NBSIR 83-2748

Smoke Movement in Rooms of Fire Involvement and Adjacent Spaces

U.S. DEPARTMENT OF COMMERCE
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Abstract

Key to the solution of fire safety design problems is the capability to predict the dynamics of enclosure fire environments. This paper presents a detailed qualitative description of the generic phenomena which occur during typical fire scenarios. The focus of attention is on effects within building compartments of fire involvement, i.e., compartments made up of a single enclosed space or a space of two or more rooms interconnected by significant penetrations such as open doors or windows. Throughout the discussion reference is made to quantitative methods for predicting some of the most significant of these effects. Reference is also made to available mathematical/computer models which use these latter methods to quantitatively predict the overall fire environment.

The basic topics that are covered are: fire growth in combustibles of fire origin; development of the fire plume and interaction of the plume with the ceiling surface; generation of ceiling jet flows which lead to actuation of detection/intervention hardware; interaction of ceiling jets and wall surfaces; growth of the smoke layer; development of wall flows which can be instrumental in drawing smoke down from the upper smoke layer into the relatively uncontaminated, shrinking lower ambient environment; downward radiation from the high temperature smoke layer and upper enclosure surfaces which can ultimately lead to flashover; onset of conditions which are untenable for human occupancy or property survivability.

Topics related to fire generated environments in multiroom fire/smoke compartments include: dynamics of the smoke and fresh air exchange between the room of fire involvement and the adjacent spaces; dynamics of door/window plumes, ceiling jets, smoke filling and wall flows within adjacent spaces; actuation of adjacent space fire detection/intervention hardware; and onset of adjacent space untenability.

The paper concludes with a brief discussion on the relationship between fire compartment smoke dynamics and smoke movement throughout the rest of a building.

1. INTRODUCTION

1.1 Purpose

This paper has a threefold purpose. The first is to describe the significant physical phenomena that lead to smoke (product of combustion) spread in rooms of fire involvement and in freely connected (e.g., open connected doorways) adjacent spaces. The second is to indicate how it is possible to predict the dynamic fire-generated environment within such spaces. The final purpose is to indicate how such predictions can be used to design for life or property fire safety.

The following introductory comments are presented in order to place the presentation of subsequent sections into the perspective of the generalized fire safety problem.

1.2 The General Problem of Establishing Facility Fire Safe Designs

The present discussion is concerned with aspects of past and ongoing developments of fire science and technology which relate to the general problem of establishing fire safety in enclosed spaces. The problem can be stated as follows:

How is it possible to <u>characterize the fire risk</u> of facilities, and to <u>establish criteria</u> for safe design, by using <u>traditional engineering methodology</u>?

In order to handle this problem successfully, three types of tasks need to be carried out. First, it is necessary to define and establish <u>measures</u> of life or property safety - measures that can be expressed in concise, quantitative terms. Second, it is necessary to <u>formulate tractable problems</u>. Tractable problems, here, refer to specific quantitative problem formulations which adequately model the real engineering problems and which can be solved with methods of mathematical analysis (e.g., graphs, equations, and/or user-friendly computer codes) ultimately available to professional fire protection practitioners. The final type of task would be to actually solve the problem(s), that is, to generate procedures for evaluating or designing adequate life or property safety relative to potentially hazardous fires.

Much of the work at the National Bureau of Standards is directed toward life safety aspects of fire technology. With regard to measures of life safety which can be used as focal points for any one of a number of problem formulations, we have identified one straightforward measure which has the desired characteristics. This measure of life safety is successful or safe egress. Thus, for fires in buildings, even if extensive provisions have been made for prevention, detection and suppression of potential threats, the ultimate condition of life safety may be identified as the ability of occupants to egress safely from all threatened spaces. Such an ability is equivalent to a condition of life safety.

The application of this equivalence principle leads to the concept that safe egress, and, therefore, life safety, can be achieved in buildings designed to have a balance between the Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET). Here, ASET is defined as the length of time interval between fire detection/(successful) alarm, t_{DET}, and the time of onset of hazardous conditions, t_{HAZ}. RSET is defined as the length of time, subsequent to alarm, which is actually required for safe occupant egress from threatened spaces to places of safe refuge.

The concept of balance between ASET and RSET leads to a quantitative test or criterion for safe building design, the Designed Safe Egress Criterion, viz.,

> Relative to a potential hazardous (to life) fire, a building is of safe design if $ASET = t_{HAZ} - t_{DET} > RSET$.

This formulation can be viewed as an algorithm for evaluating or determining the adequacy of a specific building design vis-a-vis life safety in fires. To apply the algorithm one would be required to estimate the ASET and

RSET associated with potential hazardous fires in specific buildings whose designs are under evaluation.

An estimate of ASET requires estimates of t_{DET} and t_{HAZ}. t_{DET} depends on the characteristics of available detection and alarm devices, and, in general, on the interactions of these with fire generated environments which develop around them. If fire or smoke control intervention strategies and hardware are involved, then predictions of the intervention times, t_{INTER}, of the hardware would, again, require knowledge of the nearby fire environment. Besides depending on the physiological characteristics of occupants, t_{HAZ} also depends on the fire environment. It is therefore evident that estimates of t_{DET}, t_{INTER}, and t_{HAZ}, and, therefore of ASET, require predictions of the dynamic environment which develops in buildings during fire conditions.

If property rather than life safety was the significant fire safety problem, then the successful egress measure of life safety would be replaced by a measure of property protection which could be related, say, to some unacceptable level of property loss. Then, a possible criterion of safe building design, a Designed Property Safety Criterion, might be,

> Relative to a potential hazardous (to property) fire, a building is of safe design if (on account of building construction, fire intervention, smoke control, etc.) the fire environment is never likely to develop to a state where unacceptable property loss would occur.

Just as predictions of fire environments are required to invoke the Designed Safe Egress Criterion, so would such predictions be required to invoke a Designed Property Safety Criterion. The next section will describe generic characteristics of dynamic fire environment as they develop in compartments of fire involvement.

2. THE DEVELOPMENT OF FIRE ENVIRONMENTS IN COMPARTMENTS OF FIRE INVOLVEMENT

In terms of the above discussion, the following is the generic problem that must be solved if one is to be able to establish the fire safety of building designs:

Given: initiation of a fire in an enclosed space

Predict (i.e., obtain a mathematical simulation of): the environment which develops at locations of likely occupancy; locations of likely detection devices; locations of likely fire/smoke intervention sensor hardware; and locations along likely egress paths

Compute (from above predictions and from known response characteristics of people and hardware): the time of fire detection; the time of intervention sensor response; the time of onset of hazardous conditions untenable to life and/or property.

In general, the above is only a simple sketch of the overall problem that is likely to be associated with the interesting details of many real fire scenarios. It is the long-term challenge of fire science and technology to solve the above type of problem, even when it is formulated in elaborate detail.

However, for the present and even for the future, the simple description is/will be adequate for treating important fire safety problems. In line with such a simple problem description this paper will mainly discuss the significant phenomena that occur during the development of fire environments in rooms of fire origin and in freely-connected (e.g., by open doors) adjacent spaces.

3. THE ROOM OF FIRE INVOLVEMENT

3.1 Fire Growth in the Combustible of Fire Origin

An unwanted ignition rapidly leading to flaming is assumed to occur within an enclosed space. This ignition is depicted in Figure 1 as occurring on the cushion of a couch in, say, a residential-type of occupancy. It is, however, important to realize that all of the discussion to follow, and Figure 1 itself, is also relevant to fire scenarios which may develop in other kinds of occupancies, e.g., as a result of ignitions in stacked commodity warehouse enclosures, places of assembly, etc.

