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Factors In Controlling Smoke In High Buildings

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CONTRÔLE DE LA FUMÉE DANS LES IMMEUBLES DE GRANDE HAUTEUR

SOMMAIRE

Les bâtiments étudiés sont présumés conformes à un code de bâtiment comme le Code national du bâtiment du Canada qui prescrit, par exemple, un compartimentage adéquat. Les puits d'escaliers et d'ascenseurs sont supposés susceptibles d'être ventilés vers l'extérieur au rez-de-chaussée ou de déboucher sur des espaces offrant une protection contre l'incendie et susceptibles aux aussi d'être ventilés. On propose comme critère du niveau acceptable de l'atmosphère une densité optique se situant entre 0.05 et 0.10. On cite des calculs sur la quantité de matière nécessaire pour enfumer un bâtiment. Le but des dispositions à prendre pour contrôler le mouvement de la fumée telles qu'élaborées par la DRB est décrit. Quelques solutions générales aux problèmes posés par les puits sont exposées. On discute des effets de la réduction de la pression par une ventilation des puits à partir de leur sommet et de l'augmentation de la pression dans les puits par une ventilation à partir de leur partie inférieure et une injection d'air. Enfin, on examine les avantages et les désavantages d'une dispersion de la fumée par dilution particulièrement par temps chaud.

FACTORS IN CONTROLLING SMOKE IN HIGH BUILDINGS

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In the first half of this century, high-rise buildings have not been particularly noted for posing smoke problems, despite the absence of measures specifically aimed at smoke control. This performance has resulted from strict enforcement of measures aimed, in general, at fire limitation. Extensive compartmentation and sharp restriction on the use of flammable wall and ceiling lining materials were probably the two most effective measures involved. In certain areas of North America, however, where high buildings were permitted to be constructed with design features such as open stairwells, several fire disasters associated with these features have resulted.

It cannot be expected that modern Canadian buildings will behave as well as many earlier structures in the U.S. The principal reasons for this are:

(1) the increasing size of compartments (it is now quite common for the whole of one story to constitute a single office space).

(2) the increased use of flammable interior lining materials and

(3) the general use (interior finish, insulation, furnishings) of materials that have a propensity to generating dense smoke.

TYPE OF BUILDING CONSIDERED

Smoke control methods will be discussed in the context of a building conforming to a typical North American building code and including the following features:

(1) Appropriate compartmentation by construction with adequate fire resistance to contain any fire. Every stairwell, elevator shaft and other vertical shaft should constitute an individual compartment and apart from these no other compartment should extend over more than one story.

(2) At grade level, direct access from stair and elevator shafts to the exterior or to a particularly fire-safe lobby incapable of sustaining a fire and able to be heavily vented to the exterior.

(3) Incorporation of a smoke detector in the return duct of a recirculating air handling system to shut it down and prevent recirculation of heavily contaminated air.

(4) Use of sprinklers or an alternative combination of measures, including ceiling lining flammability restrictions, to minimize the likelihood of abnormal flaming from windows that could cause ignition of the story above.

(5) Arrangements to detect a fire before it fully involves one compartment, so that doors can be closed to ensure confinement and so that early fouling of the building does not attain disastrous proportions. A sophisticated fire detector system or a sprinkler system might be used. Some Canadian authorities hold the view that in most occupied buildings detection by the occupants will be sufficiently early provided measures are taken to reduce the rate of development of a fire and the initial spread of smoke throughout the building.

Before attempting to discuss methods of controlling smoke, some comment must be made as to when an area can be described as polluted by smoke and what properties of smoke are involved.

SMOKE DENSITIES AND REQUIRED DILUTIONS

To discuss smoke levels it must first be decided to which property of "smoke" quantitative measurement will be intended to apply. It might be said that the most important feature of "smoke," using this term to mean gaseous or airborne products of combustion, is that it almost invariably contains toxic components. When a person is "trapped by smoke" and succumbs, it is generally the toxic products of combustion that are fatal and only less frequently the high temperatures associated with the fire.

