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RADIATION FROM FIRES AND BUILDING SEPARATION

by

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Summary

This report discusses the spread of fire by radiation from a burning building. The levels of radiation likely to be encountered and their effect on combustible materials are considered. Methods of framing legal requirements for building separation are outlined.

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1. Introduction

This report discusses the risk of fire spreading from a burning building to surrounding property due to radiation. It describes ways of determining the separation between buildings so as to reduce the hazard to an acceptable level, and considers methods of framing legal requirements for building separation.

Experiments have been carried out at the Joint Fire Research Organization to measure the intensities of radiation likely to be encountered from fires for different ventilation conditions, where ventilation means the air supply through doors, windows and other openings, and different amounts of combustible materials. Although the investigation into the factors affecting the growth of fire in enclosures is still incomplete, sufficient information is now available for an assessment of the range of intensities which would be found in practice insofar as they need to be known for this problem of exposure.

In another series of experiments the effect of radiation on various common materials has been investigated and in particular the minimum intensity for ignition under various conditions has been found.

Once the intensity of radiation from a fire in a building is known and the maximum acceptable level of radiation on the exposed building is decided, it is possible to calculate the minimum separation necessary between the two buildings. In practice, when a building is being planned the position of the potentially exposed building is frequently not known and it is necessary to position the former building in relation to its site boundary. For this and legal reasons it is the boundary distance, therefore, which should be specified. The implications of this are discussed later.

For administrative purposes it is desirable for legal requirements to be as simple as possible. While the basic requirements may be stated simply, their interpretation for varied types of structure may involve calculations of some complexity; it then becomes desirable to compile a series of simple conditions which are deemed to satisfy the basic requirements. Inevitably, in covering all cases, these simplifications may lead to some degree of overestimation of the required distance and it may be important in some instances, where land is extra valuable or the site area limited, that the boundary distance should be not even one foot longer than necessary. This report therefore gives not only the basis of calculation for the "deemed to satisfy" conditions but also methods of calculating more accurately the required distances in any special cases where it is considered worth while to undertake detailed calculations.

2. Intensity of radiation from a fire

The intensity of radiation, I, from a body is related to its absolute temperature T, according to the well known law:

$$I = \epsilon \sigma T^4$$

where ϵ is emissivity, less than or equal to unity;
σ is the Stefan-Boltzmann constant;
$\simeq 1.36 \times 10^{-12}$ cal cm^{-2}s^{-1} $^{\circ}$C^{-4}.

For a black body ϵ has the maximum value of unity and a uniformly heated enclosure with a small opening may be assumed to have the characteristics of a black body radiator. Thus when a room or compartment is fully involved in fire it may be thought of as a black body radiator. For a large opening this assumption is not strictly correct but the hazard is only overestimated to a slight extent. Temperatures have been measured in experimental fires for different values of ventilation(1)(2)(3)(4)(5). Peak temperatures attained inside rooms are shown in Fig. 1(6) for different values of air flow factor $A\sqrt{H}$, where A is the area and H the height of the opening through which air enters the fire and from which flames emerge. These measurements must be interpreted carefully since the temperature in the region of the measuring instrument, which was usually near the ceiling, may not be representative of, and is probably higher than, the temperature of the enclosure as a whole. However, the results in Fig. 1 do show that temperature rises with air flow eventually reaching a steady value not greater than 1,200°C above a certain degree of ventilation.

These experiments were carried out for fire loads* ranging from 25-120 kg/m^2 (5-25 lb/ft^2) and it was found that above a certain value of air flow the temperature attained depended to some extent on the fire load since if the fire load was about 25 kg/m^2 (5 lb/ft^2), the maximum temperature attained was below the line drawn in Fig. 1(6). Increasing the fire load gave higher peak temperatures but it appeared that once the fire load was about 40 kg/m^2 (8 lb/ft^2) further increases gave no further change in temperature. The effect of ventilation and fire load on temperature is shown diagrammatically as the series of curves in Fig. 2 each curve reaching a steady value of temperature which depends on the fire load.

Other experiments(7) with well ventilated fires in various scale rooms consisting of cubes completely open on one side show that the maximum intensity of radiation emitted varies with the fire load/unit floor area inside the cube. While the temperature attained by a fire is clearly some function of the total fire load and of the dimensions of the enclosure there is some reason to think that it may not be the simple concept of fire load/unit area which is the controlling factor. However, for the purpose of this report where, as it will be shown, certain broad assumptions must be made, it is enough to show that the intensity of radiation from the fire varies with the fire load/unit floor area and the results for peak intensity are shown in Fig. 3. The peak intensity was maintained for the order of 2 minutes. The range of fire load in these experiments was necessarily limited to amounts which did not restrict the ventilation; it can be seen that the values of intensity for the 1/9 scale room with the higher fire loads are low because the amount of combustible needed to give the required fire load meant that the ventilation was restricted. The equation of the line drawn in Fig. 3 is

$$I_o = 0.082F$$

where I_o is intensity of radiation cal cm^{-2}s^{-1}
F is fire load in kg/m^2

and if the line is extrapolated to a fire load of 49 kg/m^2 (10 lb/ft^2) a value of 4 cal cm^{-2}s^{-1} is obtained for I_o. Measurements of intensity from a full scale fire with this fire load gave a peak value of 4.3 cal cm^{-2}s^{-1} (2). (This corresponds to a black body temperature of 1,100°C which is approximately the limiting temperature attained in a fire, as shown in Fig. 1). Assuming that as there is a limiting value for temperature within an enclosure so there will be a limiting value of intensity of radiation from the enclosure, it then appears reasonable to take, for well ventilated fires, an intensity of 4 cal cm^{-2}s^{-1} as the steady value of intensity representative of most occupancies. For occupancies with low fire load an arbitrary value of intensity of 2 cal cm^{-2}s^{-1} may be taken.

This definition of intensity in terms of two types of fire load only is the first broad simplification.

*The fire load in these experiments was all combustible, consisting of timber; 120 kg/m^2 is an average value for most occupancies.

It is clear from Fig. 1 that when $A\sqrt{H}$ exceeds a certain value the ventilation has little effect on the temperature of the enclosure. Since one window measuring 2 m x 2.5 m. (3 ft x 8 ft) gives an air flow factor of $2.5m^{5}/2$ it is apparent that for the majority of buildings a fire may always be considered capable of reaching temperatures of 1,100 - 1,200°C. In the few cases where the windows are small and affect the ventilation it can be shown that the calculated separation distance is also small and allowing for the effect of low ventilation makes little difference to the separation distance. The effect of ventilation on intensity has therefore been neglected. Neglecting the effect of ventilation on intensity is the second simplification.

The number of openings radiating will depend on the extent of the fire inside the building. If the building is divided by fire division walls, or if fully compartmented, then only one division or compartment would in theory radiate at a time and the single division or compartment with the largest area of opening would be taken as the one on which to base the required separation distance.

An opening is any part of an external wall which does not have the required fire resistance specified for the building under consideration and hence would allow the transmission of radiation. A wall clad with timber would be considered as all opening since the burning timber would act as a source of radiation and the area of any timber on part of the wall would be added to the area of openings. Similarly, a sub-standard part of a wall is regarded as an opening.

In the foregoing, the contribution of flames outside the window to the radiation has been neglected. This is reasonable for a first approximation though there have clearly been cases where large flames have been observed for which this is not so[8]. The sizes of these flames and the factors affecting them, both in still air and in the presence of a wind, are now being investigated and may lead to some modification, in certain cases, of the separation distances recommended in this report. One way in which this could be done without changing the basis of these recommendations would be to ascribe an effective window area greater then the actual window area by some factor which could be determined separately.

3. Effect of radiation on combustible materials

When a building is exposed to radiation there is not only the hazard to any combustible material on the outside of the building but also to combustible contents of a room due to radiation entering the windows.

The most commonly found combustible material on the exterior of buildings is timber and its behaviour when exposed to radiation is representative of a large variety of building materials. If it is exposed to a sufficiently high intensity it will ignite spontaneously; at a lower intensity it will only ignite if a subsidiary source of ignition is within ½ in. of the surface(pilot ignition)and at a still lower intensity only if the source is actually on the surface (surface ignition).[9].

Spontaneous ignition will only occur for incident intensities above 0.8 cal $cm^{-2}s^{-1}$ (177 $B.Th.U.ft^{-2}s^{-1}$), pilot ignition, the second condition, for intensities above 0.3 cal $cm^{-2}s^{-1}$ and the third condition, surface ignition, for intensities above 0.1 cal $cm^{-2}s^{-1}$. With surface ignition the development of flame at low intensities is slow though it may be affected by wind.

With building fires a spark or flying brand can act as a subsidiary source of ignition. At a distance sufficiently large for the intensity to be a minimum for pilot ignition, many sparks will have burnt out before they reach the surface and it is probably only the larger burning particles which may cause ignition. If burning particles reach the surface and the intensity is too low for pilot ignition, surface ignition is possible only if the particle lodges on the surface. Even then the development of flame is likely to be slow. If we assume that the fire brigade will be available within a short time for the protection of exposed property it would appear reasonable, therefore, to adopt as our criterion a distance such that the intensity of radiation on the exposed building will be below the minimum for pilot ignition, i.e. it should not exceed 0.3 cal $cm^{-2} s^{-1}$ (66 $B.Th.U.ft^{-2}min^{-1}$).

The minimum intensities given above are for ignition of oven-dried timber unprotected by paint. In practice the timber will always contain some moisture which has the effect of raising the minimum intensity at which ignition will occur[10]. The amount of moisture in the exposed timber may vary but in no condition will it be more hazardous than the oven-dried one. Most paints also raise the minimum intensity but since weathering and cracking may expose bare timber the protective value of any paint has not been allowed for. It will thus be seen that the figures taken err on the side of safety.