Within a few seconds of ignition, early flame spread quickly leads to a flaming fire with a power output of the order of a few tens of kW (a power level characteristic of a small wastepaper basket fire). The fire continues to grow. Besides releasing energy, the combustion process also yields a variety of other products including toxic and nontoxic gases and solids. Together all of these products are referred to as the "smoke" produced by the fire.

With an adequate description of the ignition source and the involved combustible (e.g., ignited paper match on the corner of a couch whose frame, cushioning and finishing materials and construction were well defined), one would hope that fire science and technology would provide methods to predict the fire spread and growth process from the onset of ignition. Toward this end, ongoing research on flame spread and combustion is under way in a variety of different fire research institutions throughout the world. (Examples of such research include boundary layer analyses and experiments of flame spread on idealized materials and geometrics; and flame spread tests and rate of heat release tests on small samples of real material composites.) However, for the present and for the foreseeable future, it is beyond the state of the art of fire technology to make the required fire growth predictions with any generality. This situation leads to a dilemma for the modeler of enclosure fire environments since the physical and chemical mechanisms, which govern the dynamics of the combustion zone, drive the basic inter- and intra-compartment smoke migration phenomena whose simulation is being sought.

A practical engineering solution to the above dilemma, proposed and supported in references 1 and 2, lies in the following compromise in simulation accuracy. Prior to the time of potential flashover, it is reasonable to neglect the effect of the enclosure on flame spread and to assume that from the time of ignition to the time shortly before potential flashover the combustion zone in a particular grouping of combustibles develops as it would in a free burn situation. [Free burn here is defined as a burn of the combustibles in a large (compared to the combustion zone), ventilated space with relatively quiescent atmosphere.] To implement these ideas one simply uses empirical, free burn test data (which may or may not be presently available) to describe the combustion physics of a fire whose hazard is being evaluated. This compromise would, in the course of time, be supplanted by analytic models of flame spread and fire growth to the extent that future results of research lead to satisfactory methods for predicting such phenomena.

The implementation of the above compromise is, in principle, relatively simple. But for general use, it must be supported by an extensive data base acquired from a series of actual full-scale free burn tests. This kind of data is being acquired with some regularity at fire test laboratories such as those of the National Bureau of Standards and the Factory Mutual Research Corporation, and much has already been published (e.g., Tables 3.2 of reference 3, Tables 4-1 and 4-2 of reference 4, Figure G.2 and Table G.2 of reference 5, Table 3 of reference 6, and much data reported in reference 7 all provide information on energy release rates, Q(t), of fires in a variety of practical, full-scale assemblies of combustibles).

3.2 Development of the Plume

As depicted in Figure 2, a large fraction, λ_r, of the rate of energy released in the high temperature combustion zone is transferred away by radiation. The transferred energy, $\lambda_r Q(t)$, irradiates nearby surfaces of the combustible and far-away wall, ceiling, etc., surfaces which are in the line-of-sight of the combustion zone. The actual value of λ_r associated with the free burn of a specific array of combustibles is often deduced from data acquired during the aforementioned type of free burn tests. For practical hazardous flaming fires, λ_r is typically of the order of 0.35.

Because of the elevated temperature of the products of combustion, buoyancy forces drive them out of the growing combustion zone and up toward the ceiling. In this way a plume of upward moving elevated temperature gases is formed above the fire. For the full height of the plume and at its periphery relatively quiescent and cool gases are laterally entrained and mixed with the plume gases as they continue their ascent to the ceiling. As a result of this entrainment the total mass flow in the plume continuously increases and the average temperature and average concentration of products of combustion in the plume continuously decrease with increasing height. The plume dynamics at any instant of time can, with reasonable accuracy, be quantitatively described by a function of the rate of energy convected up from the combustion zone, $(1-\lambda_r)Q(t)$. A description of the concentration of combustion products in the plume would require, in addition, the combustion zone's rate of product generation. With regard to predictions of the dynamics of the plume, references 8-10 provide results in a variety of different levels of detail. Thus, reference 9 provides the formula in Figure 2 as an estimate of the mass flux in the plume, $\dot{m}_p$, at a distance Z above the combustion zone.

3.3 The Plume-Ceiling Interaction

As depicted in Figure 3, when the hot plume gases impinge on the ceiling, they spread across it forming a relatively thin radial jet. This jet of hot gases contains all of the smoke generated from the combustion zone, and all the ambient air which was entrained along the length of the plume.

As the hot jet moves outward under the ceiling surface it entrains ambient air from below; it transfers energy by conduction to the relatively cool adjacent ceiling surface, and by convection to the entrained air; and it is retarded by frictional forces from the ceiling surface above, and by turbulent momentum transfer to the entrained air from below. As a result of all this flow and heat transfer activity, the ceiling jet continuously decreases in temperature, smoke concentration, and velocity; and increases in thickness with increasing radius.

Research reported in the literature (e.g., references 11-18) has led to results for predicting the quantitative aspects of ceiling jet dynamics that can be used for selecting and locating smoke detectors and fusible link sprinkler head actuators[19,20], and for the mathematical modeling of overall enclosure fire environments.

With regard to detectors and fusible links, it is evident that knowledge of the properties of the ceiling jet, which hopefully engulfs these devices in real fire scenarios, is key to the prediction of their response. With regard to the overall modeling of enclosure fire environments, the basic information that must be extracted from the ceiling jet properties is the overall rate of heat transfer to the ceiling surface. Experiments have shown that this heat transfer will be significant, of the order of several tens of percent of the total energy released by the combustion zone, and, as a result, it is key to predicting the temperature of the smoke which ultimately spreads throughout the enclosure. Also, a reasonable estimate of this rate of heat transfer is required for estimating temperatures of the ceiling surface material itself.

3.4 The Ceiling Jet - Wall Interaction

The ceiling jet continues to move radially outward under the ceiling surface, and it eventually reaches the bounding walls of the enclosure. As depicted in Figure 4, the ceiling jet (now somewhat reduced in temperature from its highest levels near the plume) impinges and turns downward at the ceiling-wall juncture, thereby initiating a downward directed wall jet.

The downward wall jet is of higher temperature and lower density than the ambient into which it is being driven. The jet is, therefore, retarded by buoyancy in its downward descent, and at some distance below the ceiling the downward motion of the smokey jet is eventually halted. The wall jet is also retarded (probably to a lesser degree) by frictional forces at the wall surface, and it is cooled by conductive/convective heat transfer to relatively cool wall surfaces. Momentum and heat transfer from the jet occur away from the wall as its outer flow is sheared off and driven back upward on account of buoyancy. In its turn, the now upward-moving flow entrains ambient air in a manner which is reminiscent of entrainment into the original fire plume. Eventually a relatively quiescent upper gas layer is formed below the continuing ceiling jet flow activity.

The strength of the wall-jet flow activity will be determined by the strength of the ceiling jet at the position of its impingement with the wall. In particular, the closer the wall surfaces are to the fire, the larger will be the momentum and temperature of the ceiling jet at the ceiling-wall juncture; and the more important will be the details of the wall-jet flow activity to an understanding of the overall enclosure fire environment. Thus, for fire scenarios where the proximity of the walls to the fire is no greater than a room height, or so, it is reasonable to speculate that rates of conductive/convective heat transfer to wall surfaces can be significant, of the order of tens of percent of the fire's energy release, and that entrainment to the upward moving, reverse portion of the wall flow can lead to significant variations of the early rate of thickening of the upper gas layer. On the other hand, if walls are several room heights from the fire then the ceiling jet will be relatively weak by the time it reaches the walls. Under these latter circumstances the ceiling jet-wall interactions will themselves be weak, and it is not likely that they will play an important role in the dynamics of the overall fire environment.

