so that the heat flow requirements would be on the safe side (see also 4.6).

These calculations have been based on values of T_W for water, which are a few degrees less than those for the solution (see Table 4). Allowing for this and for a 15% margin of accuracy, T_c is still well below the critical temperature for steel, 550°C.

(f) EQUIVALENT FIRE LOAD

From 6.2(b) above, total water requirement, $W_W = 4570$ kg. The heat input required to evaporate this mass of water is:

$W_W H = 4570 \times 2200$

$= 10054$ MJ

Available floor area = 539m²

(from Figures 4 and 6)

$\therefore$ fire load density $= \frac{10054}{539}$

$= 18.7\ MJ/m^2$

Comparison with Table 9 shows that this corresponds to a density of combustible material within the building several times greater than that even for the 'High' category.

This demonstrates that the water protection provided in the scheme designed will resist a fire loading far in excess of that likely to be encountered in a real fire.

(g) PRACTICAL APPLICATION

The piping circuits will be divided into three self-contained zones, each containing six columns (Figure 10), so as to limit the loss of fluid in the event of a burst. The minimum required volume of water storage is 4.85 m³. It is advisable to be generous in the choice of tank and one having a capacity of 8 m³ is selected with ball valve control to maintain the stored water at a minimum of 6 m³. The excess capacity provides storage for any water expelled from the columns during a fire.

(h) PIPEWORK

The proposed schematic arrangement of the pipework is shown in Figure 10. The chief points to note are:

(i) The replenishment pipe lies within the column for one storey height. This ensures that

This calculation and those for the other pipes are most conveniently performed in tabular format as follows:

Water Flow (Graph 4)

		Flow	Trial pipe	Length m					Pressure drop N/m²		
		kg/sec	size mm	Pipe	Equiv. for joints			Total			
Circuit	Section			l	K	EL	K.EL	l + K.EL	Δp	ΔP = Δp (l + K.EL)	Total
1, 2, 3 4, 7, 8, 9	1-2	0.423	80	6.0	2.6	2.9	7.6	13.6	1.4	19.1	
	2-3 (col)									Negligible	
	3-4	0.098	65	7.2	0.4 1.0 0.2 1.6	1.8	2.9	10.1	0.25	2.4	21.5
1, 2, 3 5, 6 8, 9	1-2	0.423	80	6.0	2.6	2.9	7.6	13.6	1.4	19.1	
	3-5	0.051	40	7.2	1.6	1.1	1.8	9.0	0.84	7.6	26.7

Steam Flow (Graph 5)

		Flow	Trial pipe	Length m					Pressure drop N/m²		
		kg/sec	size mm	Pipe	Equiv. for joints			Total	Δp	ΔP = Δp (l + K.EL)	Total
Circuit	Section			l	K	EL	K.EL	l + K.EL			
1, 2, 3 4, 7 8, 9	7-8	0.098	65	7.5	1.0 0.4 0.5 0.4 0.4 2.7	3.1	8.4	15.9	215	3420	
	8-9	0.423	100	3.0	0.4 0.4 0.4 1.2	5.6	6.8	9.8	400	3920	7340
1, 2, 3 5, 6	6-8	0.051	50	7.5	2.7	2.1	5.7	13.2	240	3170	
8, 9	8-9	0.423	100	3.0	1.2	5.6	6.8	9.8	400	3920	7090

From inspection of the pressure losses it is apparent that circuit 1, 2, 3, 4, 7, 8, 9 is the most critical.

Pressure loss in water part of circuit $= 22$ N/m²
Pressure loss in steam part of circuit $= 7340$ N/m²
∴ Total pressure loss in circuit, $P_L = 7362$ N/m²
say 7400 N/m²

(k) CIRCULATORY PRESSURE

Suppose the floor of the tank os 0.8 m above the highest portion of column subject to flame impingement.

Equation 14 gives $P_c = G_s P_z$ N/m²
From Table 7, $P_z = 7843$ N/m²
and from Table 8, $G_s = 1.355$
∴ $P_c = 1.355 \times 7800 = 10\,500$ N/m² (approx)
i.e. $P_c > P_L$ and the design is suitable.

Appendix

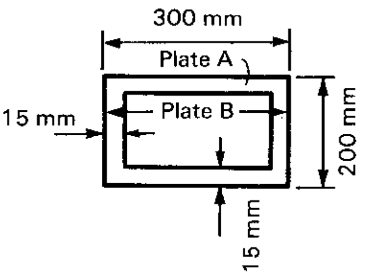
WATER COOLING WITHOUT EVAPORATION

In certain cases it is possible to connect a pair of water filled columns in such a way that, when one is affected by fire, a gravitational circulation is set up which is sufficient to provide fire protection without evaporation taking place. The chief criteria are that:

A fire compartment wall separates the columns.
The fire period is short (usually not more than $\frac{1}{2}$ hour).
The intensity of heating is low, e.g. that for an external column.

The design problem appears superficially to be similar to that presented by a gravitational central heating system, which is well explained in standard works[24]. Unfortunately, the analogy does not hold in all respects. In this case, for instance, the 'boiler' may be at the top of the circuit, i.e. in the worst position. Furthermore, the condition to be examined is when the 'boiler' is starting up, i.e. before equilibrium of flow is achieved. In addition, the factors which control flow are usually insignificant in heating systems. Here, however, cooling of the water comes chiefly from the gain in temperature of the radiator and not by loss of heat from it.

A rigorous analysis is complex and is not attempted here. The following intuitive method, however, indicates the limitations of the system and leads to a result on the safe side.



Column section at top storey

Example

Figure 11 shows two interconnected water filled columns separated by a fire barrier. They are similar in size and fire exposure to those on Grid A in the worked example (Figures 4, 5 and 6) and they have to withstand fire for a period of $\frac{1}{2}$ hour.

It is assumed that column A is subjected to fire exposure and that its fireside surface temperature at $\frac{1}{2}$ hour is 140°C, the ambient temperature being 20°C.

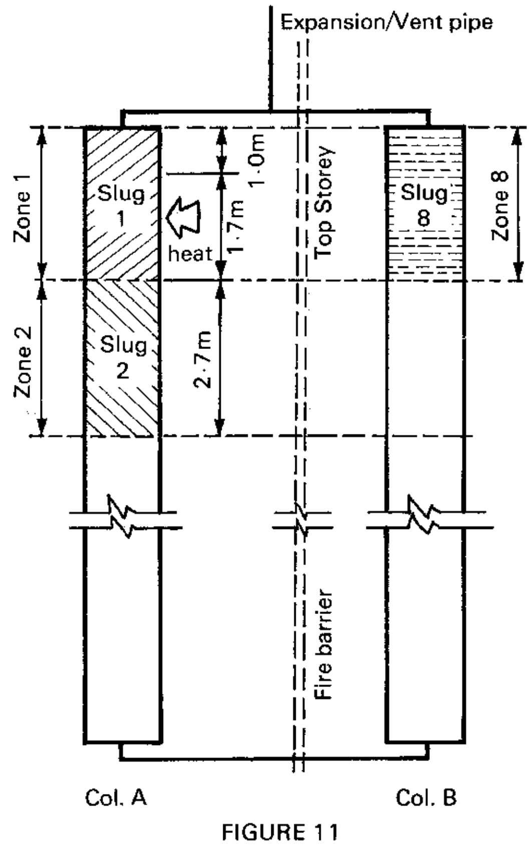


FIGURE 11

Total heat input to column A

Plate A receives 90 kW/m² at $\frac{1}{2}$ hour (Table 3)