Experiments[8] have shown that a material in an enclosure will ignite for a lower intensity of radiation than it will in the open, so that although the intensity of radiation falling on an exposed building may be below the minimum for pilot ignition in the open, there may still be a hazard to the contents of a room because of radiation coming through the window. Although the plate glass in a window can absorb about 40 per cent of the radiation from a building fire it cannot be relied on to afford protection to the contents of the room since it is so liable to crack and fall out. No figure of a maximum "safe" intensity for glass can be given with confidence since such variable factors as restraint at the edges and stresses in the glass itself affect its behaviour. The worst case of immediate cracking and falling out must therefore be assumed. Experiments[11] with 1/10 scale model rooms with an opening either 33 per cent or 100 per cent of the area of the exposed wall showed there was a greater hazard with the larger opening. The rooms were furnished and lined either with plasterboard or fibre insulating board. A small gas flame was introduced to represent a subsidiary source of ignition such as a fire in the grate or other heating appliance. The experiments showed that with the larger opening and either type of lining ignition of one of the articles of furniture near the window would occur after 20 minutes exposure to an intensity of 0.3 cal $cm^{-2}s^{-1}$. With the smaller opening pilot ignition of the lining would occur within half an hour for an intensity of 0.8 cal $cm^{-2}s^{-1}$ with the plasterboard lining and 0.56 cal $cm^{-2}s^{-1}$ with the fibre insulating board lining. There is reason to believe that on full scale higher intensities of radiation would be needed to produce the above effects[8]. We can now picture the worst situation as a room with one whole side occupied by a window, the glass completely destroyed, exposed to the peak radiation from a building fire for at least 20 minutes. When we consider the time taken for a fire to develop to its peak it is clear that the fire brigade would be available in ample time to protect the exposed building. It again appears reasonable then to specify that the separation of buildings must be such that the incident intensity of radiation will not exceed 0.3 cal $cm^{-2}s^{-1}$.

4. Calculation of intensity of radiation at any point

Given the intensity of radiation emitted by a fire and the dimensions and distribution of the windows and other openings of the building it is possible to calculate the maximum distance at which the intensity at a point on a vertical facade facing this building, if on fire, would not exceed 0.3 cal $cm^{-2}s^{-1}$.

If a burning enclosure is emitting I_o cal $cm^{-2}s^{-1}$ then the intensity at the point is given by

$$I = \phi I_o$$

where ϕ is the configuration factor[12]. The value of ϕ depends on the dimensions of the window opening in the enclosure facing the point in question and the distance of the point from the window.

For any number of windows, n, similarly radiating

$$I = (\phi_1 + \phi_2 + \phi_3 + \cdots + \phi_n) I_o$$

so that if we specify I = 0.3 cal $cm^{-2}s^{-1}$

$$\sum \phi_n = \frac{0.3}{I_o}$$

Given the dimensions and dispositions of the windows, it is possible to find the distance to give the required $\sum \phi_n$

The calculation of separation distance can thus be expressed as a purely geometrical problem and this is the approach discussed by Bevan and Webster(13). Since windows are almost invariably rectangular in shape only configuration factors for rectangular radiators will be considered and the exposed point will be assumed to be on a vertical plane parallel to the plane of the radiator. Values of ϕ calculated by various authorities (12)(14) are given in Fig. 4 for a point P on a perpendicular axis through the corner of the rectangular radiator as shown in Fig. 5(a). By using the additive property of configuration factors the value of ϕ at any point can be found. Thus in Fig. 5(b) the ϕ at P is the sum of ϕ for the rectangles AEPH, EBFP, PFCG and HPGD, and in Fig. 5(c) the sum for rectangles AEPG, GPFD minus the sum for BEPH and HPFC. For one rectangular radiator the maximum intensity at any distance lies on the perpendicular axis through the centre of the rectangle. For more than one radiator the position at which there is the maximum intensity depends on the relative positions and sizes of the radiators.

It is possible, using the above information, to calculate the separation distance for any facade but in many cases the work involved would be tedious and methods of simplification will be outlined.

5. Specification of boundary distance

It has already been stated that a building is in general positioned in relation to its site boundary. One obvious way of specifying this boundary distance is to halve the separation distance so that if two similar buildings, one the mirror image of the other, are then placed on opposite sides of the boundary the distance between them is the correct separation distance. For two dissimilar buildings, however, the one with the smaller boundary distance may be at a disadvantage if the other is on fire. To allow for such discrepancies as these a larger fraction than half the separation distance might be specified but to ensure that in every situation no less than the correct separation would be attained the boundary distance would have to be very large and in many cases there would be much wasted land. If the principle of positioning buildings in relation to the site boundary is accepted then some form of compromise seems inevitable. The remainder of this report is devoted to illustrating simplified methods of obtaining the boundary distance in terms of half the separation distance.

It has been suggested that it would be simpler to specify an intensity at the boundary rather than half the distance for an intensity of 0.3 cal $cm^{-2}s^{-1}$. However, for the correct separation distance, the intensity at the boundary depends on the shape of the building and amount of openings since the variation of intensity with distance from a rectangular radiator does not follow a simple law. A value of intensity at the boundary could be chosen so that in no case was the boundary distance less than half the separation distance and this would mean that in some cases the boundary distance might be as much as 40 per cent greater than half the separation distance. Such a specification would remove some of the discrepancies outlined in the preceding paragraph and the possibility of specifying boundary distances in this way, as another form of compromise, could be borne in mind.

6. Calculation of boundary distance

6. 1. Elevation with a number of openings

For most elevations with a number of windows the problem can be reduced to that of a single radiator. This single radiator is the rectangle which totally encloses all the openings in the elevation (termed the overall enclosing rectangle) considered as radiating at a reduced intensity, the reduction factor being the ratio of the total area of all the openings to the area of the enclosing rectangle. Thus, if the area of the openings were 50 per cent of the area of the enclosing rectangle and the building contained a high fire load, then the intensity 4 cal $cm^{-2}s^{-1}$ would be reduced by a factor $^{50}/100$ and the effective radiating intensity of the rectangle would be taken as 2 cal $cm^{-2}s^{-1}$. The appropriate configuration factor would then be calculated in order to find the required separation distance.

Consider the elevation in Fig. 6(a). The rectangle ABCD encloses all the openings and the area of the openings is 50 per cent of the area of ABCD. The equivalent radiator is shown in Fig. 6(b) with $I_o = 2.0$ cal $cm^{-2}s^{-1}$

$$\therefore \sum \phi_n = \frac{0.3}{2.0} = 0.15$$

$\sum \phi_n$ for the point P is the sum of ϕ for each of the separate rectangles, as in Fig. 5(b), and since these rectangles are identical, one may write

$$\sum \phi_n = 4 \times \phi \text{ for EBFP}$$

$$\therefore \phi \text{ for EBFP} = \frac{0.15}{4} = 0.0375$$

Referring to Fig. (4) we have

$$A = 10 \text{ ft}$$

$$n = 3$$

and for $\phi = .0375, \frac{nA}{C} = 0.69$

$$\therefore C = 44 \text{ ft}$$

and boundary distance, $b = 22$ ft

Separation distances have been calculated for different percentage openings and different length to width ratios and the corresponding boundary distances are shown in Figures 7 and 8. Where the percentage opening falls between two values shown in these figures, the boundary distance for the higher value should be taken.

The configuration factor for an elevation with any number of openings could alternatively be found with an optical analogue which uses the fact that the transmission of light radiation obeys the same laws as for heat radiation. A piece of diffusing glass is evenly illuminated and used as the radiator, portions are masked to represent the blank walls and the light intensity at any point is measured with a photo electric cell[15].

6. 2. Variation in boundary distance

The distance normal to a rectangular radiator at which the intensity is a given fraction of the intensity at the window is a maximum opposite the centre and is less opposite the edges. The difference between these distances becomes less marked as the height of the radiator increases relative to its width. In most cases, little is lost by requiring that the maximum boundary distance shall extend for the full width of the radiator but where, for example, there is an opening next to a portion of blank wall the boundary could be allowed to approach the blank portion and some simple rule must be devised to allow for this.

For a given width of radiator the intensity of radiation at the sides is greatest when the height is very large so that if we cater for an infinitely tall strip we shall cover all cases found in practice. It is shown in Appendix I that if the boundary is drawn the width of the radiator and continued as an arc of a circle with centre the edge of the radiator and radius the boundary distance, then the line so drawn is always greater than half the separation distance. The application of this rule is illustrated in Fig. 9 where the elevation is similar to the one in Fig. 6 but with a long portion of blank wall. The boundary distance, already calculated as 22 ft, is drawn as shown in Fig. 9.

6. 3. Irregular elevations

The calculation of boundary distance in terms of a single radiator has been outlined for simple elevations with evenly distributed openings. It is also possible to calculate boundary distances for irregular elevations in terms of single radiators and methods of doing this will now be given.

6. 3. 1. Elevation with uneven distribution of openings

While for a majority of elevations with a number of openings the boundary distance can be found from the dimensions of the enclosing rectangle and the percentage of openings, there may be one or more openings sufficiently large to require a local increase in the boundary distance. Consider the elevation and plan in Fig. 10. For the enclosing rectangle ABCD, there is 30 per cent area of opening, n = 5, A = 20 ft and we obtain from Fig. 7 for the boundary distance.

$$b = 18 \text{ ft}$$

For EBCF there is 90 per cent opening, n = 1, A = 20, and from Fig. 7, for 100 per cent opening

$$b = 20 \text{ ft}$$

It is necessary, therefore, to increase the boundary distance in the region of EBCF. The boundary position calculated for the whole rectangle ABCD is drawn first. A second boundary position is then drawn for the rectangle EBCF and continued as an arc of radius 20 ft until it meets the first position (see 6. 2.).