Besides being important in the prediction of the overall fire environment, knowledge of the flow and temperature environments local to vigorous ceiling jet-wall interaction zones would be key to predicting the response of wall mounted smoke detectors, fusible links, etc.

3.5 Development and Growth of the Upper Layer - "Smoke Filling"

The gases in the ceiling and wall jets redistribute themselves across the upper volume of the room. Eventually a relatively quiescent, uniform thickness, elevated temperature upper smoke layer is formed below the continuing ceiling jet flow activity. As the thickness of this layer grows, it would also eventually submerge any flow zones generated by vigorous ceiling jet-wall interactions. The bottom of the layer is defined by a distinctive material interface which separates the lower ambient air from the upper, heated, smoke-laden gases. With increasing time the level of the smoke layer interface continues to drop, and the temperature and smoke concentration of the upper layer continues to rise.

In general, one would hope that fire detection, successful occupant alarm, and, if appropriate, successful intervention hardware response would occur during the stage of fire growth described so far in this and in the previous two paragraphs. As suggested earlier, rationally engineered design in this regard would be possible with predictions of the dynamic fire environments local to deployed devices, and with predictions of the resulting response of such devices.

For reasons already mentioned, some detail in the description of plume, ceiling jet and ceiling jet-wall flow dynamics is required. However, for the purpose of understanding the implications of the overall fire environment on life and property safety, simplified descriptions compatible with the aforementioned detail, would suffice, and, for a variety of practical reasons, would actually be preferable. For this reason, available predictive models of enclosure fire environments commonly describe the bulk of the upper layer environment in terms of its spacially averaged properties. Actual full scale testing of enclosure fire environments has indicated that such a simple means of describing the smoke layer represents a reasonable compromise between accuracy in simulation and practicality in implementation.

Figure 5 is a generic depiction of the enclosure fire environment at the stage of fire development under discussion. At this stage, whether or not the space of fire involvement is fully enclosed (i.e., all doors and windows are closed and only limited leakage occurs at bounding partitions) or is freely communicating with adjacent space(s) (e.g., open or broken windows or open doors to the outside environment or to an adjacent enclosed space of virtually unlimited extent; and/or open doorways to adjacent spaces of limited extent) becomes very important in the subsequent development of the fire environment. In the sense that the upper layer thickness and temperature would grow most rapidly, the fully enclosed space with most leakage near the floor would lead to the most rapid development of potentially life and property threatening conditions.

Referring again to the depiction in Figure 5, the fire plume below the smoke layer interface continues to entrain ambient air as it rises to the ceiling. However, as the hot plume gases penetrate the layer interface and continue their ascent, additional entrainment is from an elevated temperature, smoke environment. Also, once the plume gases enter the smoke, they are less buoyant relative to this layer than they were relative to the cool lower layer of ambient air. Thus, the continued ascent of plume gases is less vigorous than it would otherwise be in the absence of the upper layer.

The new and more complex two-layer state of the enclosure environment requires that some modification of the earlier-referenced quantitative descriptions of the plume, ceiling jet, and ceiling jet-wall flow dynamics be introduced. Reference 21 has proposed some modifications along these lines.

As depicted in figure 6, a new and potentially significant wall flow can develop during the present stage of fire development. This flow, which is distinct from the previously described upper wall jet, develops on account of the condition of relatively cool upper wall surfaces which bound the elevated temperature upper smoke layer. The smoke which is adjacent to these wall surfaces is relatively cool and, therefore, more dense than its surroundings. As a result of this density difference, a continuous, downward-directed wall flow develops which is injected at the smoke interface into the lower, relatively smoke-free layer. Once in the lower layer, the smoke-laden wall flow, now of higher temperature than its surroundings, will be buoyed back upward to either mix with and contaminate the lower layer or to entrain additional (i.e., in addition to the fire plume) lower layer air into the upper layer.

It is noteworthy that the wall effect just described has been observed in full and reduced scale fire tests, and that it appears to be particularly significant in enclosures with relatively large ratios of perimeter to ceiling height (e.g., in corridors)[22].

As a result of its elevated temperature the smoky upper layer transfers energy by radiation to the ceiling and upper wall surfaces which contain it. As depicted in Figures 4 and 5 by the downward directed arrows, the layer also radiates to the lower surfaces of the enclosure and its contents. Initially, the only significant role of this downward radiation is its effect on human tissue. Indeed, only after seriously life-threatening levels of downward-directed radiant energy (characterized by smoke layer temperature levels on the order of 200°C, or by radiant flux levels of the order of 2.5 kW/m^2) would the radiant energy feedback to enclosure surfaces and combustibles have a significant impact on fire growth and spread, and on the overall fire environment[1].

Once radiation feedback becomes of general significance, say when the average upper layer temperature reaches 300-400°C, it is likely that the potential for flashover will develop within a relatively short time interval (compared to the time interval between ignition and the onset of a life-threatening environment). The events which develop during this time interval will be referred to here as the transition stage of fire development.

The onset of life threatening conditions, which could be instigated for any one of a number of reasons, would occur prior to the transition stage of fire development. Before this event can be predicted, quantitative criteria defining a "life threatening environment" must be established. These criteria must be defined in terms of those physical parameters for which predictive models of enclosure fire environments can provide reasonable estimates. Consistent with earlier discussion, such parameters would include the smoke layer thickness (or vertical position of its interface), and temperature. The concentration of potentially hazardous components of the smoke in the upper layer would also be key. Criteria for the onset of a life threatening environment could, for example, be based on the following considerations[23] (which would neglect the effect of lower layer contamination due to wall flows).

When the smoke layer interface is above some specified, characteristic, face-elevation, an untenable environment would occur if and when a hazardous radiation exposure from the upper layer is attained. Such an exposure could be defined by a specified, upper layer, critical temperature. If the interface is below face-elevation, then untenability would occur if and when a second, critical, smoke layer temperature is attained. However, the latter temperature would be lower than the former one, and untenable conditions would be initiated as a result of direct burns or inhalation of hot gases. Once the interface dropped below face elevation, untenability would also occur if and when a specified, critical concentration (or a specified exposure dosage) of some hazardous product of combustion was attained.

3.6 The Transition Stage of Fire Development

Any detailed analysis and prediction of the fire environment during the transition stage of fire development must, of necessity, take account of the effects of upper layer and upper surface re-radiation, in general (e.g., significant modification to the character of the aforementioned wall flows[24]), and of the complex effects of radiation-enhanced fire growth, in particular. Such an analysis would require a mathematical model of enclosure fire phenomena which was significantly more sophisticated than would be required to predict the fire environment prior to, and, possibly, even following the transition stage.

Regarding the potential difficulty, uncertainty, inconvenience and/or cost of carrying out transition stage analysis, it is noteworthy that conservative designs for life and property safety may be possible by implementing a strategy of fire environment analysis which avoided the details of transition stage entirely. This would be done by conservatively assuming that the relatively brief time interval associated with the transition stage shrinks to a flashover jump condition at a relatively early time in the fire scenario[1].