$\therefore$ input over full surface $= 90 \times 1.7 \times 0.3 = 45.9$ kW

Plates B receive 48.1 kW/m² (see 6.2)

$\therefore$ input over all surfaces $= 48.1 \times 1.7 \times 0.2 \times 2 = 32.7$ kW

Hence, total heat flow at $\frac{1}{2}$ hour $= 45.9 + 32.7 = 78.6$ kW

Similarly, total heat flow at 10 mins. $= 28.6 + 21.8 = 50.4$ kW

$\therefore$ total heat input

$$= \frac{50.4 \times 10 \times 60}{2 \times 1000} + \frac{(50.4 + 78.6) \times 20 \times 60}{2 \times 1000}$$

$= 92.5$ MJ

Thermal capacity of zone 1

Volume of water $= 0.27 \times 0.17 \times 2.7 = 0.124$ m³

$\therefore$ Mass of water $= 124$ kg

Thermal capacity of water $= \frac{124 \times 4.2 \times 80}{1000} = 41.7$ MJ

(specific heat, $c_p = 4.2$ kJ/kg °C; change in temperature, $\Delta T = 80$°C)

Volume of steel $= 0.015 \times 2\,(0.3 + 0.17)\,2.7 = 0.038$ m³

$\therefore$ Mass of steel $= 0.038 \times 7700 = 293$ kg (density, ρ, of steel $= 7700$ kg/m³)

Thermal capacity of steel $= \frac{293 \times 0.48 \times 80}{1000} = 11.3$ MJ

(specific heat, c_p, of steel $= 0.48$ kJ/kg°C)

Hence, total thermal capacity of zone 1 $= 41.7 + 11.3 = 53$ MJ

Thermal balance

Slug 1 (Figure 11) has been heated to 100°C. It moves by gravitational circulation towards zone 8 while cold water (at 20°C) moves up from zone 2 to zone 1. The amount of heat still to be absorbed is:

$92.5 - 53 = 39.5$ MJ

$\therefore$ percentage of slug 2 required in zone 1 is:

$$\frac{39.5}{41.7} \times 100 = 95\%$$

At this stage (at $\frac{1}{2}$ hour) the situation is therefore as shown in Figure 12. The portion of slug 1 in zone 8 loses some heat to the steel of column B. Equating thermal capacities:

$\Delta T \times 0.95\,(124 \times 4.2 + 0.48 \times 297) = 41.7 \times 0.95 \times 10^3$

Solving, $\Delta T = 63$°C, so that the final water and steel temperature of slug 1 in zone 8 is:

$63 + 20 = 83$°C.

Circulatory pressure P_c

This pressure is dependent on the density difference between:

(i) two columns of water 2.6 m high, one at 100°C and one at 83°C, **plus**

(ii) two columns of water 0.1 m high, one at 100°C and one at 20°C.

Then $P_c = 2.6 \times 9.81\ (0.97\text{-}0.958) + 0.1 \times 9.81\ (0.998\text{-}0.958)$

$= 0.306 + 0.039 = 0.345\ \text{kN/m}^2$

$= 345\ \text{N/m}^2$

(Densities of water at different temperatures are given in Table 10.)

Pipe design (for conditions at ½ hour)

Theoretical travel of pipework is 20 m, say.

Then $P_c/m = \frac{345}{20} = 17.2\ \text{N/m}^3$

Energy flow rate = 78.6 kW

and energy flow rate per °C $= \frac{78.6}{100\text{-}20} = 0.98\ \text{kW/°C}$

From graph 6 it can be seen that a 32 mm diameter pipe is adequate.

Heat losses from column B at ½ hour

Tables in the IHVE guide[22] give values of radiation and convection from heated plane surfaces.

With $E_c = 0.9$, $T_c = 80$°C and air temperature = 20°C, the tables give:

Convection loss = 320 W/m²

Radiation loss = 420 W/m²

so that the total loss at ½ hour is:

$(320 + 420) \times 2\ (0.2 + 0.3) \times \frac{2.7}{1000} = 2.0\ \text{kW}$

This is insignificant compared with the heat input of 78.6 kW.

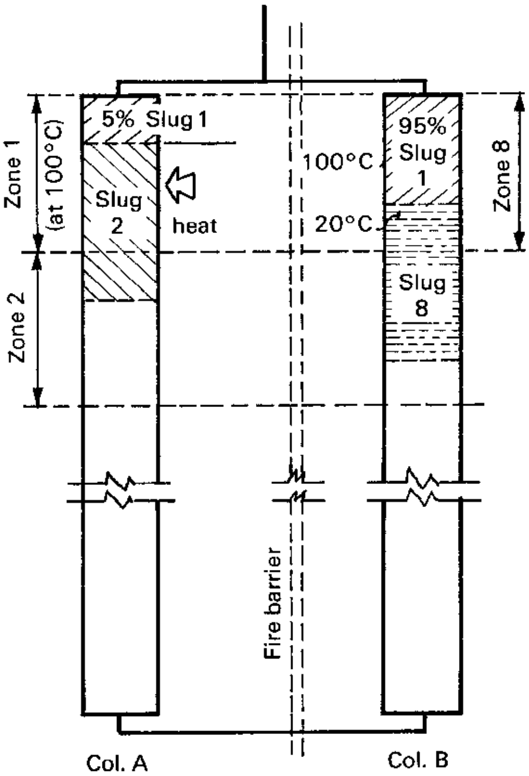


FIGURE 12

Comment

Considering the circulatory pressure, P_c, calculated above, it can be seen that this is critically dependent on the heat absorbed by the steel in the columns.

It has been demonstrated that heat lost by re-radiation and convection is insignificant and it is the thermal capacity of the cold steel which provides the heat sink necessary. This reserve is, however, quickly exhausted and it certainly could not keep circulation going for much longer than ½ hour.

This contrasts with the excellent performance one can expect from a system utilizing vaporisation.