Although it is possible to achieve a smoke that has both a high transparency and a high toxicity, this is the exception rather than the rule. In general, highly toxic smokes are usually very dense. As implied earlier, a person killed by "smoke" in a fire is first generally "trapped," finding himself unable to escape because of impairment of vision. Eye irritation is partly responsible but usually the most important factor is the optical density per unit path length of the smoke, limiting the range of visibility. As the optical density per unit path length of smoke is a quantity that can be readily defined and measured it is convenient, as well as being reasonable, to discuss smoke levels in terms of this measure. In Europe and North America, the most commonly used quantity is optical density per meter (m) defined as $D = \log_{10} (F_o/F)$ where a path length of 1 m is involved, F = flux incident on receiver and F_o = flux incident on receiver in the absence of smoke. In Japan, optical density/m appears to be more commonly defined as $\alpha = \log_e (F_o/F)$, where F and F_o have the same significance and again a path length of 1 m is involved. The relationship between D and α is $D = \alpha/2.303$. α may also be referred to as the attenuation coefficient having the same significance as in the expression $F_x = F_o e^{-\alpha x}$.

To be able to pursue its studies of possible smoke control methods, the Division of Building Research had to know the ratio of the maximum level of smoke likely to be found in a fire area compared to the limiting level tolerable to humans. Wakamatsu[1] prefaced a computer study of smoke movement in a building by assuming that the ratio of optical densities/m is 100. In deriving this he assumed that the lower limiting level was represented by an optical density/m of 0.043.

The conditions associated with the lower limiting density should be such as to permit almost indefinite exposure, without a great risk of panic among a group of building occupants and without unbearable eye irritation. Wakamatsu's choice of 0.043 appears to relate to such conditions.

Following the Los Angeles School Burning Experiments[2,3] it was suggested that a criterion appropriate to the present context would be a range of visibility of 45 ft which gave a transmission of 20% between light source and photocell with their arrangement. Some doubt exists as to the path length, which, incidentally, appears to involve reflection at a mirror. Taking it as 30 ft the corresponding optical density/m would be 0.076.

Rasbash[4] comments that, in the U.K., a range of visibility 15 ft has been quoted in the context of a brief dash to safety. Malhotra[5], a fellow worker, submits that this visibility, or to be strictly accurate, 4.5 m, corresponds to an optical density/m of 0.21. Such conditions are not acceptable in the present context and it would seem likely that a suitable choice of limiting optical density/m would lie in the range of 0.04 to 0.08.

An unfortunate feature regarding optical density per unit path length is that its relationship to the critical range of visibility is, as claimed by Rasbash,[4] highly subjective, as well as being dependent on the conditions involved. Thus Wakamatsu considers an optical density/m of 0.043 to be associated with a critical range of visibility of 25 m (82 ft) whereas a relationship developed by Rasbash[4] gives correspondence to a range of 49 ft. Extrapolation from results obtained by Williams-Leir,[6] which relate to an extreme limit of visibility under very favorable conditions, would attribute a range an order higher than this to an optical density/m of 0.043. The effect of different conditions has been investigated by Williams-Leir who compared the range associated with discerning a lighted bulb in a darkened enclosure to that at which an object could be identified by the light of a handlamp held by an observer. He found, for example, that a 4-ft visibility given by the handlamp criterion corresponded to 11 ft by the first criterion.

Information on the maximum levels of smoke likely to be found at fires is sparse. Wakamatsu suggests assuming a value of optical density/m of 4.3. Gross, Loftus, Robertson,[7] in tests using a smoke test chamber, report optical densities/m of over 5.5 for several different materials. Simple combustion calculations indicate that, during these tests, a substantial proportion of the oxygen in the chamber was being consumed. It is therefore unlikely that, during a fire in a building, substantially higher densities would be produced.

Smoke measurements were made during some burns conducted by the Division of Building Research in 1958.[8] Although the measuring techniques were only intended to relate to low smoke densities at an early stage of the fire, the results show that optical densities/m reached values of at least 3.8.

Although very limited, this information suggests that the limiting value of optical density taken to represent adverse fire conditions might lie in the range 4 to 8. These values are greater by a factor of 100 than those relating to the limit of tolerance. From this factor of 100 it is assumed that an area can be considered to be reasonably safe from the smoke point of view if its atmosphere will not be contaminated to an extent greater than 1% by the atmosphere prevailing in the immediate fire area.