4. SMOKE SPREAD FROM THE ROOM OF FIRE INVOLVEMENT TO ADJACENT SPACES

4.1 Smoke and Fresh Air Exchange Between a Room of Fire Involvement and an Adjacent Space

This and the following paragraph will discuss smoke spread phenomena associated with a room of fire involvement and a communicating adjacent space. Reference here will be made to a fully enclosed, two-room space with relatively large common penetrations (e.g., open doors or windows) through which the smoke and ambient air exchange will be so significant as to render inadequate an analysis which treats the room of fire involvement as an isolated enclosure. Regarding the two-room spacial configuration, Figures 1-5 would still be relevant to the early development of conditions within the fire room. However, once the smoke layer interface drops to the level of the soffit of the communicating doorway(s) or window(s), significant amounts of smoke would start to move into the adjacent space from above while significant amounts of ambient air would be driven out of the adjacent space (and into the fire room) from below. From that time on, as depicted in Figure 7, an interdependent smoke filling process in each of the two spaces will be initiated, and the adjacent space will itself start to develop a two-layer type of environment.

Throughout the course of real fire scenarios, changes in the absolute pressures of facility spaces are at the most of the order of one percent. Yet, dynamic, elevation-dependent pressure differences that exist between the rooms of fire involvement and adjacent spaces are large enough to drive a significant cross-door exchange of smoke and ambient air.

Toward the left side of Figure 8 is a sketch of the vertical static pressure distribution, $P_{fire}(Z)$, of the room of fire involvement. This is the pressure distribution that would be measured in the bulk of the relatively quiescent-environment room, away from vigorous door and plume flows. Notice that the rate-of-change of pressure with elevation is uniform and relatively large between the floor and the smoke interface, and is uniform and relatively small within the smoke layer. The reason for this is that the density (temperature) throughout each of the two layers has been assumed to be uniform, and the lower layer is more dense (i.e., of lower temperature) than the upper one. The pressure at the floor is designated as $P_{fire}(Z=0) = P_{fire,0}$.

Toward the right side of Figure 8 is a sketch of the vertical static pressure, $P_{adj}(Z)$, in the adjacent space. There, the change of slope occurs at the elevation of the adjacent space smoke interface, which is above the smoke interface in the fire room. Also, the slope of the pressure distribution above the interface is consistent with a smoke layer somewhat more dense or cooler than the smoke layer in the fire room. Finally, the pressure at the floor is designated as $P_{adj}(Z) = P_{adj,0}$. The two pressure distributions can be compared by the plot of the pressure difference, $\Delta P(Z) = P_{fire}(Z)-P_{adj}(Z)$, which is sketched in the doorway of Figure 8. At Z elevations below the soffit where ΔP is positive, gases would be driven from the fire room into the adjacent space. At elevations where ΔP is negative, gases would be driven from the adjacent space into the fire room. At the unique elevation, called the neutral plane, where ΔP is zero, the gases would tend to remain stagnant in both spaces. This is the elevation in the doorway which would divide outgoing fire room smoke above from inflowing adjacent space air below.

At any given elevation it is typical in the modeling of fire generated doorway/window flows to use Bernoulli's equation to estimate the velocity, $V(Z)$, of the flow coming out of or into the fire room. The flow is assumed to be accelerated from rest to a dynamic pressure, $\rho V^2(Z)/2 = \Delta P(Z)$, where ρ is the density of the gas from which the streamlines originate. Also, at any elevation the flow is assumed to be constricted at the vena contracta of the inlet/outlet jet, as with an orifice, to a fraction, C, of the width, $W(Z)$, of the doorway. Then the total rate of mass flow across the doorway per unit height at any elevation would be $\rho CV(Z)w(Z) = Cw(Z)\sqrt{2\rho\Delta P(Z)}$. With some minor variations, the Law of Conservation of Mass requires that the total rate of mass outflow (the smoke flow) from the fire room is equal to the total rate of mass inflow (the ambient-air flow) to the fire room. Imposing this conservation principle at any instant of time when the layer thicknesses and densities (temperatures) in the two rooms are known, leads to the instantaneous values of ΔP $(Z=0)$ and neutral plane elevation.

An indepth presentation of results for calculating total inlet and outlet mass flows and for general application of the above considerations are presented in reference 25. Recent results on most appropriate values to use for C have been obtained from full scale fire experiments described in reference 26.

4.2 Door Plume, Ceiling Jet and Smoke Filling of the Adjacent Space

Having been driven into the adjacent space by the cross-door pressure differential, the doorway smoke jet is buoyed upward toward the ceiling on account of its relatively low density (high temperature). The upward buoyant flow, depicted in Figure 7, is analogous to the previously discussed fire plume, and, with minor modifications, can be quantitatively described by the same kinds of equations. In using these equations, the enthalpy flux of the inflowing smoke jet would replace the strength, $Q(t)$, of the fire plume, and the "smoke jet buoyancy source" elevation, taken to be at the neutral plane elevation, would replace the elevation of the fire's combustion zone. Further quantitative details on one possible set of door-plume flow calculations are available in reference 25.

Just as the doorway smoke jet rises up in the adjacent space, is diluted by entrained fresh ambient air, and is mixed with the upper layer in the manner of a fire plume; so the relatively cool and dense doorway ambient jet enters the fire room, drops down past the upper layer, is contaminated by entrained smoke, and is mixed with the lower layer. This mechanism of lower layer smoke contamination in the room of fire involvement is in addition to the previously described wall flow mechanism which was depicted in Figure 6.

Figure 7 depicts the fire environment after the adjacent space upper layer is already well established. At earlier times, adjacent space smoke movement phenomena are closely related to those effects described above (i.e., Figures 3 and 4 and associated text) for the room of fire involvement. Thus, the doorway smoke jet plume impinges on the adjacent space ceiling, leads to the development of a ceiling jet which interacts with wall surfaces, and eventually redistributes itself to form a growing, uniform thickness, upper layer.

As was the case in the room of fire involvement, knowledge of adjacent space ceiling and upper wall jet properties would be key in predicting the response of adjacent-space-deployed fire detection/intervention hardware, and the temperatures of the adjacent space environment. Also, as discussed in reference 22, contamination of the lower layer by smoke injection from downward directed wall flows can play a relatively more important role in adjacent spaces than in the fire room itself.

All the above adjacent room effects must be predicted quantitatively with reasonable accuracy, since the fire generated environments in the fire room and in adjacent spaces are strongly coupled by cross-door mass exchanges. Also, of key importance is the ability to predict the onset of adjacent space environmental conditions which are untenable for life or property.

4.3 Multiroom and Multilevel Fire/Smoke Compartments

The discussion of the last two paragraphs was related to the two-room illustration of Figure 7. However, the general principles of smoke migration are no different in fire/smoke compartments of more than two connected spaces.

In multiroom or even multilevel compartments, smoke migration occurs as smoke in successive rooms fills to the door/window soffits, and then starts to "spill out" into the adjacent spaces. At the same time, in each room where filling has been initiated, the phenomena related to plumes, ceiling jets, different wall flows and upper layer-lower layer mixing are also taking place. In each of the spaces these various phenomena are generally coupled together through the connecting door/window flows. For this reason, all effects must be analyzed simultaneously. For example, in a multiroom fire/smoke compartment one needs to satisfy the principle of conservation of mass when it is applied not just to a single doorway, but to all envelopes which completely bound each room of the compartment. To do so, one needs to solve for the pressure difference distributions, and the resulting inflows and outflows across all intercompartment penetrations.