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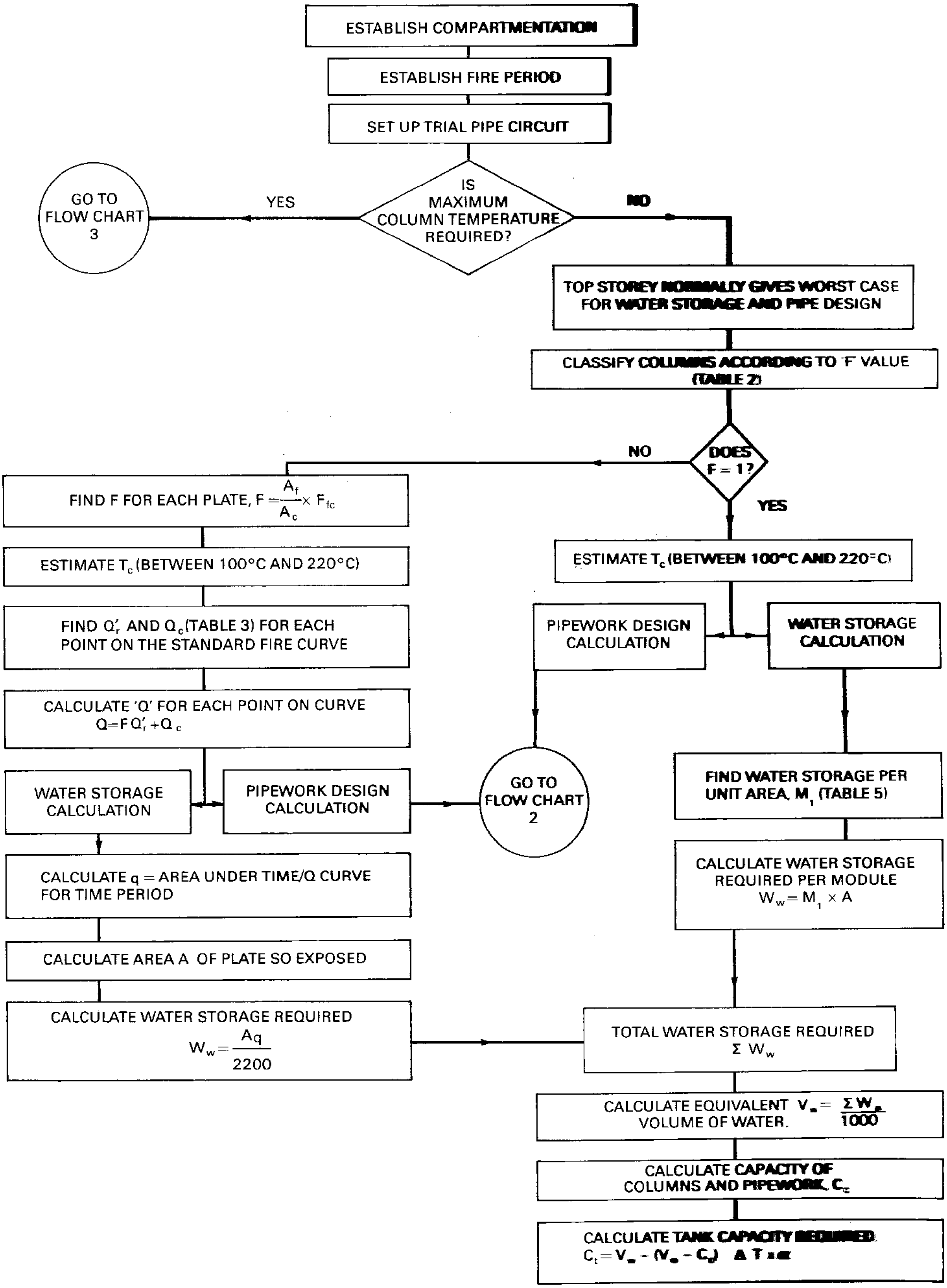
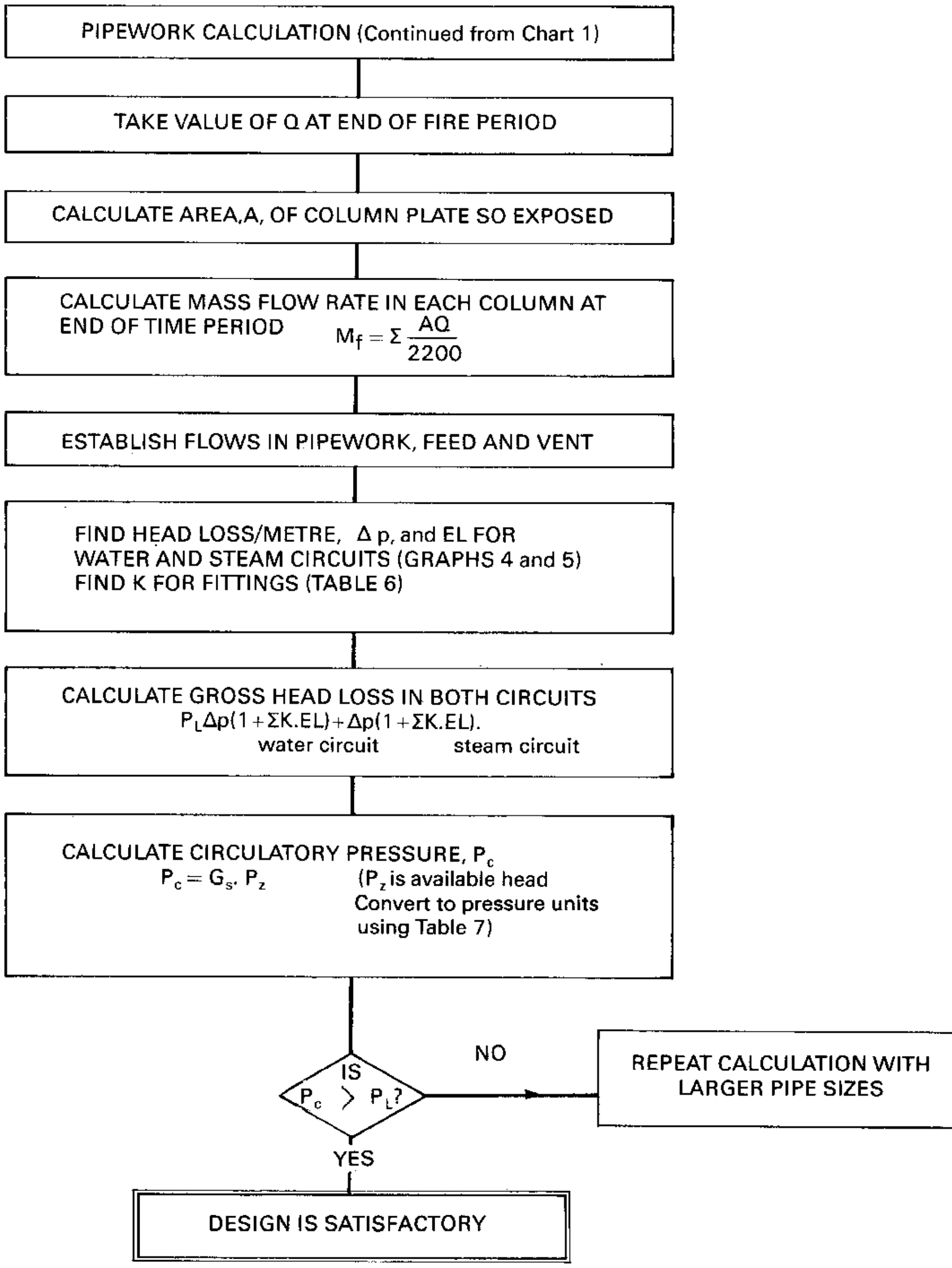
Flow charts, graphs and tables.