The procedure therefore in all cases is to find first the boundary distance for the overall enclosing rectangle and then to increase this locally where necessary. It will be found in practice that in most cases no local increase is necessary.

6. 3. 2. Elevation with widely spaced openings

If openings are spaced very widely apart then a point opposite one opening may receive negligible amount of radiation from the next opening and for the purposes of calculating boundary distance the openings may be considered separately. The boundary distance may be calculated firstly for the rectangle enclosing all the openings and it is shown in Appendix 2 that if the distance between the openings is greater than four times this boundary distance, they may be treated as separate radiators.

Considering the elevation in Fig. 11 the enclosing rectangle ABCD has 20 per cent opening, n = 5, A = 20 ft and we obtain from Fig. 7

$$b = 12 \text{ ft}$$

The distance between the two rectangles AEHD and FBCG is 60 ft which is greater than 4 x b so that these rectangles may be considered separately. For AEHD with 50 per cent opening, n = 1.5, A = 20 ft and b = 16 ft. For FBCG with 50 per cent opening, n = 2, A = 10 ft and b = 10 ft.

6. 3. 3. Elevation with recessed portion

If one part of an elevation is recessed, then there may be a corresponding change in the boundary distance, the effect of the recess depending on the amount of openings. If the recess contains openings on all three walls, then it will appear as a radiating enclosure and if for example there were 100 per cent openings on all the walls it would have the same effect as a 100 per cent opening at the front of the aperture. In general, the total area of the openings in the recess should be added together, expressed as a percentage of the area of the aperture, the aperture then being considered as a radiator and the boundary distance for the whole elevation found accordingly. Where the total area of the openings is equal to or greater than the area of the aperture, the aperture should be considered as a radiator with 100 per cent openings.

In Fig. 12 the rectangle EFGH is set back 15 ft. The total area of openings in this recess is 60 per cent of the area of the rectangle EFGH. Assuming this area to be at the aperture and with 40 per cent opening in the other two rectangles, the area of opening for the enclosing rectangle ABCD is 45 per cent.

In Fig. 7 for 50 per cent opening, n = 4, A = 20 ft.

$$b = 24 \text{ ft}$$

Where there are openings on the rear wall only of the recess, then a reduction in the boundary distance may be effected as follows. A first value of the boundary distance b_1, may be made assuming as before all the openings to be radiating at the aperture. The area of openings in the recess can then be reduced by the factor, $\left(\frac{2b_1}{2b_1 + r}\right)^2$, where r is the depth of the recess, and a second boundary distance, b_2, found. This second value is taken as the final boundary distance. (It would be possible to repeat the process to reduce b_2 and continue until there was no further change in successive values but such refinement is not necessary for building purposes).

In Fig. 13 the rectangle EFGH is set back 16 ft and there are no openings on the side of the recess. Each of the three rectangles contains 40 per cent area of openings. For the enclosing rectangle ABCD, n = 5, A = 20 ft and from Fig. 7 for 40 per cent opening

$$b_1 = 23 \text{ ft}$$

The openings in the recess can be reduced by the factor

$$\left(\frac{2b_1}{2b_1 + r}\right)^2 = \left(\frac{46}{62}\right)^2$$

so that EFGH can be considered to have 22 per cent opening. For the enclosing rectangle ABCD this gives 30 per cent opening and for n = 5, A = 20 ft, from Fig. 7

$$b_2 = 18 \text{ ft}$$

The adoption of the reduction factor, $\left(\frac{2b_1}{2b_1 + r}\right)^2$ is due to simple geometrical considerations of the apparent size of the openings in the recess as compared with the other openings when viewed from a point at the separation distance. This is illustrated in Fig. 13 which shows the equivalent radiator used.

The boundary distance for a building with some upper floors recessed can be calculated in the same way. Where some floors are recessed a distance r_1, and others a distance r_2, then the reduction factors

$(\frac{2b_1}{2b_1 + r_1})^2$, $(\frac{2b_1}{2b_1 + r_2})^2$ should be applied to the area of openings in the relevant portions.

6. 3. 4. Elevation with set back

When part of a building is set back there can be a corresponding set back in the boundary and its final position is found by considering the building from two aspects. A boundary position is first found assuming no set back and then part is altered to allow for the set back. This allowance is made by viewing from the side and constructing an equivalent radiator which encloses all the openings, these openings being expressed as a percentage of the equivalent radiator and the appropriate boundary position found. For the final boundary position, the first one is taken until it meets the second.

In Fig. 14 the rectangle FBCG is set back 30 ft behind AEHD. Assuming no set back then for the enclosing rectangle ABCD, n = 5, A = 20 ft, and for 40 per cent opening, from Fig. 7

$$b = b_1 = 23 \text{ ft.}$$

Now consider the equivalent radiator, A^1B^1 on the plan. A^1B^1 = 103 ft and the height of this radiator is 20 ft. The openings in AEHD, EFGH, FBCG are 50 per cent of the area of the equivalent radiator. For this radiator n = 5.15, A = 20 ft, and from Fig. 7 for 50 per cent opening

$$b = b_2 = 27 \text{ ft.}$$

The positions of the two boundaries are shown in Fig. 14 the portions of each which are nearer to the elevation being taken as the final boundary position.

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APPENDIX I

Consider a radiator of infinite height. The configuration factor ϕ at a point P on a vertical plane, not necessarily parallel with the plane of the radiator, is given by[12]

$$\phi = \tfrac{1}{2}(\cos\alpha + \cos\beta) \qquad (1)$$

where α and β are shown in Fig. 15(a).

The value of β which will give the maximum value of ϕ at any point is required. For a given point the angle γ subtended by the radiator at P is independent of β.

Writing $\alpha = 180 - (\beta + \gamma)$

we obtain $\dfrac{d\phi}{d\beta} = \tfrac{1}{2}\left[\sin(\beta + \gamma) - \sin\beta\right]$

For ϕ to be a maximum

$$\gamma = 180 - 2\beta$$

and

$$\alpha = \beta$$

For a given value of ϕ and $\alpha = \beta$ = constant, then γ is constant and the locus of P is therefore the circumference of a circle subtended by the radiator as a chord.

If the width of the radiator is W the maximum value of separation distance C from the centre of the radiator is obtained from

$$\phi_c = \frac{W}{\sqrt{W^2 + 4C^2}} \qquad (2)$$

where ϕ_c is the required value of ϕ i. e. $C = \dfrac{W}{2}\sqrt{\dfrac{1}{\phi_c^{\,2}} - 1}$ (3)

The boundary distance is then given by

$$b = \frac{C}{2} = \frac{W}{4}\sqrt{\frac{1}{\phi_c^{\,2}} - 1}$$

By requiring the boundary distance to be not less than b at all points, the boundary will always be at a distance greater than or equal to half the separation distance since C is the maximum separation distance.

APPENDIX 2

Widely spaced openings

Consider two infinitely high radiators, 1 and 2, widths W_1 and W_2, separated by a blank wall length l.

Then from equation (3), Appendix I, the separation distance C_2 for the radiator 2 is given by

$$C_2 = \frac{W_2}{2}\sqrt{\frac{1}{\phi_2^2} - 1}$$

For $I_o = 4.0$ cal cm^{-2}s^{-1}, $\phi_2 = \frac{0.3}{4.0} = 0.075$

and $C_2 = 6.65\ W_2$ (4)

It is required to find the value of l such that for a point at a distance C_2, opposite 2, the radiation received from the radiator 1 is negligible. The configuration factor for radiator 1 is given by, from equation (1) Appendix 1)

$$\phi_1 = \frac{1}{2}\left[\frac{l + W_1}{\sqrt{C_2^2 + (l + W_1)^2}} - \frac{l}{\sqrt{C_2^2 + l^2}}\right]$$

If the effect of radiator 1 is considered negligible when its contribution to the total radiation is not greater than 5 per cent, i.e.

$$\phi_1 \leqslant 0.00375$$

and if $W_1 = W_2$ we have

$$\frac{l + W_2}{\sqrt{C_2^2 + (l + W_2)^2}} - \frac{l}{\sqrt{C_2^2 + l^2}} \leqslant .0075 \qquad (5)$$

From equations (4) and (5)

$$l \geqslant 17.4W_2$$

It is convenient to express l in terms of the boundary distance for the whole elevation.