4.4 Some Special Classes of Multiroom Fire Scenarios

Single room vented to the outside. One practical, special class of multiroom fire scenario is the single room of fire involvement which is vented to the outside ambient environment. One can carry out an analysis of the fire environment in such vented spaces by bringing to bear all considerations relevant to the Figure 7 discussion, but by assuming the adjacent space to be arbitrarily large, i.e., large enough so that it would never be filled with smoke to the point where such smoke would interact with the fire room itself. The pressure distribution of the adjacent space from the floor to the top of the door/window would be specified to be the same as that of an outside ambient environment; dynamics of the plume, which is driven by the smoke jet entering the adjacent space from the fire room, would not be affected by the adjacent space ceiling or far wall surfaces; and all inflow to the fire room would be uncontaminated, ambient air.

Treating the adjacent space in the above manner leads to considerable simplifications in mathematically modeling the room fire environment. It is noteworthy in this regard, that the only mathematical models to date for predicting post-flashover fire environments are related to this configuration of a single room of fire involvement vented to the outside.

<u>Single room vented to a large space</u>. Another important class of fire scenario, which is directly related to the last one, is the single room of fire involvement which is actually vented to a very large space. Such is the configuration, for example, when a room of fire involvement is vented to a large atrium.

Under the above circumstances one could analyze the fire environment which develops in the large containing space (the atrium) as one would analyze the environment in a space with a single isolated fire (e.g., see Figures 4-6). Here, the energy and products of combustion release rates of the fire would be taken to be the enthalpy and combustion products' fluxes of the effluent from the doorway/window jet of the fire room. As before (i.e., independent of changes in the large, but now finite, adjacent space), and at least for some significant time into the fire, the development of the environment in the fire room itself, and the resulting door/window smoke jet could hopefully be obtained analytically. Short of analytic predictions, however, actual measurements of the door/window effluent acquired in full scale, free burn tests of the fire room, up to and even beyond flashover, could be used as inputs in the analysis of the (large) adjacent space problem.

The latter, combined experimental/analytic approach has been used to predict the environment which develops in large prison cell blocks during fires in single cells of different design[27].

<u>Single- and freely connected multi-room fire compartments</u>. For those times of fire development when the compartment of fire involvement consists of a single enclosed space, analysis of the fire environment is considerably simplified. This is because an accounting of inflow and outflow at windows and doors (which are presumably closed) is not required.

When the fire compartment is partitioned into separate but freely connected spaces, the relatively simple, single enclosed space analysis, where the area of the single space is taken to be the total area of the fire compartment, can continue to be relevant. Here, "freely connected" refers to fire scenarios and spacial configurations where common openings between rooms are large enough, and/or the energy release rate of the fire is small enough so that smoke layers remain reasonably uniform in thickness, temperature and product concentration throughout the bulk of the compartment area.

Quantitative criteria for establishing whether a specific fire compartment is freely connected relative to a specified fire threat are not yet available. However, the concept of the freely connected, multiroom, fire/smoke compartment has been shown to be valid during full scale multiroom fire experiments reported in references 2 and 28.

5. SOME AVAILABLE MATHEMATICAL MODELS/COMPUTER CODES FOR PREDICTING DYNAMIC ENCLOSURE FIRE ENVIRONMENTS

In recent years many mathematical models and associated computer codes for predicting dynamic enclosure fire environments have been developed in a variety of different research institutions throughout the world. To the extent that these models/computer codes take account of any of the individual fire phenomena discussed earlier, the accounting tends to be relatively similar from model to model. Nonetheless, there is a good deal of variation between them. Some of the significant differences tend to be in the number and detail of the individual physical phenomena that are taken into account, the number and complexity of interconnected fire compartment spaces that can be analyzed, the capability of the computer hardware that is required to run the computer code, the user-friendliness of the computer code, and its available documentation.

While it is well beyond the scope of this paper to exhaustively catalogue and describe the capabilities and special features of all currently available fire models, it is at least appropriate to identify some of them. Attention here will be focused on a listing of some zone-type, enclosure fire growth models and associated computer codes which are available with some documentation through the Center for Fire Research of the U.S. National Bureau of Standards. It is noteworthy that these models tend to be in a continuing state of development/improvement. In this regard, only the capabilities of their "user-ready" versions are identified here.

Building Research Institute (BRI) - Japan: Communicating multiroom multilevel space vented to the outside[29].

California Institute of Technology: Two communicating rooms, both vented to the outside[25,30].

Center for Fire Research of National Bureau of Standards (CFR/NBS):

- Single room vented to the outside[32,33].
- Single enclosed space (ASET)[1,2,23].
- Postflashover predictions for a single room vented to the outside (COMPF2)[34].

Harvard University: Single room with vents to the outside[31].

Illinois Institute of Technology Research Institute (IITRI): Single room with vents to the outside (RFIRES)[5].

6. SMOKE SPREAD OUTSIDE THE SMOKE COMPARTMENT OF FIRE INVOLVEMENT

This paper has concentrated on smoke spread phenomena within smoke compartments of fire involvement. Yet, the outline of the generic fire safety problem which was presented above in the second section is also relevant to the general problem of predicting smoke environments throughout an entire facility.

Figure 9 illustrates a practical concept for modeling the development of smoke environments both inside and outside the smoke compartment of fire involvement. Facility spaces that would be included in the smoke compartment (on the left of the figure) are distinguished from those included in the rest of the building or facility (on the right) by the detail which is required to describe or mathematically model the fire-generated environments within them. In the smoke compartment of fire involvement, smoke would spread within a room, and would be driven from room to room by strong buoyancy forces which lead to layered smoke environments. These environments must be analyzed in the context of (at least) a two-layer model with associated phenomena of plume flow, surface flows, etc. In the "rest of the building", it is reasonable to describe the smoke in each space as being uniformly dispersed. Here, dynamic changes in the distribution of the environment comes about from room-to-room pressure differences which are generated by stack effects, wind effects and forced ventilation, and which lead to smoke movement, mixing, and dilution.

The fire compartment is the source of smoke to the rest of the building. The rate of introduction of this smoke depends on the pressure differences across common partition assemblies, and on their leakage characteristics[35]. Once the rate of smoke leakage across common partitions can be expressed quantitatively, the "rest of the building" problem could be analyzed with a model of smoke movement similar to those presented in references 36 and 37.

An overall view of the research and development required to implement the above concept for modeling fire environments and designing for fire safety in complex enclosed facilities is presented in reference 38.

7. ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Health and Human Services, and the Bureau of Mines and National Park Service of the U.S. Department of Interior.

8. REFERENCES

1. Cooper, L.Y., A Concept for Estimating Available Safe Egress Time in Fires, in Fire Safety Journal, 5, (2), pp. 135-144, 1983.

2. Cooper, L.Y., A Mathematical Model for Estimating Available Safe Egress Time in Fires, Fire and Materials, 6, (3/4), pp. 135-144, 1982.

3. Butcher, E.G. and Parnell, A.C., Smoke Control and Fire Safety Design, E. and F.N. Spon Ltd., London, 1979.

4. Guide for Smoke and Heat Venting, NFPA 204M, 1982.

5. Pape, R., Waterman, T. and Eichler, T.V., Development of a Fire in a Room From Ignition to Full Room Involvement - RFIRES, IITRI Rpt. NBS-GCR-81-301 for National Bureau of Standards, 1981.

6. Friedman, R., Quantification of Threat from a Rapidly Growing Fire in Terms of Relative Material Properties, Fire and Materials, 1, (1), pp. 27-33, 1978.