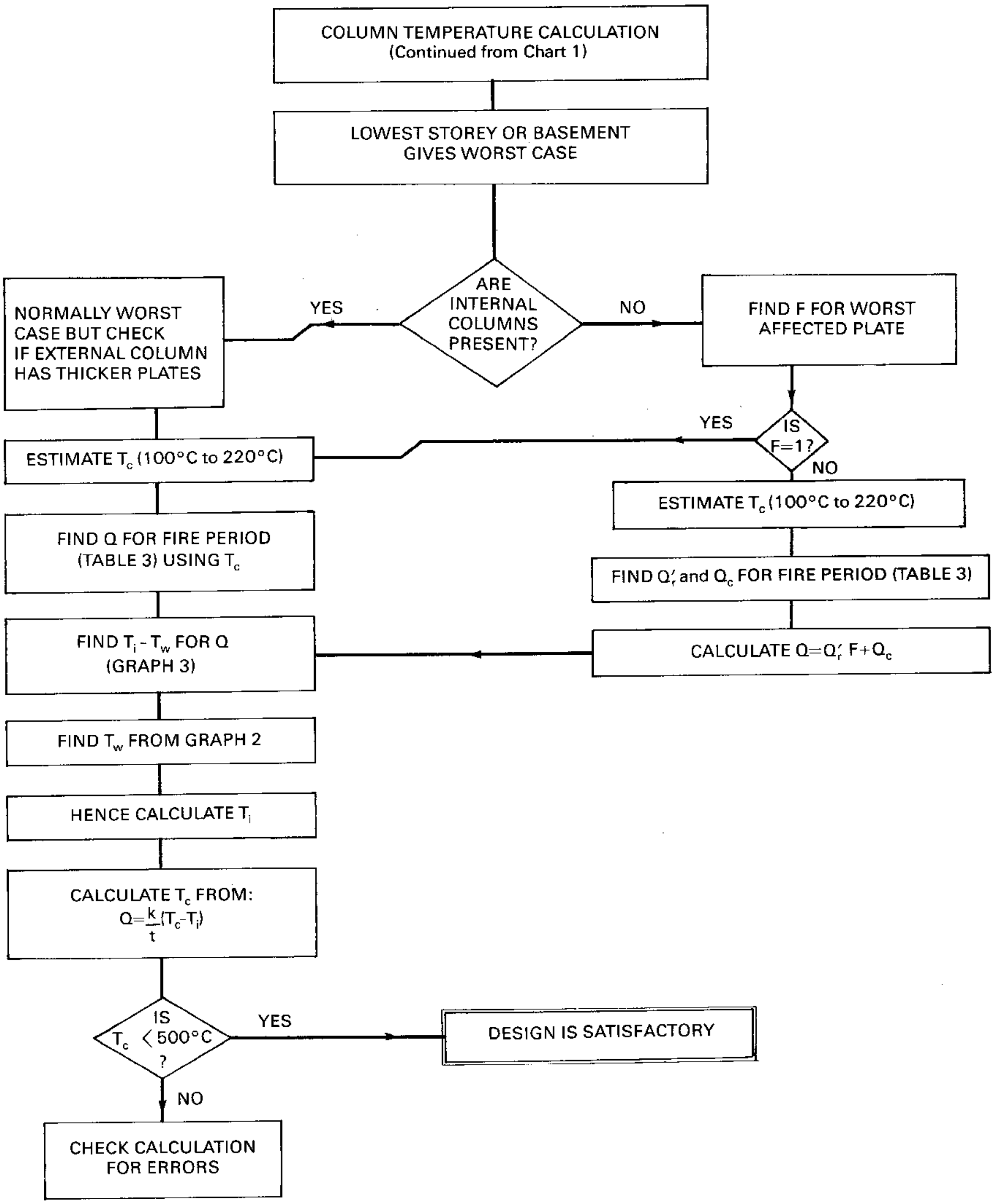
FLOW CHART 1
Basic calculation procedure