For the whole elevation the percentage opening is

$$\frac{W_1 + W_2}{W_1 + W_2 + l} \times 100 = \frac{2W_2}{2W_2 + l} \times 100$$

and

$$I_o = 4.0 \times \frac{2W_2}{2W_2 + l}$$

$$\therefore \quad \phi_c = \frac{0.3}{4.0} \times \frac{2W_2 + l}{2W_2} \qquad (6)$$

From equation (2) Appendix 1

$$\phi_c = \frac{2W_2 + l}{\sqrt{(2W_2 + l)^2 + 4C^2}} \qquad (7)$$

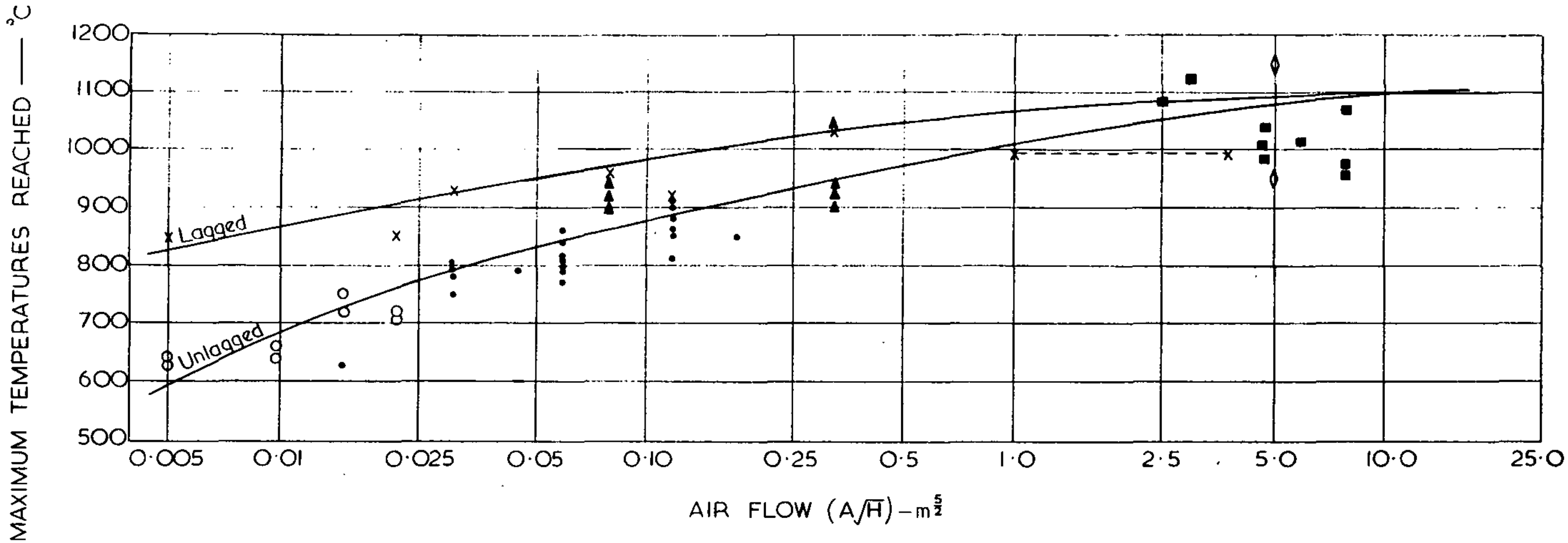
where C is the separation distance for the whole facade.

From (6) and (7)

for $l = 17.4W_2 \quad C = 9.17W_2$

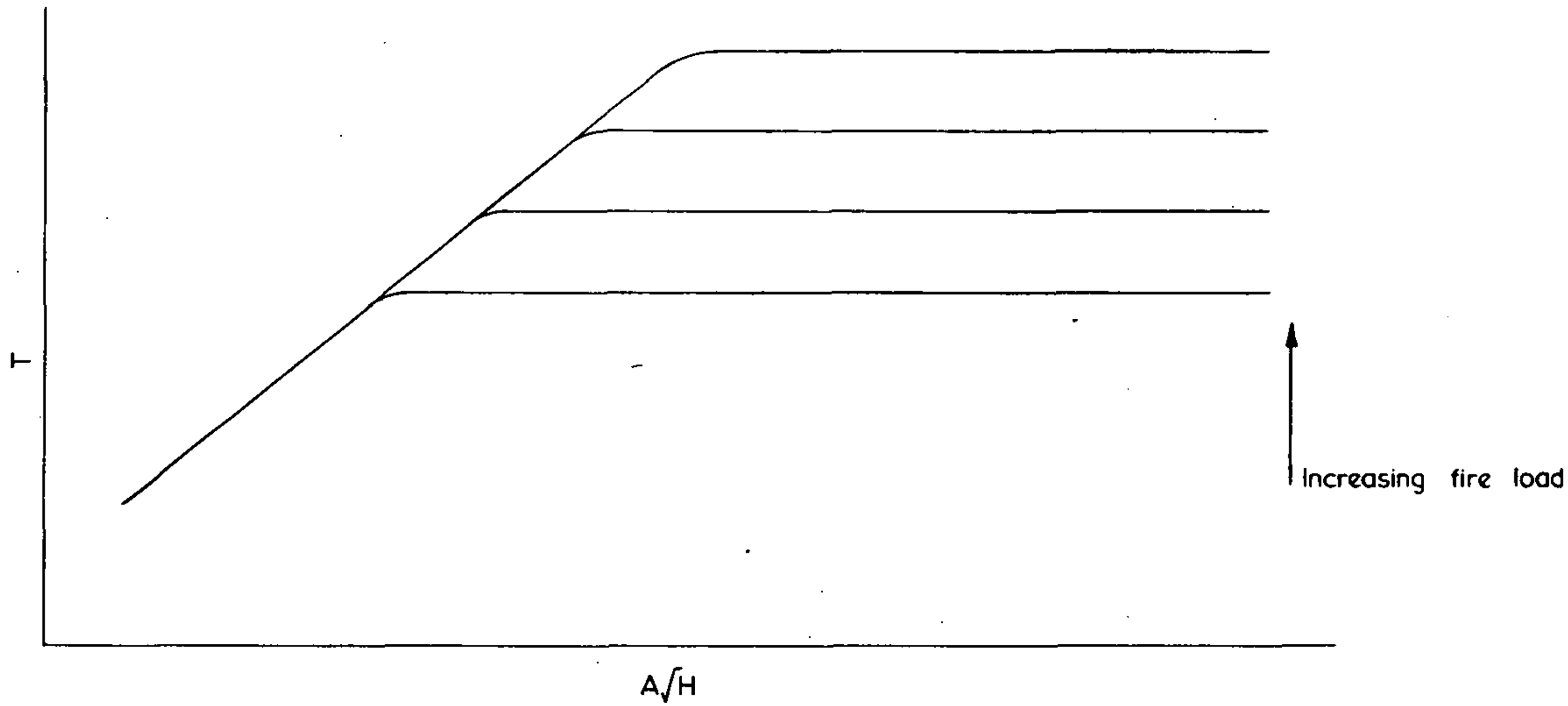
i. e. $l = 3.8b$ where $b = C_2$

∴ for $l > 4b$ one radiator has negligible effect at a point opposite another of the same size. Since the interaction of the two radiators is greatest when they are equal, this rule holds for all cases.



	Scale I Floor area (·3x ·3) m	Scale II Floor area (·7x ·7) m	Scale III Floor area (1·0 x 1·0) m	Half scale Floor area (1·8 x 2·75) m	Full scale Floor area (3·0 x 3·0) m
Hird and Wraight [1]	○	•	▲		
Hird and Wraight (lagged boxes)	x	x	x		
Malhotra [2]					■
Swedish test [3]					x- - - -x
Hird and Fischl [4]					♦
Dwelling house [5]					◊