FLOW MECHANISMS

An understanding of the flow mechanisms responsible for polluting a building is also an essential prerequisite to the development of smoke control measures. So far as movement mechanisms are concerned, smoky and normal atmospheres are very similar. It is possible, however, that an unusually high moisture content, such as occurs during fire fighting, might also have an influence and might, in association with temperature-density effects, be responsible for sustaining stratification after a smoky atmosphere has migrated to remote parts of a building.

In general the principal mechanisms responsible for dispersing smoke throughout a building will be those creating the customary air movement in the building. These have been discussed by Tamura.[9,10] Although they will not be discussed in this paper it is worth emphasizing that, from the Canadian point of view, the principal mechanism to be combatted is the stack action associated with building heating during winter.

Expansion is another mechanism of considerable importance and yet is not usually responsible for the movement of air within a building. The volume occupied by a gas depends linearly on its absolute temperature which during a fire may rise by a factor of 3 (e.g. 900 K, 627 C, cf. 300 K, 27 C). Two volumes of gas will thus be displaced and even if this later cools it will still occupy a volume of 2/3 of the fire enclosure. Considering winter conditions in a 20-story building with ground floor area of 120 sq ft it was predicted that expansion could give rise to as much contamination as stack action over a period of 30 min with an interior-exterior temperature differential of 70 F deg.

While it is not feasible to counteract the pressures developed by fairly rapid expansion, its effect can be reduced to negligible proportions by venting to the exteriors.

MATERIAL REQUIRED TO FOUL A BUILDING

One obvious means of reducing or eliminating smoke pollution within a building is to limit its contents to materials that have little propensity to generating smoke. Gross et al[7] give the smoke densities that were established in the test chamber by 3-inch-square samples of various materials. By combining this information with calculations by Tamura[9] on the leakage rates to be expected in a hypothetical 20-story building during the winter, the rates of destruction by fire of materials necessary to foul a building can be predicted.

Among the samples examined by Gross et al were several that gave the highest rating that could be measured by their equipment (an optical density/m of 5.5 in a chamber of volume 18 cu ft). The results of the present calculation can be taken as relating to any of these samples, as they are expressed in terms of an area of the same thickness of material used in the test. The materials are listed in Table I.

TABLE I

MATERIALS GIVING HIGH RATING IN SMOKE TEST

Material	*Thickness, in.*	*Density, lb/cu ft*
Polystyrene	0.25	66
PVC	0.25	88
ABS	0.046	65
Natural rubber foam	0.75	6
Red oak flooring*	0.78	41

* Non-flaming exposure

It is to be noted that the test conditions for the red oak flooring differed from those for the remaining materials. Two conditions, flaming and non-flaming exposure, are used to assess the fire behavior of a material. In both cases the specimen is irradiated, but for "flaming exposure" a small pilot flame is also used. The non-flaming exposure is characterized by smouldering and thermal exposure in an over-rich, lean or inhibited atmosphere. These conditions can be quite localized and can be witnessed, for example in a fireplace where considerable flaming prevails. A noticeable feature of the results presented by Gross et al[7] is that cellulosic materials generally behave more poorly under non-flaming exposure, whereas the reverse tends to be the case with plastics and rubber.

The 20-story hypothetical building considered by Tamura had a floor area of about 14,000 sq ft and leakage areas between floors, to the exterior, and to the shafts of 3.75 sq ft, 2.5 sq ft/story and 5 sq ft/story respectively. With a 70-deg differential between the interior and exterior the flow from the ground floor to the shafts was about 2,800 cfm. If this is considered to be the fire area serving as the source of contamination, adaptation of the results of Gross et al indicates that the steady destruction of 0.8 sq ft/min of any of the materials listed in Table I would pollute the shafts and top half of the building to an undesirable degree.

This is a steady-state calculation and some time would elapse before these conditions were achieved. The time scale would become short if, at the outset, a further 40 sq ft of the material were consumed on the ground floor to give rapid contamination of this story.