7. Babrauskas, V., Combustion of Mattresses Exposed to Flaming Ignition Sources. Part I. Full-Scale Tests and Hazard Analysis, NBSIR 77-1290, National Bureau of Standards, 1977.

8. Heskestad, G., Engineering Relations for Fire Plumes, to appear in Fire Safety Journal.

9. Zukoski, E.E., Kubota, T. and Cetegen, B., Entrainment in Fire Plumes, Fire Safety Journal, 3, pp. 107-121, 1980/81.

10. McCaffrey, B.J., Purely Buoyant Diffusion Flames: Some Experimental Results, NBSIR 79-1910, National Bureau of Standards, 1979.

11. Alpert, R.L., Turbulent Ceiling-Jet Induced by Large Scale Fires, Combustion Science and Technology, 11, pp. 197-213, 1975.

12. Heskestad, G., Similarity Relations for the Initial Convective Flow Generated by Fire, Paper 72-WA/HT-17, Winter Annual Mtg. ASME, 1972.

13. Heskestad, G. and Delichatsios, M.A., Environments of Fire Detectors - I: Effect of Fire Size, Ceiling Heights, and Material. Vol. 1. Measurements, FMRC Rpt. NBS-GCR-77-86 for National Bureau of Standards, 1977.

14. Heskestad, G. and Delichatsios, M.A., Environments of Fire Detectors - I: Effect of Fire Size, Ceiling Heights, and Material. Vol. 2. Analysis, FMRC Rpt. NBS-GCR-77-95 for National Bureau of Standards, 1977.

15. Heskestad, G. and Delichatsios, M.A., Environments of Fire Detectors - II: Effect of Ceiling Configuration. Vol. 1. Measurements, FMRC Rpt. NBS-GCR-78-128 for National Bureau of Standards, 1978.

16. Heskestad, G. and Delichatsios, M.A., Environments of Fire Detectors - II: Effect of Ceiling Configuration. Vol. 2. Analysis, FMRC Rpt. NBS-GCR-78-129 for National Bureau of Standards, 1978.

17. Veldman, C.C., Kubota, T. and Zukoski, E.E., An Experimental Investigation of Heat Transfer from a Buoyant Plume to a Horizontal Ceiling - Part I. Unobstructed Ceiling, C.I.T. Rpt. NBS-GCR-77-97 for National Bureau of Standards, 1975.

18. Cooper, L.Y., Heat Transfer from a Buoyant Plume to an Unconfined Ceiling, J. Heat Transfer, 104, pp. 446-451, 1982.

19. Alpert, R.L., Calculation of Response Time of Ceiling Mounted Fire Detectors, Fire Technology, 3, pp. 181-195, 1972.

20. Benjamin, I., Heskestad, G., Bright, R. and Mayes, T., An Analysis of the Report on Environments of Fire Detectors, Fire Detection Inst., 1979.

21. Cooper, L.Y., Convective Heat Transfer to Ceilings Above Enclosure Fires, Proceedings of 19th Inter. Symp. on Comb., Haifa, 1982.

22. Cooper, L.Y., On the Significance of a Wall Effect in Enclosures with Growing Fires, to be presented at 22nd ASME/AIChE National Heat Transfer Conf., Seattle, 1983.

23. Cooper, L.Y. and Stroup, D.W., Calculating Available Safe Egress Time (ASET) - A Computer Program and User's Guide, NBSIR 82-2578, National Bureau of Standards, 1982.

24. Jaluria, Y., Buoyancy-Induced Wall Flow Due to Fire in a Room, to appear as NBSIR, National Bureau of Standards.

25. Zukoski, E.E. and Kubota, T., Two-Layer Modeling of Smoke Movement in Building Fires, Fire and Materials, 4, (1), pp. 17-27, 1980.

26. Steckler, K., Quintiere, J. and Rinkinen, W., Flow Induced by Fire in a Compartment, Proceedings of 19th Inter. Symp. on Comb., Haifa, 1982.

27. Life Safety Code, NFPA 101, A-15-3.1.3, 1981.

28. Cooper, L.Y., Harkelroad, M., Quintiere, J. and Rinkinen, W., An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multiroom Fire Scenarios, J. Heat Transfer, 104, pp. 741-749, 1982.

29. Tanaka, T., A Model of Multiroom Fire Spread, to appear as NBSIR, National Bureau of Standards.

30. Zukoski, E.E. and Kubota, T., A Computer Model for Fluid Dynamic Aspects of a Transient Fire in a Two Room Structure, C.I.T. Rpt. prepared for National Bureau of Standards, 1978.

31. Mitler, H.E. and Emmons, H.W., Documentation for CFC V, the Fifth Harvard Computer Fire Code, Harvard Univ., Home Fire Proj. Rpt. 45, 1981.

32. Quintiere, J., Steckler, K. and McCaffrey, B., A Model to Predict the Conditions in a Room Subject to Crib Fires, presented at First Specialists Mtg. of Comb. Inst., Bordeaux, 1981.

33. Steckler, K., A Calculation of Wall Fire Spread in an Enclosure, to appear as NBSIR, National Bureau of Standards.

34. Babrauskas, V., COMPF2 - A Program for Calculating Post-Flashover Fire Temperatures, NBS TN991, National Bureau of Standards, 1979.

35. Cooper, L.Y., The Need and Availability of Test Methods for Measuring the Smoke Leakage Characteristics of Door Assemblies, to appear as NBSIR, National Bureau of Standards.

36. Wakamatsu, T., Calculation of Smoke Movement in Buildings, Research Paper 34, Building Research Inst., Tokyo, 1968.

37. Evers, E. and Waterhouse, A., A Computer Model for Analyzing Smoke Movement in Buildings, SCS Ltd. Rpt. CP 68/78 for Fire Research Station, 1978.

38. Cooper, L.Y. and Nelson, H.E., Life Safety Through Designed Safe Egress - A Framework for Research, Development and Implementation, 6th Mtg. UJNR Panel on Fire Research and Safety, Tokyo, 1982.