FIG.1. MAXIMUM TEMPERATURES AND AIR FLOW



Fire load effect limited to 40 kg/m²

FIG. 2. EFFECT OF FIRE LOAD

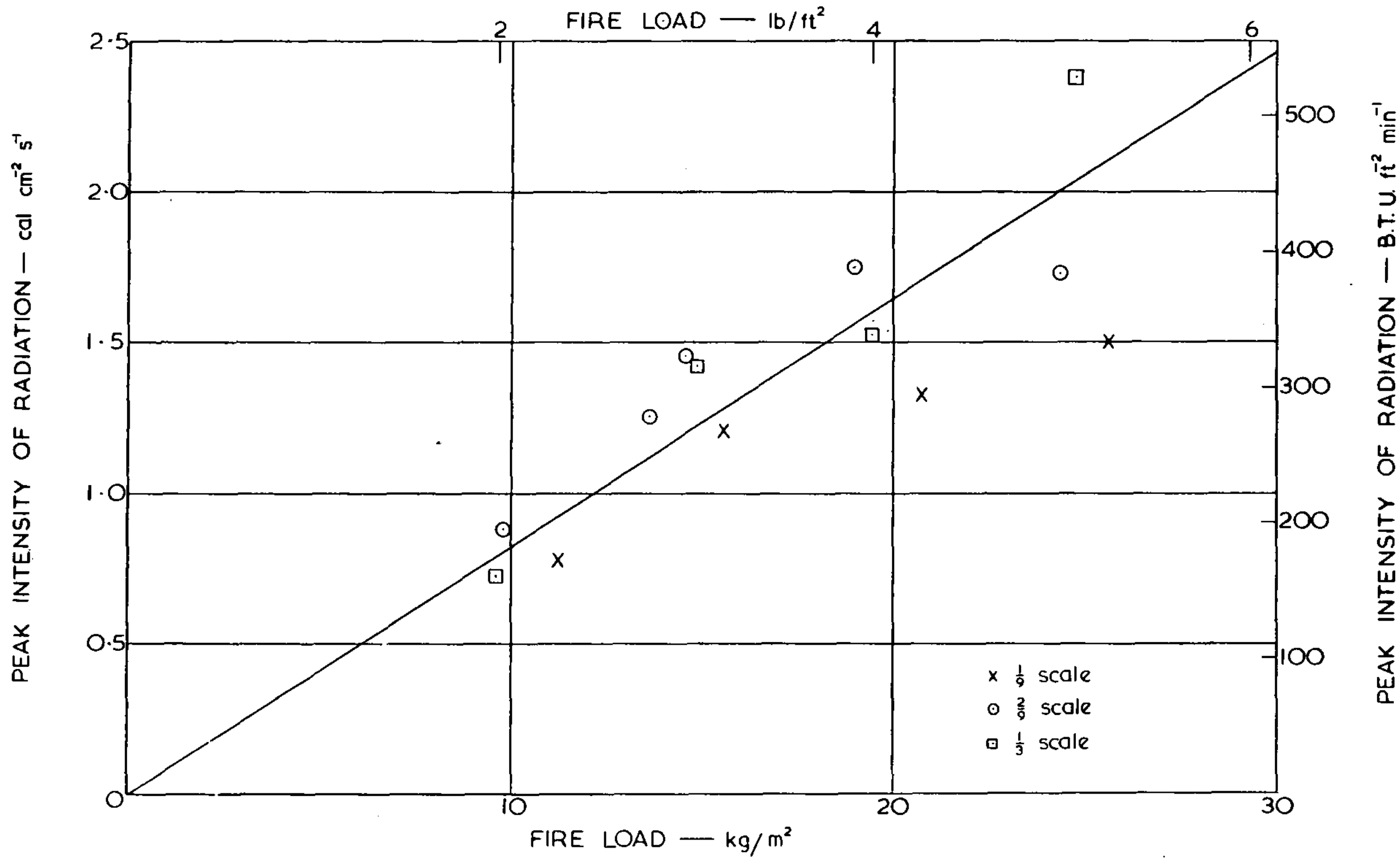


FIG.3. PEAK INTENSITY OF RADIATION AT OPENING FOR WELL VENTILATED FIRE

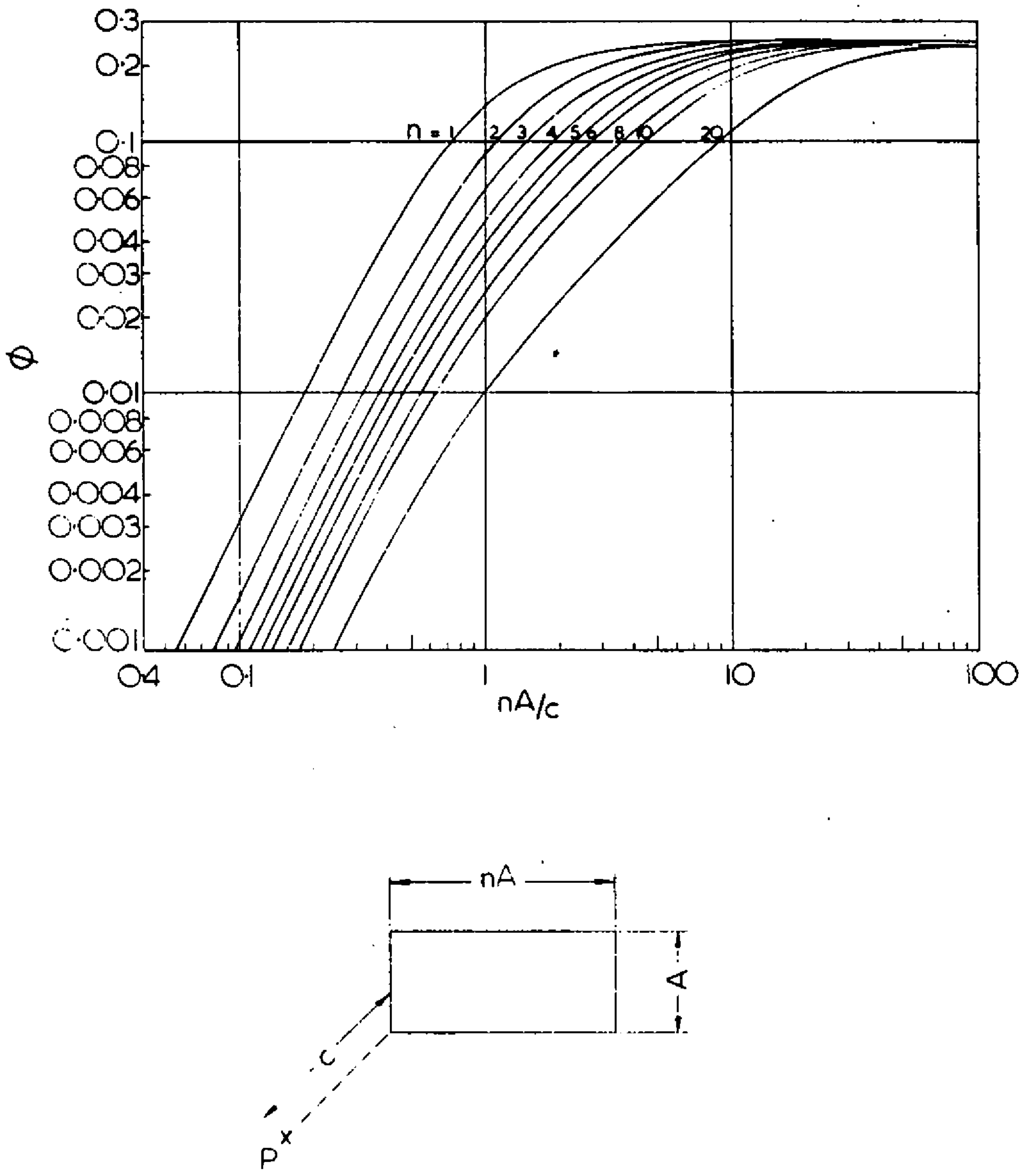


FIG. 4. CONFIGURATION FACTOR ϕ FOR DIFFERENT SHAPE RADIATORS

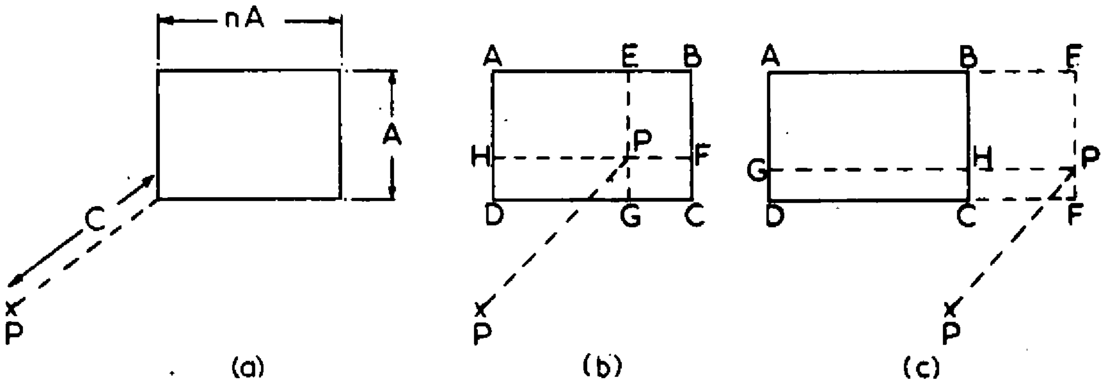
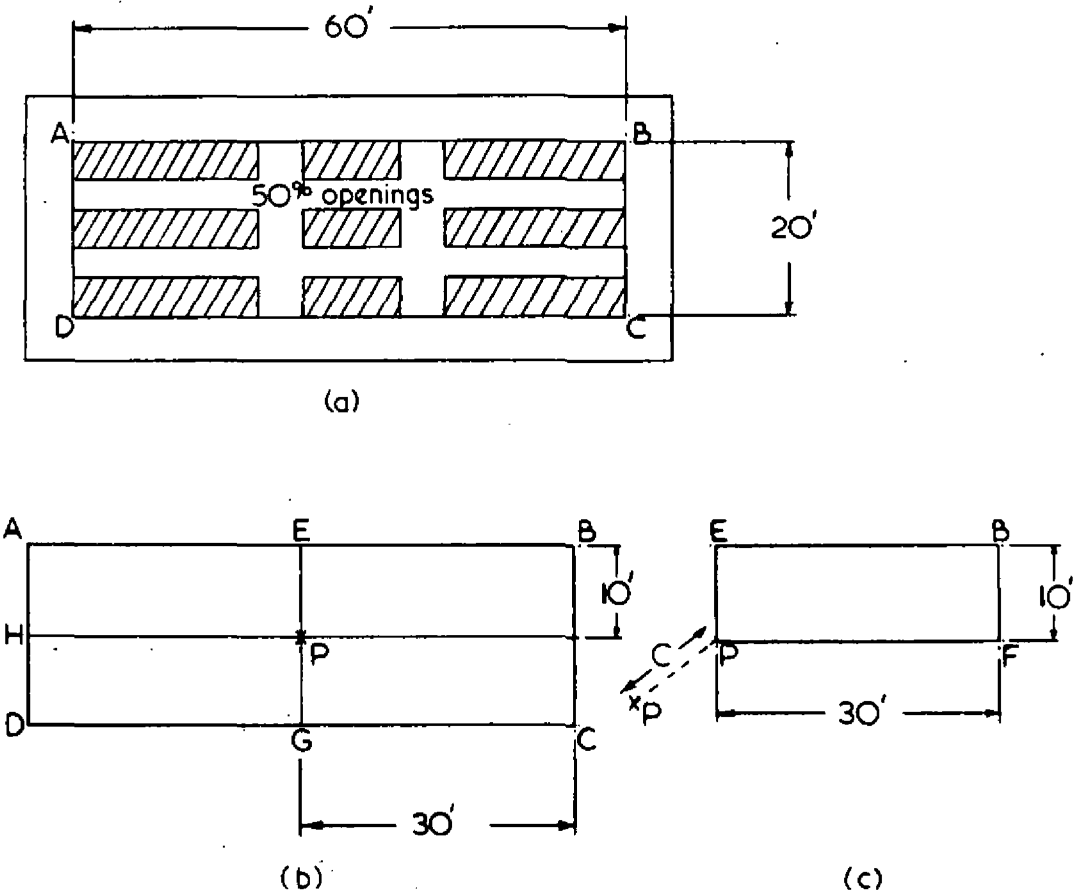