If it were assumed that the smoke-generating potentialities of the materials involved were not unduly high, greater quantities of material would be needed to pollute the shafts and top half of the building. The smoke rating of red oak under flaming exposure, for example, is a sixth of the non-flaming value and hence the quantities required to achieve the conditions discussed above would be six times those quoted.

From these calculations it becomes apparent that smoke control in a building cannot usually be achieved solely by attempting to control the nature of the constructional materials, although such measures are often helpful. Positive measures aimed at controlling air movement are generally called for.

AIM OF SMOKE CONTROL MEASURES

Following the work of Tamura[9] in investigating the nature of air and smoke movement within a building, the Division of Building Research has attempted to devise techniques of smoke control. In general their development has been based on the following premises:

(1) That the measures are only likely to be implemented shortly after the outbreak of a fire so that initial contamination of various important areas (e.g. stairwells) is not likely.

(2) That an area may be considered tenable if its atmosphere is only contaminated by that from the fire area to an extent of less than 1%.

(3) That evacuation of a high building within a matter of 10 min or so, by way of stairs, is not usually possible. This subject has been investigated in some detail by Galbreath[11] who shows that periods in excess of this might be involved in a conventional building of 10 stories, with the time for evacuation increasing in proportion to building height.

(4) That the primary mechanism of smoke movement to be combatted in Canadian high-rise buildings is stack action resulting from building heating during cold weather.

(5) That vertical shafts constitute the principal path by means of which smoke migrates throughout a conventional high-rise building.

(6) That, in very high buildings, fire will not originate in elevator shafts. Tamura[12] has shown that the effective venting of shafts proves substantially less feasible when the shaft itself is directly involved in fire.

The objective of all the techniques developed was to arrange that within a few minutes of implementing smoke control measures, the following areas should become tenable and remain so indefinitely:

(a) stairwells

(b) one or more chosen elevator shafts, and

(c) sufficient floor areas, reasonably distributed throughout the building, to accommodate all the occupants. In some cases where a refuge area concept has been developed the area apparently necessary has been doubled to cater for untenability of the refuge areas on the fire floor.

These aims relate to avoiding a disaster within the building rather than to eliminating all life loss. In general it was found very difficult to attempt to ensure safety in regions immediately adjacent to the fire area. Only two techniques appeared to satisfy this requirement, which was thought to be highly desirable for such occupancies as apartments.

PRINCIPLES UNDERLYING SMOKE CONTROL TECHNIQUES

Devising a technique aimed at minimizing smoke movement in a building will usually involve consideration of the pressure characteristics of the building. Fig. 1 shows a

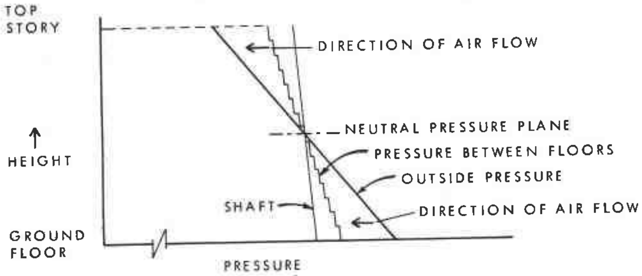

Fig. 1 Pressure characteristics within a building (winter conditions)

convenient method of illustrating pressure characteristics, which in this particular case relate to a 15-story building. All the pressure differentials depicted have been generated by stack action associated with heating the building during winter. As the abscissa represents pressure, increasing towards the right, it follows that the flow of air or smoke between two adjacent areas will always originate from the region with a higher pressure characteristic, i.e. to the right of the other. At low levels in a building, air will flow from the exterior to the floor areas and thence mainly to the shafts. At high levels in a building the reverse will prevail, flows being towards the exterior. There will also be some flow from story to story but it will be small in comparison with the flow in the shafts. A study of stack action in a 20-story building by Tamura[9] showed that over 95% of the air that flowed into the lower portion of the building and out at a higher level moved upwards in the building via vertical shafts.