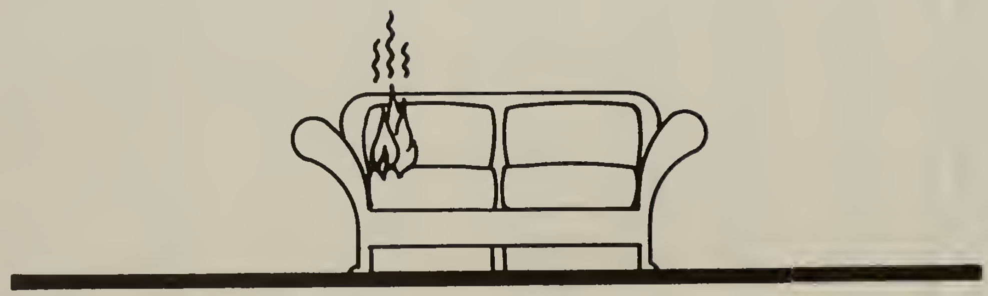
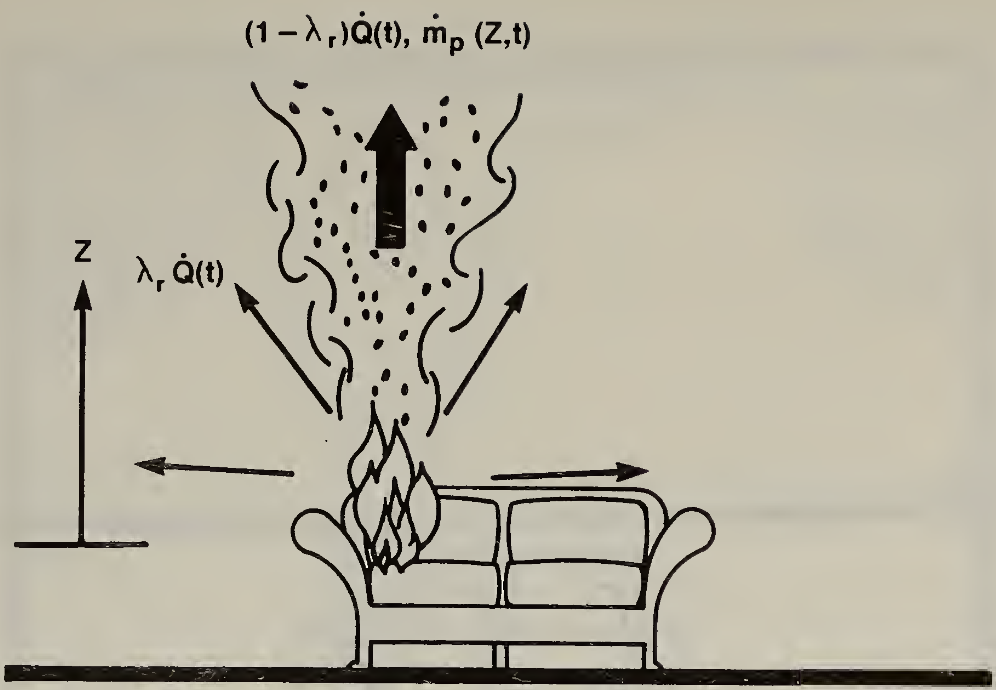


Figure 1. Events immediately after ignition.



$$\dot{m}_p(Z,t) =$$

$$0.21\,\rho_\infty (gZ)^{1/2} Z^2 Q^*(Z,t)^{1/3}$$

$$\text{where } Q^* = \frac{(1-\lambda_r)\dot{Q}(t)}{\rho_\infty C_p T_\infty (gZ)^{1/2} Z^2}$$

Figure 2. Development of the plume.

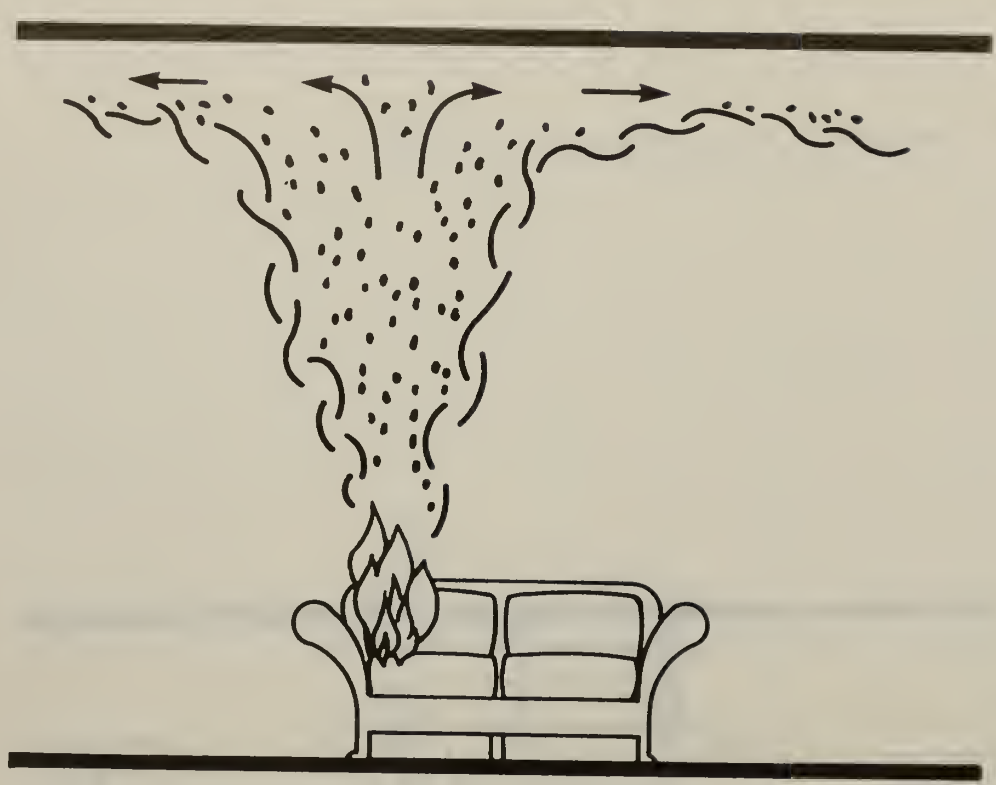


Figure 3. The plume-ceiling interaction.

Figure 4. Ceiling jet-wall interactions.

Figure 5. Fully enclosed space with developed growing upper layer.

Figure 6. Further "smoke filling".

Figure 7. Smoke and fresh air exchange between a room of fire involvement and an adjacent space.