FIG. 5. ADDITIVE PROPERTY OF CONFIGURATION FACTORS



Equivalent radiator with $I_0 = 2$ cal cm^{-2} s^{-1}

FIG. 6. ELEVATION WITH A NUMBER OF OPENINGS

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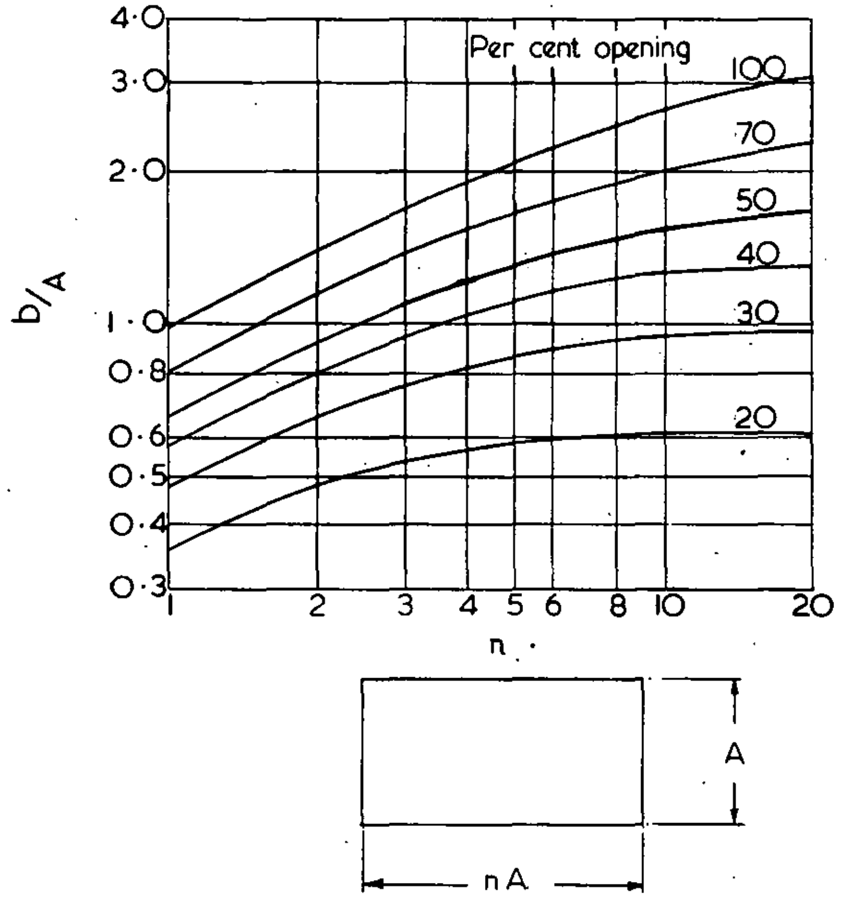