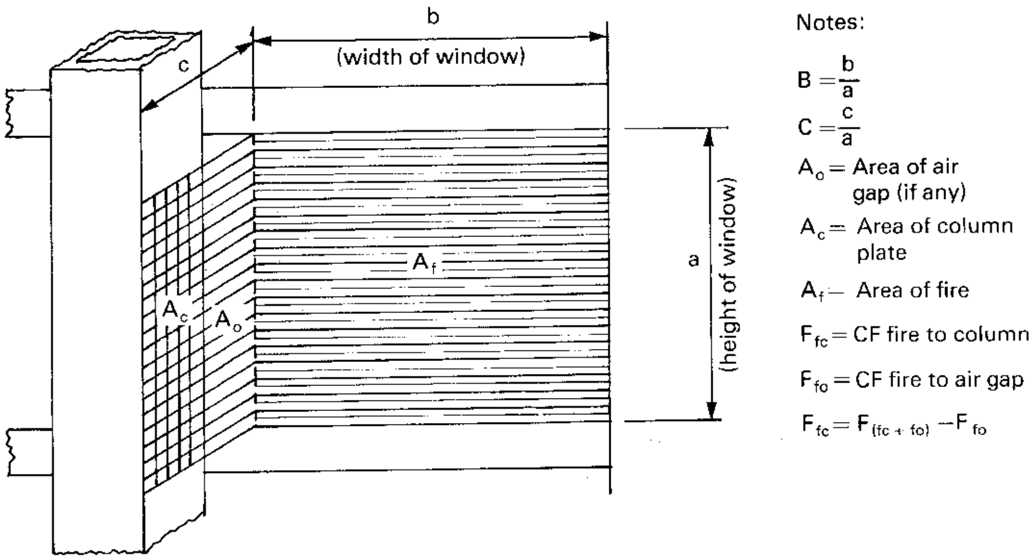


FLOW CHART 2
Pipework calculation procedure

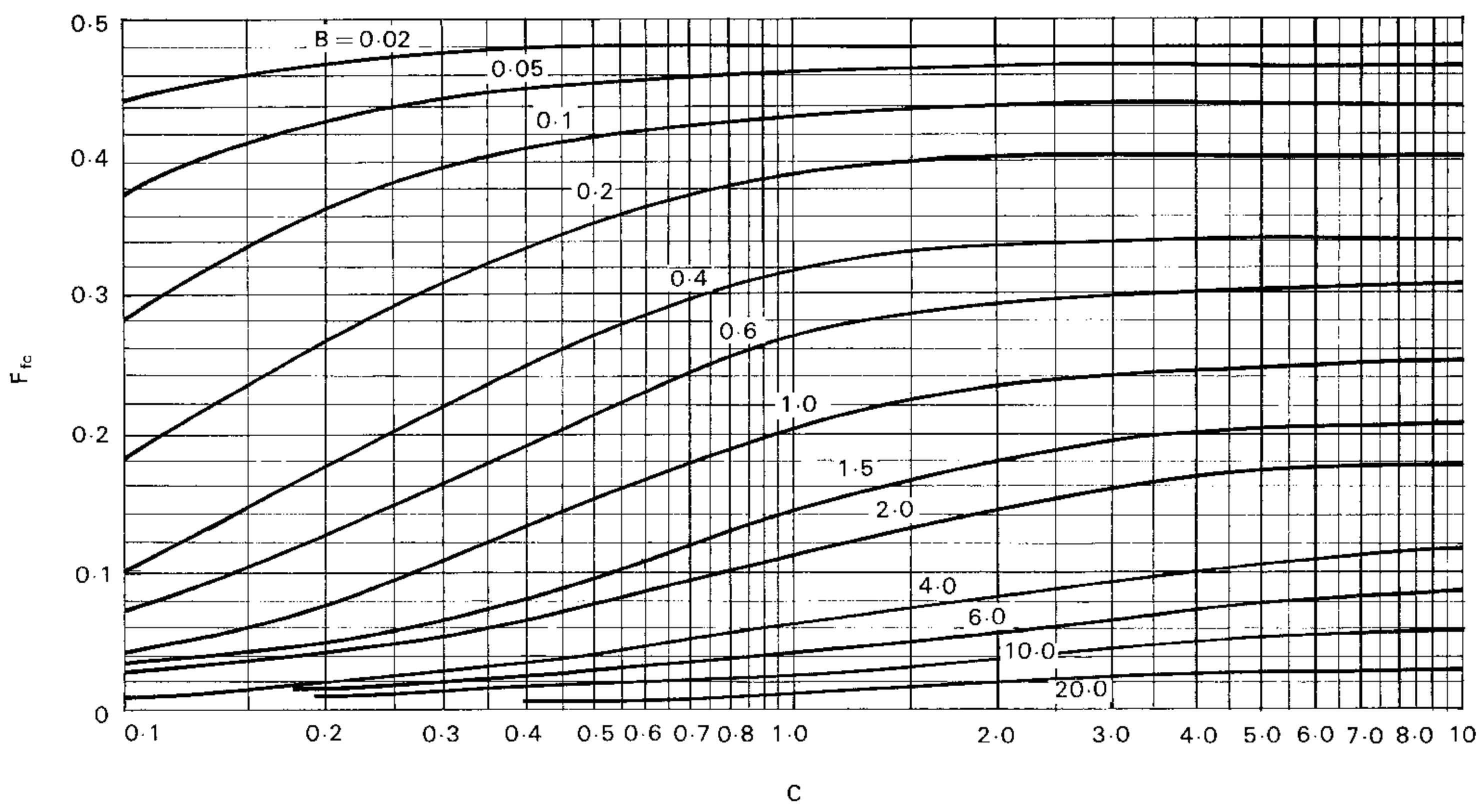


FLOW CHART 3
Column temperature calculation procedure

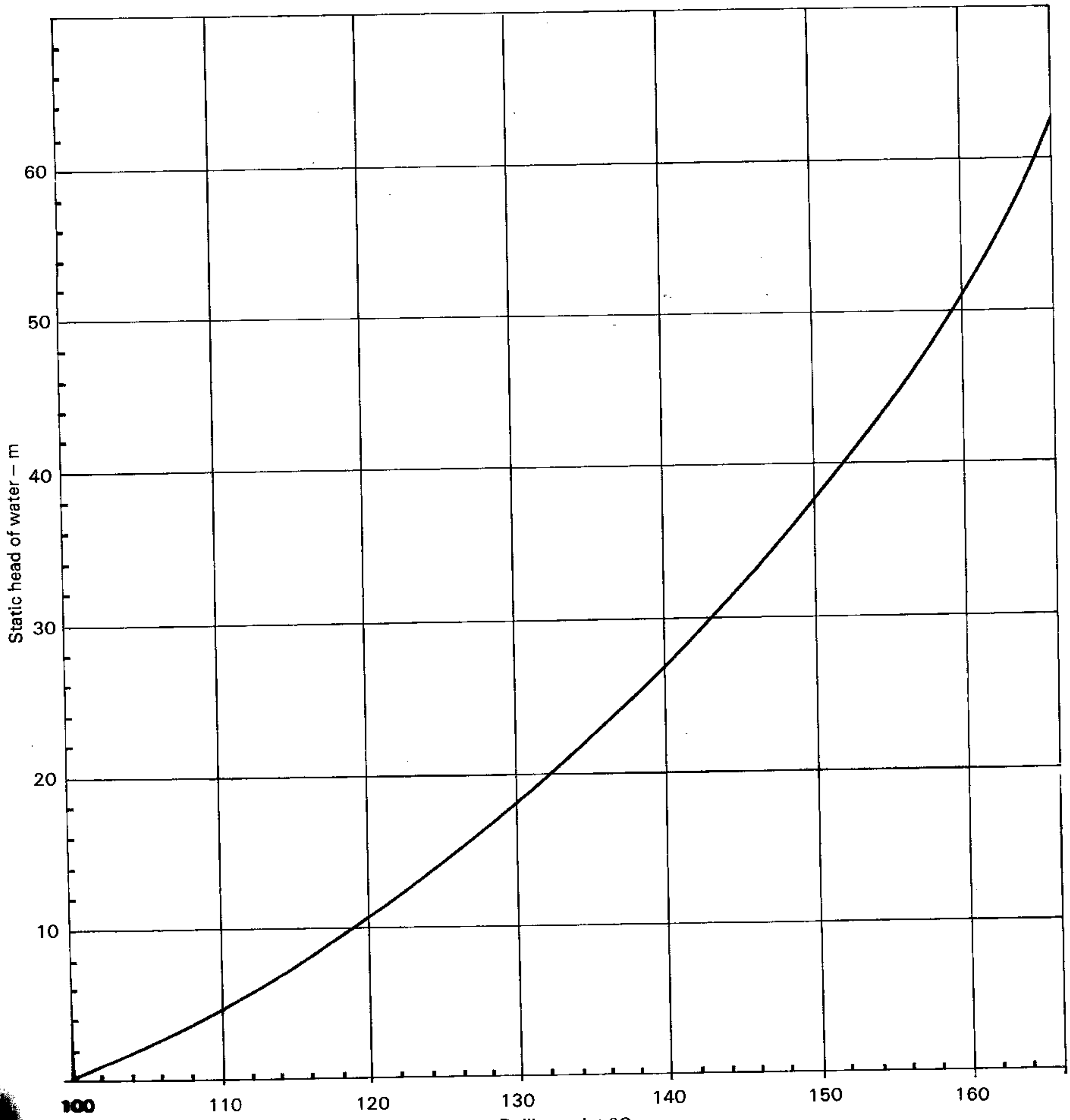




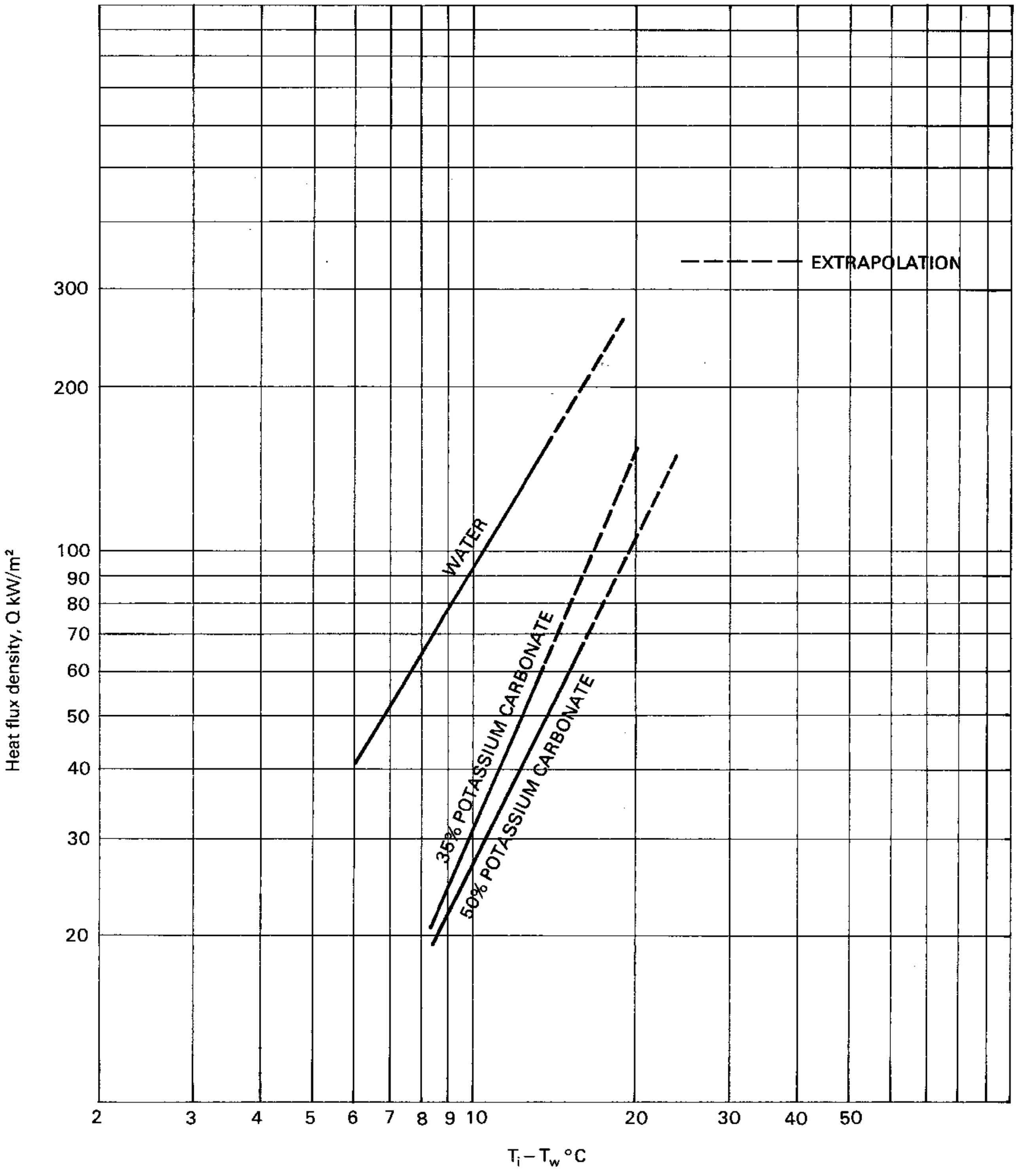
Key Diagram



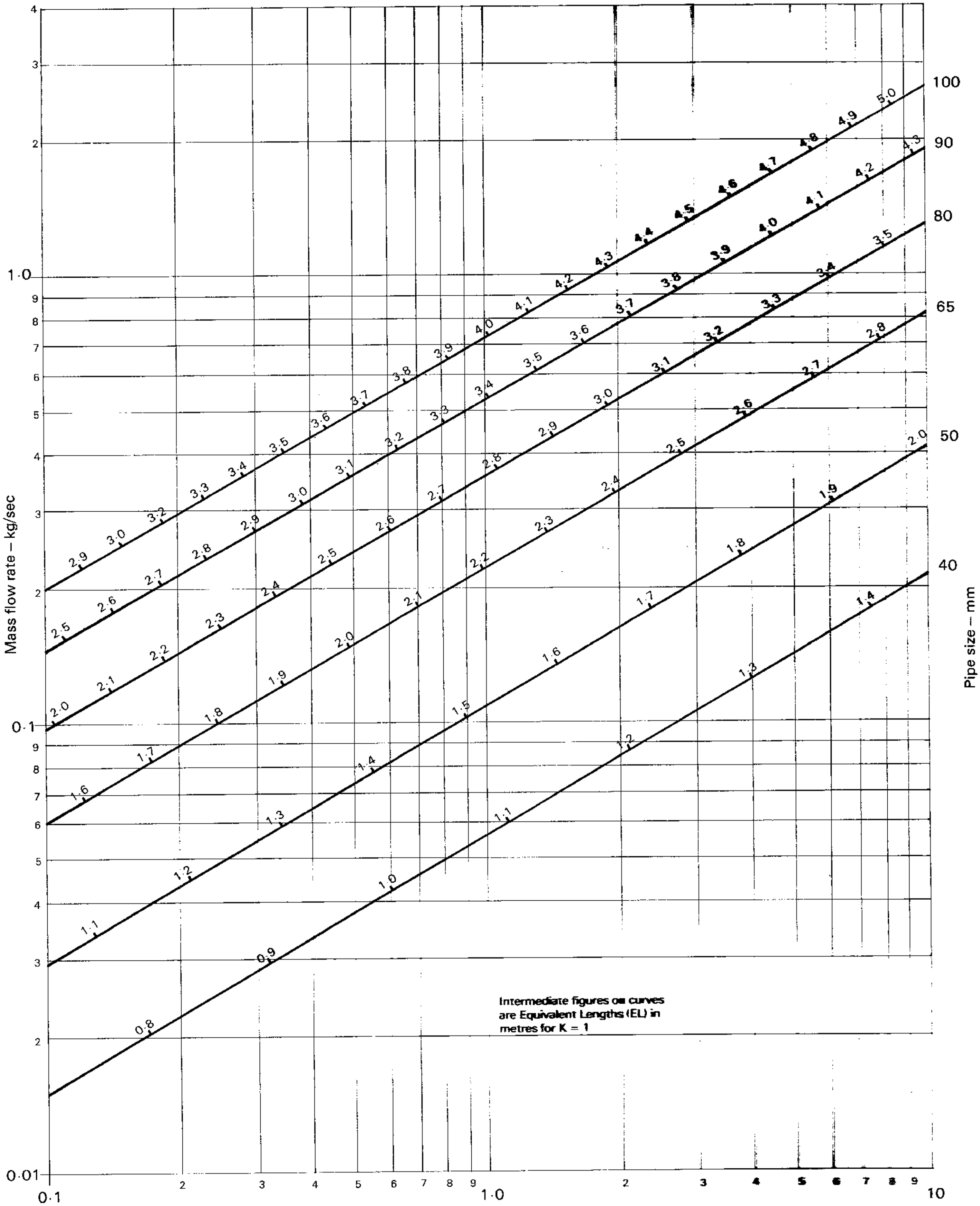