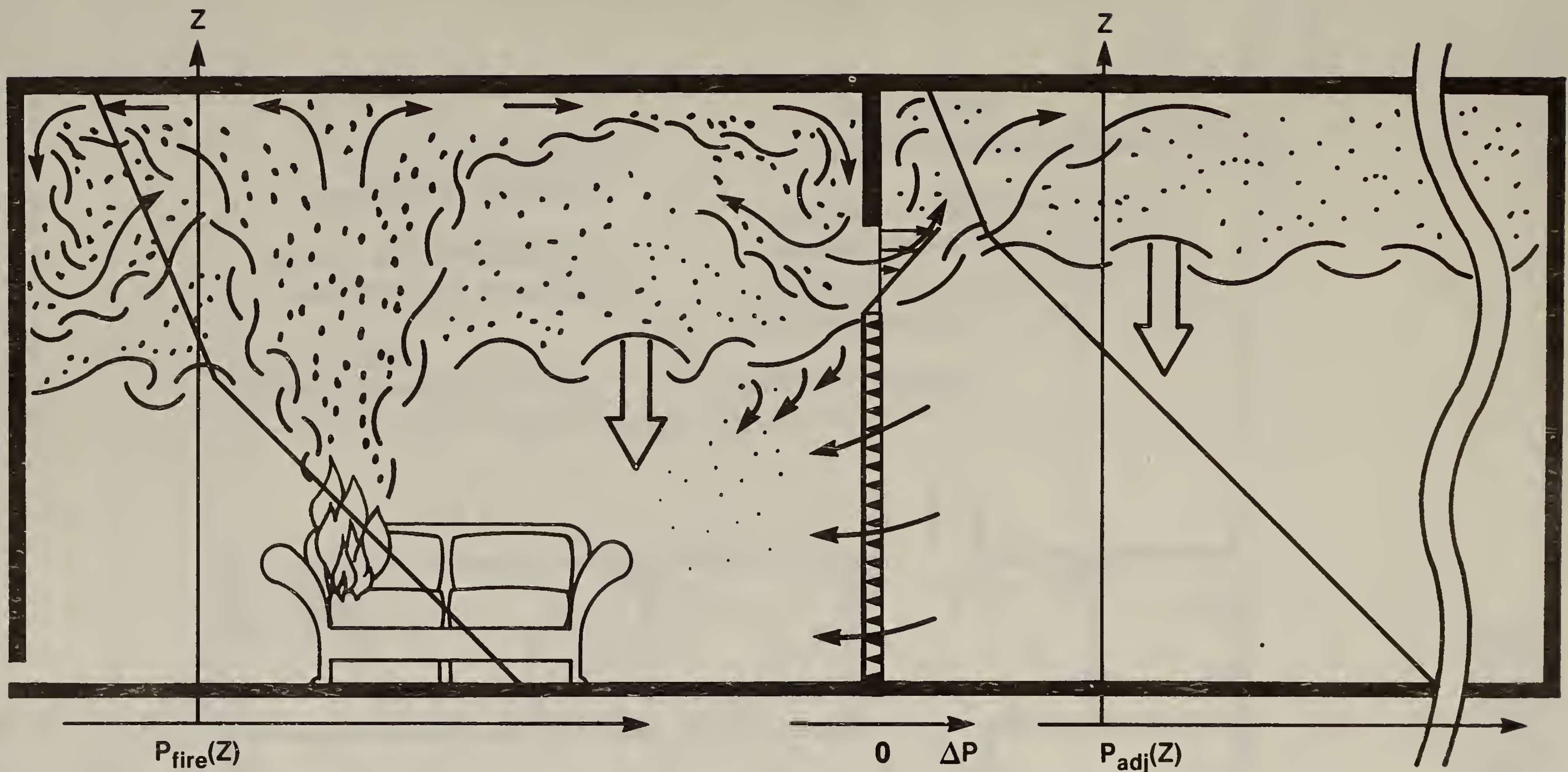


Figure 8. Figure 7 with sketches of pressure distributions.

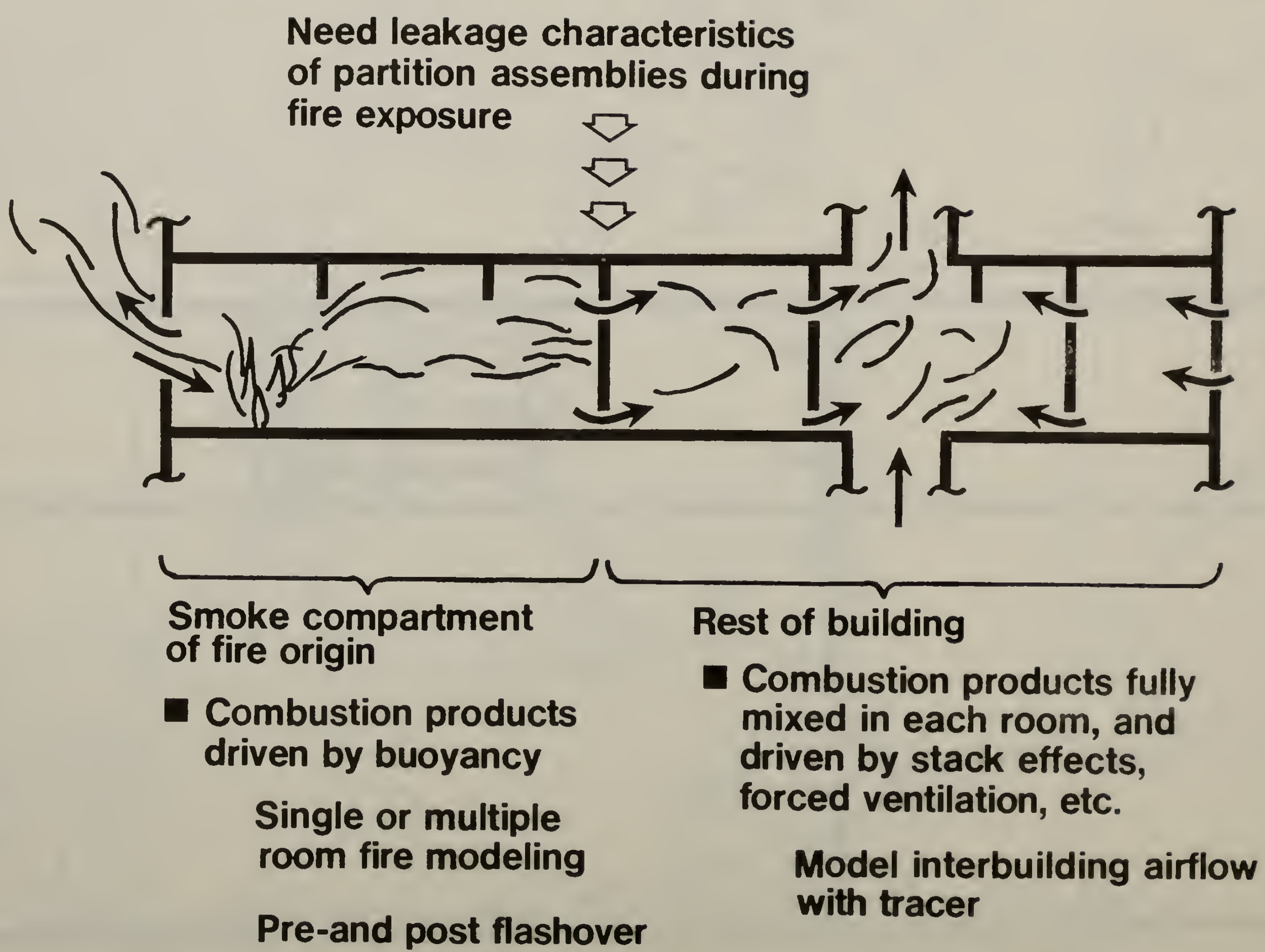


Figure 9. A concept for modeling smoke spread throughout complex facilities.

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 83-2748	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE	5. Publication Date
Smoke Movement in Rooms of Fire Involvement and Adjacent Spaces	July 1983
	6. Performing Organization Code
7. AUTHOR(S) Leonard Y. Cooper	8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, DC 20234	10. Project/Task/Work Unit No.
	11. Contract/Grant No.
12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)	13. Type of Report & Period Covered
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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Key to the solution of fire safety design problems is the capability to predict the dynamics of enclosure fire environments. This paper presents a detailed qualitative description of the generic phenomena which occur during typical fire scenarios. The focus of attention is on the effects within building compartments of fire involvement, i.e., compartments made up of a single enclosed space or a space of two or more rooms interconnected by significant penetrations such as open doors or windows. Throughout the discussion reference is made to quantitative methods for predicting some of the most significant of these effects. Reference is also made to available mathematical/computer models which use these latter methods to quantitatively predict the overall fire environment. The basic topics that are covered are: fire growth in combustibles of fire origin; development of the fire plume and interaction of the plume with the ceiling surface; generation of ceiling jet flows which lead to actuation of detection/intervention hardware; interaction of ceiling jets and wall surfaces; growth of the smoke layer; development of wall flows which can be instrumental in drawing smoke down from the upper smoke layer into the relatively uncontaminated, shrinking lower ambient environment; downward radiation from the high temperature smoke layer and upper enclosure surfaces which can ultimately lead to flashover; onset of conditions which are untenable for human occupancy or property survivability. Topics related to fire generated environments in multiroom fire/smoke compartments include: dynamics of the smoke and fresh air exchange between the room of fire involvement and the adjacent spaces; dynamics of door/window plumes, ceiling jets, smoke filling and well flows within adjacent spaces; actuation of adjacent space fire detection/intervention hardware; and onset of adjacent space untenability.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Combustion products; compartment fires; egress; enclosure fires; fire detection; fire growth; fusible links; hazard analysis; mathematical models; room fires; smoke movement; tenability limits.

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