One obvious way of ameliorating the problem created by the main vertical shafts is to dissociate them, effectively, from the building. They might, for example, be confined to a tower, communication with the building being by walkways or lobbies substantially open to the exterior. If all vertical shafts were thus confined the resulting pressure-characteristics would be as illustrated in Fig. 2. The pressure differentials between adjacent stories would then be greater than in conventional buildings so that a fire in one story could be expected to pollute the story above it to a greater extent than usual.

An approach, which has some similarities to the separate shaft concept, is to divide a building vertically into two, with a view to maintaining one half, including a set of elevators and stair shafts, smoke free. Where the two portions are spatially separated and communication is by vented walkways, the arrangement corresponds closely to that just described. Some refinement is called for where the

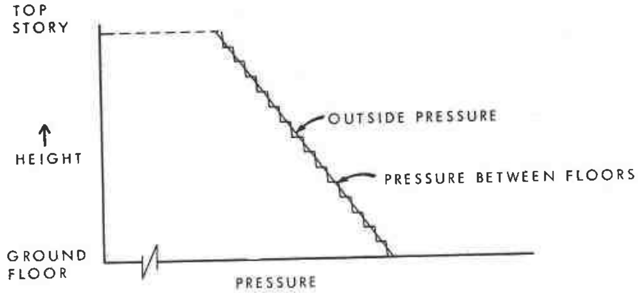

Fig. 2 Pressure characteristics in a building without vertical shafts (winter conditions)

division between the two portions of the building is by a wall that has a leakage area of more than about 6 sq in. A problem may arise because the pressure patterns in the two portions of the building may not necessarily be symmetrical. One of the most undesirable asymmetries occurs when a fire at a low level vents itself to the exterior. The pressure in that region then assumes that of the exterior and hence the flow to the same story in the other half of the building, per unit leakage area, will be the same as that of fresh air through exterior walls. A partition wall leakage area of 1% or more of that of the exterior walls could thus, in the steady state, create an unacceptable level of pollution. This particular condition could be eliminated by venting the floor area to the exterior on the "safe" side of the building, adjacent to the fire area.

A completely different type of solution to the problem associated with shafts is to ensure that shaft pressures are in every case either higher or lower than pressures on floor areas. Relating this statement to Fig. 1 would mean moving the pressure characteristics of the floor area. Moving the shaft pressure adequately to the left, in all but the highest buildings, can usually (but not always) be achieved by top venting. No smoke entering the shaft from the fire area will then return to any other story of the building. Tamura has discussed this subject in considerable detail.[12]

Moving a shaft characteristic to the right by either bottom venting or mechanical pressurization has the advantage of maintaining the shaft itself smoke free. In adopting this approach, however, it should not be considered sufficient to move the shaft merely to the position marked "B" in Fig. 3. Such a characteristic becomes unsatisfactory when a fire area at a low level in a building vents itself to the exterior. The effect is illustrated in Fig. 3 where the third floor pressure characteristic (dotted) has moved over to be coincident with that of the exterior at that level. Being to the right of the shaft at position "B" it can contaminate it with smoke. To avoid this, the shaft pressure characteristic must be moved further to the right to the position marked "C."

Achieving the location of shaft "C" in Fig. 3 is in the first instance usually possible by bottom venting of the

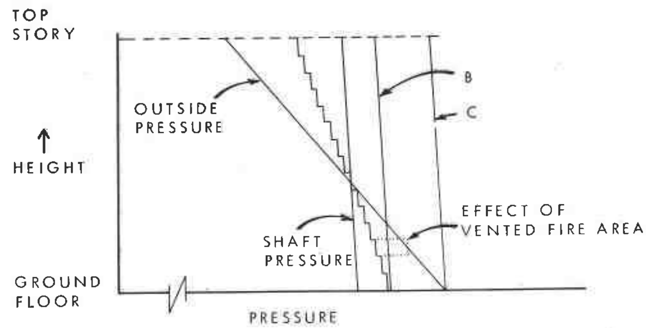

Fig. 3 Maintaining a shaft free of smoke (winter conditions)

shaft. After some time, however, the influx of cold air is liable to bend the pressure characteristic undesirably. Injecting heated air into the shaft can achieve the required objective without this disadvantage.