GRAPH 1. CONFIGURATION FACTOR FOR PERPENDICULAR RECTANGLES WITH A COMMON EDGE



GRAPH 2. BOILING POINT OF WATER UNDER PRESSURE



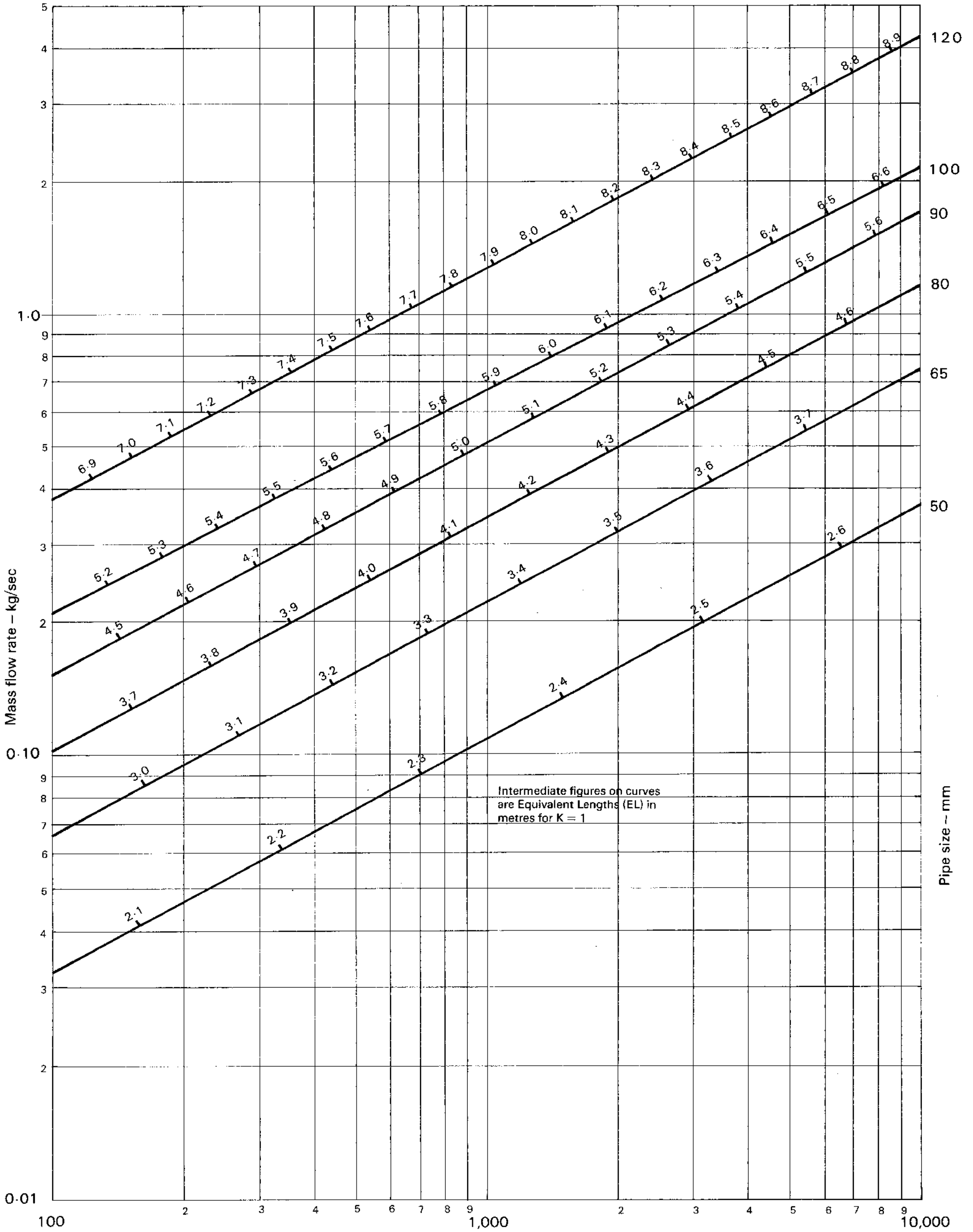
GRAPH 3 TEMPERATURE DROP, STEEL TO CIRCULATORY FLUID



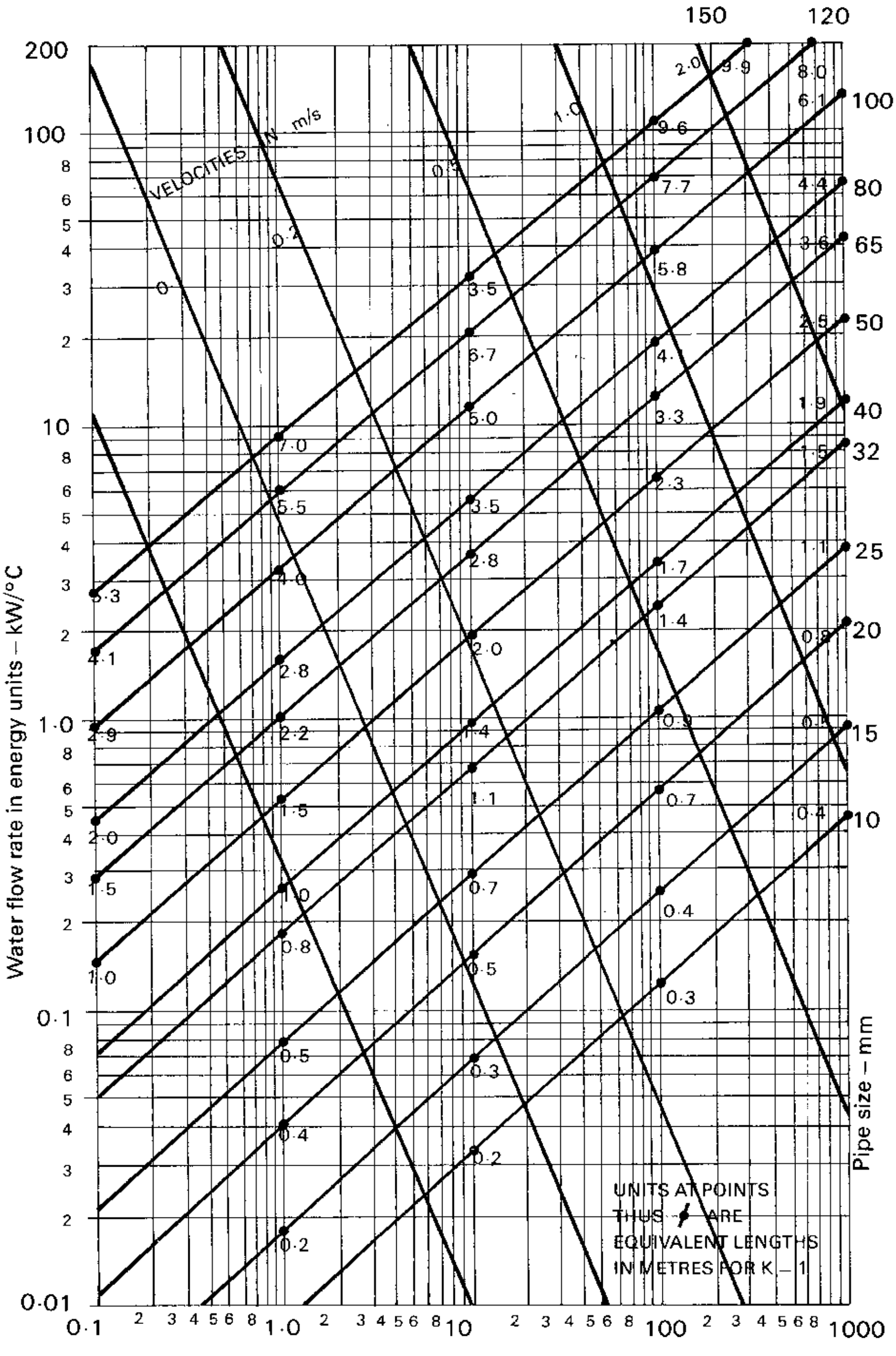
GRAPH 4. PIPE SIZING CHART FOR WATER AT 75°C **IN STEEL PIPE**

Pressure loss in N/m² per metre run **(N/m³)**

*(Note: Pressure loss against **mass flow**)*



GRAPH 5. PIPE SIZING CHART FOR SATURATED STEAM IN STEEL PIPE – PER METRE RUN



GRAPH 6. PIPE SIZING CHART FOR WATER AT 75°C IN STEEL PIPE

Pressure loss in N/m² per metre run (N/m³)