FIG. 7 BOUNDARY DISTANCE b FOR HIGHER INTENSITY AND DIFFERENT OPENINGS. FIRE LOAD > 5lb/ft²

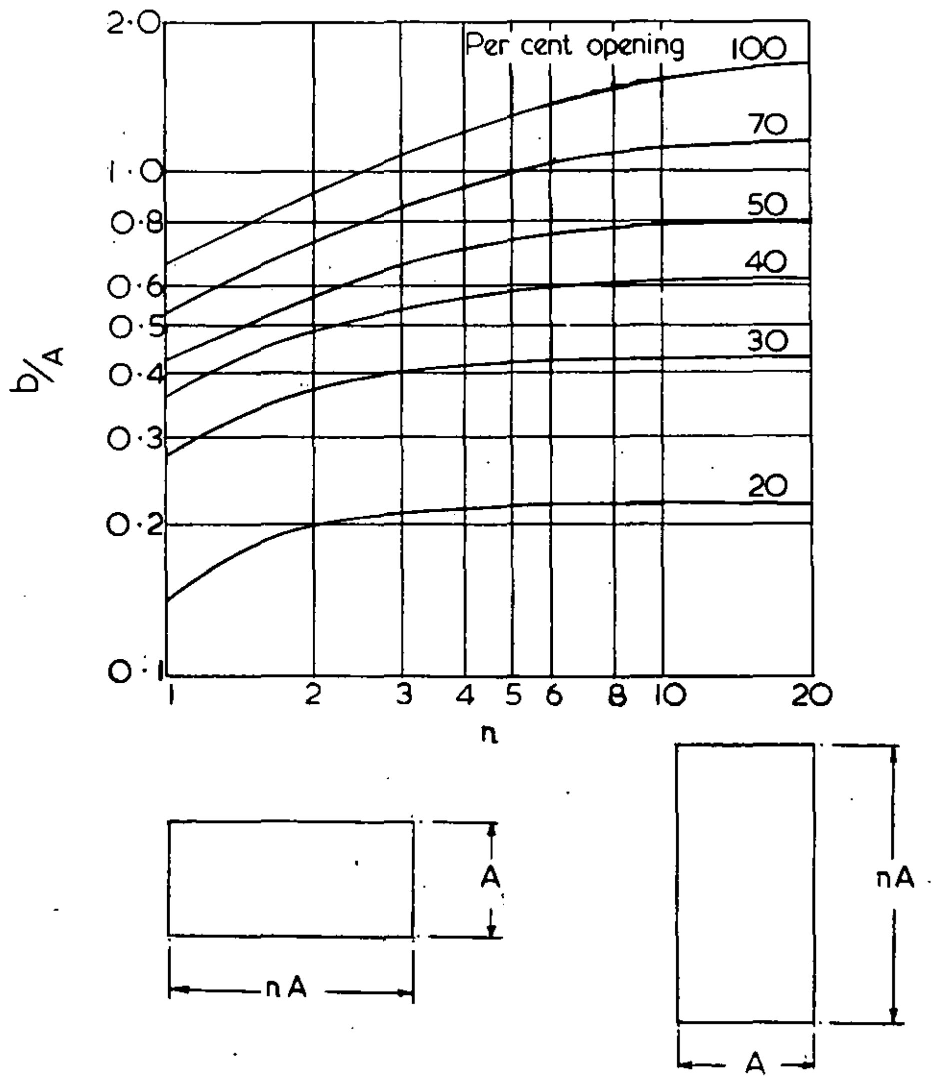

FIG. 8. BOUNDARY DISTANCE b FOR LOWER INTENSITY AND DIFFERENT OPENINGS. FIRE LOAD < 5lb/ft²

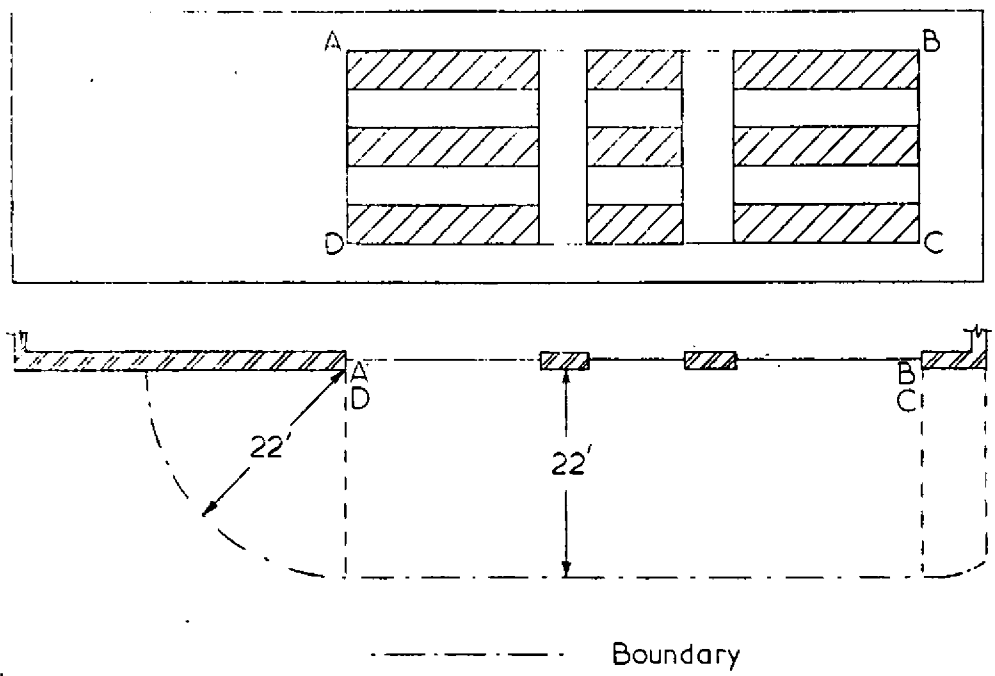

FIG. 9. BOUNDARY DISTANCE AT EDGE OF ENCLOSING RECTANGLE

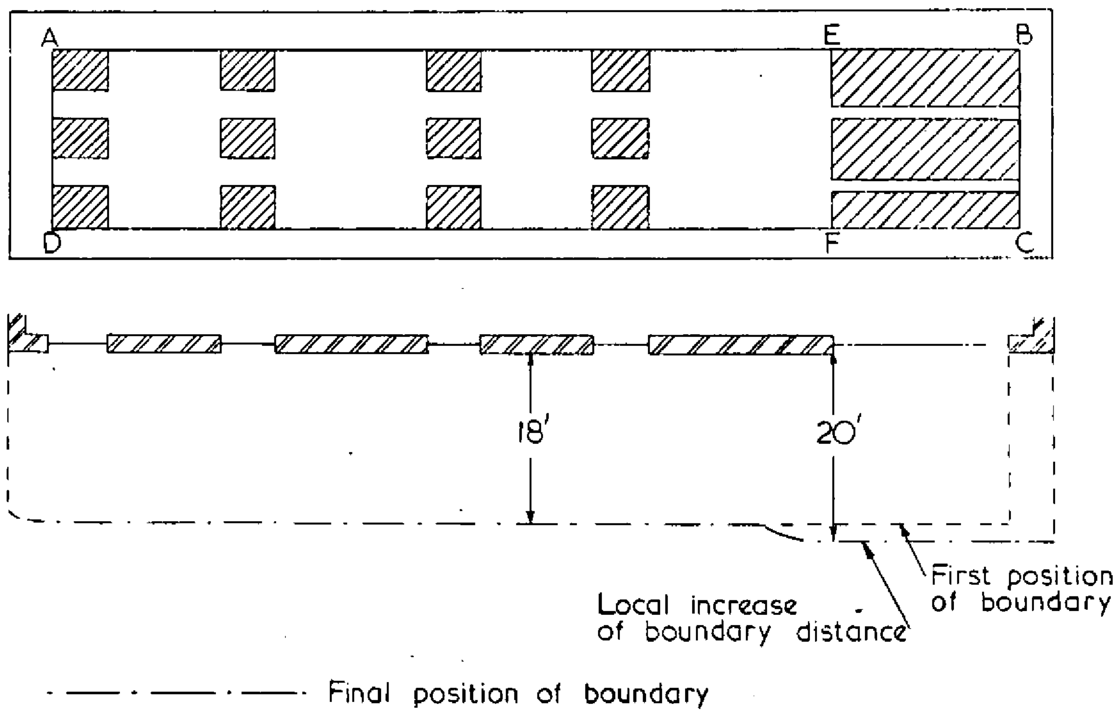

FIG. 10. LOCAL INCREASE OF BOUNDARY DISTANCE

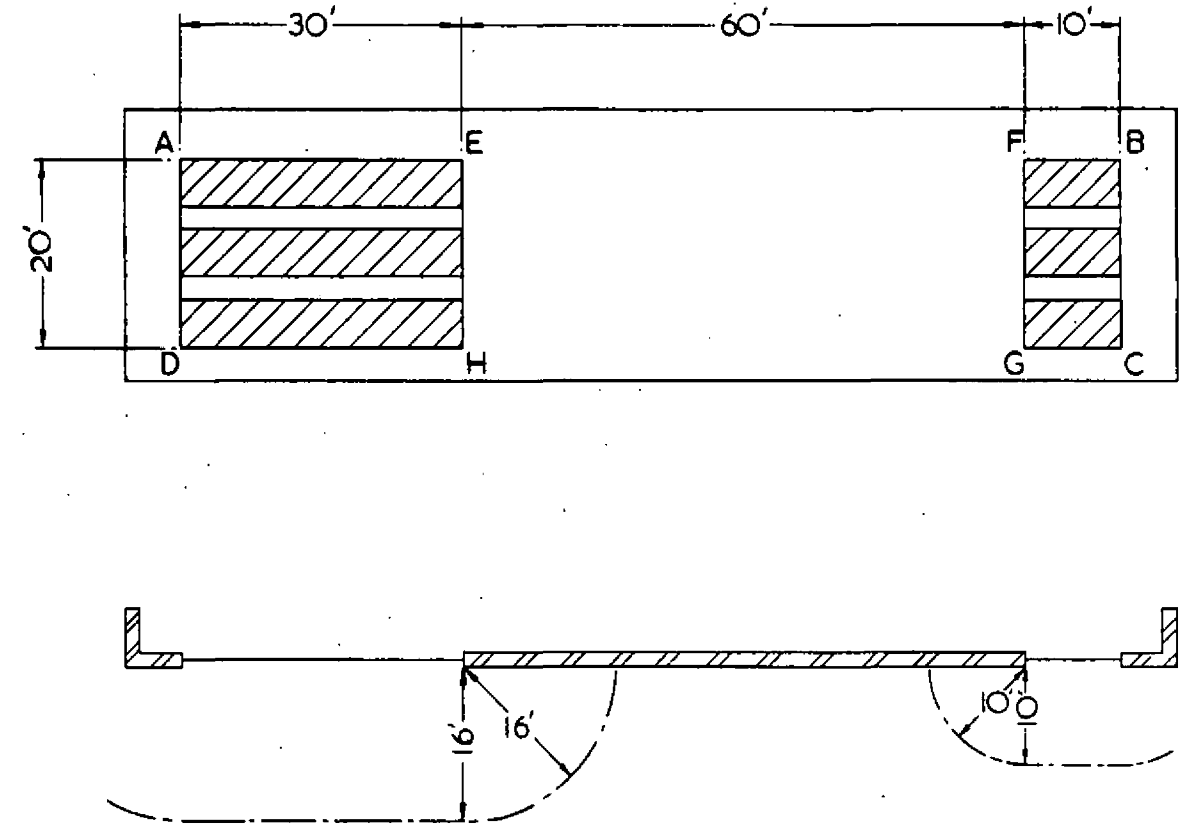