Where shafts are particularly leaky, required rates of air injection can be sufficiently great to cause the floor area pressure characteristics to follow those of the shaft in moving to the right to the extent that neutral planes are lowered near to ground level. In such cases it is convenient actually to aim at pressurizing the building after the manner

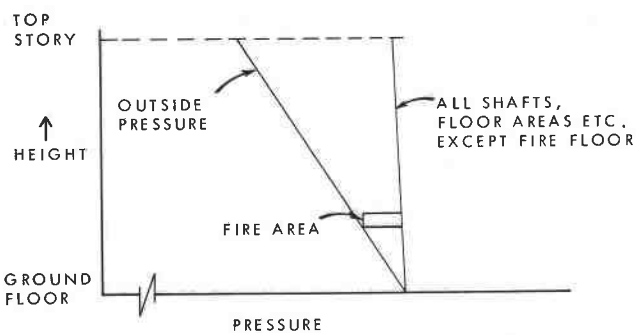

Fig. 4 Pressurized (idealized) (winter conditions)

depicted (in an idealized fashion) in Fig. 4. When the fire area is vented to the exterior all flows between the fire area and adjacent regions will be towards the fire area and no pollutant will flow to other parts of the building.

Considerable care will be called for in implementing any sophisticated smoke control technique. Detailed knowledge of the leakage characteristics will be required, together with an analysis of the effects to be expected from the various measures adopted. Thus in many buildings various shafts (garbage chutes, laundry chutes), including possibly some elevator shafts, will be vented. This could have a sharp influence on the location of the floor area pressure characteristic, which in turn would influence the air supply required to establish the desired location of other shaft characteristics.

Various other factors will need consideration and not the least of these will be the development of undesirable pressure across various doors. Conventional doors cannot readily be opened if a force of much more than 20 lbs is required, and such forces can result where adverse pressure differentials of more than 0.4 in. wg exist. In determining whether such a differential might exist in a particular case, all likely eventualities should be considered. The opening of doors in the vicinity of, or elsewhere in, a shaft, together with the breakage of windows in the fire area, might constitute important factors.

Where pressure characteristics are moved heavily to the right as already discussed, substantial air flow rates will often be called for and the secondary objective of diluting and dispersing residual pollution may be satisfactorily achieved. If the atmosphere in an enclosure is assumed always to be perfectly mixed, dilution will follow a simple exponential law and smoke densities will be reduced by a factor of 0.368 (i.e. to approximately 1/3 of the original value) for each volume of fresh air injected. Dilution by a factor greater than 100 is never called for and hence after 4.6 volumes of fresh air have been injected, an atmosphere is sure to be satisfactory (provided no further pollutant enters). As often as not adequate dilution would be achieved after injection of two volumes.

It is probably desirable, to disperse residual pollution, that flow rates should be somewhere in the range of a volume every min to a volume every 10 min. Flow rates for stair and elevator shafts, aimed at establishing suitable pressure characteristics, will also usually be found to meet this suggestion thus achieving both objectives simultaneously. In general, however, the stair and elevator shaft flow rates will be less than 100 times the rate at which polluted atmosphere could flow into the enclosure considered, were pressure characteristics not modified. Under severe winter conditions, therefore, the object of injecting air into most enclosures should be considered to be, firstly, to modify pressure characteristics and, secondly, to disperse residual pollution. To achieve adequate steady state dilution, without modifying pressure characteristics, would require even more air which would involve greater expense particularly as the air would need to be heated.

This raises yet another approach to smoke control, that of steady state dilution. Although it has been suggested that this approach is not the most appropriate for very high buildings in cold weather, it deserves consideration for mild climate applications. Two factors begin to weigh in its favor as interior-exterior temperature differentials decrease. Firstly, provided expansion problems are eliminated by venting, smoke flows as a result of stack action in the absence of control measures, are markedly reduced (theoretically to 0 with no temperature differential). Dilutent air requirements are thus reduced. The second feature is that supply air requires no heating thus greatly reducing the expense involved in its delivery. Combatting smoke movement by creating favorable pressure differentials would also prove less expensive in warm climates and a study of the relative merits of the two systems of combatting smoke movement in mild climates would be worthwhile.

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