(Note: Pressure loss against energy flow)

TABLE 1. BS476 : PART 8 : 1972
FURNACE TEMPERATURE

Time min	Temp. Range °C	Temp. T_f Starting point at 40°C °C
5	556	596
10	659	699
15	718	758
30	821	861
60	925	965
90	986	1026
120	1029	1069
180	1090	1130
240	1133	1173
360	1193	1233

TABLE 2. SUGGESTED VALUES FOR
CONFIGURATION FACTOR

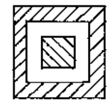
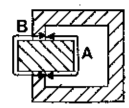
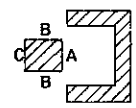
Position of column		F_{fc}	F	Remarks
	All plates	$\frac{A_f}{A_c}$	1	Column centrally placed in furnace
	Surface A	$\frac{A_f}{A_c}$	1	Plates exposed to fire
	Surface B	0	0	Plates not exposed to fire
	Plate A	—	1	$A_f \gg A_c$
	Plate B	See graph 1	$F_{fc} \frac{A_f}{A_c}$	
	Plate C	0	0	

TABLE 3. HEAT FLOW DENSITIES FOR F = 1.0
($Q = Q_r' F + Q_c$ kW/m²)

T_c °C		10	30	60	120	180	240	360
		FIRE RESISTANCE – min						
100	Q_r'	40.2	70.0	107.2	148.3	177.3	200.2	235.7
	Q_c	17.4	21.5	25.1	28.1	29.9	31.1	32.8
	Q	57.6	91.5	132.3	176.4	207.2	231.3	268.5
140	Q_r'	39.7	69.5	106.7	147.9	176.9	199.8	235.3
	Q_c	16.2	20.3	23.9	26.9	28.7	29.9	31.7
	Q	55.9	89.8	130.6	174.8	205.6	229.7	267.0
180	Q_r'	39.1	68.9	106.1	147.3	176.3	199.2	234.7
	Q_c	15.0	19.2	22.8	25.8	27.6	28.8	30.5
	Q	54.1	88.1	128.9	173.1	203.9	228.0	265.2
220	Q_r'	38.3	68.1	105.3	146.5	175.5	198.4	233.9
	Q_c	13.9	18.0	21.6	24.6	26.4	27.6	29.4
	Q	52.2	86.1	126.9	171.1	201.9	226.0	263.3

TABLE 4. PROPERTIES OF SOME FLUIDS

FLUID	Q kW/m²	T_w °C	T_i-T_w °C	K_l W/m² °C	μ kg/m s	ρ kg/m³
WATER	41.0	99.6	6.9	5406		
	106.5	99.3	10.9	9767		
	165.6	98.9	13.7	12350		
	—	100			3×10^{-4}	958
35% K_2CO_3	53.1	104.8	12.4	4292		
	62.7	105.2	13.5	4741		
	—	106			8×10^{-4}	1305
50% K_2CO_3	59.8	112.4	14.3	4042		
	69.7	112.6	16.2	4395		
	—	114			14×10^{-4}	1484

TABLE 5. WATER STORAGE REQUIREMENT
(M_1 kg/m² of column surface)

T_c °C	10	30	60	120	180	240	360
	FIRE RESISTANCE – min.						
100	7·9	48·6	140·1	392·7	706·5	1066	1884
140	7·7	47·5	137·4	387·2	697·0	1054	1867
180	7·5	46·2	134·7	381·5	689·5	1043	1849
220	7·2	44·9	132·0	375·8	681·0	1032	1832

Note. F=1·0; H=kJ/kg; Q from Table 3.

TABLE 6. K FACTORS

DESCRIPTION		K
ENTRY INTO LARGE VESSEL		1·0
EXIT FROM LARGE VESSEL		0·4
90° SCREWED M.S. BEND	32 - 50 dia	0·5
	65 - 90 dia	0·4
	Over 100 dia	0·3
90° MALLEABLE C.I. ELBOW	32 - 50 dia	0·7
	65 - 90 dia	0·6
	Over 100 dia	0·6
PARALLEL SLIDE GATE VALVE		0·2
SEE REFERENCE 22 FOR VALUES OF K FOR OTHER PIPEWORK CONFIGURATIONS		

TABLE 7. PRESSURE IN N/m² AGAINST HEAD OF WATER IN m

Metres	0	1	2	3	4	5	6	7	8	9
0·0	0	9 804	19 607	29 411	39 215	49 018	58 822	68 626	78 430	88 233
0·1	980	10 784	20 588	30 391	40 195	49 999	59 803	69 606	79 410	89 214
0·2	1 961	11 764	21 568	31 372	41 176	50 979	60 783	70 587	80 390	90 194
0·3	2 941	12 745	22 549	32 352	42 156	51 960	61 763	71 567	81 371	91 174
0·4	3 921	13 725	23 529	33 333	43 136	52 940	62 744	72 547	82 351	92 155
0·5	4 902	14 706	24 509	34 313	44 117	53 920	63 724	73 528	83 331	93 133
0·6	5 882	15 686	25 490	35 293	45 097	54 901	64 704	74 508	84 312	94 116
0·7	6 863	16 666	26 470	36 274	46 077	55 881	65 685	75 488	85 292	95 096
0·8	7 843	17 647	27 450	37 254	47 058	56 861	66 665	76 469	86 273	96 076
0·9	8 823	18 627	28 431	38 234	48 038	57 842	67 646	77 449	87 253	97 057

TABLE 8. DENSITY OF POTASSIUM CARBONATE SOLUTIONS
(g/cm^3 at 20°C)

5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
1.044	1.090	1.139	1.190	1.243	1.298	1.355	1.414	1.476	1.540

Note. The percentages are by weight of anhydrous salt in solution.

TABLE 9. FIRE LOADING CORRELATIONS
(Derived from reference 25)

Classification	Fire Load MJ/m²	Equivalent density of combustibles kg/m²	Fire protection time min.
Low	0–1.1	0–63	60
Moderate	1.1–2.2	63–126	120
High	2.2–4.5	126–260	240

TABLE 10. DENSITY OF WATER
(g/cm^3 for pure air-free water under 1 atm.)

Temp. (°C)	0	20	40	60	80	100
0	0.999 84	0.998 21	0.992 22	0.983 2	0.971 8	0.958 4
2	0.999 94	0.997 77	0.991 44	0.982 2	0.970 5	
4	0.999 97	0.997 29	0.990 6	0.981 1	0.969 3	
6	0.999 94	0.996 79	0.989 8	0.980 0	0.968 0	
8	0.999 85	0.996 24	0.988 9	0.978 9	0.966 7	
10	0.999 70	0.995 65	0.988 0	0.977 8	0.965 3	
12	0.999 50	0.995 03	0.987 1	0.976 6	0.964 0	
14	0.999 25	0.994 38	0.986 2	0.975 5	0.962 6	
16	0.998 94	0.993 69	0.985 2	0.974 3	0.961 2	
18	0.998 60	0.992 97	0.984 2	0.973 0	0.959 8	

Constructional Steel Research & Development Organisation
12 Addiscombe Road, Croydon CR9 3JH

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