FIG. 11. ELEVATION WITH WIDELY SPACED OPENINGS

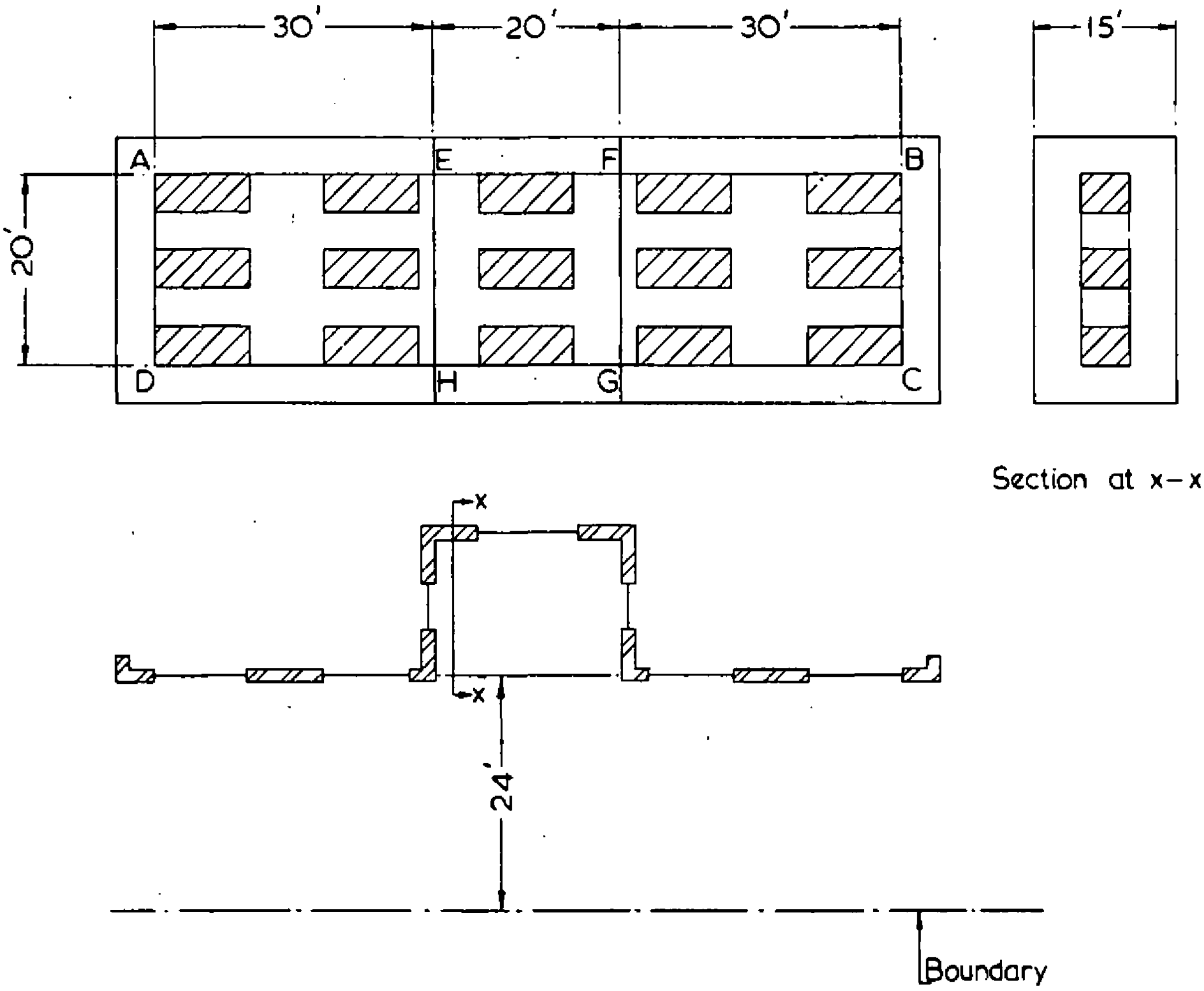

FIG. 12. RECESSED ELEVATION: OPENINGS IN ALL SIDES

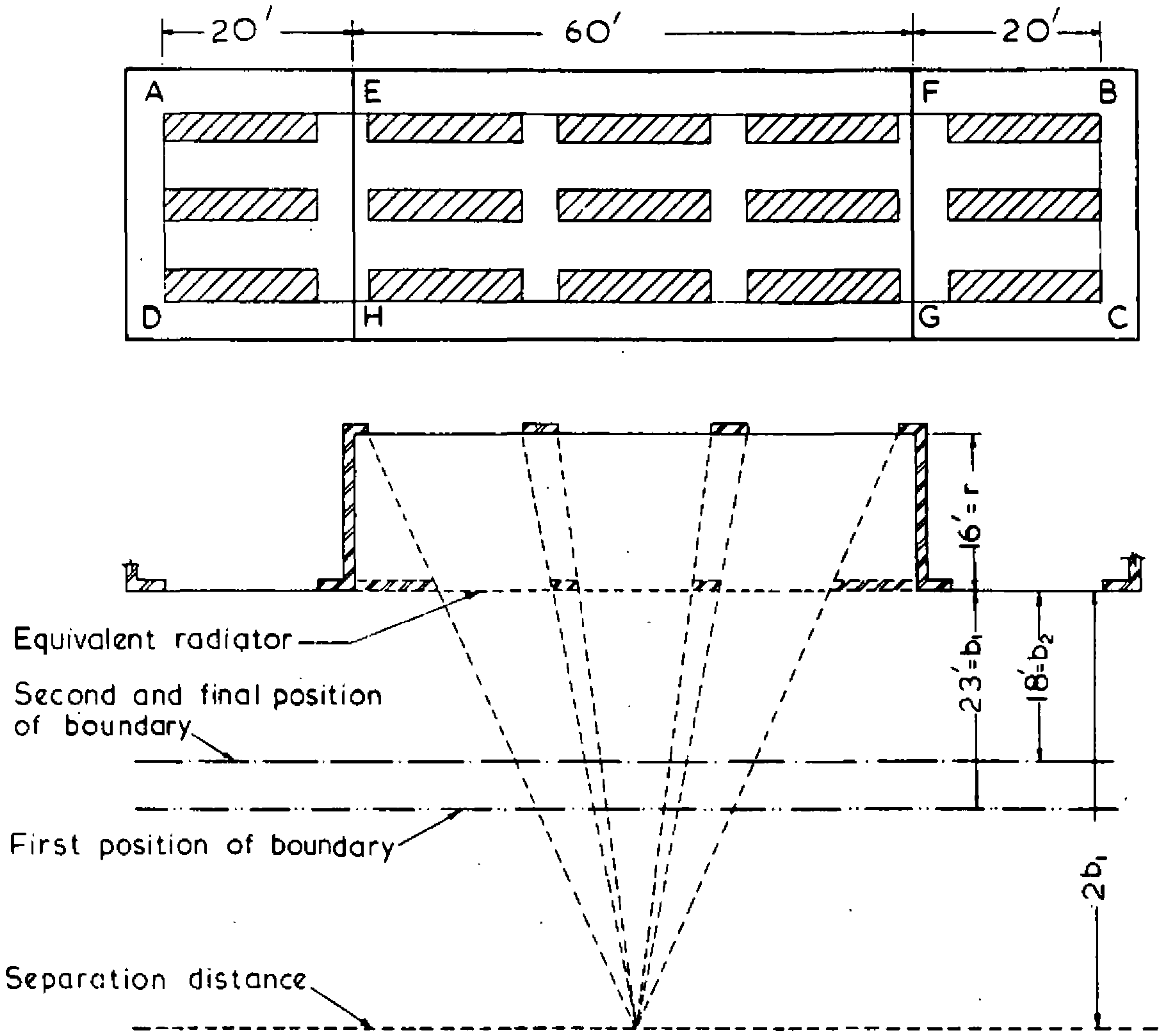

FIG. 13. RECESSED ELEVATION. OPENINGS IN REAR WALL ONLY

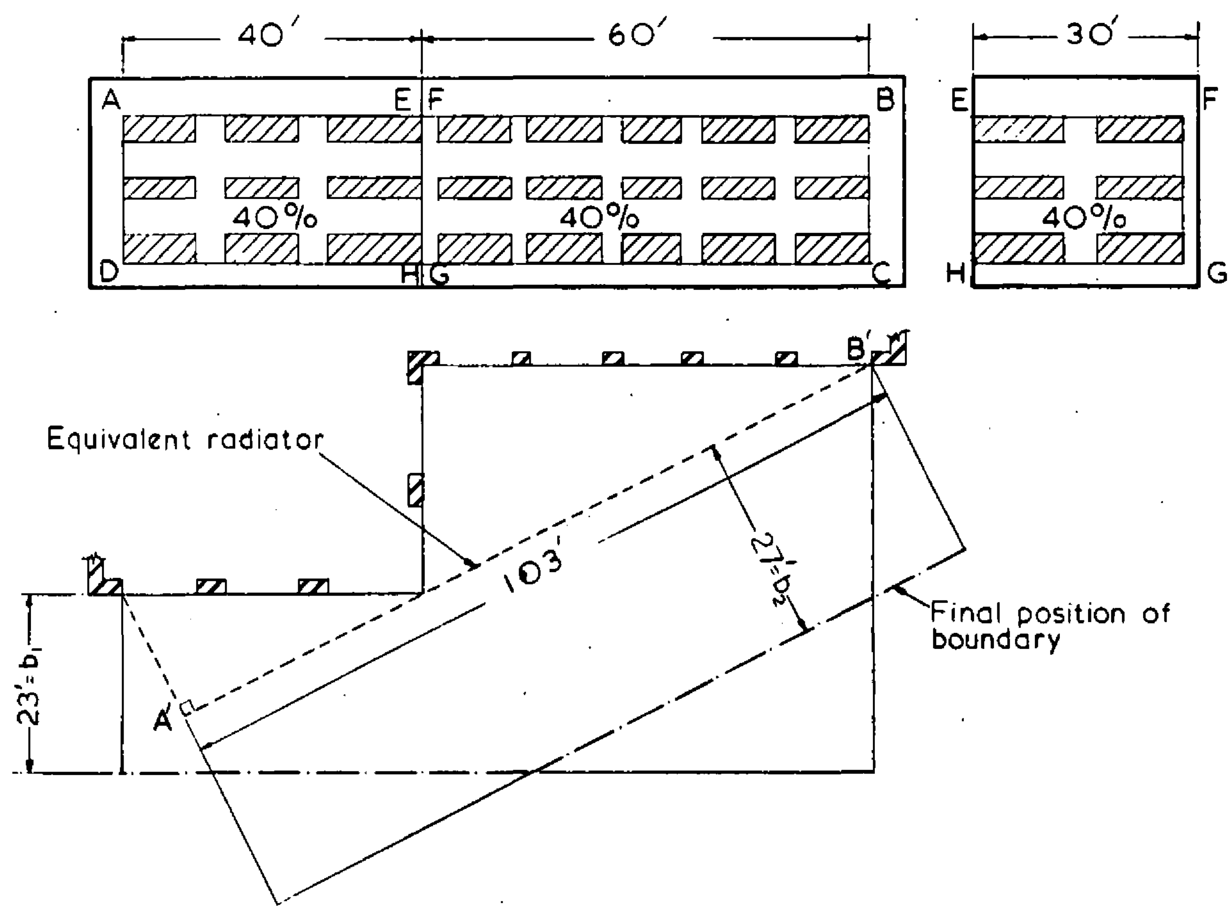

FIG. 14. ELEVATION WITH SET BACK

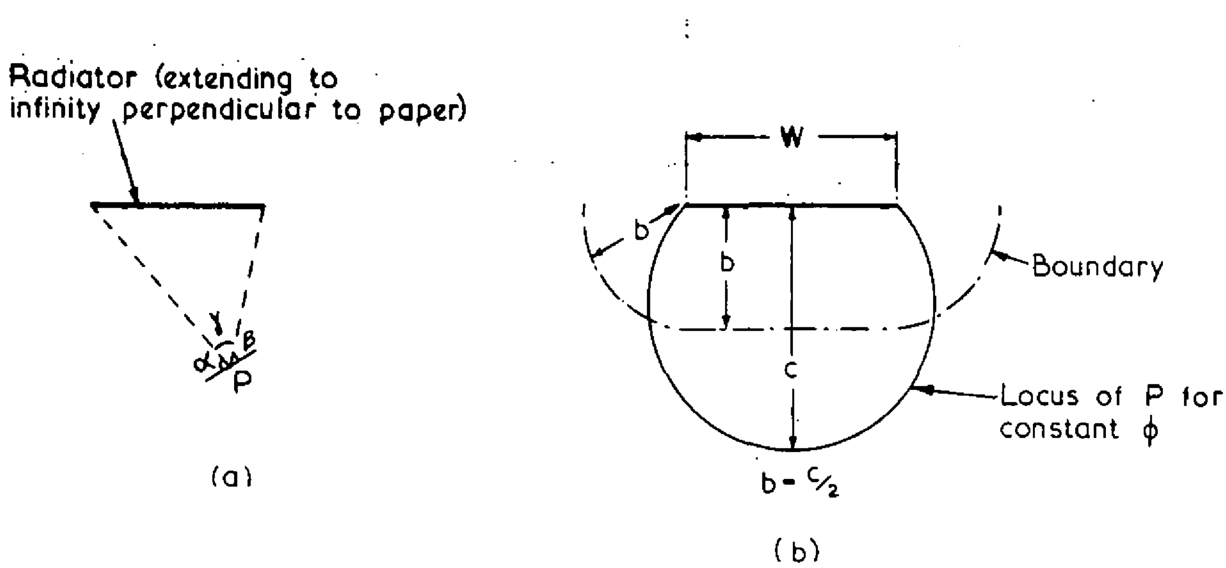

FIG. 15. VARIATION IN BOUNDARY DISTANCE

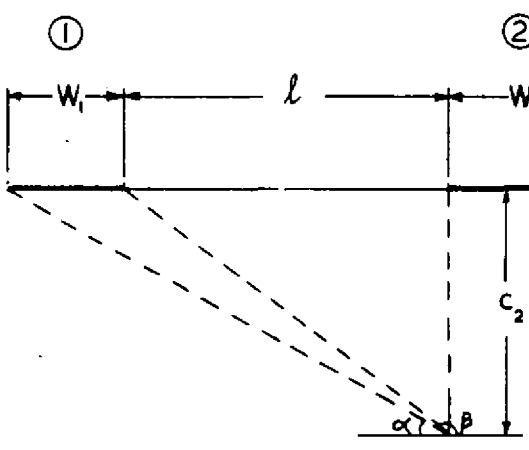

FIG 16. WIDELY SPACED OPENINGS